Rit Veðurstofu Íslands

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The transfer function of the SIL seismic data acquisition system

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Fjölritun og frágangur: OFFSETFJÖLRITUN HF, Mjölnisholti 14, sími 562 7890

1. INTRODUCTION

The frequency response or transfer function of a system relates the input signal, $x(s)$, to the output $y(s)$ of the system by an equation of the form:

$$y(s) = T(s)x(s) \tag{1}$$

By convention the frequency variable s is the complex frequency, i.e. $s = i\omega$.

At present the SIL seismic data acquisition system consists of 28 remote seismic stations. Each station is equipped with an RD3/OSD3 digitizer and a seismometer. The digitizer is composed of a fourth order low–pass filter, a second order anti–alias filter, a 56–coefficient FIR filter and amplifiers. The response of the FIR filter is not included in the following description. It is flat up to approximately 40 Hz and falls off abruptly for higher frequencies (Nanometrics 1990).

At present six types of seismometers have been implemented, the 1 Hz Lennartz LE–3D, the 5 sec Lennartz LE–3D/5s (Lennartz 1990), the Streckheisen STS–2 used at the IRIS station in Borgarfjörður, Guralp CMG–3T, provided by the University of Cambridge and Guralp CMG–3T and CMG–3ESP from the Passcal instrument pool.

The velocity response of the RD3/OSD3 digitizer is independent of frequency from approximately 1 Hz up to about 40 Hz. All the seismometer types in use in the SIL network also have flat response curves in this frequency band. However, their sensitivity differs by more than a factor of five and for the broadband instruments the passband extends down to 0.01 Hz. The difference in amplification has to be accurately accounted for in the analysis of the data, especially since estimates of absolute spectral amplitudes are used to constrain the focal mechanisms of earthquakes recorded by the SIL system.

This report documents the frequency response of the digitizer and geophones currently in use in the SIL network and describes the implementation of instrument calibration data in the system.

2. THE RD3/OSD3 DIGITIZER

Referring to Figure 1 (Nanometrics 1990), the equations to be solved to find the relationship between input and output signals (V_{in} and V_{out}) of the fourth order low–pass filter are:

$$\begin{aligned}
V_{in} &= V_1 + \left(\frac{V_1 - V_2}{R_9} - \left(V_{out} - V_1\right) C_{23} s\right) R_8 && (2)\\
V_1 &= V_2 + \left(\frac{V_2 - V_3}{R_{10}} + V_2 C_{25} s\right) R_9 && (3)\\
V_2 &= V_3 + \left(\frac{V_3 - V_4}{R_{11}} - \left(V_{out} - V_3\right) C_{24} s\right) R_{10} && (4)\\
V_3 &= V_4 + V_4 C_{26} s R_{11} && (5)\\
V_4 &= 1/2 V_{out} && (6)
\end{aligned}$$

After some algebra, equations 2–6 give:

$$\begin{aligned}
T_1(s) &= \frac{V_{out}}{V_{in}}\\
&= \frac{2}{1 + k_1 s + k_2 s^2 + k_3 s^3 + k_4 s^4} && (7)
\end{aligned}$$

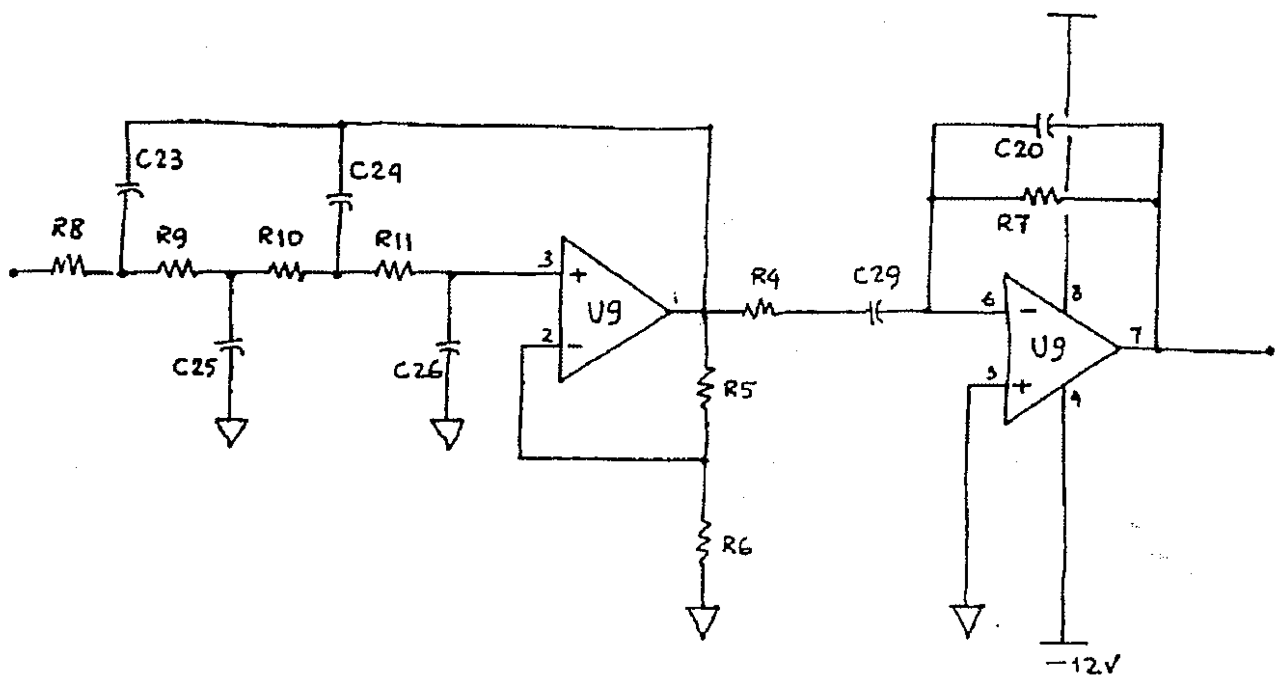

Figure 1. *Schematic diagram of the analogue low–pass and band–pass filters in the RD3/OSD3 digitizer (Nanometrics 1990).*

