 doi:10.20944/preprints202104.0514.v1

Article

Long-Range Optical Fiber Based Distributed Mechanical Vibration Sensing

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Abstract: The paper deals with the sensing system utilizing the standard single-mode optical fiber as a distributed sensor for detection, localization and classification of the mechanical vibrations that can be generated by various events such as walking or running people, moving cars, trains, etc. Sensor system capabilities were tested both in the laboratory and in the real situation with 88 km telecom optical link and the results are presented.

Keywords: optical fiber, distributed sensor, mechanical vibrations, ϕ-OTDR

1. Introduction

Optical fibers have found a broad range of applications during several last decades. The most visible and known application is in the area of telecommunications as the optical fiber technologies can provide bit rates in the range of terabits per second and per fiber when DWDM (Dense Wavelength Division Multiplexing) systems are applied. Fibers have been deployed not only in the area of wide-area networks (WANs) but they are also more and more common in data centers, in complex telecommunication control nodes, and also in access networks (“first-mile”) as FTTx technologies (Fiber-To-The x = given point between customer and provider central office, e.g. H = Home) mainly in the form of passive optical networks (PONs) and also within enterprise networks and data centers, [1].

Sensor applications are another attractive area of optical fiber usage. Fiber construction, the principle of operation (total reflection) and the form of signal (light) makes the transmission of data very safe and resistant to many sources of disturbances but nevertheless fiber parameters are partially sensitive to ambient conditions, such as temperature, strain, vibrations or strong ambient electromagnetic field and this has impact on optical signal travelling through a fiber. These facts are used for sensing application, [3]. Chemical and biochemical sensors using fibers are also available.

Majority of sensor applications are point sensors or quasi-distributed but more and more applications using optical fiber in fully distributed manner are investigated where not only physical quantity value can be measured but also the location information is provided so that long ranges of fiber length can be used for multiple simultaneous measurements.

Distributed sensors are used to measure quantities such as temperature, strain, mechanical vibrations, solutions are used to guard pipelines, rails, frontiers, territories, etc., [4].

1.1. *Sensing capabilities of fibers*

Fiber sensors can be divided into two groups, [3]:

1. Extrinsic (hybrid) fiber optic sensors,
2. Intrinsic fiber optic sensors.

Extrinsic sensors are sensors where sensing place is located outside the fiber itself while the second group of sensors uses optical fiber material as a sensory medium. Fiber sensors can be used as:

- a point sensor where there is only one point of sensing or where the quantity is spread equally along the fiber, or
- a distributed sensor where the measured quantity has local influence and the used measurement method is capable to localize it, so that the fiber trace can represent hundreds or thousands of sensors.

A general scheme of a sensor utilizing optical fibers is shown in **Figure 1**:

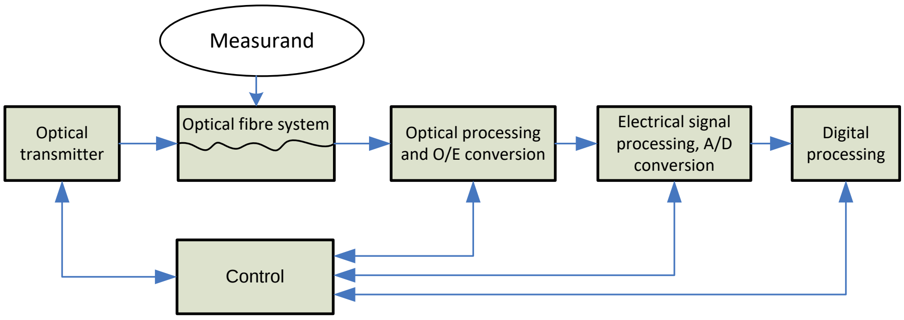

Figure 1. General architecture of optical fiber-based sensing system.

Optical transmitter contains light source, a laser is the most frequently used type, and in majority applications also a modulator, amplifiers, filters and other components are present to generate a special form of the light signal with appropriate power level and limited spectrum. In most cases the monochromatic and stable, i.e. highly coherent light source is required to obtain high sensor sensitivity and required accuracy.

