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A metrological comparison of Raman-distributed temperature sensors

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ABSTRACT

Raman distributed temperature sensing techniques (Raman-DTS) are currently meeting a growing interest from the industry as they are a promising and cheap alternative to classical temperature measurements which require the deployment of many sensors. The reliability of the DTS measurements, as well as the traceability to the temperature standards, must be ensured throughout the entire period of use (typically over a few tens of years for nuclear waste repositories and hydraulic structures). LNE, in association with Andra and EDF has developed facilities dedicated to the metrological characterization of Raman DTS devices. A first benchmark performed on five devices from different manufacturers has been performed following experimental procedures which enable a relevant comparison of these instruments. This paper defines the proposed metrological features to be evaluated for each Raman DTS system, and presents a ranking method enabling to provide useful pieces of information to the final users for the selection of the most appropriate device to the requirements of their applications.

1. Introduction

Since the early 80′s, DTS technologies by optical fibres have been continuously developed and improved [1–4]. The most known and mature technologies are based on the Raman scattering which enables to measure a temperature profile along the whole length of an optical fibre with a length up to 30 km (for a multimode fibre) and even up to 70 km (for a single-mode fibre). This sensing technique consists in scanning an optical fibre (OF) by the means of a pulsed laser and in filtering and analyzing the Raman radiation which is a spectral component of the backscattered light returned by the OF. As Raman radiation is sensitive to the OF temperature (anti-stokes line), it is possible to perform a distributed temperature measurement along the whole OF by collecting samples separated by distances typically from 0.5 to 1 m, which are mainly dependant on the laser pulse width (typically 10 ns). The sensing OF is equivalent to a distribution of a few tens/hundreds/thousands of temperature probes located along the whole OF. These techniques have met very promising and useful applications for the structure health monitoring (nuclear reactor confinement enclosures) [5–9], for fire detection (tunnels) [10], for subsea cables monitoring [11], and for fluid leakages (hydraulic dams and dikes [12], oil-gas-water pipelines [13,14]). Another specific potential application is the temperature monitoring of Cigeo, the future French deep geological long-lived radioactive waste repository site, currently evaluated with the support of the underground laboratory of Andra, the French national radioactive waste management agency [15–17].

In the framework of the Joint Research Projects (JRPs) ENV54 MetroDecom [18–20] and 16ENV09 MetroDecom 2 [21], LNE works in a close partnership with Andra and Electricité de France (EDF) for developing a metrological infrastructure devoted to the Raman-DTS technologies.

Despite some actions lead at the international level (i.e. IEC and ASTM standardization committees [22], US Seafom platform [11]), the dissemination of the Raman DTS technologies to the involved industries is suffering from a lack of well-established standardization. For that reason, users are often lost with the performances of Raman-DTS systems which are only based on the specifications proposed by manufacturers (as resulting of a heterogeneous – sometimes mistaken – vocabulary used for describing the characteristics of Raman-DTS systems).

From its experience in providing new calibration services to industries, LNE, in association with Andra and EDF, has defined a set of metrological criteria, and developed some dedicated experimental facilities and protocols for characterizing Raman-DTS devices [23]. The objective is to enable the users (Andra and EDF) to perform a relevant comparison of such systems (taking into account the requirements specific to their applications) with the highest level of confidence.

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In this paper, the results obtained from a first benchmark of several Raman-DTS devices (including both single-mode and multimode sensing OF) are presented and discussed. The perspectives provided by these works in terms of standardization are also introduced.

2. Metrological characteristics of a Raman DTS device

Raman-DTS systems might be deployed in different situations according to the specific applications. In the case of the long-term monitoring of its dams and dikes, EDF aims to detect local temperature variations, in order to introduce these variations into phenomenological numerical models for the water leakages detection. For such an application, the accuracy of the Raman-DTS system is not the most important metrological characteristic. A special attention is paid to the ability of the system to detect a localized thermal event with a sufficient repeatability performance in order to discriminate any influence from the environment. Conversely, the accuracy of a Raman-DTS system is a crucial characteristic when these devices are used for the thermal monitoring of geological repository for the long-lived radioactive wastes. It is indeed necessary to alert the operator if the concrete walls temperature of the structure (which surround the disposal galleries) exceeds the limit of 60 °C, or if the host rock temperature approaches 90 °C.

