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Towards uniformity of rotational events recording – initial data from common test engaging more than 40 sensors including a wide number of fiber-optic rotational seismometers

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Abstract

Rotational seismology is one of the fastest developing fields of science nowadays with strongly recognized significance. Capability of monitoring rotational ground motions represents a crucial aspect of improving civil safety and efficiency of seismological data gathering. The correct sensing network selection is very important for reliable data acquisition. This paper presents initial data obtained during the international research study which has involved more than 40 various rotational sensors collected in one place. The key novelty of this experiment was the possibility to compare data gathered by completely different rotational sensors during artificially generated ground vibrations. Authors collected data by four interferometric optical fiber sensors, Fiber-Optic System for Rotational Events & Phenomena Monitoring (FOSREM), which are mobile rotational seismographs with a wide measuring range from 10^{-7} rad/s up to even few rad/s, sensitive only to the rotational component of the ground movement. Presented experimental results show that FOSREMs are competitive in rotational events recording compared with the state-of-the-art rotational sensors but their operation still should be improved.

1. Introduction

Characterization, quantification, as well as modelling of ground motion require data about translational ground displacements and strain measurements. Recently, it turned out that three rotational components which have been often neglected, can provide additional valuable information for seismology society [1-3]. These three components can help to understand the Earths inner structure, seismic sources as well as they are significant for engineering purposes [4,5], e.g., high-rise buildings [6,7] or wind farms monitoring. In line with the recently developing interest in rotational seismology, there is a significant need for both theoretical but mostly experimental research. It influences the development of rotational sensors technology which must meet stringent technical requirements [8]. The very wide measuring range is the most crucial parameter (signals amplitude from 10^{-7} rad/s to 10 rad/s, frequency from 0.01 Hz to 100 Hz). There are three basic groups of rotational sensors: mechanical such as TAPS (by *Polish Academy of Science*), Rotaphone (by *Czech Academy of* Science), MEMS technology – Horizon (*EMCORE*), electromecha-nical - R1, R2 (*Eentec*), and optical: RLG (by *LMU, Germany*), blueSeis-3A (*iXblue*), SRS-5000 (*Optolink*) widely compared in Ref. 8. However, the total insensitivity to linear motion, wide measuring range, high sensitivity, and portability make systems based on FOGs the most appropriate sensors for rotational seismology. At this point it should be mentioned that the large gyroscopes ROMY located near Munich, Germany are now the most sensitive devices capable of providing high-resolution observations of the Earth's rotation rate, as well as local earthquake- or otherwise-induced rotational ground motions [9,10]. However, since it is a stationary system, it cannot

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be regarded as a device meeting all requirements of the rotational seismology presented in Ref. 8.

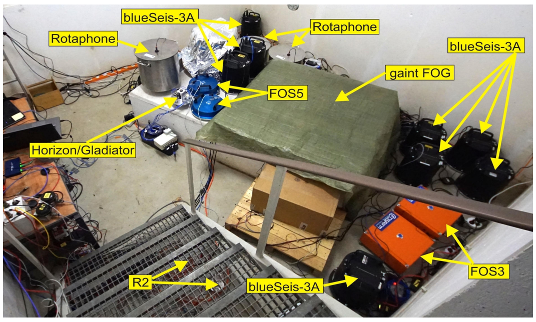
Yet, the proper seismic monitoring requires a long-term planning and effective data gathering. For this data reliability recorded by one device can be confirmed by appropriate correlation with the data received by another one, where seismic monitoring involves deploying and operating seismic instruments in the field. The comparative measurements of local seismic rotations by different independent devices can be found in recent literature, for example between three devices [11] or two [12] of them, but it was an independent action by a separate group of researchers. Regardless of this fact, the researchers emphasized the requirement of international cooperation from the very beginning of work in rotational seismology [13]. For such action the International Working Group on Rotational Seismology (IWGoRS) has been established to spread investigations of rotational motions in seismology and their implications for several associated disciplines, including seismology, earthquake engineering, geodesy, and even the Earth-based detection of Einstein's gravitation waves. Rotational seismology researches complexity requires perfection of recording methods and devices to receive, process and analyze seismic data.