Optical fiber system includes one or more segments of optical fiber and also other components, such as optical splitters, couplers, isolators, circulators and others. Polarization controllers, polarization splitters, prisms, lenses and mirrors can be also required. Optical processing block may include optical preamp and/or block for coherent detection that may precede an o/e converter. Optical detectors change a stream of photons into electrical signal, i.e. current and/or voltage that can be processed by conventional electronics. PIN and avalanche photodiodes are the most common photodetectors used for sensing purposes. The most important parameters of the photodiodes are the optical power range, spectral sensitivity and quantum efficiency, the frequency response, noise level and voltage and temperature dependencies of parasitic effects like junction capacitance and dark current. The temperature has negative impact mainly on the dark current where the temperature increases by approximately 8 °C doubles the value of dark current. Dynamic behavior (response time) of the photodiode is dependent on several factors, on the size of photoelement, the bias voltage and especially on the wavelength for which the photodiode was designed - the shorter wavelength, the thinner depletion region has to be implemented in photodiode and faster response is reached. The shorter response time can be reached by narrowing the silicon layer at the cost of lower quantum efficiency and of the overall sensitivity. Low noise amplifier is also the necessary part of the optical detector. Signal processing is realized in digital form, so that A/D converter with antialiasing filter is the input part of the signal processing block. The sampling frequency should fulfil Nyquist–Shannon sampling theorem and the dynamic range (a number of bits per sample) should correspond to the maximum signal-to-noise ratio. For example, to measure the signal, whose dynamics is 70 dB, A/D converter with 12-bit resolution is required.

1.2. Principles of sensing

There is a number of principles using optical fiber that have been designed, tested and used for sensing purposes during the decades by many scientist and engineers

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working in this area of research [3]. The first group of methods is based on the simplest effect, i.e. light intensity change. These sensors are either based on violation of total reflection principle of light propagation along the fiber (pressure or position sensors based on fiber microbending) or they belong to the extrinsic sensors when external light propagation parameters change when the light leaves the fiber, reflects from the reflector and returns back to the detector. A big group of sensors uses a light interferometry principle. This group of sensors is based on the result of light interference. They use phase differences between light beams that travel through interferometer arms and then meet each other and interfere. The proper function requires interfering beams to be highly coherent and therefore the difference of arm lengths must be lower than the coherence length of the laser source. Michelson, Fabry-Pérot, Mach-Zehnder and Sagnac are the most known interferometer principles, [3]. The interferometric methods are very sensitive but if used as intrinsic sensor for vibration sensing their results do not give information about the location.

1.3. Distributed fiber sensors

Distributed optical fiber sensors have capability of mechanical vibrations sensing in its vicinity in distributed manner, i.e. it can detect and localize many events located at different points along the sensing fiber. The measurement scheme is based on an analysis of Rayleigh backscattered signal from interrogating pulses, similar to the reflectometry principle used in OTDR, see Figure 2. but the sensor principle is based on the changes of interference patterns among discrete scattering centers within half of the optical pulse width.

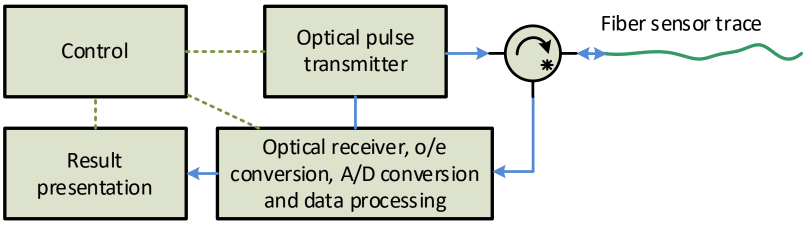

Figure 2. Architecture of the sensor using backscattering / reflectometry principle.

Therefore highly coherent lasers are required. Narrow and highly coherent optical pulses are regularly sent to the fiber that may be exposed to mechanical vibrations and backscattered optical signal is received at the same sensing fiber end. Mechanical vibrations change the sensing fiber parameters (length and refracting index) and so do the parameters of a propagating optical signal. Received signal is processed and a huge amount of information from it can be obtained about the fiber. Obtained data is used firstly for detection of events and in positive case the event sources can be localized and also classified. "Time-of-flight" technique is used for localization. Sophisticated signal processing techniques are necessary is used for event classification if required.

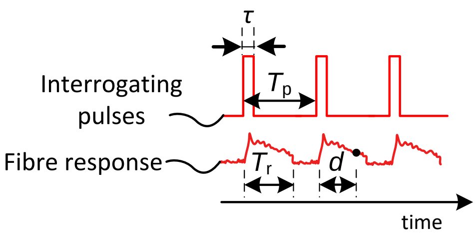

Figure 3. Interrogating optical pulse sequence and the fiber response.

A portion of this scattered signal is re-captured by the fiber and is being spread either back (in opposite direction than original signal) or in the direction together with original signal or in both directions. Capturing and processing of back-scattered signal is the most common technique, see **Figure 3**. The pulse width τ limits distributed sensor spatial resolution R that can be calculated as:

$$R = \frac{\tau v_g}{2}, \quad (1)$$

where v_g is the group velocity of the light in the fiber core. The resolution can be increased by narrowing the interrogation pulses. On the other hand, the narrower pulse carries less energy and therefore shorter sensing ranges are usually reached because of the limited detector sensitivity and a noise presence.

