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Traceable sea water temperature measurements performed by optical fibers

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ABSTRACT

This paper describes a technique to perform traceable temperature measurements of the seawater column and seawater surface, based on optical fiber Bragg gratings. The paper explains the different phases of the work done: design of the optical fibers, its optical and thermal calibration and onsite measurements of the seawater temperature. In the design of these thermometers, special attention was paid to the involved materials in order to prevent any damage of the fibers due to the exposure to such rugged environment.

The fibers were subjected to optical and thermal calibration, with the aim to get traceable measurements and reliable uncertainty calculation of the seawater temperature. The fibers were deployed in the Mediterranean Sea and water temperatures were continuously monitored and compared with the most common used thermometer in this environment, CTD, located in the submarine observatory OBSEA.

1. Introduction

Understanding the behaviour, evolution and characteristics of the sea is an essential issue to address some of the raging global concerns of the moment: climate change, the carbon cycle, ocean acidification, variations in the marine circulation and their effects, etc. For this reason, the number of studies about the sea has been increasing for the last years.

The quantity sea temperature is explicitly mentioned in Annex III of the Marine Strategy Framework Directive of the European Union [1] as one of the parameters requiring attention. Meaningful and coherent measurements of seawater temperature are essential to understand its influence in nearly all marine processes, as well as to understand the heat exchange mechanisms between the sea and the atmosphere.

Currently, seawater temperature is mainly measured by three different methods. In the first one, the temperature measurements are performed via satellite observation [2,3]. A second method consists in the attachment of thermometers to buoys and their deployment into the sea, at fixed positions [4]. In the third one, the seawater temperature is measured in research campaigns, by ships, where different arrays, CTDs [5], are launched in order to perform measurements of conductivity, temperature, and depth [6]. Each method present disadvantages: temperature measurements by satellites are not possible at higher sea depths than 1 m, the buoys provide measurements at fixed sea depths and the research campaigns do not supply measurements for long periods.

The CTD [5] is the most commonly used instrument within the scientific community for marine measurements. The measurements of seawater temperature profile with this instrument imply the manual intervention by the deployment of a CTD in a profiler. The CTD is deployed from a vessel with a winch from the sea surface to the seabed in a specific point and time. During the deployment, the CTD is recording the sea water temperature and other magnitudes in its internal memory. Other technique to perform measurements with the CTDs consists in the use of underwater vehicles like the Argo floats [7]. These vehicles usually move freely, following the water currents. These systems perform vertical profiles in a 10 days interval and then, through a satellite link and after the data are filtered, by quality control procedures, these data are available on open repositories. Both solutions (manual deployment of using a float) provide water temperature profiles at specific

Abbreviations: CTD, device to measure the sea water conductivity and temperature and depth of the CTD; FBG, Fiber Bragg grating; OBSEA, underwater observatory (); Pt-100, platinum resistance thermometer with a resistance value of approximately 100 Ω at the triple point of water, 0.01 °C; Pt-25, platinum resistance thermometer with a resistance value of approximately 25 Ω at the triple point of water, 0.01 °C

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times, without a continuous recording in time and for hence, hindering the study of the evolution with time of the seawater temperature profile.

Other two different options allow the monitoring of water temperature profile in a specific position and for long term. One option is the use of a permanent winch on a surface buoy or at the seabed, moving periodically a CTD up and down. The other option is to deploy an array of thermistors coupled on a mooring line with an inductive modem to provide real time measurements. Drawbacks for these two systems could be the power consumptions for the winch system and the number of measurements points for the thermistor array.

This paper describes and analyzes a new technique for seawater temperature measurements. This technique is based on the use of thermometers distributed along an optical fiber. It allows determining the seawater temperature profile, seawater surface temperature by measuring the seawater temperature at the sensor's positions. The continuous monitoring of both variables are also possible during long periods of time. Besides, the use of the optical fibers, as thermometers intends to solve partially the problems of the actual systems in terms of power consumption.

The paper is structured in seven sections. In the first one, the design and the optical calibration of the fiber optics, performed at IO-CSIC, is described. Then the thermal calibration of the optical fibers and CTD, performed by CEM, is analyzed. The fifth section explains the deployment of the fiber optics in the permanent underwater observatory OBSEA [8] performed by UPC. The sixth section describes the onsite measurements of seawater temperature profile and sea surface temperature. The last section compares the temperature measurements taken by the optical fibers and by the CTDs.