where:

$$\begin{aligned} k_1 &= (R_8+R_9+R_{10}+R_{11})\,C_{26} \\ &\quad -(R_8+R_9+R_{10})\,C_{24}+(R_8+R_9)\,C_{25}-R_8C_{23} \qquad (8)\\ k_2 &= R_{11}\,(R_8+R_9+R_{10})\,C_{24}C_{26}-(R_8+R_9)\,(R_{10}+R_{11})\,C_{25}C_{26} \\ &\quad -R_{10}\,(R_8+R_9)\,C_{25}C_{26}-(R_9+R_{10}+R_{11})\,C_{23}C_{26} \\ &\quad -R_8\,(R_9+R_{10})\,C_{23}C_{24}+R_8R_9C_{23}C_{25} \qquad (9)\\ k_3 &= (R_8+R_9)\,R_{10}R_{11}C_{24}C_{25}C_{26}-R_8R_{11}\,(R_9+R_{10})\,C_{23}C_{24}C_{26} \\ &\quad +R_8R_9\,(R_{10}+R_{11})\,C_{23}C_{25}C_{26}-R_8R_9R_{10}C_{23}C_{24}C_{25} \qquad (10)\\ k_4 &= R_8R_9R_{10}R_{11}C_{23}C_{24}C_{25}C_{26} \qquad (11) \end{aligned}$$

Inserting numbers for the components of the 4th order filter (see Appendix A) gives:

$$\begin{aligned} k_1 &= 6.910\cdot10^{-3} \\ k_2 &= 2.267\cdot10^{-5} \\ k_3 &= 3.907\cdot10^{-8} \\ k_4 &= 3.341\cdot10^{-11} \qquad (12) \end{aligned}$$

Similarly, for the second order bandpass filter, the frequency response is:

$$\begin{aligned} T_2(s) &= \frac{R_7C_{29}s}{1+(R_7C_{20}+R_4C_{29})\,s+R_4R_7C_{20}C_{29}s^2} \\ &= \frac{B_0s}{b_0+b_1s+b_2s^2} \qquad (13)\\ &= \frac{0.301s}{1+0.318s+7.800\cdot10^{-4}s^2} \end{aligned}$$

The frequency response of the two filters is then given by:

$$
\begin{aligned}
T_{RD3}(s) &= T_1 T_2 \\
&= \frac{2B_0 s}{P(s)}
\end{aligned}
\tag{14}
$$

where:

$$
\begin{aligned}
P(s) = {} & b_0 + (b_1 + b_0 k_1)s + (b_0 k_2 + b_1 k_1 + b_2)s^2 + (b_0 k_3 + b_1 k_2 + b_2 k_1)s^3 \\
& + (b_0 k_4 + b_1 k_3 + b_2 k_2)s^4 + (b_1 k_4 + b_2 k_3)s^5 + b_2 k_4 s^6
\end{aligned}
\tag{15}
$$

and the k's are given by equation 12 and the b's by equation 13. Inserting numbers, the frequency response of the RD3 system is:

$$
T_{RD3}(s) = \frac{0.602s}{\begin{array}{c}1 + 0.325s + 3.003 \cdot 10^{-3}s^2 + 1.265 \cdot 10^{-5}s^3 \\ +3.016 \cdot 10^{-8}s^4 + 4.111 \cdot 10^{-11}s^5 + 2.606 \cdot 10^{-14}s^6\end{array}}
\tag{16}
$$

The function T_{RD3} obviously has one zero at zero frequency. The poles where found using standard numerical routines (programmes `zroots` and `laguer`, (Press et al. 1988)) and are:

$$
\begin{array}{lcr}
-405.1531 & - & 4.2385 \cdot 10^{-6}i \\
-344.4844 & + & 195.8466i \\
-344.4844 & - & 195.8466i \\
-240.2125 & - & 364.5749i \\
-240.2125 & + & 364.5749i \\
-3.1646 & + & 0.0000i
\end{array}
$$

The frequency independent gain of the system is the multiple of the pre–amplifier (0.908), the post–amplifier ($\frac{255R_{38}}{2.55(R_{37}+R_{38})} = 53.64$) and the filter gains (137μV/bit), i.e.:

$$
\begin{aligned}
g_{DC} &= 0.908 \times 53.64 \times \frac{1}{137 \cdot 10^{-6}} \\
&= 3.56 \cdot 10^5 [count/V]
\end{aligned}
\tag{17}
$$

See Figure 4 in Nanometrics (1990) and Appendix B for explanations of the numbers given above. The frequency response of the RD3/OSD3 digitizer can then be written:

$$
T_{RD3} = \frac{2B_0 g_{DC} s}{P(s)}
\tag{18}
$$

3. THE SEISMOMETERS

The seismometers can be thought of as having a mass M attached to a point of the earth's surface through a parallel arrangement of a spring and a dashpot. Denote the ground motion by $u(t)$ and the motion of the mass relative to the earth as $\xi(t)$. The spring will exert a force proportional to its elongation $\xi(t) - \xi_0$ and the dashpot will exert a force proportional to the velocity $\dot{\xi}(t)$ between the mass and the earth. Denoting the constants of proportionality by k and D respectively, the equation of motion for the mass is (Aki and Richards 1980):

$$
M(\ddot{\xi}(t) + \ddot{u}(t)) + D\dot{\xi}(t) + k(\xi(t) - \xi_0) = 0
\tag{19}
$$