To further establish high quality standards in recording seismic ground rotations, a special experiment has been organized known as "Rotation and strain in Seismology: A comparative Sensor Test" which took place in Geo-physical Observatory of Fürstenfeldbruck, Germany between November 18-22, 2019 and gathered more than 40 different rotational motion and strain sensors. The performed experiment consisted of initial huddle tests and the final field deployment measurements, and focused on the analysis of sensors self-noise, signal-to-noise ratios, and data comparison during artificially generated vibrations. The first published results cannot be regarded as a fully satisfactory comparison of data from different sensors, as it can be concluded from the fundamental Bernauer *et al.* paper [14]. However, the separate data from different kind of rotational devices, including Rothaphone-CY [15] or FOS5 [16], show a "light at the end of the tunnel" regarding future harmonization of data collected by such devices.

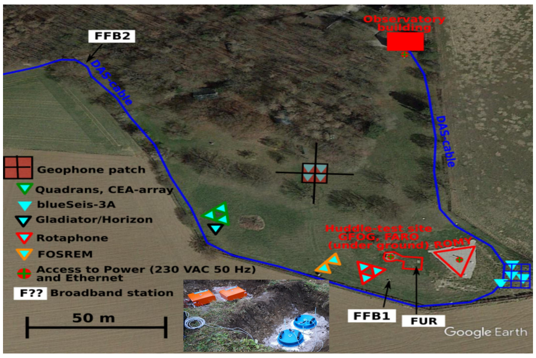
In this paper, we present the first proceeded data from one part of the Fürstenfeldbruck experiment recorded by four interferometric optical fiber sensors constructed by the authors and named Fiber-Optic System for Rotational Events & phenomena Monitoring (FOSREM). FOSREM is a single-axis device that uses the technical implementation of FOG to record rotational motion. FOSREM most significant attribute is its theoretical sensitivity equal to $2 \cdot 10^{-8}$ rad/s/√Hz. In the aforementioned experiment two types of such instruments have been used. Both have the same optical part design consisting of commercially available fiber-optic elements based on a standard single-mode telecommunication fiber (SMF) with a 0.25-m diameter sensor loop and about 5 km long SMF. The electronic part is the main difference between the two types of FOSREM, where the first - FOS3 system, uses an open loop configuration and the second - FOS5, uses a closed loop configuration. Both were prepared to fully meet all technical requirements for rotational seismology [8]. It should be noted that a similar fiber-optic system was proposed also by *iXblue* company from France as blueSeis-3A [17]. This device allows measurements of rotation in three perpendicular axes and has already been successfully demonstrated to perform a 6 degree-of-freedom measurement in local earthquakes [18], as well as a dynamic tilt correction for pure acceleration measurements [19].

2. Experiment description

The most significant feature of the "Rotation and Strain in Seismology: A Comparative Sensor Test" experiment is the number of various rotational sensors delivered by different research centers. More than 40 sensors have been placed together in a bunker and in the field (see Fig. 1) to record artificial vibrations which makes this experiment the first of its kind. One can distinguish the following applied sensors: two blueSeis-3A, ROMY (large 4-component ring laser gyroscope), and three permanent broadband stations (by *Ludwig Maximilian University of Munich*, Germany), 80 Channels Geophone system (by *ETH*, Switzerland), three blueSeis-3A (by *University of Potsdam*, Germany), blueSeis-3A (by *Bundesanstalt für Geowissenschaften und Rohstoffe*, Germany), blueSeis-3A (by *ISAE SUPAERO*, Toulouse) four Rotaphones (by *Charles University*, Czech Republic), two Gladiator and three Horizon (by *Opole Univ. of Technology*, Poland), four Quadrans, one Octans and several accelerometers (by *CEA*, France), giant FOG, blueSeis-3A (*iXblue*, France), giant FOG FARO Sensing cable (DAS, *ETH Zurich*, Switzerland), as well as (*Streckeisen GmbH*, Germany), Distributed Acoustic FOSREMs - two FOS3 and two FOS5 (by *Military Univ. of Technology*, Poland).



a)



b)

Fig. 1. Experiment "Rotation and strain in Seismology: A comparative Sensor Test", Geophysical Observatory Fürstenfeldbruck, Germany: a) rotational sensors mounted in the bunker; b) the field of experiment. At the bottom: the view of FOSREMs during installation.

