Filters and Seismometers

(after F. Scherbaums book “Of Poles and Zeroes”)

Motivation

From source to receiver...

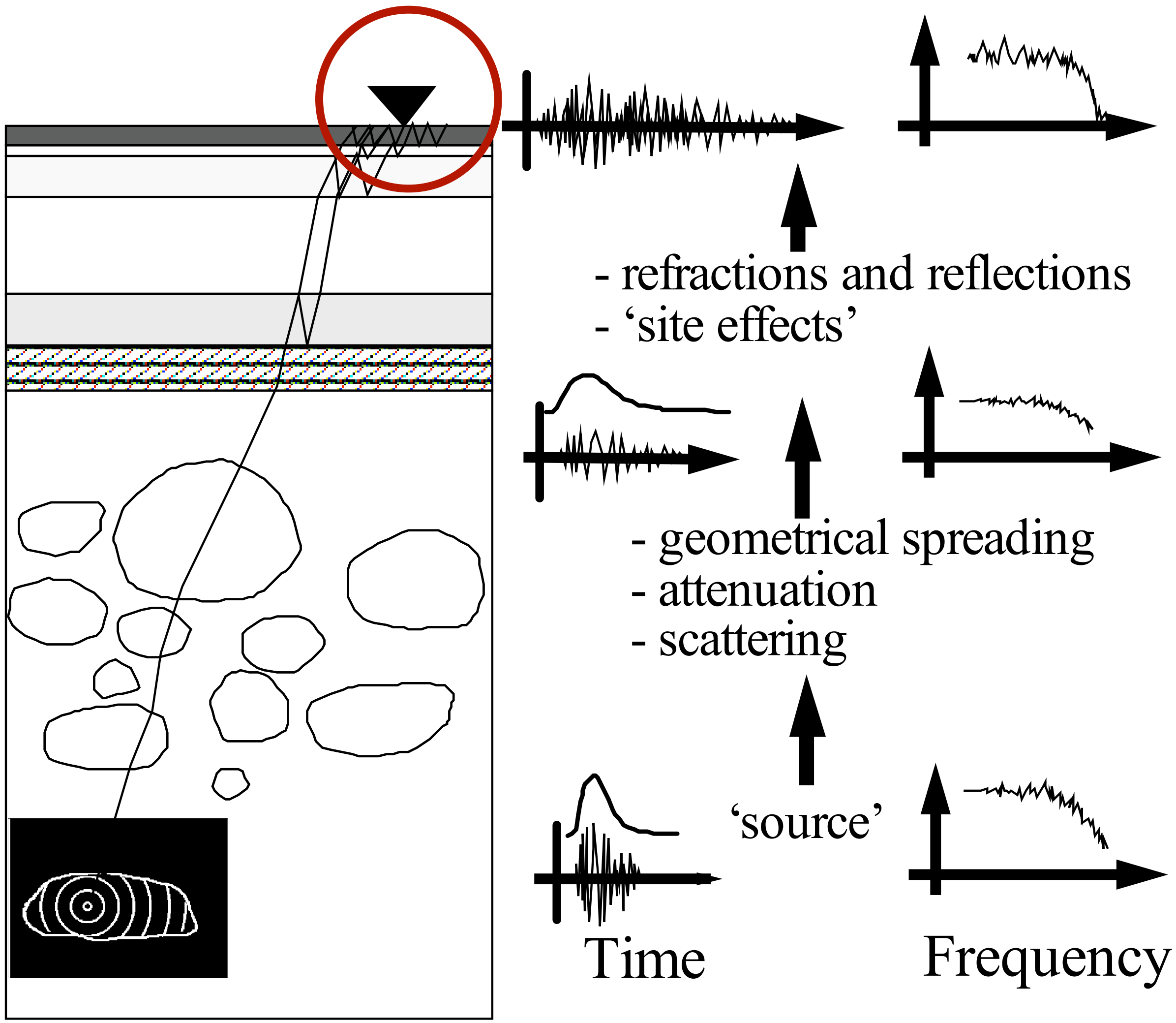


Fig. 1.1 Signal distortion during wave propagation from the earthquake source to the surface.

