Technical Note on TRUSTED thermistors, metrology and temperature sensors

TRUSTED

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11 rue Hermès, Parc Technologique du Canal — 31520 Ramonville Saint-Agne, France
Tel +33 (0)5 61 39 47 00 Fax +33(0)5 61 75 10 14
www.cls.fr

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1 Introduction

The Copernicus TRUSTED project (Towards Fiducial Reference Measurements of Sea-Surface Temperature by European Drifters) organized a remote workshop on 'High-Resolution Sea Surface Temperature (HRSST) drifting buoys for satellite SST' from the 1st March 2021 to the 4th March 2021. It was broken down into 5 sessions. Each session consisted of a series of presentation followed by questions and answers and a general discussion.

During those discussions, a few questions were raised which would benefit from further written elaboration, contained within this technical note. These points concerned:

- The Thermistor technology
- The Metrology:
  - The steps towards SI traceability for drifting buoys;
  - Details of the SHOM calibration and accreditation.
- Temperature Sensor:
  - Definition and technical details of the technology used for the SVP-BRST SST sensor.
- Calibration procedure
  - Expanded uncertainty table

2 Thermistors

There are many ways to translate a temperature measurement from an electronic signal. Amongst the most used nowadays are resistance temperature detectors (RTDs) and thermistors.

A thermistor is a semi-conductor sensor, whose resistance is dependent on temperature. The term is a combination of "thermal" and "resistor". It is made of metallic oxides, pressed into a bead, disk, or cylindrical shape and then encapsulated with an impermeable material such as epoxy or glass.

There are two types of semi-conductor sensors: Negative Temperature Coefficient (NTC) and Positive Temperature Coefficient (PTC). Thermistors are NTC, when the temperature increases, resistance decreases. Conversely, when temperature decreases, resistance increases. This is type of semi-conductor sensors that is used the most.

A PTC thermistor works a little differently. When temperature increases, the resistance increases, and when temperature decreases, resistance decreases.

2.1 NTC

Most NTC types of thermistor are normally usable for a temperature range between −55 and 200 °C.

The temperature sensitivity of an NTC sensor is expressed either in ohm/°C or as "percentage change per degree C". Depending on the materials used and the specifics of the production process, the typical values of temperature sensitivities range from -3% to -6% per °C. This sensitivity is not constant throughout the range of thermistor temperature. That leads to their non-linear response (see fig.1) compared to platinum 100 Ω sensors.

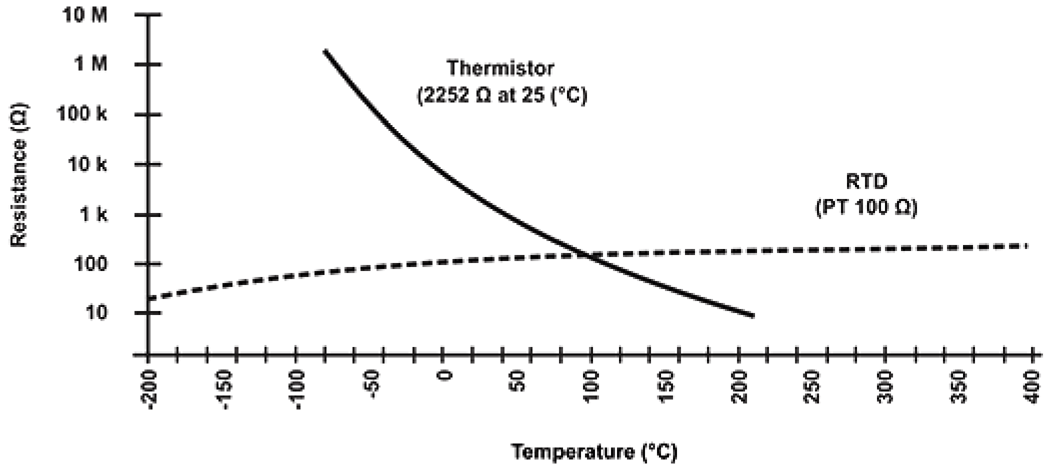

Figure 1 :Characteristic NTC curve

As can be seen from the figure, the NTC thermistors have a much steeper resistance-temperature slope compared to platinum RTDs, which translates to better temperature sensitivity.

Since the relationship between resistance and temperature (the R-T curve) is highly nonlinear, certain approximations must be utilized in practical system designs.

2.1.1 First-order approximation

One approximation, and the simplest to use, is the first-order approximation which states that:

$$\Delta R = k\Delta T$$

Where k is the negative temperature coefficient, ΔT is the temperature difference, and ΔR is the resistance change resulting from the change in temperature. This range over which k can be considered constant depends on the accuracy desired.

