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ORIGINAL PAPER

Industrialization of advanced optical technologies for environmental monitoring

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Abstract In this work, an innovative fully integrated monitoring infrastructure based on optical fibre sensors was developed and implemented. In the framework of the research project named PROTEU [Tecnologias Avançadas para a Monitorização de Sistemas Estuarinos e Costeiros (PDCTM/P/MAR/15275/1999)], an 11 km optical fibre cable with Bragg sensors each 500 m was installed from the lagoon mouth to Vouga river, along the bed of the Espinheiro channel, allowing the real-time measurement of water temperature at each sensor location. The results of this project are currently feeding several studies concerning Ria de Aveiro and the surrounding area and are crucial for a continuous assessment and management of the environmental conditions. Meanwhile, a fibre optic sensing system for simultaneous measurement of temperature and salinity based on fibre Bragg grating (FBG) technology was also developed. In the following sections, a complete description of the fabrication process, as well as theoretical and experimental results regarding this particular sensing system, are addressed. Earlier in situ local measurements, as well as the latest remote monitoring and data processing scheme, are described. The developed technology is now being exploited by FiberSensing, an INESC Porto spin-off company devoted to the development of optical fibre Bragg grating-based sensor systems for advanced monitoring applications. The main markets of the company are the ones of structural health monitoring in civil and geotechnical engineering, energy production and distribution, and environment.

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Introduction

Ria de Aveiro has an adjacent surface of about 250 km^2 and more than 300,000 people living around its channels. This human concentration in a small area brings up several environmental and pollution problems. Biologically, it can be considered as being rich in nutrients and organic matter, constituting a highly productive environment, characterized by the existence of a large diversity of species. It provides natural conditions for harbour, and navigation facilities and it is also a place of discharge of domestic and industrial wastes. It offers good conditions for agricultural development along its borders and for the set up of a large number of small and medium industries. There are a considerable number of semi-professional and part-time fishermen who economically depend on the productivity of the lagoon waters. Nowadays, there are only a small number of operational salt pans as compared with previous decades. Meanwhile, an increasing number of recovered pans for aquaculture purposes imply that in near future this activity may become economically promising. The harbour reveals a strong development in recent years due to the increasing number of industries in Aveiro region. It is the terminal point of a main road connecting Aveiro with Spain, which anticipates its future expansion.

Due to the development of some of the referred activities, the lagoon is being subjected to considerable pollution stress. For example, the most enclosed and remote arms of the lagoon show evident signs of advanced eutrophication, some communities and animal species have survival problems, there is microbiological contamination from large discharge of untreated sewage and there is industrial pollution. The recent progress of saline intrusion is another important problem, responsible for significant saline stress in the low-lying lands of Baixo Vouga. Once flooded by sea water, previously fertile lands are unsuitable for growing crops for several years because of the saline deposits which remain after the floods have receded.

The study of these kinds of problems must be based upon an understanding of the biological, chemical and geological processes, which are highly dependent on the lagoon's hydrodynamics, and implies the existence of an extensive data set concerning physical parameters. Therefore, it is fundamental to have data with good spatial and temporal resolution. Due to the human and material limitations, it is difficult to have enough information provided by conventional field measurements. These data are also fundamental to use as boundary conditions for the implementation of numerical models that allow the forecast and diagnostics of Ria de Aveiro, as well as to properly perform its calibration and validation.

It is currently recognized that the measurement and control of physical, chemical and biological parameters in natural environments is of major importance for ecosystems protection. In this context, salinity and temperature measurements in coastal and estuarine environments are required as part of a process directed to the health assessment of their bio-diversity. In particular, the level of salinity is relevant, not only because of its intrinsic influence in the development of some grass-wrack, but also as an indicator of water conductivity. This last parameter allows the prosecution of studies in tidal dynamics by the measurements of induced currents generated by a huge mass of water in motion (Dias et al. 2000).

Fibre optic sensors offer numerous advantages over electric transducers due to their immunity to electromagnetic interference, small size, higher sensitivity and the possibility of distributed measurement over large distances with negligible signal degradation. In this field, the sensors based on fibre Bragg gratings (FBGs) have attracted considerable attention, essentially due to the fact that the measurand-induced modulation is over an absolute parameter (wavelength) (López-Higuera 2002).

