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Traceable Sea Temperature measurements performed by Optical fibers

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Abstract – In the framework of the EMRP project "ENV 58. Metrology for essential climate variables", a new technique to perform traceable temperature measurements of the sea water column and sea water surface was designed and it is being studied and applied to real situation in the submarine observatory (www.obsea.es).
This new technique is based on optical fiber Bragg gratings, which implies the distribution of temperature sensors along the fiber. In the design of these distributed thermometers special attention was paid to the involved materials in order to avoid the damages of such corrosive environment.

These fibers were calibrated as optical instruments and as thermometers, in order to get traceable measurements, as well as, reliable uncertainty calculation of the seawater temperature profile and of the sea water surface temperature, that are being continuously measured. Besides, these new devices are continuously compared to the current thermometers, CTD, located in the submarine observatory.

I. INTRODUCTION

The behaviour and characteristics of the sea is a key parameter to be studied since it plays a very important role in the climate evolution due to the continue heat interchange between the seawater surface and the atmosphere. For this reason, the number of studies about sea has been increasing for the last years. Nowadays a big amount of studies is focused on the measurements of parameters like acidify, salinity and acoustic noise. But temperature of the sea water is, by far, one of the most important parameter. Currently, the sea water temperature is mainly measured by three different methods. In the first one, the temperature measurement is performed via satellite observation. A second method consists on the attachment of thermometers to buoys and its launched into the sea at fixed positions. In the third one, the seawater temperature is measured in research campaigns by ships, where different arrays, known as CTD [1] are launched in order to perform measurements of conductivity, temperature, and depth. All these three methods present disadvantages like, satellite measurements are not possible at higher sea depths than 1 metre, the buoys provides measurements at fixed positions and the research campaigns do not supply measurements for a long period of time.

In this paper the use of thermometers based on the distribution of temperature sensors along an optical fibre is proposed, explained and analysed to measure seawater temperature profile and seawater surface temperature. After the design of the fiber optics, the characterization, and calibration of these thermometers with the evaluation of all the associated uncertainty components are analysed and the real test in an onsite environment, permanent underwater observatory OBSEA [1] is described.

The paper is structured in six parts. In the first part, the design and optical calibration of the fiber optics, performed at IO-CSIC, is described. Then the calibration of the optical fibers and CDTs as thermometers, performed by CEM, is analysed. The fifth point consist on the explanation of the deployment of the fiber optics in the sea performed by UPC. The sixth point describes the on site measurements of seawater temperature profile and sea surface temperature. The last point explains the comparison of the temperature measurements taken by the fiber optics and by the CTDs.

II. DESIG AND THE OPTICAL CHARACTERIZATION OF THE FIBER OPTICS

Two different fiber optics were designed, built and charactrized. One of them with 10 points of measurements and the other one with three point of measurements. The reason of designing two different fiber optics is to keep the fiber optics with more points of measurements, measurements fiber, permananently in the sea water, since its removement means a risk of damage. The fiber optic with three points of measurements, control fiber, would work as a drift control of the measurement fiber. The original idea was that the control fiber would be removed each short periods of time for its calibration and evaluation of its drift.

The distributed temperature sensors designed for this experiment are based on the insertion of several Bragg gratings along the 40 meters of the fiber optics. The FBGs (Fiber Bragg Gratings) are written on Single Mode Optical Fiber SM-ITU652 coated with Acrylate. In the design of these distributed temperature sensors special attention was payed to the involved materials in order to avoid the damages of such corrosive environment. The fiber is inside a 1/4" x 0.35 wall thickness 316L stainless steel tube and the final encapsulation is done with a layer of Polypropylene/PEEK with resistance to sea water.

Each Bragg grating reflects the light pulses, with a specific wavelength, sent and received by an interrogator. The particular frequency reflected by eacg Bragg grating depends on its period. Small variations in the frecuency of the reflected pulses are temperature dependence by means the thermal expansion of the Bragg gratings´ period.

