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Calibration of the Wiechert seismograph relative to a reference seismometer

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The horizontal 1000 kg Wiechert seismograph has been calibrated on the basis of a comparison of its records to the ones that were obtained by the reference seismometer. The resulting magnification curve shows notable deviations from the theoretical one. Its most prominent feature is a sudden magnification increase observed for frequencies above 5 Hz, which is attributed to frame oscillations excited by the seismic waves. Also, the observed average response curve exhibits larger magnification for frequencies below the resonance frequency. The results indicate a non-linear behaviour of the Wiechert instrument related to the degree of impulsiveness of the excitation.

Keywords: Seismograph calibration, historical instrumentation, Wiechert seismograph.

Kalibriranjenje Wiechertovog seizmografa u odnosu na referentni seizmometar

Horizontalni Wiechertov seizmograf s masom od 1000 kg kalibriran je na osnovi usporedbe njegovih zapisa sa seizmogramima zabilježenim referentnim seizmometrom. Opažena krivulja povećanja značajno odstupa od teorijske. Njezino najizrazitije svojstvo je nagli i izražen porast povaćanja za frekvencije veće od 5 Hz, što se pripisuje oscilacijama osnovne konstrukcije seizmografa, kao i povećanje veće od teorijskog na frekvencijama manjim od vlastite. Opaženo je također i nelinerno ponašanje instrumenta ovisno o jednolikosti pobude.

1. Introduction

The first Wiechert seismograph with a mass of 80 kg that recorded horizontal ground motion was installed in Zagreb by A. Mohorovičić in 1908. Soon afterwards, in 1909, a new horizontal instrument was obtained with a mass of 1000 kg. It was originally installed in the basement of the building of the Geophysical Institute at Grič 3 in Zagreb, and has been operating with almost no interruptions until 1983 when it was moved together with the small (80 kg) horizontal and the vertical (1300 kg) instrument to the Institute's new location on Horvatovac bb, Zagreb. These seismographs were restored and are now in an operating condition.

In the original setup, the horizontal components were oriented in the NW–SE and NE–SW direction, *i.e.* rotated by 45° with respect to the standard setup. This was preserved also in their present location.

The 1000 kg Wiechert instrument (together with a similar 1200 kg version) was one of the most widespread mechanical seismographs in the world in the first half of the 20th century. It was one of the first damped seismographs, and its characteristics allowed local as well as teleseismic events to be well recorded. The free period of oscillations of these instruments is in the range 6–10 s, and the static magnification is about 200.

The seismographs in Zagreb were regularly calibrated, and the instrument constants are known for the whole period of their operation. The seismograms are also preserved and are kept in the archives of the Geophysical Institute.

The calibration of the seismographs was performed by measuring the traces on the smoked recording paper produced by lifting a weight of a known mass from the perimeter of the seismometer's mass, with and without damping (*e.g.* Errulat, 1928). In this way one is able to estimate the damping constant (h), the free period of oscillations (T_0) and the static magnification (V_0), that are needed to compute the instrument's response (or dynamic magnification, V_T) to the harmonic excitation with the period T:

$$V_T = \frac{V_0}{\sqrt{\left(1-\frac{T^2}{T_0^2}\right)^2 + 4h^2\frac{T^2}{T_0^2}}} \qquad (1)$$

The basic assumption that has to hold for (1) to satisfactorily describe Wiechert seismograph response function is that the relative motion of the mass with respect to the instrument's frame during earthquakes is accurately represented by the theory of a single-degree-of-freedom damped linear oscillator throughout the frequency range of interest. There are, however, good grounds to reconsider this *a priori* assumption.

During the calibration procedure only the mass of the instrument moves and oscillates about the frictionless pivot K (Fig. 1), while no force acts on the frame (represented by the rigid plate P and recording drums in Fig. 1). During an earthquake, however, the forces act mostly on the frame, and the mass oscillates about the centre of oscillations located, in the case of the Zagreb instrument 97 cm above the pivot K (or 38 cm below the point A) in Fig. 1. The »frame« here is understood to include all parts of the seismograph excluding the mass and styluses, *i.e.* the basic frame skeleton, many levers, damping devices, springs, recording drums, timing device, etc. In order for our assumption to be valid, the coupling between the frame and the mass should be negligible, *i.e.* the frame should be absolutely rigid. By our definition the frame is far from being rigid and is strongly coupled to the mass through restoring springs (B in Fig. 1) that keep the mass upright, and through stylus pivots (F in Fig. 1). The true relative motion of the mass with respect to the frame is therefore hard if not impossible to be analytically expressed, and equation (1) represents the best hypothesis in these circumstances.

Realising that a large part of our knowledge of the world seismicity in the first half of this century comes from Wiechert seismograms, and given present

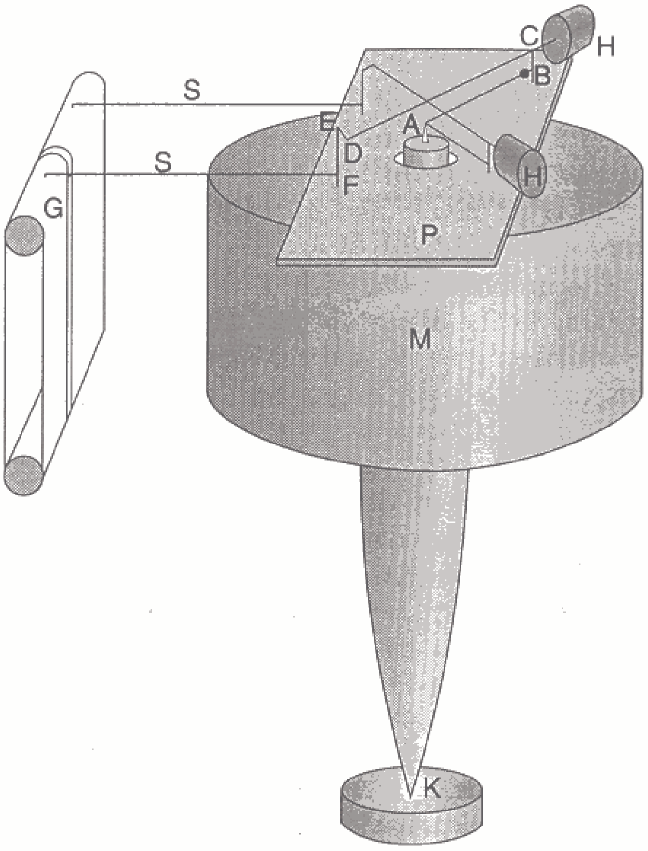

Figure 1. Schematic presentation of the main components of the 1000 kg horizontal Wiechert seismograph. M – seismometer mass; P – metal plate (part of the frame); H – damping devices; F – stylus pivots; S – styluses; G – recording drums; B – restoring leaf-springs; AB, BC, CD, DE – magnifying levers.

much improved measuring abilities, it seems worthwhile to try to actually measure the Wiechert seismograph response function instead of calculating it on the basis of some a priori assumptions. An obvious way would be to place the instrument on the shaking-table and directly compare the known input to the recorded seismogram. In practice, this is however nearly impossible to accomplish due to the complicated procedures of disassembling, moving and reassembling the seismograph – the process of moving and restoring the instrument in Zagreb took well over a year! Another approach is to compare the Wiechert records to the ones obtained by a modern, well calibrated instrument recording in the same place, which is the method used here.

2. Experimental setup

The measuring procedure used is essentially the same as described in Pavlis and Vernon (1994), who used records of ambient noise obtained simultaneously on a well calibrated seismometer and on the one to be calibrated. Denoting the respective response functions for either the displacement, velocity or acceleration as I_0 and I_1, and the respective spectra of recorded ground motion as S_0 and S_1, the unknown response I_1 is given by

$$I_1 = \frac{S_1}{S_0} I_0 \tag{2}$$

As the reference instrument a horizontal Sprengnether seismometer S-5100H was used and tuned to have the same damping and free period as the Wiechert NW–SE component. Its output was sampled with the sampling frequency of 50 Hz and digitally recorded by a Teledyne PDAS-100 digital recorder.

The problem to be solved was then how to make the Wiechert recording available in the digital format. Digitisation of smoked records is very difficult and often impossible, particularly in case of very small, very large events or events rich in high frequencies, and is further complicated by the necessary rectification of circular stylus movement. It was therefore decided to record the Wiechert seismograms digitally too. With this purpose, a coil-magnet transducer system had to be installed on the seismograph so that it would cause minimal mechanical (or any other) disturbance, while at the same time would record movements that are as similar as possible to the ones of the stylus tip. The fine mechanics of the Wiechert magnifying lever-system makes these two requirements partially contradicting, since any addition of the mass close to the stylus-tip would significantly change the overall performance. Furthermore, the nature of the moving coil transducer requires the relative motion of the magnet and the coil to be small and linear. The compromise was found by installing a light coil close to the point B (»•« in Fig. 1), on the lever connecting the point A on the mass with the restoring spring, while the magnet was placed and fastened onto the plate P. At this point, the motion of the mass has already been decomposed into two orthogonal components, the lever AB moves almost linearly, and magnification is small enough so that the coil moves in the homogeneous magnetic field even for strong signals. The output of the coil was also digitised at 50 sps and stored in the same way as the signal from the reference Sprengnether seismometer.

If I_0 in (2) is taken to be the Sprenghnether velocity response function, that relation yields the velocity response of the Wiechert seismograph equipped with that particular coil-magnet assembly. We are however interested in its displacement response, and it is easy to show that the velocity response of a pendulum with a coil moving in the magnetic field is the same as the displacement response of the same pendulum without a coil, so that I_1 in (2) is of the *shape* given by (1). The *absolute level* of I_1 (or static magnification V_0 in (1)) cannot be estimated by this procedure, since the amplitudes of motion of the coil and the stylus tip differ by an unknown factor. This is not a serious shortcoming as V_0 is only geometry dependent and is a known constant.

The measurements started on 25 June, 1996, and lasted four months. In that period 37 seismic signals (earthquakes, man-induced signals and microseismic noise) were satisfactorily recorded by both seismometers. Prior to the measurements the absolute calibration of the Sprengnether seismometer was performed and repeated after the observation period, with no noticeable change in the response function. At the same times the Wiechert seismograph was also calibrated using the classical procedure (yielding T_0 = 7.8 s, h = 0.5 and V_0 = 208), and again no significant change in response was noticed. The step-responses of the two instruments are shown in Fig. 2 (see caption for details).

3. Results

For each of the recorded events result sheets were prepared, like the ones presented in Figs. 3a-f. Each sheet consists of three parts. The upper part presents the respective event in time domain as recorded by Wiechert and Sprengnether seismometers (upper and lower trace, respectively). The ordinate gives the ground velocity (in mm/s) after the Sprengnether instrument, while the Wiechert signal is scaled by a common factor necessary to obtain an effective average magnification equal to the Sprengnether seismometer for all 37 measurements. The root-mean-square value is also given for the lower trace. The left lower part of each result sheet presents smoothed velocity amplitude spectra of the above signals, with the Wiechert spectrum being displaced by two orders of magnitude for clarity. The lower right-hand side part gives the estimated Wiechert magnification obtained after (2) by dividing the two spectra on the left and multiplying the ratio by the Sprengnether response function. The theoretical Wiechert response is superimposed. The

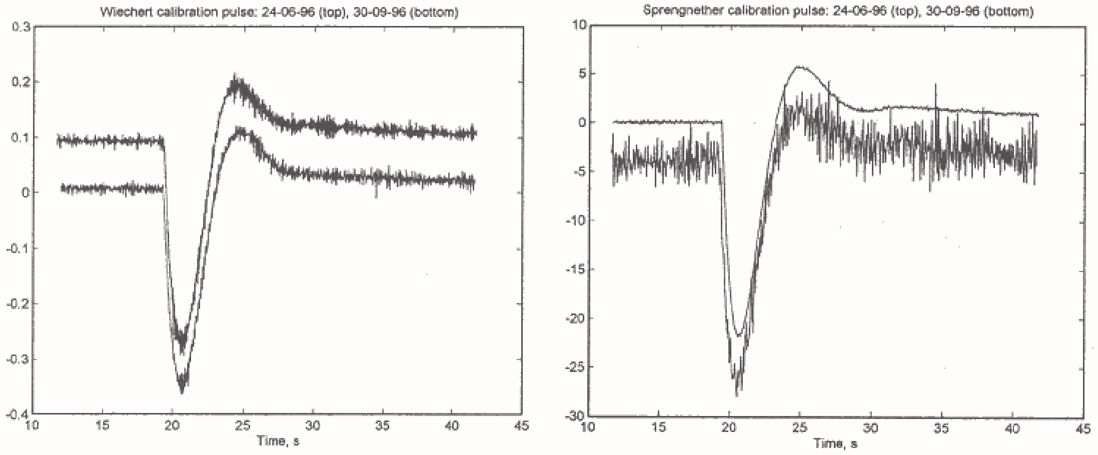

Figure 2. Velocity response of Wiechert (left) and Sprengnether (right) to a step produced by lifting a weight off the perimeter of the seismometer mass in the Wiechert case, and by turning on a constant current through the Sprengnether seismometer's calibration coil. The two traces in each part of the figure refer to calibrations at the beginning and at the end of the experiment. The current used for Sprengnether calibration in September was 10 times lower then the one used in June.

average estimated magnification is given also numerically for the five frequency bands in the upper left corner. The inset in the lower right corner gives the same magnification curve in the linear scale for frequencies up to 5 Hz. As stated previously, the procedure used here does not yield the absolute level of the estimated Wiechert response, which was therefore scaled by a common constant factor so as to obtain the magnification of 208 in the frequency band 0.5–4.0 Hz as an average for all 37 measurements.

The six events presented in Fig. 3 have been selected to illustrate the main features of what has been observed for various excitation signals, while all other result sheets are presented in the Appendix.

The first example (Fig. 3a) is related to a small local earthquake with an epicentral distance of some 25 km. This event is of short duration, and is very rich in high frequencies. The two seismograms share little similarity, with the Wiechert seismometer producing larger amplitudes. The computed Wiechert response function coincides with the theoretical one for frequencies 0.2–4.5 Hz and is higher for frequencies outside this band. The high-frequency response ($f > 5$ Hz) is characterised by a large increase in magnification (visible in all observations, see also Appendix) reaching several thousands. The two characteristic peaks at 10 and 20 Hz are observed on many other events, too. The minimum between them is more evident here than in other examples.