During the last decade, several configurations have been proposed in order to remotely determine accurate measurements of salinity. Minato et al. (1989) and Zhao and Liao (2002) made use of the deviation of the light beam travelling across a water cell divided in two adjacent blocks and filled with reference water and seawater; a charge-coupled device (CCD) array collects the emerging signal and, after processing, a linear relationship is established. Another technique proposed by Esteban et al. (1999) is based on surface plasmons, i.e., on the interaction between the fundamental mode of a side polished fibre and the modes that propagate in a thin metallic layer deposited on the fibre polished surface. The overall effect results in a strong dependence of the transmitted power on the refractive index of the medium surrounding the metallic layer. Other techniques which are complementary to the one proposed here to the simultaneous measurement of temperature and refractive index makes use of the sampled fibre Bragg grating (Shu et al. 2001), tilted fibre gratings (Laffont and Ferdinand 2001), and long-period gratings (Gwandu et al. 2002).

This work presents an alternative sensing system based on fibre Bragg grating technology, oriented to the simultaneous measurement of water salinity and temperature. The development of this technology towards its commercialization is analysed taking into consideration the implementation of sensors, measurement systems and software packages for remote environmental monitoring.

Theory: temperature and salinity sensing system

The sensor head contains two in-line fibre Bragg gratings, with one of them only sensitive to temperature, while the other is also sensitive to salinity, through the respective changes in the refractive index of water. Fibre Bragg gratings are periodic modulations of the fibre core refractive index that are formed by exposing the fibre to an interference pattern of UV light. They are characterized by the periodicity, Λ, of the refractive index modulation and by the effective refractive index of the waveguide mode, n_{eff}. Therefore, these structures show resonance behaviour with a Bragg wavelength given by López-Higuera (2002):

$$\lambda_B = 2n_{\mathrm{eff}}\Lambda. \qquad (1)$$

The reflectivity of these structures is directly related to the fibre photosensitive characteristics, as well as to the UV exposure conditions during manufacturing, and directly influences the signal-to-noise ratio (Asseh et al. 1998). The temperature sensitivity of the Bragg wavelength arises from the coefficient of thermal expansion of silica, α, and the thermo-optic coefficient of the material, ξ, i.e.,

$$\Delta\lambda_B = \lambda_B\left(\frac{1}{\Lambda}\frac{\partial\Lambda}{\partial T} + \frac{1}{n}\frac{\partial n}{\partial T}\right) = \lambda_B(\alpha + \xi)\Delta T. \quad (2)$$

For silica, the values of α and ξ are 0.55 and $8 \times 10^{-6}\ \mathrm{K}^{-1}$ respectively, which indicates that the temperature response of the FBG (~ 11 pm °C^{-1} at 1,550 nm) is dominated by the refractive index thermal dependence (López-Higuera 2002).

In this paper, refractive index measurements are achieved by etching the fibre cladding in the region of the grating to a diameter such that the evanescent field of the mode interacts with the immediate surrounding environment. With this configuration, the value of the effective refractive index of the waveguide mode is directly affected by the refractive index of the medium where the fibre is immersed. Indeed, during the etching process, when the fibre diameter is shrinked till the region where the fundamental mode edges then its own propagation constant starts to be affected and the values change gradually (Snyde and Love 1983).

Considering the relation addressed in Eq. 1, this means that associated with the etching process there is a variation of the Bragg wavelength of the FBG given by:

$$\partial\lambda_B = 2\Lambda\partial n_{\mathrm{eff}}. \quad (3)$$

When the etching process is complete, η_p becomes fixed at a value η_{po} and the variation of the effective refractive index of the waveguide mode is related to the variation of the environment refractive index, i.e., $\partial n_{\mathrm{eff}} = \eta_{po}\,(n_{\mathrm{sur}} - n_{\mathrm{cl}})$. From Eq. 3 this means that

$$\delta\lambda_B = 2\Lambda\eta_{po}(n_{\mathrm{sur}} - n_{\mathrm{cl}}). \quad (4)$$

Therefore, in such conditions the variation of the Bragg wavelength of the FBG is only related with the variation of the refractive index of the surrounding medium. FBG central peak can be made at any location within the region [600, 1,600] (nm) with no impact on the sensing head response. This constitutes the principle of the salinity sensor proposed in this paper.

Experiment and discussion: temperature and salinity sensing system

As shown in Fig. 1, the sensor head consists in two in-line FBGs fabricated in monomode optical fibre by the phase mask method using an ultraviolet KrF excimer laser emitting at 248 nm with 400 mJ cm^{-2} at 20 Hz. To enhance the photosensitivity, the fibre was previously hydrogen-loaded with a pressure of 100 atmospheres at room temperature. The central wavelengths of the two FBGs were around 1,550 nm.

For the second FBG to become a wavelength-based evanescent field sensor, chemical etching in the grating fibre length was done by exposing it to a chemical solution of hydrofluoric acid (HF) at 40%. During etching, the grating spectrum must be monitored in real-time to be able to stop the process when the grating reflectivity decreases below a certain value which is related to the expected refractive index sensitivity as well as with the mechanical strength that is necessary to ensure for the etched region.