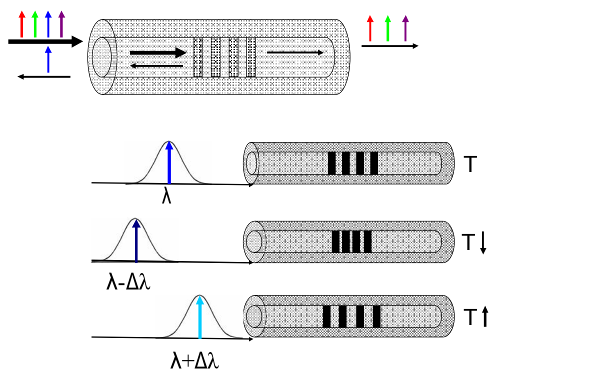

Figure 1. Theoretical explanation of the FBG working as thermometers

The optical calibration of the fiber Bragg gratings (FBG), figure 2 implies the determination of the measurement errors of the interrogator, following the calibration procedure and technique developed at IO-CSIC [2], figure 2. In the uncertainty evaluation all the influence quantities are considered and evaluated, following the requirements expressed in the Guide to the expression of uncertainty in measurements m guide [3]

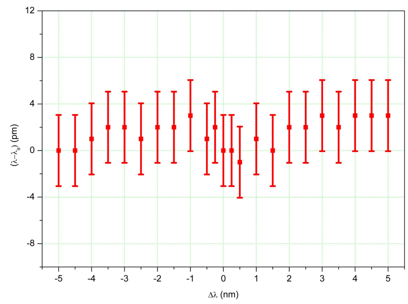

Figure 2 SM-125 calibration results

III. CALIBRATION OF THE FIBER OPTICS AS THERMOMETERS

The relation between wavelength displacement and temperature was determined by means the calibration of the optical system, fiber optics and interrogator, as thermometers, against the Spanish National Standard of Temperature at CEM. The calibration was performed in the temperature range (0, 30) ºC in a large calibration bath of 195 liters, specifically designed for this purpose. The results of the calibrations of the two optical fibers with the uncertainty evaluation of such calibration is shown in figure 3 and figure 4 .

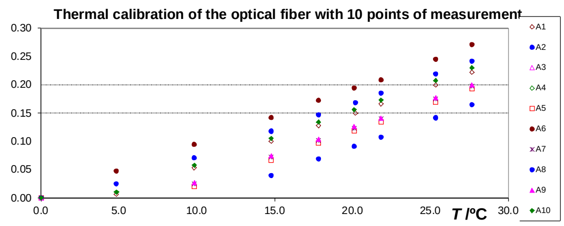

Figure 3. Calibration of the optical fiber, with 10 measurements points, as a thermometer.

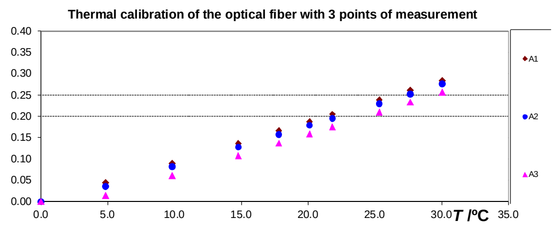

Figure 4. Calibration of the optical fiber, with 3 measurements points, as a thermometer.

The reference temperature at each calibration point was determined by two platinum resistance thermometers, Pt-100, calibrated by comparison with an expanded uncertairy (k = 2) of 10 mK. The reading of the Pt-100 were measured by a resistance bridge ASL, F-700. The stability and uniformity of the calibration bath was determined at each calibration point, having as maximum value of 10 mK for both componentes. The total expanded uncertainty (k = 2) for the calibration of the fiber optics as thermometers is 80 mK. The complete budget of the uncertainty calculation with all the considered componentes is displayed in table 1.

The sensitivity of the fiber optics, working as thermometers was determined in the calibration, taking a value of 0.1 ºC/pm.

Source of uncertainty	Units		probability distribution	Divisor	coeficient $c_i=\partial f/\partial x_i$	Standard uncertainty component, $u(x_i)$
Laboratory system						ºC
L_p	Ω/Ω	0.000001	Rectangular	√3	Rs/sp	0.000 15
dL	Ω/Ω	0.0000061	Rectangular	√3	Rs/sp	0.000 90
R_s	Ω	0.000021	Normal	2	Lref/sp	0.000 05
dR_{sd}	Ω	0.0001	Rectangular	√3	Lref/sp	0.000 30
δt_c	ºC	0.01	Normal	2	1	0.005 00
δt_d	ºC	0.005	Rectangular	√3	1	0.002 89
δt_e	ºC	0.009	Rectangular	√3	1	0.020 21
δt_u	ºC	0.008	Rectangular	√3	1	0.020 21
Componentes due to the instrument:						
δt_i/resolution	pm	0.5	Rectangular	√3	1/sf	0.03
			Standard uncertainty/ ºC			0.04
			Expanded Uncertaity/ ºC		k = 2	0.08

Table 1. Calibration uncertainty of the fiber optics working as thermometers.

