KOD Digital Seismograph System

The KOD digital seismograph system consists of a three-component set of long-period SKD seismometers (T_0=30 sec) and a three-component set of short-period SKM-3 seismometers (T_0=3.5 sec), galvanometer phototube amplifier, three-channel KOD-I amplifier system, analog-to-digital converter and a tape recorder (Shishkevish, 1975). The KOD system, which was operating at several locations in the former Soviet Union since 1966, is important as one of the few digital systems anywhere in the world in the late 1960s and early 1970s. The KOD-I amplifier system consists of a postamplifer, a low-pass RC (resistor-capacitor) filter with a drop of 40 dB at 50 Hz, and a RC notch filter with notch frequency around 0.145 Hz ($\sim$ 6.9 s period) with an attenuation rate of 32 dB/octave and a drop of 40 dB at the notch (Shishkevish, 1975). The KOD-I has two outputs per channel with a gain of 10 and 100. However, excluding the sawtooth control voltage, only four data channels can be recorded on magnetic tapes, with the usual combination being three-component high gain and a vertical-component low-gain, or vice versa.

Seismic signals from the KOD-I amplifier system are sampled sequentially by an analog-to-digital (A/D) converter at a rate of 33 samples per second. The A/D converter is a 10-channel (only 5 are used), 11-bit unit with a dynamic range of $\pm$5 V (volts) and hence, the least significant bit represents $\pm$4.88 mV/count (= $\pm$ 5 V /$\pm$ 1024 counts). The five data channels are recorded in parallel in 11-bit code on 17-track 35-mm magnetic tape of a LMR type recorder. The 12th bit on the tape is a parity check.

The absolute time in 12-bit time code is recorded at every 30 s intervals, resulting in the loss of a data point from each of the five channels every 1,000 conversions. A quartz clock synchronized by radio wave signal once every 12 hours maintains an overall accuracy of 0.1 s per day (Osadchiy & Daragan, 1966).

The KOD seismograph system at Borovoye had only three-component, short-period seismometers – SKM-3, which had natural period, T_0 = 3.5 s and damping constant, D_s = 0.7 (Adushkin & An, 1990). The KOD system at Borovoye operated from 1966 to Nov. 1973 and had nominal gains of 3,000 counts/μm and 300 counts/μm for high- and low-gain channels, respectively (Adushkin & An, 1990). It is noted that the KOD system at Borovoye had polarity reversal on all channels. Four data channels and a sawtooth control voltage channel are recorded with the usual combination being three-component high-gain and a vertical-component low-gain (called KODB) and three-component low-gain and a vertical-component high-gain system (KODM) (Osadchiy & Daragan, 1966). The de-glitched Borovoye waveform archive includes records from KODB (high-gain channels) and KODM (low-gain channels) systems during 1967–1973.

KODB: 3-Component High-Gain and a Low-Gain Vertical-Component System

This is the main data stream for 3-component, short-period signals from SKM-3 seismometers with a vertical-component low-gain recording. Signals are recorded on channels 1, 3 and 4, for high-gain vertical-, NS-, and EW-component, respectively. Although, we do not know the exact instrument response and gains of the KOD system, the Borovoye waveform data archive included instrument responses in discrete frequencies as in the fap (frequency, amplitude and period) files (see Kim et al., 2001). Figure 6 shows all 78 fap files available for the KODB system. These fap files are not associated with any events or specific time periods. 44 fap files do not cover notch filter bands and cover insufficient frequency band, and we selected 34 fap files that cover complete frequency bands between 0.05 and 10 Hz. The selected fap response files are plotted in Figure 7 and are used to determine the nominal response of each channel. Figures 8, 9 and 10 show nine selected frequency-amplitude calibration curves for these channels and the average value at each frequency with its standard deviation. Figure 11 shows seven frequency-amplitude calibration curves for low-gain vertical-component channel and the average value at each frequency with its standard deviation.

These channels had the listed nominal gains of 3,000 counts/μm and 300 counts/μm for high- and low-gain channels, respectively and recorded with sampling interval of 30 msec during their operation (Adushkin & An, 1990). The gains of each channel are obtained by averaging values from these calibration curves and the peak amplitude at 1.8 Hz are listed in Table 8 as the gains.

KODM: 3-Component Low-Gain and a High-Gain Vertical-Component System

This is an additional data stream for 3-component, short-period signals from SKM-3 seismometers on low-gain with a vertical-component high-gain recording. Signals are recorded on channels 1, 3 and 4, for low-gain vertical-, NS-, and EW-component, respectively.

Figure 13 shows all 64 fap files available for the KODM system. These fap files are not associated with any events or specific time periods. 32 fap files do not cover notch filter bands and cover insufficient frequency band, and we selected 32 fap files that cover complete frequency bands between 0.05 and 10 Hz. The selected fap response files are plotted in Figure 14 and are used to determine the nominal response of each channel.

Figure 15 shows averaged frequency-amplitude calibration curves for low-gain vertical-component (SLZ), NS-component (SLN), and EW-component (SLE) as well as a high-gain vertical-component channel. Seven to nine calibration curves were available for each channel and the averaged values at each frequency are plotted with their standard deviation. The gains of each channel are obtained by averaging values from seven to nine calibration curves and the peak amplitude at 1.8 Hz are listed in Table 8.

Table 8: Instrument Characteristics and Gains of the KOD System at Borovoye$^{(*)}$

System	Seismometer	T_0 (s)	D_s	Channel name	Gain (counts/μm)	fn$^{(1)}$ (Hz)	Chan no.	Time period
KODB	SKM-3	3.5	0.7	SHZ	3,385.7 ± 277.0	1.8	1	67-02-26
				SHN	2,939.8 ± 342.8	1.8	3	–73-10-26
				SHE	3,353.6 ± 233.8	1.8	4	
				SLZb	423.4 ± 35.9	1.8	2	
KODM	SKM-3	3.5	0.7	SLZ	421.3 ± 33.8	1.8	1	67-06-29
				SLN	321.4 ± 31.3	1.8	3	–73-10-26
				SLE	371.1 ± 30.7	1.8	4	
				SHZm	3,385.7 ± 277.0	1.8	2	

(1) fn = Normalization frequency where gain (=sensitivity) is measured.

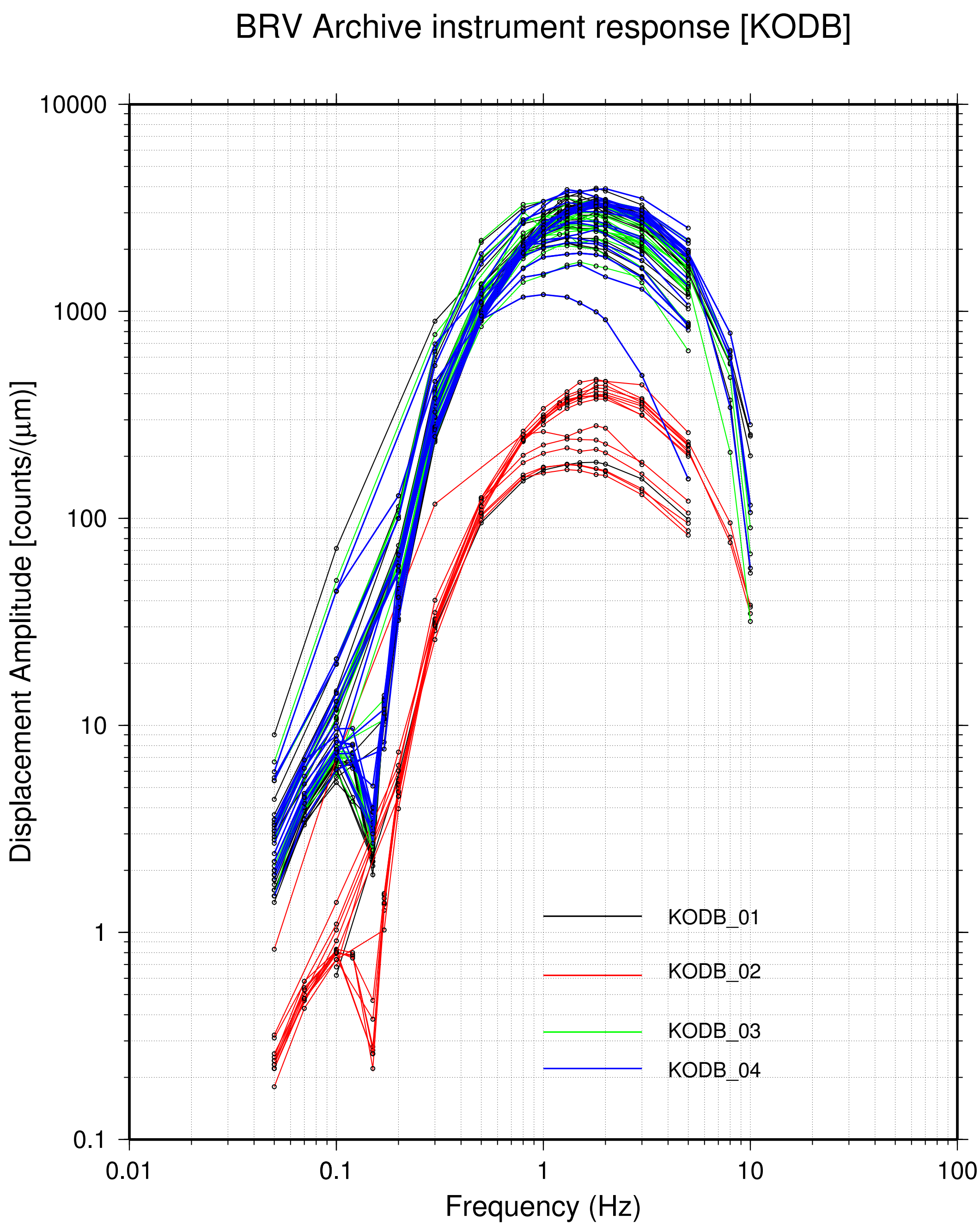

Figure 6: 78 frequency-amplitude calibration curves of the KODB system during 1967–1973.

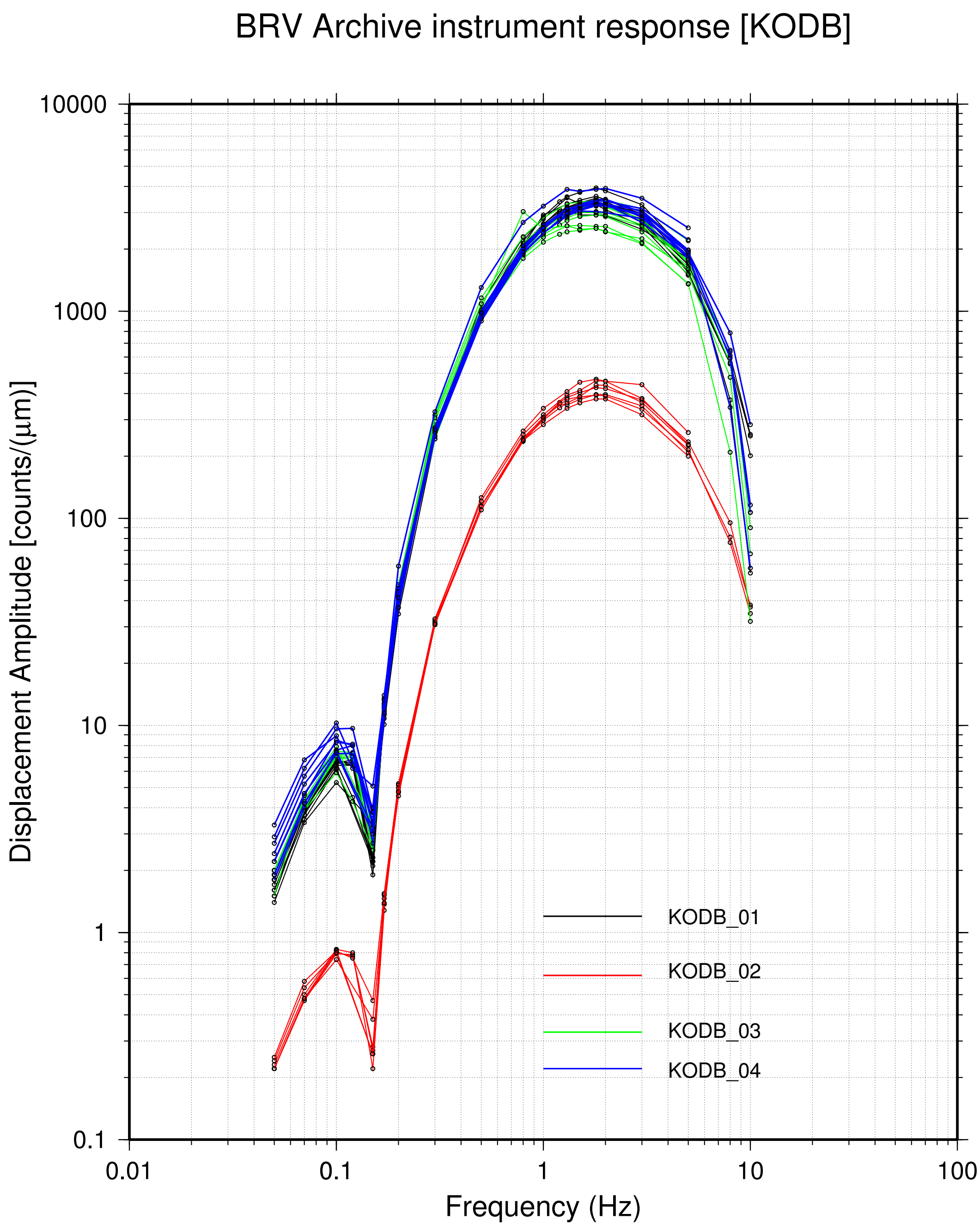

Figure 7: 34 selected frequency-amplitude calibration curves of the KODB system during 1967–1973.

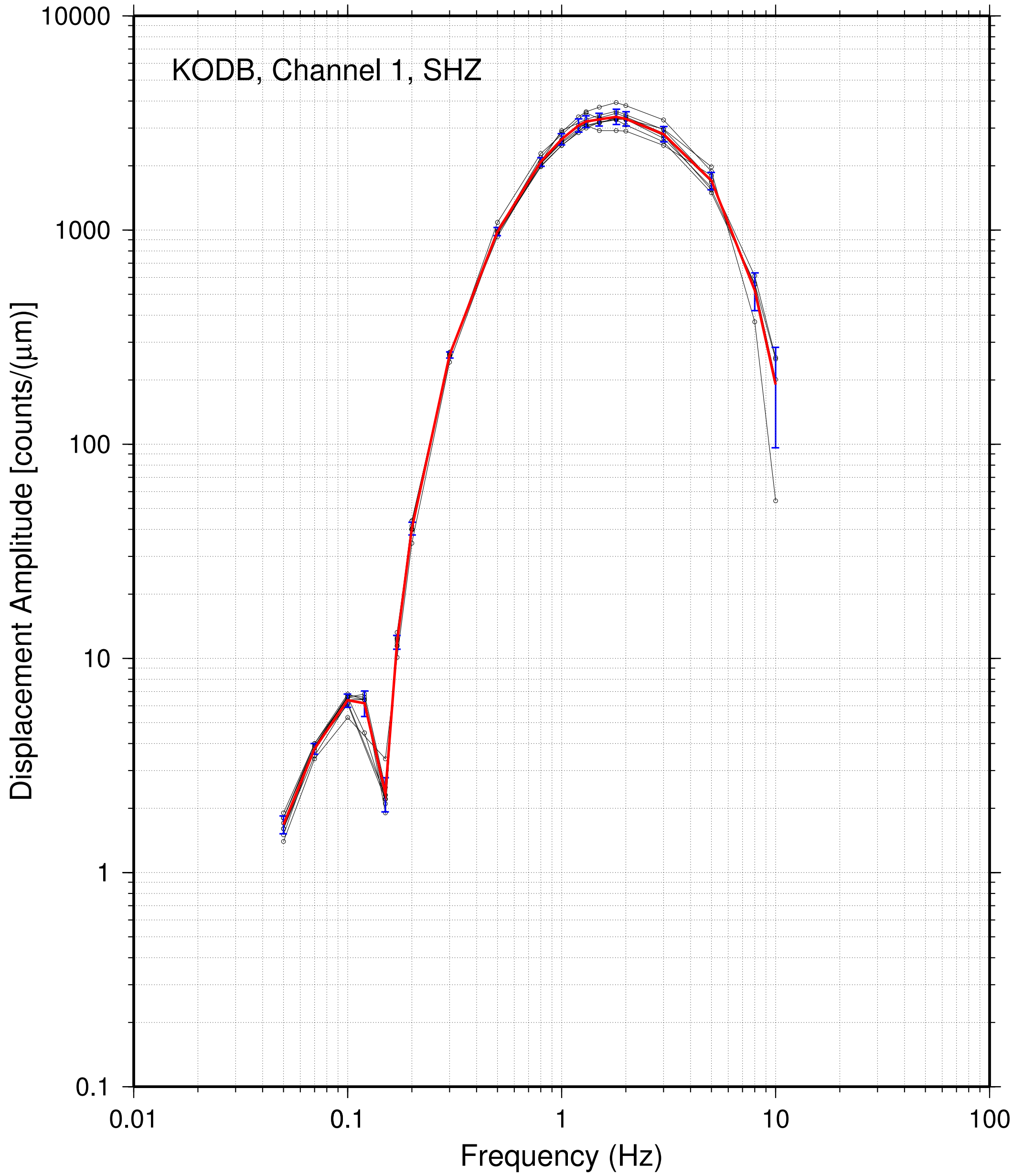

Figure 8: Frequency-amplitude calibration curves of short-period, vertical-component (channel #1, SHZ) of KODB system during 1967–1973. The averaged values at each frequency are plotted with their standard deviations.