If the process is not stopped in this point, the fibre simply disappears in the etching region. To avoid this, the fibre is removed from the acid and immersed in a liquid basis for stabilization and chemical compensation. Figure 2 shows the spectrum of the two FBGs for the measurement of temperature and salinity.

To calibrate the sensing head, two steps were undertaken. In the first step, the Bragg wavelength shift of the two FBGs was determined versus temperature variation (Fig. 3) in the water. In the second step, the Bragg

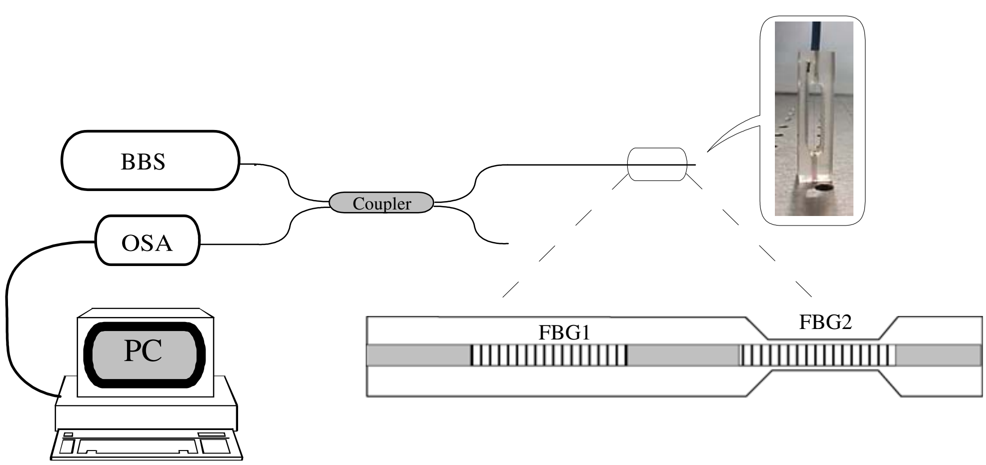


Fig. 1 Experimental setup (*BBS* broadband optical source, *OSA* optical spectrum analyser)