2.1.2 Beta formula

Another equation describes the general response curb of thermistors. It is dependent on a single material constant β which can be obtained by measurements. The equation can be written as:

$$R(T) = R(T_0) \cdot e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

Where R(T) is the resistance at the temperature T in Kelvin, R(T0) is a reference point at temperature T0. If two points calibration are used to linearize this relation, the accuracy will be no more inferior to ±5°C over the complete useful range of the NTC thermistor.

2.1.3 Steinhart-Hart equation

Another approximation often used is the Steinhart-Hart formula, published in 1968:

$$\frac{1}{T} = A + B(ln\ R) + C(ln\ R)^3$$

Where ln R is the natural logarithm of the resistance at temperature T in Kelvin, and A, B and C are coefficients derived from experimental measurements. These coefficients are usually published by thermistor vendors as part of the datasheet. As with the Beta relationship, The Steinhart-Hart formula accuracy depends on the number of calibration points used. In the TRUSTED project, this is the equation used for the SST sensors.

As demonstrated in Liu et al, (2018), the Steinhart-Hart equation is not the most efficient to inverse the Beta relation and to reduce the non-linearity of the thermistor's responses. This is why the HRSST sensors of the TRUSTED project have been linearized with the Bennett relation.

2.1.4 Bennett or Hoge-2 equation

This approximation, published in 1971 is considered more accurate (Liu et al, 2018) but requires the determination of 4 coefficients:

$$t(°C) = \frac{1}{[A + Bln(x) + Cln(x)^2 + Dln(x)^3]} - 273.15$$

According to the measurements made by Liu at al., for temperatures between 278.15 K and 328.15 K, the interpolation error is of 5.93 mK with the Steinhart-Hart relation so that it is only of 0.23 mK with the Bennett or Hoge-2 equation. Residuals in the same error ratio had been found at the SHOM, leading to the adoption of the Bennett relation instead of the Steinhart one for the HRSST sensor in the TRUSTED project.

<u>Reference:</u>

Liu, G., Guo, L., Liu, C., Wu, Q., 2018. Evaluation of different calibration equations for NTC thermistor applied to high-precision temperature measurement, Measurement, 120, 21-27. http://doi.org/10.1016/j.measurement.2018.02.007

2.2 Linearized Thermistors

By adding some very basic electronics, such as the addition in parallel of resistors, it is possible to reduce the non-linear behavior of thermistors over a given temperature range.

The following equations are an example used by ILX light wave to determine the parallel resistance of the thermistor at specific value:

$$R_{Therm} = R_{25} e^{\beta\left(\frac{1}{T} - \frac{1}{T_{25}}\right)}$$

$$R_{Linearized} = \frac{1}{\frac{1}{R_{Therm}} + \frac{1}{R_{10k}}}$$

Where β is the Beta value of the thermistor, R25is the resistance value at 25°C, R10kis the resistance value of a 10kΩ resistor and T25 is the reference temperature of 25°C converted to Kelvin

Setting the value of β determines the thermistor resistance accuracy over the chosen range.

Thermistors offer a distinct advantage over other temperature sensors - high sensitivity. But thermistors come with a price. The resistance versus temperature curve is highly non-linear. However, a simple technique can straighten out the bow in the curve, at least over a reasonable temperature range.

3 Metrology

Following the TRUSTED session presentations, the definition of 'traceability' and its application to the field of operational oceanography was discussed, including the laboratory accreditation required for SI-traceability.

In the framework of the TRUSTED project, the metrology laboratory can provide evidence that all the instruments used, and measurements performed are linked to the standards of the French primary temperature metrology laboratory, LNE-CNAM.

The SHOM metrology laboratory also regularly inter-compares its results with instruments calibrated by the metrology laboratory of the American company Sea Bird, whose fixed reference points are attached to NIST US national references. Although Sea Bird is not accredited, its produces and calibrates 100 % of ARGO floats temperature sensors to ± 0.002 °C and almost 98 % of reference CTD measurements.

The SHOM Metrology laboratory is ISO9001-2015 certified. During quality audits, evidence must be shown of the links to national references and the conformity of the reports produced to the ISO 10012 standard. The regularity of those links is also checked during the audits.

From the VIM-2012 definition of 'traceability', it is written (definition 2.41 p29): *metrological traceability is the property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty*.