Influence of recording system

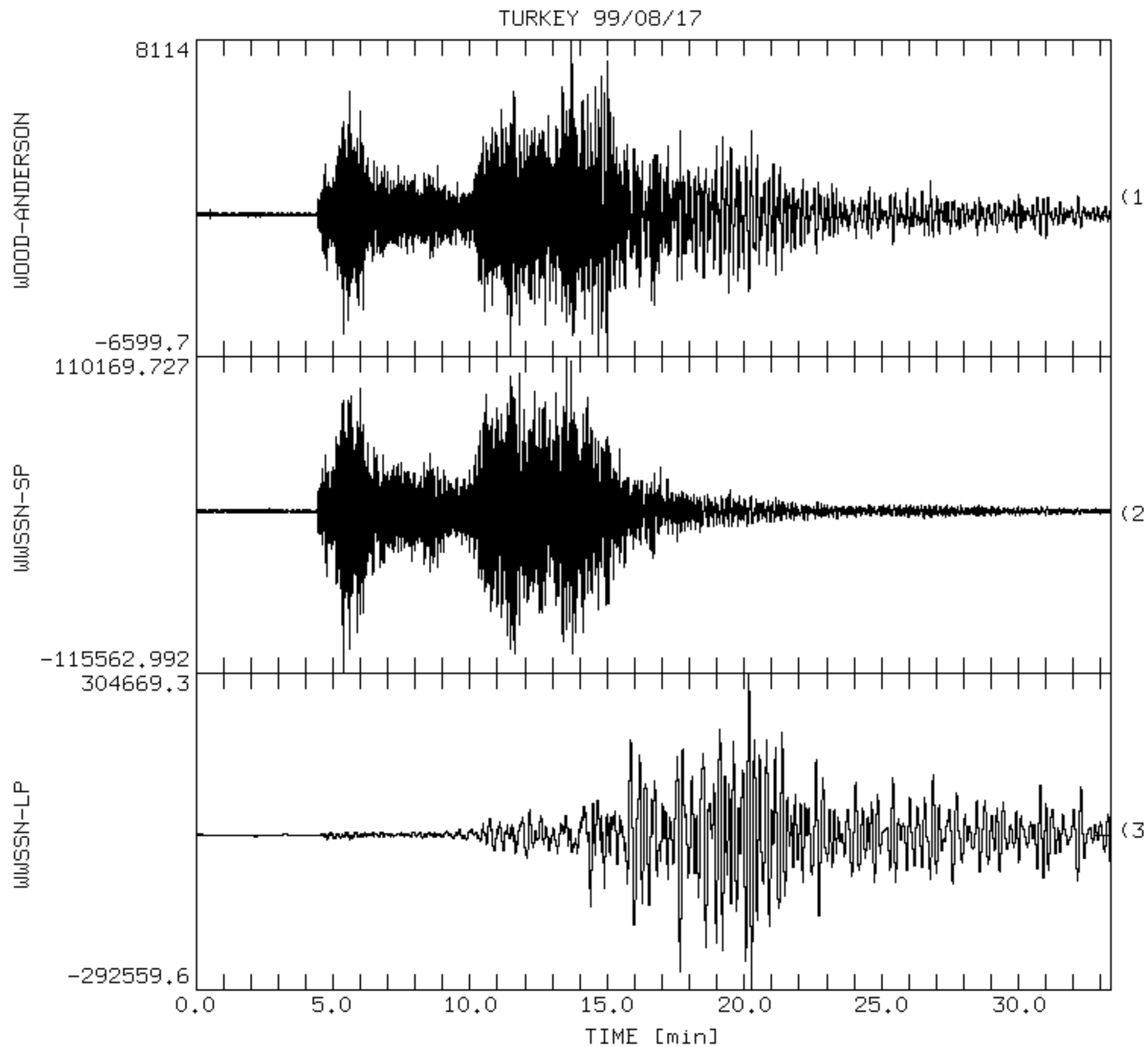


Fig. 1.2 Vertical component record of the Izmit earthquake in Turkey (1999/08/17) recorded at station MA13 of the University of Potsdam during a field experiment in Northern Norway. Shown from top to bottom are the vertical component records for a: Wood-Anderson, a WWSSN SP, and a WWSSN LP instrument simulation.

Displacement spectrum

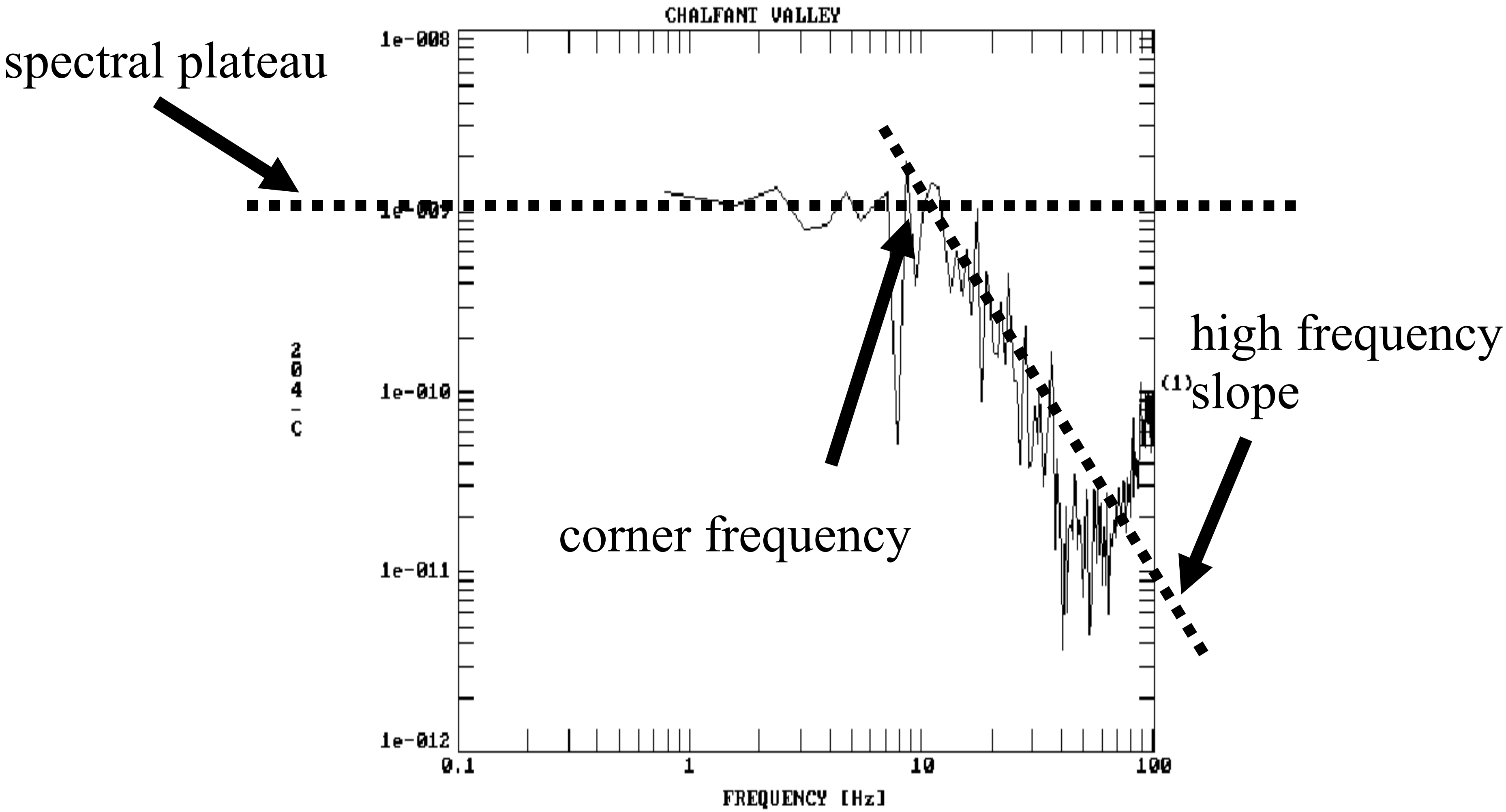


Fig. 1.8 Displacement spectrum for the P- wave portion of the instrument corrected displacement record of station 204 (top trace in Fig. 1.7).