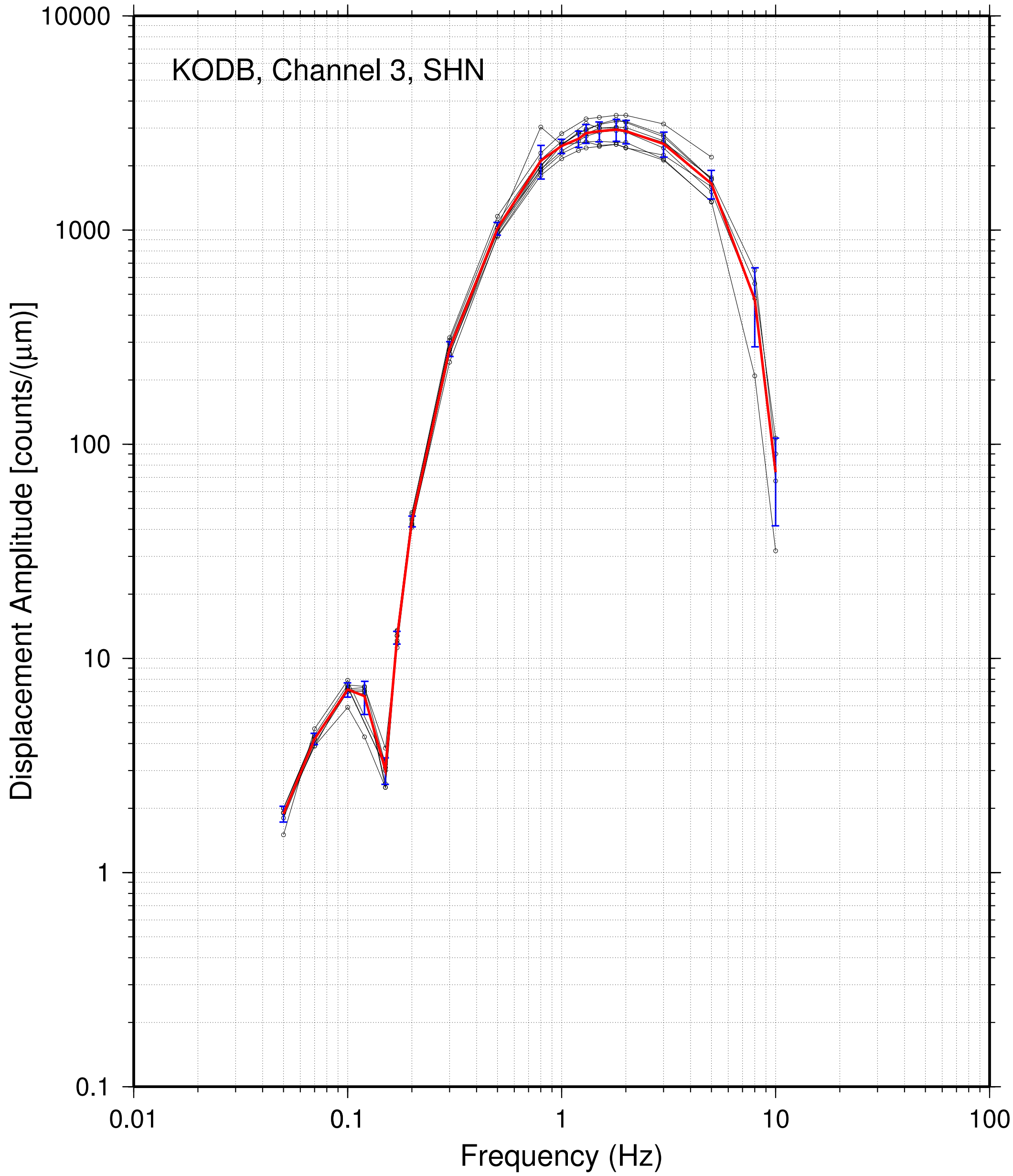

Figure 9: Frequency-amplitude calibration curves of short-period, NS-component (channel #3, SHN) of KODB system during 1967–1973. The averaged values at each frequency are plotted with their standard deviations.

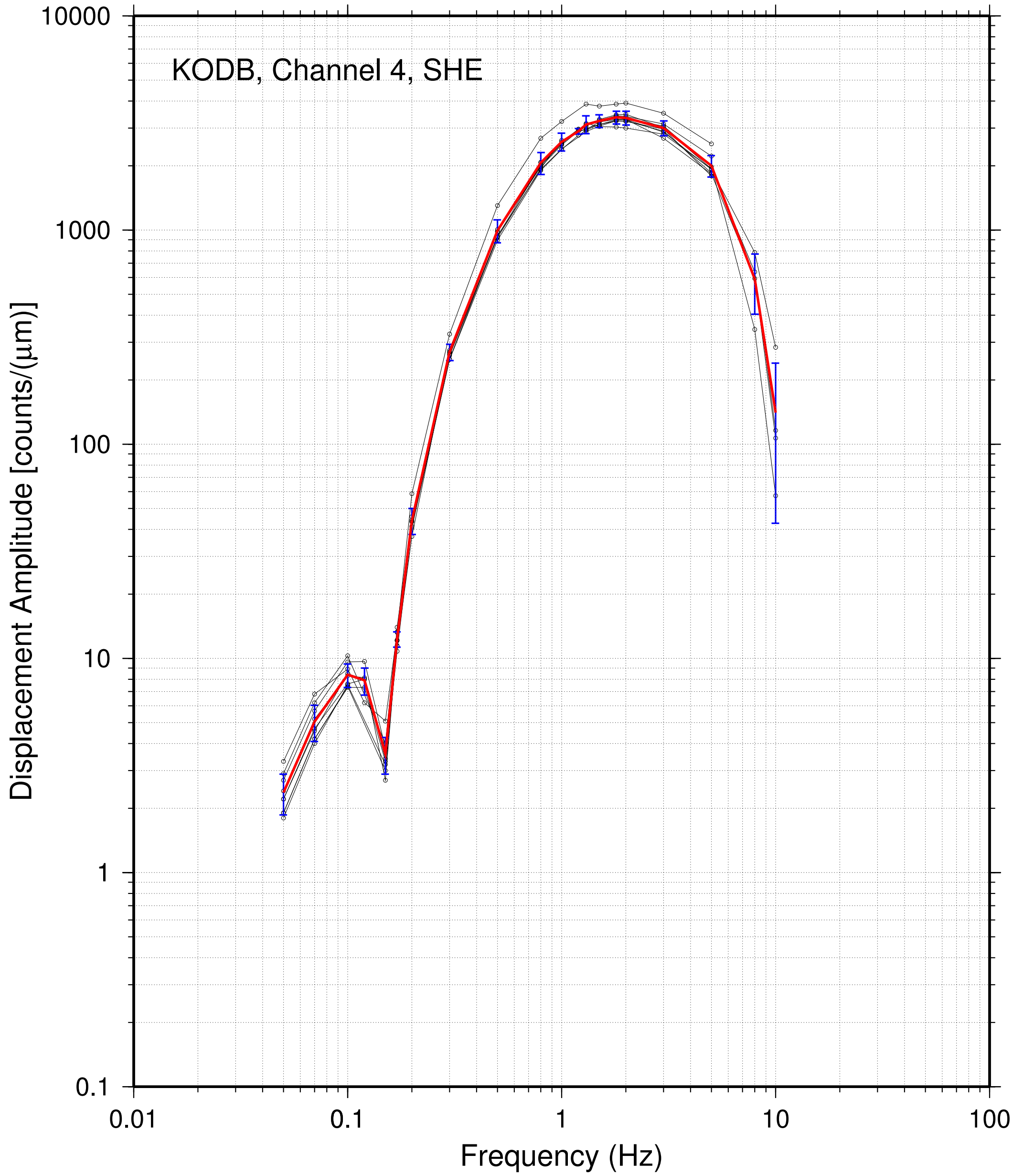

Figure 10: Frequency-amplitude calibration curves of short-period, EW-component (channel #4, SHE) of KODB system during 1967–1973. The averaged values at each frequency are plotted with their standard deviations.

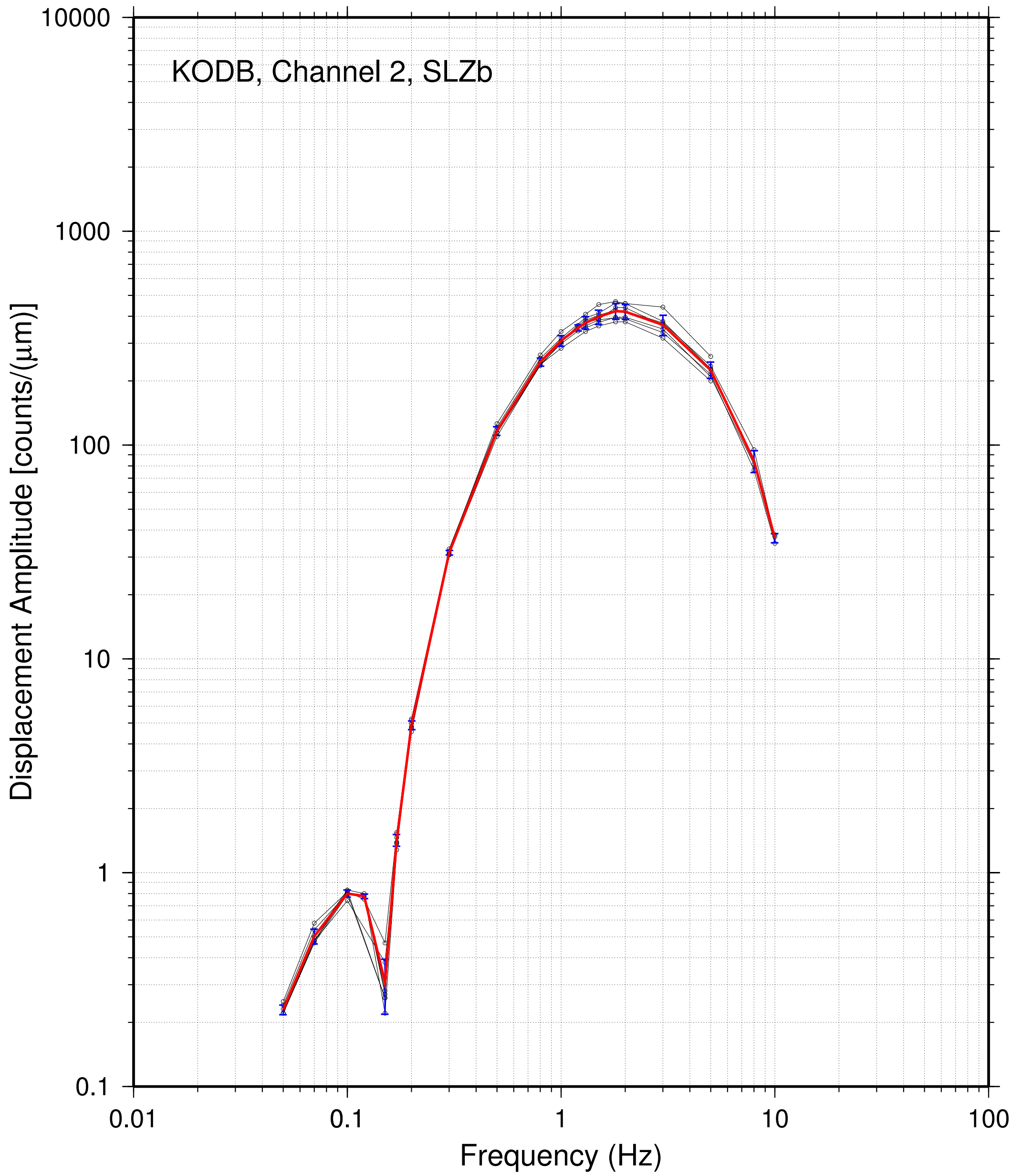

Figure 11: Frequency-amplitude calibration curves of short-period, low-gain vertical-component (channel #2, SLZb) of KODB system during 1967–1973. The averaged values at each frequency are plotted with their standard deviations.

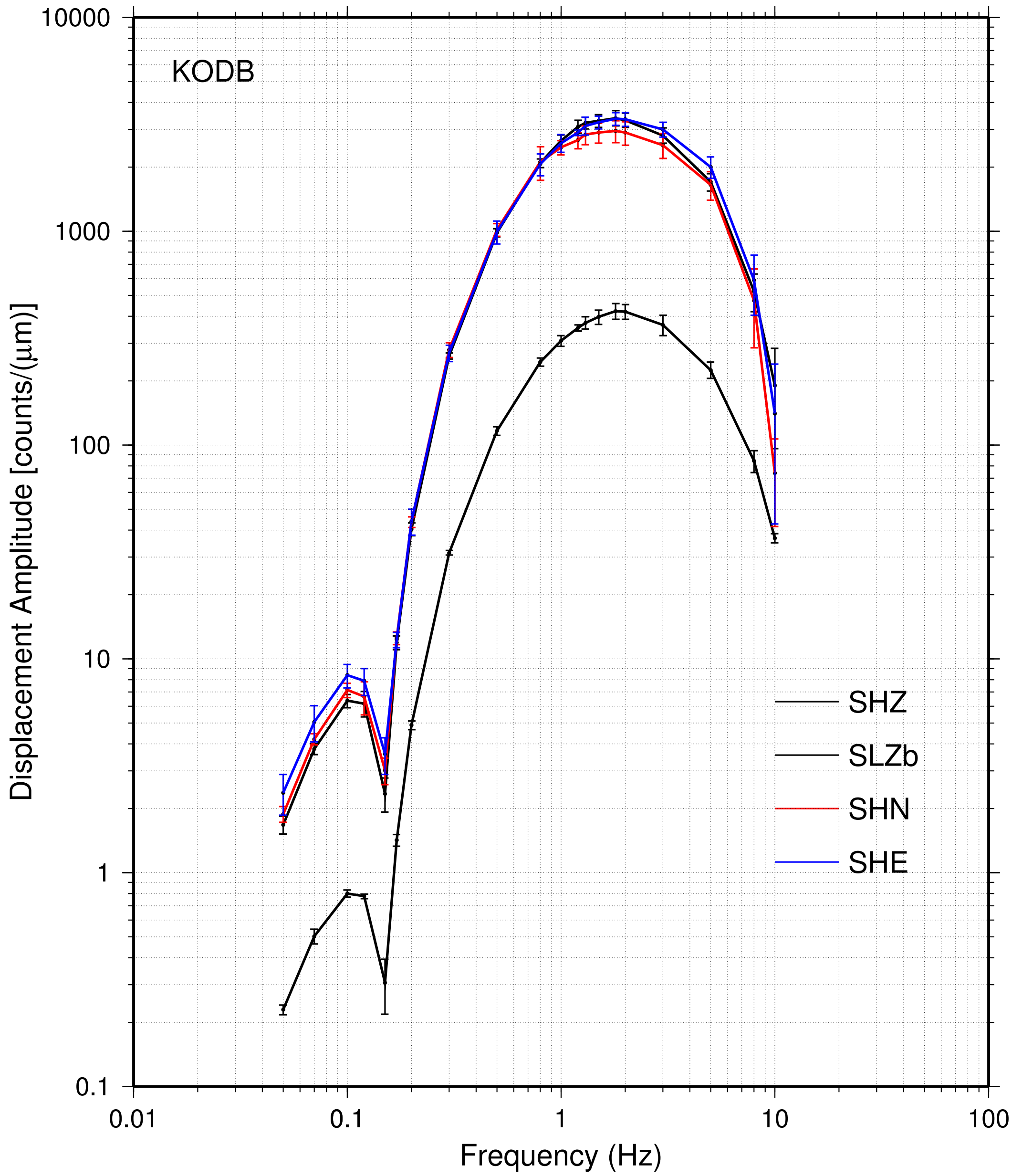

Figure 12: Averaged frequency-amplitude calibration curves of the high-gain vertical-, NS- and EW-component as well as the low-gain vertical-component channels of the KODB system are plotted.

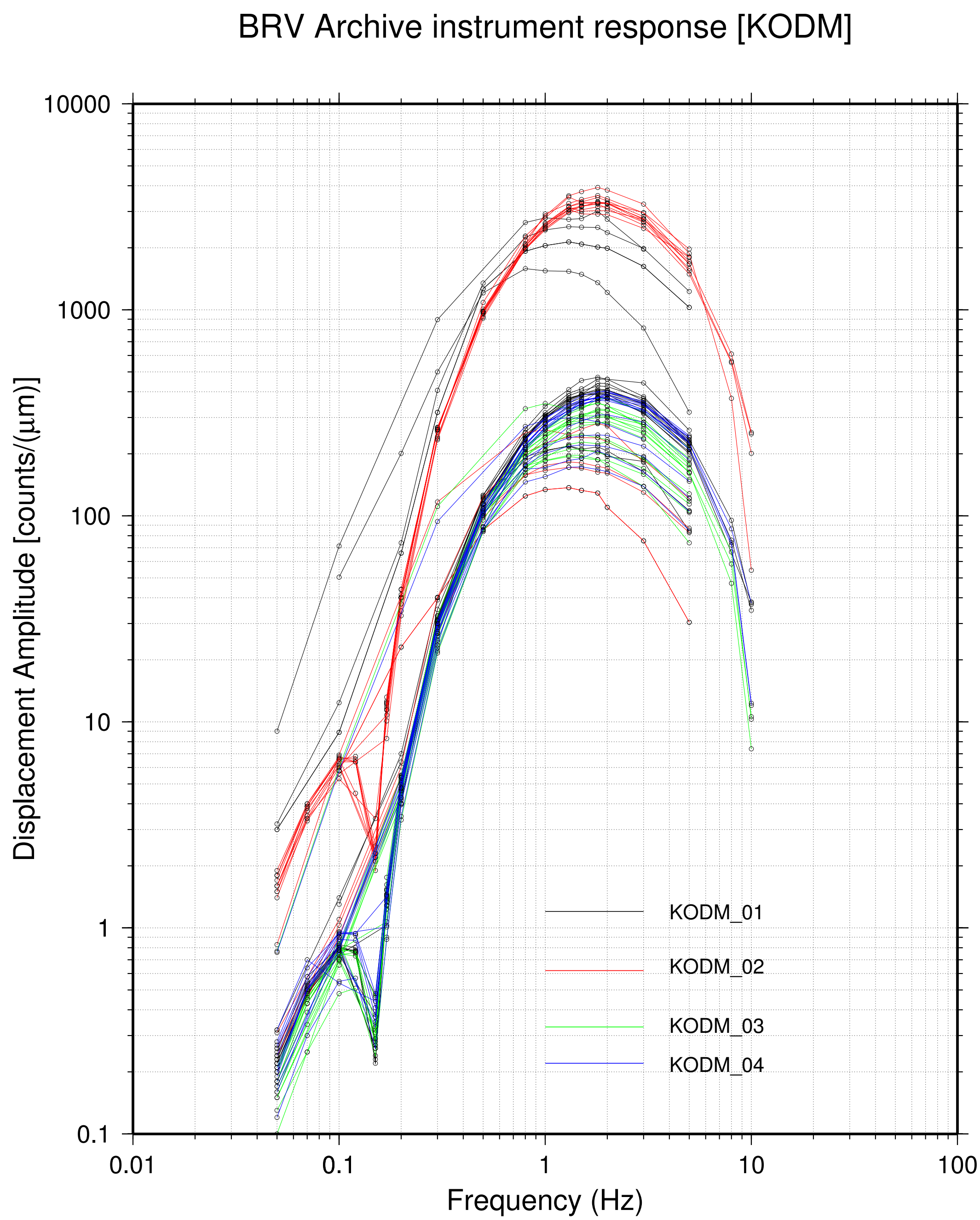

Figure 13: 64 frequency-amplitude calibration curves of the KODM system during 1967–1973.