IV. CALIBRATION OF CTDS.

The submarine observatory OBSEA already had two different devices to perform measurements of sea temperature water located at seabed. These devices are CTDs. They perform measurements of the conductivity and temperature of the sea water and depth. In order to perform a comparison about the measurements taken by the CTDs and by the fiber optics, it was needed to calibrate CTDs in temperature quantity. The calibration was performed in the calibration bath described previously and the reference temperature at each calibration point was determined by two resistance thermometers Pt-25, calibrated in fixed points with an expanded uncertainty (k = 2) of 2.2 mK. An equalizer block was added to the calibration bath in order to improve its thermal stability and uniformity, having values of 2 mK and 1 mK respectively.

The CTDs used in the submarine observatory OBSEA are Seabird model 37SMP and model 16plus.

The calibration results of both CTDs with the corresponding uncertainty calculation are shown in figures 5, 6 and table 2. The calibration uncertainty of the CTD seabird 16 plus is higher due to in this calibration was performed with pt-100 as standards and calibrated by comparion with an expanded uncertainty (k = 2) of 10 mK

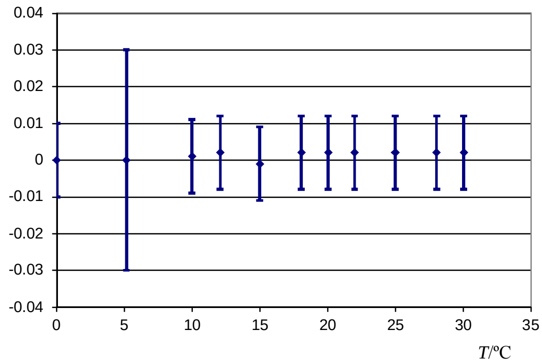

Figure 5. Thermal calibration of the CTD seabird 37SMP

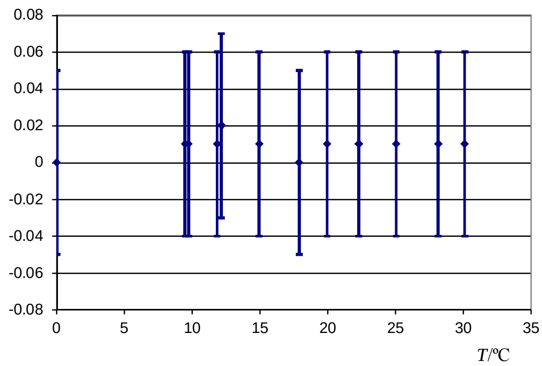

Figure 6. Thermal calibration of the CTD seabird 16plus.

Uncertainty component description	Quantity x_i	Unit	Uncertainty	Probability distribution	Divisor	Sensitivity coefficient c_i	Standard deviation $u(x_i)$ °C
	Measuring system of the laboratory						
Resistance bridge calibration	L_p	Ω/Ω	1.00E-06	Rectangular	√3	R_s/sp	1.48E-04
Drift of the resistance bridge	δL	Ω/Ω	6.10E-06	Rectangular	√3	R_s/sp	9.03E-04
Reference Resistor calibration	R_s	Ω	2.80E-04	Normal	2	L_{ref}/sp	7.18E-04
Drift reference Resistor	δR_{sd}	Ω	1.00E-04	Rectangular	√3	L_{ref}/sp	2.96E-04
Calibration of Reference thermometers	δt_c	ºC	0,002 2	Normal	2	1	1.00E-03
Drift of Reference thermometers	δt_d	ºC	0.002	Rectangular	√3	1	1.15E-03
Temperature bath Stability	δt_e	ºC	0.002	Rectangular	√3	1	1.15E-03
Temperature bath Uniformity	δt_u	ºC	0.001	Rectangular	√3	1	5.77E-04
	Characteristics of the CTDs						
Resolution of CTD	t_i	ºC	0.005	Rectangular	√3	1	0.0029
				Combined uncertainty	ºC		0.004
				Expanded uncertainty	ºC	k = 2	0.008

Table 2. Uncertainty budget of the calibration of CTDs

V. DEPLOYMENT OF THE FIBER OPTICS UNDERWATER

The fiber optics were deployed following the draft of figure 7, between a buoy in the sea surface and the OBSEA underwater observatory, located on the seabed, at 20 m sea depth, close to the coast of Vilanova i la Geltrú (Barcelona, Spain).

