Distributed Temperature Sensing Using Cyclic Pseudorandom Sequences

Guillermo Daniel Brinatti Vazquez, Oscar Eduardo Martínez, and Darío Kunik

***Abstract*— An alternative for commercial Raman-Optical Time Domain Reflectometry (OTDR) distributed temperature sensors is presented, where a pseudorandom pulse sequence is used to increase the signal to noise ratio. Additionally, a deconvolution algorithm is proposed to eliminate distortions in the reconstruction arising from the real correlation properties of the sensing signal. An improvement in SNR of a factor 11 respect to the Raman-OTDR method at the same peak power was achieved, allowing 2 m and 1.5 °C resolution in a 6 s measurement using a 90-mW Continuous wave semiconductor laser.**

***Index Terms*— Optical fiber sensors, temperature sensors.**

I. INTRODUCTION

DISTRIBUTED measurements are an important tool in a big variety of problems, ranging from detecting fire spots in a tunnel to monitoring wings performance in airplanes [1], [2]. In the oil industry, distributed temperature sensing (DTS) plays a important role in real time monitoring of wellbore health, fracture efficiency and water injection profiling [3]. The majority of DTS systems nowadays are based on the Optical Time Domain Reflectometry (OTDR) technology, developed for fault location in telecommunication fibers. The fiber is used as a distributed sensor, where local temperature is recovered from Raman interactions between the pump laser and the fiber. In order to achieve high spatial resolution, short laser pulses and fast detectors must be employed. As the resulting signal level is proportional to the total amount of light injected in the fiber, there is a tradeoff between SNR and spatial resolution at fixed peak power.

To deal with this problem, a variety of techniques were developed. Optical Frequency Domain Reflectometry (OFDR) was proposed as a posible solution [4]. A continuous wave laser is sinusoidally modulated and the Raman light produced in the fiber is detected in a lock in scheme. The spatial information is recovered after a frequency sweep, computing the inverse Fourier transformation of the amplitud and phase data for each frequency. As the energy of the OTDR pulse is distributed in the whole fiber, this allows, in principle, to reduce the peak power of the lasers employed to perform DTS measurements. On the other hand, each frequency measurement requires to fill the whole fiber with the modulated signal prior detection. This implies that one has to wait a dead time for each frequency component to empty the fiber before starting the measurement with a new frequency. As the total amount of frequencies in the sweep scales linearly with fiber length and inversely with spatial resolution, this method results several times slower than OTDR.

Other time resolved methods for DTS have been developed, with the idea of spreading the spectrum of the OTDR pulse to extend it along the fiber. Correlation methods are used were pulse sequences with delta like correlations are exploited [5]. This methods have the disadvantage that all possible sequences exhibit *side lobes*, meaning deviations in the correlation from the perfect delta behavior. This introduces a distortion in the reconstruction of the spatial dependence of the signal when the correlation with the sequence is computed. To avoid this, Golay sequences have been proposed [5], [6], as they allow the use of complementary pairs of sequences. This sequence pairs have opposite side lobes, enabling to achieve perfect delta correlation by summing the signal corresponding to each sequence. Hence, two separated measurements are needed with two different pulse sequences to complete the spatial reconstruction. Simplex codes were also proposed [7], [8] but this type of technique uses a greater amount of code words, increasing measuring time.

This paper proposes the use of Maximum Lenght Sequences (MLS) for correlation OTDR measurements in DTS. This kind of measurements are a standard in the field of acoustics [9], [10], where high amplitude pulses lead to serious nonlinealities. The method was proposed [11] and discarded [5] in the context of telecommunications OTDR because of its cyclic behavior. This caused the detectors to saturate with the signal coming from scattering in the very first meters of the sensor and from reflections in the coupling. In DTS applications this is not a problem, as the detection is performed in a wavelength different from that of the laser. This leads to the possibility of measuring with the whole fiber illuminated by the sequence, maximizing the signal levels as in the OFDR method. Similar ideas using cyclic sequences were presented for Brillouin Optical Time Domain Analysis (BOTDA) [12] and Raman [13] but using low repetition rate pulsed lasers where the sequence is generated by an acousto-optic modulator or any other type of modulation. In this way the fiber is not completely illuminated and the increase in signal to noise ratio is not maximized. In our approach, a semiconductor laser is used with the possibility of continuously emitting when two ore more consecutive pulses in the sequence have the same value. To correct

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linear distortions in the correlation, a simple deconvolution algorithm is presented, with the only need of single additional measurement. Our results show an improvement in the SNR scaling with the square root of the number of pulses in the fiber. This allows to perform faster measurements or to reduce peak power (and cost) of the lasers required for DTS.