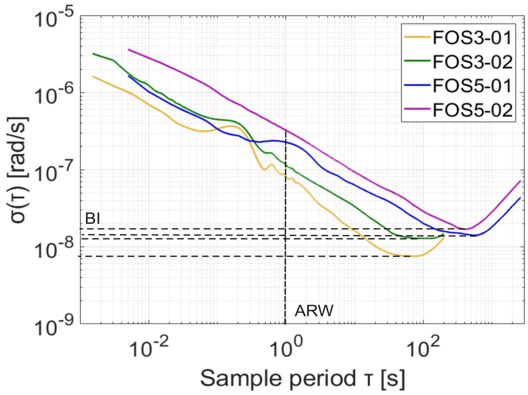
The experiment consisted of two parts. The first part– "huddle test" was to record the self-noise of instruments placed in the bunker [Fig. 1a)], as well as register two artificial explosions between 0.5 kg and 1 kg of explosive material. During the second part - "active experiment", all sensors were spread in the field [Fig. 1b)] and they recorded vibrations generated by a special VibroSeis truck (peak force: 275 kN) provided by TU Bergakademie Freiberg, as well as small explosions (1.0 kg to 1.5 kg) within the distances from 10 m to 2 km, which were carried out by the Bayrisches Landesamt für Umwelt, Germany.

3. Construction of the Fiber-Optic System for Rotational Events&phenomena Monitoring

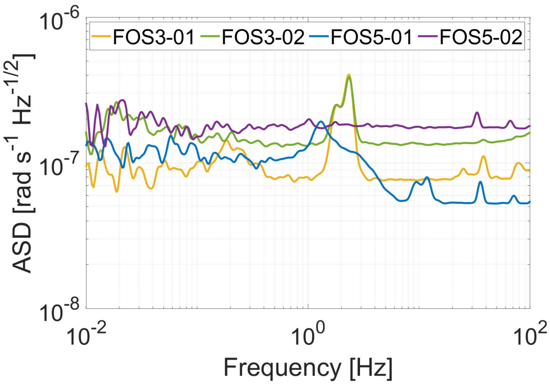
Authors have used two pairs of FOS3s and FOS5s, which record one single rotation component (vertical). As have been mentioned in the introduction, all of them use the identical FOG minimum configuration of about 5-km SMF-28e+ (*Corning Inc.*, USA) sensor loop, 10-mW SLED source (*Exalos AG*, Switzerland) and MIOC unit (*IdealPhotonics Ltd.*, China). The FOS3s operate with an open-loop electronic module and provide an output frequency of 656.16 Hz, corresponding to a sampling rate of 1.524 ms [20], whereas FOS5s operate in a closed-loop configuration with a sampling rate of 1 ms, which provides 1000 Hz data transfer [16]. An independent power supply for all FOSREMs, as well as a data transfer in miniSEED format have been implemented. In the mentioned above papers [16,20], the data obtained by pairs of the same type devices have already been compared. In this paper, we decided to focus on a comparison between data registered by both FOS3s and FOS5s. Although both fully meet all technical requirements for rotational seismology, validated by the Allan variance [21,22] investigation [see Fig. 2a) and data in Table 1], FOS5s are more environmentally stable, mainly due to the hermetic shelling. Also, a self-noise analysis of the presented instruments was undertaken in order to estimate their sensitivity, which is shown in a form of amplitude spectral distributions (ASDs) in Fig. 2b). The self-noise is the output signal from the sensor when the sensor is at rest and no input motion is present. The calculated ASD characteristics were filtered by means of Konno-Ohmachi filter [23] with a smoothing coefficient equal to 40.

Based on the presented results of ASDs for all sensors, an overall sensitivity in the required frequency range of 0.01–100 Hz was estimated to be below 5 mrad/s/√Hz, which is suitable for a weak rotation rate detection.

As shown in Fig. 2b), the typical flat self-noise spectrum in the presented range was obtained only with FOS5-02, while for both FOS3 devices the increase in the ASD value to 4 mrad/s/√Hz is visible in the range from 1.5 Hz to 3.0 Hz, possibly originating from interaction between optical and open-loop electronic configuration. Also, in FOS5-01 ASD we can distinguish a low-noise part above 5 Hz and a part with a higher self-noise below this frequency. This type of noise characteristic may come from slow-changing thermal variations in the sensor or non-perfect electronic part calibration with regard to the optical part. Therefore, although during the field tests all four devices were installed, in the next part of this paper only a comparison of FOS3-02 and FOS5-02 is presented due to their similar ASD characteristics.



a)



b)

Fig. 2. Graphs of: a) Allan variance and b) ASD calculated in the MUT, Warsaw laboratory for FOS3 and FOS5.