Unlike the previous example, the two seismograms of the earthquake in the Greece-Albania border region ($m_b = 5.0$) (Fig. 3b) show remarkable coherence, even in small details. This similarity is reflected in spectral shapes, and the computed response curve follows the theoretical one rather closely up to

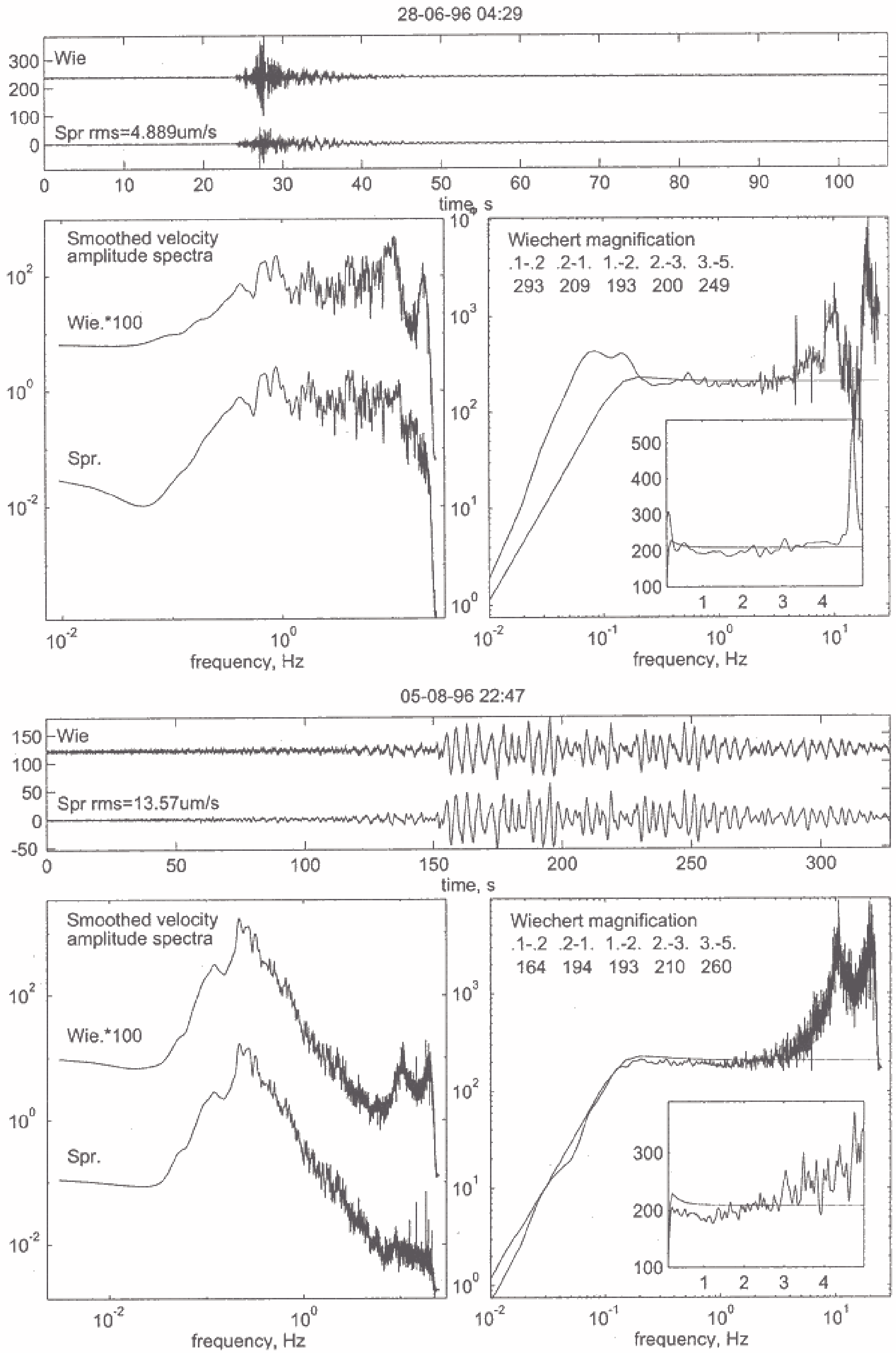

Figure 3. The result sheets related to six selected events (from a total of 37 recorded). For details see text (first paragraph of section 3).

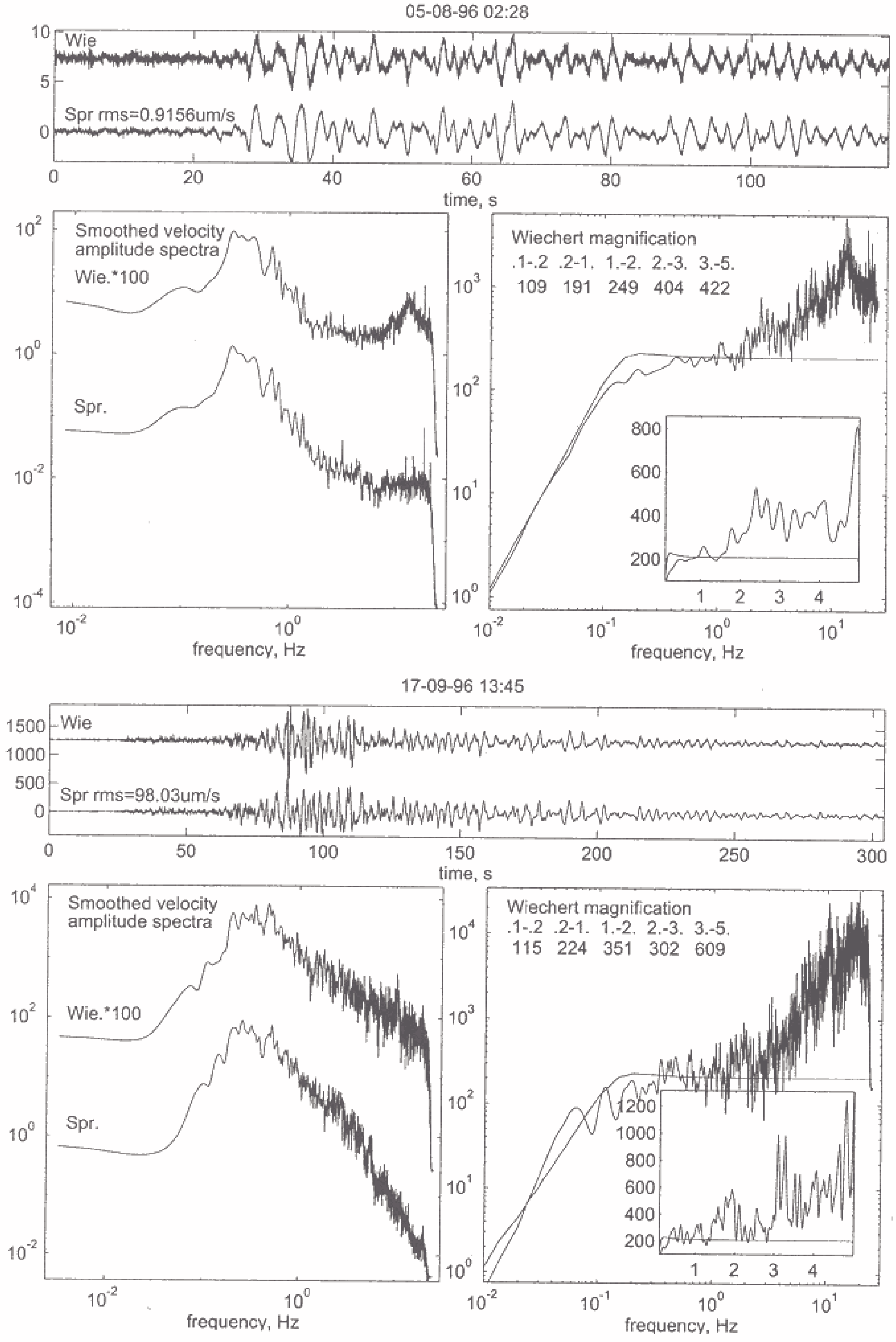

Figure 3. Continued.

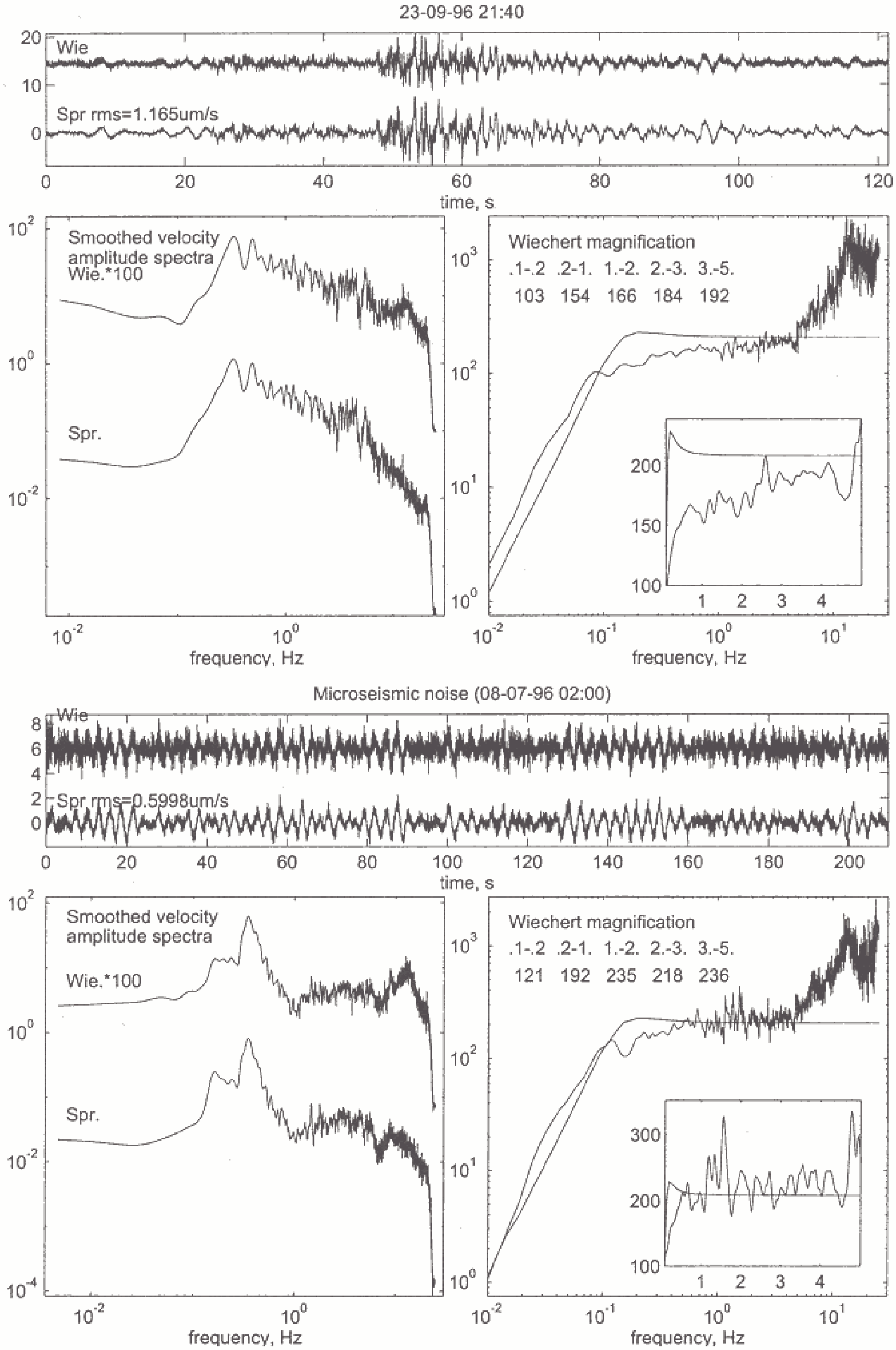

Figure 3. Continued.

some 3–4 Hz. For higher frequencies, a characteristic increase in response is observed again with spectral peaks at 10 and 20 Hz. In linear display (inset in the lower right part of the figure), a steady, almost linear increase of response is visible for the intermediate frequency band, which is characteristic of most of the observations.

The teleseismic event (Tonga islands, $M_S = 6.7$) record presented in Fig. 3c clearly shows relative abundance of the Wiechert seismogram in high frequency components. The computed response curve agrees with the theoretical one for small frequencies up to 0.1 Hz. Smaller magnification is observed around the free period of the Wiechert pendulum. The high-frequency increase of response begins here as low as 1.5 Hz. Instead of the peaks at 10 and 20 Hz only one maximum at about 13 s is visible.

The earthquake of 17 September 1996 ($M_S = 5.5$) (Fig. 3d) is the second strongest aftershock of the large Ston earthquake ($M_S = 5.9$). The main shock and the strongest aftershock were not correctly recorded since they displaced the Wiechert styluses from their bearings. The maximum amplitude on the Sprengnether instrument gives peak ground velocity in Zagreb of 615 mm/s at $T = 6.2$ s. This would correspond to stylus displacement of some 11 cm, which is about the maximum possible for the Wiechert recorder. The two seismograms show clear similarity except for the period of strongest shaking. While the low-frequency magnification agrees with the theoretical one rather well, the observed response for frequencies above 1 Hz is larger than expected by a factor of 2–3 for intermediate frequencies and exceeds 10^4 for $f > 10$ Hz.

The earthquake near Šibenik ($M = 3.4$, epic. distance = 230 km) is shown in Fig. 3e. In this case, the Wiechert response is mostly lower than expected for frequencies within the 0.1–5.0 Hz band. Outside this interval the magnification is higher than expected, and a single high-frequency peak is observed at some 12 Hz.

Finally, a record of the microseismic noise is presented in Fig. 3f, with a clear difference of the two seismograms in the high-frequency content. For $f < 5$ Hz, the response is close to the theoretical one, except for the frequencies between 0.1 and 0.5 Hz, where it is lower than expected.

All 37 observed response curves are plotted together in Fig. 4a along with their average. The average curve is displayed together with the theoretical one in Fig. 4b. The most consistent measurements were obtained in the frequency band 0.2–0.8 Hz, where the dispersion of observations is the smallest. According to Fig. 4b, the observed average response curve may be divided into four parts: 1) for frequencies up to 0.12 Hz the magnification is larger than the theoretical but is still proportional to f^2; 2) between 0.12 and 1.0 Hz the response is somewhat lower than theoretically expected, 3) for frequencies between 1.0 and 4.5 Hz the magnification is equal on the average to the expected value; and 4) for frequencies above 4.5 Hz a pronounced increase in magnification is observed exceeding 10^3 for $f > 10$ Hz on the average.

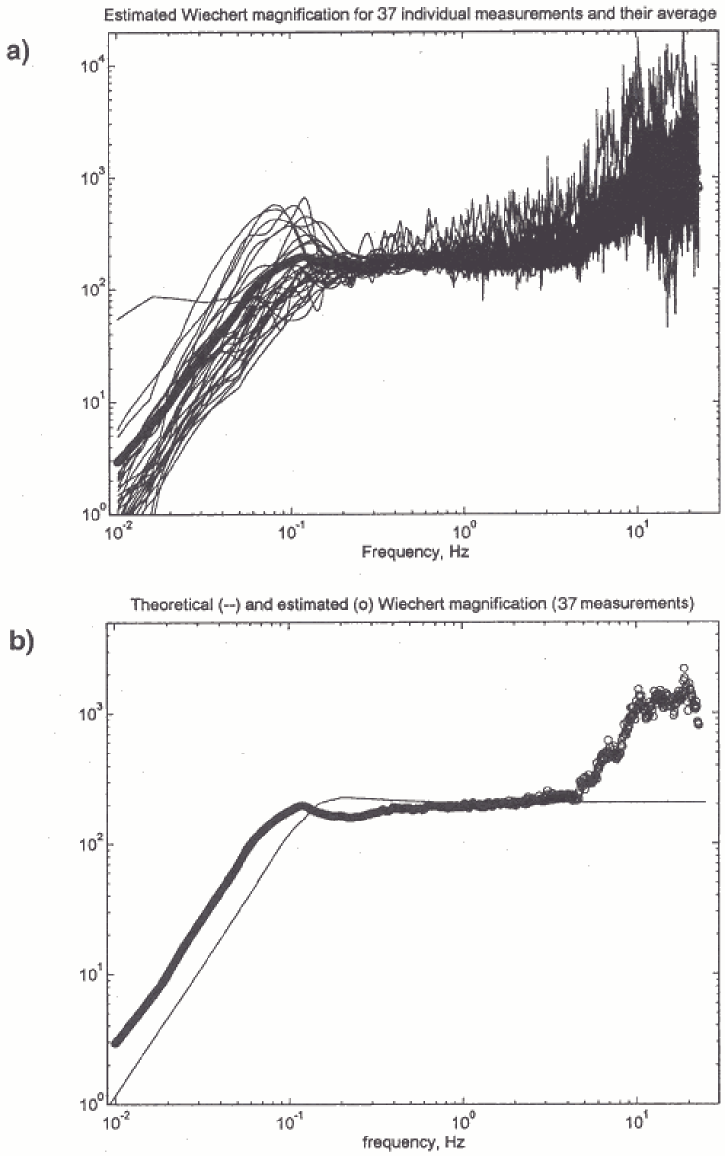

Figure 4. a) Estimated Wiechert magnification curves for all 37 events (thin lines), and their average (thick line); b) The average Wiechert magnification estimated here (thick line, circles), and the theoretical curve (thin line) obtained by classical calibration.

