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ORIGINAL ARTICLE

Usefulness of AFORS—autonomous fibre-optic rotational seismograph for investigation of rotational phenomena

Leszek R. Jaroszewicz · Zbigniew Krajewski · Krzysztof P. Teisseyre

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Abstract We outline the research leading to development and application of the autonomous fibre-optic rotational seismograph (AFORS), which utilises the Sagnac effect for a direct measurement of rotation. The main advantage of AFORS comparing to other kinds of rotational seismometers is it completes insensitivity to linear motions as well as a direct measurement of rotational components emitted during seismic events. The presented system contains a special autonomous signal processing unit which optimises its operation for the measurement of rotation motions, whereas a newly applied telemetric system based on the Internet allows for a remote AFORS control. The laboratory investigation of the two such devices indicated they keep accuracy no less than $5.1 \cdot 10^{-9}$ to $5.5 \cdot 10^{-8}$ rad/s in the frequency bandpass from 0.83 to 106.15 Hz. Moreover, they protect linear changes of sensitivity in above bandpass. The first experimental results of AFORS-1 operation in the Książ (Poland) seismological observatory are also presented and compared with data obtained from other types of rotational devices simultaneously used in this observatory.

Keywords Fibre-optic device · Seismograph · Rotational seismic motions · Experimental investigation

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1 Introduction

The existence of rotational motions in the seismic field is discussed from the beginning of the earthquake investigations. The interest in this phenomenon has been stimulated by strange, rotary and even screw-like deformations after earthquakes, often appearing on the parts of the tombs and monuments (Ferrari 2006; Kozak 2006). The classical textbooks on seismology deny any possibility of rotational motions, so the rotational effects of the earthquakes were explained by an interaction of seismic waves with a compound structure of the objects they penetrate, which, in fact, might be the case (Teisseyre and Kozak 2003). Nevertheless, it was proved theoretically that rotation motions, especially in form of seismic rotational waves (SRWs), could propagate through grained rocks; later on, this possibility was extended to rocks with microstructure or defects

(Eringen 1999; Teisseyre and Boratyński 2002), or even without any internal structure (Teisseyre 2005; Teisseyre et al. 2005; Teisseyre and Górski 2009), due to the asymmetric stresses in the medium. It should be underlined that the SRWs were for the first time effectively recorded in Poland in 1976 (Droste and Teisseyre 1976). From this time, waves of this type have been studied in a few centres all over the world. Recently, the first monographs have been published (Teisseyre et al. 2006; Teisseyre et al. 2008; Lee et al. 2009a) covering the theoretical aspects of the rotation motion generation and propagation, as well as the examples of the field experiments.

However, the experimental verification of the above research required a new approach to the construction of the measuring devices, because the rotational measurements, based on the conventional seismographs (Teisseyre and Nagahama 1999), have high sensitivity to translational motions which can disturb the signals of rotational phenomena (Jaroszewicz et al. 2003). For the above reason, the new instrumentations are necessary, especially those designed for a direct measuring of the rotational components of ground motion (i.e. Takamori et al. 2009; Brokesova et al. 2012; Bernauer et al. 2012). However, in our opinion, the most promising seem to be the devices based on the Sagnac effect (Sagnac 1913). This effect measures rotation directly; thus, an application of the sensor based on Sagnac effect seems to be ideal for the construction of the rotational seismometer or seismograph system. We distinguish two types of required rotation measurement systems: a ring laser (Schreiber et al. 2001) and a fibre-optic seismometer (Jaroszewicz et al. 2001; Takeo et al. 2002; Nigbor et al. 2009), both based on a technical implementation of the Sagnac interferometer. The main advantage of such an approach is a possibility to detect the absolute rotation impossible to be measured in any other way. Additionally, the data obtained from the measurement are straightforward to be analysed.

An implementation and simultaneous measurement by a mechanical (TAPS, two antiparallel pendulum seismometers) and optical (FORS-II, fibre-optic rotational seismometer) type of rotational seismometers installed at the seismological observatory in Ojców, Poland proves directly that a SRWs may occur during earthquakes (Jaroszewicz and Krajewski 2008). The sensitivity of the FORS-II was estimated as $4.3\cdot10^{-8}$ rad/s (for 2σ, where σ is the standard deviation of measured noise level) for an electronically fixed detection bandpass at 20 Hz (Jaroszewicz et al. 2006a), hence probably the FORS-II has limited usefulness—only for investigation of the local-type seismic events. A new fibre-optic rotational system named autonomous fibre-optic rotational seismograph (AFORS) has been developed for a more complex investigation (Jaroszewicz et al. 2011a). A higher accuracy, compactness as well as a special signal processing unit ensuring the autonomous operation are AFORS' main novelties. Moreover, AFORS can be monitored as well as remotely controlled via Internet (Jaroszewicz et al. 2011b); thus, we are convinced about greater usefulness of such system for the future investigation of the seismic rotational phenomena. In Section 2, we present a short description of the AFORS and we summarise the data concerning operation range and accuracy of two such devices named AFORS-1 and AFORS-2. Finally, in Section 3, the first measurements obtained by the AFORS-1 during the earthquakes are presented and compared with the measurements performed simultaneously by the TAPS—the electromechanical rotational seismometer, both installed at the seismological observatory in Książ.

2 AFORS construction and main parameters

Since a detailed description regarding the AFORS-1 construction, its calibration and laboratory investigation was presented before (Jaroszewicz et al. 2011a), here we summarise the above data for two devices: AFORS-1 and AFORS-2 with the latest corrections. The optical head of the constructed AFORS devices uses a fibre interferometer in a minimum optical gyro configuration (Jaroszewicz et al. 2006a), as it is shown in the upper part of Fig. 1. Application of the wideband, low coherence superluminescent diode (SLD) gives a possibility of minimisation of a polarisation influence on the system operation by achieving light depolarization in a sensor loop (Krajewski et al. 2005). The use of the same arm of a coupler as an input/output way from a sensor loop gives reciprocity condition for interfering beams, but an additional coupler is needed to separate returned beam on a detector, and a fibre optic isolator for SLD protection. Next, the set of cascade fibre polarisers enables a true single-mode operation of the whole