Figure 4 shows a sequence of pulses sent to the fiber and the fiber responses to them. It is clear that the pulse period T_P should be longer than the response T_r of the fiber on the pulse, otherwise the responses from the successive pulses would overlap and the information from the fiber will be lost. For example, the pulse period should be longer than 100 µs for the 10 km silica fiber, provided the light carrier frequency remains unchanged.

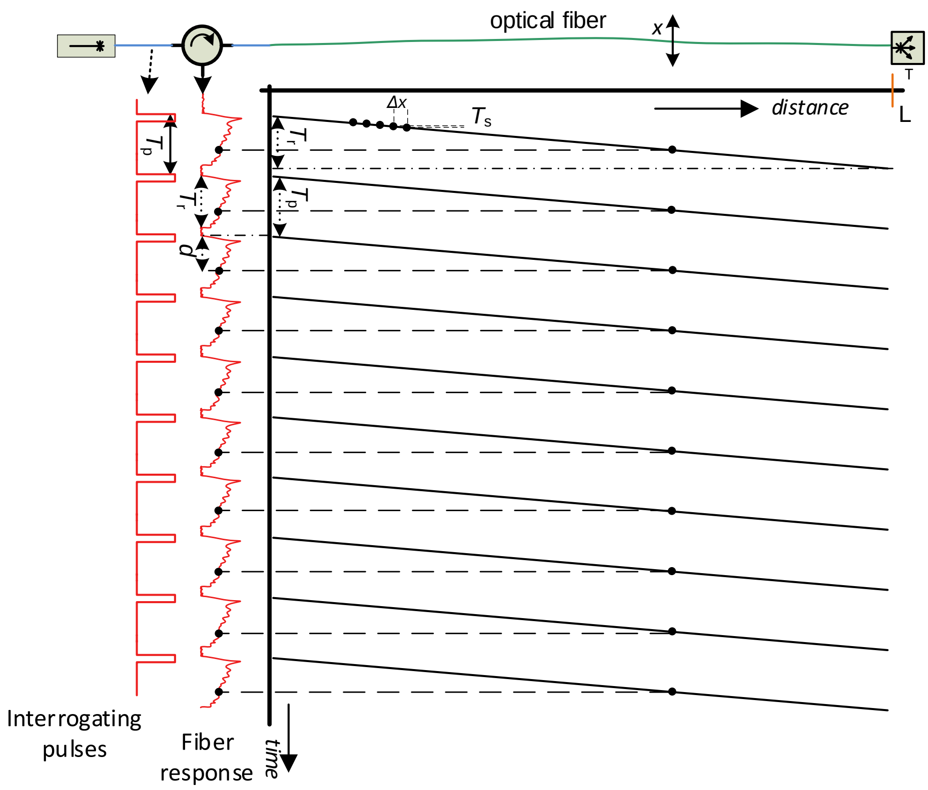

Figure 4. Time-spatial response of the fiber on the sequence of optical pulses.

According to the time delay d between instances of light pulse transmission and the instance of the response sample reception (see **Figure 4**) the location x of an event can be calculated using formula

$$x \approx \frac{d * v_g}{2}. \quad (2)$$

Geographical location of the event is derived by an approximation between two closest points on the fiber that have precise geographical locations stored in a database.

Typical course of the fiber response based on the technique described above and converted to electrical signal and displayed on an oscilloscope is shown in **Figure 5**. The

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course shows fast signal attenuation and high fluctuations. The attenuation is caused by double attenuation both of interrogating pulses in forward direction and of backscattered signal in backward direction. Fluctuations of backscattered signal occur due to the usage of ultra-narrow laser source, random locations of scattering centers within the fiber and random phase of scattered signals that are superimposed during the path to the receiver side, [6]. As shown in **Figure 5** the signal level falls close to zero level at many time instants and this deteriorates the sensor sensitivity at corresponding locations along the sensing fiber. This is caused by a destructive phase combination within the sum of particular signal contribution from randomly distributed backscattering centers within the fiber covered by half of interrogating pulse and in the case of coherent detection also by mutually almost orthogonal polarization between the local oscillator and received backscattered signal.