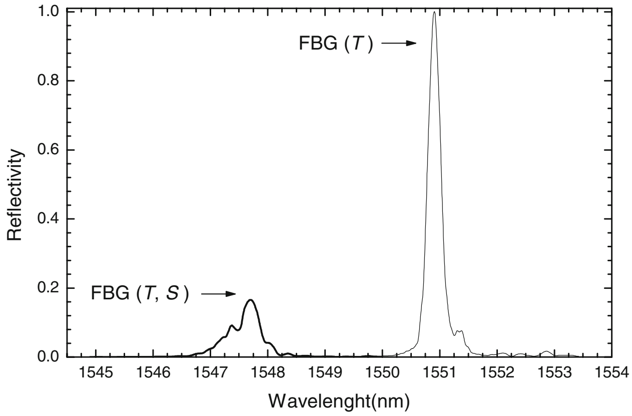


Fig. 2 Spectral response of the Bragg grating sensors

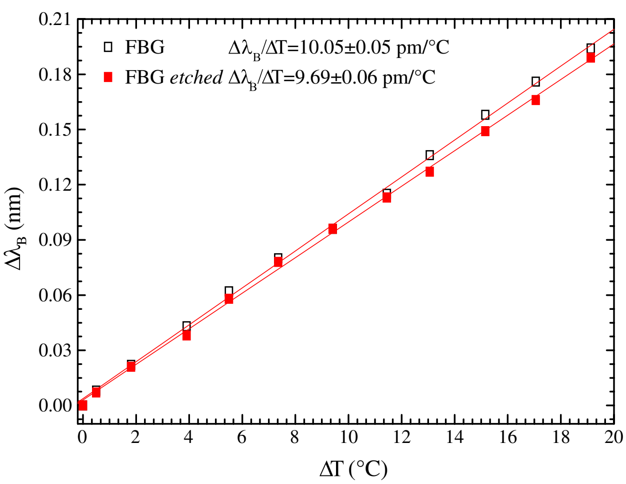


Fig. 3 Temperature response of the FBG sensors

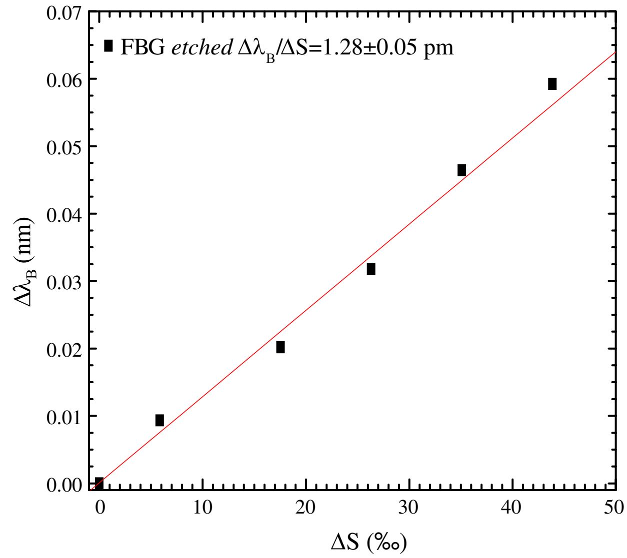


Fig. 4 Bragg wavelength shift of the etched FBG versus water salinity

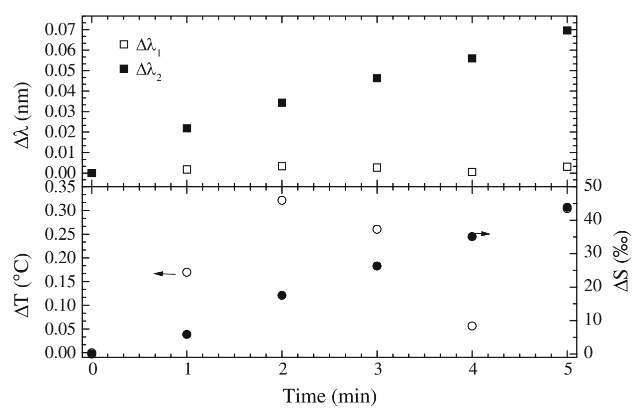


Fig. 5 Time measurements of the two simultaneously parameters

wavelength of the etched FBG was monitored once immersed in samples of salt water at room temperature (Pereira et al. 2004).

Figure 4 presents the etched FBG wavelength shift versus the salinity of the water, resulting from the date and from the known linear relation between the refractive index of salt water and the respective degree of salinity (Minato et al. 1989; Zhao and Liao 2002).

The sensitivity coefficients given in Figs. 3 and 4 allow writing the following matrix, which enables us to determine the variations of the salinity of water and, if its temperature from the readings of the wavelength shifts, of the two FBGs:

$$\begin{bmatrix} \Delta T \\ \Delta S \end{bmatrix} = 77 \begin{bmatrix} 1.28 & 0 \\ -9.69 & 10.05 \end{bmatrix} \begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \end{bmatrix}. \tag{5}$$

In the matrix equation, one of the coefficients is zero due to the insensitivity to refractive index variations of non-etched FBG.

To test the concept behind Eq. 5, a simultaneous measurement experiment was performed. For the different samples addressed data corresponding to $\Delta\lambda_1$ and $\Delta\lambda_2$ were recorded. The temperature variations arise directly from the difference in temperature found between the samples, registered independently using a thermocouple. For the level of salinity, there were no independent measurements, existed only the indication that the next sample had higher salinity than the previous one. The obtained raw results and those processed via Eq. 5 are shown in Fig. 5. From this the adequate recovery of the temperature information and the expected behaviour for the salinity variation can be inferred. Owing (Rms) to the spread of the processed data associated with an integration time of 25 ms one obtains (resolution) ±0.38°C and ±1.3‰ for temperature and salinity respectively. These values can be translated to normalized resolutions of $\pm 0.06°C/\sqrt{Hz}$ and $\pm 0.2‰/\sqrt{Hz}$.

Optical cable: distributed temperature measurement

In this section, the results obtained with the pair optical cables installed at Ria de Aveiro are addressed. During the manufacturing process of the cables (ref. TONGERE executed by the company CABELTE S.A) three major issues were considered: integration of the optical fibres and sensors on a mechanical and strain-free cable, elastic variations inside the tubes free allowance (contractions, dilations) and adequate design of the cable to withstand installation and subsequent use: salt water, traction, torsion, crushing, impact. The ultimate goal was therefore to ensure the mechanical protection of the optic core without isolating the fibres from the surrounding medium (water). The first optical cable tested comprises three optical fibres (SMF 28®) with nine FBGs each (see Fig. 6). Groups of three sensors were formed in the same section of the cable in such a way that all nine groups were effectively distributed along the cable extension. This distribution allows not only a distributed monitoring of temperature but also a statistical treatment in each section ensuring a minimum of three individual readings. Table 1 presents the mechanical specifications of the optical cable.

The cable was installed using a floating raft near the Vagueira Bridge, at Mira Channel, towards Costa Nova over approximately 850 m. To ensure that the sensors were measuring the temperature at the Ria's water, several concrete supports were used all over the cable. The first data acquisition system installed on a local station was a replica of the most common acquisition system used on lab environment—i.e., a super luminescent erbium doped fibre source to illuminate the FBG sensors, an optical spectrum analyser and an optical fibre switch. All the instruments were inter-connected through a GPIB bus controlled by a personal computer running LabView™.