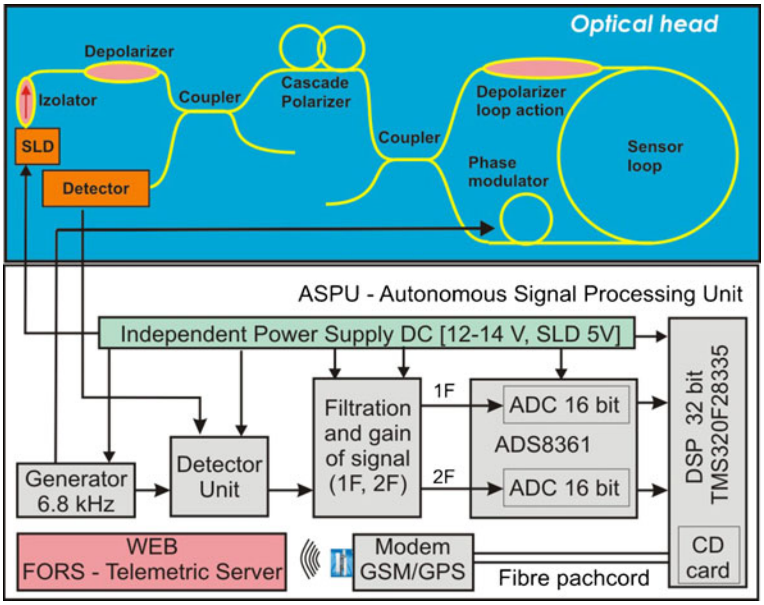


Fig. 1 General schema of the AFORS: *upper*—the optical head (generation of the Sagnac phase shift proportional to measured rotation rate Ω), *bottom*—autonomous signal processing unit (rotation calculation and recording)

system and guarantees that only nonreciprocal effect in system is the Sagnac effect. Moreover, the 0.63 m diameter sensor loop has been made from a special composite material with permalloy particles for shielding sensor from magnetic field. A long length of SMF-28 fibre has been winded in a double-quadrupole mode (Dai et al. 2002) with the 0.2-mm Teflon insulation between each fibre layer which is used for the thermal stabilisation of the sensor's work, for expected 2–4° per day temperature fluctuation in seismic observatories. System optimization made for AFORS (15.000 m length of fibre with attenuation equal to 0.436 dB/km in sensor loop and SLD with high optical power equal to 20.8 mW) allows for a theoretical sensitivity equal to $1.97 \cdot 10^{-9}$ rad/s Hz$^{1/2}$ and $2.46 \cdot 10^{-9}$ rad/s Hz$^{1/2}$, respectively, for AFORS-1 and AFORS-2. The abovementioned difference between two constructed devices is connected to their total optical loss which is equal to 13.33 dB and 14.47, for AFORS-1 and AFORS-2, respectively (Jaroszewicz et al. 2011a, b).

The Sagnac phase-shift obtained directly in the interferometric system contains an unseparated noise component; hence, the special signal processing is needed. Since a rotational seismograph is designed for recording sudden changes of rotation rate with an assumed amplitude, we have used the FOG system operating in open-loop architecture with digital data processing (Böhm et al. 1984; Krajewski 2005). For AFORS, ELPROMA Ltd. constructed a new prototype autonomous signal processing unit (ASPU), according to the scheme shown in the lower part of Fig. 1. ASPU enables the detection of rotation rate (Ω) by properly selecting and processing the first ($A_{1\omega}$) and the second ($A_{2\omega}$) amplitude of the harmonic output signal on base of the following relation (Jaroszewicz et al. 2011a):

$$\Omega = S_o \arctan[S_e \cdot u(t)], \quad u(t) = A_{1\omega}/A_{2\omega}$$

where: S_o–optical and S_e—electronic constants related to parameters of the applied components, which are obtained during the sensor calibration. It should be noticed that it is a different approach compared to a common method used in the FOG, where the best way for measurement of angular changes is applying the time integration of the rotational rate obtained via separation of the first harmonic amplitude by a synchronous detector.

The detailed description regarding the applied procedure for AFORSs calibration and investigation and their accuracy is described in our previous paper (Jaroszewicz et al. 2011a) for AFORS-1. Here, we noticed only that the AFORS calibration was based on measurement of the Earth rotation for Warsaw, Poland, i.e. $\Omega_E = 9.18\text{deg/h} \equiv$

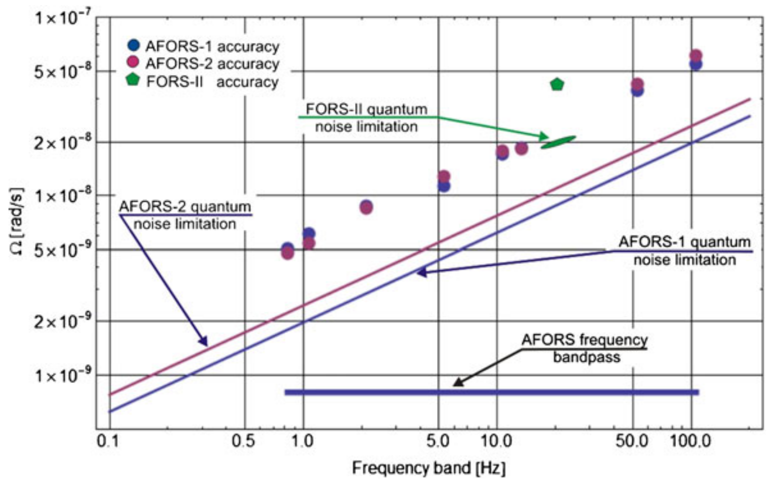


Fig. 2 The accuracy measured in Warsaw, Poland for the chosen detection bandpass for three devices: AFORS-1, AFORS-2 and FORS-II