Seismogram

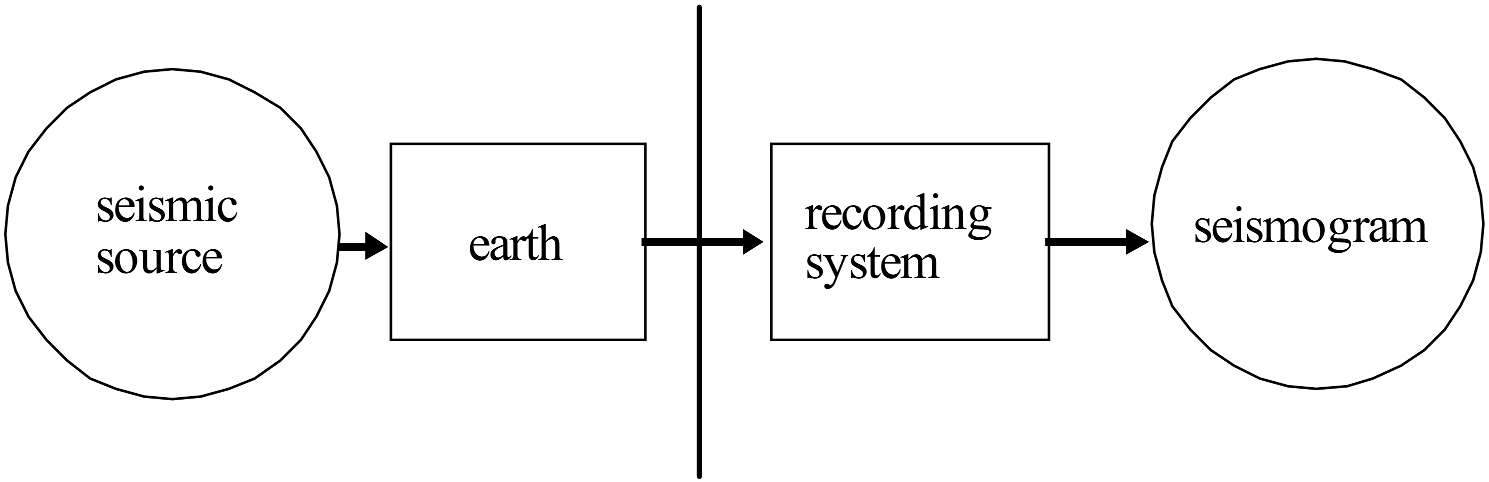
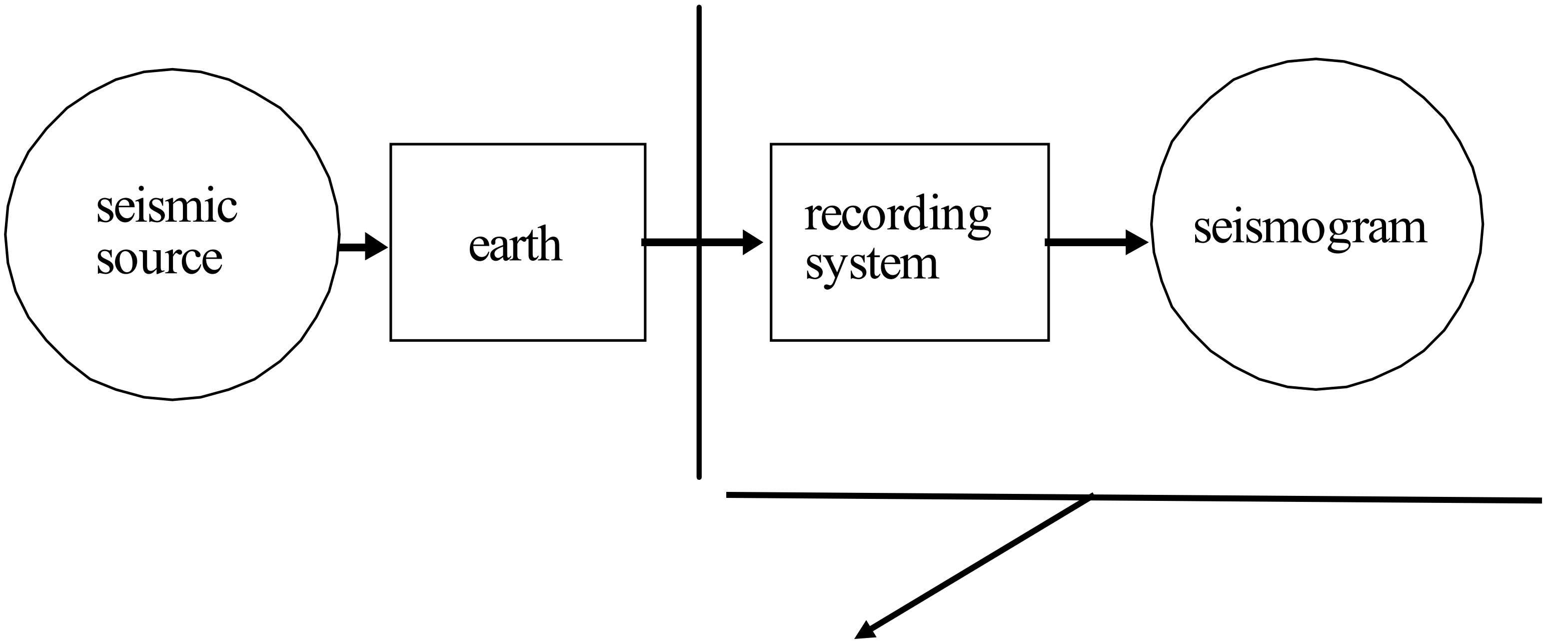
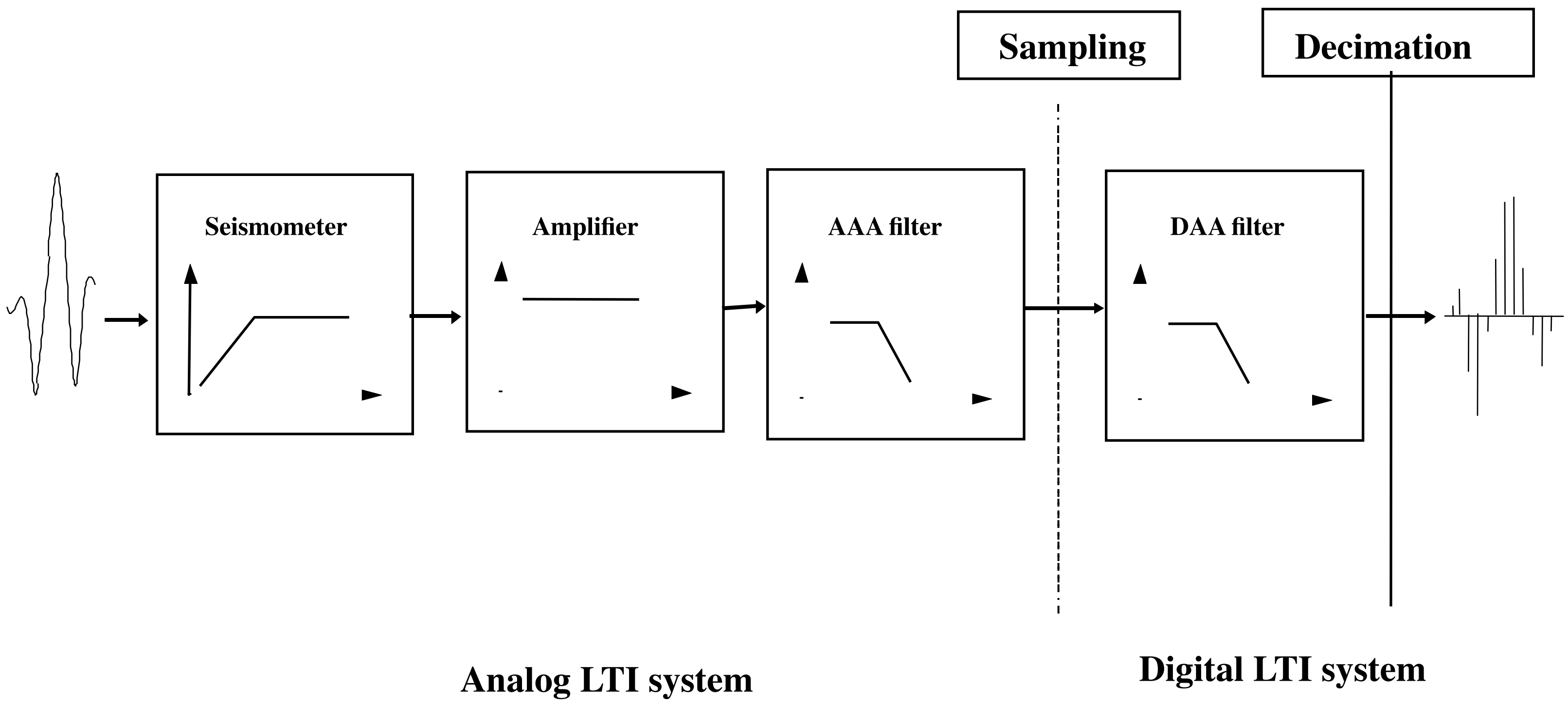