4. Conclusions

The results of the measurements indicate that the Wiechert response function is more complex than the simple theoretical form as given by (1). Its most prominent feature observed in all the examples examined is a sudden and large increase of magnification for frequencies exceeding some 5 Hz. In some cases two maxima are observed (at approximately 10 and 20 Hz), some-times there is only one peak at an intermediate frequency, while occasionally all three peaks are simultaneously present. At this stage of investigation, we suggest that this increase of magnification may be attributed to the oscillations of some of the frame components as defined in the first section, when shaken by an earthquake. Although Wiechert analogue records rarely contain frequencies exceeding 5 Hz, they are clearly present in seismograms of local earthquakes. Indeed, there are frequent remarks in the Zagreb seismological bulletins indicating that periods on the seismograms appeared too short to be determined. Neglecting the observed magnification increase may therefore lead to serious overestimation of local earthquakes' magnitudes.

No apparent explanation may be offered for the behaviour of the response curve at the low-frequency part of the spectrum. As this is observed for the average magnification curve (Fig. 4b) and not in all of the cases, we feel that more experiments are needed to confirm this observation. Should it be confirmed, the consequences regarding *e.g.* M_S computation would be important, resulting in M_S values lower by 0.3–0.4 magnitude units.

As far as the issue of Wiechert's nonlinearity is concerned, Fig. 5 provides a hint that there is the positive answer to the question: »Does the Wiechert dynamic magnification depend on the nature of the input signal?«. The figure presents observed Wiechert magnification in four frequency bands for which the theoretical magnification should be equal to the static magnification, *i.e.*

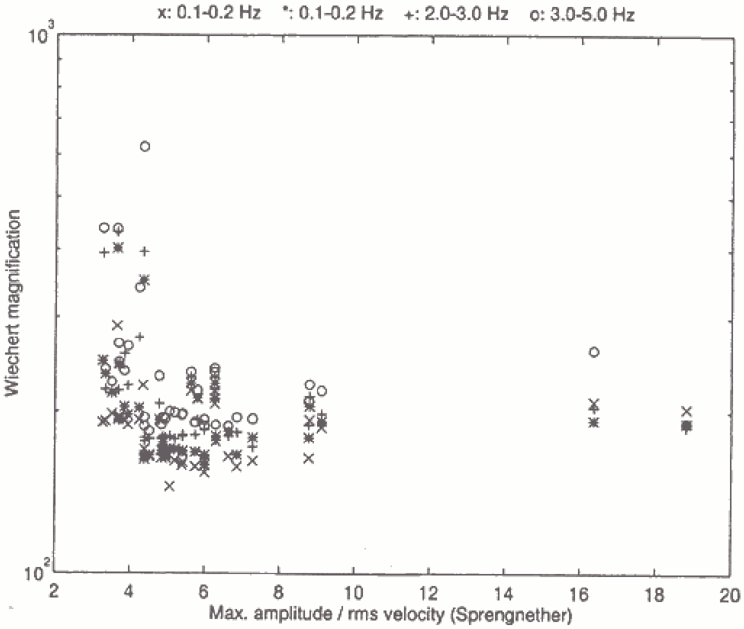

Figure 5. Estimated Wiechert magnification in four frequency bands versus the ratio of the observed maximum velocity and the root-mean-square velocity of the ground.

208 in our case. The observed magnification is plotted against the ratio of the maximum velocity and the root-mean-square velocity of the corresponding ground motion as determined from the Sprengnether record. This ratio is a kind of measure of the impulsiveness of the signal: high values correspond to an impulse-like signal, while low ones indicate more steady-state motion with no expressed maxima. The figure indicates that the Wiechert magnification increases for signals whose (maximum amplitude) / (rms amplitude) ratio falls below 4, *i.e.* for uniform shaking. This effect is more visible for higher frequencies. At present we may only speculate as to the significance and the cause of such a behaviour. It seems probable that uniform ground motion can cause resonance of parts of the frame, thus increasing the overall magnification, but again, more experimentation seems to be necessary to draw firm conclusions.

While the experimental results outlined above indicate that the true Wiechert response could be more complicated than it is usually assumed, there are several points that need to be borne in mind or clarified by further investigation.

(1) The response curve obtained is representative of the movement of the coil fixed at point marked by »•« in Fig. 1, and therefore does not properly describe the movement of styluses during earthquakes. Although it may be argued that high-frequency components will be strongly damped as the motion of the lever AB is further transmitted and amplified, it is improbable that this process could lead to the annihilation of high-frequency maxima in magnification.

(2) The measurements would have been more reliable, particularly for low frequencies, if a broad-band seismometer was available as a reference one. We hope this will be the case in future experiments.

(3) As the Wiechert instruments have unfortunately not been protected from the influence of the motion of surrounding air by placing them into the protective housing after the restoration, it may prove advantageous to limit the future analyses only to relatively large signals, for instance those that would cause displacements of styluses greater than 1 mm.

(4) Rather great scattering of the individual measurements about the mean response (Fig. 4a), both in the low- and high-frequency ranges, call for additional experimentation in order to increase the reliability of averages. It should then be possible to use the improved data set as the basis for theoretical modelling, probably in terms of a pair (or several) coupled pendulums.

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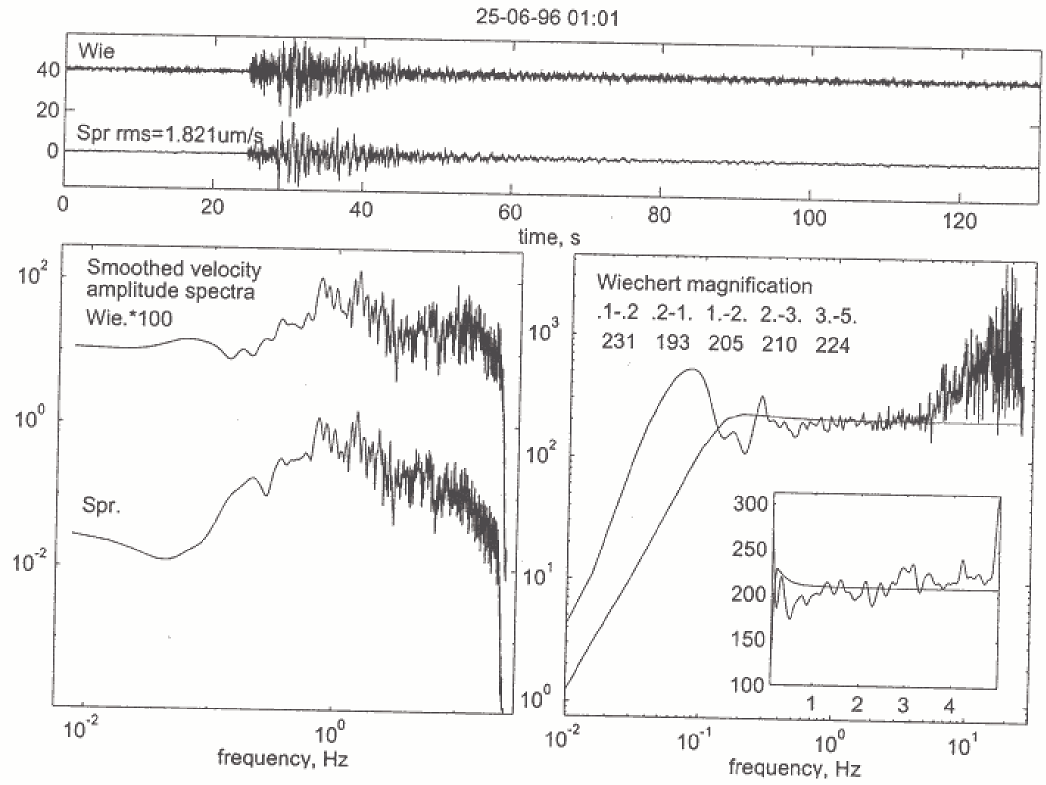
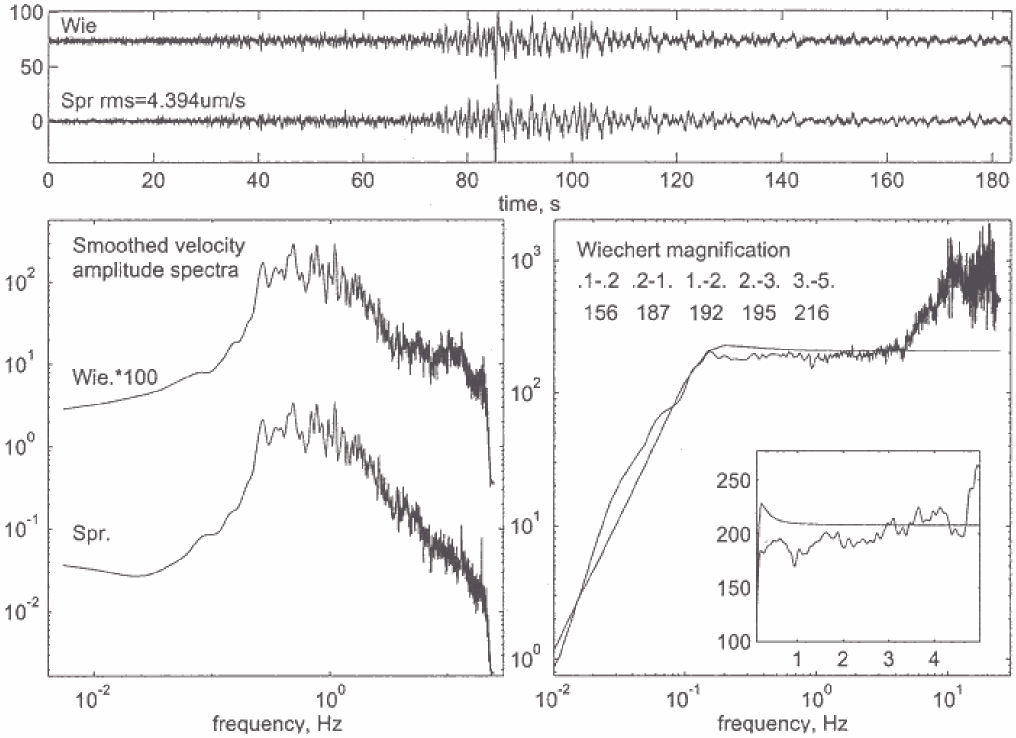
Appendix

The result sheets for the 31 events not shown above in the text. For description of the data presented, please refer to the first paragraph of section 3.