Rewriting the displacement $\xi(t) - \xi_0$ relative to the equilibrium position of the spring ξ_0 as $\xi(t)$, this can be written:

$$\ddot{\xi}(t) + 2\varepsilon\dot{\xi}(t) + \omega_0^2\xi(t) = -\ddot{u}(t) \tag{20}$$

where $2\varepsilon = D/M$ and $\omega_0^2 = k/M$. ε then describes the damping of the geophone and ω_0 the eigen frequency. Laplace transforming both sides of equation 20 and rearranging gives the frequency response $T_{geo}(s)$ of the seismometer as:

$$\begin{aligned} T_{geo}(s) &= \frac{u(s)}{\xi(s)} \\ &= \frac{-s^2}{s^2 + 2\varepsilon s + \omega_0^2} \end{aligned} \tag{21}$$

In general the geophone will also have some frequency independent gain, g_{geo}. The frequency response of the geophone will then be:

$$T_{geo}(s) = \frac{-g_{geo}s^2}{s^2 + 2\varepsilon s + \omega_0^2} \tag{22}$$

For the Lennartz geophones g_{geo} = 400.0V/m/s (Lennartz 1990). The poles of $T_{geo}(s)$ are given by:

$$s_p = -\varepsilon \pm \sqrt{\varepsilon^2 - \omega_s^2} \tag{23}$$

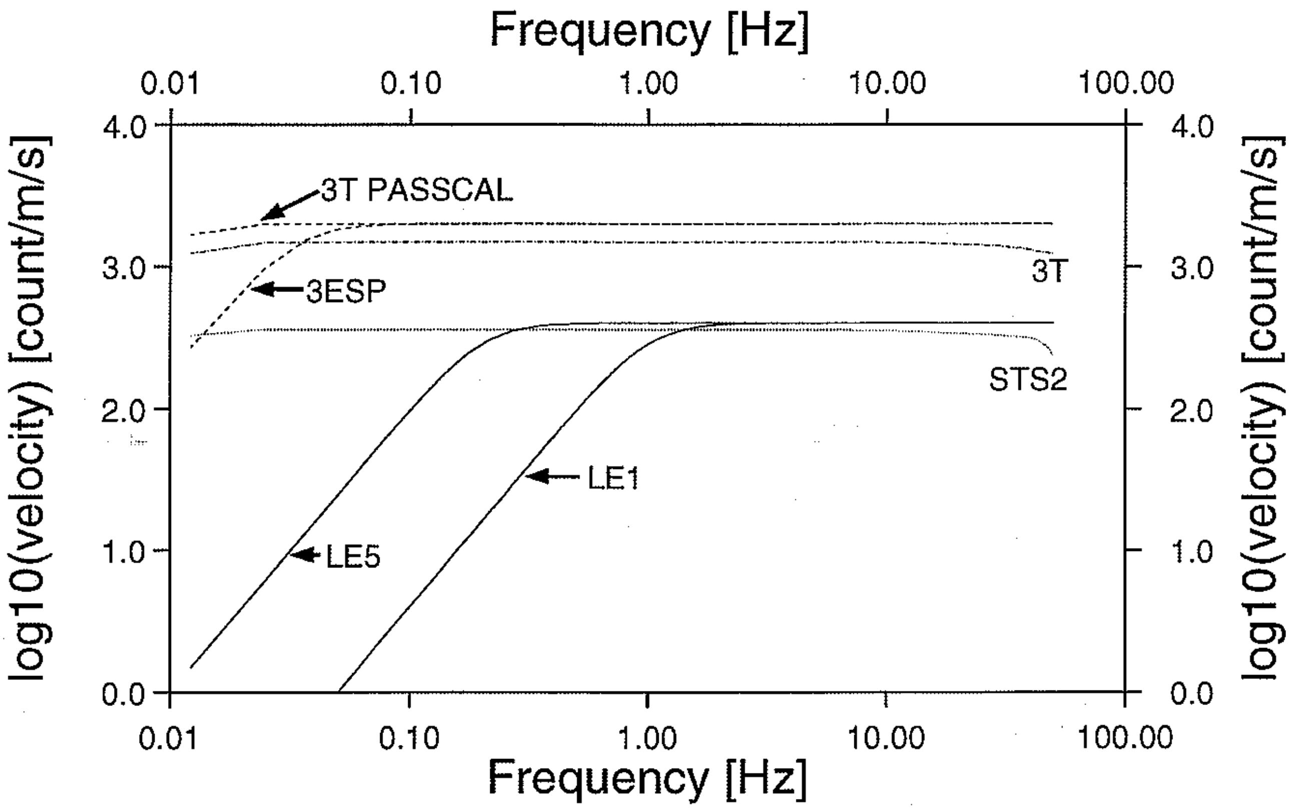

Figure 2. *The frequency response of the six geophone types currently in use in the SIL network. The LE1 and LE5 are Lennartz 1 and 0.2 Hz geophones, STS2 is the Streckheisen geophone at station ASB, 3T is Guralp CMG–3T, calibrated at Bullard Laboratories, 3T PASSCAL is a Guralp CMG–3T from the Passcal instrument pool and 3ESP refers to a Guralp CMG–3ESP from Passcal.*