II. METHOD

Given a time independent linear system, characterized with the function $g(t)$, and a forcing signal $x(t)$, the response of the system $y(t)$ is calculated as the convolution of this two elements. For a sampled signal, this can be written as

$$y_n = (x * g)_n = \sum_{m=1}^{L} g_m x_{n-m} \tag{1}$$

where the sub index n refers to the n^{th} time sample of each function. From 1 follows that choosing x to be a delta function, the characteristic signal g can be measured directly and used to extract information about the studied system. This is the idea exploited in the Raman OTDR method, leading to the need of high energy short laser pulses to use as pump light. An alternative to this scheme are the correlation methods, where the system is forced with a sequence of pulses and the reconstruction of the impulse response g arises from the correlation properties of the sequence. To see this, we start by defining the cross correlation between the functions y and x as

$$\rho(y, x)_n = \frac{1}{N} \sum_{m=1}^{L} y_m x_{m-n}. \tag{2}$$

Combining 1 and 2, the expression for the cross correlation can be written as

$$\rho(y, x) = g * \rho(x, x), \tag{3}$$

where $\rho(x, x)$ is usually called the autocorrelation of x. With 3, the problem of finding a function that approximates a delta in time domain is switched to the autocorrelation. This can lead to an improvement in the signal to noise ratio of the measurement in systems where the pulse energy available is limited or where intensity must be reduced to avoid non-linearities. This work proposes the use of Maximum Length Sequences (MLS) for DTS measurements. This are binary sequences usually defined to take the values ± 1 resulting in a pulse train pseudorandomly distributed in time. This leads, using Wiener-Kintchin theorem, to a flat frequency spectrum, making the former suitable for impulse response measurements. The autocorrelation (as defined in 2) of the sequence is valued 1 for zero displacement and $-1/L$ for any other, where L is the sequence length defined as $L = 2^N - 1$, with N a natural number.

It can be seen that this constant term has the effect of subtracting the mean value of the signal, which must be measured by other means. The process can be easily adapted for the case of light pulses, where the states of interest are 0 and 1 for the laser off and on respectively, simply by summing a DC component to the signal. In that case, the impulse response is recovered exactly as in the previous case, this is, performing the cross correlation between the system response and the symmetric sequence, where only the information concerning the DC component of the signal is corrupted in the process.

The last advantage of the studied sequences is its cyclic behavior, meaning that any cyclic permutation of its elements results in a new sequence. Then, if the element exiting the fiber is being simultaneously reinyected at the input, then the light propagation through the fiber is changing the basis element where the Raman distribution is being projected. The whole basis is then measured in a single travel time, as in the Raman OTDR method. This also maximizes the improvement in the signal to noise ratio, as the fiber is completely filled during the entire measurement. Averaging is also simple, as the next measurement can be started right after the first one is taken, avoiding dead time between measurement as result of the fixed repetition rate of pulsed lasers. After this, the impulse response is reconstructed simply by taking the cross correlation between the averaged Raman signal and the sequence.

With the normalized definition of the cross correlation given in 2, the signal level in the reconstruction is equivalent to the one obtained in the single pulse scheme. Then, signal to noise improvement can be calculated propagating noise through the correlation process. As each data point in the reconstruction is calculated as an average of the points where the fiber was illuminated, the noise is diminished as the square root of the amount of light pulses. As approximately half of the sequence entries correspond to a light pulse, in the assumption that the noise is the same for both measurements (Raman OTDR and MLS) the improvement in the SNR will be simply

$$\frac{\mathrm{SNR}_{\mathrm{MLS}}}{\mathrm{SNR}_{\mathrm{OTDR}}} = \sqrt{L/2}, \tag{4}$$