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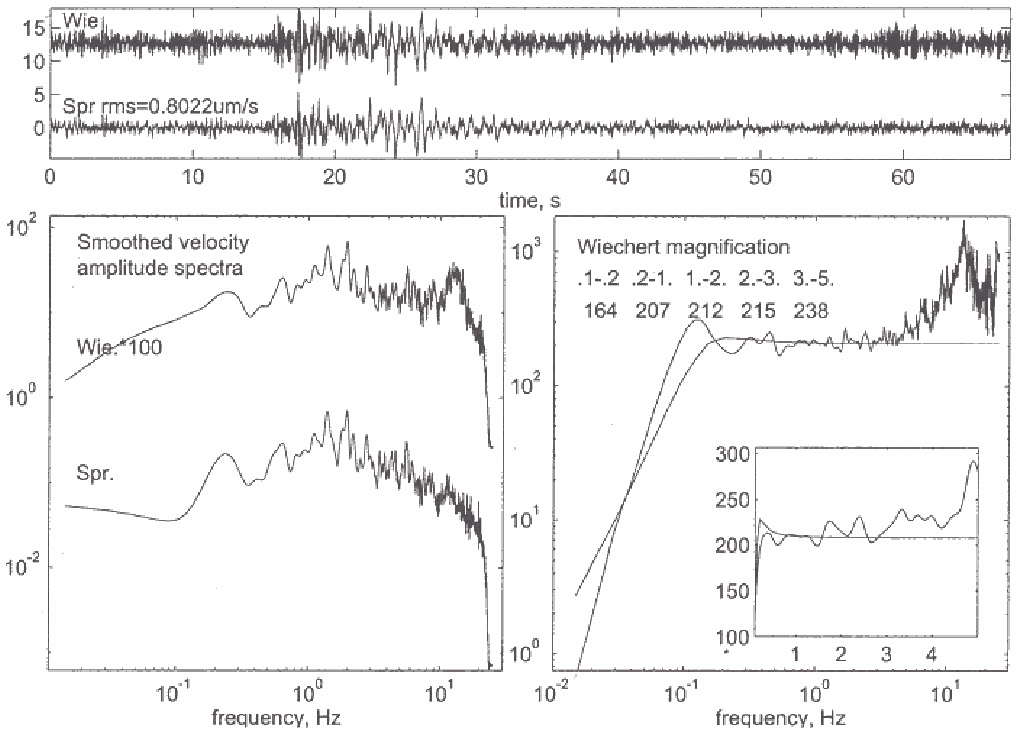
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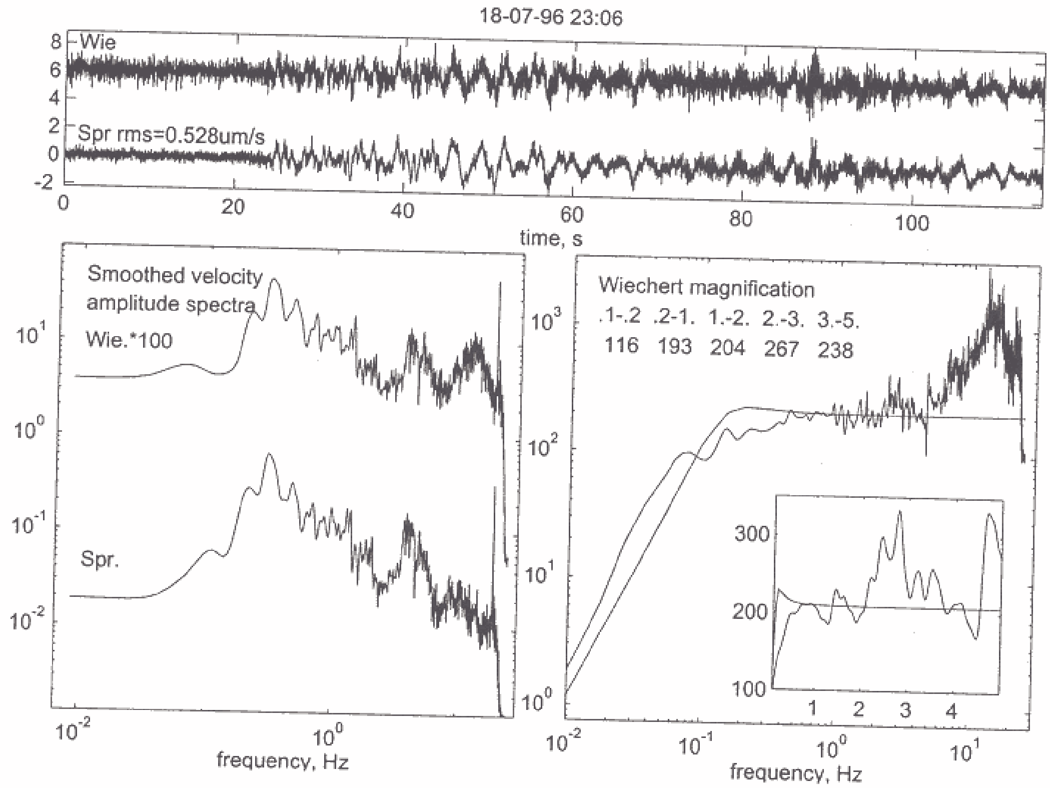
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6
4
2
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time, s
Smoothed velocity amplitude spectra
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10^1
10^0
10^-1
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10^-2
10^0
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
116 193 204 267 238
10^3
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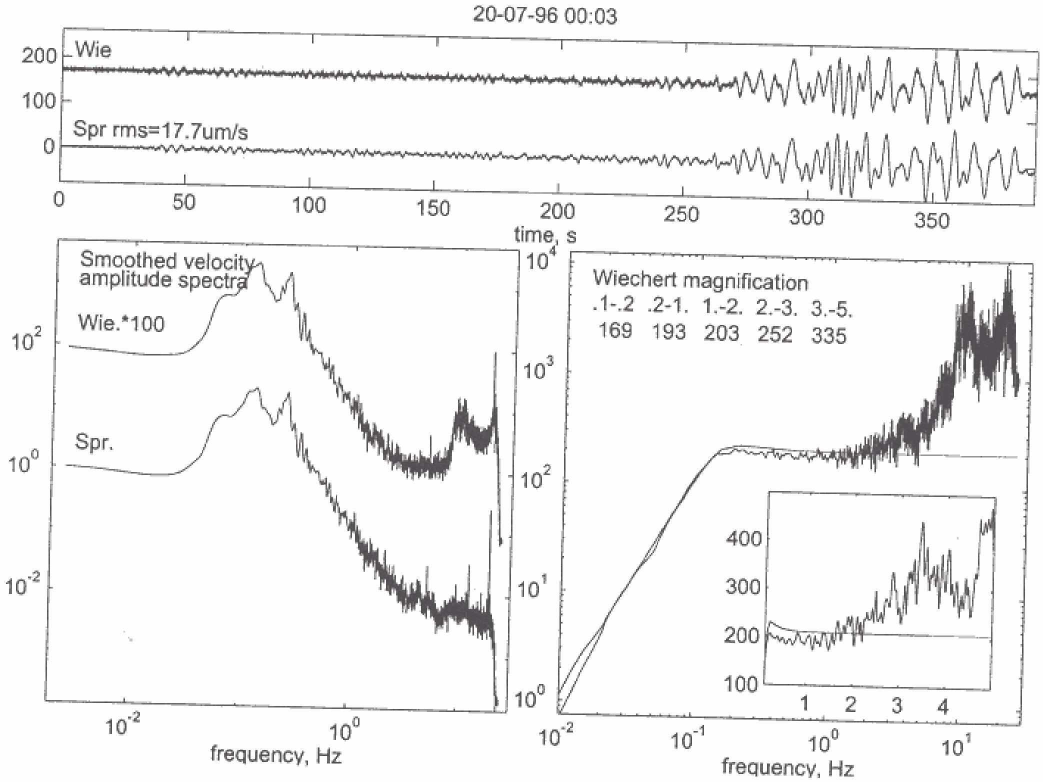
10^0
10^1
frequency, Hz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time, s
Smoothed velocity amplitude spectra
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Spr.
10^2
10^0
10^-2
10^-2
10^0
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
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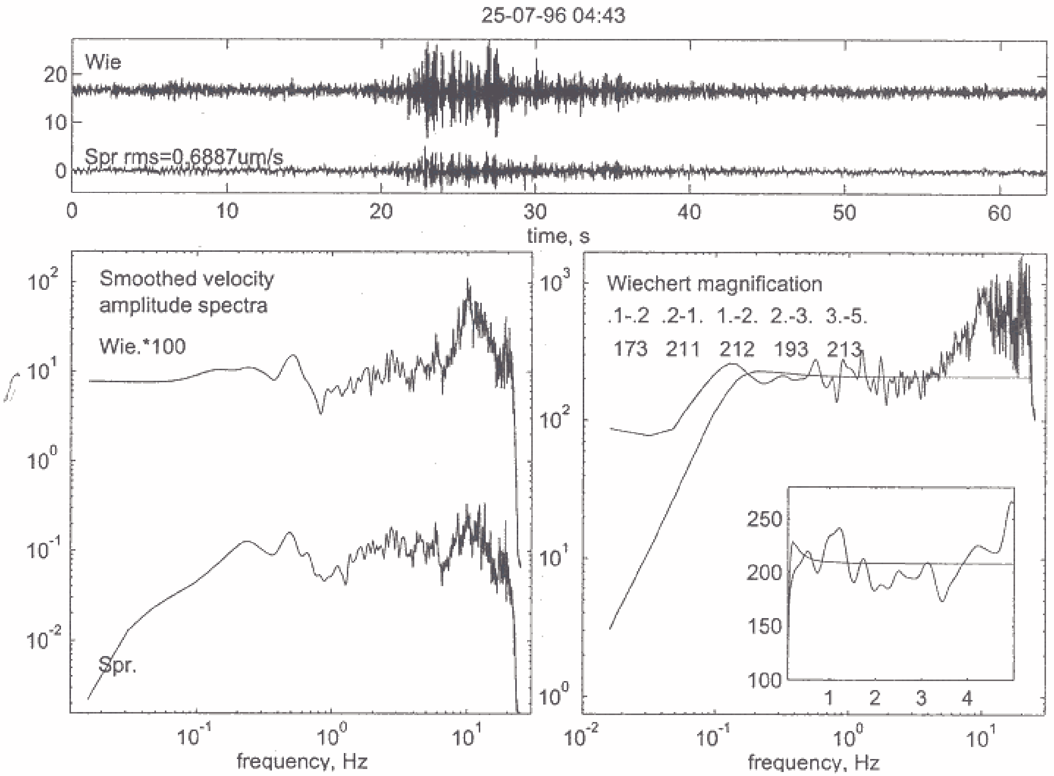
frequency, Hz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Smoothed velocity amplitude spectra
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10^-1 10^0 10^1
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
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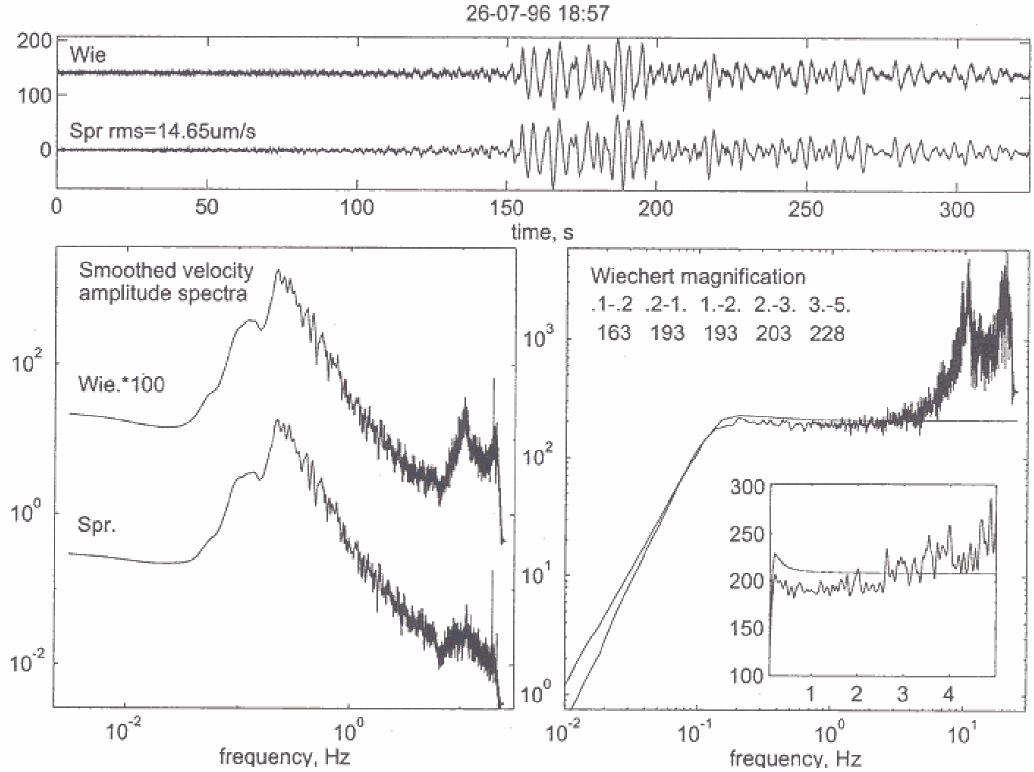
frequency, Hz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Spr.
10^2 10^0 10^-2
10^-2 10^0
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
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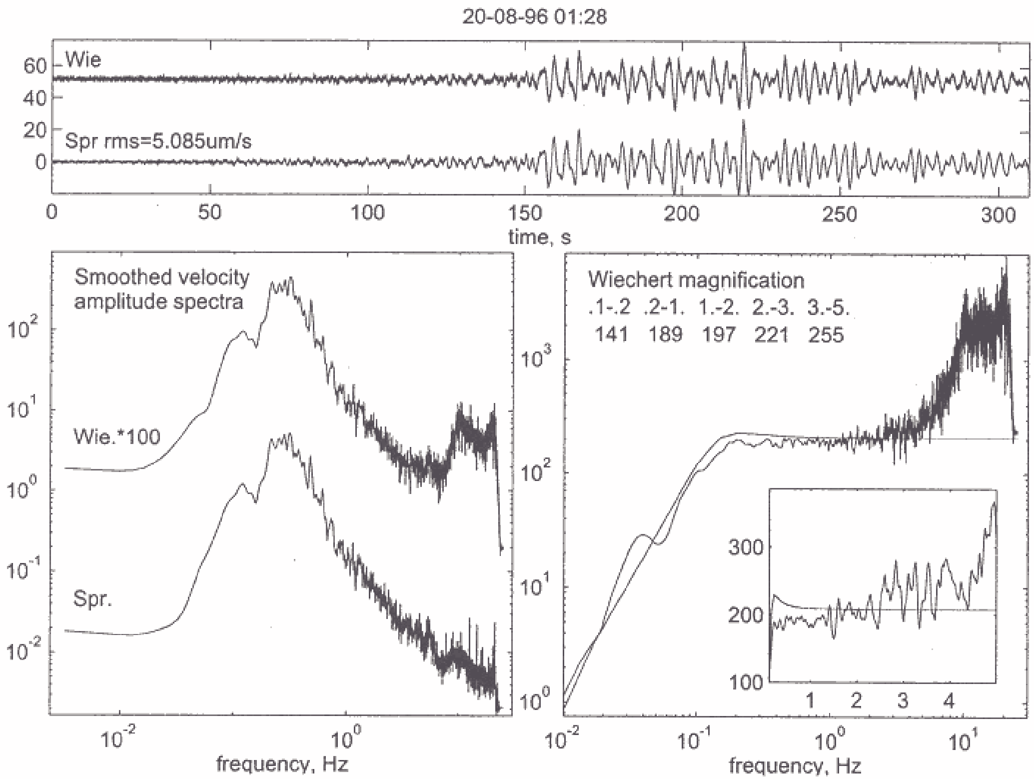
300 250 200 150 100
1 2 3 4
10^-2 10^-1 10^0 10^1
frequency, Hz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Smoothed velocity amplitude spectra
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10^2
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frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
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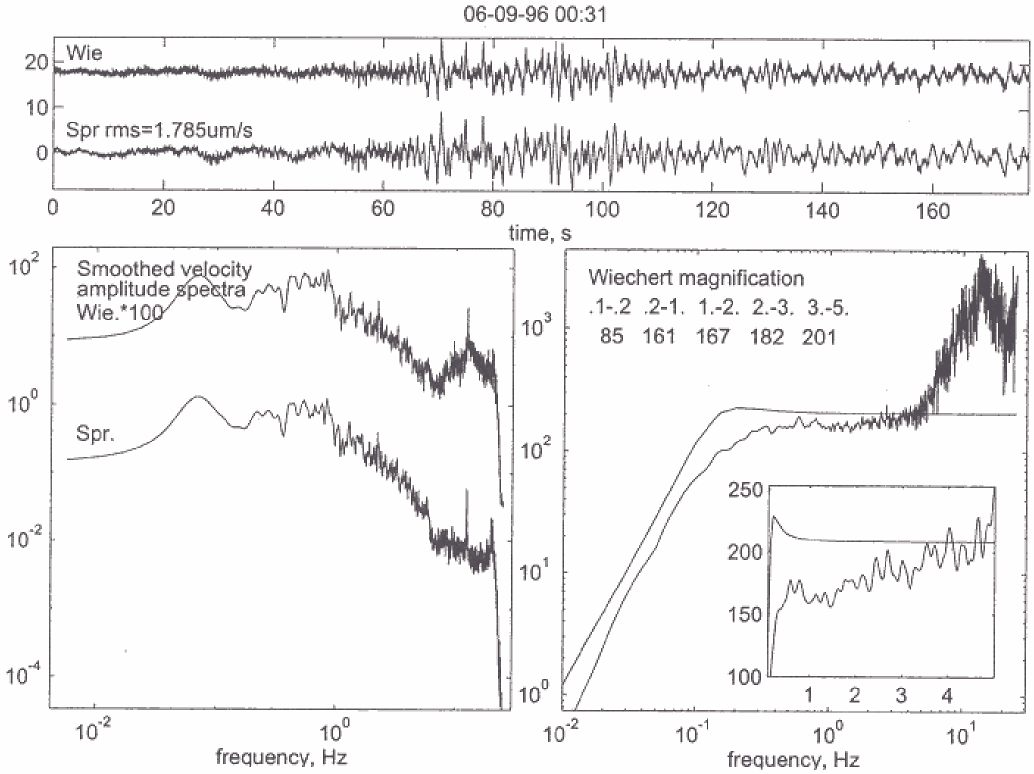
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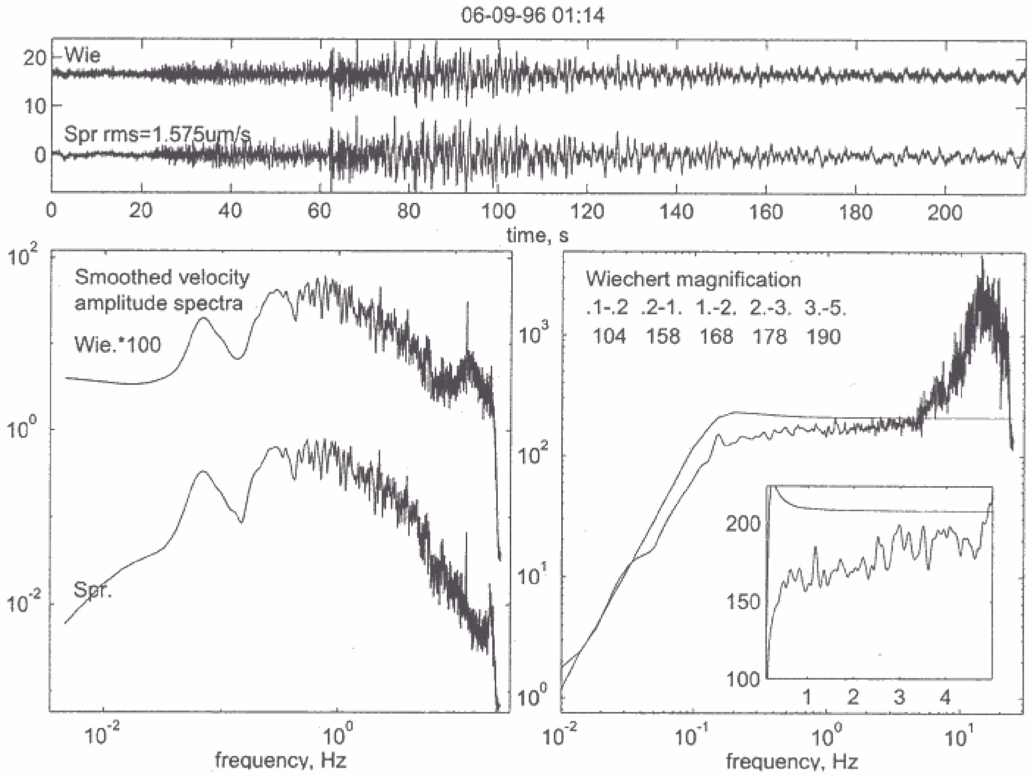
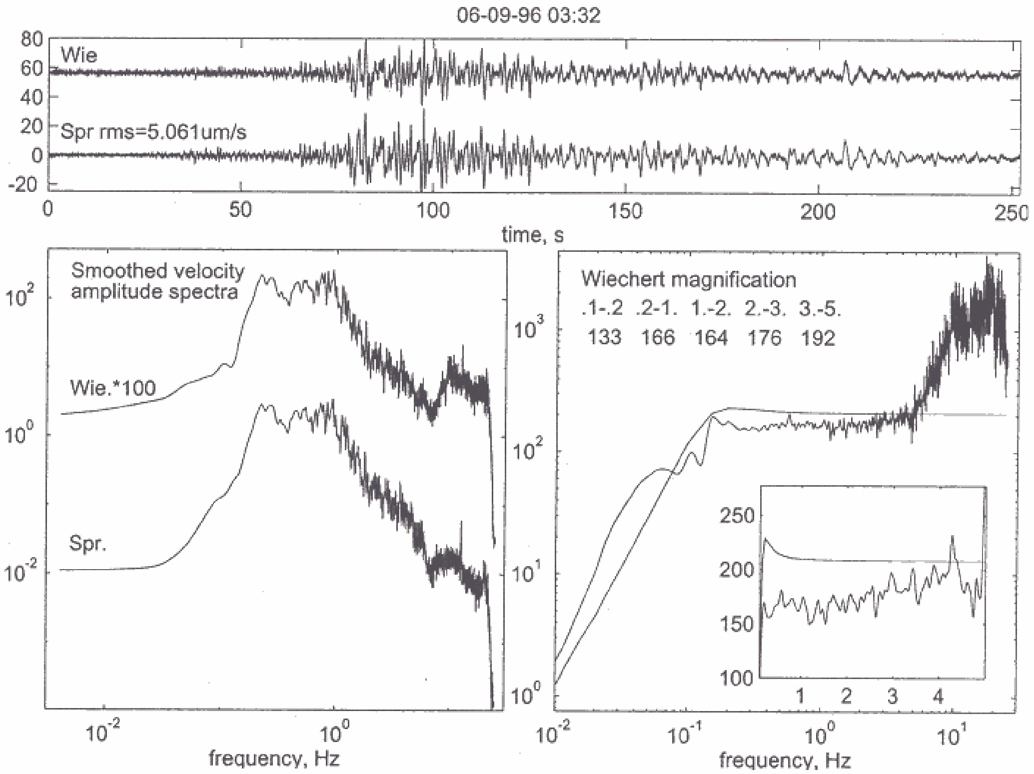
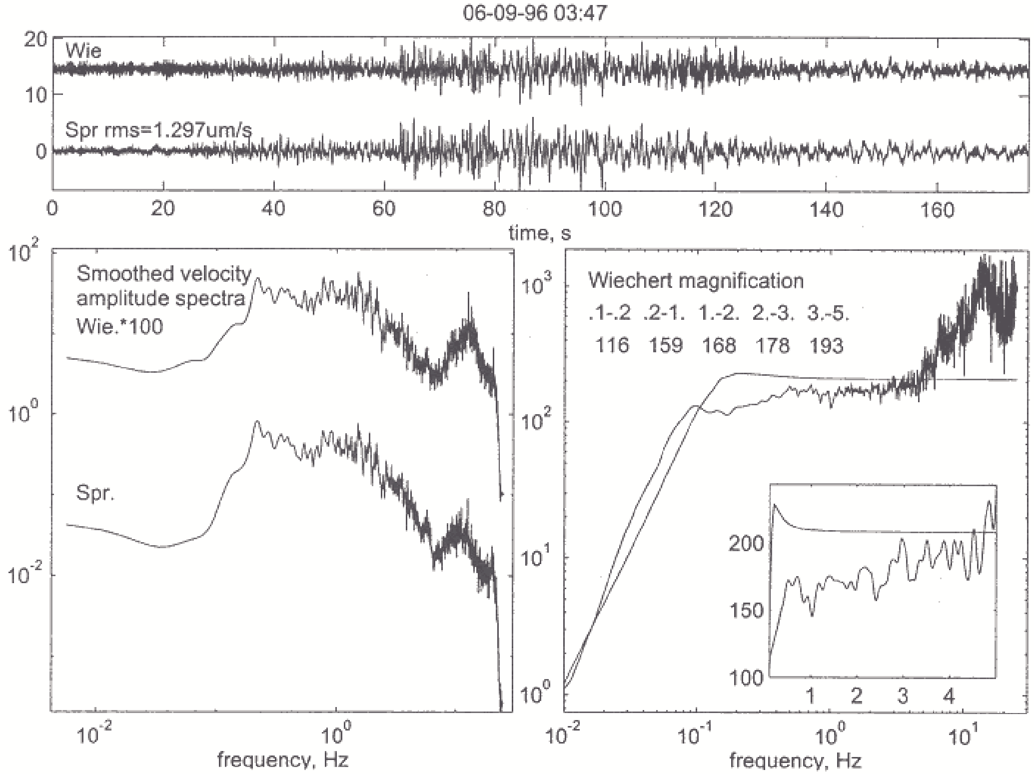
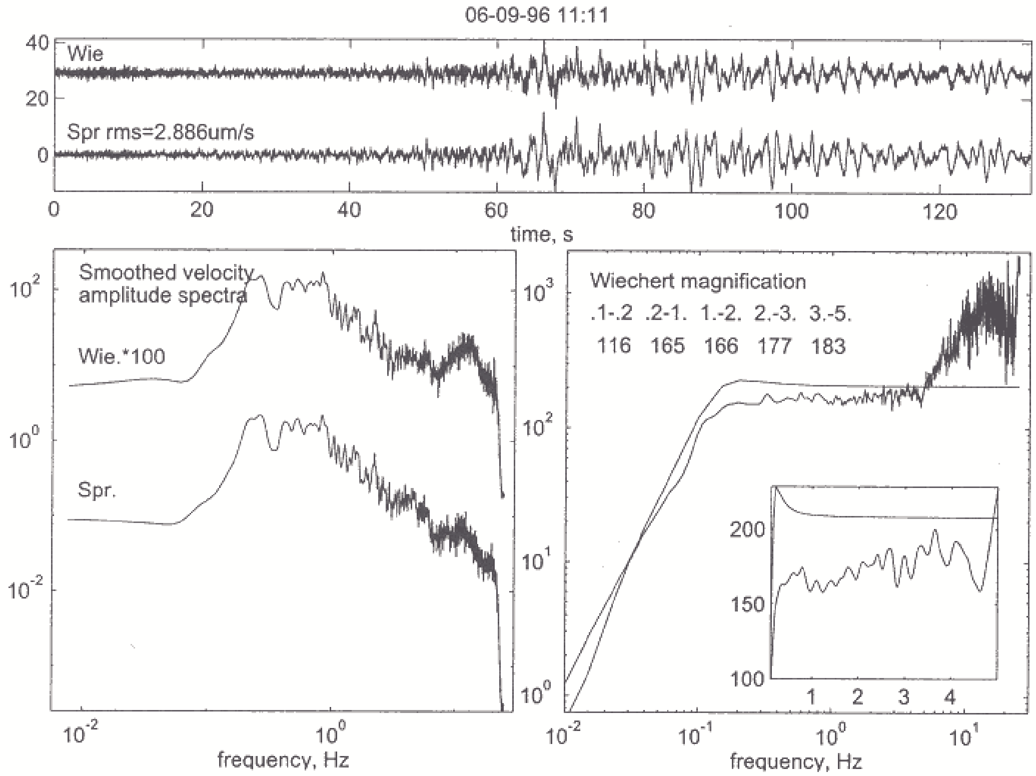
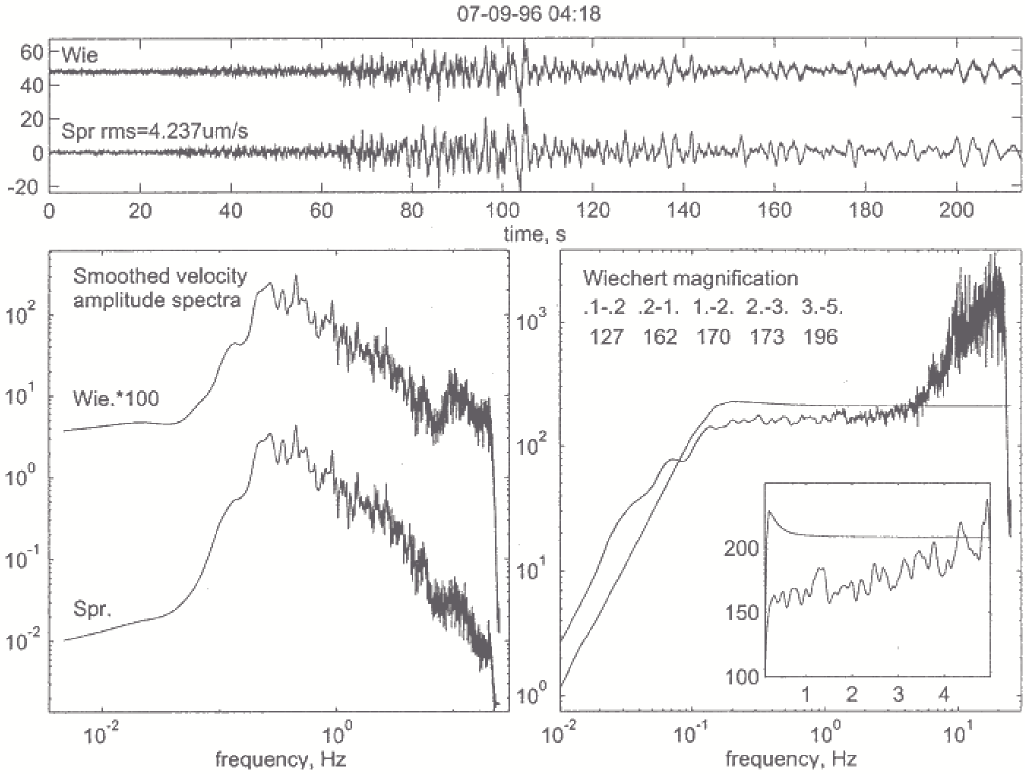
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
85 161 167 182 201
10^3
10^2
10^1
10^0
250
200
150
100
1 2 3 4
10^{-2}
10^{-1}
10^0
10^1
frequency, Hz

