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Fibre Optic Sensing: Modified Spectral Flatness Approach for Robust Train Localisation

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Abstract

This paper presents a novel metric for the analysis of Distributed Acoustic Sensing (DAS) data for train localisation. Instead of using the average signal power to detect trains, the presented method uses a modified measure of the Spectral Flatness (SF), called Entropy Spectral Flatness (ESF), which overcomes the numerical instabilities of the traditional SF. This measure is independent of the signal dynamic range and requires no previous calibration. A comparison between the power and ESF approaches is shown and discussed. Ground truth data was also available and was used to compare the values of the position, speed, and length of trains measured using the ESF. The results show that our approach provides results that largely meet the railways localisation requirements.

Keywords: fibre optic sensing, distributed acoustic sensing, train localisation, spectral flatness, power spectral density, entropy spectral flatness

1 Introduction

Fibre Optic Sensing (FOS) offers an interesting potential as a supporting technology for absolute localisation as well as for speed and integrity determination and monitoring of trains. Fibre optic cables are usually already installed in the majority of the railway networks for communication purposes and there usually are spare cables which can be used.

The FOS technique usually used for train localisation is called Distributed Acoustic Sensing (DAS). It uses a fibre optic cable in order to sense mechanical vibrations (sound) in sections of the fibre optic cable. This creates a high sensitivity passive distributed sensor which can report the vibration profile across the whole cable at a rate of thousands of times per second[1, 2].

The cable is logically divided into equal length sections (channels) so it can be seen as an array of “microphones”. It is expected that the measurement values for each channel are proportional to the acoustic vibration (sound) at its representative point. However, each “microphone” has a different attenuation profile and reports signals which, in general, bear little resemblance with each other, especially in relation to their dynamic ranges and noise levels.

These variations make it very difficult to distinguish between signal (vibrations) and silence (no vibrations) without previous calibration. Even though a good system can be designed around signal power calculations, each channel must be calibrated with its respective noise and signal threshold power levels in order to return acceptable results. These levels are dependent on both the channel attenuation profile as well as the source signal power (train weight, speed, etc) and should also be dynamically adjusted in order to cope with temperature variations.

This paper presents a numerically stable measure of Spectral Flatness (SF) based on the concept of entropy, called the Entropy Spectral Flatness (ESF), in order to determine with a certain degree of confidence when there is silence (white noise) and report any significant deviation from this condition. This measure works on a normalised signal and is, therefore, independent of the signal dynamic range and also requires no previous calibration. It does however rely on the premise that the signal reported during periods of silence possesses white noise characteristics, i.e., possesses a flat power spectrum.

In order to present the results and algorithms, measurements were made on a suburban railway line. The timetable during the FOS recordings and GNSS readings from a measurement coach served as ground truth.

2 Methods

The signal analysis can be broken down into two distinct phases. An intra-channel analysis which analyses each channel individually and an inter-channel analysis, which receives the data from the intra-channel analysis and looks across channels.

For simplicity, we assume that each channel receives a value at every ΔT seconds, which is equivalent to a sampling frequency $F = 1/\Delta T$. Therefore, the signal for each channel can be seen as a sequence of values $\{y_0, y_1, \dots\}$.

The input sequence is then broken into possibly overlapping segments of length N . For each segment, the Power Spectral Density (PSD) is estimated using the method of averaged periodograms, also known as the Welch method[3]. In order to reduce spectral leakage, the Hann window function[4] was used for each periodogram. Assuming that a DFT of length $2M$ was used, the resulting PSD is described by a sequence of non-negative values $\{x_0, x_1, \dots, x_{M-1}\}$.

The resulting PSD is then filtered by discarding some low and high frequency bins (frequency domain filtering) and the resulting sequence $\{x_a, x_{a+1}, \dots, x_{b-1}, x_b\}$ where $0 \leq a \leq b < M$ of length $K = b - a + 1$ is used for the calculation of both the average power and the ESF.