Defining the damping constant h as $h = \varepsilon/\omega$, a critically damped geophone will have $h = 1.0$. For an underdamped geophone $h \ll 1.0$ and for an overdamped geophone $h \gg 1.0$ (Aki and Richards 1980). Equation 23 can then be rewritten as:

$$s_p = \left(-h \pm \sqrt{h^2 - 1}\right) \omega_0 \tag{24}$$

For a 1 Hz geophone, damped at $0.707 \times$ critical damping (i.e. $h = 0.707$), $\omega_0 = \frac{2\pi}{T} = 2\pi$, where T is the period, the poles are (from equation 24):

$$s_p = -4.442 \pm 4.443i \tag{25}$$

For a seismometer with a 5 sec eigen period and a damping constant of 0.707 (i.e. the LE-3D/5s geophone), equation 24 gives:

$$s_p = -0.888 \pm 0.889i \tag{26}$$

The above description is valid for the classical mechanical devices widely used and also for the Lennartz seismometers which simulate these devices. For other active seismometers, such as instruments with displacement transducers, the equations are slightly different but have the same general form. The poles and zeros of all seismometer types currently in use in the SIL network are given in Appendix A. For all seismometers other than the Lennartz instruments the specifications are taken from manuals shipped with the instruments. The frequency response of the six geophones is shown in Figure 2.

In the first three years of operation of the SIL network (1989–1991), the poles used for the Lennartz LE–3D 1 Hz geophones ($s_p = -3.83 \pm 4.98i$) where obtained from specifications of S13 seismometers with a damping constant of 0.61. This frequency response differs slightly from the actual Lennartz response for frequencies around 1 Hz (see Figure 3).

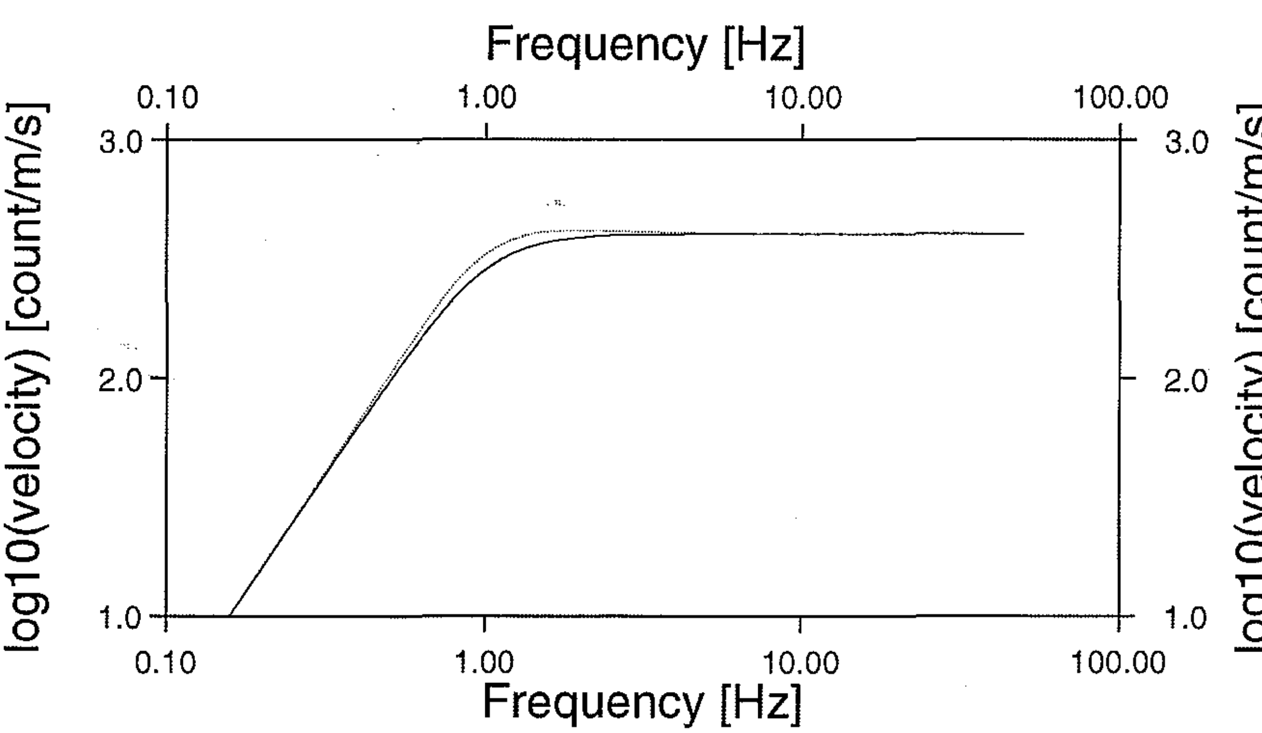

Figure 3. *The frequency response of 1 Hz geophones with 0.6 (dotted line) and 0.707 times critical damping (solid line).*

4. THE DIGITIZER AND SEISMOMETERS

A more general form of the digitizer transfer function (equation 22) is:

$$T_{dig}(s) = \frac{g_{dig}p(s)}{P(s)} \tag{27}$$

Similarly the frequency response of a geophone can be expressed as:

$$T_{geo}(s) = \frac{g_{geo}q(s)}{Q(s)} \tag{28}$$

where q and Q are polynomials in s.