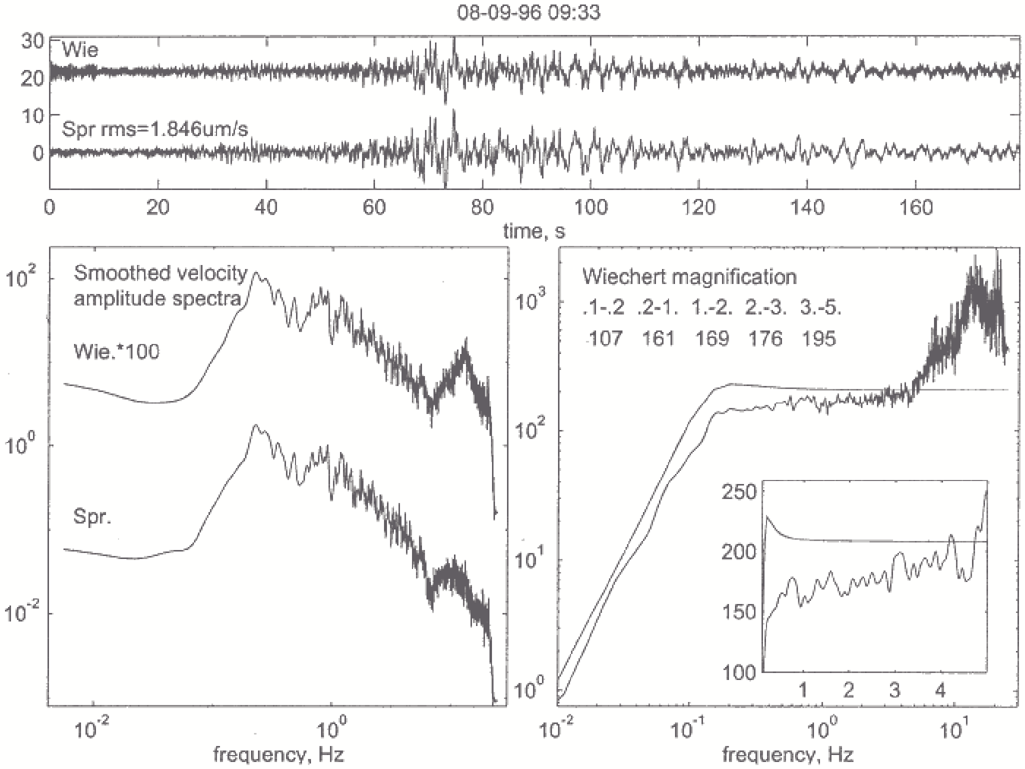

06-09-96 01:14
Wie
Spr rms=1.575um/s
20
10
0
0 20 40 60 80 100 120 140 160 180 200
time, s
Smoothed velocity amplitude spectra
Wie.*100
Spr.
10^2
10^0
10^{-2}
10^{-2} 10^0
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
104 158 168 178 190
10^3
10^2
10^1
10^0
200
150
100
1 2 3 4
10^{-2} 10^{-1} 10^0 10^1
frequency, Hz