The traditional SF is a measure to characterize an audio spectrum. It is defined as the geometric mean divided by the arithmetic mean and produces a number between 0 and 1.

$$\text{SF} = \frac{\sqrt[K]{\prod x_i}}{\sum x_i / K} \quad (1)$$

The SF should be close to 1 for white noise and close to 0 for a signal composed of a single frequency. It should, theoretically, gradually go from 0 to 1 as more and more energy is distributed among the frequencies. The SF, however, suffers from some serious numerical instabilities due to its numerator being the geometric mean, which will suffer greatly if a single coefficient is unusually small.

A modified SF measure which possess all the characteristics of the SF while not suffering from the numerical instability described above is described in [5] and is defined here as the ESF. It is calculated by first defining the normalized sequence $\{\bar{x}_i \mid i \in [a, b]\}$ as

$$\bar{x}_i = \frac{x_i}{\sum x_i} \quad (2)$$

where each \bar{x}_i can be seen as a probability so that $\sum \bar{x}_i = 1$. The ESF can then be defined as

$$\log_2(\text{ESF} + 1) = -\frac{\sum \bar{x}_i \log_2 \bar{x}_i}{\log_2 K}. \quad (3)$$

The resulting (1-ESF) value is then appropriately thresholded in order to output a 0 for

no signal (white noise) and 1 otherwise. These values are then fed to the inter channel analysis which consists of a median filter followed by a Kalman filter to improve the tracking of the objects [1].

3 Results

Figures 1 and 2 show a plot of the PSD (db) and ESF (1 - ESF) for all channels for a 15 minute interval of the FOS recordings (the PSD method here uses the average power calculated as the arithmetic mean of the remaining PSD frequency values after filtering). Both the power and ESF were filtered to contain only frequencies from 120Hz to 400Hz.

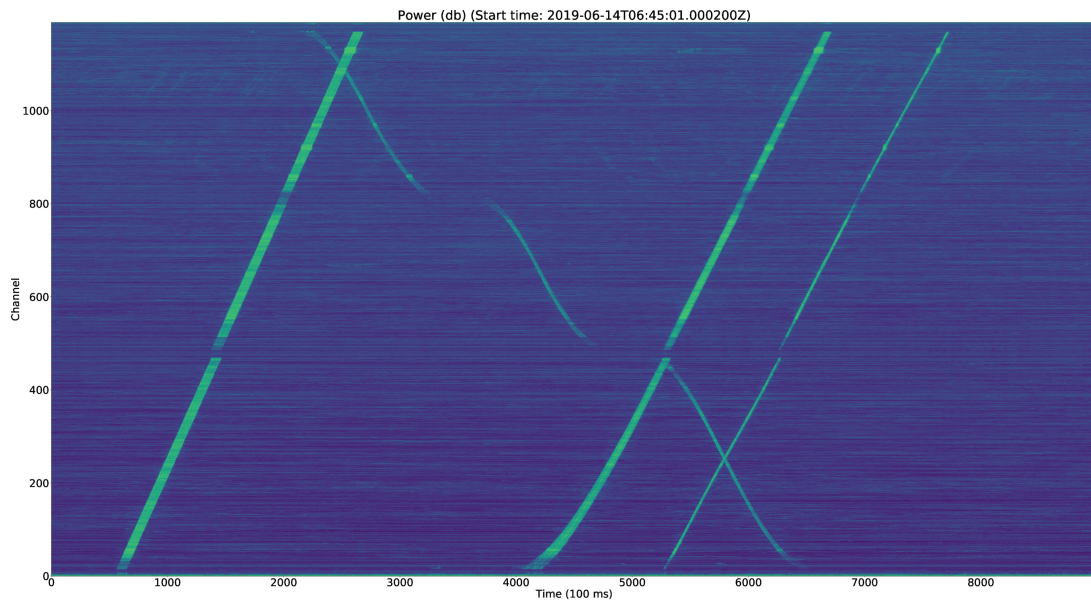


Figure 1: Cable PSD (db) from 120 Hz to 400 Hz.