The combined frequency response of a digitizer and a seismometer is the multiple of the two response functions, $T_{dig}(s)$ for the digitizer and $T_{geo}(s)$ for the response of the geophone, i.e.:

$$\begin{aligned} T_{total}(s) &= T_{dig}T_{geo} \\ &= g_{dig}\frac{p(s)}{P(s)}g_{geo}\frac{q(s)}{Q(s)} \end{aligned} \tag{29}$$

where g_{dig} and g_{geo} are the gains of the digitizer and geophone and p, P, q and Q are polynomials. For the RD3/OSD3, $p(s)$ is of first order and $P(s)$ of forth order. For the Lennartz geophones, both $q(s)$ and $Q(s)$ are second order polynomials, where as for the Streckheisen STS–2 $q(s)$ is of order three and $Q(s)$ of order eleven.

The velocity proportional frequency response of the SIL system is shown in Figure 4 for the six types of geophones.

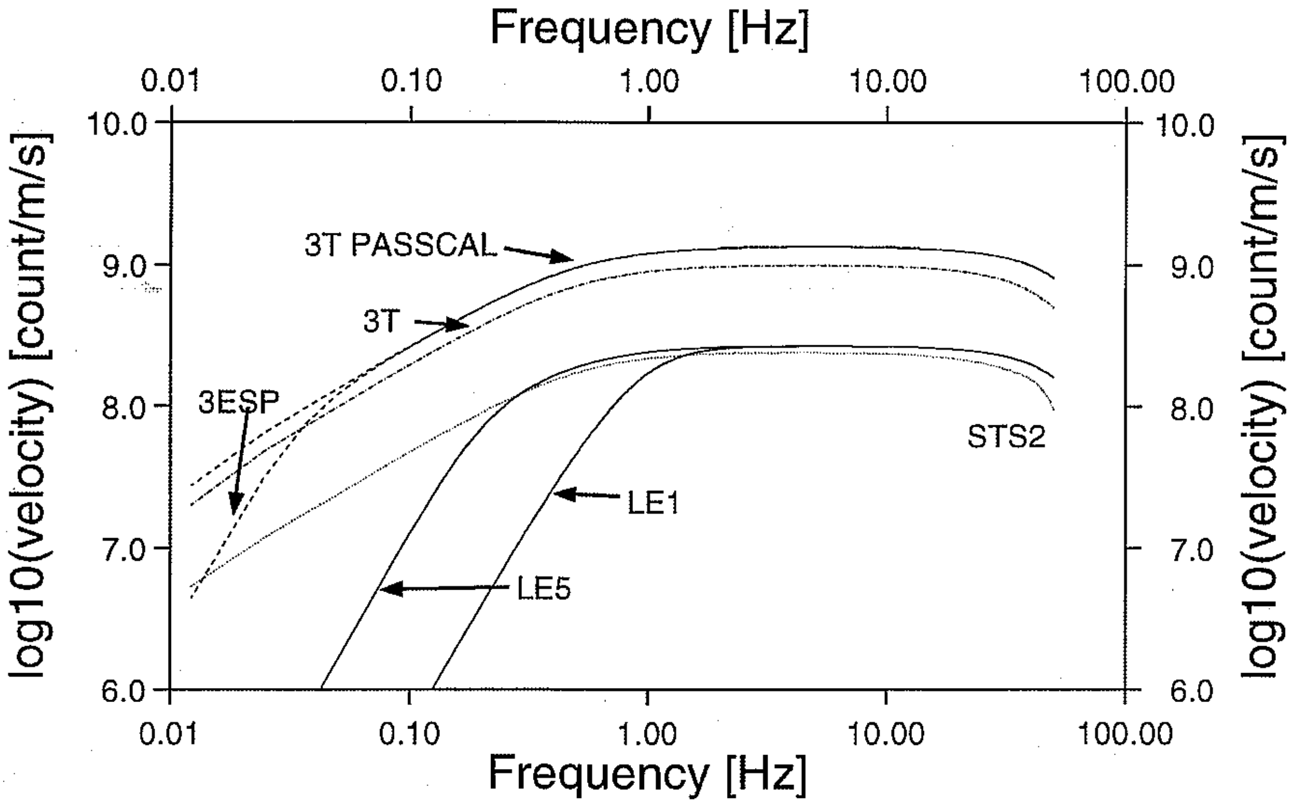

Figure 4. *The frequency response of the RD3/OSD3 digitizer and six different geophones.*

The total gain of the system is the multiple of the filter gain $2B_0$ (equation 14), the frequency independent gain g_{DC} of the digitizer (equation 17), and the generation constant of the geophone, g_{geo}, i.e.:

$$\begin{aligned} g &= 2B_0 g_{DC} g_{geo} \\ &= 0.602 \times 3.559 \cdot 10^5 \times g_{geo} \end{aligned} \quad (30)$$

For the Lennartz geophones g_{geo} is 400.0 V/m/s while for Guralp seismometers from the Passcal instrument pool g_{geo} is 2000.0 V/m/s, giving a factor five difference in over all gain.

5. GROUND DISPLACEMENT AND ACCELERATION

The seismometers of the SIL array can be used as accelerometers by modifying the transfer function slightly. The frequency response described by equation 29 and shown in Figure 4 is proportional to the velocity of the ground motion at the geophone site. Acceleration is the time derivative of velocity. In the frequency domain this corresponds to multiplying the input signal (i.e. ground velocity) by s. To find the response of the SIL system to ground acceleration the velocity proportional transfer function is divided by frequency, i.e. one extra pole is added at (0.0, 0.0). Equation 29 then becomes:

$$\begin{aligned} T_{acc}(s) &= \frac{1}{s} T_{total}(s) \\ &= \frac{g_{dig} g_{geo}}{s} \frac{p(s)}{P(s)} \frac{q(s)}{Q(s)} \end{aligned} \quad (31)$$