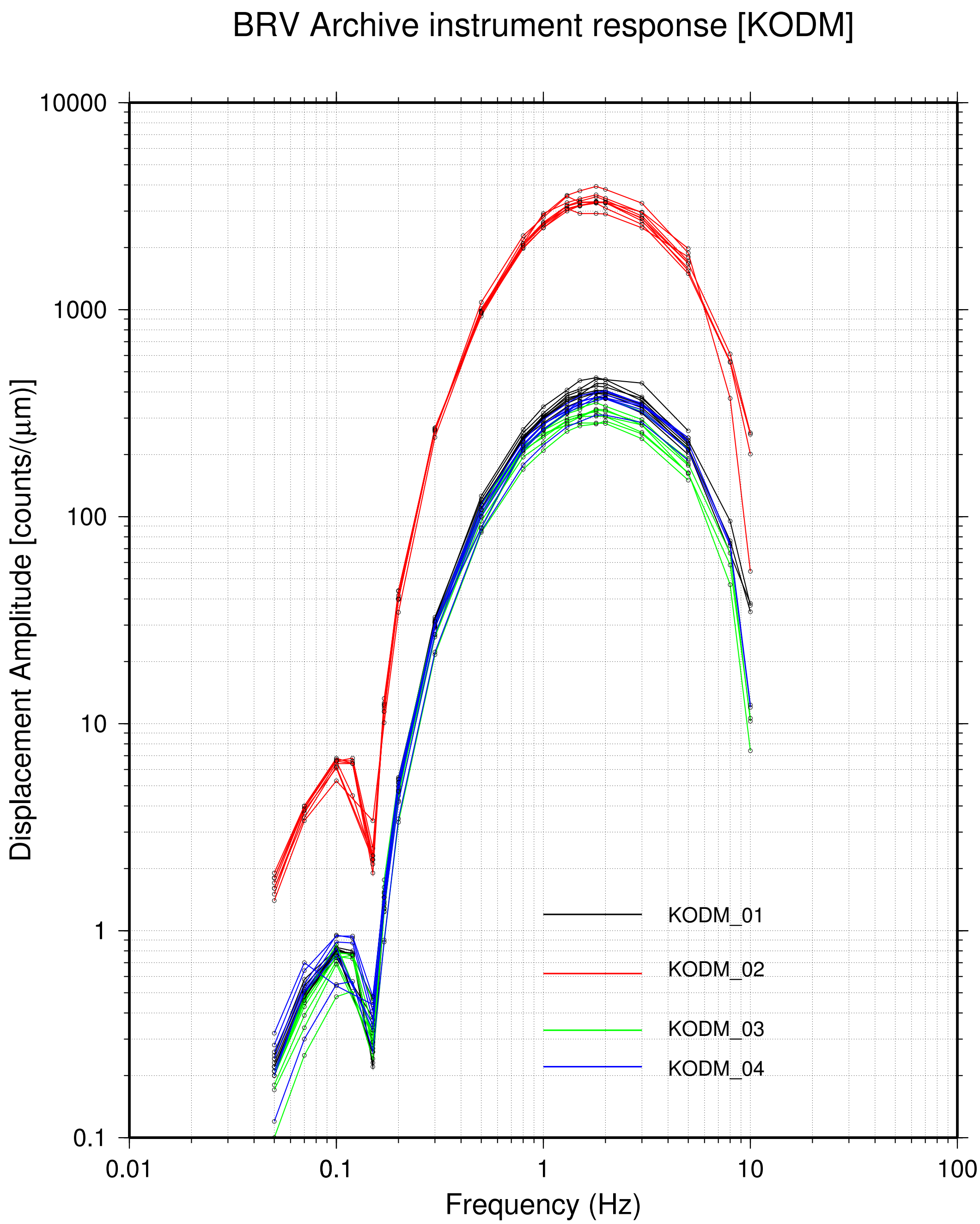

Figure 14: 32 selected frequency-amplitude calibration curves of the KODM system during 1967–1973.

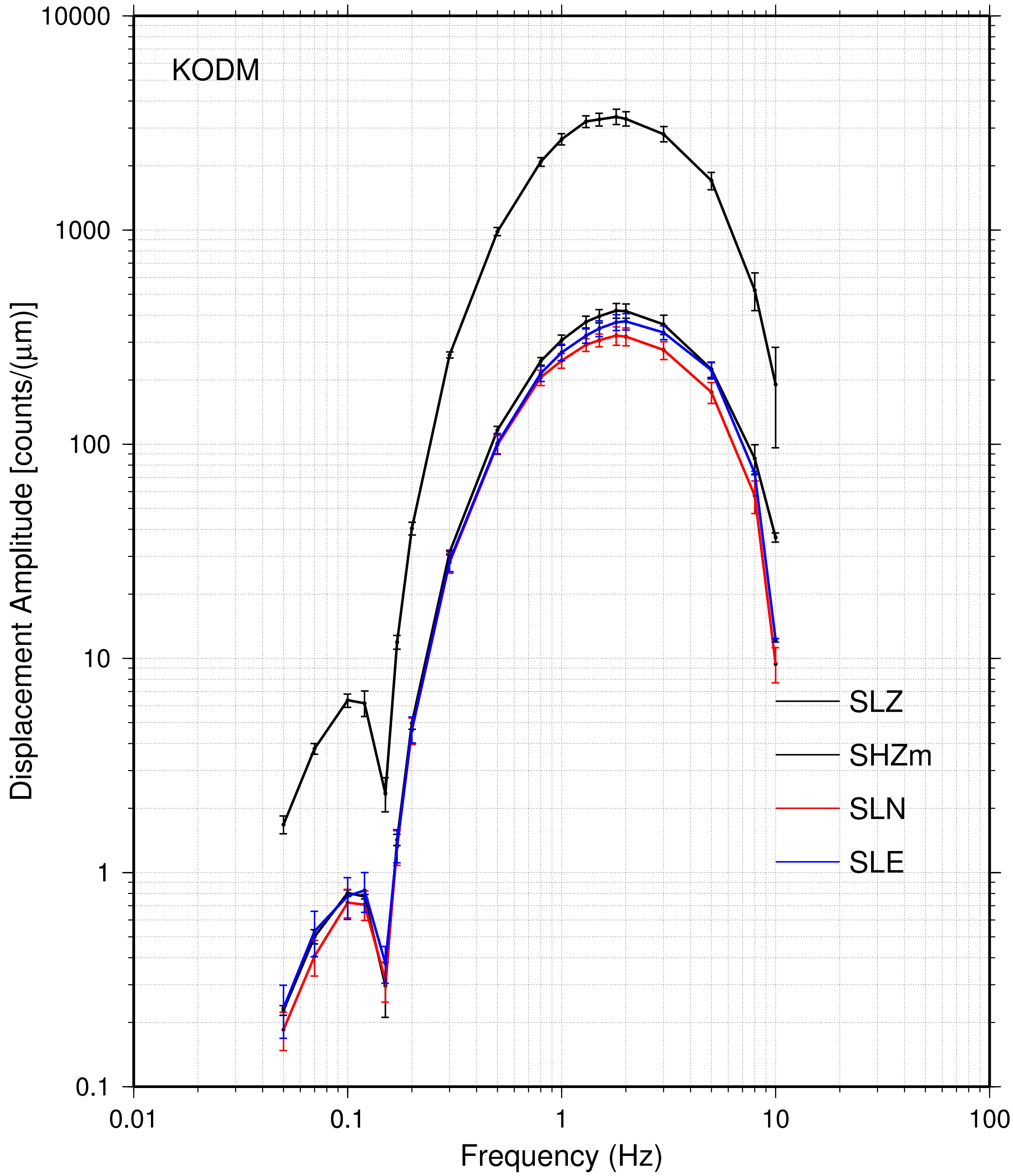

Figure 15: Averaged frequency-amplitude calibration curves of low-gain vertical-, NS- and EW-component as well as the high-gain vertical-component channels of the KODM system are plotted.

Instrument Response of KOD System

The KODB (high-gain channels) and KODM (low-gain channels) systems at Borovoye consist of SKM-3 short-period seismometers, a notch filter with notch at 0.145 Hz ($\sim$ 6.9 s period), and low-pass RC filter (Shishkevish, 1975). We fit the observed frequency-amplitude calibration curves with additional component such as, a first order RC high-pass filter with cutoff at 0.06 Hz, a first order RC high-pass filter with cutoff at 0.7 Hz, 2nd order Butterworth low-pass filter with cutoff at 3.0 Hz and a 2nd order Butterworth low-pass filter with cutoff at 8 Hz. The instrument response can be represented by 10 complex poles and 6 complex zeros as listed in Table 9. A comparison between the observed frequency-amplitude calibration curve and theoretical amplitude response calculated using these poles and zeros is shown in Figure 16. This is the most used channel due to its unclipped waveform traces produced by low-gain setting of 423.3 $\pm$ 35.9 counts/μm at 1.8 Hz.

Table 9: Instrument Constants of SKM-3 high-gain, KODB and low-gain, KODM Seismographs, 1967–1973

<table>
<tr><th>Component</th><th>Z-component (SHZ)</th><th>NS-component (SHN)</th><th>EW-component (SHE)</th></tr>
<tr><td>SKM-3
Seismometer
T_0=3.5s, D_S=0.5</td><td colspan="3">two poles (-1.269395, 1.269395), (1.269395, -1.269395)
two zeros at origin (0.00, 0.00), (0.00, 0.00)</td></tr>
<tr><td>Notch filter with
notch at 0.145 Hz</td><td colspan="3">two poles (-7.172775, 0.00), (-0.115720, 0.00)
two zeros (-0.0364424, 0.910333), (-0.0364424, -0.910333)</td></tr>
<tr><td>1st order high-pass
filter cutoff 0.06 Hz</td><td colspan="3">(-0.3769910, 0.00)
a zero at origin (0.00, 0.00)</td></tr>
<tr><td>1st order high-pass
filter cutoff 0.7 Hz</td><td colspan="3">(-4.398230, 0.00)
a zero at origin (0.00, 0.00)</td></tr>
<tr><td>2nd order Butterworth
low-pass filter</td><td colspan="3">(-13.3286, 13.3286), (-13.3286, -13.3286)
cutoff frequency at 3 Hz</td></tr>
<tr><td>2nd order Butterworth
low-pass filter</td><td colspan="3">(-35.5431, 35.5431), (-35.5431, -35.5431)
cutoff frequency at 8 Hz</td></tr>
</table>

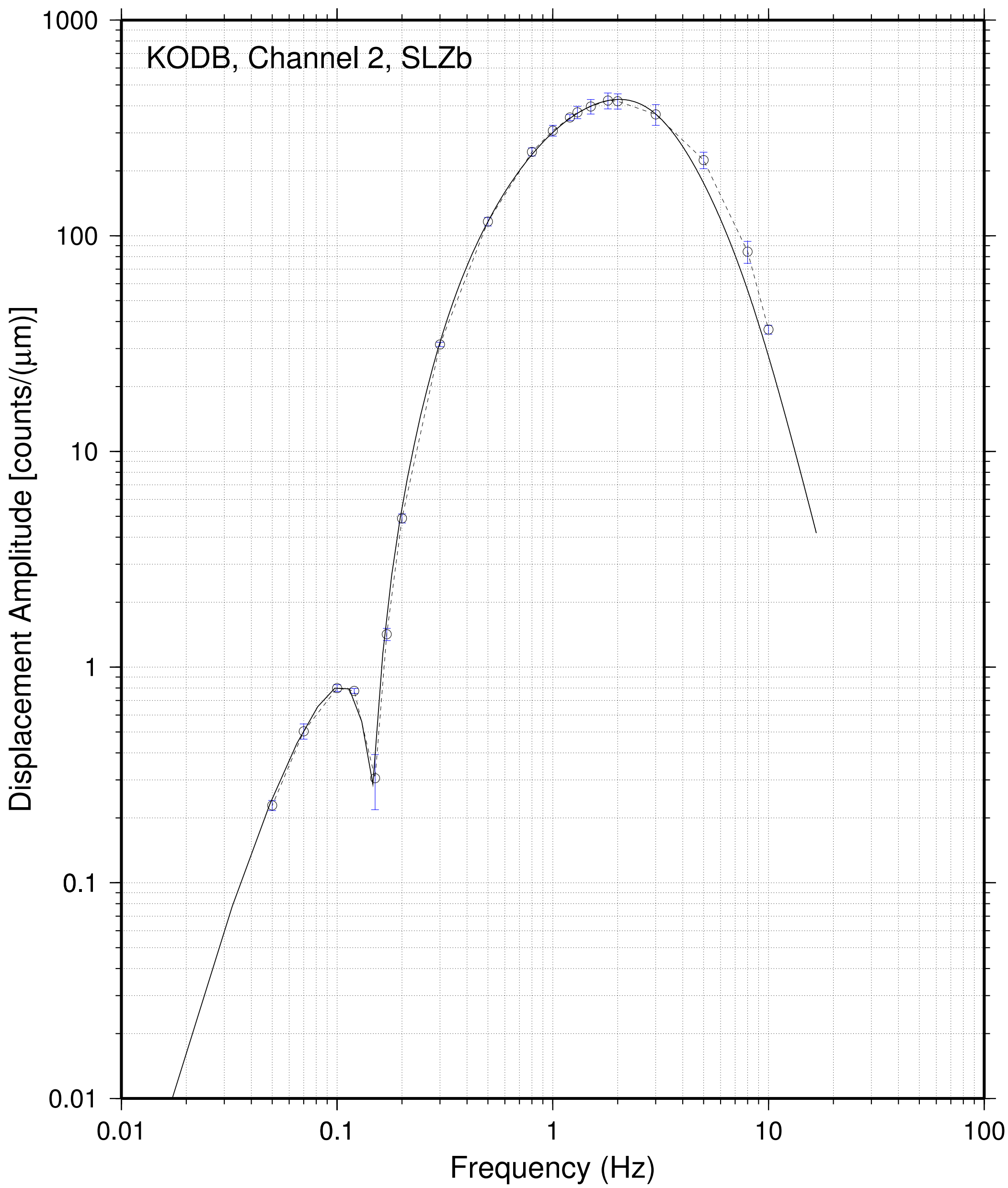

Figure 16: Frequency-amplitude calibration curve of the low-gain, short-period vertical-component channel (SLZb) during 1967–1973 is compared with the theoretical amplitude response curve obtained by using the instrument response listed in Table 9.

STsR-SS System

The STsR-SS system consists of a 3-component, short-period seismometer – SKM-3 (Kirnos high-gain) and a 3-component, extended-period seismometer – SKD (Kirnos-Arkhangel'skiy broadband) (Shishkevish, 1974). The STsR-SS system recorded a total of 10 channels on 17-track tape with 11-bit analog-to-digital conversion. Usually, the data streams consisted of signals from 3-component short-period, 3-component extended-period, and a low-gain short-period vertical-component. Shishkevish (1974) called the SKD seismometer with the natural period, T_0=25 s, as *extended-period* seismometer and we will adopt this term throughout this report. SKM-3 seismometer is the later model of SKM seismometer and has adjustable natural period, T_0, between 1.5 to 3.5 s (Shishkevish, 1974). Hence, it is also called short-to-intermediate-period high-gain seismometer. We will call it a high-gain *short-period* seismometer throughout this report.

During 1973-06-06 – 1981-06-30, 3-component short-period signals from SKM-3 seismometer were recorded on channels 7, 8 and 9 for vertical-, NS-, and EW-component, respectively. These three-component data are assigned with component names s07Z, s08N and s09E; low-gain vertical-component SKM-3 data is recorded on channel 1 (s01Z); 3-component extended-period signals from SKD seismometer are recorded on channels 2, 3, and 4 (l02Z, l03N and l04E); and channels 5, 6 and 10 were unused.

During 1981-08-14 – 1982-07-04, 3-component short-period signals from SKM-3 seismometer were recorded on channels 7, 8 and 9 for vertical-, NS-, and EW-component, respectively. The sampling interval for these channels were changed form 0.032 s to 0.024 s. The low-gain vertical-component SKM-3 data is recorded on channel 6 (s06Z) with a sampling interval of 0.096 s. 3-component extended-period signals from SKD seismometer are recorded on channels 2, 3, and 4 (l02Z, l03N and l04E); and channels 1, 5 and 10 were unused. Although the sampling intervals have changed for short-period channels (6, 7, 8, and 9), the shapes of the amplitude responses for these channels followed the previous period.

During 1982-08-23 – 1991-07-15, 3-component short-period signals from SKM-3 seismometer were recorded on channels 7, 8 and 9 (component name: s07Z, s08N and s09E); low-gain vertical-component signals from the SKM-3 seismometer were recorded on channel 6 (s06Z); 3-component extended-period signals from SKD seismometer are recorded on channels 2, 3, and 4 (l02Z, l03N and l04E); and low-gain 3-component extended-period SKD data were recorded on channels 1, 5 and 10 (l01Z, l05N and l10E); hence all of the 10 channels of the STsR-SS system were utilized during this period (see Table 19). The shapes of the amplitude responses for all channels have changed from the previous periods.

Figure 17 show 40 available frequency-amplitude calibration curves for STsR-SS system given in the Borovoye waveform data archive.