Taking into account the different application fields where the Raman-DTS systems are used, the following metrological characteristics are proposed:

- Spatial resolution (SR): this is the shortest length of an OF which has to be subjected to a localized temperature step in order that the system returns 100% of the response (full scaled temperature variation). Note that COST [24] defines also the detection resolution such as the shortest length of an OF which has to be subjected to a localized temperature step in order that the system returns a 90% response of the temperature variation.
- Mean trueness error (MTE): at one given point of the OF (sample), a mean temperature (MT) value is computed over an interval of 10 successive samples centred on this considered point. The mean trueness error (MTE) is the difference between the mean temperature MT and the true temperature measured at the same time by a 100 Ω standard platinum resistance thermometer (SPRT) traceable to the ITS-90 [25].
- Temporal dispersion: defined at each point of the OF, this is the standard deviation of the MTE computed from three successive measurements over time performed under the same experimental conditions. In other words, this characteristic corresponds to the repeatability of the instrument (measurement precision).
- Spatial dispersion: defined at each point of the OF, this is the standard deviation of the MTE averaged over an interval of ten samples centred on the considered point (moving average method applied to the standard deviation). It consists in quantifying the lowest measurable temperature gradient over the OF length which corresponds to ten times the sampling interval.

3. Comparison on a set of Raman-DTS systems

A Raman-DTS setup can be separated into two parts: the interrogator which contains the pumping laser source and the detection path, and the optical fibre which is the active sensor.

This metrological study has been performed on a set of five interrogators commercially available and already used by Andra and EDF in their respective facilities. The investigated interrogators are anonymized for obvious reasons of confidentiality and are thus only identified in this paper by different letters. Table 1 provides some specifications about these devices. Tested instruments can be used with either single-mode or multimode fibres; they work at different pumping wavelength (typically 1064 nm or 1550 nm). They were paired with the same optical fibre, either a single-mode from Corning (SMF28e+) or multimode, graded index type OM-2 from Draka.

Table 1
Technical specifications given for each Raman-DTS interrogator tested within this benchmark.

Label	Distance range (km)	Sampling interval (m)	Temperature range (°C)	Laser pulse width (ns)	Optical fibre[a]
A	20	1	5–45	10	MM
B	5	0.127/1	5–40	1/10	MM
C	20	0.5/1	5–40	10	MM
D	20	0.1/1	−10–60	10	MM
E	20	0.32/1	NA	10/30	SM

[a] MM: Multimode fibre; SM: Single-mode fibre.

For this benchmark, the efforts were focused on single-end measurements only: double-end measurement is never experimented neither by Andra nor EDF.

In general, confusion is possible between the concepts of spatial resolution and sampling interval. As defined above the spatial resolution is the characteristic which corresponds to the ability of the system to detect a local temperature variation at the full scale. The sampling interval corresponds to the distance between two measurement samples along the OF.

The sampling interval is directly linked to the pulse edge steepness which depends on the optical pulse width and shape used by the interrogator for scanning the OF. That is why, following the strategy decided by the manufacturer, the laser pulse width can be tuneable. Then, users have to find an optimum setup between a high dynamic (high measurement speed) and a high resolution which affects the response time of the instrument. Some manufacturers introduce a spatial resolution parameter, also adjustable by the operator, but unrelated to the metrological characteristic proposed above. This parameter enables to smooth the temperature trace by a moving average over a distance which corresponds to a few consecutive samples.

For performing a metrological comparison of such a set of Raman-DTS systems, it is required to adjust them in order to have the same sampling interval (1 m in this study). If the interrogator software proposes a tuneable smoothing parameter, it should be adjusted to be by default equal to the value of the sampling interval.

The procedures applied to assess the metrological characteristics of these five interrogators are detailed in the following sections.

3.1. Calibration of the Raman-DTS interrogators

Prior to start any thermal characterization on DTS-Raman interrogator, it is required to calibrate it at a reference temperature. This reference temperature is arbitrarily chosen as 23 °C since it is considered as the normal temperature in a metrology laboratory.

As it is depicted in Fig. 1, the interrogator and the sensing OF are placed in their own thermal enclosures. The initiating and ending sections of optical fibre are immersed into the thermal enclosure dedicated to the interrogator, in order to decouple them from the main part of the sensing OF.

The temperatures of the two enclosures are controlled by using 100 Ω SPRTs. In the present study, two configurations of optical fibre length are used: the sensing/effective optical fibre is either 4 km or 19 km length and the two initiating/ending optical fibre sections are each 500 m long. Therefore the whole optical fibre length is 5 or 20 km. Each optical fibre section is wound without any spool support, and simply arranged on the floor of the thermal enclosure, in order to limit the mechanical constraints. Prior to this benchmark it has been checked that results were identical if the optical fibre was placed linearly, without any curvature, along a 25 m long horizontal furnace [23].