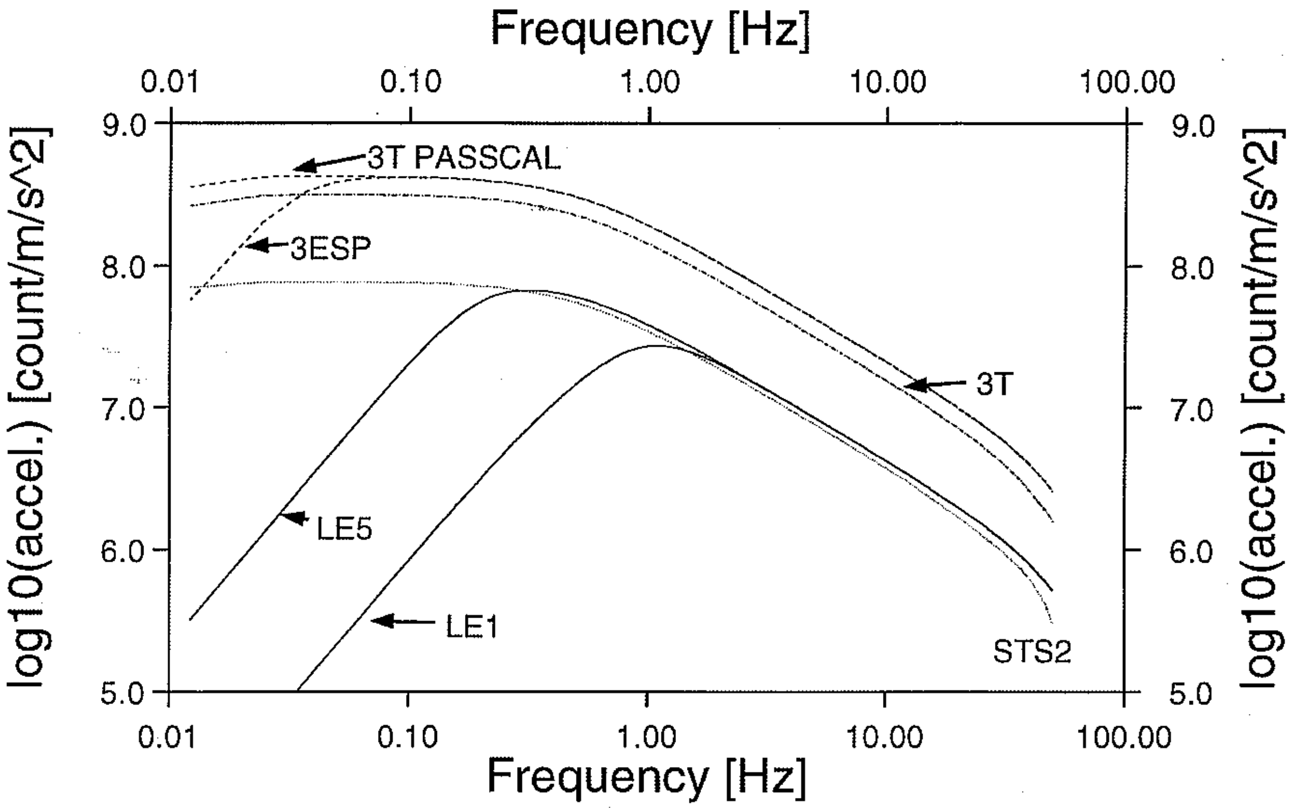

Figure 5. *The acceleration response of the RD3/OSD3 digitizer with six different geophones.*

To obtain the acceleration at the recording station, the spectra of the seismograms are divided by T_{acc}. Figure 5 shows a plot of T_{acc} versus frequency for the six types of geophones used in the SIL system. For the two short period instruments, the response has a peak at their respective eigen frequencies. For the broadband instruments the acceleration response is flat from about 0.2 Hz (determined by the digitizer) down to the respective eigen frequency of each geophone type.

The ground displacement at the geophone sites can be obtained from the velocity proportional seismograms by integration. In the frequency domain this corresponds to dividing the input of the system by s or, equivalently, multiplying the transfer function by s. This implies adding one zero at (0.0, 0.0). Equation 29 then gives the displacement proportional transfer function as:

$$\begin{aligned} T_{dis}(s) &= sT_{total}(s) \\ &= g_{dig}g_{geo}s\frac{p(s)}{P(s)}\frac{q(s)}{Q(s)} \end{aligned} \tag{32}$$

To obtain the ground motion, the spectra of the seismograms are divided by T_{dis}. Figure 6 shows T_{dis} as a function of frequency for the six seismometer types.

6. IMPLEMENTATION

The information on what type of instrument is in operation at a given SIL station is stored in the master configuration file /usr/sil/etc/sil.cf at each station. Calibration data (poles, zeros and gain) for all implemented geophone and digitizer types are stored in separate files, called