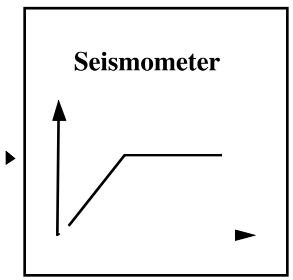
Fig. 1.11 System diagram of a seismogram

Seismogram



This part is covered by stationXML


Sampling
Decimation
Seismometer
Amplifier
AAA filter
DAA filter
Analog LTI system
Digital LTI system

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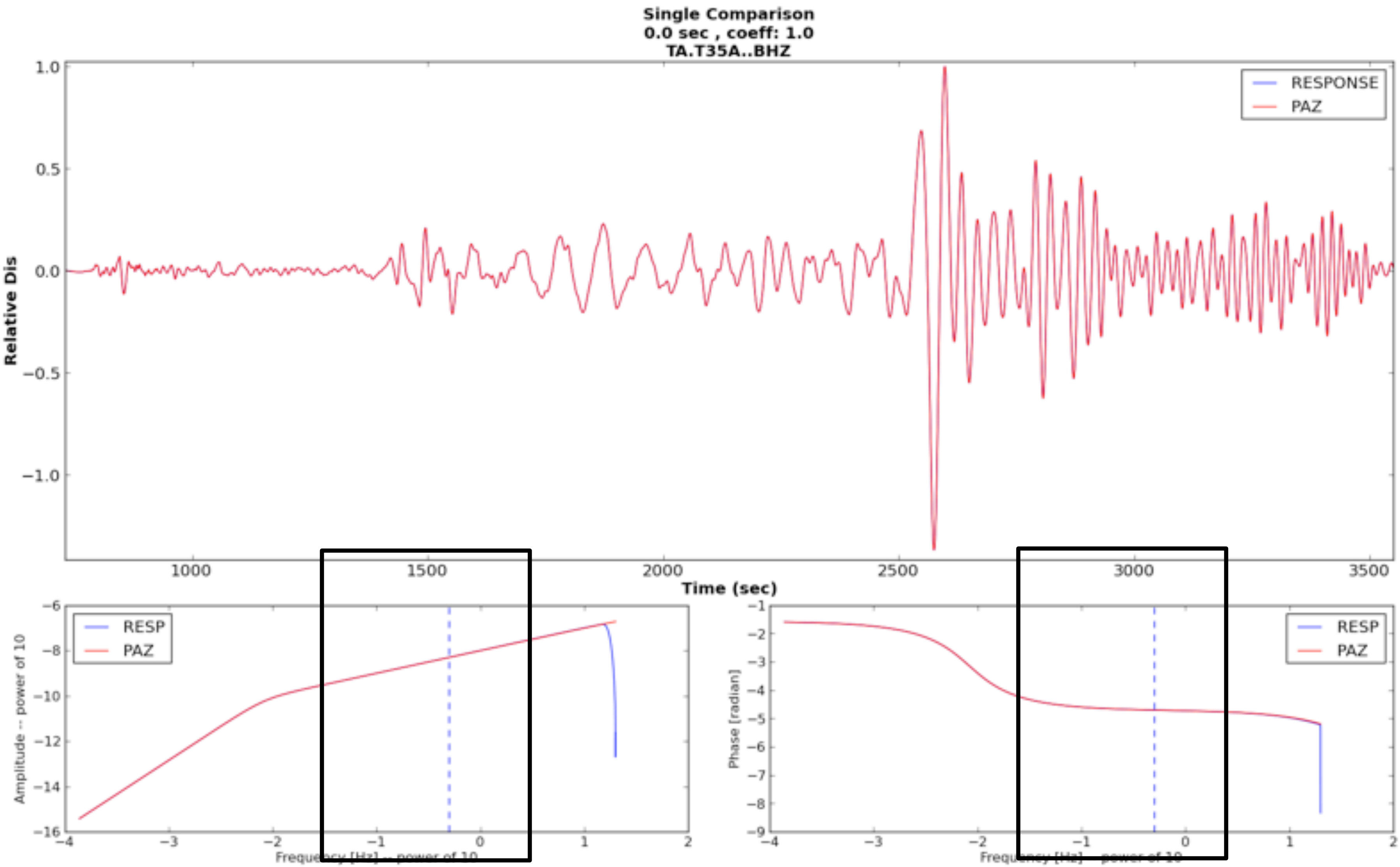
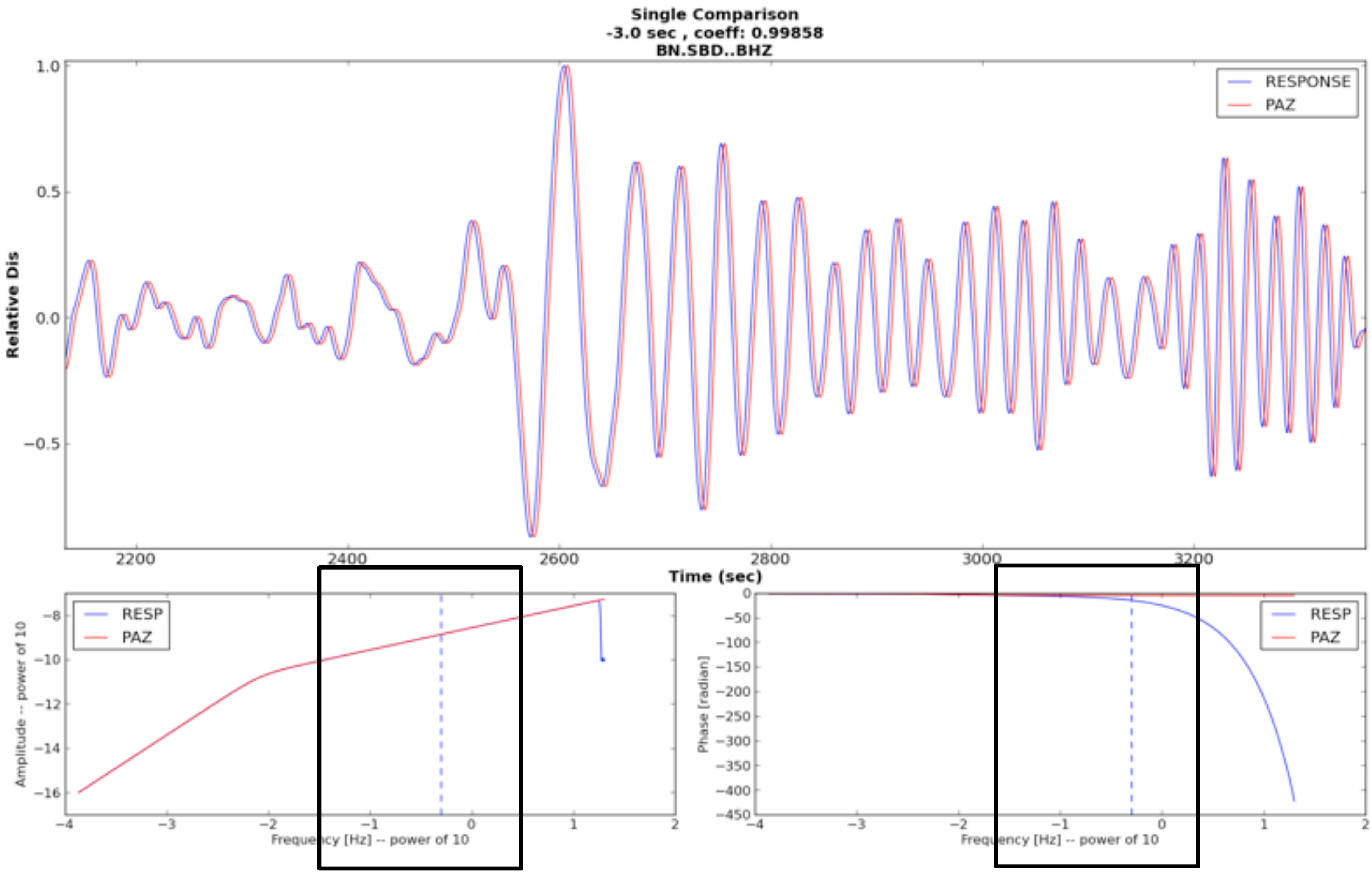
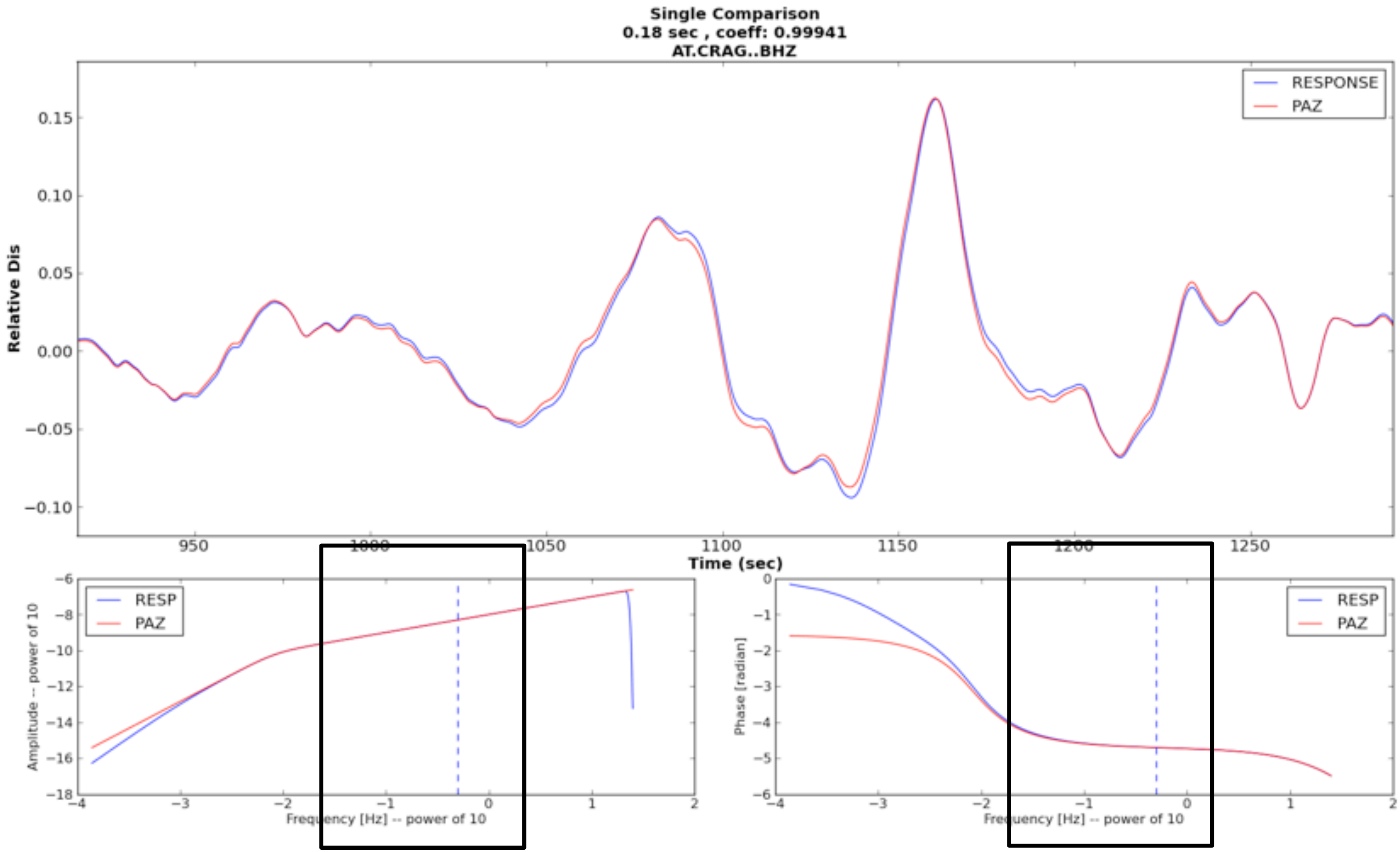
#
#           ======== CHANNEL RESPONSE DATA ========
B050F03     Station:     RJOB
B050F16     Network:     BW
B052F03     Location:    ??
B052F04     Channel:     EHZ
B052F22     Start date:  2007,199
B052F23     End date:    No Ending Time
#           =======================================
#           +            +------------------------------------------+            +
#           +            |  Response (Poles & Zeros),  RJOB ch EHZ  |            +
#           +            +------------------------------------------+            +
#
B053F03     Transfer function type:          A [Laplace Transform (Rad/sec)]
B053F04     Stage sequence number:           1
B053F05     Response in units lookup:        M/S - Velocity in Meters per Second
B053F06     Response out units lookup:       V - Volts