where same peak power is assumed. Equation 4 holds if detection is made in the dark noise limit. If noise depends strongly on the amounts of signal being measured (shot noise), one must consider the detected signal level in each method. If same peak power is used in both, the total signal in the MLS scheme will be greater than in the OTDR by a factor equal to the amount of light pulses coupled into the fiber. Assuming that the sequence length can be matched to the ratio between the sensor length and the desired spatial resolution, then the fiber will be illuminated by the entire sequence at all time, resulting in a signal $L/2$ times larger. With the proper noise modeling as a function of signal amplitude, the comparison between the SNR in both methods can be performed. For the studied system, the model used for noise was simply

$$\sigma = \sqrt{\sigma_o^2 + \alpha P}, \tag{5}$$

where σ_o is the dark noise and αP corresponds to the shot noise term, where P is the pulse peak power and α is a constant scale factor. With this assumption, the expression for the comparison between the SNRs results

$$\frac{\mathrm{SNR}_{\mathrm{MLS}}}{\mathrm{SNR}_{\mathrm{OTDR}}} = \sqrt{\frac{L}{2}} \sqrt{\frac{\sigma_o^2 + \alpha P}{\sigma_o^2 + \alpha L P/2}} \tag{6}$$

Two limits are of interest in this expression. In the low power limit, the noise is dark noise for both methods and 4 is

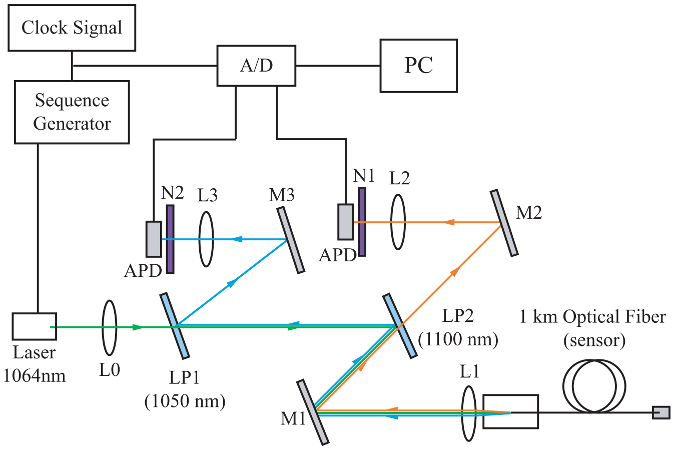

Fig. 1. Experimental setup representation. A 1064 nm laser is coupled to the sensor and backscattered Raman light is colected and divided by means of two longpass filters (LP1, LP2) to separately detect Stokes and antiStokes spectrum. An aspheric lens (L0) is used to colimate the light coming from the laser. A microscope objective (L1) is used to couple the light to the optical fiber and to collect the Raman scattering. Lenses L2 and L3 are used to focus the desired light in the detectors. Notch filters (N1, N2) are used to block pump wavelength. Mirrors (M1, M2, M3) are used to ease alignment. Sequence generation and detection are synchronized by a clock signal.

recovered. In the high power limit, the noise is dominated by the signal component, and the resulting SNR ratio is 1. This means that for any peak power, the SNR is greater in the MLS method.

An additional measurement can be done if the response of the laser, the detectors or any other components distorts the sequence pulse shape, as this distortion will be passed through the correlation to the Raman profile. The idea is to measure the impulse response of the experiment itself and then deconvolve this from the Raman measurement. For this we can replicate the procedure to get 3, but considering that x, the forcing signal, is the distorted sequence. If the correlation is made with the theoretical sequence x', the correlation of the measured signal and the latter is the convolution of the Raman response and the cross-correlation (instead of autocorrelation) between the theoretical and the distorted sequences. This can be written as

$$\rho(y, x') = g * \rho(x, x') = g * D, \tag{7}$$

where we defined function D, that must differ sightly from a Dirac's delta function due to the systematic sequence distortion. The frequency spectrum of function D must be flat, making it suitable for the normal deconvolution algorithm, namely, performing the inverse Fourier transformation of the ratio between the frequency spectrums of $\rho(y, x)$ and D. Besides, this function can be easily measured only by making some light from the laser (emitting the exact same sequence used for the Raman measurement) reach the detectors.