It can be seen that the ESF method produces a less noisy background (more certainty in relation to silence) than the PSD method. The ESF method also works well in regions with high attenuation (around channel 820) without any previous calibration. Also for comparison, figure 3 shows the PSD (db) and ESF (1-ESF) for channel 190 (which is a channel with low attenuation) for the same time interval.

To detect trains, a threshold is applied for both methods. The threshold for the PSD method has to be calibrated with known data before being used. The contour plot is shown in figure 4. The train traveling from low to high channels (track near fibre) shows similar results for both methods. The other train (far from fibre), however gets 'lost' with the PSD approach at low speeds as well as at the final channels.

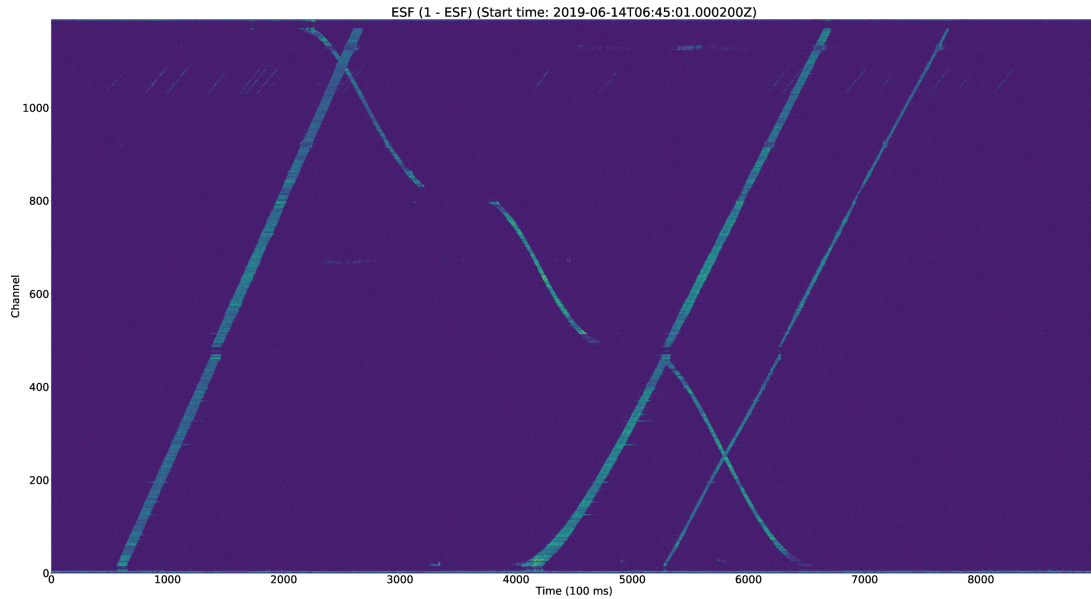


Figure 2: Cable (1-ESF) from 120 Hz to 400 Hz.

An important point for FOS systems is the geo-calibration, i.e. the mapping of the optical fibre channels to the track including the removal of typical excess lengths of the optical fibre.

Looking at the whole measurement interval using the output of the inter-channel analysis and the channel mapping, it was possible to detect all 121 trains with our approach and the determined train length was compared to the target length provided in the timetable. Figure 5 shows the achieved error distribution.

Figure 6 shows the localisation error distribution between GNSS and FOS. The mean value is an estimation of the GNSS antenna position from the front end of the train. The real antenna position is shown in green.