The note 7 of this definition says that: "*The ILAC considers the elements for confirming metrological traceability to be an unbroken metrological traceability chain to an international measurement standard or a national measurement standard, a documented measurement uncertainty, a documented measurement procedure, accredited technical competence, metrological traceability to the SI, and calibration intervals (see ILAC P-10:2002)*". ILAC is the International Laboratory Accreditation Cooperation and the metrology performed on the TRUSTED sensors conforms to this definition.

The SHOM laboratory reference cells were calibrated at the LNE-CNAM.

The LNE regularly calibrates all sorts of equipment for industry, including temperatures sensors. It is not a primary reference laboratory, and its reference cells have the following uncertainties:

- ptH_2O, 0.62 mK,
- pfGa, 1.24 mK.

Consequently, in its documentation its state that it cannot calibrate instruments to better than ± 0.006 °C in the range 0 – 100 °C.

The SHOM reference cells were calibrated at the primary temperature laboratory (National Reference, NMI)), the LNE-CNAM (ex INM, Institut national de Metrologie). The uncertainties given by the LNE-CNAM for the SHOM reference were as follows:

- ptH_2O, 0.1 mK, (calibrated at the LNE-CNAM)
- pfGa, 0.24 mK. (calibrated at the LNE-CNAM)

This enables the SHOM to calibrate its reference sensors to meet the World Ocean Circulation Experiment (WOCE) and general oceanographic standards (± 0.002 °C).

If temperature sensors of satellite radiometers need to be calibrated from – 50 °C to + 50 °C, the oceanographic temperature range is -2 °C to 35 °C. In this range, the calibration of thermometers to ptH_2O and pfGa is sufficient to meet the tolerance ± 0.002 °C,

For the range – 50 °C to +50 °C the calibration of the sensors must be made to the pt of Mercury at -38.8344 °C, probably to the pt of Argon to -189.3442 °C and to the freezing point of Indium at 156.5985 °C. The expanded calibration of these points given in the LNE document (Attestation d'Accreditation N° 2-02 rév. 6 https://tools.cofrac.fr/annexes/Sect2/2-02.pdf) is respectively 2.93 mK, 2.15 mK and 1.78 mK. This leads to an uncertainty close to ± 0.006 °C for that temperature range.

4 SVP-BRST SST sensor

The SST temperature used in the SVP-BRST buoy is a Negative Temperature Coefficient thermistor. The NTC used is the same as the one used in the HRSST sensor and the acquisition chain is similar to the one used as part of the NKE INSTRUMENTATION logger range. The technologies applied to the SST sensor (Signal conditioning, acquisition chain and processing) are the result of over 20 years of experience in temperature measurement and are not based on a linearized thermistor technology.

Aged glass components have been employed by Sea Bird since the 80's to stabilize its thermistors before use. Using glass to protect thermistors is necessary when the thermistor is used without a protecting tube. But in the case the NKE INSTRUMENTATION sensors, the thermistor is enclosed in a sealed hermetic tube. The thermistor is therefore protected from humidity and using a glass hermetic encapsulation is not mandatory and would not improve the quality of the measurements.

The drift of NKE INSTRUMENTATION SST sensor was presented to be 0.004 °C/year, for the two recovered buoys after a year at sea. If the life expectancy of a buoy is 3 years, this gives a drift of 0.012 °C, within the specified tolerance.

Figure 2 :Analog SST sensor before being screwed into the buoy

The non-HRSST (SST) sensor is adapted to have samples equally distributed during the HRSST acquisition. The acquisition is set to 5 measurements with a sampling period of 1 minute.

The Steinhardt equation is implemented in the microcontroller to determine the temperature from the NTC thermistor, and the equation is adjusted due to 3 calibration points carried out (5°C, 15°C and 25°C) in the NKE INSTRUMENTATION metrology laboratory. (Thermo-regulated bath, 3m°C stability and Seabird reference temperature).

Note that the HRSST sensor uses the more accurate Bennett equation which requires at least 4 calibration points.

All of the (non-HRSST) SST sensors are calibrated in the metrological facility using 3 points of calibration. The following figures show an example of deviation at 25°C between NKE Instrumentation SBE reference and HRSST / SST sensors for SC40 Y18 N0024 buoy.