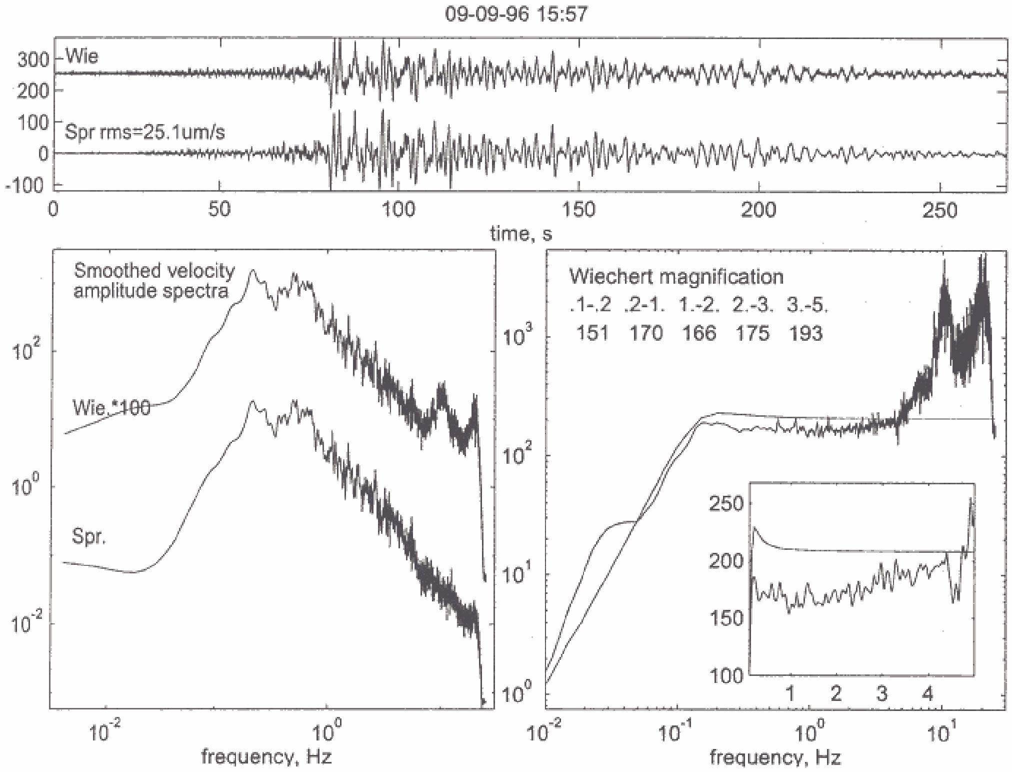

06-09-96 03:32
Wie
Spr rms=5.061um/s
80
60
40
20
0
-20
0 50 100 150 200 250
time, s
Smoothed velocity amplitude spectra
Wie.*100
Spr.
10^2
10^0
10^{-2}
10^{-2} 10^0
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
133 166 164 176 192
10^3
10^2
10^1
10^0
250
200
150
100
1 2 3 4
10^{-2} 10^{-1} 10^0 10^1
frequency, Hz

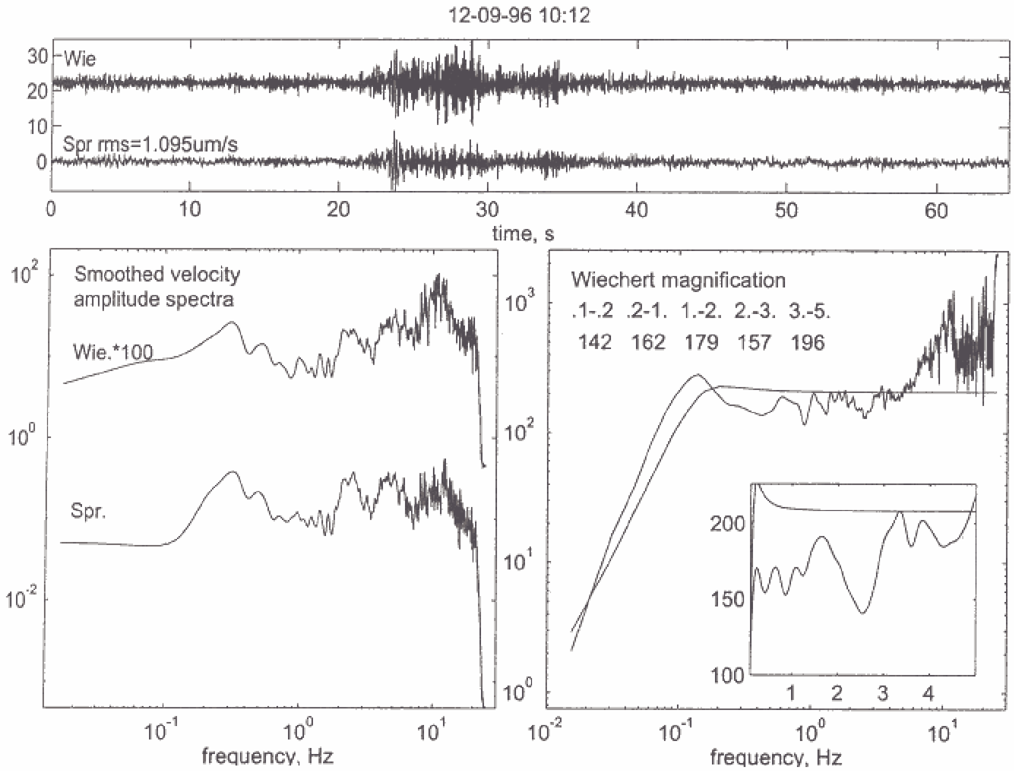

06-09-96 03:47

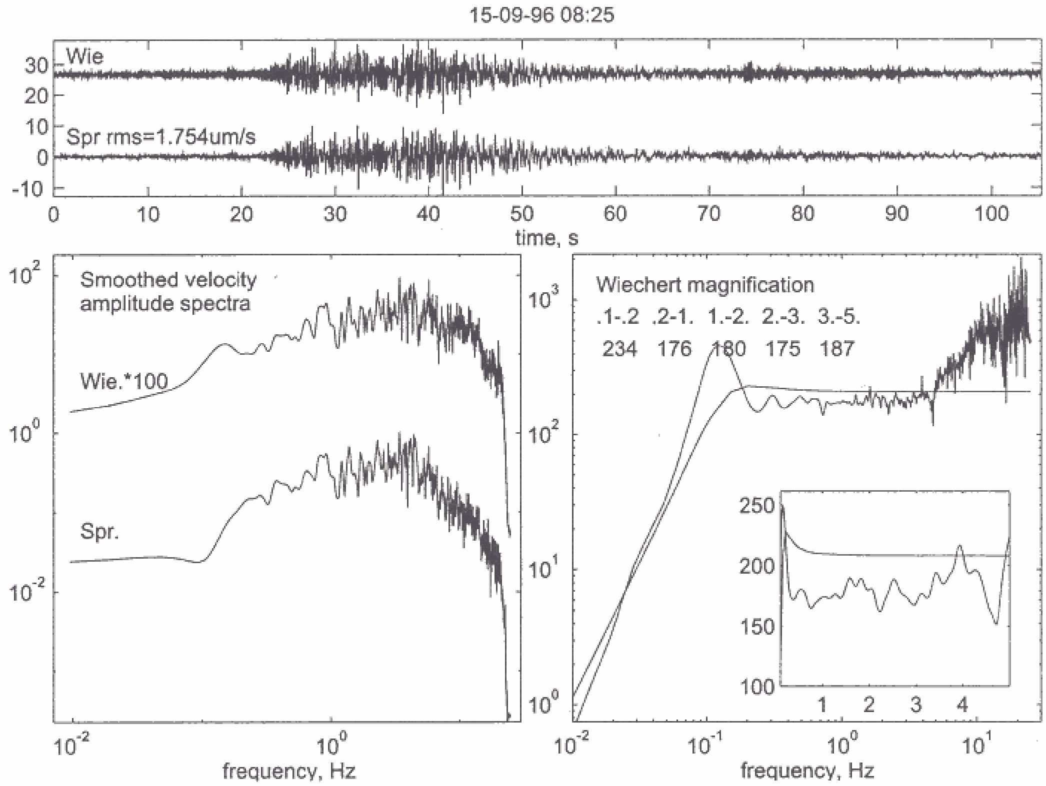

06-09-96 11:11

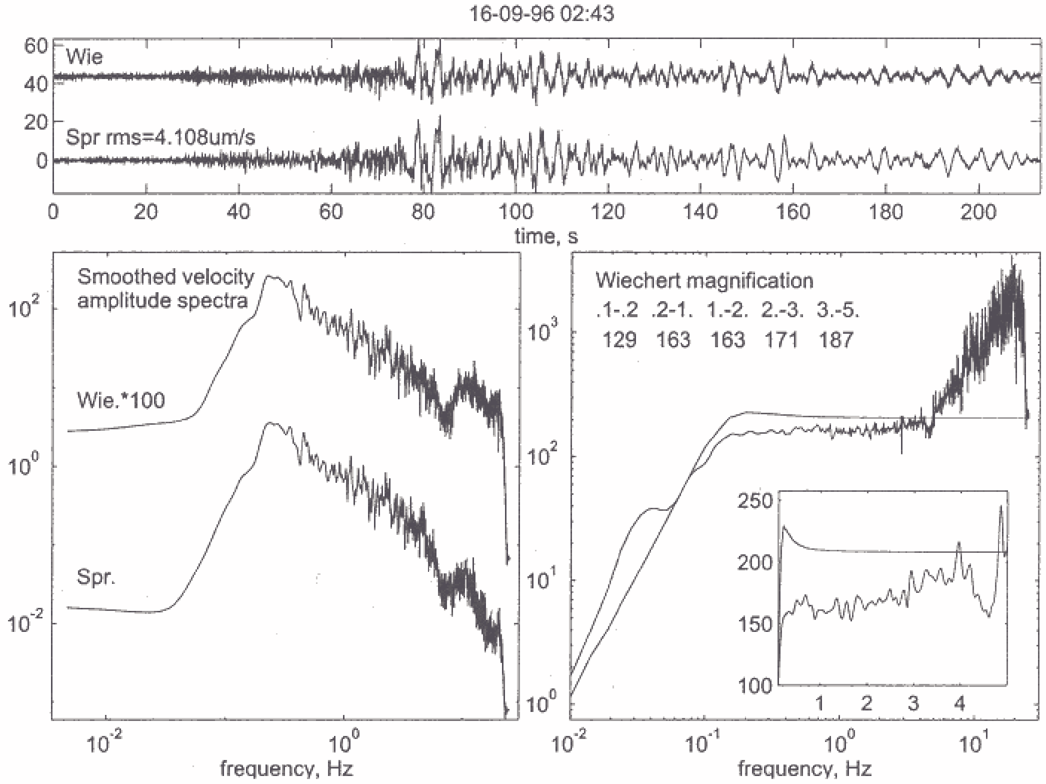

07-09-96 04:18
Wie
Spr rms=4.237um/s
time, s
Smoothed velocity amplitude spectra
Wie.*100
Spr.
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
127 162 170 173 196
frequency, Hz

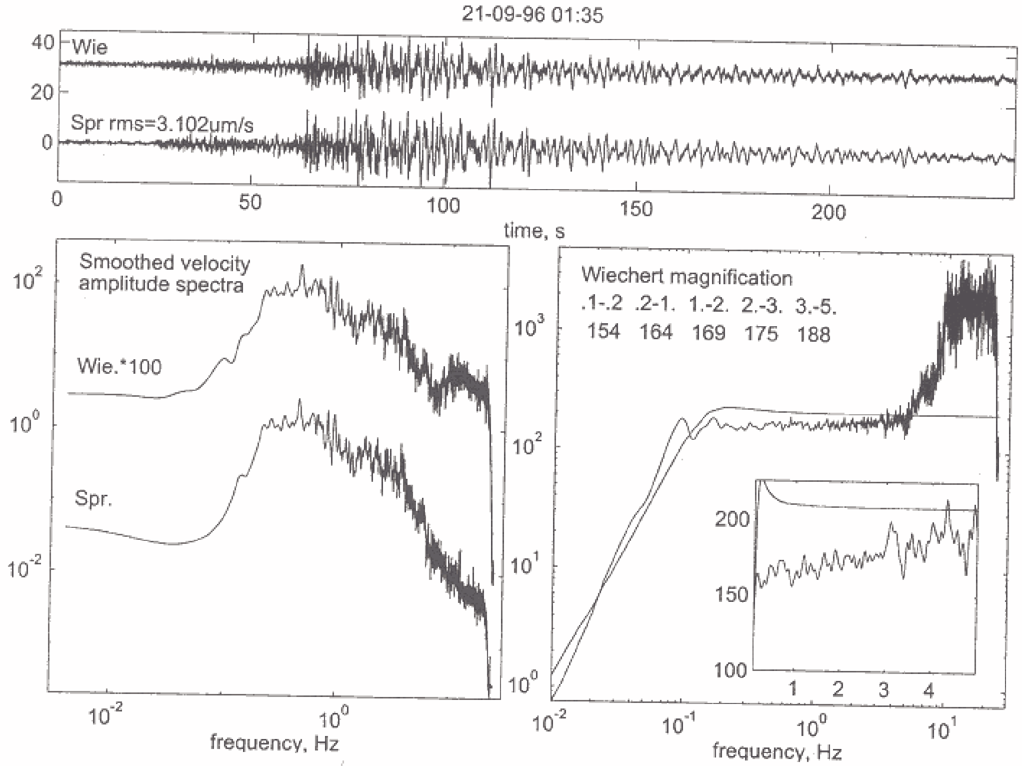

08-09-96 09:33
Wie
Spr rms=1.846um/s
time, s
Smoothed velocity amplitude spectra
Wie.*100
Spr.
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
107 161 169 176 195
frequency, Hz