B053F07     A0 normalization factor:         6.0077E+07
B053F08     Normalization frequency:         1
B053F09     Number of zeroes:                2
B053F14     Number of poles:                 5
#           Complex zeroes:
#             i  real          imag          real_error    imag_error
B053F10-13    0  0.000000E+00  0.000000E+00  0.000000E+00  0.000000E+00
B053F10-13    1  0.000000E+00  0.000000E+00  0.000000E+00  0.000000E+00
#           Complex poles:
#             i  real          imag          real_error    imag_error
B053F15-18    0 -3.700400E-02  3.701600E-02  0.000000E+00  0.000000E+00
B053F15-18    1 -3.700400E-02 -3.701600E-02  0.000000E+00  0.000000E+00
B053F15-18    2 -2.513300E+02  0.000000E+00  0.000000E+00  0.000000E+00
B053F15-18    3 -1.310400E+02 -4.672900E+02  0.000000E+00  0.000000E+00
B053F15-18    4 -1.310400E+02  4.672900E+02  0.000000E+00  0.000000E+00
```

Automatic Data Retrieval Using obspyDMT

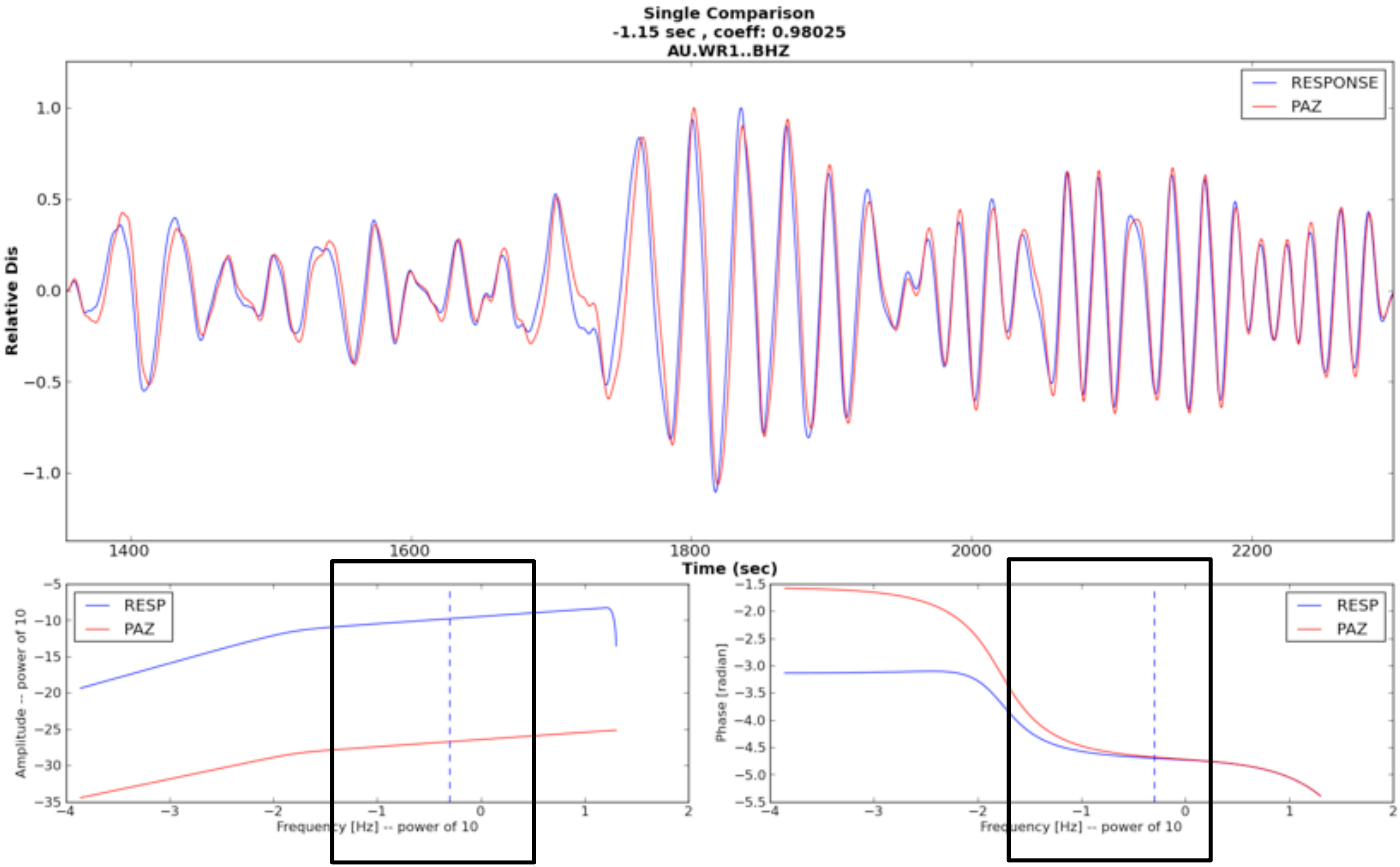




Single Comparison
-3.0 sec , coeff: 0.99858
BN.SBD..BHZ
RESPONSE
PAZ
Relative Dis
Time (sec)
RESP
PAZ
Amplitude -- power of 10
Frequency [Hz] -- power of 10
RESP
PAZ
Phase [radian]
Frequency [Hz] -- power of 10



Single Comparison
0.18 sec , coeff: 0.99941
AT.CRAG..BHZ