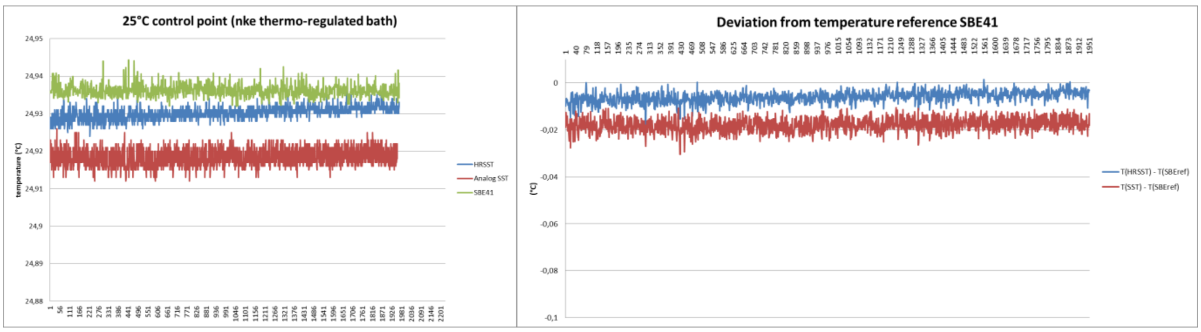

Figure 3 :Comparison of the SVP-BRST SST and HRSST sensors to an SBE41

As described above, the SHOM laboratory has also performed verification of the SST (non-HRSST) sensor of the SVP-BRST buoy.

An example of the result of the verifications made on the SST sensor by the SHOM is visible in figure 4. All SST (non-HRSST) sensors have been calibrated at NKE INSTRUMENTATION before delivery.

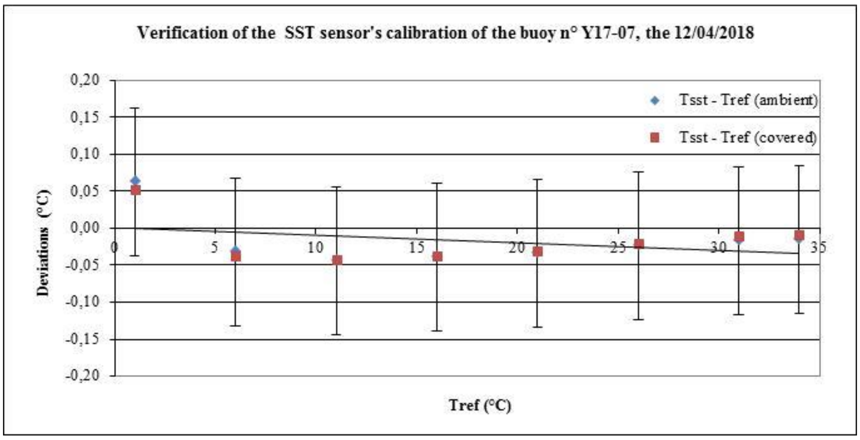

Figure 4 : results of the verifications made on the buoy n° Y17-07 SST sensor.

The uncertainty error bars show that deviations respect the ± 0.1 °C tolerance from 1 to 35 °C, whatever the external temperature of the buoy or the cooling or warming of the water.

5 Calibration Procedure

In the TRUSTED project, both the SST and the HRSST sensor are calibrated by NKE INSTRUMENTATION prior to being mounted on the drifter. This calibration is used to determine the coefficients for the Steinhart-Hart equation (3 coefficients) for the SST sensor and the Bennett equation for the HRSST sensor (4 coefficients). The SHOM then performs a reference calibration on all HRSST sensors and it is the coefficients calculated by the SHOM which are used by the HRSST sensor micro controller.

A verification is then performed on a single drifter from every batch of 10 to check that the insertion of the HRSST sensor within the buoy does not lead to any added uncertainties.

The results are presented as expanded uncertainties tables.

Uncertainty budget of HRSST measurements	N° Y17-07 (mK)	N° Y18-24 (mK)
Reference temperature (u_{tref})	0.9	0.9
Bath stability (u_{Bath})	0.3	0.3
Buoy HRSST reproducibility (S)	2.5	3.4
Buoy HRSST repeatability (S_{rep})	0.5	0.5
Expanded uncertainty (U_C)	5.5	7.2

Figure 5 :Example of a buoy Uncertainty Table

The full details of the calibration procedure implemented in the TRUSTED project is presented in Le Menn et al, 2019.

Reference:

Le Menn M., P. Poli, A. David, J. Sagot, M. Lucas, A. O'Carroll, M. Belbeoch, K. Herklotz, 2019, Development of Surface Drifting Buoys for Fiducial Reference Measurements of Sea-Surface Temperature, Frontiers in Marine Science,6,

https://doi.org/10.3389/fmars.2019.00578

6 Summary

This technical note gives further information on the thermistor technology, the metrology and temperature sensors used within the TRUSTED project. The technical note gives information on the calibration procedures performed and the steps towards traceability achieved.