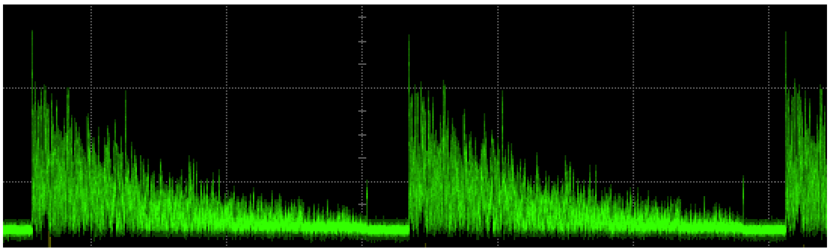

Figure 5. Typical fiber response to narrow spectral linewidth interrogating pulses

Two basic schemes are used for backscattered signal reception – direct detection and coherent detection, which can be seen in **Figure 6** and **Figure 7**.

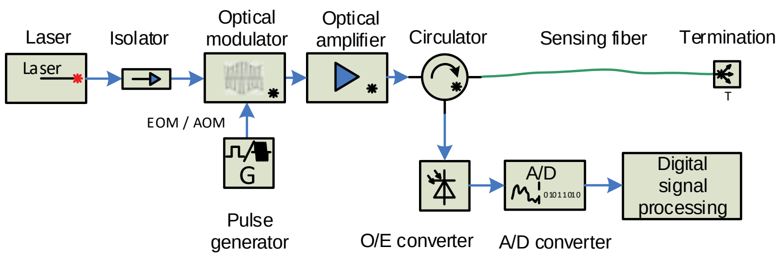

Figure 6. Direct detection scheme

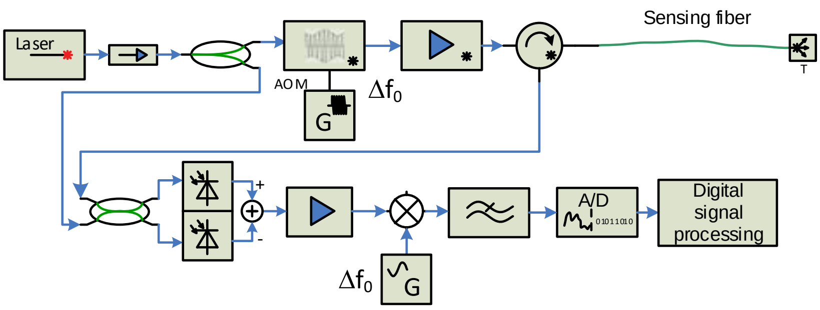

Figure 7. Coherent detection scheme

Direct detection scheme has lower complexity than coherent one but it has a number of issues described in [5] that limit its performance. Coherent detection technique consists in mixing of backscattered signal with optical local oscillator and in a balanced o/e conversion. The strong local oscillator signal is mixed with a weak backscattered signal in a 50/50 coupler and converted to an electrical signal in a balanced photodetector. This method improves sensor sensitivity and provides higher dynamic range. The cost for these advantages is that ultra-narrow spectrum light source (laser) with high stability is

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required. Spectrum line width has to be in order of kHz or better, thus the laser is the most expensive component of the system.

2. Experimental measurements

To test the principles mentioned above several experimental test-beds were designed and realized. The direct detection architecture was found less sensitive than coherent one and thus we focused on the coherent detection system and the result design scheme is shown in **Figure 8**.

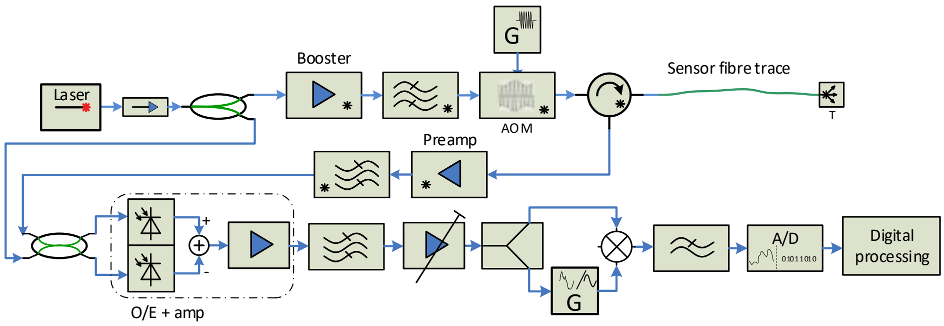

Figure 8. Scheme of the test-bed.