The second optical cable about 13 times longer was installed along Espinheiro Channel of Ria de Aveiro

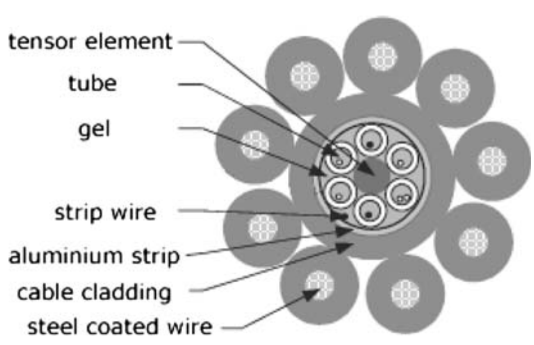


Fig. 6 Optical cable schematics

Table 1 Mechanical specifications of the optical cable

Exterior diameter (mm)	16
Approximate weight (kg)	1,500
Maximum installation traction (kgf)	400
Maximum operation traction (kgf)	200
Procedure temperature (°C)	−10 to 60

Fig. 7 Optical cable location map. Coordinates: 40°38′4.32″N 8°42′45.22″W

(Fig. 7) after the preliminary results as well the infrastructure itself have been qualified. Therefore, the first set of measurements acted like a probe for technical constrains of the infrastructure providing the information needed for system upgrade. Figure 8 shows the layout of the second optical cable installed. This time it was chosen to place four arrays of ten distinct gratings on four different fibres. On each fibre, the gratings were 500 m apart and were spliced two pair of fibres in such a way that all spatial extension of the optical cable was covered. Once again, for redundancy it was decided to duplicate every measurement inserting four fibres in the cable. Two extra fibres without gratings were added to monitor the attenuation in the fibres. These measurements were performed with an OTDR enabling to monitor both FBGs position along the cable and the attenuation of optical cable.

The first set of measurements performed with the first cable (850 m long) took place on June 2002. The values of temperature variation were reported for the period between 4 June and 23 June (Fig. 9a). Reporting the same period but on the year 2005 addressed the results of the temperature variation within a 9 km range obtained with the second cable.

The analysis of Fig. 9a, b reveals that the values measured have periodic evolution, similar to that observed by Dias et al. (2000) using STD observations in near locations. The maximum values of the curves are observed at the local low tide, while the minimum values occur at the local high tide. In this season the oceanic water, which propagates through the Mira Channel during the flooding, is cooler than both freshwater and the water inside the lagoon. Then the observed temperature pattern is coherent with the tidal dominance of the channel dynamic.

Regarding the analysis addressed on Fig. 10, that includes the water temperature monitoring over the first semester of 2005 using the sensors located at the edges of the optical cable, the occurrence of a small gap between the water temperature step in both locations should be

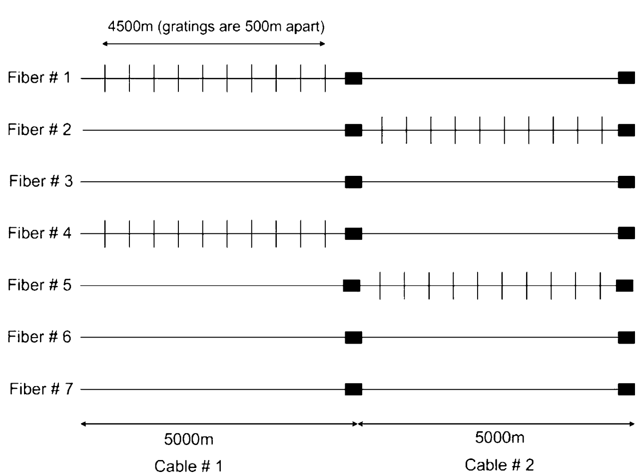


Fig. 8 Schematic drawing of the optical cable

reported. At first glance, this behaviour comes straight from the water thermal gradient established across the channel from the mouth inwards, causing the water nearby the mouth to warm up less than the water in the estuary.

In essence, the water temperature variations in shallow tidal environments, as is the case, are essentially dependent on the tidal dynamics and on surface heating, even though under some circumstances temperature variations due to the freshwater inflow need to be also considered.

Optical cable: remote monitoring system architecture

In this section, the major upgrades implemented to the acquisition system are addressed, when the second cable was installed. As indicated before, the characteristics of Ria de Aveiro make it an ideal place to study, implement and test innovative sensing systems dedicated to monitor estuaries, lagoons and coastal zones (Dias et al. 2000; López-Higuera 2002; Minato et al. 1989).