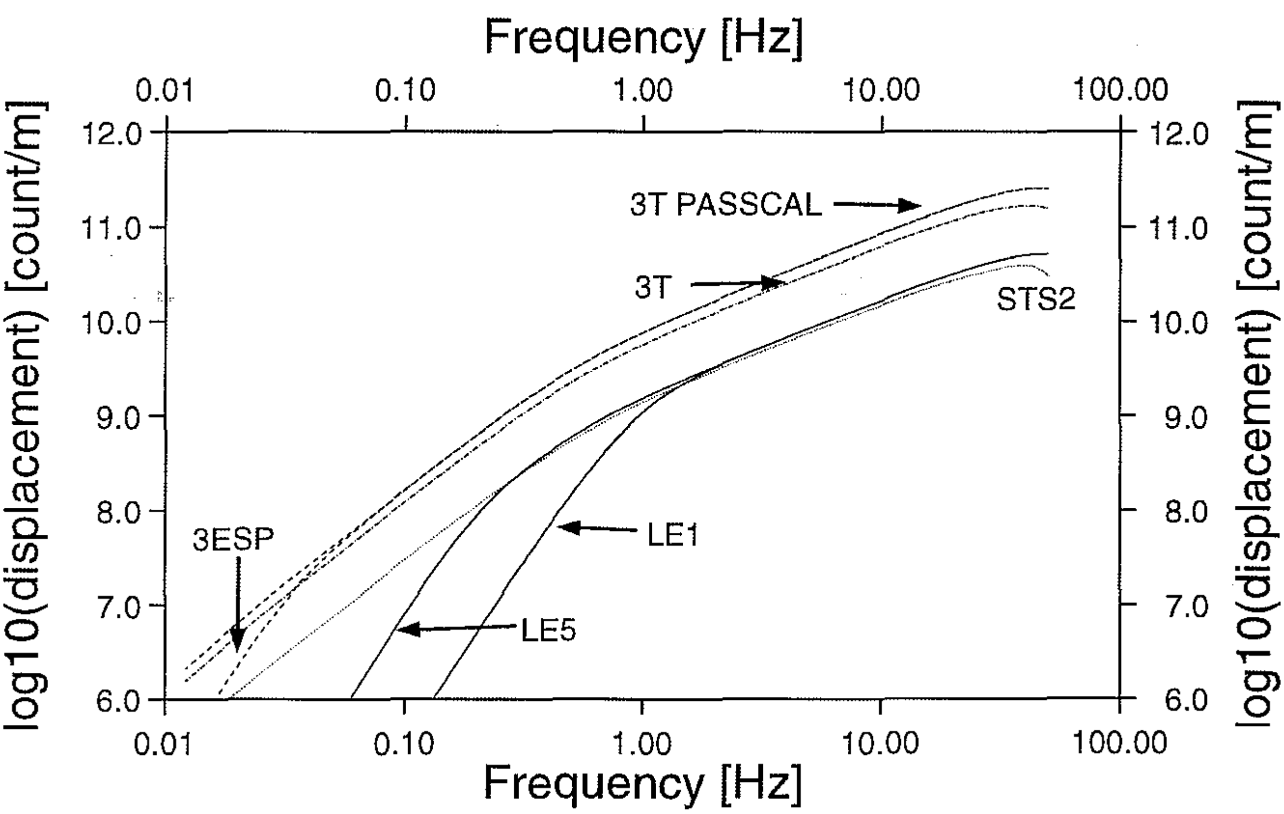

Figure 6. *The displacement response of the RD3/OSD3 digitizer with six different geophones.*

NAME.resp, on the /usr/sil/etc directory. Here NAME is the instrument type, e.g. LE1 for the Lennartz LE-3D geophone, RD3 for the RD3/OSD3 digitizer, etc. The calibration data file for Guralp CMG-3T GURALP.resp is printed below.

```
#
# GURALP.resp:
# The gain, poles and zeros of the transfer function for the
# Guralp CMG-3T broadband geophone.  Data from "Test and calibration
# data, CMG-3T Serial No:  T3192, T3193, T3194, T3196 and T3197",
# Guralp Systems report.
# Author:
# Sigurdur Th. Rognvaldsson
# Date:
# 24-06-1995
# Note:
# The gain quoted here is the multiple of output sensitivity (G in
# the Guralp report) and the normalizing factor (A in Guralp report).
# A factor of 2pi is also included to convert from s=if used in the
# calibration report to s=2pi*if used in IMO report.  Thus:
# gain = 2pi*G*A.  The output sensitivity or velocity output, G, is
# taken as the mean of all 15 channels which have been calibrated,
# i.e. G=2*756 +- 5 [V/m/s].  A = -49.5.  Hence
# gain = 2*pi*2*756*(-49.5) = -4.702587e+05
#
-4.702587e+05 # Guralp geophone gain.
4  # Number of poles.
-4.44221e-02 4.44221e-02  # Poles
-4.44221e-02 -4.44221e-02
-5.057964e+02 1.935221e+02
-5.057964e+02 -1.935221e+02
3 # Number of zeros.
0.0 0.0 # Zeros
0.0 0.0
9.456194e+02 0.0
```

The calibration information in the RD3.resp file contains one additional zero to transform the data from ground velocity to displacement.

At start-up, the data acquisition software reads the instrument type from the configuration file, looks for the appropriate NAME file and reads the necessary calibration data. This is needed to estimate the absolute spectral amplitudes of triggering phases and to produce normalized amplitude data for use by the central selection software.

At the center similar calibration data files are used by the central processing software to remove the instrument response from the recorded waveforms. When the waveforms arrive from the site stations, appropriate calibration data for the recording station is written in the *ah* header before the data is stored on disk. The transfer function is specified by its poles and zeros in the s-domain. The calibration information in the *ah* header also contains one additional zero to transform the data from ground velocity to displacement. The coefficient of the highest power of s in equation 16 is used as a normalization factor in the *ah* programmes.

Storing the calibration data in every waveform data file is a waste of disk space and in future versions of the database calibration data will be kept in separate tables linked to the compactly stored waveforms.

Acknowledgements
Reviews by Kristín Vogfjörð and Helgi Gunnarsson improved the manuscript.

APPENDIX A. Poles and zeros of the different geophone types

The following sections summarize the calibration data for the six different seismometers currently in use in the SIL network.