SKM-3 High-gain Short-period Seismometer

1) Channels 7, 8 and 9 (s07Z, s08N and s09E; 1973–1982-07-04)

This is the main data stream for 3-component, short-period signals from the SKM-3 seismometer in the SS system. Signals are recorded on channels 7, 8 and 9, for vertical-, NS-, and EW-component, respectively. According to Adushkin & An (1990), these channels had the nominal gains of 2,000 counts/μm and recorded with sampling interval of 24 msec during their operation. However, the waveform data and frequency-amplitude calibration curves given in the Borovoye waveform data archive indicate that there must have been at least two different instrument responses used for the 3-component short-period data from the SKM-3 seismometer. It is apparent that the sampling interval of these channels changed around August 04, 1981, and the instrument response of these channels changed around August 21, 1982.

During 1973–1981-06-30, these channels were recorded with the sampling interval of 32 msec and the gain at 2 Hz as listed in Table 10. The sampling interval of these channels changed to 24 msec around August 14, 1981, but the shapes of the amplitude responses for these channels remained the same.

Frequency-amplitude calibration curves during 1973-03-07–1982-07-04 are plotted in Figure 18.

Table 10: Gains at 2 Hz for Channels 7, 8 and 9 during 1973-1982

Time period	Z, s07Z (counts/μm)	NS, s08N (counts/μm)	EW, s09E (counts/μm)	sampling interval (msec)
1973-06-06–1973-09-27	1249	1330	1336	32
1973-10-27 07:04 (1.5 Hz)	75.3	73.4	75.4	32
1974-07-10–1979-06-28	1249	1330	1336	32
1979-07-07–1981-06-30	1489	1378	1416	32
1981-08-14 02:26	814	744	800	24
1981-09-13–1982-07-04	1301	1278	1263	24

Instrument Response: Poles and Zeros

The SKM-3 seismometer used in the STsR-SS system has natural period, T_0=2.0 s, and damping constant, D_s=0.5 (Table 19 and Adushkin & An, 1990). However, very little is known about its recording system and use of filters such as the anti-alias filters. For the STsR-SS system, we did not find any calibration pulse that can be used to determine instrument constants as shown by Kim & Ekström (1996) for STsR-TSG system. Examining the calibration curves plotted in Figure 18, we construct a preliminary instrument response consisting of a SKM-3 seismometer, a 2nd order RC (resistor capacitor) high-pass filter with cutoff frequency at 0.5 Hz, a 2nd order Bessel low-pass filter with cutoff at 3 Hz and a 2nd order Bessel low-pass filter with cutoff frequency at 8 Hz. We fit the averaged frequency-amplitude calibration curves in the frequency domain by a trial and error method. Figure 19 shows comparison of observed frequency-amplitude calibration curves with corresponding theoretical frequency-amplitude curves obtained by using the instrument constants constrained by the trial and error fit.

The instrument constants constrained for three components are listed in Table 11 for natural period and damping constant of SKM-3 seismometers as well as the gain of channels 7, 8 and 9.

Other instrument constants are: 2nd order high-pass filter with cutoff at 0.5 Hz, a 2nd order Bessel low-pass filter with cutoff at 3 Hz and a 2nd order Bessel low-pass filter with cutoff at 7

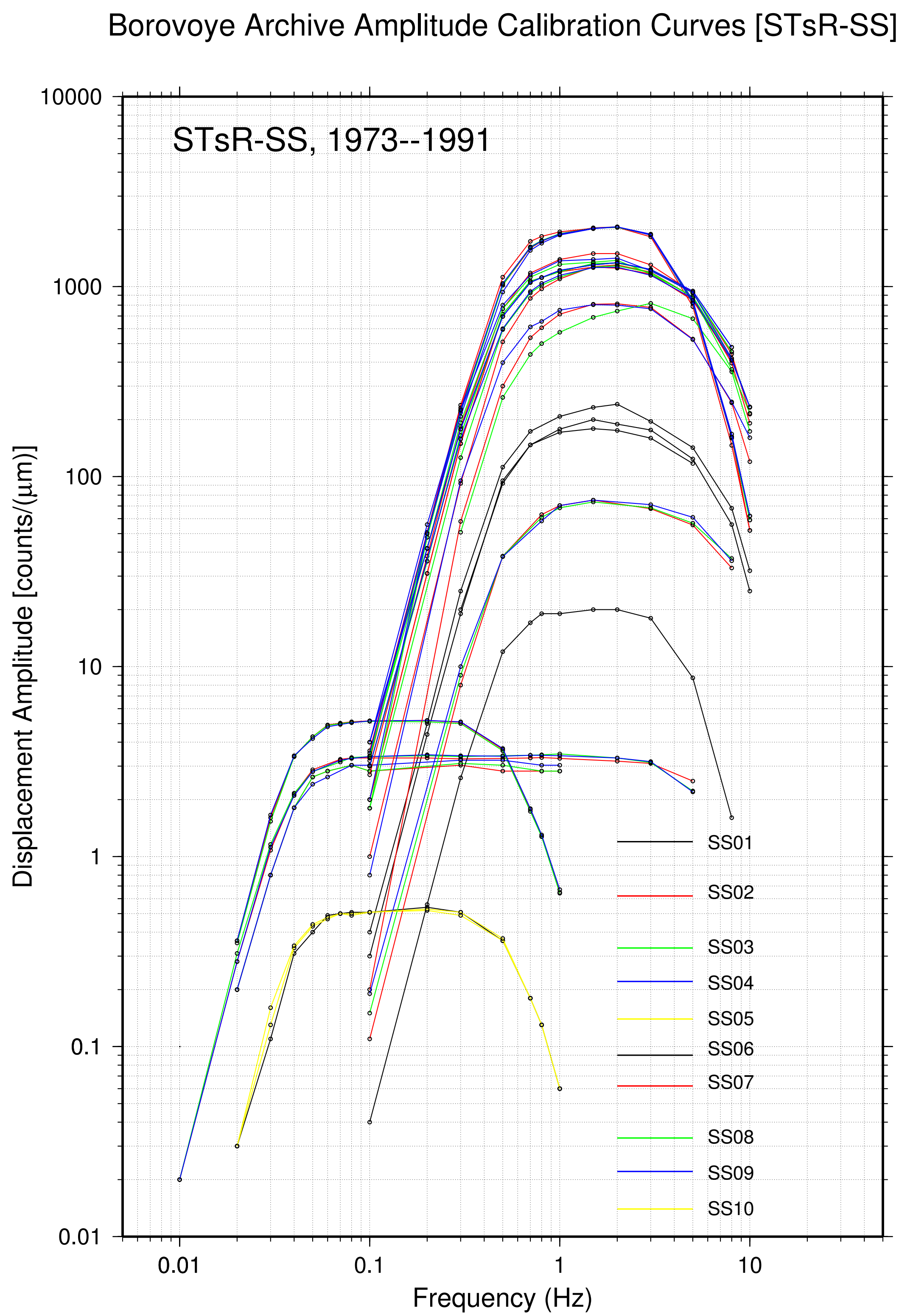

Figure 17: Frequency-amplitude calibration curves of 10-channel STsR-SS system are plotted.

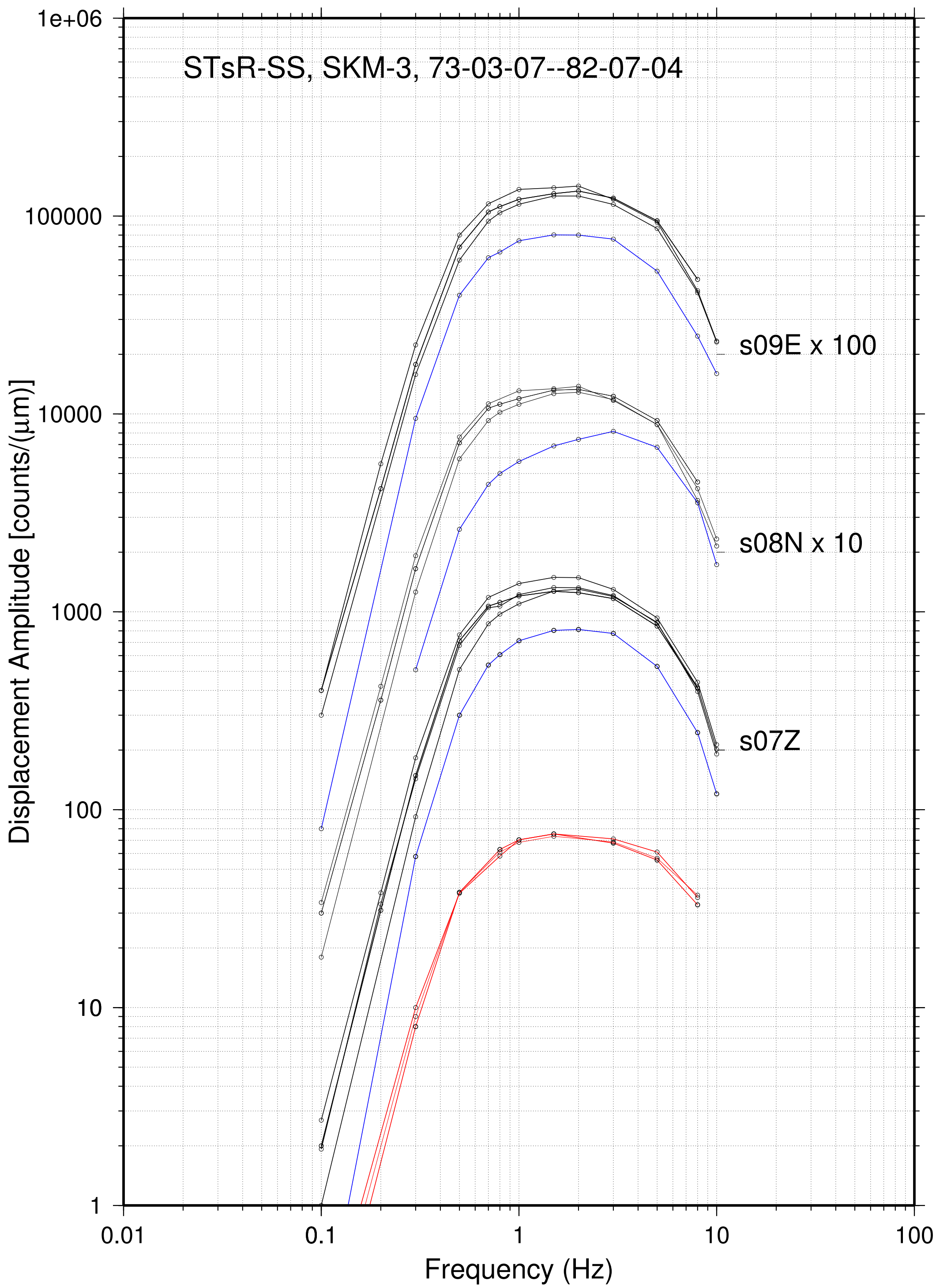

Figure 18: Frequency-amplitude calibration curves of 3-component short-period SKM-3 channels during 1973–1982. s07Z = vertical-component, s08N = NS-component, and s09E = EW-component. The curves for the NS-component are plotted with their amplitudes multiplied by 10, and EW-component are plotted by multiplying the amplitude by 100 to show the response curves separately. *Red lines* are for the curve on 1973-10-24 and *blue lines* are for the curve on 1981-08-04.

Table 11: Instrument constants of the high-gain SKM channels 7, 8 and 9, 1973–1982

Channel name	Natural period (sec)	Damping constant	Gain at 2 Hz (counts/μm)
s07Z	2.0	0.55	1249
s08N	2.2	0.55	1330
s09E	2.3	0.60	1336

Hz. Hence, the short-period high-gain channels of the SKM-3 seismometers can be represented by eight poles and four zeros as listed in Table 12. The theoretical frequency-amplitude curves in Figure 19 are calculated using poles and zeros for each component (Table 12).

Table 12: Poles and Zeros for the instrument response of the high-gain SKM channels 7, 8 and 9, 1973–1982

Component	Z-component (s07Z)	NS-component (s08N)	EW-component (s09E)
Seismometer SKM-3	(-1.72788, 2.62375) (-1.72788,-2.62375)	(-1.57080, 2.38523) (-1.57080,-2.38523)	(-1.63909, 2.18546) (-1.63909,-2.18546)
	two zeros at origin (0.0, 0.0), (0.0, 0.0)		
2nd order RC high-pass filter	(-3.14159, 0.00), (-3.14159, 0.0000) two zeros at origin (0.0, 0.0), (0.0, 0.0)		
2nd order Bessel low-pass filter	(-28.2743, -16.3242), (-28.2743, 16.3242) cutoff frequency= 3 Hz		
2nd order Bessel low-pass filter	(-65.9734, 38.0898), (-65.9734, -38.0898) cutoff frequency= 7 Hz		

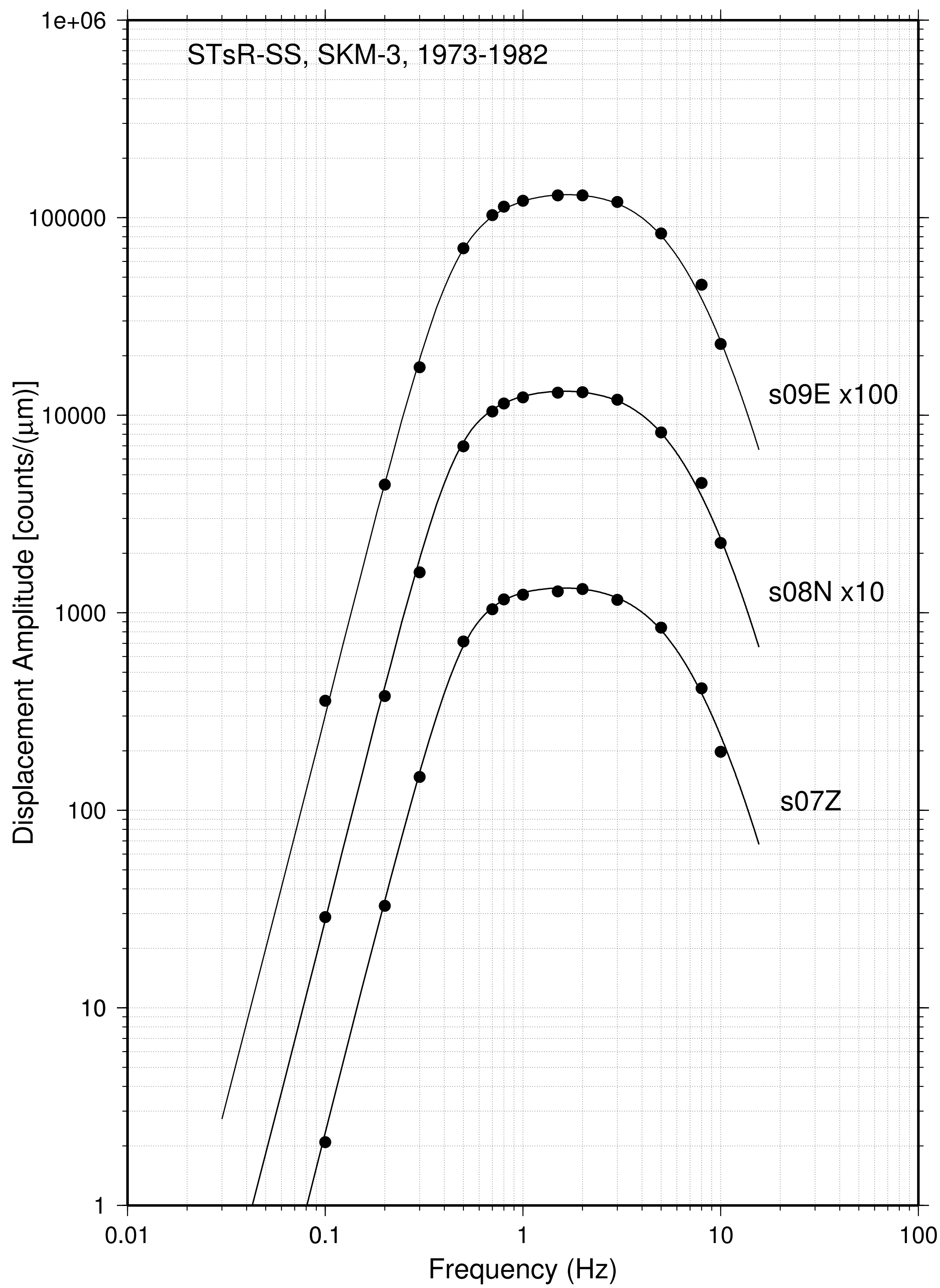

Figure 19: Comparisons of observed (*solid circles*) and theoretical (*solid lines*) frequency-amplitude curves of 3-component short-period SKM-3 channels during 1973–1982. s07Z = vertical-component, s08N = NS-component, and s09E = EW-component. The curves for the NS-component are plotted with their amplitudes multiplied by 10, and EW-component are plotted by multiplying the amplitude by 100 to show the response curves separately.

2) Channel 1 (s01Z; 1973–1981)

Channel 1 of the STsR-SS system was used to record short-period vertical-component signals from the SKM-3 seismometer during 1973–1981-01-15 with a nominal gain of 200 counts/μm at about 2 Hz (Adushkin & An, 1990). Two frequency-amplitude calibration curves are in the archive database: on 1973-04-19 and on 1979-07-02 (Table 13). Figure 20 shows the frequency-amplitude curves available for this period.

Table 13: The gain at 2 Hz for channel 1 during 1973-1981

Time period	Channel 1 (s01Z) (counts/μm)
1973-04-19–1979-06-28	175
1979-07-07–1981-01-15	241

Instrument Response: Poles and Zeros

Channel 1 of the STsR-SS system recorded vertical-component signals from the SKM-3 seismometer with a low-gain. Two frequency-amplitude curves available during 1973-1982 indicate that the channel has the same response as the high-gain vertical-component (s07Z). A comparison of observed and theoretical amplitude response curves are shown in Figure 21 (cf. Figure 19).