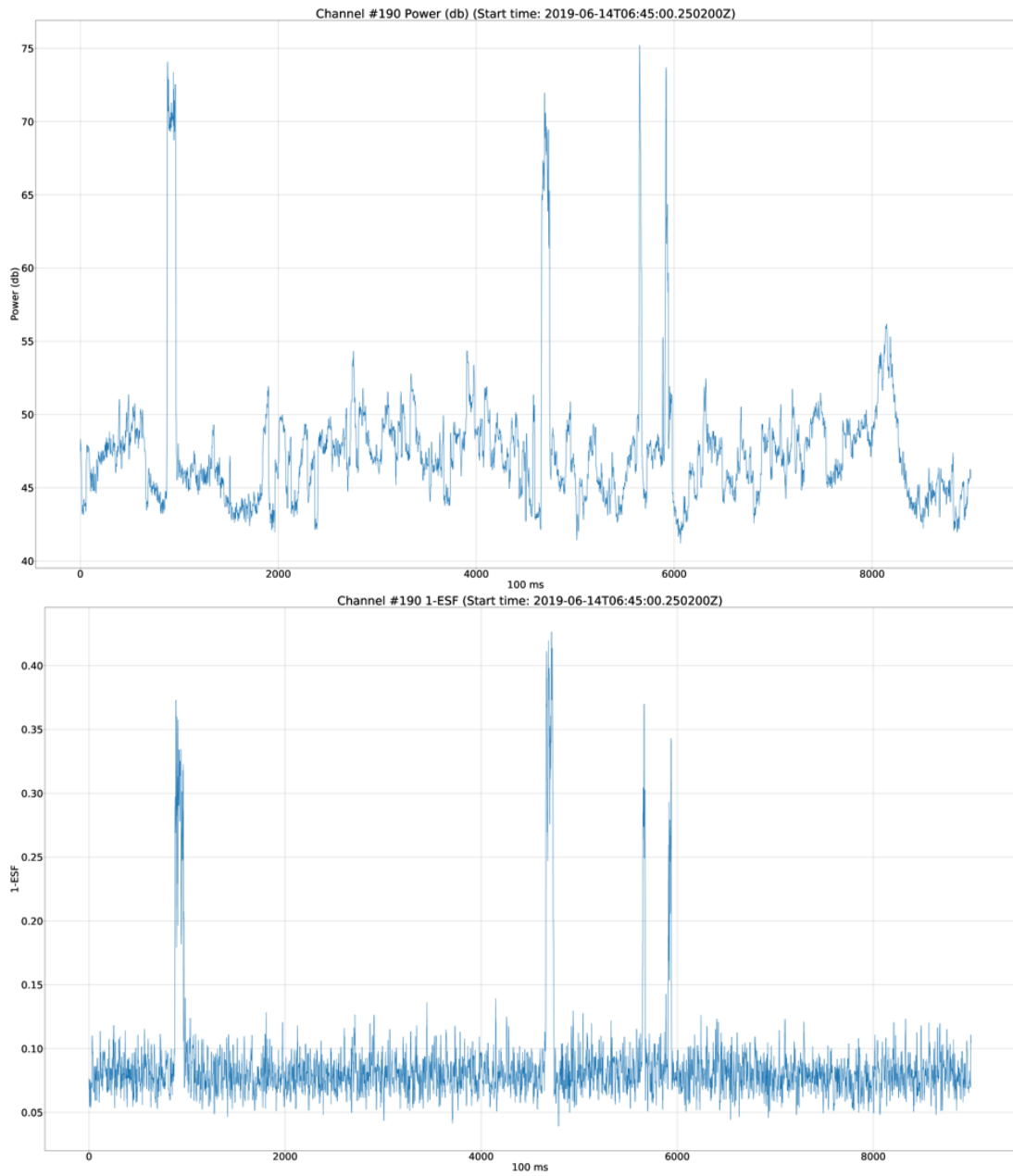


Figure 3: Channel 190 PSD (dB) (top figure) compared to (1-ESF) (bottom figure) from 120 Hz to 400 Hz.