III. EXPERIMENTAL SETUP

The setup is shown in Fig. 1. A semiconductor laser emitting 90 mW of light at 1064 nm is fed with a pulse sequence from a function generator. The light emitted is coupled to the optical fiber acting as temperature sensor and the scattered Raman light is collected and filtered. This is achieved by means of two long pass filters (1050 nm and 1100 nm cutoff wavelengths) used to separate the Stokes and antiStokes parts of the scattered light spectrum (centered around 1115 nm and 1017 nm respectively). Once separated, each Raman component is directed to a Si avalanche photodiode (APD) for its detection as function of time. An additional notch filter is incorporated to eliminate any residual light at the pump wavelength. The signals generated by the APDs is digitalized and then processed in a personal computer. A clock signal is used to synchronize the sequence with the acquisition devices. This process can be repeated to average the signal as required to achieve the desired signal to noise ratio. For the application in the oil industry that motivated this work the sensor length requirements are in the order of a kilometer. Hence we decided to use a 1 km length graded-index multimode fiber in order to increase the power coupled to the sensor and the amount of light detected. In longer range applications attenuation becomes important and it is preferable to work at telecommunication's wavelengths and single mode optical fibers. The presented method is quite general and can be easily adapted to each particular application.

As a demonstration of the technique a 511 elements sequence (N=9) composed of 20 ns pulses was used achieving two meters resolution. This requires a sampling frequency of at least 50 MHz in the A/D converter and the equivalent bandwidth in the detectors. If higher spatial resolution is required, pulse width must be adjusted as done in the single pulse method and the sequence period decided in base of the fiber length. As the possible total pulse number is given by $L = 2^N - 1$ the value of N must be chosen to be the minimum value that makes L greater than the ratio between the fiber length and the spatial resolution. The additional points arising from this inequality are used to determine the DC component of the signal, as they bring information of light coming from points outside the fiber and then these must vanish. In this particular example, 511 measuring points at 2 meters resolution gives an effective sensing length of 1.022 km. As the real fiber length was of 1 km, this gives eleven extra points with null signal. This allows defining the DC component of the signal (lost in the deconvolution process) as the one that makes the mean value of the last eleven points vanishes.

To test the temperature resolution of the method, a temperature difference was generated in the last thirty meters of the optical fiber using a regulated thermal bath. Measurements were performed in the range between 22°C and 74°C. Additionally, as mentioned, an extra measurement is necessary to compensate the temporal response of the light and the detectors. This involves measuring directly a light pulse train directly from the laser to the detectors. This is achieved by interposing a mirror before the fiber coupling and directing a portion of the light trough the notch filter into each one of the APDs. The correlation of this signal with the ideal pulse sequence gives the experiment impulse response and allows to deconvolve this distortion in the Raman measurement. Finally the signal used to calibrate with temperature is obtained from the ratio between the corrected antiStokes and Stokes signals after compensating the differential attenuation coefficient [14] previously measured.

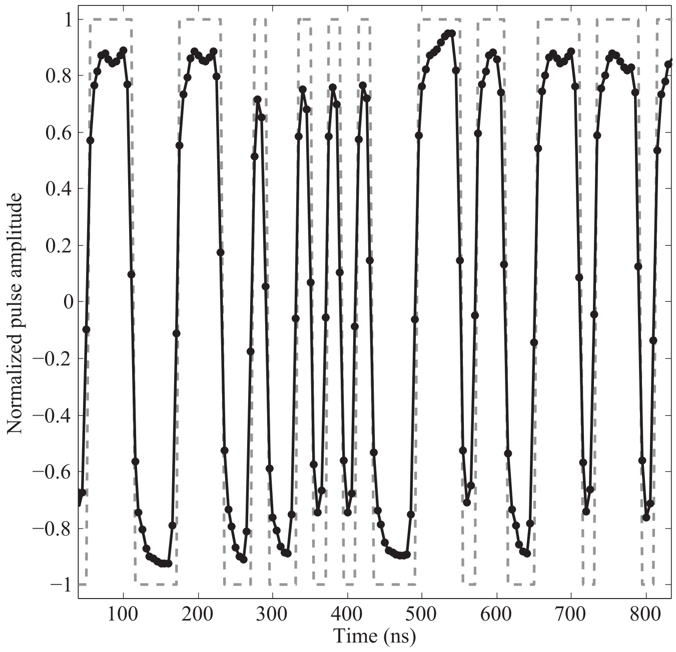

Fig. 2. Comparison between measured (solid) and theoretical (dashed) pulse sequences. Pulse height modulation is observed as function of width, causing distortion in the correlation.