RESPONSE
PAZ
Relative Dis
Time (sec)
RESP
PAZ
Amplitude -- power of 10
Frequency [Hz] -- power of 10
RESP
PAZ
Phase [radian]
Frequency [Hz] -- power of 10



Single Comparison
-1.15 sec , coeff: 0.98025
AU.WR1..BHZ
RESPONSE
PAZ
Relative Dis
Time (sec)
RESP
PAZ
Amplitude -- power of 10
Frequency [Hz] -- power of 10
RESP
PAZ
Phase [radian]
Frequency [Hz] -- power of 10

Block diagram

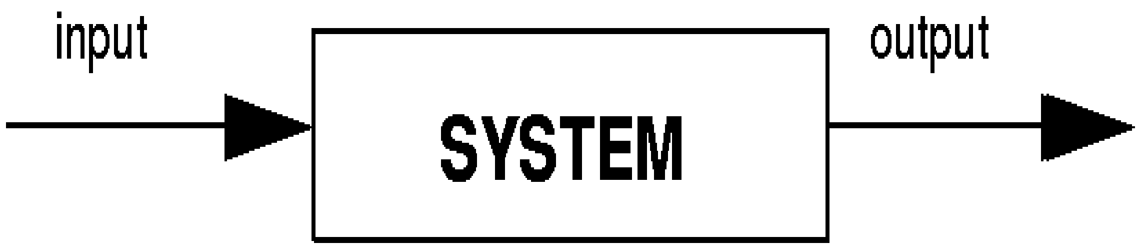


Fig. 1.10 Block diagram of a system

Fourier Transformation

Definition: $$\mathbf{F}\left\{x(t)\right\} = X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}dt$$

Common practice to write (with $\omega = 2\pi f$): $$X(j\omega) = \int_{-\infty}^{\infty} x(t)e^{-j\omega t}dt$$

Back transformation: $$x(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} X(j\omega)e^{j\omega t}d\omega$$

Eigenschaften der FT

($\Leftrightarrow$ indicates a transform pair, x(t) $\Leftrightarrow X(j\omega)$):

- *Time shifting —* $x(t-a) \Leftrightarrow X(j\omega)\cdot e^{-j\omega a}$
- *Derivative —* $\frac{d}{dt}x(t) \Leftrightarrow j\omega \cdot X(j\omega)$
- *Integration —* $\int_{-\infty}^{\infty} x(t)dt \Leftrightarrow \frac{1}{j\omega}\cdot X(j\omega)$

Faltung