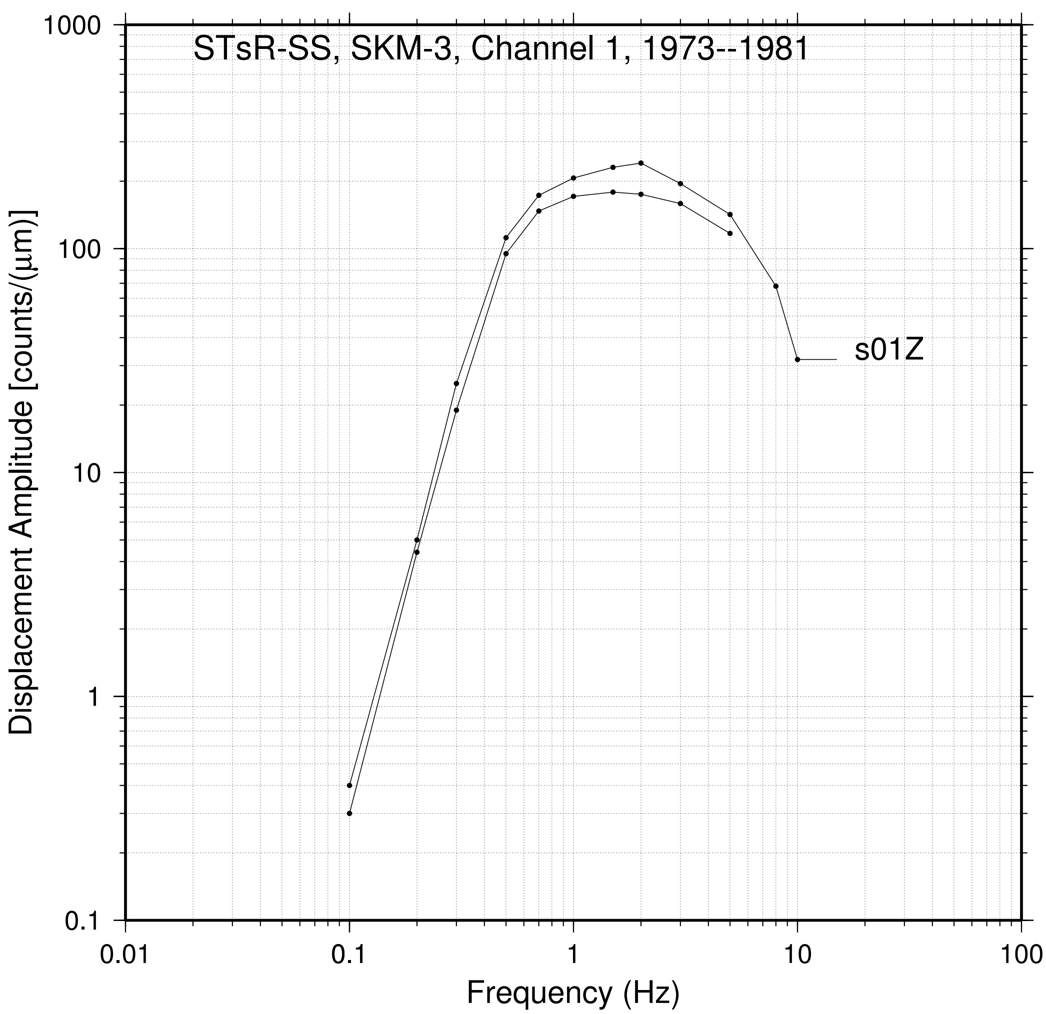

Figure 20: Two frequency-amplitude calibration curves of the low-gain, vertical-component short-period SKM-3 channel during 1973–1981. s01Z = low-gain vertical-component. The curves are similar to those of channel 7 (s07Z) except the gain.

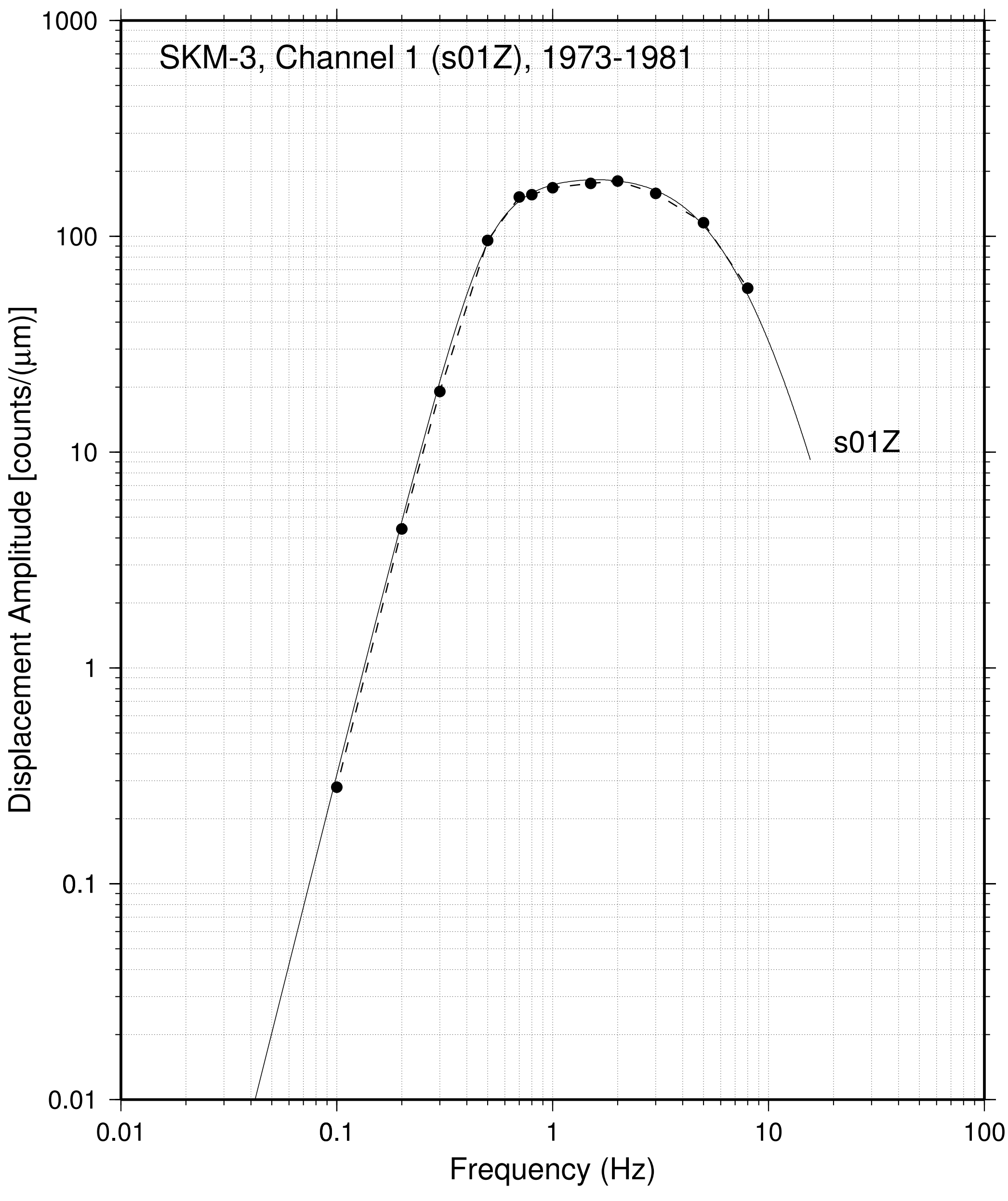

Figure 21: Comparisons of observed (*solid circles* with *dashed line*) and theoretical (*solid line*) frequency-amplitude curves of low-gain vertical-component short-period SKM-3 channel (s01Z) during 1973–1981-01-15.

3) Channels 7, 8 and 9 (s07Z, s08N and s09E; 1982–1991)

This is the main data stream for 3-component, short-period signals from the SKM-3 seismometers of the STsR-SS system during 1982–1991. Signals are recorded on channels 7, 8 and 9, for vertical-, NS-, and EW-component, respectively as before, but recorded with a sampling interval of 24 msec. The instrument characteristics and parameters reported in Adushkin & An (1990) for SKM-3 refer to this period.

Two frequency-amplitude calibration curves during 1982-08-21–1991-07-15 for these channels plotted in Figure 22 indicate that the gains are 2,059, 2,054 and 2,057 counts/μm at 2 Hz for vertical-, NS-, and EW-component, respectively for most of this period (Table 14).

Table 14: The gains at 2 Hz for channels 7, 8 and 9 during 1982-1991

Time period	Channel 7 (s07Z) (counts/μm)	Channel 8 (s08N) (counts/μm)	Channel 9 (s09E) (counts/μm)
1982-08-23–1985-06-30	2048	2067	2067
1985-07-20–1991-07-15	2059	2054	2057

Instrument Response: Poles and Zeros

The SKM-3 seismometer used in the STsR-SS system has natural period, T_0=2.0 s, and damping constant, D_s=0.5 (Table 19 and Adushkin & An, 1990). However, very little is known about its recording system and use of filters such as an anti-alias filter.

Comparing the calibration curves plotted in Figures 18 and 22 for 1973–1982 and 1982–1991, respectively, it is obvious that the amplitude response of the SKM-3 data stream has changed. The sampling interval is reduced to 0.024 s from 0.032 s, and the amplitude fall off at frequencies higher than 3 Hz is very significant – from about -20 dB to -40 dB. Perhaps, it may have been realized that the data stream from SKM-3 seismometer during 1973–1982 were somewhat aliased, due to insufficient amplitude attenuation at high frequencies prior to digitization with the Nyquist frequency=15.6 Hz. The amplitude responses at low frequencies – 0.1 – 3 Hz, are nearly identical for both periods (Figure 23).

The amplitude response for the 1982–1991 period must be the same as those during 1973-1982 at frequencies below 3 Hz, and we add a 4th order Butterworth low-pass filter with cutoff at 4 Hz to fit the amplitude response. We constrained instrument parameters by fitting the averaged frequency-amplitude calibration curves in the frequency domain by trial and error. Figure 24 shows comparison of observed frequency-amplitude calibration curves with corresponding theoretical frequency-amplitude curves obtained by using the instrument constants constrained by trial and error: seismometer with T_0=2.0 s and damping constant, D_s=0.5, 2nd order RC high-pass filter with cutoff at 0.5 Hz, and 4th order Butterworth low-pass filter with cutoff at 4 Hz. The instrument response of these channels can be represented by eight poles and four zeros as given in Table 15.

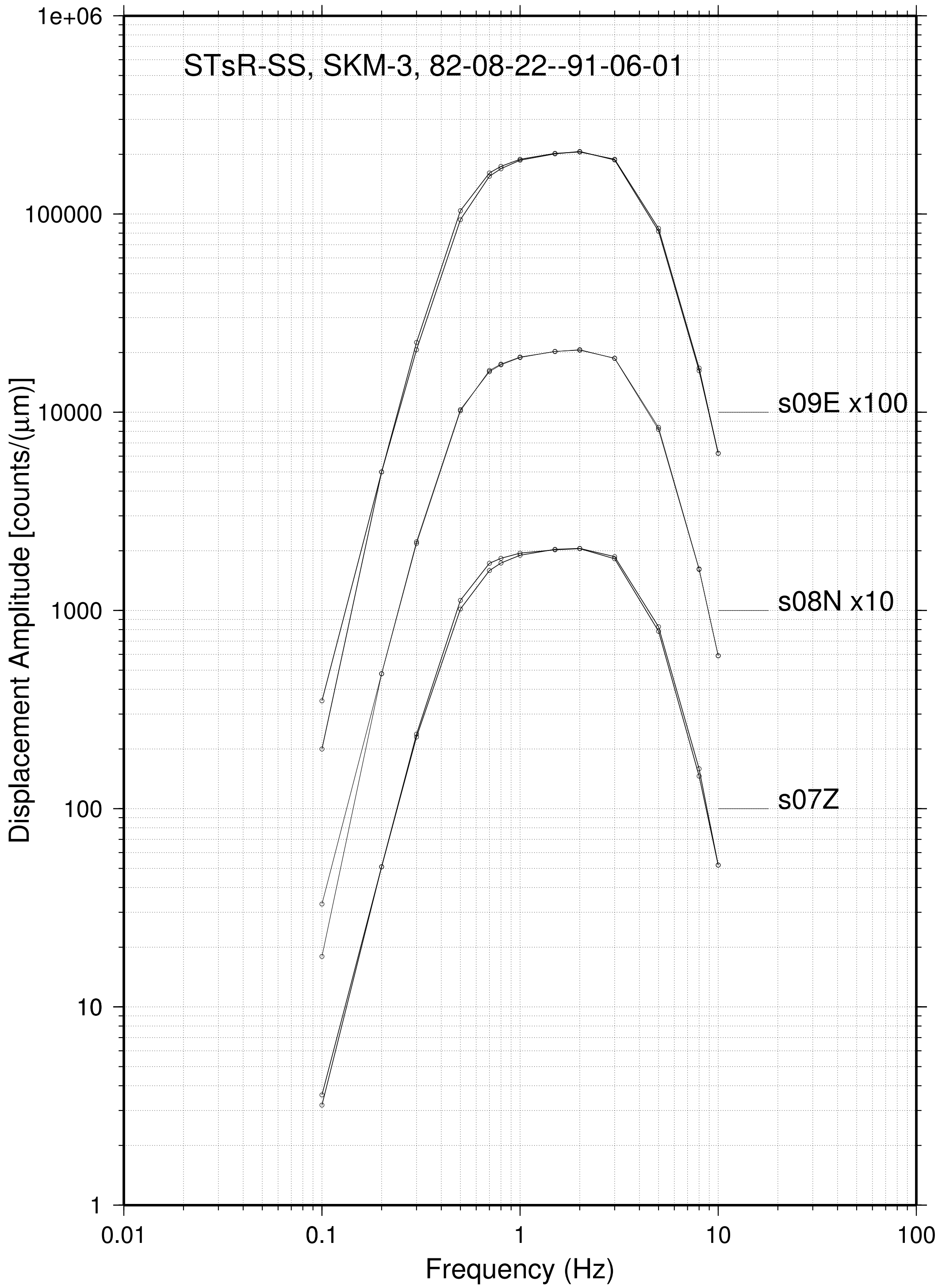

Figure 22: Frequency-amplitude calibration curves of 3-component short-period SKM-3 channels during 1982–1991. s07Z = vertical-component, s08N = NS-component, and s09E = EW-component. The curves for the NS-component are plotted with their amplitudes multiplied by 10, and EW-component are plotted by multiplying the amplitude by 100 to show the response curves separately.

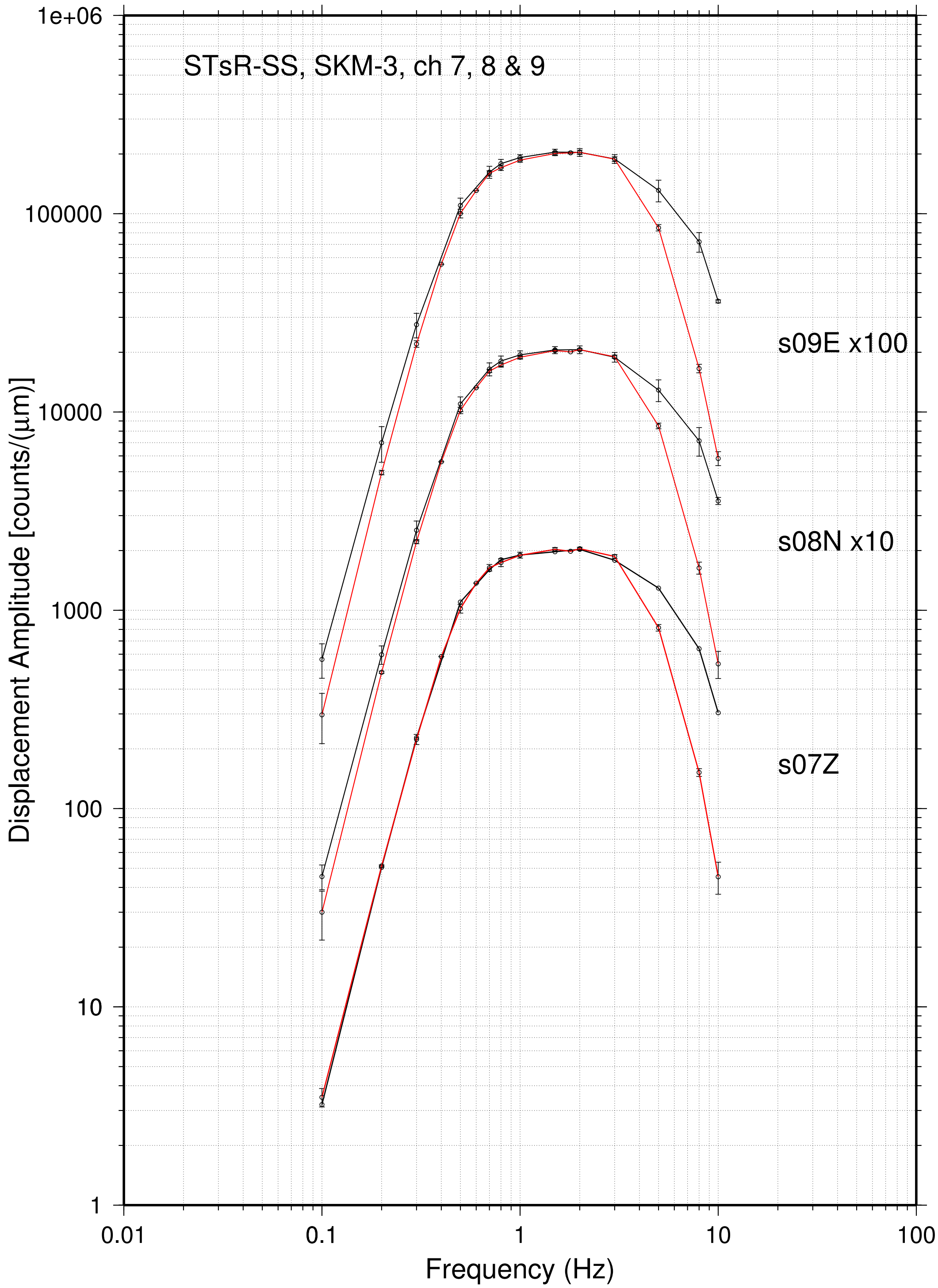

Figure 23: Comparison of frequency-amplitude calibration curves of 3-component short-period SKM-3 channels during 1973–1982 (*solid lines*) and 1982–1991 (*red lines*). Amplitude responses are nearly identical at frequencies up to 3 Hz for both periods. s07Z = vertical-component, s08N = NS-component, and s09E = EW-component. The curves for the NS-component are plotted with their amplitudes multiplied by 10, and EW-component are plotted by multiplying the amplitude by 100 to show the response curves separately.