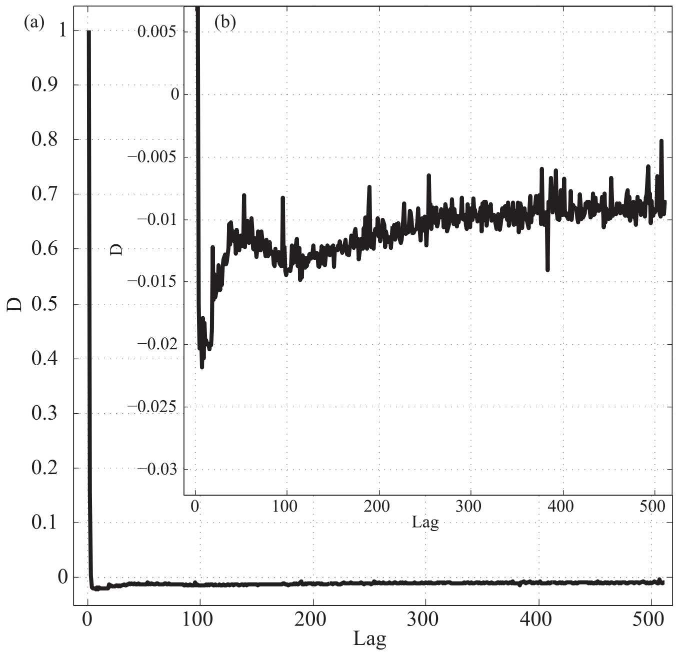

Fig. 3. (a) Correlation function between theoretical and measured sequence signal, showing delta like behavior but with a distortion for lags grater than cero. (b) Same plot in a different range, where this systematic noise component is better observed.

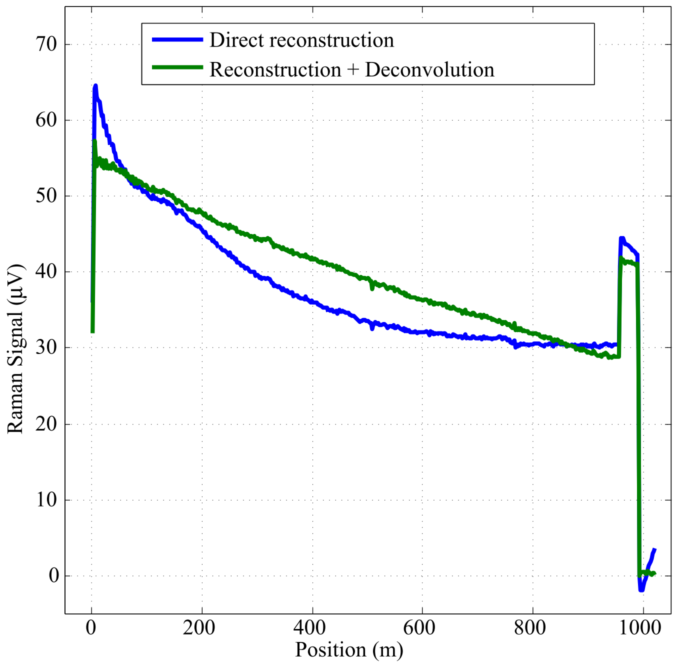

Fig. 4. Spatial reconstruction of antiStokes signal for the MLS method with and without system response deconvolution. Last 30 m of the fiber length were submerged in a 69°C thermal bath.

IV. RESULTS AND DISCUSSION

We start by showing in Fig. 2 the comparison between the ideal and the measured pulse sequence. There, the measured pulse sequence is sampled four times faster than needed allowing to visualize the rise time of each individual pulse, that can be estimated around 16 ns. As this value is similar to the time constant chosen for the sequence, this results in a reduced peak height in the isolated 20 ns pulses. When the sequence exhibits two or more consecutive equal entries, the system has more time to respond to the forcing signal, and a higher peak value is achieved. This leads to a distortion in the correlation between the theoretical and the measured sequence, as shown in Fig. 3. In plot (a) a good delta like behavior is displayed, with some low frequency distortion close to the peak. Looking closer, in plot (b), a systematic noise pattern is observed.