The interrogator of the fiber optics was located on the seabed, but as this system is not water proof, a holder for keeping the interrogator underwater was designed and built. Several pressure tests in an hyperbaric chamber was performed to such device in order to guaranty the lack of contact of the interrogator with the sea water

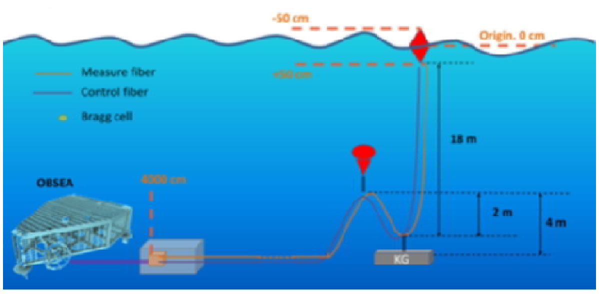

Figure 7 .Scheme the connections underwater

During the on site measurements several problems had to be faced. In January 2017 a storm destroyed all the experiment with irreparable injury in the fibers and severe damages in the surface buoy. Then a leakage was detected in the device for holding the interrogator, with the risk of the interrogator being in contact with water, with the corresponding irreversible damage. The holder device was repaired and since then the system had been collected data from June 2017 to September 2017.

In order to have all the system under control and in order to know the influence of air temperature on sea surface temperature, an air thermometer with a radiation shield was attached to the buoy, as it is shown in figure 8.

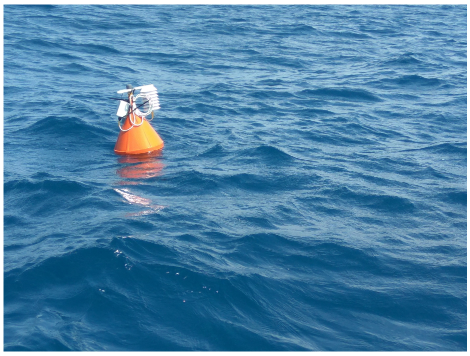

Figure 8. Air thermometer attached to the buoy

VI. SEA TEMPERATURE MEASUREMENTS

At the time this paper was written, the measurements performed by optical fibers, CDTs and air thermometer were being analysed, but, even this fact, some conclusions came from the preliminary analysis.

The preliminary analysis of the measurements taken along three months show several problems. One of the problem is related with the noise observed in the measurements (Figure 9). An explanation of this noise could be the vibration of the fiber optics under water due to the marine currents. Although the fibers were calibrated in stirred liquid bath, the fibers were affected by lower movement during the calibration than when the onsite measurements were taken. Additional tests are needed in order to confirm this noise is due to the movement of the fiber optics.

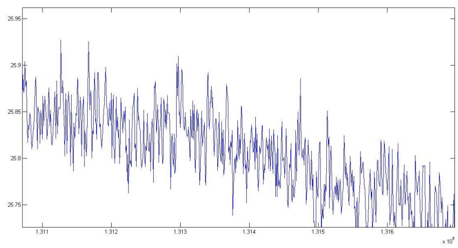

Figure 9. Noise of the sea water temperature measurements.

The data were statistically treated in order to reduce the influence of the noise on sea temperature measurements. The methodology used was the encapsulation of the measurements in sets of 20 samples, taking one measurement every 3 seconds and with and elapsed time of 1 minute between sets of 20 measurements. In each set of measurements, the mean and its standard deviation was calculated. The standard deviation is added to the uncertainty budget of sea temperature measurements, as it is shown in figure 10.