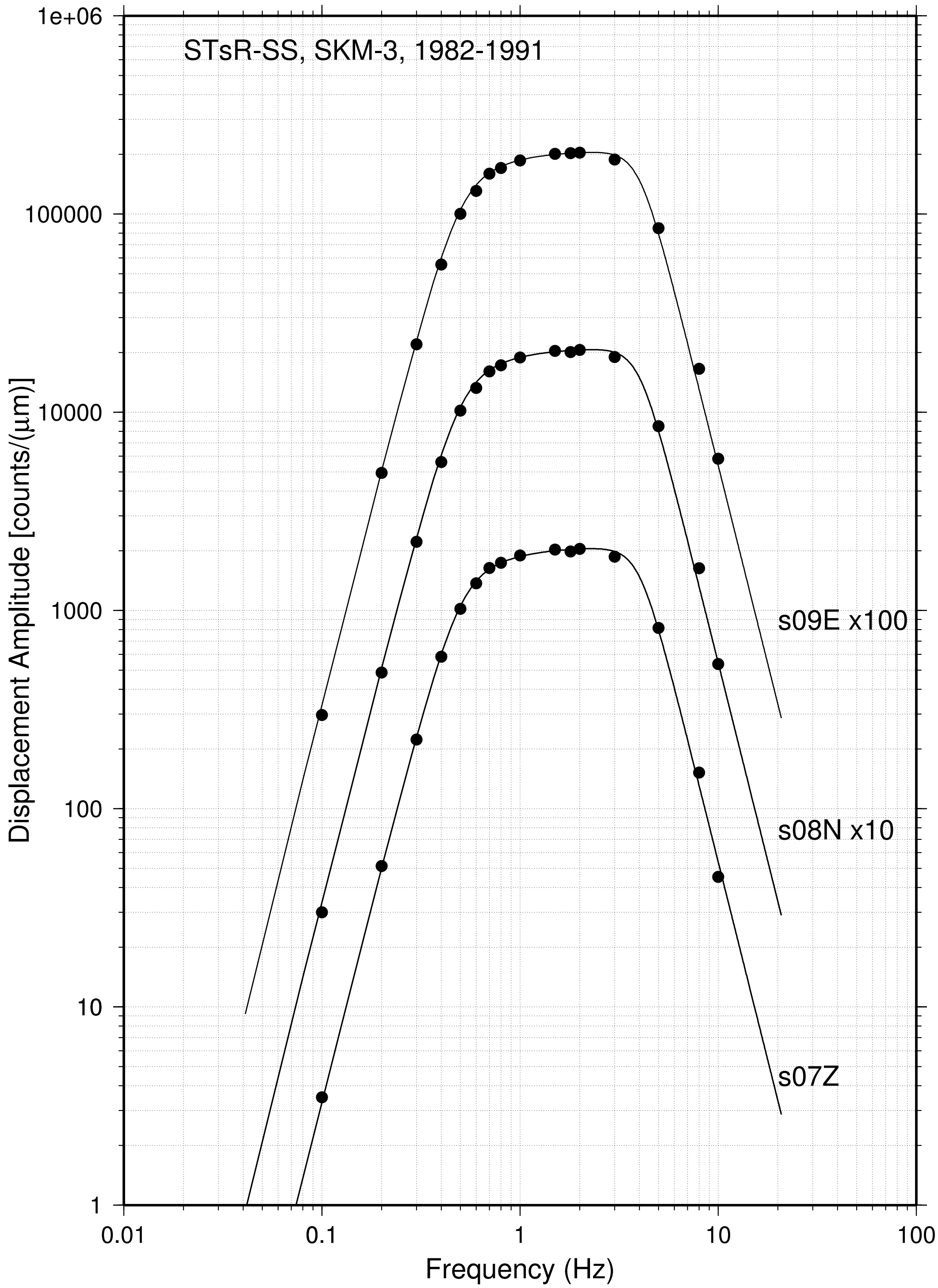

Figure 24: Comparisons of observed (*solid circles*) and theoretical (*solid lines*) frequency-amplitude curves of 3-component short-period SKM-3 channels during 1982–1989. s07Z = vertical-component, s08N = NS-component, and s09E = EW-component. The curves for the NS-component are plotted with their amplitudes multiplied by 10, and EW-component are plotted by multiplying the amplitude by 100 to show the response curves separately.

Table 15: Instrument constants of the high-gain SKM channels 7, 8 and 9, 1982–1991

Component	Z-component (s07Z)	NS-component (s08N)	EW-component (s09E)
Seismometer SKM-3	(-1.57080, 2.72070), (-1.57080, -2.72070) two zeros at origin (0.00, 0.00), (0.00, 0.00)		
2nd order RC high-pass filter	(-3.14159, 0.00), (-3.14159, 0.00) two zeros at origin (0.00, 0.00), (0.00, 0.00)		
4th order Butterworth low-pass filter	(-9.617798, 23.21964), (-9.617798, -23.21964) (-23.21964, 9.617798), (-23.21964, -9.617798) cutoff frequency= 4 Hz		

4) Channel 6 (s06Z; 1981-08-14–1991-07-15)

Short-period vertical-component signals from SKM-3 seismometer are recorded as low-gain on channel 6 with the gain of 20 counts/μm at 2 Hz and the sampling interval of 96 msec during 1981–1991. Figure 25 shows a frequency-amplitude curve on 1982-08-21. Notice that the frequency-amplitude curve is given up to 8 Hz, which is inconsistent with the sampling interval of 0.096 s with its Nyquist frequency of 5.2 Hz.

The instrument response of the channel 6 during 1981-08-04–1982-07-04 is the same as channel 1 during 1973-1981 shown in Figure 21.

Instrument Response: Poles and Zeros

This is the same data stream from the SKM-3 vertical-component but with low-gain recording. Figure 26 shows comparison of observed frequency-amplitude calibration curves with corresponding theoretical amplitude response calculated by using the instrument constants identical to high-gain vertical component s07Z shown in Figure 24. Notice that if this amplitude response is used as indicated by the available frequency-amplitude curves, then it may suggest that there must be some aliasing of singnals with frequencies higher than 5.2 Hz into the lower frequencies due to insufficient anti-aliasing filters applied prior to the digitization.

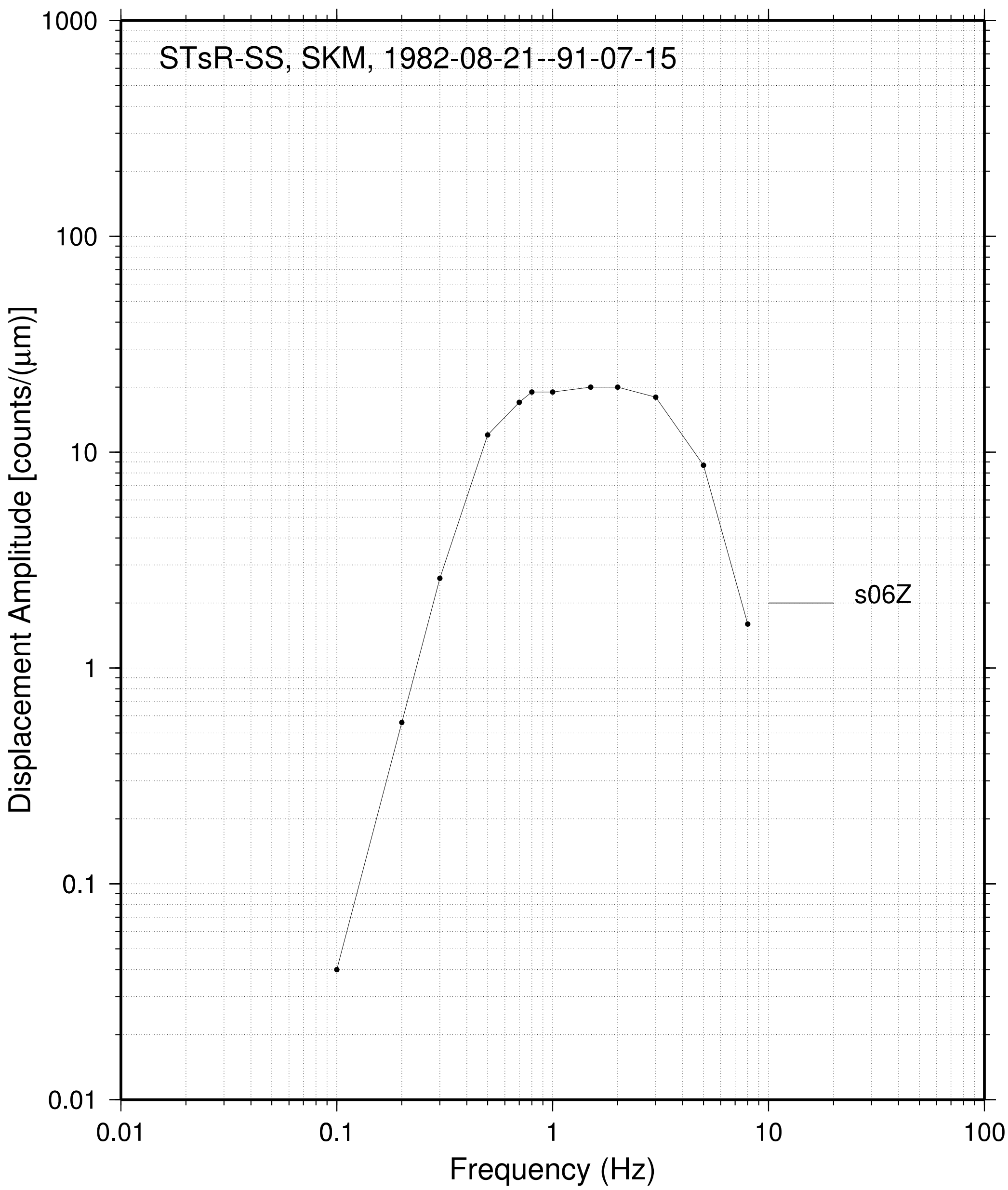

Figure 25: A frequency-amplitude calibration curve of vertical-component, low-gain short-period SKM-3 channels during 1981–1991. s06Z = low-gain vertical-component. The curve is similar to those of channel 7 (s07Z) shown in Figure 22 except the gain.

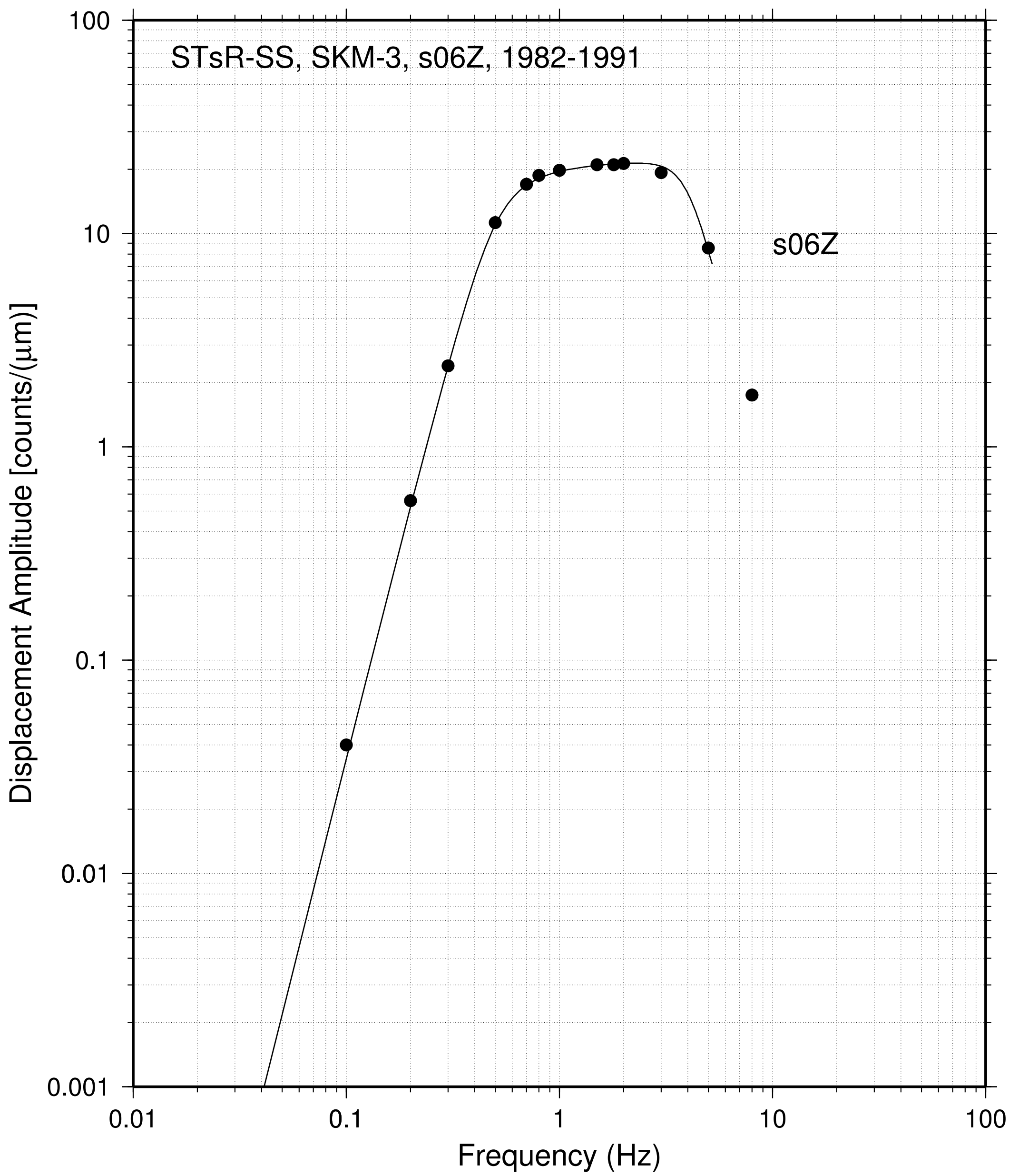

Figure 26: Comparisons of observed (*solid circles* with *dashed line*) and theoretical (*solid line*) frequency-amplitude curves of low-gain vertical-component short-period SKM-3 channels (s06Z) during 1982–1991.

SKD Extended-period Seismometer

1) Channel 2, 3 and 4 (l02Z, l03N, l04E; 1973–1982)

This is the main data stream for 3-component, extended-period SKD seismometers of the STsR-SS system. Signals are recorded on channels 2, 3 and 4, for vertical-, NS-, and EW-component, respectively. The channel names are assigned as l02Z, l03N and l04E for vertical-, NS-, and EW-component, respectively. Although, Adushkin & An (1990) reported that these channels had the nominal gains of 5 counts/μm and recorded with a sampling interval of 0.192 s during their operation, the waveform data and frequency-amplitude calibration curves available indicate that there must have been at least two different instrument responses as in the case of 3-component short-period SKM-3 data.

During 1973–1981-06-30, the gains of these channels were 3.31, 3.36 and 3.36 counts/μm at 0.1 Hz for vertical-, NS-, and EW-component, respectively, which is given by a frequency-amplitude calibration curve oon 1973-03-17 as shown in Figure 27.

It is noted that these frequency-amplitude curves plotted in Figure 27 are not consistent with the system configuration, that is, the Nyquist frequency of the extended-period channels is 2.60 Hz (for 0.192 sec sampling interval), and hence, the frequency-amplitude curve on 1973-03-17 that listed amplitude beyond 3 Hz must be incorrect. These frequency-amplitude curves seem to lack anti-alias filter component prior to digitizing.

Instrument Response: Poles and Zeros

Two available frequency-amplitude calibration curves during this period for the channels 2, 3 and 4 are inconsistent with the data stream with sampling interval of 0.192 sec. The frequency-amplitude calibration curves covering 1973–1982 and for frequency band 0.02 and 1 Hz are plotted in Figure 28 and are compared with the amplitude response calculated with the instrument response for 1982–1991.

The amplitude response and the calibration curves are fairly well fit in the frequency band from 0.02 to 0.2 Hz. Hence, the instrument response for these channels may be the same as those of the later years.

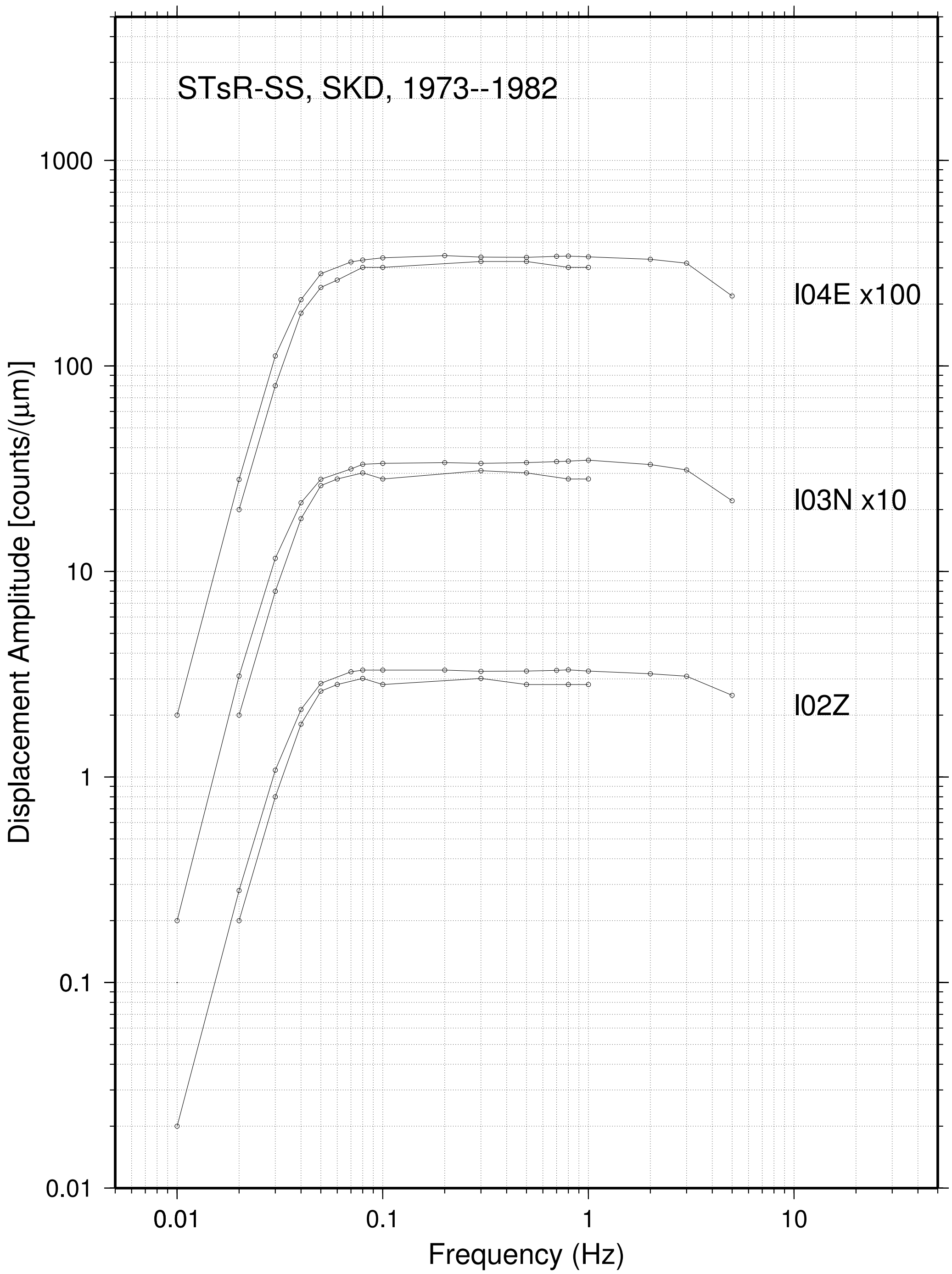

Figure 27: Frequency-amplitude calibration curves of 3-component extended-period SKD channels during 1973–1982. l02Z = vertical-component, l03N = NS-component, and l04E = EW-component. The curves for the NS-component are plotted with their amplitudes multiplied by 10, and EW-component are plotted by multiplying the amplitudes by 100 to show the response curves separately.