Remote monitoring of estuaries and coastal environments, involves four fundamental blocks: transducers network, acquisition system, GSM data transmission link and the data centralization unit to provide data visualization in the form of a web-based database (Fig. 11). In this section, the architecture and features of the remote monitoring system are described, with special emphasis on the final user interface and communication link. On a simple basis, the system can be dropped down into three fundamental sub-systems: sensing unit(s), central unit and user interface. The sensing unit must be understood as the element able to measure several different parameters (e.g. temperature, salinity) while the central unit is the element where data undergoes pre-processing (unit conversion, filtering and transmission on-demand over GSM). The final user interface is the block where data are stored and displayed on a web page. To ensure a full integration of the system, several platforms were used: Labview^{TM} on the local unit(s), Java, PHP and HTML on the user interface. The major prerequisites for the software selection are robustness, security and low integration cost. Taking in account these constraints, it was decided to use the Apache as HTTP server and MySQL as the database, due to its widespread distribution, with the added bonus of being open source. Communication between the central unit and remote unit was established with GSM implemented on a Java platform. Once again, the local acquisition process is entirely controlled by Labview^{TM}, which is an industry standard for acquisition and process control.

Figure 12 shows the schematics of the local acquisition system. The interrogation unit is a single instrument that launches and collects light through the same optical fibre. Once the reflected light signal from each of the fibre Bragg