$$g(t) = f(t) * h(t) = \int_{-\infty}^{\infty} f(\tau) \cdot h(t-\tau) d\tau$$

• *Convolution Theorem —*

$$\mathrm{f(t)} * \mathrm{h(t)} \Leftrightarrow \mathrm{F(j\omega)} \cdot \mathrm{H(j\omega)}$$

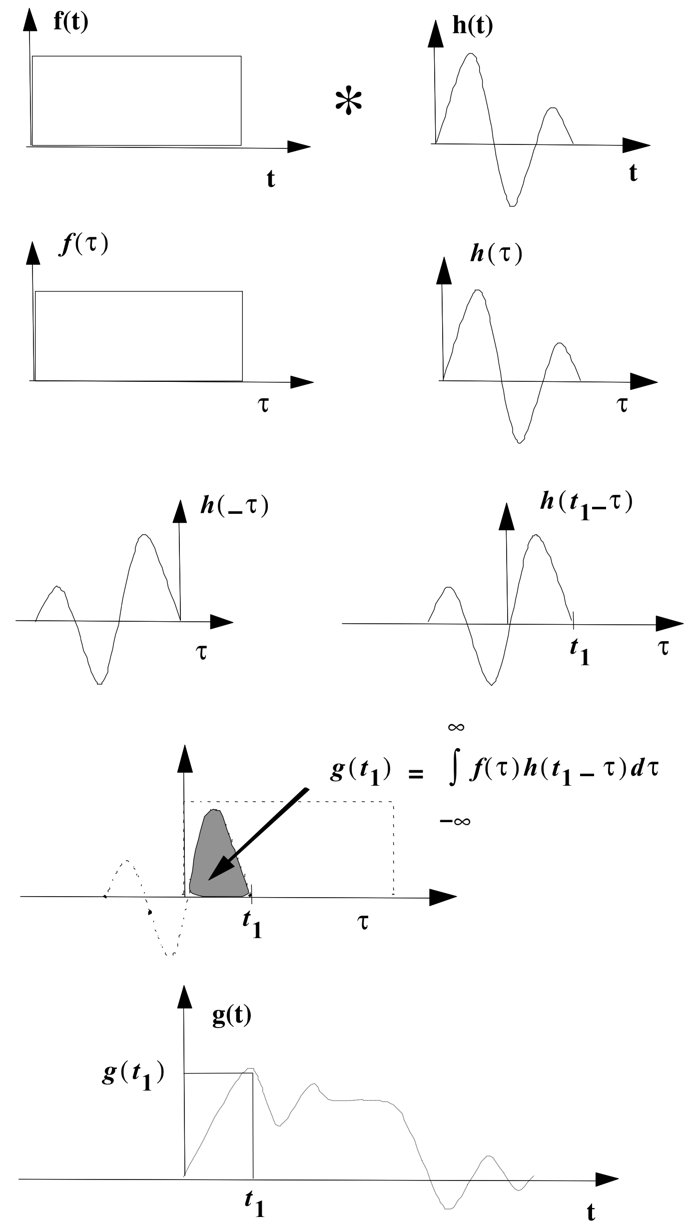


Fig. 2.5 Graphical interpretation of the convolution operation.

Harmonic input signals

$$RC\dot{y}(t) + y(t) - x(t) = 0$$ for harmonic input signal x(t)

Harmonic input signal: $x(t) = A_i e^{j\omega t}$

Ansatz for the output signal: $y(t) = A_0 e^{j\omega t}$

$$\dot{y}(t) = j\omega A_0 e^{j\omega t}$$

$$\Longrightarrow \quad A_0 e^{j\omega t}(RCj\omega + 1) = A_1 e^{j\omega t}$$

$$\frac{A_o}{A_i} = \frac{1}{RCj\omega + 1} = T(j\omega)$$

Frequency response function

Input/output relation

$$\boxed{A_o = T(j\omega)A_i}$$

Transfer function and Laplace transform

Bilateral Laplace transform of *f(t):* $$L[f(t)] = \int f(t)e^{-st}dt$$

with the complex variable $s = \sigma + j\omega$

$L[f(t)]$ will be written as $F(s)$

Property: $L[\dot{f}(t)] = sF(s)$

Transfer function and Laplace transform

Transforming equation $RC\dot{y}(t) + y(t) - x(t) = 0$

is becoming

$$RCsY(s) + Y(s) - X(s) = 0$$

with $Y(s)$ and $X(s)$ being the Laplace transforms of $y(t)$ and $x(t)$, respectively.