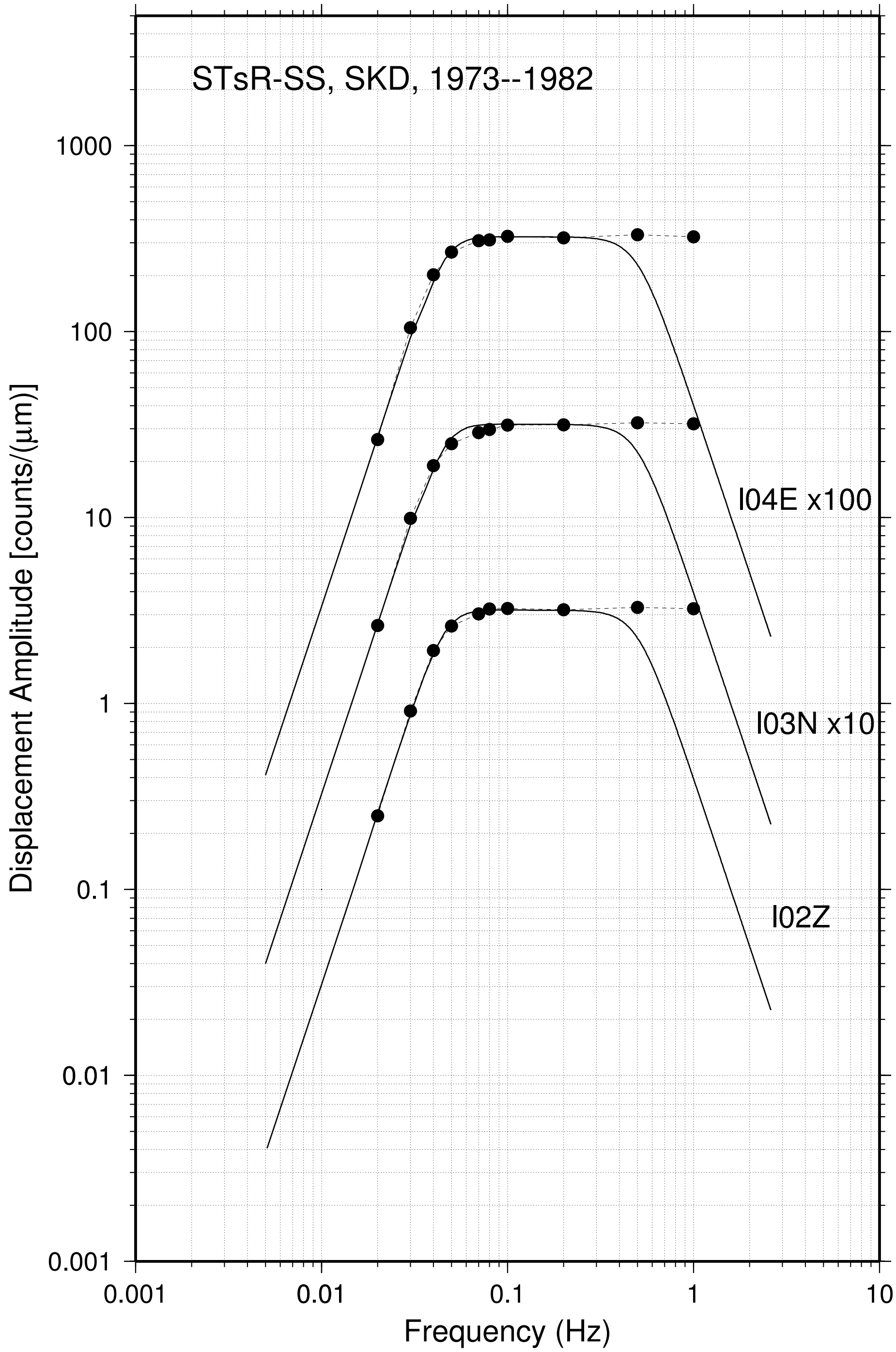

Figure 28: Comparisons of observed (*solid circles*) and theoretical (*solid lines*) frequency-amplitude curves of 3-component extended-period SKD channels during 1973–1982. l02Z = vertical-component, l03N = NS-component, and l04E = EW-component. The theoretical amplitude response is calculated using the instrument response for the later time period 1982–1991. The curves for the NS-component are plotted with their amplitudes multiplied by 10, and EW-component are plotted by multiplying the amplitude by 100 to show the response curves separately.

Table 16: Gains, Poles and Zeros of the instrument response of the Extended-period SKD Channels 2, 3 and 4, 1973-1982

Component	Z-component (l02Z)	NS-component (l03N)	EW-component (l04E)
Gain at 0.1 Hz (73-06-06–81-06-30)	3.31 counts/μm	3.36 counts/μm	3.36 counts/μm
Gain at 0.1 Hz (81-08-14–82-07-4)	2.82 counts/μm	2.82 counts/μm	3.02 counts/μm
Seismometer T_0=22 s, Ds=0.45	(-0.128520, 0.255048), (-0.128520, -0.255048) two zeros at origin (0.00, 0.00), (0.00, 0.00)		
1st order RC high-pass filter	cutoff at 0.05 Hz, one pole (-0.314159, 0.00) one zero at origin (0.00, 0.00)		
3rd order Butterworth low-pass filter	cutoff at 0.5 Hz, three poles (-3.14159, 0.00) (-1.57080, -2.72062), (-1.57080, 2.72062)		

2) Channel 2, 3 and 4 (l02Z, l03N and l04E; 1982–1991)

During 1982–1991, these channels recorded the signals from 3-component, extended-period SKD seismometer with the gains of 5.18, 5.14 and 5.17 counts/μm at 0.1 Hz for vertical-, NS-, and EW-component, respectively. A frequency-amplitude curve available during 1982–1991 is plotted in Figure 29. This is the instrument response shown in Adushkin & An (1990).

Instrument Response: Poles and Zeros

Instrument response of these channels can be represented by 6 poles and 3 zeros, which consists of seismometer with natural period T_0=25 s and damping constant of D_s=0.5; a first order RC high-pass filter with cutoff frequency at 0.05 Hz and a third-order Butterworth low-pass filter with cutoff at 0.5 Hz. Comparison of observed and theoretical responses for vertical-, NS- and EW-component are plotted in Figure 30. The observed frequency-amplitude calibration curves can be best fit by using the instrument constants that are slightly different from the nominal values. The seismometer with natural period T_0=22s and damping constant of D_s=0.45 fits the best. Six poles and three zeros can represent instrument response of these channels during 1982–1989 as listed in Table 17.

Table 17: Instrument Constants of the Extended-period SKD Channels 2, 3 and 4, 1982–1991

Component	Z-component (l02Z)	NS-component (l03N)	EW-component (l04E)
Gain at 0.1 Hz	5.18 counts/μm	5.14 counts/μm	5.17 counts/μm
Seismometer SKD, 82-08-23–91-07-15	two poles (-0.128520, 0.255048), (-0.128520, -0.255048) two zeros at origin (0.00, 0.00), (0.00, 0.00)		
1st order RC high-pass filter	cutoff at 0.05 Hz, one pole (-0.314159, 0.00) one zero at origin (0.00, 0.00)		
3rd order Butterworth low-pass filter	cutoff at 0.5 Hz, three poles (-3.14159, 0.00) (-1.57080, -2.72062), (-1.57080, 2.72062)		

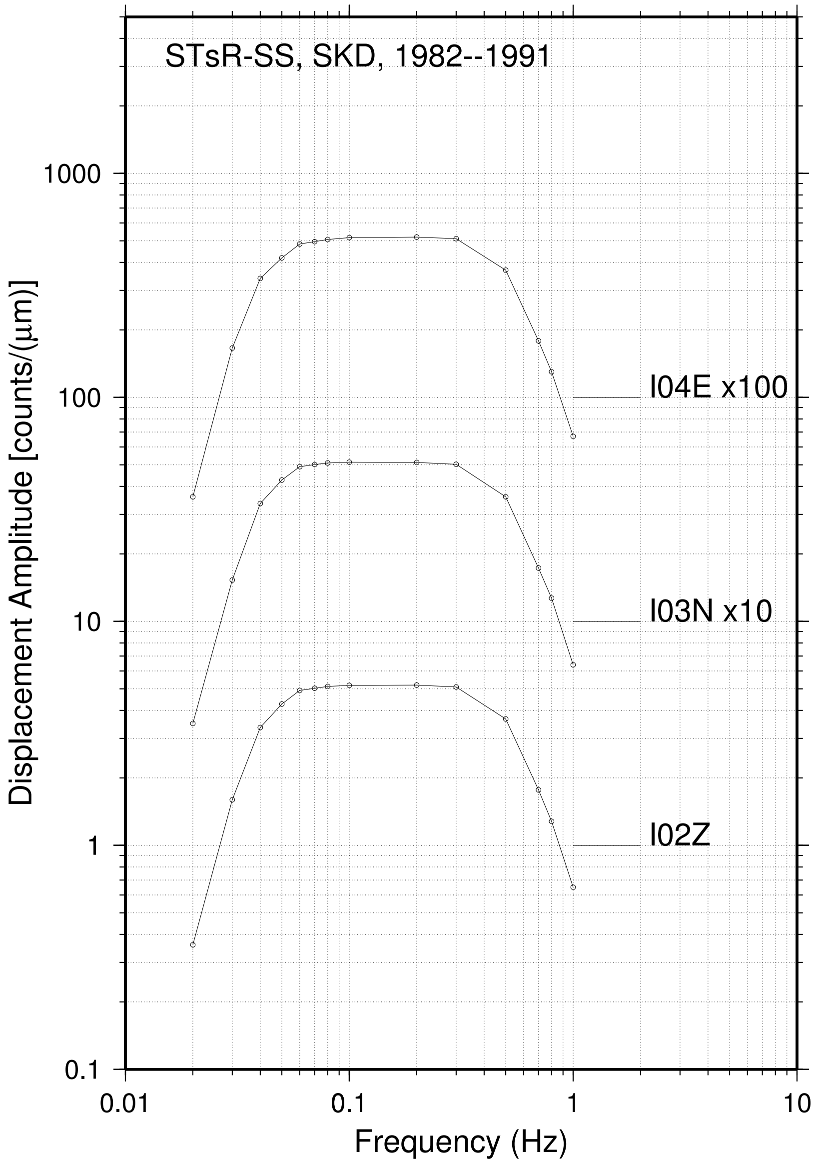

Figure 29: Frequency-amplitude calibration curves of 3-component extended-period SKD channels during 1982–1991. l02Z = vertical-component, l03N = NS-component, and l04E = EW-component. The curve for the NS-component is plotted with their amplitudes multiplied by 10, and EW-component is plotted by multiplying the amplitude by 100 to show the response curves separately.

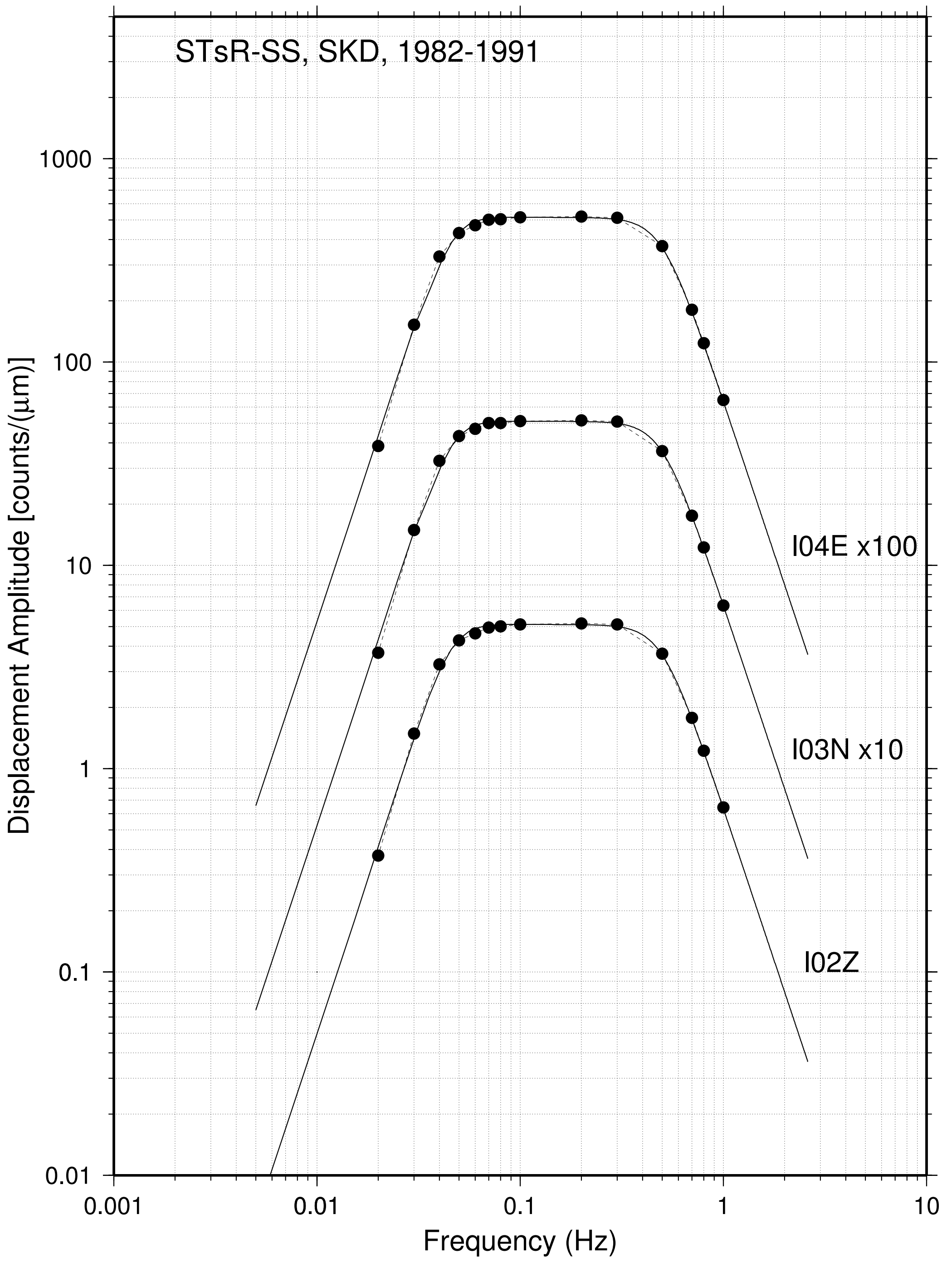

Figure 30: Comparisons of observed (*solid circles*) and theoretical (*solid lines*) frequency-amplitude curves of 3-component extended-period SKD channels during 1982–1991. l02Z = vertical-component, l03N = NS-component, and l04E = EW-component. The curves for the NS-component are plotted with their amplitudes multiplied by 10, and EW-component are plotted by multiplying the amplitude by 100 to show the response curves separately.

3) Channel 1, 5 and 10 (l01Z, l05N and l10E; 1982–1991)

These channels recorded signals from the 3-component, extended-period SKD seismometer with a low-gain configuration. The channel names are assigned as l01Z, l05N and l10E for vertical-, NS-, and EW-component, respectively. These channels were recorded only during 1982–1991 when the STsR-SS system was reconfigured. The waveform data and the frequency-amplitude calibration curves available for the period indicate that the gains of these channels were 0.51 counts/μm at 0.1 Hz for vertical-, NS-, and EW-component, respectively and were recorded with a sampling interval of 0.192 sec (Figure 31). During the 2nd half of the STsR-SS system operation, all 10 channels of the system were utilized: 3-component short-period SKM-3 data stream (s07Z, s08N and s09E); a low-gain vertical-component SKM-3 (s06Z); 3-component extended-period SKD data stream (l02Z, l03N and l04E); and low-gain 3-component extended-period SKD data stream (l01Z, l05N and l10E).

Instrument Response: Poles and Zeros

These channels are low-gain 3-component SKD data stream with the similar instrument responses as those of channels 2, 3 and 4. These channels are added since 1982 when the STsR-SS system was reconfigured. Comparison of observed and theoretical amplitude responses for vertical-, NS- and EW-component are plotted in Figure 32. The observed frequency-amplitude calibration curves are fairly well fit by the curve calculated using instrument constants identical to channels 2, 3 and 4 given in Table 17. The gains of each component at 0.1 Hz are listed in Table 18.