The reconstruction of the antiStokes signal using the MLS method is shown in Fig. 4 for both direct reconstruction and reconstruction plus deconvolution of the experiment response. The measurement was made using a 1 km fiber with the last 30 meters submerged in a water bath at 69°C. For the simplest algorithm a low frequency distortion is observed as result of pulse height modulation. The deconvolution process using 7 and the information concerning the system response shown in Fig. 3 corrects this distortion and the exponential attenuation is recovered in the portion of the fiber at ambient temperature. The method successfully reconstructs the location and width of the warm zone. Same results are observed for the Stokes signal.

An estimation of spatial resolution is shown in Fig. 5. This measurement shows the response distance of the signal to an abrupt change in temperature. We can see that the signal reaches 81% of its final value in a distance shorter than 2 m which is the sampling distance given by the method itself (one sampling point per light pulse). This is an upper bound for the spatial resolution as the exact location at which the signal starts rising is somewhere between the last pulse before the jump and the point at 81% of the peak. The limitation after deconvolution then results simply the pulse duration (20 ns)

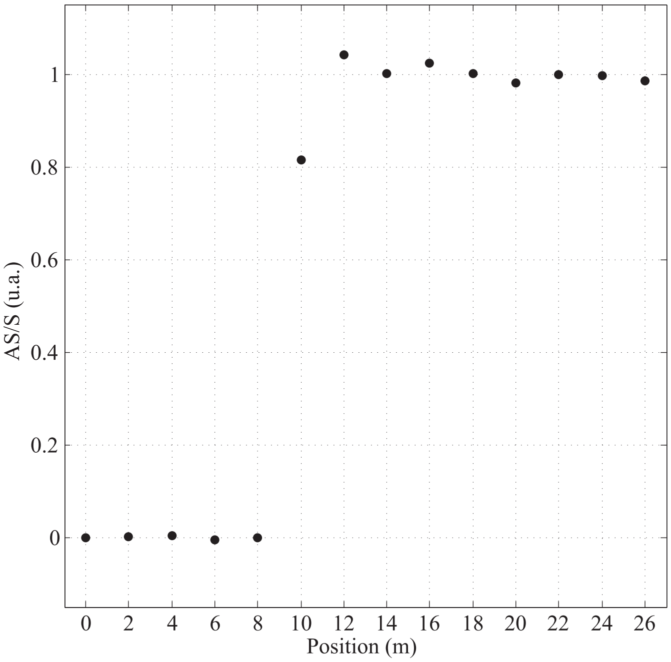

Fig. 5. Spatial resolution estimation for the calibration signal (ratio between antiStokes and Stokes signals) studying an abrupt change in temperature. The signal reaches 81% of its final value in a distance shorter than 2 m, the theoretical resolution for the method.

that corresponds to the time the light travels back and forth a distance of 2 m.

Changing the thermal bath temperature, a calibration was made for the ratio between antiStokes and Stokes signal, with an exponential correction of the differential loss coefficient. Each data point was obtained from the averaging of $6 \cdot 10^5$ individual measurements, each one taking one round trip time of the light trough the fiber (10 μs) resulting in a total acquisition time of 6 s. The result of this process is shown in Fig. 6. There we can see that the signal has a linear dependence with temperature in the explored range. The error of each data point is estimated as the standard deviation of the signal coming from the portion of the fiber at ambient temperature. This results in a temperature resolution of around 1.5°C for this number of averages.

In Fig. 7 a comparison of the SNR achieved as function of pulse peak power, from cero to Stimulated Raman Scattering (SRS) limit, is shown for our experimental conditions (sequence of length $L = 511$ ($N = 9$), graded-index multimode fiber, 1 km sensor length). The solid red line represents SNR in the Raman MLS method, and dashed blue line represents SNR in Raman OTDR method. We can see that for all powers below the SRS threshold the proposed method has a higher SNR, meaning that the same measurements can be achieved in shorter times or at lower peak powers. Although a multimode fiber was used in this demonstration, the same principle can be applied to other fibers depending on the application. For example in single mode fibers at 1550 nm the SRS threshold is around 50 W and then the improvement in SNR by increasing the pulse power can be severely limited. In that context measuring using MLS sequences can be very useful. For the explored power range (under 100 mW) an improvement of 11 times was acomplished and an improvement of 16 times is possible for dark noise limited detection. In the general case, the total number of pulses in the fiber is proportional to its length and inversely proportional to the pulse width, meaning that the relative SNR improvement is greater for high spatial resolution and long sensor applications. The speed improvement achieved for a given temperature resolution is the square of the SNR