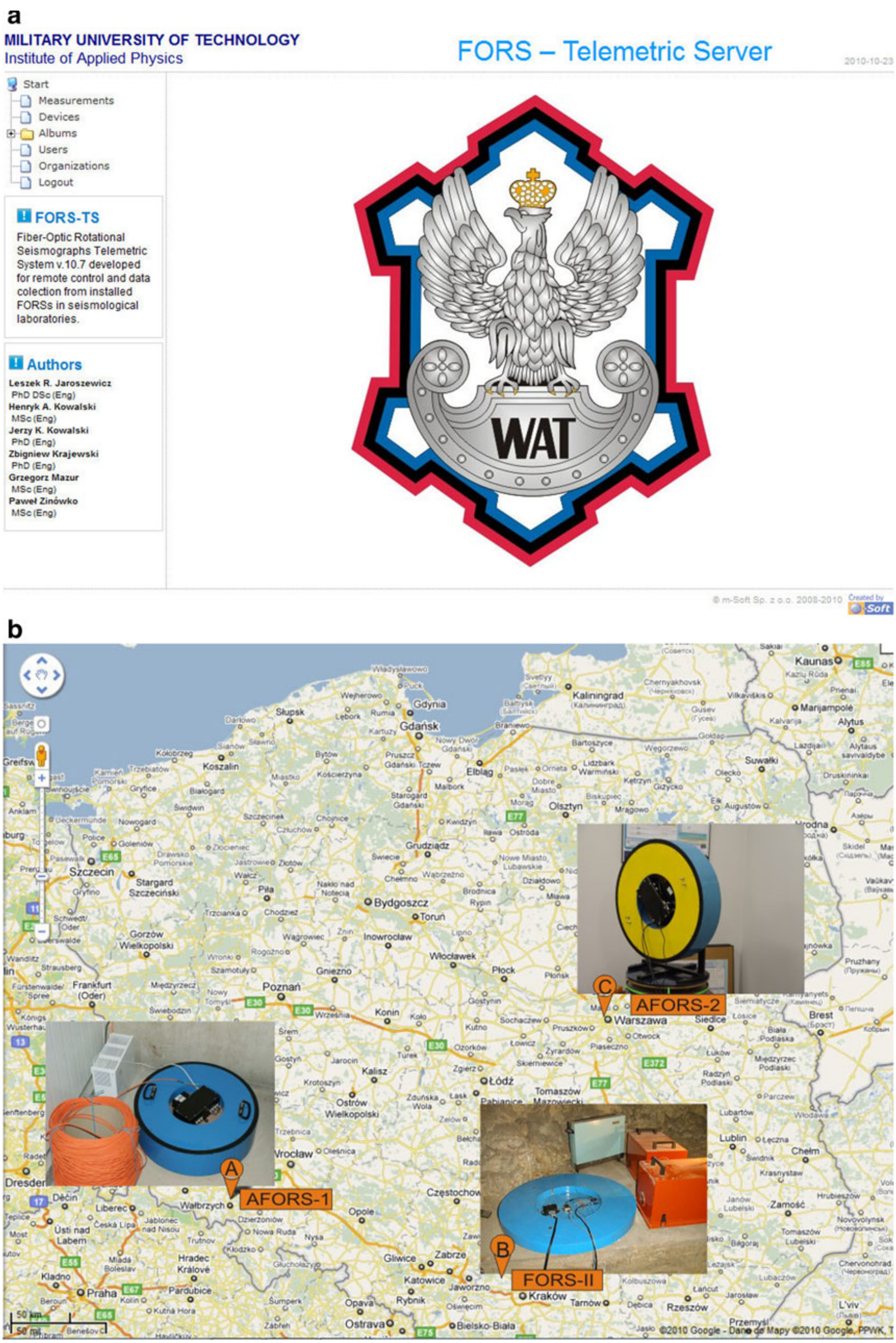
$4.45 \cdot 10^{-5}$rad/s (Krajewski et al. 2005). During this calibration, the AFORS was mounted vertically on a rotation table. For a sensor loop directed in the east–west, the measured rotation equals zero because in this direction its plane is collinear with the Earth rotation axis, whereas for the north–south direction, the measured signal obtains maximum plus or minus values because the sensor loop plane is perpendicular to the vector component of the Earth rotation Ω_E. The set of above four signals is used next for the calculation value of S_0 and S_e parameters for given AFORS.

In the next step, the accuracy of a constructed AFORS device has been checked by measurement of the noises' level for given devices (see detailed description in Jaroszewicz et al. 2011a). However, this work made at Military University of Technology located in Warsaw, Poland could give limited information on the system accuracy because of town noises. Figure 2 summarises these measurements. Since the ASPU allows for step changes of the detection frequency band in the range from 0.83 to 106.15 Hz (which are corrected values compared to previously reported in Jaroszewicz et al. 2011a, b), the obtained accuracy is at the level of $5.07 \cdot 10^{-9}/4.81 \cdot 10^{-9}$rad/s – $5.51 \cdot 10^{-8}/6.11 \cdot 10^{-8}$rad/s (for AFORS-1/AFORS-2), respectively for lower and higher working frequency bandpass. As one can see, the obtained values are well correlated with Ω_{min} in quantum noise limitation. It should be noticed that linear dependence of AFORS sensitivity and accuracy on the detected frequency bandpass is the advantage of this system, taking into account the expected frequency characteristic of the rotational seismic waves (Teisseyre et al. 2006). For comparison, Fig. 2 includes also the measured accuracy of the older system FORS-II which was $4.3 \cdot 10^{-8}$ rad/s (Jaroszewicz et al. 2006a, b; Jaroszewicz and Krajewski 2008) at 20 Hz—the fixed detection frequency.

The new *FORS-Telemetric Server* with its main page shown in Fig. 3 (the reader may use http://fors.m2s.pl with the same login and password—'AFORS-book' for the open access to the system) is used for data storing and for monitoring the work of the FORS-II and the AFORS. Since ASPU of the AFORS contains a GSM/GPS module, its work can be remotely controlled via server. Moreover, ASPU contains an additional, independent power supply for all electronic components of the system; hence, the AFORS became a fully autonomous and mobile system. At present, the three devices are managed via server: FORS-II, AFORS-1, AFORS-2 located in Ojców, Książ and Warsaw, Poland, respectively.

The applied technology gives a possibility of remote (via Internet) controlling and changing all the electronic parameters of the ASPU for given AFORS, as it is presented by the bookmark *Config* for the AFORS-1 in Fig. 4a. This remote control may comprise the software upgrade. Moreover, the bookmark *Data&Variables* (Fig. 4b) monitors in real time the main data and variables with possibility of remotely changing of the threshold—the level of

Fig. 3 The main page of FORS-Telemetric Server (**a**) and the GOOGLE map with devices localization (**b**) ▶