The probe according to the scheme was constructed. We used ultra narrow laser (10 kHz linewidth) at 1550 nm wavelength to minimize the signal attenuation (both interrogating pulse and backscattered signal) along the fiber. The pulses are generated by acousto-optic modulator (AOM), which in addition to modulation process with high extinction ratio (> 50 dB) shifts the spectrum of optical signal in order of tens MHz. We used AOM with 110 MHz frequency shift. The pulse width is adjustable in the range 100 ns - 1 µs. The pulse width corresponds to a spatial resolution that is in a range 10 - 100 m. Generated pulses are amplified by EDFA booster, filtered by an optical bandpass filter and sent via circulator to the fiber. Backscattered optical signal from the fiber returns via circulator to the EDFA preamplifier and after filtering is mixed with optical local oscillator (OLO) signal generated by the laser in 50/50 coupler. Result signal is converted to the electrical form by a balanced O/E converter where PIN photodiode and transimpedance amplifier were used. Electrical signal is again amplified and then splitted to two branches. The signal of one is used to recover the beat carrier, i.e. 110 MHz signal that enters with the second branch a mixer. High frequency components (above 10 MHz) of the mixer output are filtered out and the result signal is converted to the digital form by A/D converter with sampling frequency 50 MSPS. Obtained data is processed by additional filtering and averaging techniques. The system was constructed and tested firstly in a laboratory (fiber coils of length 20 and 50 km) and later with a real optical telecom link.

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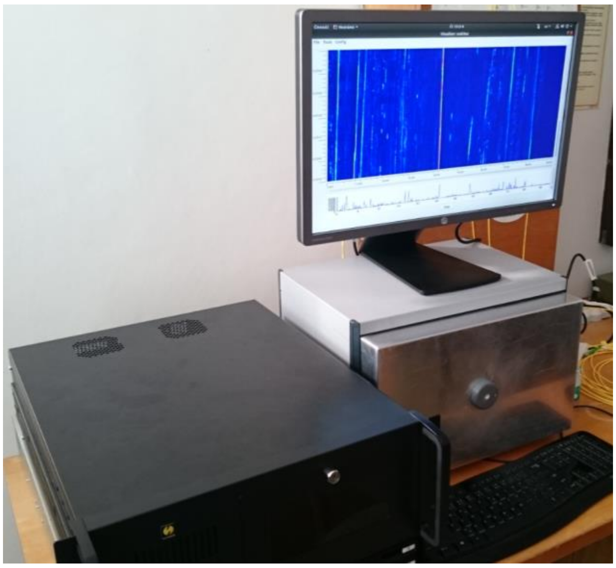

Figure 9. The sensing system test in a real enviroment

Sensing optical fiber was a dark fiber in a standard telecommunication optic cable with total length of 88 km.

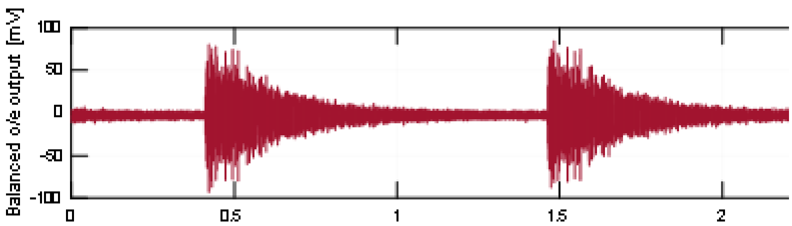

Figure 10. The beat signal at the output of balanced o/e converter

Small segment of output signal from O/E converter in coherent heterodyne detection system is shown in **Figure 11**. What we are interested in, is the envelope of the result beat signal, which will be obtained after mixing with the carrier frequency as described above. We recovered the carrier from the received beat signal as depicted in **Figure 8**.

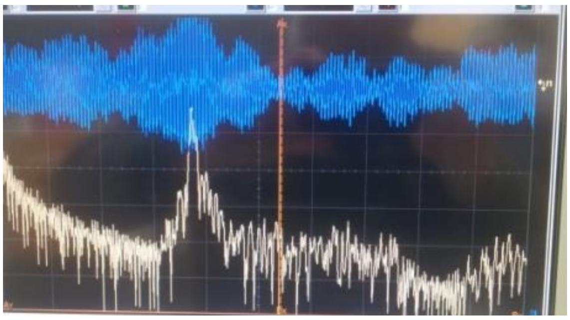

Figure 11. Signal detail after an o/e conversion and its spectrum – coherent heterodyne detection system.

After low-pass filtering the signal similar to that from **Figure 12** is obtained.

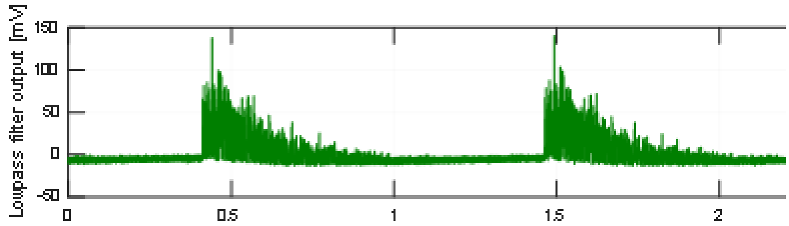

Figure 12. Signal after demodulation without equalization (almost 2 periods)

Due to the exponential attenuation of the fiber response we proposed signal equalization. To equalize the response the beat signal was amplified by a logarithmic variable gain amplifier (VGA) whose gain was controlled by sawtooth shaped signal synchronized with pulse generation.