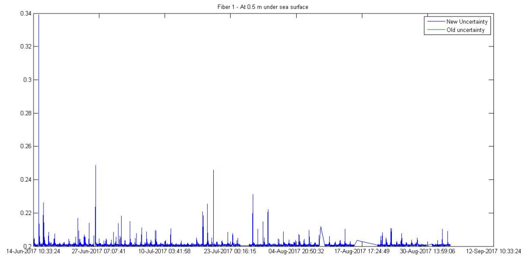

Figure 10. Uncertainty of sea temperature measurements performed by fiber optic at 0.5 m under the water.

A sample of the temperature measurements taken by fiber optic with 10 points of measurement along a specific time interval is shown in figure 11. This figure shows that the decrease in temperature with depth is lower than 3 ºC in the first 10 meters. Probably the high air temperatures along the summer and the fact that the time period corresponds to the end of the summer are fundamental factors to be considered in the low temperature variations. This explanation is in agreement with figure 12, where a difference 6 ºC between the sea surface and 10 m depth is observed at the beginning of the summer. Even this agreement, further analysis and measurements in other seasons would be useful to confirm the explanation.

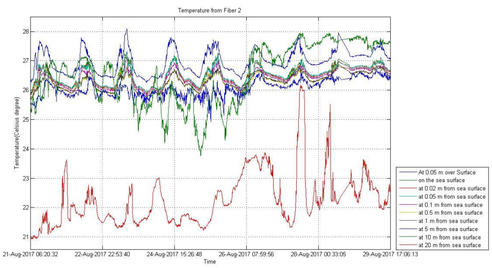

Figure 11. Sea water temperature profile in August.

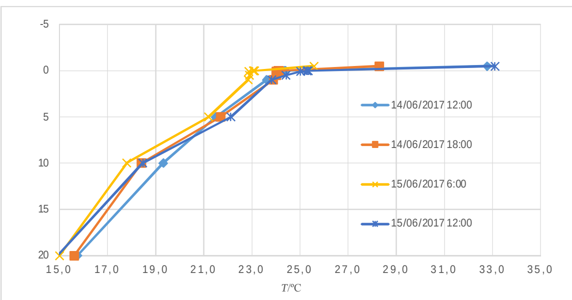

Figure 12. Sea water temperature profile in June

VII. COMPARISON BETWEEN TEMPERATURE MEASUMENTS TAKEN BY FIBER OPTICS AND CTD

One of the objectives of this activity was the comparison of the temperature measurements taken by fiber optics and by CTDs and a preliminary analisys shows that the difference between both methods is lower than 0.1 ºC. Figures 13 and 14 shows temperature measurements taken by both means in a specific time interval

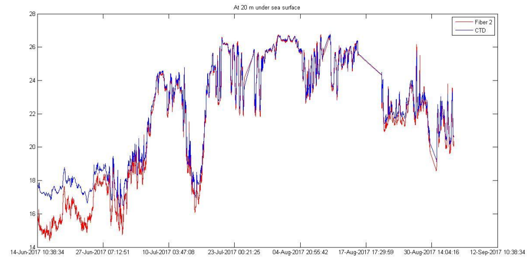

Figure 13. Values obtained in by fiber optic and CTD, both at 20 m of depth.

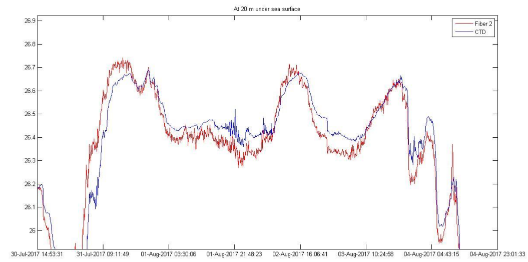

Figure 14. Zoom from figure 13

VIII. CONCLUSIONS

Optical systems based on optical fibers were designed, built and calibrated as optical instruments and as thermometers, with an expanded uncertainty of 80 mK (*k* =2)

CTDs sited in underwater observatory were calibrated with an uncertainty of 8 mK (*k* =2).

A watertight system was designed and tested. This system allows to put the interrogator of the fiber optics at the seabed

The deployment of all the instrumentation associated with the experiment was performed and traceable sea temperature measurements were taken.

Some problems related with the onsite measurements appeared, like the noise of the measurements. Additional tests are needed in order to check if this noise is due to the movement of the fiber optics under the sea and due to merine currents. Even this fact, the fiber optics allows the measurement of traceable sea temperature profile and sea surface temperature during long periods of time.

IX. ACKNOWLEDGMENTS

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