a
MILITARY UNIVERSITY OF TECHNOLOGY
Institute of Applied Physics
FORS – Telemetric Server
2010-10-23
Start
Measurements
Devices
Albums
Users
Organizations
Logout
FORS-TS
Fiber-Optic Rotational Seismographs Telemetric System v.10.7 developed for remote control and data colection from installed FORSs in seismological laboratories.
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WAT
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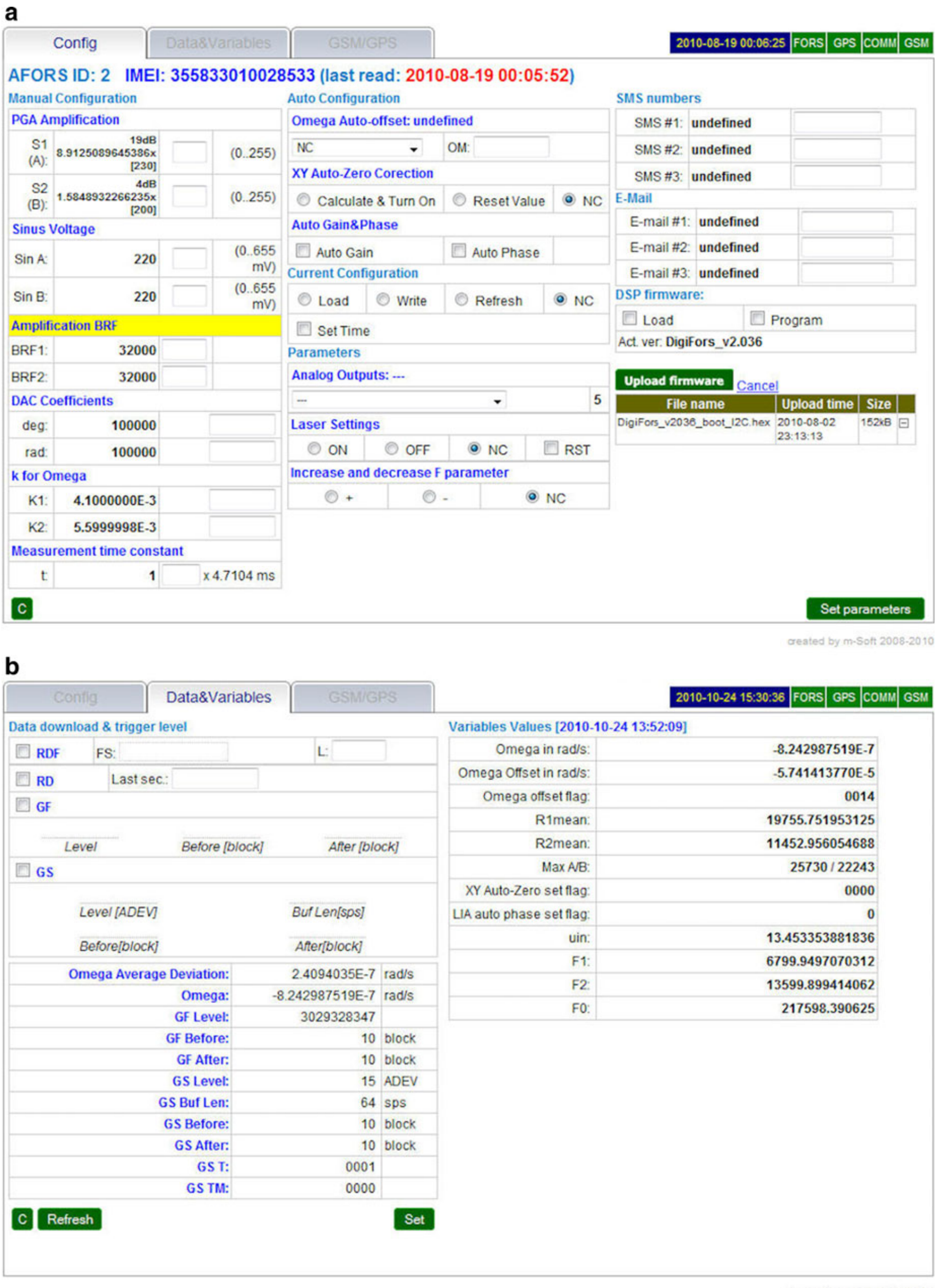
b
A
AFORS-1
B
FORS-II
C
AFORS-2
Warszawa
Kraków
Wrocław
Poznań
Gdańsk
Łódź
Szczecin
Bydgoszcz
Lublin
Kaliningrad
©2010 Google - Dane do Mapy ©2010 Google, PPWK


a
Config
Data&Variables
GSM/GPS
2010-08-19 00:06:25
FORS
GPS
COMM
GSM
AFORS ID: 2 IMEI: 355833010028533 (last read: 2010-08-19 00:05:52)
Manual Configuration
PGA Amplification
S1 (A): 19dB 8.9125089645386x [230] (0..255)
S2 (B): 4dB 1.5848932266235x [200] (0..255)
Sinus Voltage
Sin A: 220 (0..655 mV)
Sin B: 220 (0..655 mV)
Amplification BRF
BRF1: 32000
BRF2: 32000
DAC Coefficients
deg: 100000
rad: 100000
k for Omega
K1: 4.1000000E-3
K2: 5.5999998E-3
Measurement time constant
t: 1 x 4.7104 ms
C
Auto Configuration
Omega Auto-offset: undefined
NC
OM:
XY Auto-Zero Corection
Calculate & Turn On
Reset Value
NC
Auto Gain&Phase
Auto Gain
Auto Phase
Current Configuration
Load
Write
Refresh
NC
Set Time
Parameters
Analog Outputs: ---

5
Laser Settings
ON
OFF
NC
RST
Increase and decrease F parameter
+
-
NC
SMS numbers
SMS #1: undefined
SMS #2: undefined
SMS #3: undefined
E-Mail
E-mail #1: undefined
E-mail #2: undefined
E-mail #3: undefined
DSP firmware:
Load
Program
Act. ver: DigiFors_v2.036
Upload firmware
Cancel
File name
Upload time
Size
DigiFors_v2036_boot_I2C.hex
2010-08-02 23:13:13
152kB
Set parameters
created by m-Soft 2008-2010
b
Config
Data&Variables
GSM/GPS
2010-10-24 15:30:36
FORS
GPS
COMM
GSM
Data download & trigger level
RDF
FS:
L:
RD
Last sec.:
GF
Level
Before [block]
After [block]
GS
Level [ADEV]
Buf Len[sps]
Before[block]
After[block]
Omega Average Deviation: 2.4094035E-7 rad/s
Omega: -8.242987519E-7 rad/s
GF Level: 3029328347
GF Before: 10 block
GF After: 10 block
GS Level: 15 ADEV
GS Buf Len: 64 sps
GS Before: 10 block
GS After: 10 block
GS T: 0001
GS TM: 0000
C
Refresh
Set
Variables Values [2010-10-24 13:52:09]
Omega in rad/s: -8.242987519E-7
Omega Offset in rad/s: -5.741413770E-5
Omega offset flag: 0014
R1mean: 19755.751953125
R2mean: 11452.956054688
Max A/B: 25730 / 22243
XY Auto-Zero set flag: 0000
LIA auto phase set flag: 0
uin: 13.453353881836
F1: 6799.9497070312
F2: 13599.899414062
F0: 217598.390625
created by m-Soft 2008-2010

◀ **Fig. 4** The view of two main bookmarks: *Config* (**a**) and *Data&Variables* (**b**) for AFORS-1at the FORS-Telemetric Server

signals which initialize an automatic data storing and its GSM transfer. Additionally, the top right corner of bookmarks, for the given system on server, contains information on the current date and time and four main AFORS' positions of the work status (good as green, partially good as yellow or no work as black). The bookmark *GSM/GPS* monitors in real time the GSM parameters as well as GPS parameters which include the AFORS global localization. Yet, another bookmark named *Measurement* presents the collection of data recorded by different devices connected to the server.

3 Analysis of data recorded in seismological observatory in Książ, Poland

Since AFORS-1 is a new device which has never been used before for investigation of the rotational events in a field test, we decided to use it together with another kind of rotational seismometers available in Poland. For this reason, at the beginning of July 2010, the AFORS-1 has been installed in the seismological observatory in Książ, Poland together with a set of the two TAPSs (*TAPS-1* and *TAPS-2*) constructed by the Institute of Geophysics (Teisseyre et al. 2003). As usually, TAPSs are placed perpendicularly in the N-E and E-W directions.