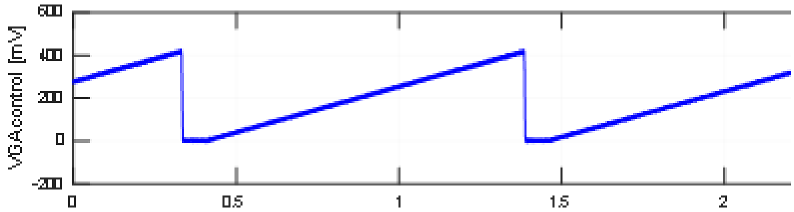

Figure 13. VGA control voltage

After equalization and demodulation processes and lowpass filtering (see **Figure 14**) the signal is sent to A/D convertor for digital processing.

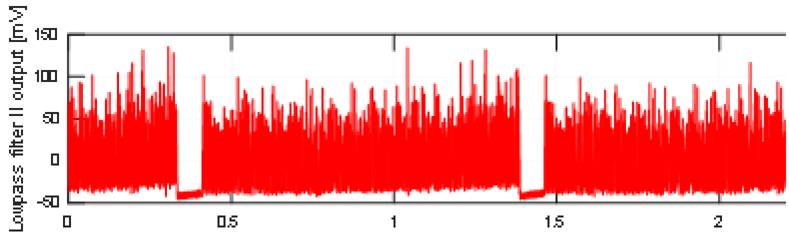

Figure 14. Signal after demodulation and equalization

In a computer software the fiber responses are arranged in two dimensions with the color representing signal level, then a signal representation that is called "waterfall" in a raw form is obtained. Two-dimensional signal displays information in time (vertical axis, latest response is at the top) and along the fiber (horizontal axis), see **Figure 15** (only a narrow part of waterfall in the horizontal direction with a static event occurence within the interval of 7 seconds is shown). The event caused by hammer strokes on a rail was detected at the distance of 74.4 km along the fiber.

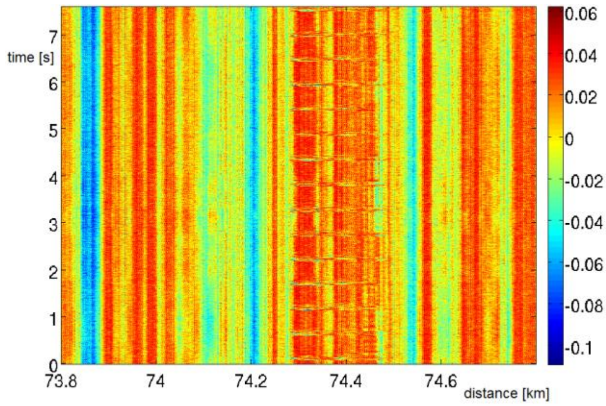

Figure 15. "Waterfall" of raw captured data.

Using FIR filtering along the time axis the vibration events along the fiber can be emphasised while the quiet areas are cleaned as shown in **Figure 16**.

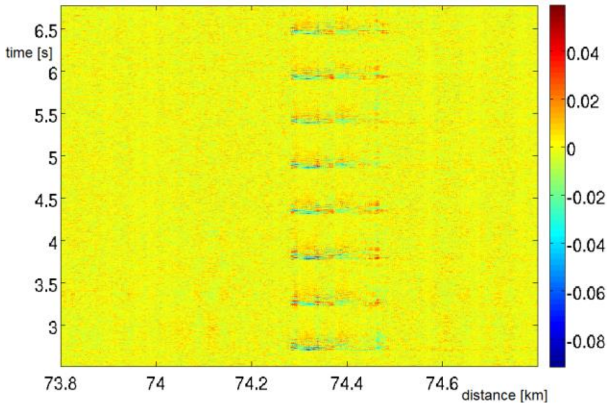

Figure 16. "Waterfall" after filtering

Corresponding time-domain course of signal (hammer strokes) from single point is shown in **Figure 17**.

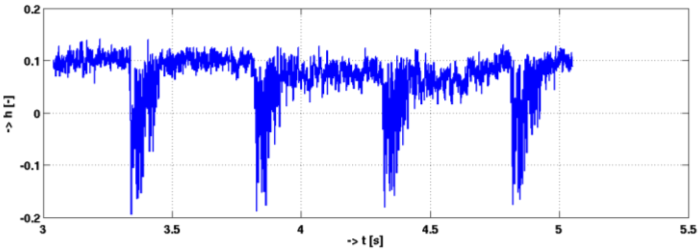

Figure 17. Time-domain signal course from the event location – hammer strokes

The waterfall with non-static events along the complete sensing fiber (88 km long) is depicted in **Figure 18**. The speed of vibration source movement can be derived from the slope of the track in the waterfall.