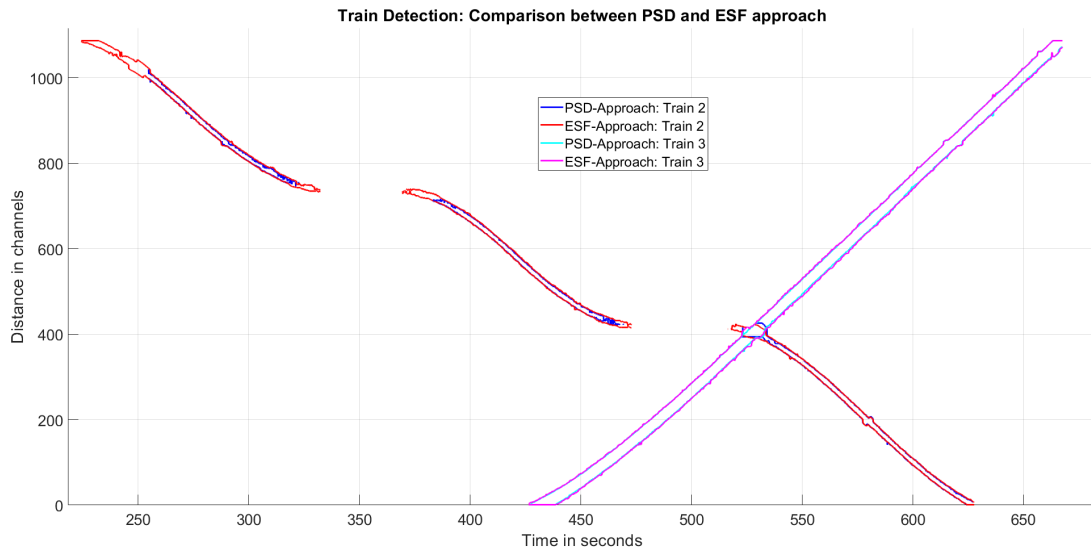


Figure 4: Train detection after thresholding the PSD and ESF data for two trains (no Kalman-Filter applied).

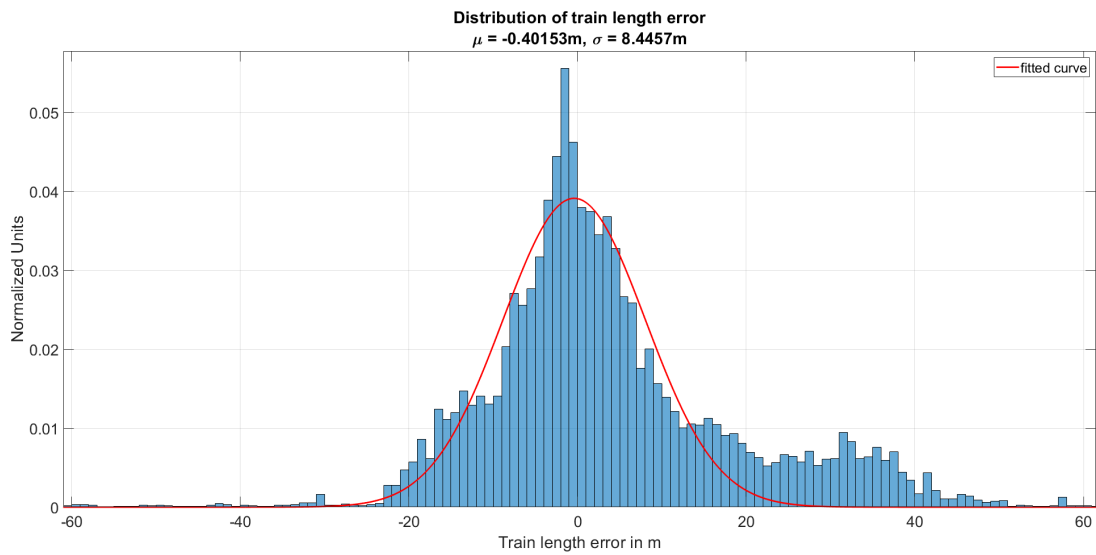


Figure 5: Distribution of the train length error for all measured trains.