The histogram shown in Fig. 5 is an example of the data collected in Książ, Poland on March 11, 2011 at 6 h and 58 min (after the Honshu earthquake M=9.0 on March 11, 2011 at 5 h and 46 min 23 s UT, recorded in Książ, Poland on March 11, 2011 at 5 h and 58 min 35 s UT). The above data were obtained from a common, for AFORS and TAPS, standard seismic recording system named KSPROT which samples a signal with the frequency of 12.8 kHz and after the re-sampling stores it with the frequency of 100 Hz. It should be noticed that in the previous paper (Jaroszewicz et al. 2006b), we used the wrong name for this station—KST. We underline that here only the AFORS-1 shows the rotational component in a direct way (plots marked as AFORS-1). The rotational component is obtained also from the TAPS systems calculated from recordings of linear motions of four channels (data named TAPS-1 channel 1, TAPS-1 channel 2, TAPS-2 channel 1 and TAPS-2 channel 2) with the application of a suitable mathematical procedure, which has been widely described in the previous paper (Solarz et al. 2004).

Since AFORS records rotation in a direct way, we use this recording as a reference source despite the

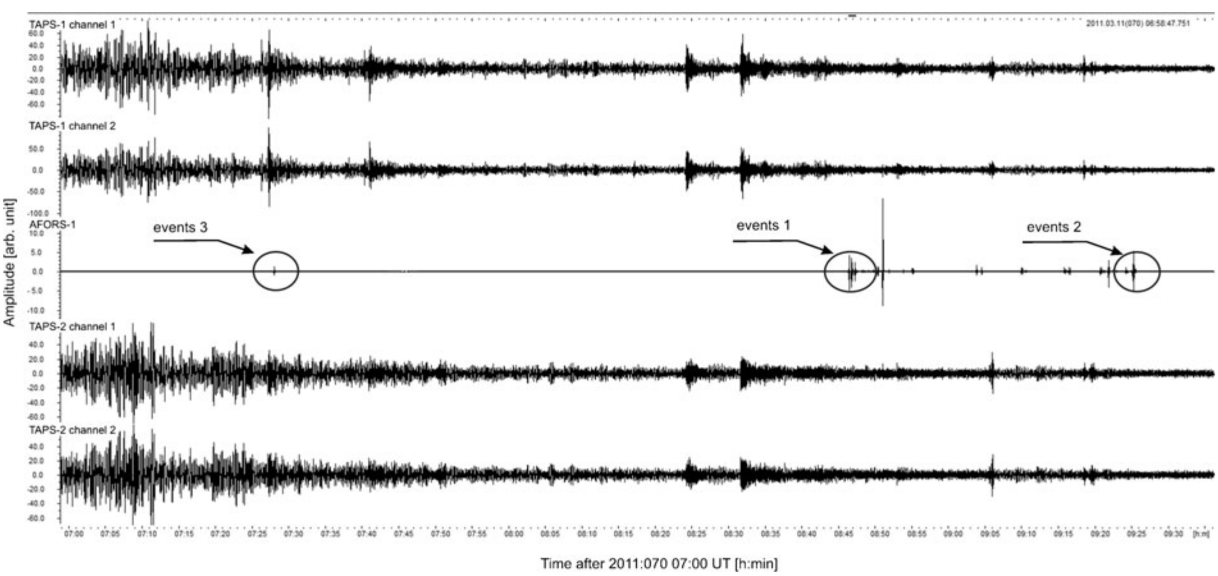


Fig. 5 Plots of the seismic events recorded in Książ, Poland on March 11, 2011, starting from 06:58 UT, after the Honshu M=9.0 earthquake

fact that the rotations calculated on TAPSs are generally poorly correlated with it. In the results presented in Fig. 5, a good correlation has been found mainly in short bursts of seismic oscillations, marked here as “events 3”, “events 1” and “events 2”. These were clusters of short peaks found when the traces of the great Honshu earthquake were studied (without much success in the domain of a rotational field component, but this is not strange while taking under consideration, both the distance from the earthquake focus and our instruments’ characteristics). After a preliminary analysis, only one event from each group was chosen and this one we call event 3, event 1 and event 2, respectively.

For event 1, the data from AFORS-1 were identified by FORS-Telemetric Server (see original copy from server presented in Fig. 6a) as the rotational event of an amplitude of about $1.5{\cdot}10^{-5}$ rad/s with AFORS-1 accuracy equal to $0.4{\cdot}10^{-7}$ rad/s for a given frequency bandpass which was about 10.6 Hz. The rotation calculated on linear motions recorded in the TAPS system has similar characteristics, as it is seen in Fig. 6b (calculation made on recorded data base in *Mathematica* software). It should be noticed that the rotation amplitude calculated on the base of KSPROT is more than 1 order less than the one calculated on the base of AFORS-1. It is probably connected to a different frequency bandpass sensitivity of two devices as it is later discussed. Nevertheless, we observed time advance for TAPS in relation to the AFORS-1 registration as well as apparent disturbances visible before and after the event which may result from a limited accuracy of TAPS as it was previously mentioned (Jaroszewicz and Krajewski 2008). The high amplitude recorded by two devices may be contradicted with the observations given by other authors, which indicate that theoretically most of the teleseismic events produce rotation events with an amplitude at the level of 10^{-8} rad/s. However, in literature, we can find information about much higher amplitudes. The TAPS application in Książ, Ojców and Warsaw observatories recorded of seismic rotational events with the amplitude of 10^{-6} rad/s (Teisseyre 2006) and $6{\cdot}10^{-6}$ rad/s (Teisseyre 2007). The origin of these events was Silesia mining; hence, they should be taken as near-field seismic events. The above data are in agreement with Lee et al. (2009b) discussion indicating that rotational ground motions are 10 to 100 times larger than expected from the classical elasticity theory.

The event 2, which was about three times lower in magnitude, shows a good correlation between rotational signals recorded from AFORS-1 in the server and calculated on TAPS—see Fig. 7. The latter system seems again to show lower accuracy than the AFORS-1, which is manifested as what looks as signal disturbances.

Unfortunately, the application of the above approach to the analysis of event 3 (from Fig. 5) shows that this time the signals are different. From our studies, including the present one, we find that rotational signals are clearer when viewed in relatively narrow frequency bands. Such an approach is especially useful in comparing different seismic events, or one event recorded with various equipment—these procedures allow to find more differences (and also similarities) in the compared signals. The results of such analysis of the event 3 are shown in Fig. 8. We observe much more disturbed rotations from TAPS system than from AFORS-1, as well as appearance of the maximum rotation signal from TAPS before the one recorded by AFORS-1. However, the separated signals of different frequency bands show also similarity between the systems, especially in the frequency bands of 10.0÷12.5 and 12.5÷18.0 Hz.

Finally, the results shown in Fig. 9 are the examples of the rotation component of the seismic field recorded in Książ, Poland on March 18, 2011 at 16 h and 34 min UT, which source is the near-field (local) seismic mining event of the magnitude M=3.3, which occurred in the Lubin area (the Legnica-Głogów Copper Mining District, in the Western Poland). As one can see, the recorded signals are generally different, the AFORS-1 signals contain much more peaks and have maximum amplitude at a different time (in this case, delayed) than the rotation calculated on TAPS. However, the separated signals for different frequency bands show again some similarity between the signals from AFORS-1 and TAPS, especially for the frequency bands of 10.0÷12.5 and 7.5÷10 Hz.