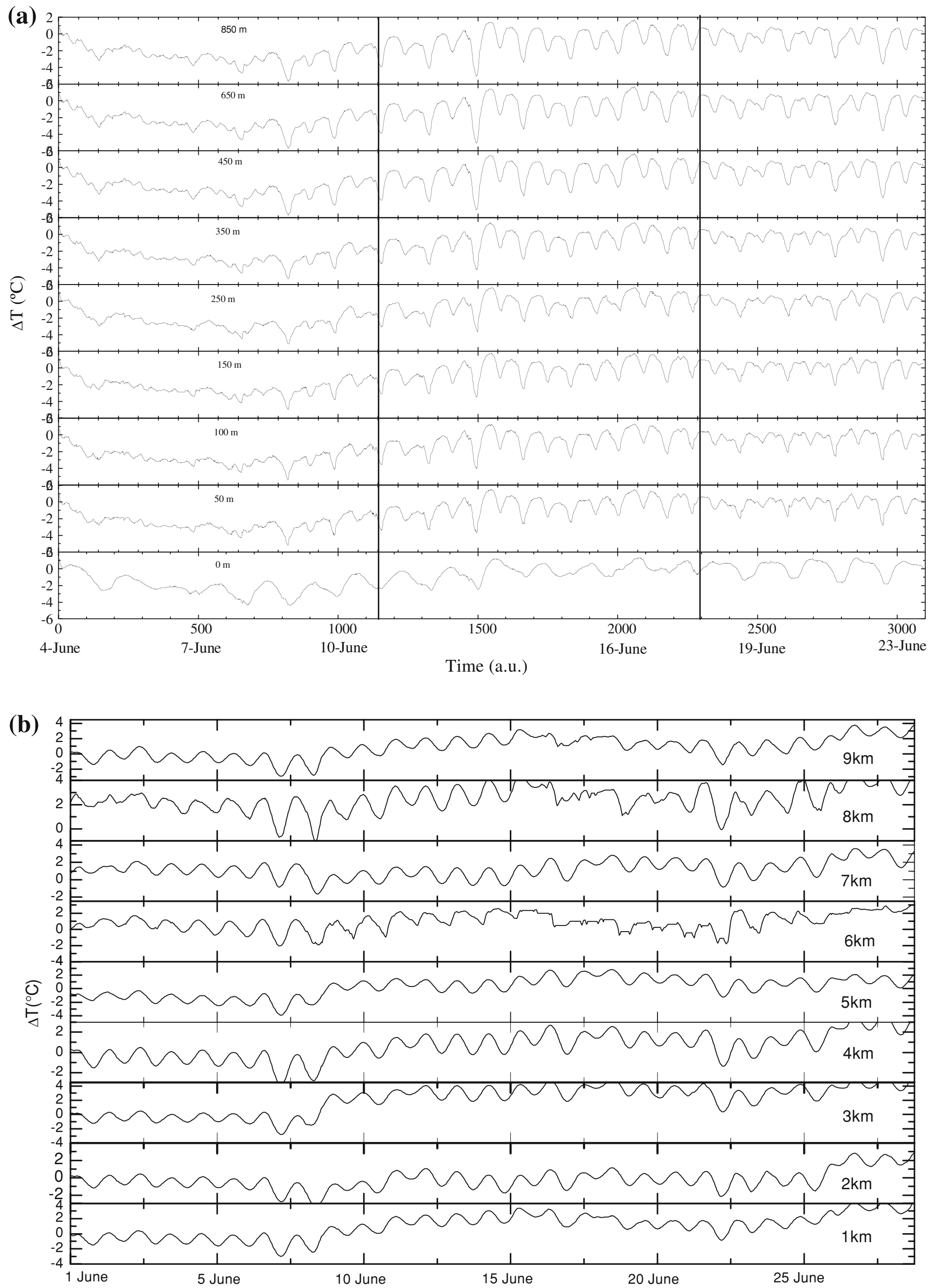


Fig. 9 Temperature variation: **a** June 2002 using the first optical cable, **b** June 2005 using the second optical cable

gratings array returns to the unit it passes through a tunable filter that sweeps the wavelengths of each Bragg grating. The optical switch selects the fibre array under measurement; thus, the measuring system prototype combines wavelength and spatial multiplexing. Due to the environmental thermal shift of the grating peak, very accurate measurements can be provided.

Recalling the user interface topic, it should be mentioned that it is possible to discriminate two types of users: registered and system administrators. Registered users can search the historical database (updated daily) (Fig. 13a) and visualize on-the-fly (graph) (Fig. 13b), the behaviour of the selected transducers within the selected timeframe. The system administrator is allowed to download data on demand from the remote units.

In essence, the advantages that this remote system presents when compared to traditional systems, where data collection is made locally, can be summarized as follows: (a) provides centralization and easy access to information remotely from anywhere on the world, as long as it has an

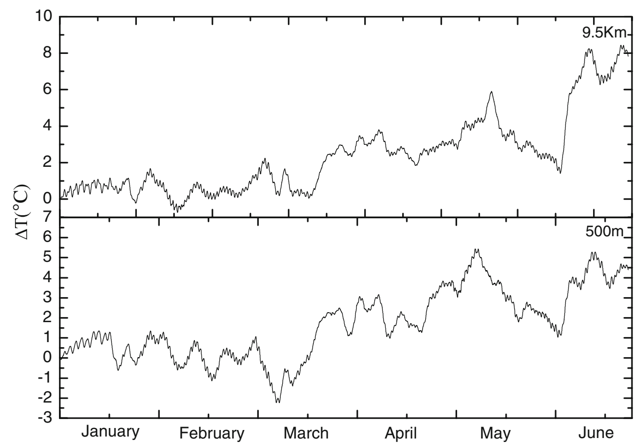


Fig. 10 Temperature variation between January and June 2005 on the first and last section of the optical cable

internet connection, (b) offers the possibility of data filtering and pre-processing, (c) enables user tailored dynamic searches and (d) facilitates on-the-fly graph searches, allowing the user to quickly analyse the data without having to resort processing tools.

Conclusions

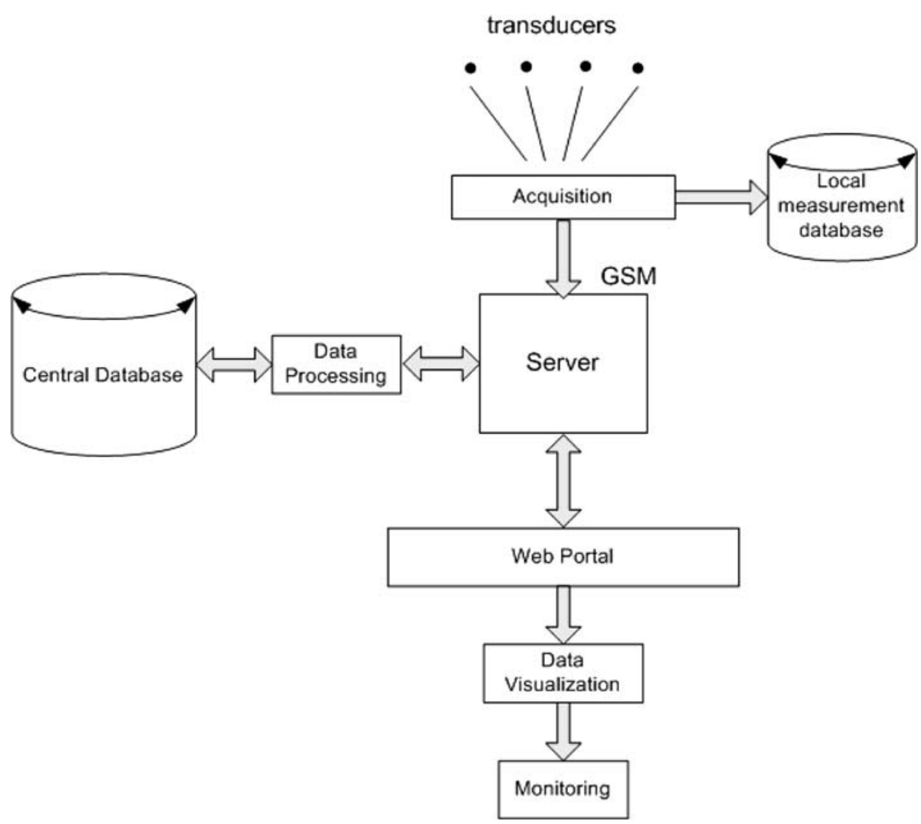
The major results achieved must be summarized in two self-connected topics. The first one relies on the compact sensing head based on fibre Bragg grating technology that was developed for simultaneous measurement of temperature and salinity. The second one regards the sensing cables installed in-field for underwater distributed temperature mapping. The sensing head consists of two in-line FBGs with one of them etched in order to become sensitive to refractive index variations of the surrounding liquid environment. It is envisaged that the proposed sensing head configuration has the potential to be integrated in systems directed to remote monitoring of the health of liquid bio-environments.