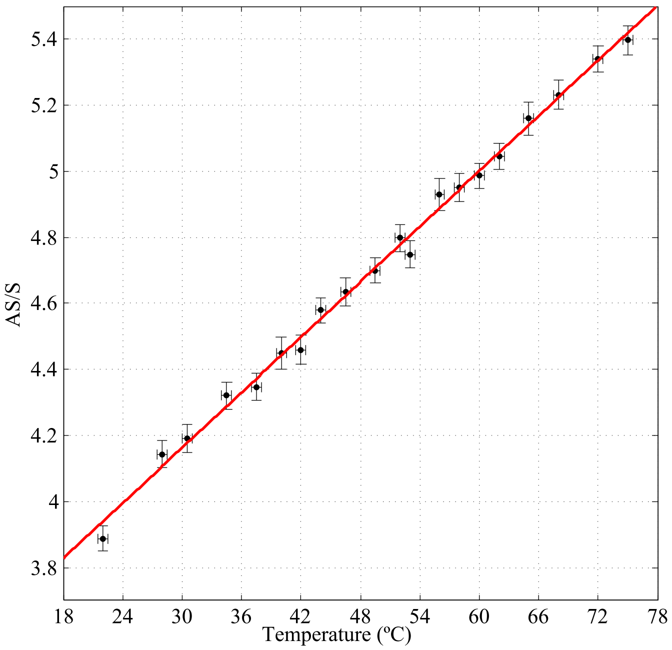

Fig. 6. Temperature calibration for the ratio between antiStokes and Stokes signals with compensated differential loss. Each data point corresponds to a 6 s measurement averaging $6 \cdot 10^5$ individual measurements, resulting in a temperature resolution of 1.5°C.

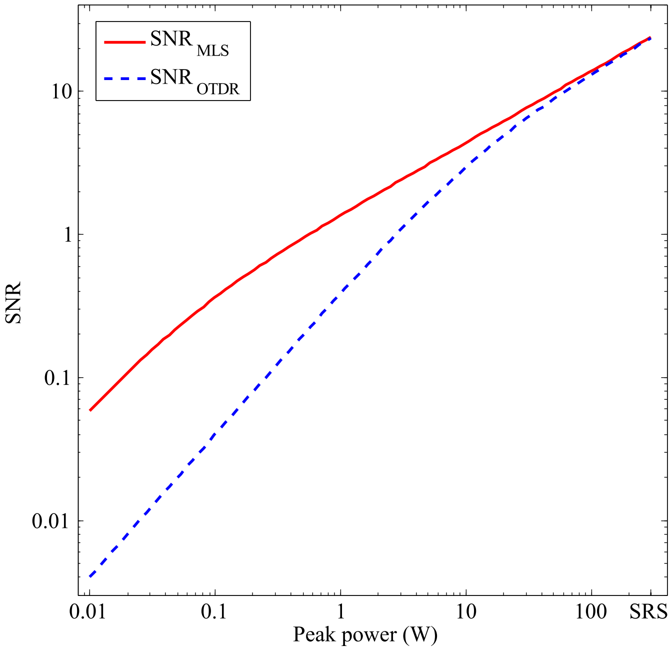

Fig. 7. Signal to noise ratio comparison between the different methods as function of peak pulse power in our experimental configuration. The power limit is the Stimulated Raman Scattering threshold (SRS) at a power of approximately 300 W.

upgrade (equation 4), scaling linearly with sequence length. For the particular sensor length and pulse width used in our experiment, the speed improvement in dark noise limited detection is up to $16^2 = 256$ times the achieved for the single pulse method.

V. CONCLUSION

A method for Distributed Temperature Sensing using Maximum Length Sequences was presented, together with an algorithm to deconvol the distortion caused in the correlation process with the real sequence. This was proven in a laboratory experiment using a 90 mW semiconductor laser and a 1 km fiber length, where 2 m spatial resolution and around 1.5°C temperature resolution was achieved in a 6 s measurement. Compared to the standard Raman Optical Time Domain Reflectometry, this results in an improvement in signal to noise ratio scaling as the square root of the number of light pulses coupled to the fiber (approximately half the sequence length) and consequently a reduction in measuring time directly proportional to this parameter. As sequence length must be chosen to approximate the ratio between the fiber dimensions and the desired spatial resolution, the improvement is greatly increased in high resolution, long sensor applications.

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