By comparing the values at vertical axes of the diagrams, one may notice that the AFORS-1 has a 2-order greater sensitivity to the rotation motions than the TAPS. However, we have to explain the relation between amplitudes for TAPSs and AFORS-1. They are generally different for different frequency bands as it is additionally shown in Table 1. In our opinion, it is connected to a different sensitivity of the above devices in these bands and will be investigated in the

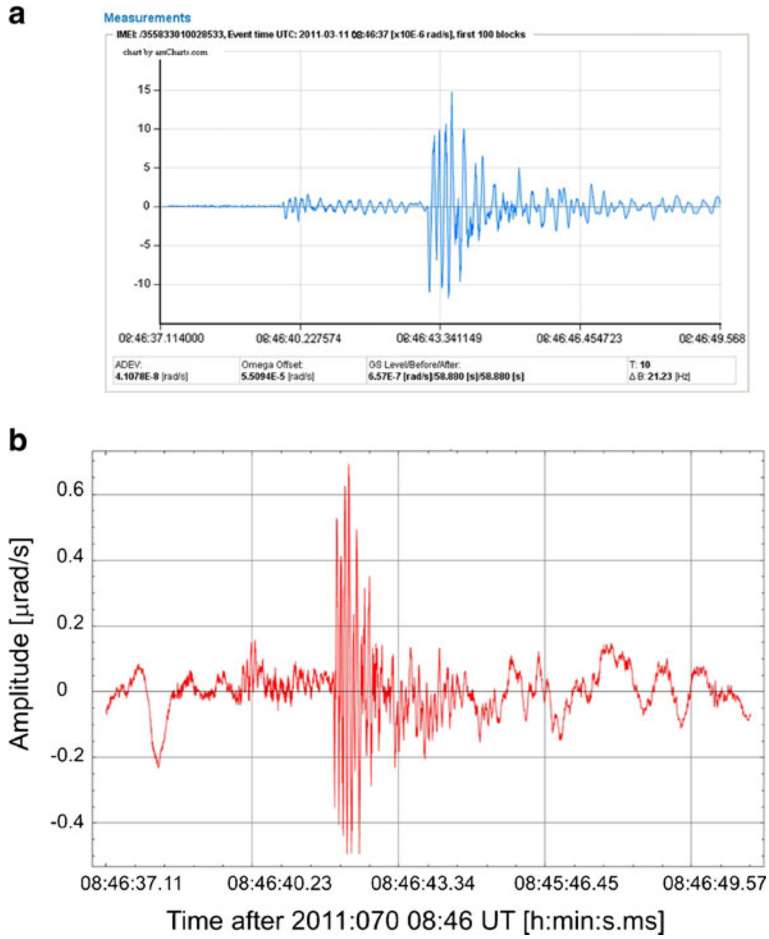


Fig. 6 The rotational event 1 from Fig. 5 on March 11, 2011-**a**: recorded from AFORS-1 in the FORS-Telemetric Server at 08:46 UT;-**b**: calculated on TAPSs four channels

future. Moreover, the difference between two plots appears greater in the case of short peaks which bear high proportion of high-frequency oscillations (further discussed).

Situation is not a simple–substantial sensitivity of AFORS-1 to high-frequency motions is an issue by itself. It calls for further research, but on the other hand, it helps in differentiation of the recorded events. And these differ, for example seismic fields from mining shocks in the Lubin area studied in Książ, Poland contain variable proportion of high-frequency rotational motions.

The seismic event 1 looks like a typical mining seismic event which occurred probably in one of the several mines in the vicinity of Książ, Poland. The seismic events 3 and 2 are just examples of very short seismic phenomena having very small magnitude but exerting rotational motions; such peaks often appear in the rotational recordings in Ojców, Poland (Jaroszewicz et al. 2006a, b) and in Książ, Poland either after arrival of the seismic waves generated by an earthquake at local or greater distance or seen in the background of long-lasting oscillations coming from a powerful, distant great earthquakes. We do not dare to state that these peaks come from the earthquake focus, but they may not necessarily be just mere disturbances. They may be excited locally by vibrations caused by waves from a distant earthquake, but they may also have completely other origin as well which requires a further study. Such events give visible peaks in the signals of FORS-II or AFORS-1, but only barely discernible wrinkles in short-period recordings from the seismometers which constitute TAPS system; after drawing the rotational component out of mess, the event appears here, too. Eventual relation between these peaks and the earthquakes, local and distant alike, calls for a statistical study.