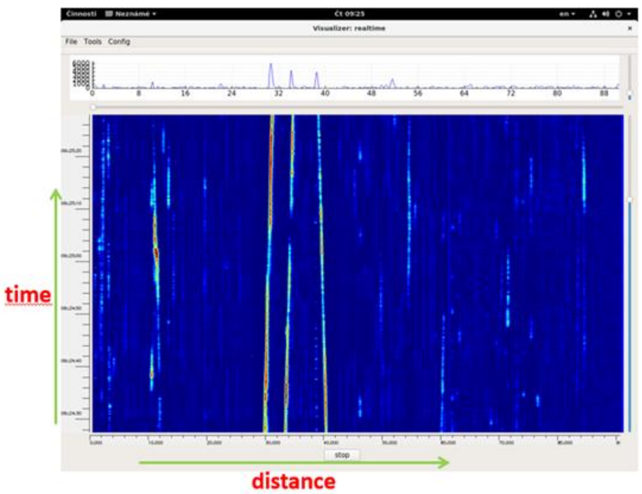

Figure 18. Spatially-temporal presentation of the occurrence of events - "waterfall"

There can be some troubles to establish the speed precisely. First, we need to determine the reference points on the fiber at particular time instants. This can be trouble both when sources produce too strong or too weak vibrations, see **Figure 19**. In the first case the track is wide and its width changes, and in the second case the track can vanish, so that the extrapolation method is required. The sensing fiber bends and rolls along the sensing cable track so it can cause that calculated distances can differ significantly. After the locations at different time instants on the fiber are obtained from the detection process, geographical coordinates have to be determined. Precise information about sensing cable laying is required.

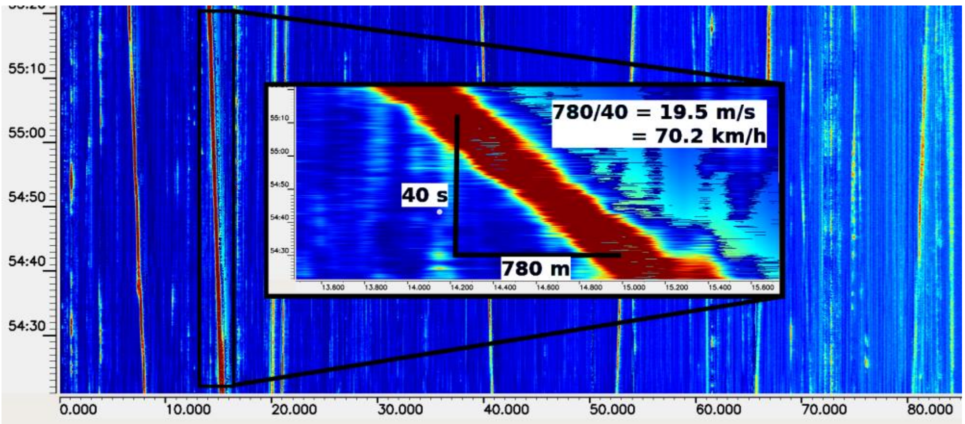

Figure 19. The waterfall with moving vibration sources (trains) and the source movement speed estimation

When the sensing cable is laid down along the railway line the train speed profile can be obtained as shown in **Figure 20**. This can provide useful information when needed.

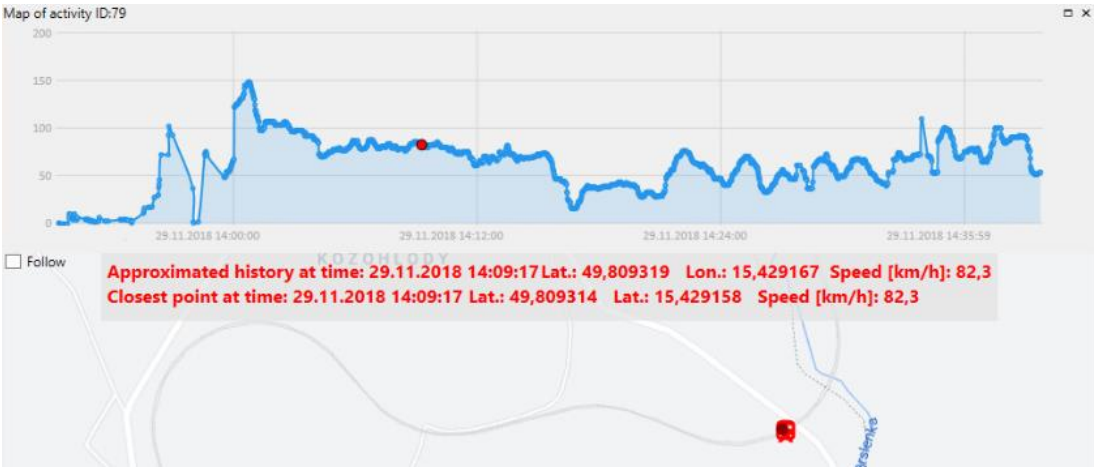

Figure 20. The speed profile of the train and its map location at selected time instant