Table 1
Parameters of FOS3 and FOS5 calculated basing on the Allan variance analysis presented in Fig. 2a): ARW – Angle Random Walk, BI – Bias Instability.

FOSREMs field view	FOSREM	ARW [rad/√s]	BI [rad/s]
	FOS3-01	$8.70 \cdot 10^{-8}$	$1.13 \cdot 10^{-8}$
	FOS3-02	$1.30 \cdot 10^{-7}$	$1.96 \cdot 10^{-8}$
	FOS5-01	$2.16 \cdot 10^{-7}$	$2.28 \cdot 10^{-8}$
	FOS5-02	$3.24 \cdot 10^{-7}$	$2.55 \cdot 10^{-8}$

4. First data from the "Rotation and strain in Seismology: a comparative Sensor Test"

During the first part of experiment two explosions took place, the first one at 10:26 UTC and the second one at 15:16 UTC on Nov. 19th, 2019 where the second one was twice as strong and closer to the sensors by about half of the distance relative to the first explosion. Figures 3-5 present these events seismograms prepared in the commercial software SeisGram2Kv7.0. The presented data in Fig. 3 identify the overall correct time for FOSREMs to register explosions, as well as the existing rotational motion in the vertical axis (FOSREMs detection direction).

However, the more precise data comparison regarding the given event shows some nonuniformity (even for FOSREMs prepared in the same technology [16]). As it can be seen in Fig. 4, FOS5-02 and FOS3-02 have recorded events with small (but noticeable) different start times

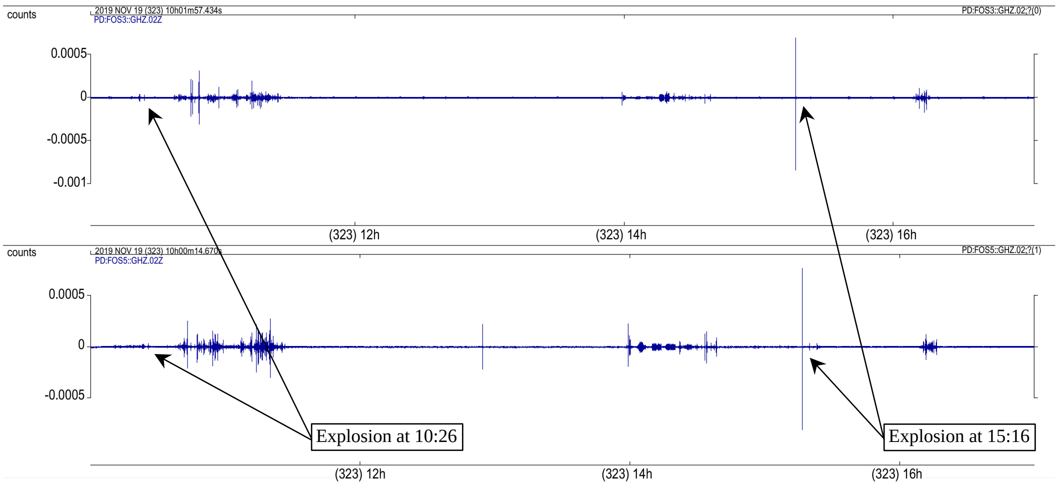


Fig. 3. Seismograms for FOS3-02 (top) and FOS5-02 (bottom) with identification of the artificial explosions at 10:26 and 15:16 UTC on Nov. 19th, 2019