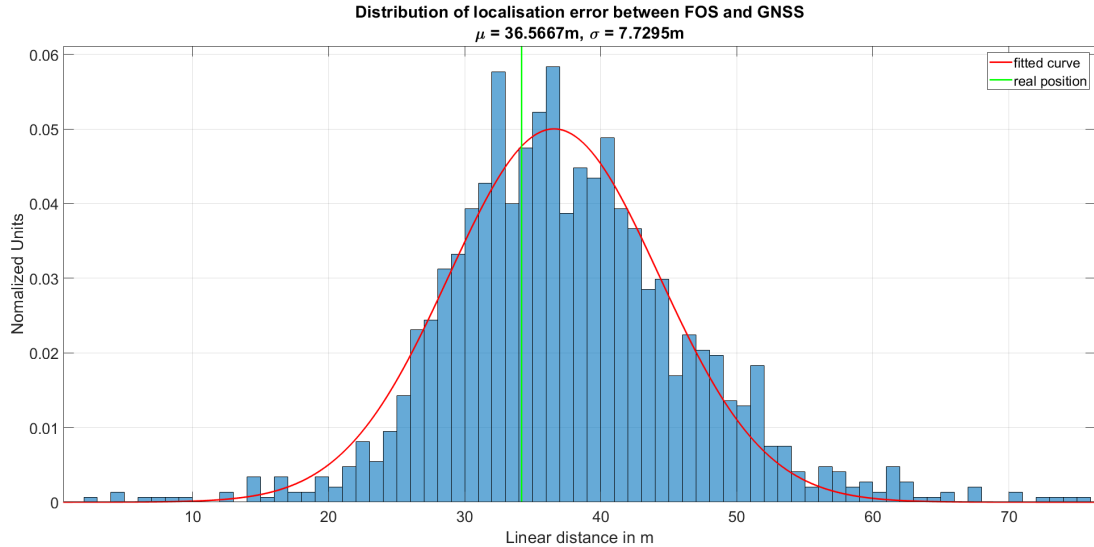


Figure 6: Distribution of the localisation error between GNSS and FOS.

4 Conclusion

This paper described a robust approach for train localisation using a numerically stable measure called Entropy Spectral Flatness. ESF is based on normalised values and, therefore, the disadvantages of the strongly varying values in the commonly used method via signal power disappear, which makes it a lot easier to work with.

We have seen that with the ESF method silence is very well detected but other signal sources besides trains (e.g. cars, etc.) are still noticeable. Improvements could definitely be made here by analysing more measurement data.

One usage for FOS would be as a fallback option for train integrity determination or localisation in areas where other sensors show disadvantages. With our approach it was possible to recognize and track all trains. The error between calculated length and real length lies with an interval of $\pm 20\text{m}$ for about 87% of all the data points. The outliers should be further investigated and errors in the schedule should not be discarded.

The evaluation of the test runs showed that the localisation error is mostly within the required ranges which are defined in [6]. As long as the FOS system delivers results within the safety-relevant limits, it is considered reliable. This period is called Mean Time To Extended Failure (MTTEF). The period during which the FOS system delivers results outside these limits is called Mean Time To Extended Recovery (MTTER). Values of 95s for the MTTEF and 2.5s for the MTTER were achieved.

In summary, it can be said that the modified spectral flatness approach for train detection with FOS works very well but there is still a lot to improve. There are some

different models which can be tried for the tracking with Kalman Filter and also the signal filtering can be improved by analysing more data.

In the future, a system which is already approved for railway applications in the safety-critical area, e.g., balises, should be used as reference for comparison.

Nevertheless, our approach demonstrated the great potential of FOS in the railway sector. In addition to train localisation or train integrity determination, this sensor can also be used to detect rockslides, animals or people on tracks.

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