Not only strong vibration sources can be detected at far distance but also human or bigger animal presence in the vicinity of the sensing fiber are reported by our sensing system, see **Figure 21**. Optical power 23 dBm and 1µs pulse width was used. The cable was standard telecommunication cable laid 1 m under ground. The signal from running person is clearly detectable including the direction of movement.

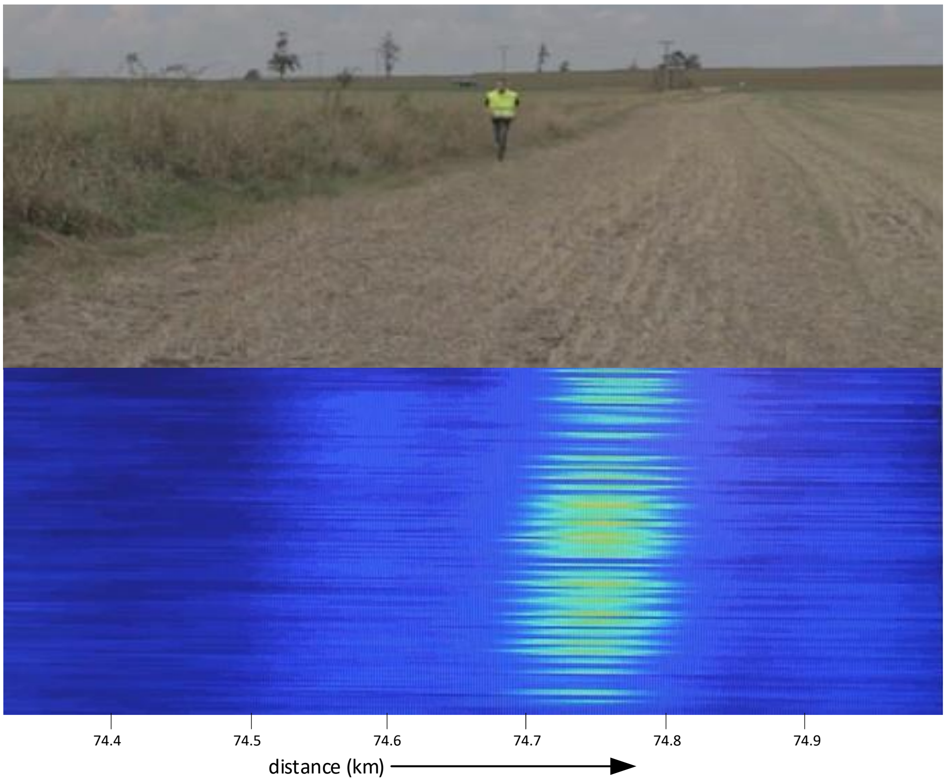

Figure 21. Detection of runing person at the distance 74.75 km

3. 4. Discussion

The distributed vibration sensing system based on Rayleigh backscattering and on the coherent detection principle was designed and constructed. It is capable to detect and to localize many vibration sources, both static and moving ones. Maximum sensing length reachable by our system is above 90 km. Using additional signal processing our system can also identify several groups of vibration sources – trains, cars, persons (jumping, walking, running), ground digging, drilling, hammer blows. At this time we are finishing a two-fiber sensor unit with approximately doubled maximum sensing length. Described sensing system we used in a more complex sensing system, which we designed and which is described in [12].

Author Contributions: System architecture, methodology, Novotny, V.; hardware design Novotny, V., Hanak, P., Prokes, A.; software, Sysel, P., Prinosil, J.; system validation, Novotny, V., Sysel, P., Slavicek, K.; investigation, Novotny, V.; data processing, Sysel, P., Prinosil, J.; writing, Novotny, V., Sysel, P., Slavicek, K. visualization, Sysel, P.; supervision Novotny, V.; project administration, Novotny, V.; funding acquisition, Novotny, V.

Funding: This research was funded by Ministry of Interior of the Czech Republic under grant no. VI20202017078.

Conflicts of Interest: The authors declare no conflict of interest.

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