2. Design and optical characterization of the optical fiber

The use of the optical fiber as thermometer presents the advantages of its immunity to electromagnetic interferences, its multiplexing capacity, reliable work in hostile environments and that they can play the role of both, sensor and transmission medium, in a unique device and at the same time. Other advantage is the optical fibers do not generate any impact in their surrounding due to their passive nature (it is not a source of electromagnetic noise), small size and low weight.

A measurement instrument based on optical fiber is composed by three principal elements: the transmission medium, the sensor and the optoelectronic device, known as interrogator. The transmission medium is the optical fiber itself; the sensor is the element located inside the optical fiber and the interrogator illuminates the fiber usually with a broadband spectrum light and it collects the reflected or transmitted light by each of the sensors located inside the optical fiber.

The sensor has the sensitivity to notice the change of the quantity to be measured. This sensitivity can be based on by different physical phenomena and in linear or non linear properties of the optical fiber. The choosing of the most suitable physical phenomena, and for hence, the most appropriate sensor depends on the intended use.

In this experiment, the optical fiber sensors consist in Bragg gratings, FBG, working in reflexion mode. FBGs are narrow band filters, that are induced inside a photo-sensitive optical fiber by its exposition to spatially varying UV light. This modifies the local structure of silica, creating a periodic variation in the local refractive index, which behaves like a Bragg grating. The wavelength of light that is resonant with the Bragg period is reflected back, while non-resonant wavelengths pass through the grating [9]. This is explained in Fig. 1 where the broadband spectrum light are represented by different arrows and the reflected one represents the resonant wavelength.

A change of temperature produces a small variation in the Bragg gratings' period and, for hence; the wavelength of the reflected light changes and if this wavelength change is big enough, it can be detected by the interrogator (Fig. 2). Then, this type of thermometers are limited by the minimum wavelength variation detected by the interrogator and for hence by the minimum temperature variation detected by the interrogator.

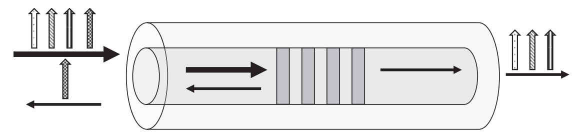

Fig. 1. Theoretical explanation of the FBG working principle.

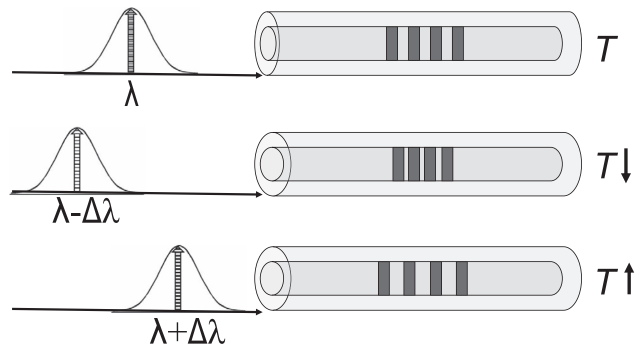

Fig. 2. Theoretical explanation about the use of FBG as thermometers.

The multiplexing capacity of the optical fibers means that several Bragg gratings can be recorded in a unique optical fiber. In this experiment, two different optical fibers were designed, one of them with ten measurement points and the other one with three measurement points, both distributed in 40 m optical fiber. The original reason of these two different designs was to consider each of them for a different function. The ten points optical fiber, *Measurement fiber*, in principle, would have been permanently in the seawater for a year and the sea water profile would have been measured with this ten points optical fiber. The reason of keeping this fiber under the water continuously is its extraction and deployment in the sea is a risk of its damage. To assembly an additional fiber was decided. This fiber has three points of measurement and it is named the *Control fiber*. It would have worked as a drift control of the measurement fiber. The control fiber would have been deployed and extracted from the water at specific time intervals for its calibration and for hence to control de drift of both optical fibers. However, at the end, and due to some experimental problems, the time of the experiment was shorter than expected and both fibers were extracted from the sea at the same tame. Their drift were determined by their calibrations at the beginning and at the end of the experiment, as it is explained in the point 3.3. Tables 1 and 2 summarize the position of the sensors inside the optical fibers.

The FBGs designed for this experiment were written on Single Mode Optical Fiber SM-ITU652 coated with Acrylate. In the design of these optical fibers, special attention was payed to the involved materials in

Table 1
Position of the sensors inside the *Measurement fiber* and their positions in the sea.

Brag Grating	Position of the sensors inside the optical fiber. Distance from the interrogator/m	Depth in the sea/m
A1	39.80	−0.5
A2	39.30	0.0
A3	39.28	0.02
A4	39.23	0.05
A5	39.20	0.1
A6	38.80	0.5
A7	38.30	1
A8	34.30	5
A9	29.30	10
A10	19.30	20