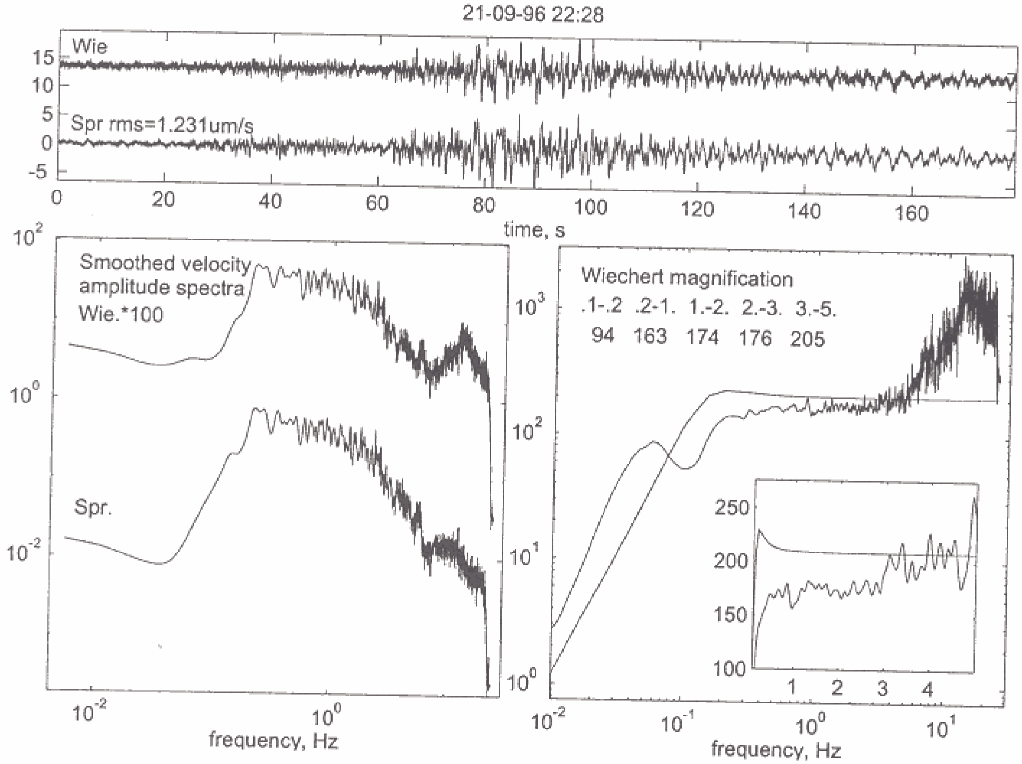

09-09-96 15:57
Wie
Spr rms=25.1um/s
300
200
100
0
-100
0
50
100
150
200
250
time, s
Smoothed velocity amplitude spectra
Wie.*100
Spr.
10^2
10^0
10^{-2}
10^{-2}
10^0
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
151 170 166 175 193
10^3
10^2
10^1
10^0
250
200
150
100
1 2 3 4
10^{-2}
10^{-1}
10^0
10^1
frequency, Hz

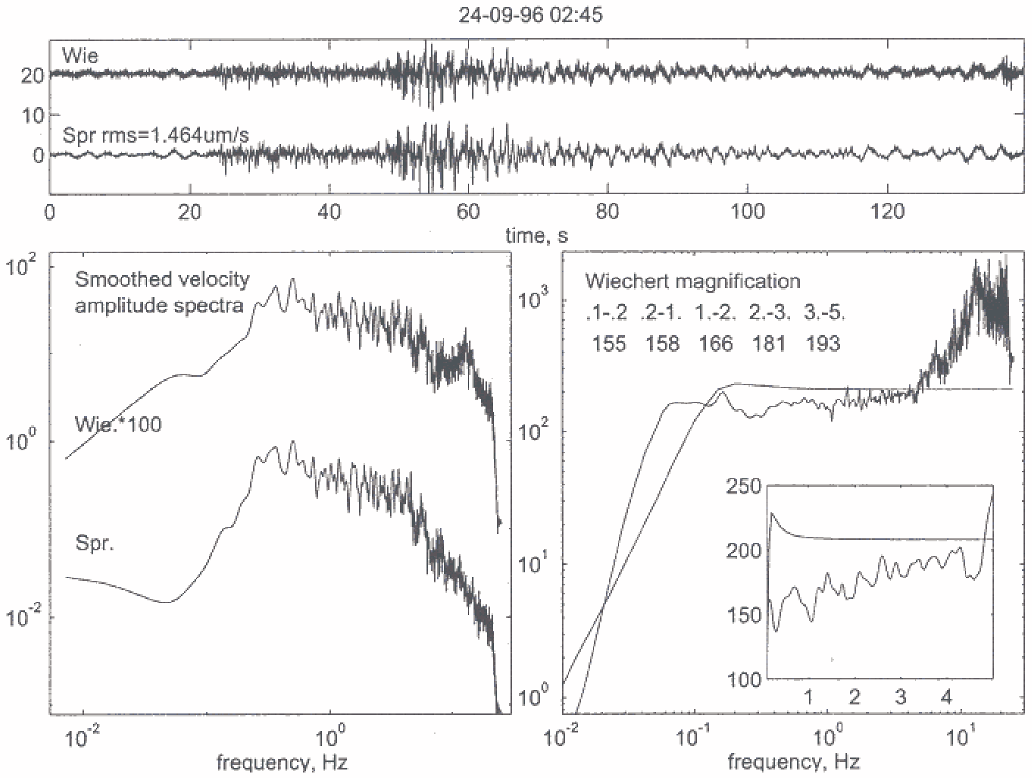

12-09-96 10:12
Wie
Spr rms=1.095um/s
30
20
10
0
0
10
20
30
40
50
60
time, s
Smoothed velocity amplitude spectra
Wie.*100
Spr.
10^2
10^0
10^{-2}
10^{-1}
10^0
10^1
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
142 162 179 157 196
10^3
10^2
10^1
10^0
200
150
100
1 2 3 4
10^{-2}
10^{-1}
10^0
10^1
frequency, Hz

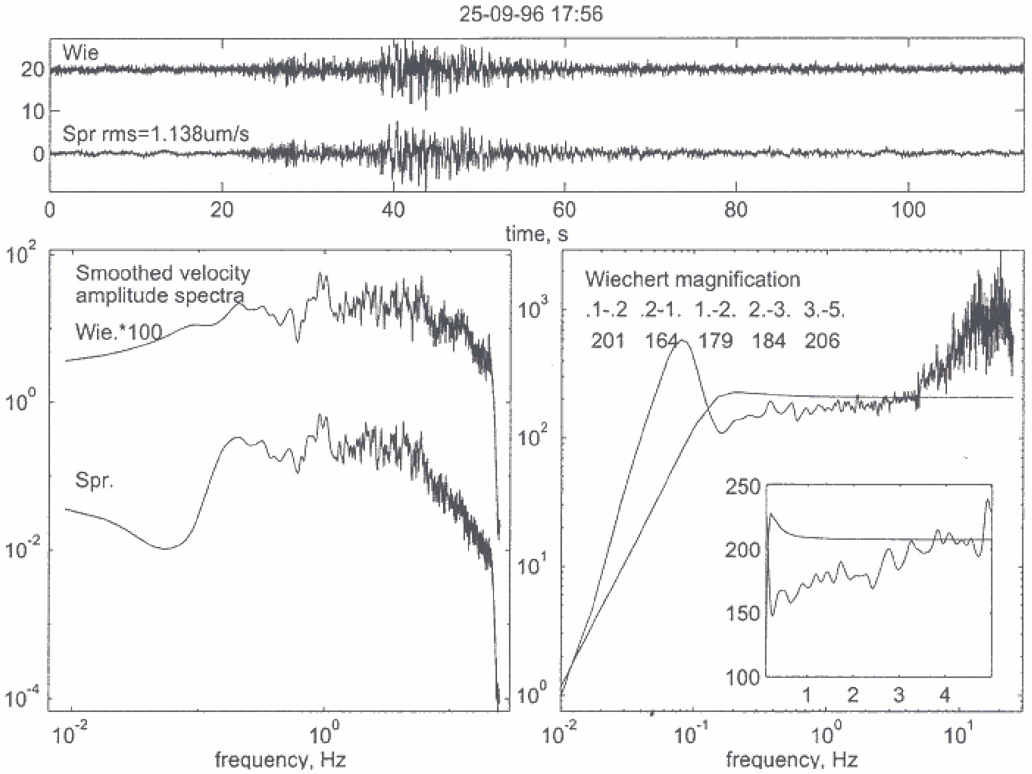

15-09-96 08:25
Wie
Spr rms=1.754um/s
30
20
10
0
-10
0 10 20 30 40 50 60 70 80 90 100
time, s
Smoothed velocity amplitude spectra
Wie.*100
Spr.
10^2
10^0
10^{-2}
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
234 176 180 175 187
10^3
10^2
10^1
10^0
10^{-2} 10^{-1} 10^0 10^1
250
200
150
100
1 2 3 4
frequency, Hz

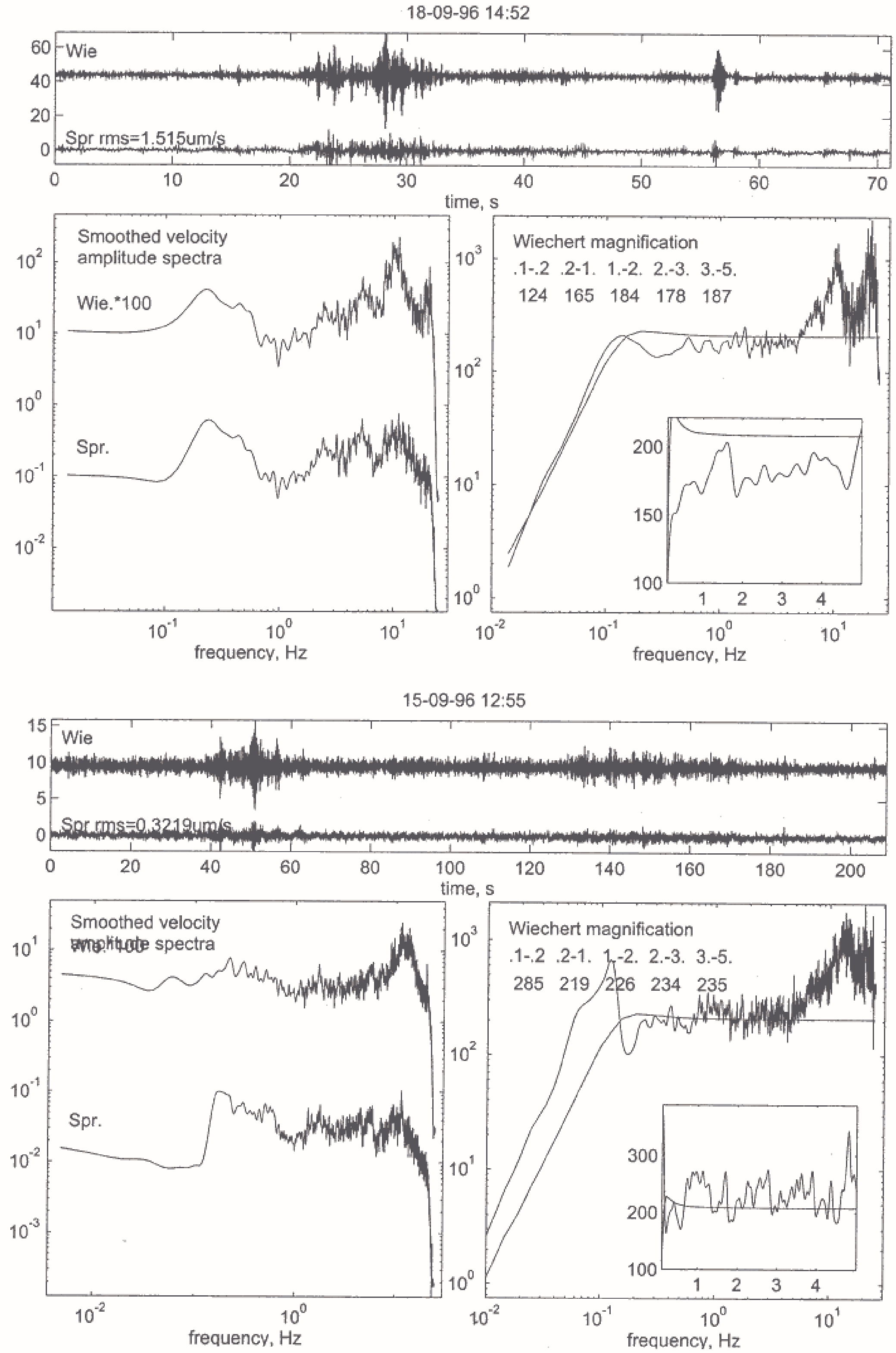

16-09-96 02:43
Wie
Spr rms=4.108um/s
60
40
20
0
0 20 40 60 80 100 120 140 160 180 200
time, s
Smoothed velocity amplitude spectra
Wie.*100
Spr.
10^2
10^0
10^{-2}
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
129 163 163 171 187
10^3
10^2
10^1
10^0
10^{-2} 10^{-1} 10^0 10^1
250
200
150
100
1 2 3 4
frequency, Hz


21-09-96 01:35
Wie
Spr rms=3.102um/s
40
20
0
0
50
100
150
200
time, s
Smoothed velocity amplitude spectra
Wie.*100
Spr.
10^2
10^0
10^{-2}
10^{-2}
10^0
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
154 164 169 175 188
10^3
10^2
10^1
10^0
10^{-2}
10^{-1}
10^0
10^1
frequency, Hz
200
150
100
1 2 3 4

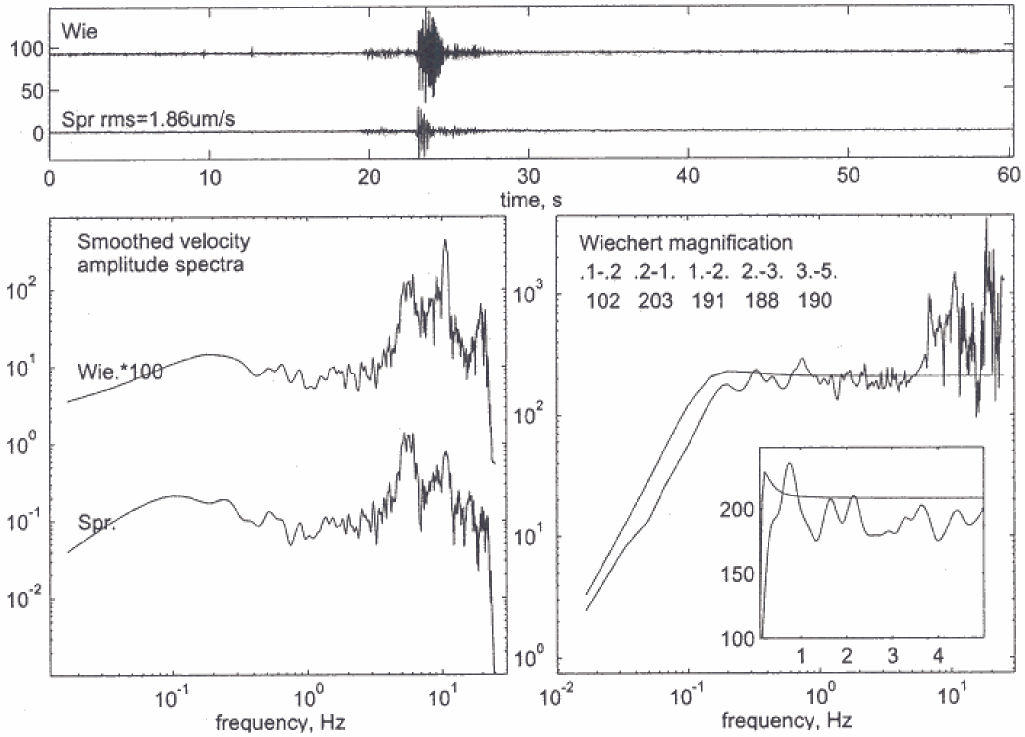

21-09-96 22:28
Wie
Spr rms=1.231um/s
15
10
5
0
-5
0
20
40
60
80
100
120
140
160
time, s
Smoothed velocity amplitude spectra
Wie.*100
Spr.
10^2
10^0
10^{-2}
10^{-2}
10^0
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
94 163 174 176 205
10^3
10^2
10^1
10^0
10^{-2}
10^{-1}
10^0
10^1
frequency, Hz
250
200
150
100
1 2 3 4