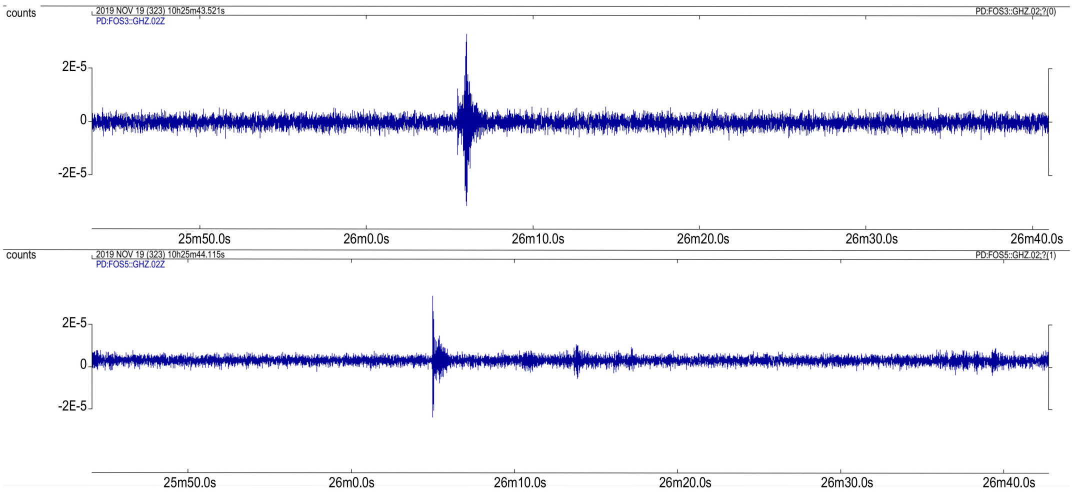


Fig. 4. Seismograms with a more accurate time scale of the identified explosion at 10:26 on Nov. 19th, 2019 for FOS3-02 (top) and FOS5-02 (bottom).

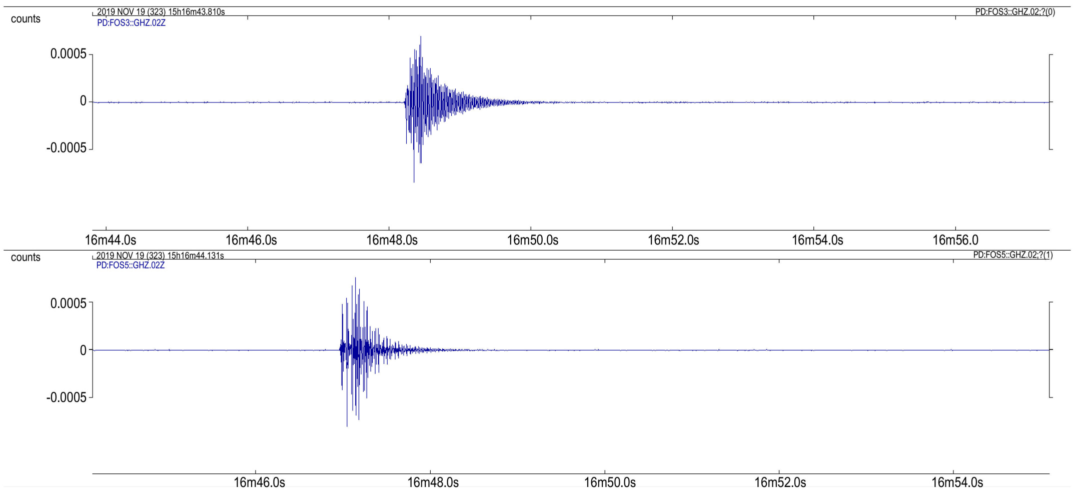


Fig. 5. Seismograms with a more accurate time scale of the identified explosion at 15:16 on Nov. 19th, 2019 by FOS3-02 (top) and FOS5-02 (bottom).

(about 2-s difference), amplitude and frequency content. It should be noted that both devices have been positioned in similar conditions next to each other, in a distance of about 1.5 m, as is shown in Fig. 1a.

The above statements are valid also for data obtained by this pair of sensors for the second explosion (Fig. 5). Since a stronger and closer explosion also generated a stronger rotational event (about 25 times in amplitude) the data are more similar, but differences are still noticeable. However, for FOSREMs made in a different technology (FOS5-02 and FOS3-02) mentioned above, differences are much more visible, as can be seen in the data comparison presented in Fig. 5.

To better characterize the signals acquired during huddle test 1 and test 2, the power spectra and spectrograms for FOS5-02 and FOS3-02 are shown in Fig. 6. For an easier identification and comparison of the results obtained for both devices, the signals from FOS3-02 were time-shifted to match FOS5-02.

As shown in the spectrograms, in both cases the signals from FOS3-02 have the strongest component in the range from 30 Hz to 60 Hz visible during the whole duration of a registered signal, while a similar component in FOS5-02 is visible in the range from 60 Hz to 80 Hz. Moreover, in the results of both huddle tests for FOS5-02 an additional component in the range from 90 Hz to120 Hz, lasting up to 2/3 of the signal can be observed. A similar component can be discerned in the signal registered by FOS3-02 in the range from 10 Hz to 20 Hz. Based on the presented results it should be concluded that both analysed devices have different spectral properties resulting from their design and electronics used. Especially noticeable is the hardware-based signal filtration in FOS5 with a cut-off frequency at about 160 Hz, which is sufficiently higher than any rotation frequencies observed in nature, while no similar filtration was used in FOS3.