A.1 Poles and zeros of the 1 Hz Lennartz LE–3D geophones

Poles:

$$-4.442 + 4.443i$$
$$-4.442 - 4.443i$$

Zeros:

$$0.0 + 0.0i$$
$$0.0 + 0.0i$$

The sensitivity of the Lennartz LE–3D is 400.0 V/m/s.

A.2 Poles and zeros of the 0.2 Hz Lennartz LE–3D/5s geophones

Poles:

$$-0.888 + 0.889i$$
$$-0.888 - 0.889i$$

Zeros:

$$0.0 + 0.0i$$
$$0.0 + 0.0i$$

The sensitivity of the Lennartz LE–3D/5s is 400.0 V/m/s.

A.3 Poles and zeros of the Streckheisen STS–2 seismometer

The velocity response of the Streckheisen STS–2 seismometer used at the IRIS station in Borgarfjörður has a passband from about 40 Hz down to at least 10^{-2} Hz (Figure 2).
Poles:

$$\begin{aligned}
-3.702404 \cdot 10^{-2} &+ 3.702401 \cdot 10^{-2}i \\
-3.702404 \cdot 10^{-2} &- 3.702401 \cdot 10^{-2}i \\
-2.513274 \cdot 10^{2} &+ 0.000000i \\
-1.310396 \cdot 10^{2} &+ 4.672899 \cdot 10^{2}i \\
-1.310396 \cdot 10^{2} &- 4.672899 \cdot 10^{2}i \\
-3.034778 \cdot 10^{2} &+ 8.122339 \cdot 10^{1}i \\
-3.034778 \cdot 10^{2} &- 8.122339 \cdot 10^{1}i \\
-2.221442 \cdot 10^{2} &+ 2.221441 \cdot 10^{2}i \\
-2.221442 \cdot 10^{2} &- 2.221441 \cdot 10^{2}i \\
-8.130442 \cdot 10^{1} &+ 3.034561 \cdot 10^{2}i \\
-8.130442 \cdot 10^{1} &- 3.034561 \cdot 10^{2}i
\end{aligned}$$

Zeros:

$$0.0 + 0.0i$$
$$0.0 + 0.0i$$

The Streckheisen STS–2 geophone has a leading factor ($A0$ in the *ah* header) of $5.699996 \cdot 10^{22}$ and its gain (DS in the *ah* header) is 360.0 V/m/s. Information on the poles and zeros of the STS–2 seismometer comes from Pete Davis, pdavis@yin.ucsd.edu.

A.4 Poles and zeros of the Guralp CMG–3T seismometer

Poles:

$$\begin{array}{lcl} -4.44221 \cdot 10^2 & + & 4.44221 \cdot 10^2 i \\ -4.44221 \cdot 10^2 & - & 4.44221 \cdot 10^2 i \\ -5.05796 \cdot 10^2 & + & 1.93522 \cdot 10^2 i \\ -5.05796 \cdot 10^2 & - & 1.93522 \cdot 10^2 i \end{array}$$

Zeros:

$$\begin{array}{lcl} 0.0 & + & 0.0i \\ 0.0 & + & 0.0i \\ 9.45619 \cdot 10^2 & + & 0.0i \end{array}$$

The average sensitivity of the five Guralp CMG–3T geophones installed in Iceland is 1512 ± 5 V/m/s. The normalizing factor is $-2\pi \times 49.5$. The gain is then $-4.702587 \cdot 10^5$. The poles and zeros for the Guralp seismometer are taken from a report on the calibration of the five instruments installed in Iceland (Guralp 1995).

A.5 Poles and zeros of the Guralp CMG–3T seismometer from the Passcal instrument pool

Poles:

$$\begin{array}{lcr} -0.044 & + & 0.044i \\ -0.044 & + & -0.044i \end{array}$$

Zeroes:

$$\begin{array}{lcl} 0.0 & + & 0.0i \\ 0.0 & + & 0.0i \end{array}$$

The sensitivity of the Guralp CMG–3T Passcal geophones is 2000.0 V/m/s, according to the "Summary sheet for Passcal sensor" information.

A.6 Poles and zeros of the Guralp CMG–3ESP seismometer from the Passcal instrument pool

Poles:

$$\begin{array}{lcr} -0.147 & + & 0.147i \\ -0.147 & + & -0.147i \end{array}$$

Zeroes:

$$\begin{array}{lcl} 0.0 & + & 0.0i \\ 0.0 & + & 0.0i \end{array}$$

The sensitivity of the Guralp CMG–3ESP Passcal geophones is 2000.0 V/m/s, according to the "Summary sheet for Passcal sensor" information.

APPENDIX B. The components of the digitizer

The numerical values of the resistors and capacitors of the RD3/OSD3 digitizer (Figure 1) are given below. See Figure 4, Nanometrics (1990).

$$
\begin{aligned}
R_4 &= 316k\Omega \\
R_5 &= 2.67k\Omega \\
R_6 &= 2.67k\Omega \\
R_7 &= 301k\Omega \\
R_8 &= 8.25k\Omega \\
R_9 &= 29.4k\Omega \\
R_{10} &= 29.4k\Omega \\
R_{11} &= 2.00k\Omega
\end{aligned}
$$

$$
\begin{aligned}
C_{20} &= 8.2nF \\
C_{23} &= 0.22\mu F \\
C_{24} &= 0.22\mu F \\
C_{25} &= 0.22\mu F \\
C_{26} &= 0.22\mu F \\
C_{29} &= 1.0\mu F
\end{aligned}
$$

The relevant components (cf. equation 17) of the amplifiers are the two resistors R_{37} and R_{38}.

$$
\begin{aligned}
R_{37} &= 1.91k\Omega \\
R_{38} &= 2.21k\Omega
\end{aligned}
$$

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