Regarding the infrastructure, it should be specified that it offers a widespread potential of applications, due to its low size and weight, almost non-intrusive character and possibility of expansion to other relevant, yet to be chosen, measurands, including the abovementioned salinity sensor. The almost free maintenance remote system architecture offers outstanding added value, not only due to on-demand data update, but also for the quick diagnosis of error measurements or faults.

As a direct result of this work, we now have one underwater cable that is continually monitoring the temperature of the Espinheiro Channel, providing information that has already been used to study the dynamics of this ecosystem.

In the long run, the accumulation of data will be used to evaluate models and provide insight into to the global

Fig. 11 System overview



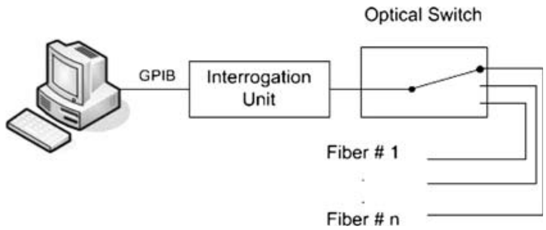


Fig. 12 Local Bragg interrogation and multiplexing system

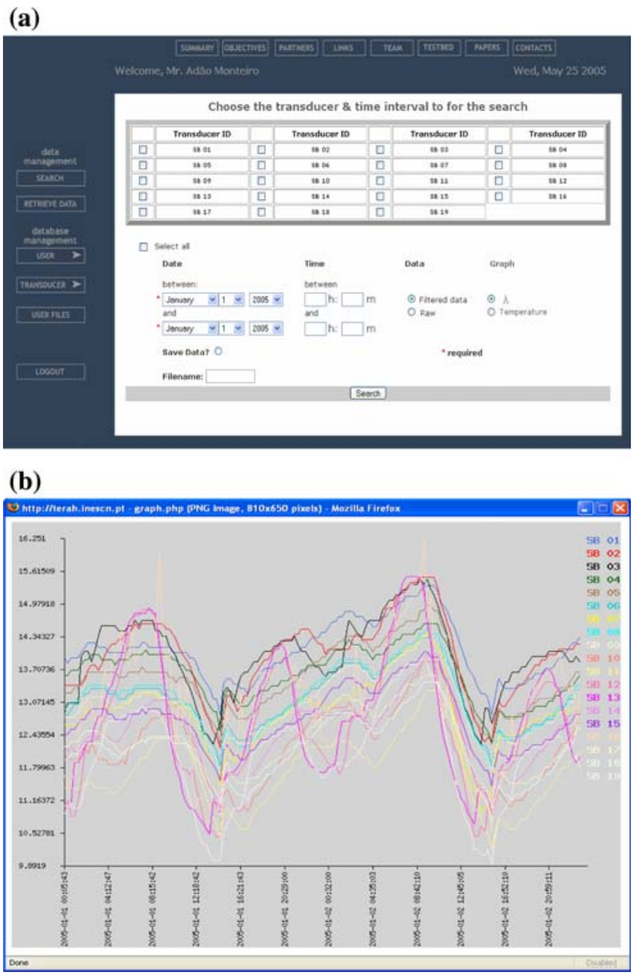


Fig. 13 **a** Main search page, **b** search results (on-the-fly graph)

behaviour of the Ria de Aveiro estuary. It was also demonstrated that this technology has enormous potential for the commercialization of sensors, measurement systems and software packages for remote environmental monitoring. The market assessment is currently being conducted at FiberSensing, an INESC Porto spin-off company devoted to the commercialization of optical fibre Bragg grating-based sensor systems for advanced monitoring applications.

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