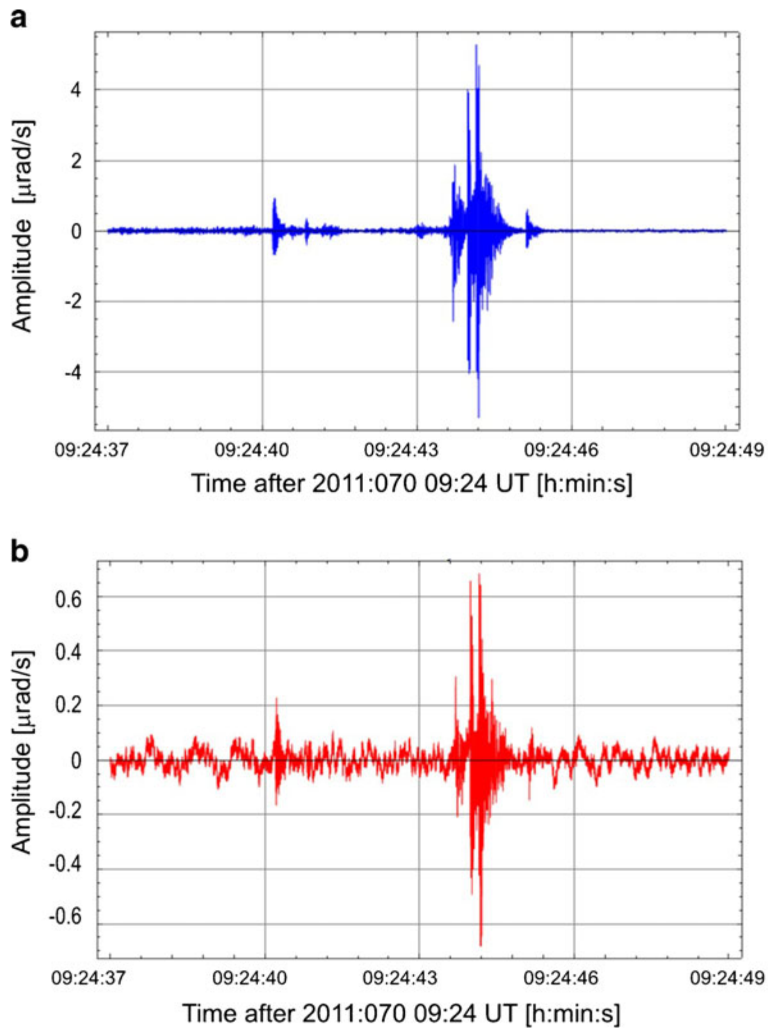


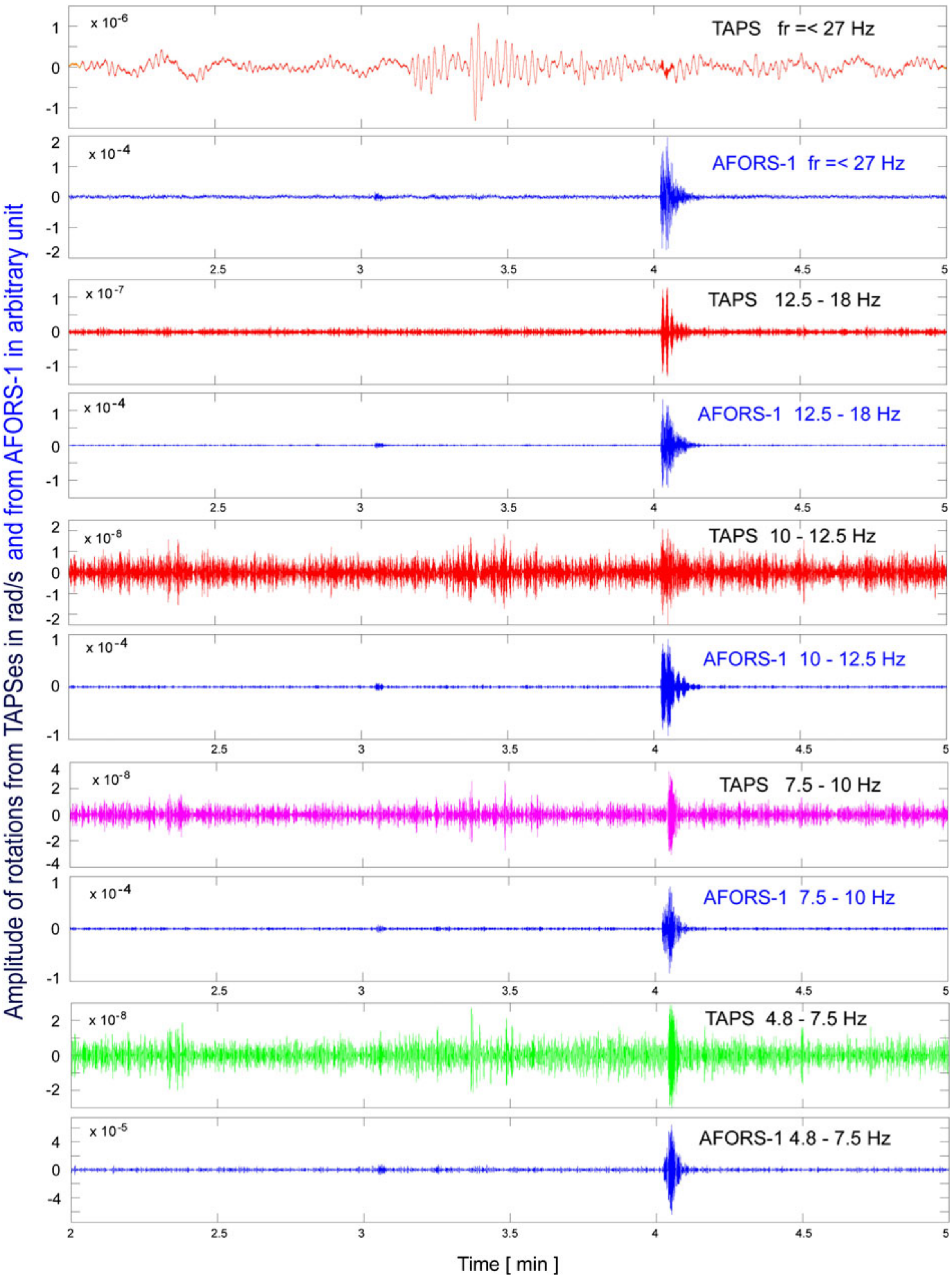
Fig. 7 The rotational event 2 from Fig. 5 on March 11, 2011-**a**: recorded from AFORS-1 in the FORS-Telemetric Server at 09:24 UT;-**b**: calculated on TAPSs four channels

4 Conclusions and final remarks

The presented AFORS-1 seems to be a promising device because it provides a possibility of the absolute rotation rate detecting. In this way the system based on the Sagnac effect seems to be a unique device which can detect seismic rotational events in a direct way and it seems that the data obtained this way are clear enough for an identification of rotational motions. Other devices based on different physical principles need an additional data processing which can be source of measurement errors. The results obtained during the AFORS-1 calibration suggest its linear accuracy down to $5.1 \cdot 10^{-9}$ to $5.5 \cdot 10^{-8}$ rad/s, for the detection frequencies bandpass from 0.83 to 106.15 Hz. For the above reason, we decided to conduct a field test by an implementation of the AFORS-1 in the seismological observatory in Książ, Poland. Unfortunately, since AFORS-1 was the unique device, the system AFORS-2 was submitted to a laboratory investigation in Warsaw, Poland in the summer of 2011 and we decided to use AFORS-1 for a field test together with TAPSs and to compare the obtained results.

Trials to analyse rotations in the seismic field of distant earthquakes with the use either of AFORS-1 or TAPSs, or both systems recording simultaneously, did not lead us to any success, so far. Both systems detect an increased rotation which makes a kind of a trace of

Fig. 8 The rotational event 3 from Fig. 5 on March 11, 2011 recorded after 07:24 UT at KSPROT station and seen in various frequency ranges (fr). Rotation obtained from TAPSs is calculated on four channels. Time scale in minutes ▶


TAPS fr =< 27 Hz
AFORS-1 fr =< 27 Hz
TAPS 12.5 - 18 Hz
AFORS-1 12.5 - 18 Hz
TAPS 10 - 12.5 Hz
AFORS-1 10 - 12.5 Hz
TAPS 7.5 - 10 Hz
AFORS-1 7.5 - 10 Hz
TAPS 4.8 - 7.5 Hz
AFORS-1 4.8 - 7.5 Hz
Amplitude of rotations from TAPSes in rad/s and from AFORS-1 in arbitrary unit
Time [min]