5. Conclusions

The presented results were based on single vertical axis rotational event records from artificial explosions during the 2019 experiment in Fürstenfeldbruck, Germany. The data collected by FOSREMs are representations of the actual rotational ground motions, as these devices were designed for direct measurements of the rotation rate. Despite this advantage, the initial results presented in this

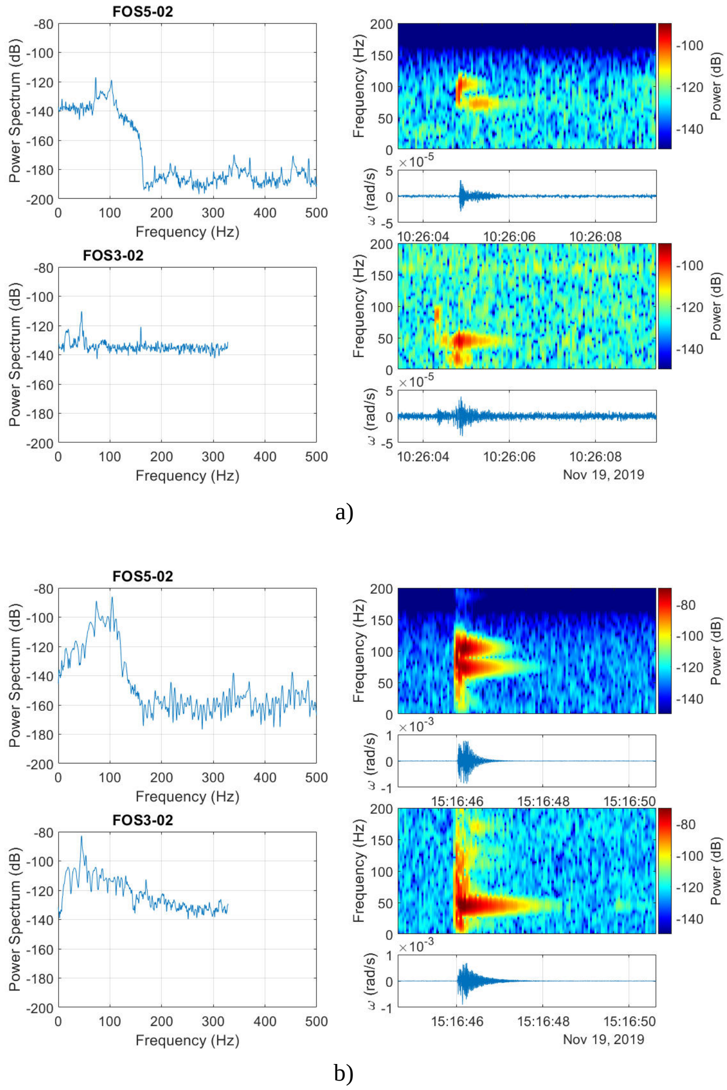


Fig. 6. Spectral characteristics of signals recorded by FOS5-02 and FOS3-02 for the explosion registered: a) at 10:26 on Nov. 19th, 2019, b) at 15:16 on Nov. 19th, 2019 recorded with a fundamental 1-kHz frequency.

paper indicated that the analyzed rotational seismometers require further calibration in terms of amplitude, sampling rate, and precise time identification.

It should be noted that the source of the differences is the coupling of the FOSREM optical part, which detects a critically low value of signals, with a specialized electronic system which requires a precise analog-to-digital conversion, as well as a data transfer with different sampling rate. Nevertheless, the presented results show sensors data similarity and compatibility. As the amount of sensing data continues to grow, optimization of data analysis structures is critical to the efficiency of recorded data processing. The whole set of rotational data from the presented experiment is still being processed and analyzed, and hopefully will be published as soon as possible.

Authors' statement

A. T. Kurzych, L. R. Jaroszewicz: FOSREM optical part design and article preparation, as well as research conducting; M. Dudek: data processing and analysis, and article preparation, J. K. Kowalski, B. Sakowicz: FOSREM electronic part design and data processing.

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