Table 18: The gains of the Extended-period SKD Channels 1, 5 and 10, 82-08-23–91-07-15

Component	Z-component (l01Z)	NS-component (l05N)	EW-component (l10E)
Gain at 0.1 Hz	0.51 counts/μm	0.51 counts/μm	0.51 counts/μm

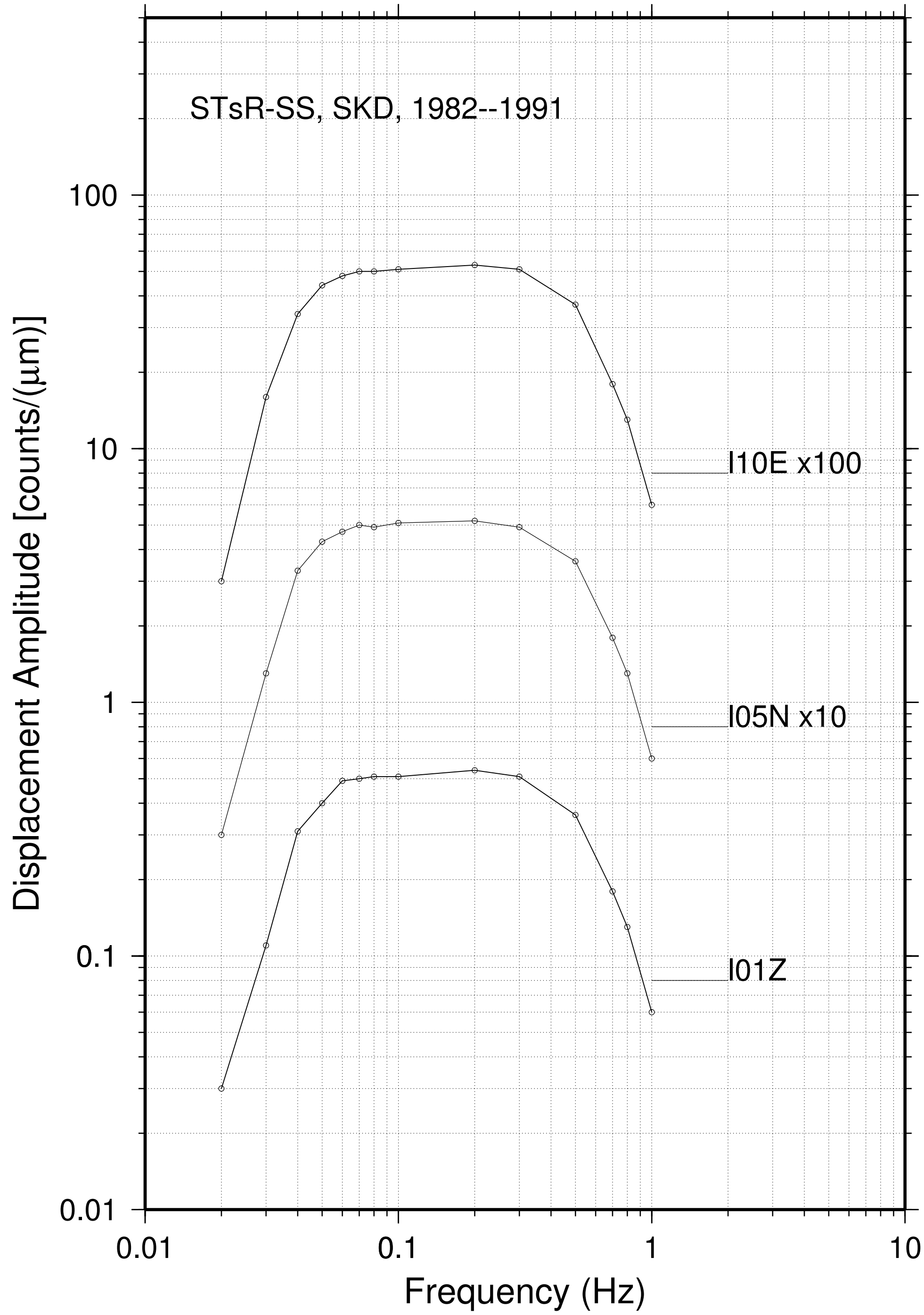

Figure 31: Frequency-amplitude calibration curves of 3-component extended-period SKD channels during 1982–1991. l01Z = vertical-component, l05N = NS-component, and l10E = EW-component. The curve for the NS-component is plotted with its amplitudes multiplied by 10, and EW-component is plotted by multiplying the amplitude by 100 to show the response curves separately.

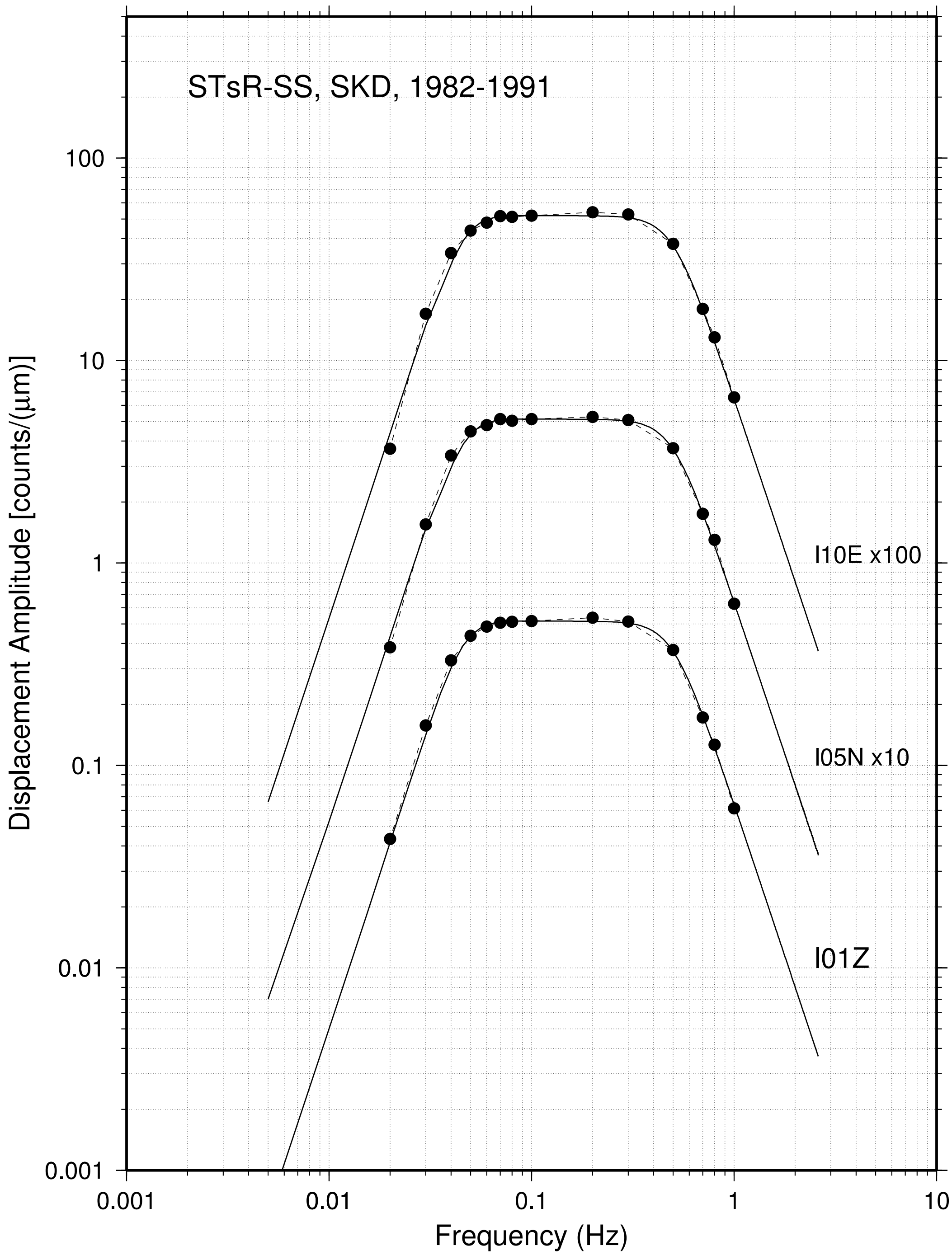

Figure 32: Comparisons of observed (*solid circles*) and theoretical (*solid lines*) frequency-amplitude curves of low-gain, 3-component extended-period SKD channels during 1982–1991. l01Z = vertical-component, l05N = NS-component, and l10E = EW-component. The curves for the NS-component are plotted with their amplitudes multiplied by 10, and EW-component are plotted by multiplying the amplitude by 100 to show the response curves separately.

Note on Instrument Types (Shishkevish, 1974)

SKD: Kirnos-Arkhangel'skiy broadband extended-period system or any of its three components:
SGKD or SKD (N-S, E-W) – horizontal-component SKD seismographs
SVKD or SKD (Z) – vertical-component SKD seismograph

SKM: Kirnos high-gain, short-period system or any of its three components:
SGKM or SKM (N-S, E-W) – horizontal-component SKM seismographs
SVKM or SKM (Z) – vertical-component SKM seismograph

SKM-3: Kirnos high-gain, short-period system (later model of SKM) or any of its three components:
SGKM-3 or SKM-3 (N-S, E-W) – horizontal-component SKM-3 seismographs
SVKM-3 or SKM-3 (Z) – vertical-component SKM-3 seismograph

KPCh: Low-gain seismograph channel obtained by connecting a galvanometer to the seismometer damping coil and used mostly with SK and SKD seismograph (SK-KPCh, SKD-KPCh).

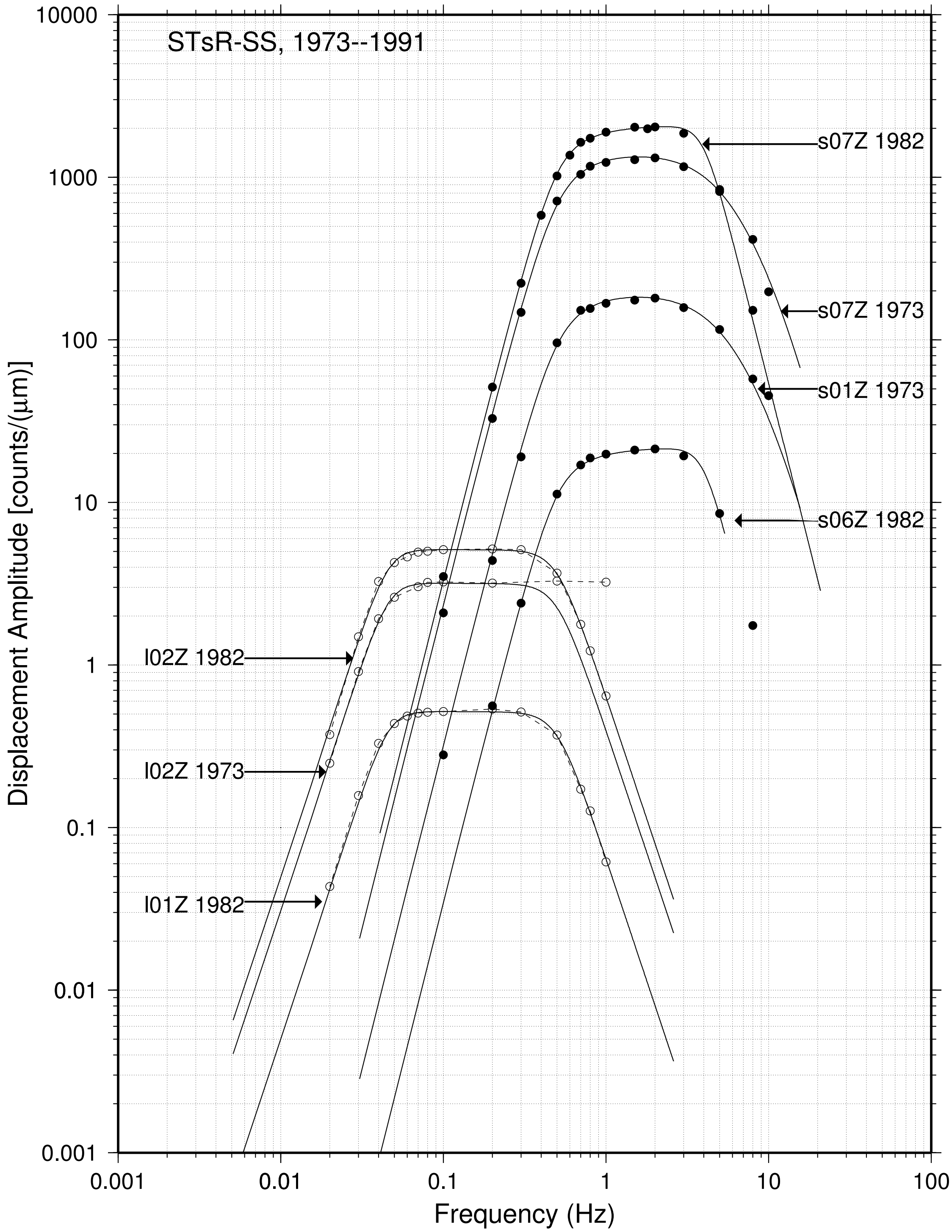

Figure 33: A summary plot of the averaged frequency-amplitude calibration curves of all data streams of the STsR-SS system (*open circles*=SKD and *solid circles*=SKM-3 seismometers). Theoretical amplitude responses are plotted by *solid lines*. SKM-3 data streams: s07Z 1982= 3-component (s07Z, s08N and s09E, 1982–1991); s07Z 1973= 3-component (s07Z, s08N and s09E, 1973–1982); s01Z 1973= low-gain vertical-component, 1973–1981; s06Z 1982= low-gain vertical-component, 1982–1991. SKD data stream: l02Z 1973= 3-component (l02Z, l03N and l04E, 1973–1982); l02Z 1982= 3-component (l02Z, l03N and l04E, 1982–1991); l01Z 1982= low-gain 3-component (l01Z, l05N and l10E, 1982–1991).

Table 19: Instrument Characteristics at Borovoye (BRV)$^{(*)}$

System	Seismometer	$T_0^{(1)}$ (s)	$D_s^{(2)}$	Chan name	Gain$^{(3)}$ (C/μm)	fn$^{(4)}$ (Hz)	dt$^{(5)}$ (ms)	Chan no.	Time period
KOD	SKM-3	3.5	0.7	SHZ	3,386	1.8	30	1	67-02-26
				SHN	2,940	1.8	30	3	–73-10-26
				SHE	3,354	1.8	30	4	
	LG(Z)$^{(6)}$			SLZb	423	1.8	30	2	
				SLZ	421	1.8	30	1	67-06-29
				SLN	321	1.8	30	3	–73-10-26
				SLE	371	1.8	30	4	
				SHZm	3,386	1.8	30	2	
SS	SKM-3	2.0	0.5	s07Z	1249	2.0	32	7	73-06-06
				s08N	1330	2.0	32	8	–82-07-04
				s09E	1336	2.0	32	9	
	LG(Z)			s01Z	175	2.0	32	1	–81-01-15
				s07Z	2059	2.0	24	7	82-08-21
				s08N	2054	2.0	24	8	–91-07-15
				s09E	2057	2.0	24	9	
	LG(Z)			s06Z	20	2.0	96	6	81-08-14–
	SKD	25.0	0.5	l02Z	3.31	0.10	192	2	73-06-06
				l03N	3.36	0.10	192	3	–82-07-04
				l04E	3.36	0.10	192	4	
				l02Z	5.19	0.10	192	2	82-08-23
				l03N	5.14	0.10	192	3	–91-07-15
				l04E	5.17	0.10	192	4	
	LG			l01Z	0.51	0.10	192	1	82-08-23
				l05N	0.51	0.10	192	5	–91-07-15
				l10E	0.51	0.10	192	10	
TSG	KSVM	1.5	0.5	sZ01	50	1.0	26	1	80-07-20–96-01-27
				sZ02	4,600	1.0	26	2	83-12-16–96-01-27
	KSM	1.5	0.5	sZ03	1,000	1.0	26	3	85-03-23
				sN04	1,000	1.0	26	4	–96-01-27
				sE05	1,000	1.0	26	5	
	KS	1.5	0.71	sZ06	1,000	1.5	26	6	85-03-23–96-01-27
				sZ07	2,000	1.5	26	7	74-12-16
				sN08	2,000	1.5	26	8	–82-01-30
				sE09	2,000	1.5	26	9	
				sZ07	4,500	1.5	26	7	82-03-24
				sN08	4,500	1.5	26	8	–91-01-27
				sE09	4,500	1.5	26	9	

continued on next page

System	Seismometer	$T_0^{(1)}$ (s)	$D_s^{(2)}$	Chan name	Gain[3] (C/μm)	fn[4] (Hz)	dt[5] (ms)	Chan no.	Time period
	KSM	1.5	0.5	sZ10	100,000	1.0	26	10	85-01-22
				sN11	100,000	1.0	26	11	–88-10-31
				sE12	100,000	1.0	26	12	
	DS	20.0	0.71	lZ19	50	0.1	312	19	74-07-12
				lN20	50	0.1	312	20	–88-06-28
				lE21	50	0.1	312	21	
	DSM	28.0	0.71	lZ22	1,000	0.07	312	22	75-11-19
				lN23	1,000	0.07	312	23	–88-12-02
				lE24	1,000	0.07	312	24	
				lZ15	10	0.07	312	15	85-01-26
				lN16	10	0.07	312	16	–88-12-02
				lN17	10	0.07	312	17	
	DS	20.0	0.71	lZ13	50	0.1	312	13	83-11-03–84-01-18
				lN14	50	0.1	312	14	83-11-03–85-02-13

(*) KOD (KODB and KODM) systems were operated from 1966–Nov 1973 and had polarity reversal on all channels, STsR-SS (SS) and STsR-TSG (TSG) systems were operated from Feb. 1973 to 1995.

(1) T_0= Seismometer natural period in seconds.

(2) D_s= Seismometer damping constant, critical damping=0.71.

(3) Gain = Sensitivity in counts/μm for ground displacement.

(4) fn = Normalization frequency where the gain is measured.

(5) dt = Sampling interval in millisecond.

(6) LG = low-gain channels and (Z) indicates that it is only vertical-component.

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