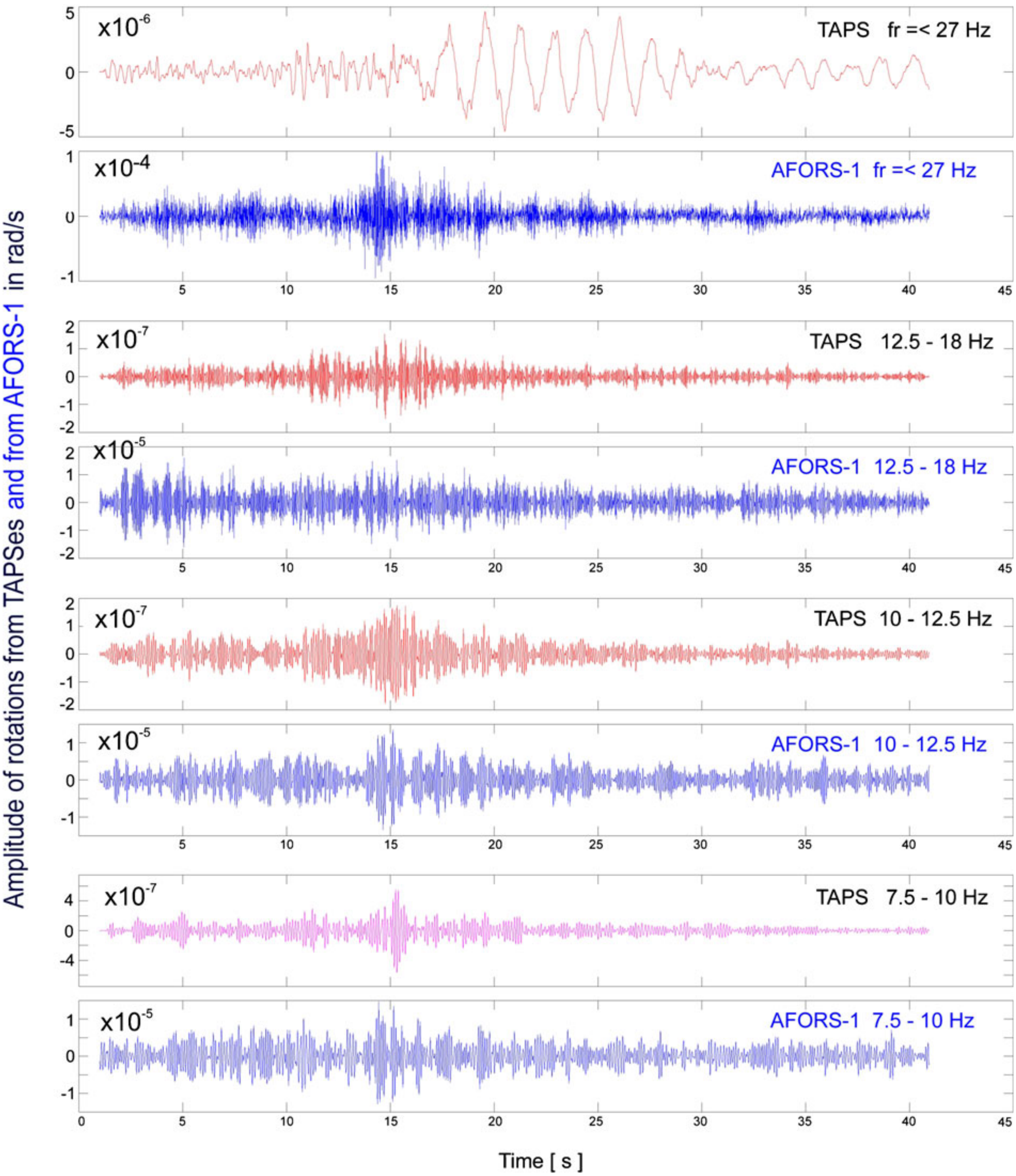


Fig. 9 The rotational component of the seismic event in the Lubin-area copper mine (Poland) on March 18, 2011, recorded after 16:34 UT at KSPROT and seen in various frequency ranges (fr). Rotation obtained from TAPSs is calculated on four channels. Time scale in seconds

the seismic event, but this trace resembles just an increased noise. In the obtained traces, generally no correlation can be found between the rotational signals from AFORS-1 and those derived from the

Table 1 Comparison of the maximum amplitude of rotation events in different frequency band for AFORS-1 and TAPSs recorded at seismic observatory in Książ, Poland by seismic station MK-6

Seismic events [UTC, Mn]	Frequency band [Hz]	TAPS max. ampl. A_{TAPS} [rad/s]	AFORS-1 max. ampl. A_{AFORS} [rad/s]	Relation [A_{TAPS}/A_{AFORS}]
2011-04-30 03:32:15 UT M=2.9 Lubin	All	1×10^{-6}	4×10^{-5}	40
	12.5–18.0	2×10^{-8}	8×10^{-6}	400
	10.0–12.5	3×10^{-8}	5×10^{-6}	167
	7.5–10.0	1×10^{-7}	1×10^{-5}	100
	4.8–7.5	2×10^{-7}	5×10^{-6}	25
	3.0–4.8	1×10^{-6}	1×10^{-5}	10
	1.7–3.0	2×10^{-7}	2.5×10^{-6}	12.5
2011-06-28 23:16:03 UT M=3.2 Lubin	All	2×10^{-6}	2×10^{-5}	10
	12.5–18.0	8×10^{-8}	8×10^{-6}	100
	10.0–12.5	1×10^{-7}	6×10^{-6}	60
	7.5–10.0	3×10^{-7}	1×10^{-5}	33
	4.8–7.5	1×10^{-6}	1.5×10^{-5}	15
	3.0–4.8	2×10^{-6}	1×10^{-5}	5
	1.7–3.0	2×10^{-6}	5×10^{-6}	2.5
2011-03-18 16:34:05 UT M=3.3 Lubin	All	5×10^{-6}	1×10^{-4}	10
	12.5–18.0	1.8×10^{-7}	1.8×10^{-5}	100
	10.0–12.5	1.9×10^{-7}	1.3×10^{-5}	68
	7.5–10.0	5×10^{-7}	1.3×10^{-5}	26
	4.8–7.5	7.5×10^{-7}	1.5×10^{-5}	20
	3.0–4.8	1×10^{-6}	1×10^{-5}	10
	1.7–3.0	2×10^{-6}	5×10^{-6}	2.5

TAPS systems. The most prominent peaks in these traces came from short bursts of the seismic oscillations, either of secondary character, generated probably in the Książ area or even completely not related to the earthquake seismic field. In some of these peaks, the rotations recorded by AFORS and calculated on TAPS recordings are similar.

Study of earthquakes of the mining provenience, comparing the plots of seismic rotations acquired from AFORS-1 and from TAPS systems, *in relatively narrow frequency bands*, allowed us to find that the time periods of increased rotation of both kinds roughly coincide. Similarity between two signals becomes much worse when the waveforms are magnified in time axis so that the individual indentations appear. In fact, the calculated correlation coefficients between the rotations obtained from AFORS-1 and those from TAPS appear very low. Therefore, other methods are needed which could show more convincingly similarity of the concerned records. On the other hand, differences between the recordings by AFORS-1 and by TAPSs are worth of further research.

But the most important one remains the problem of the rotational motions propagation. Therefore, in the next step, we decide to use the system of two AFORSs located in different places to conduct simultaneous observations based on the AFORS-Telemetric Server. It would be better, if the involved observation sites are at the same line with the area where seismic events often occur. We believe that such an approach will be useful for the experimental study of SRWs (seismic rotational waves).

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