24-09-96 02:45
Wie
Spr rms=1.464um/s
20
10
0
0 20 40 60 80 100 120
time, s
Smoothed velocity
amplitude spectra
Wie.*100
Spr.
10^2
10^0
10^-2
10^-2 10^0
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
155 158 166 181 193
10^3
10^2
10^1
10^0
250
200
150
100
1 2 3 4
10^-2 10^-1 10^0 10^1
frequency, Hz

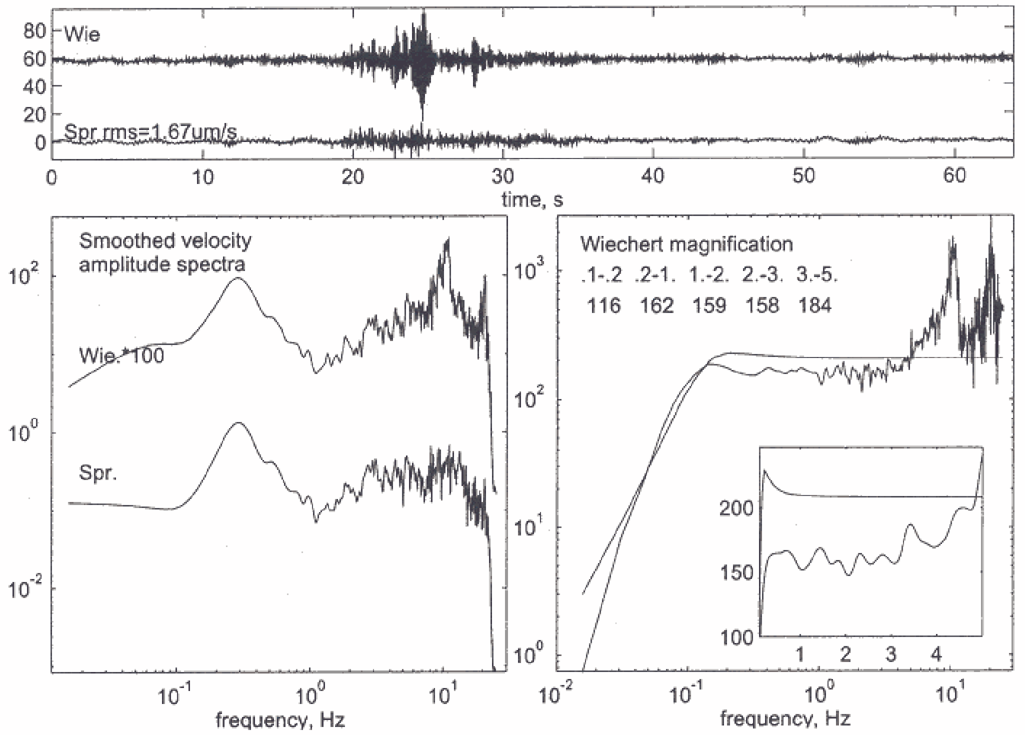

25-09-96 17:56
Wie
Spr rms=1.138um/s
20
10
0
0 20 40 60 80 100
time, s
Smoothed velocity
amplitude spectra
Wie.*100
Spr.
10^2
10^0
10^-2
10^-4
10^-2 10^0
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
201 164 179 184 206
10^3
10^2
10^1
10^0
250
200
150
100
1 2 3 4
10^-2 10^-1 10^0 10^1
frequency, Hz

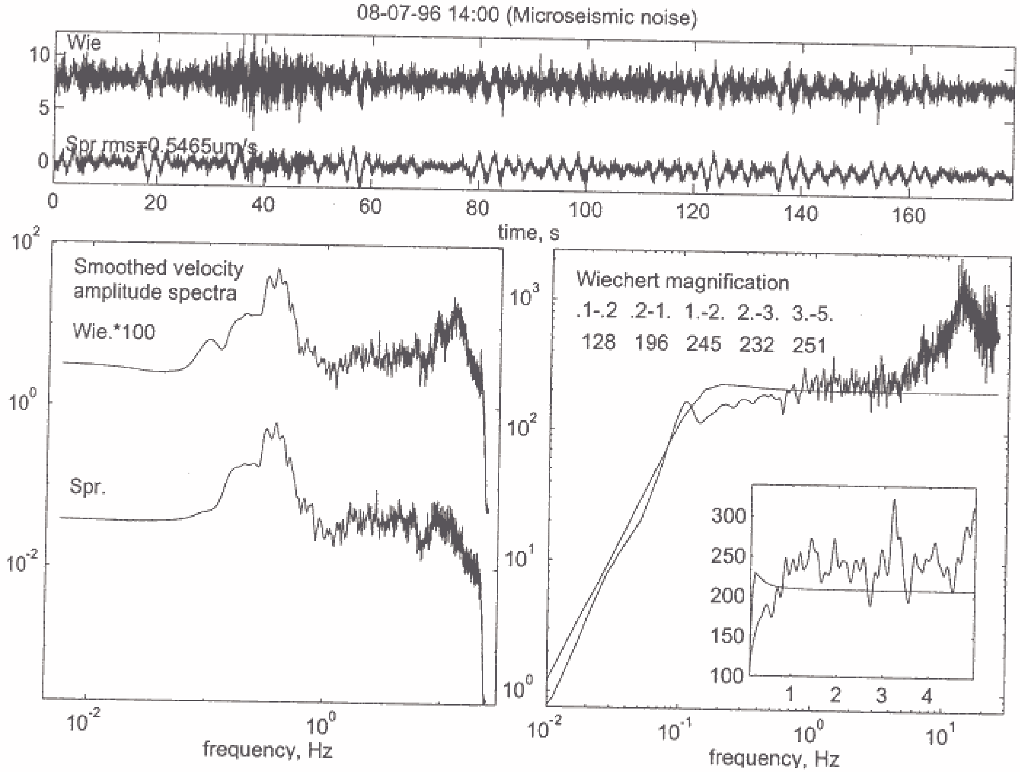

18-09-96 14:52
Wie
Spr rms=1.515um/s
time, s
Smoothed velocity amplitude spectra
Wie.*100
Spr.
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
124 165 184 178 187
frequency, Hz
15-09-96 12:55
Wie
Spr rms=0.3219um/s
time, s
Smoothed velocity amplitude spectra
Wie.*100
Spr.
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
285 219 226 234 235
frequency, Hz

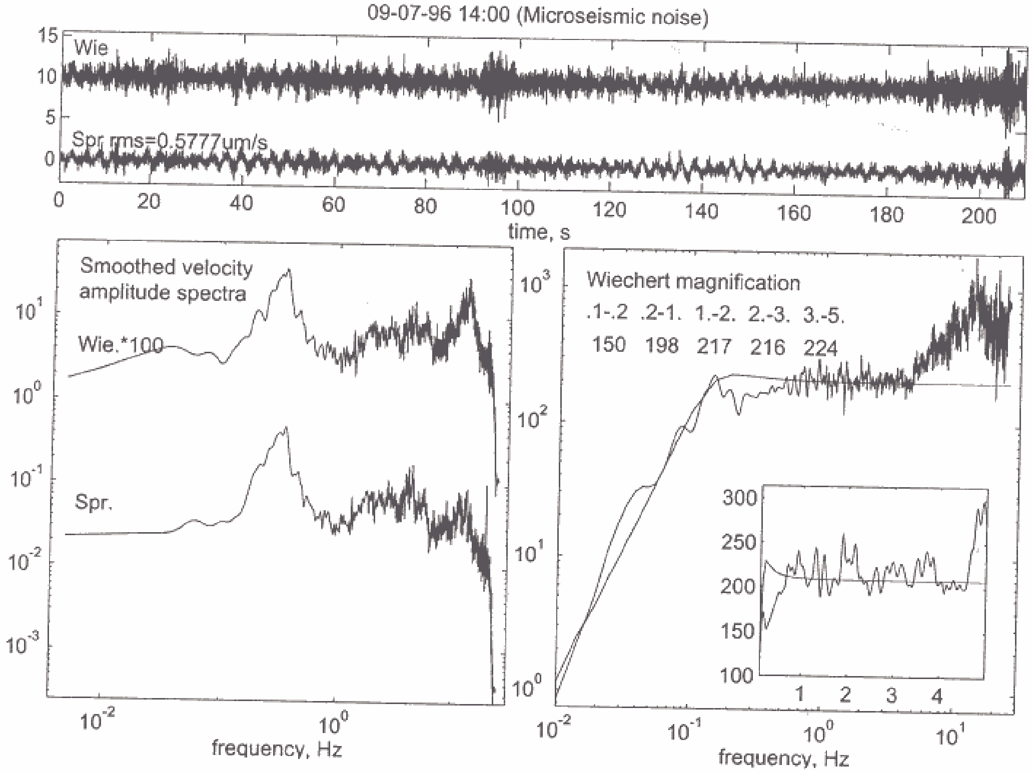
15-09-96 14:14 (Thunder)

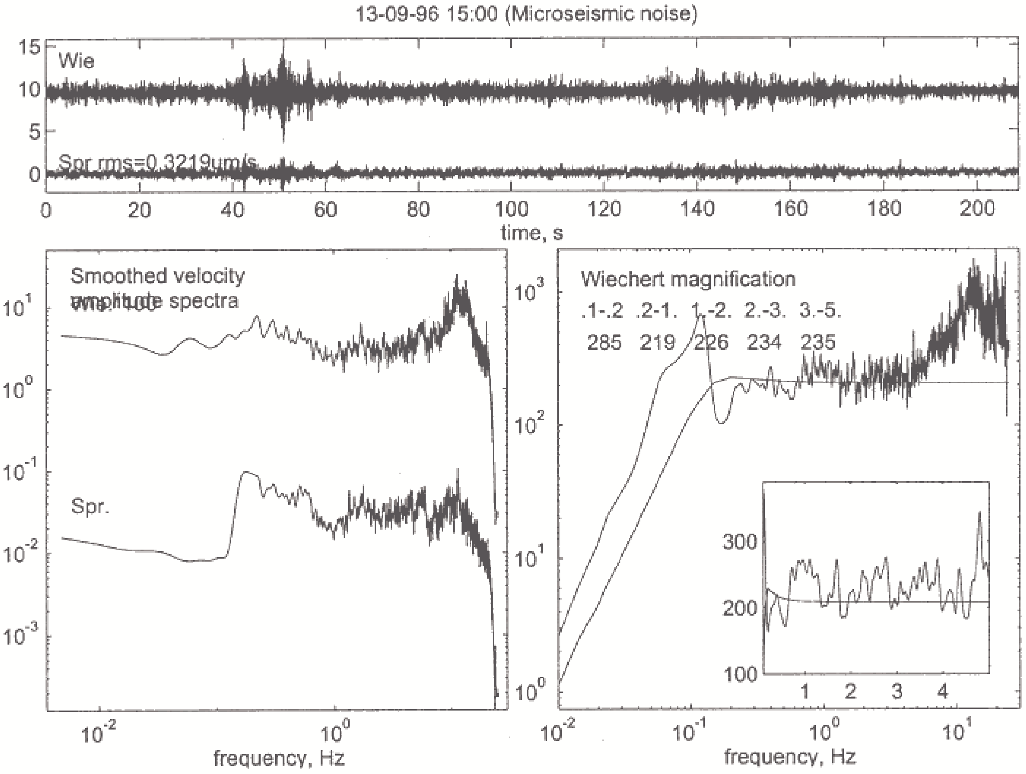


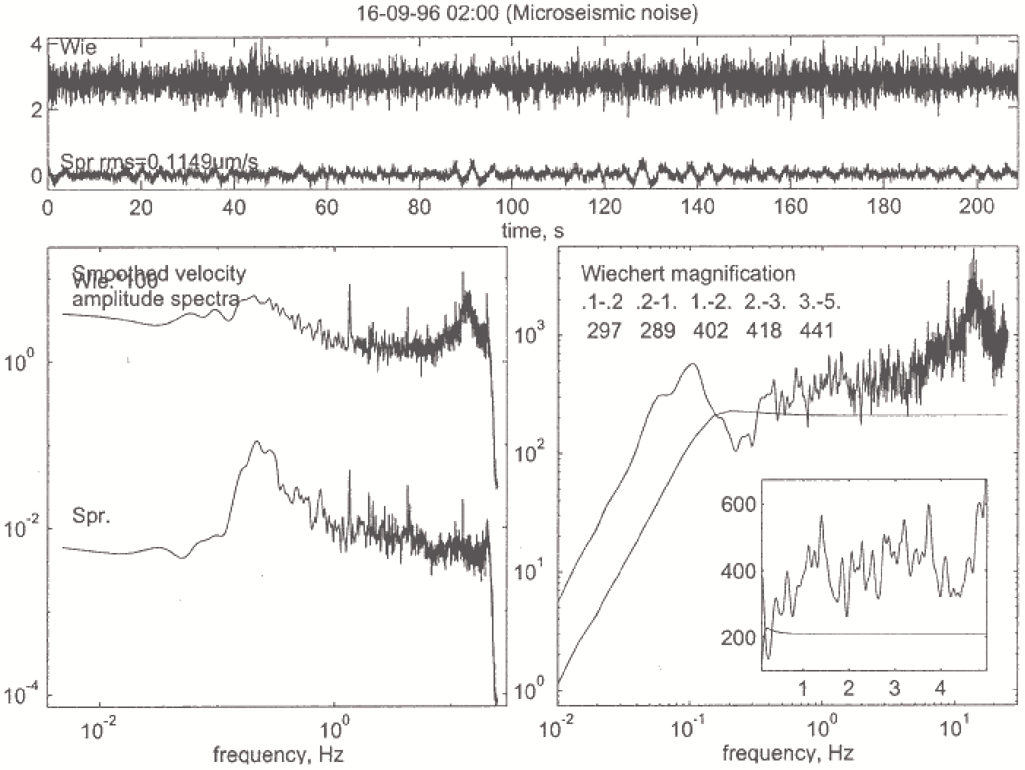
19-09-96 09:19




08-07-96 14:00 (Microseismic noise)
Wie
Spr rms=0.5465um/s
time, s
Smoothed velocity amplitude spectra
Wie.*100
Spr.
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
128 196 245 232 251
frequency, Hz


09-07-96 14:00 (Microseismic noise)
Wie
Spr rms=0.5777um/s
time, s
Smoothed velocity amplitude spectra
Wie.*100
Spr.
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
150 198 217 216 224
frequency, Hz


13-09-96 15:00 (Microseismic noise)
Wie
Spr rms=0.3219um/s
15
10
5
0
0 20 40 60 80 100 120 140 160 180 200
time, s
Smoothed velocity
amplitude spectra
Wie. 100
Spr.
10^1 10^0 10^-1 10^-2 10^-3
10^-2 10^0
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
285 219 226 234 235
10^3 10^2 10^1 10^0
10^-2 10^-1 10^0 10^1
frequency, Hz
300
200
100
1 2 3 4


16-09-96 02:00 (Microseismic noise)
Wie
Spr rms=0.1149um/s
4
2
0
0 20 40 60 80 100 120 140 160 180 200
time, s
Smoothed velocity
amplitude spectra
Wie. 100
Spr.
10^0 10^-2 10^-4
10^-2 10^0
frequency, Hz
Wiechert magnification
.1-.2 .2-1. 1.-2. 2.-3. 3.-5.
297 289 402 418 441
10^3 10^2 10^1 10^0
10^-2 10^-1 10^0 10^1
frequency, Hz
600
400
200
1 2 3 4