$$\Longrightarrow \quad T(s) = \frac{Y(s)}{X(s)} = \frac{1}{1 + sRC} = \frac{1}{1 + s\tau}$$

transfer function

Filtering

$$y(t) = h(t) * x(t)$$

$$Y(j\omega) = H(j\omega)X(j\omega)$$

$$Y(s) = H(s)X(s)$$

General linear time invariant systems

Generalization of concepts

Rewrite the differential equation for the RC filter:

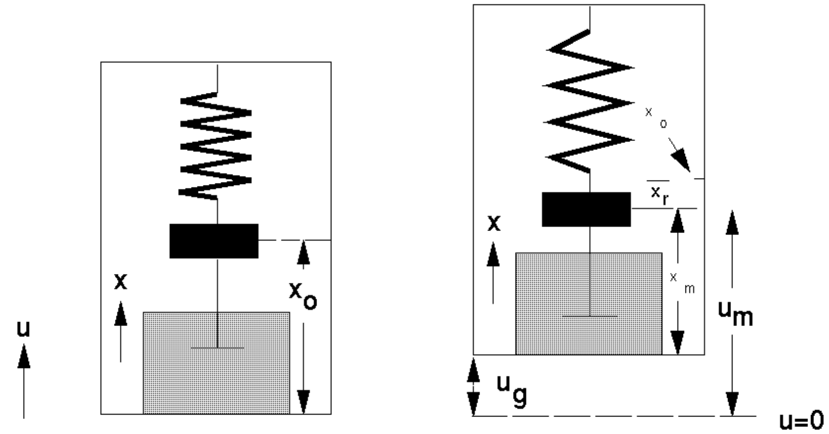
$$RC\dot{y}(t) + y(t) - x(t) = \alpha_1 \frac{d}{dt}y(t) + \alpha_0 y(t) + \beta_0 x(t) = 0$$

RC filter special case of Nth order LTI system

$$\sum_{k=0}^{N} \alpha_k \frac{d^k}{dt} y(t) + \sum_{k=0}^{L} \beta_k \frac{d^k}{dt} x(t) = 0$$

WHAT IS IT GOOD FOR????

Seismometer



• *The inertia of the mass* — $f_i = -m\ddot{u}_m(t)$

• *The spring* — $f_{sp} = -kx_r(t)$

k = spring constant (strength)

• *The dashpot* — $f_f = -D\dot{x}_m(t)$

D = friction coefficient

$$-m\ddot{u}_m(t) - D\dot{x}_m(t) - kx_r(t) = 0$$

2nd order LTI !!

Equilibrium – Conditions

$$-m\ddot{u}_m(t) - D\dot{x}_m(t) - kx_r(t) = 0$$

Since $u_m(t) = u_g(t) + x_m(t)$

$$\Rightarrow \quad -m(\ddot{u}_g(t) + \ddot{x}_m(t)) - D\dot{x}_m(t) - kx_r(t) = 0$$

With $\dot{x}_m(t) = \dot{x}_r(t)$

and $\ddot{x}_m(t) = \ddot{x}_r(t)$

$$\Rightarrow \quad m\ddot{x}_r(t) + D\dot{x}_r(t) + kx_r(t) = -m\ddot{u}_g(t)$$

$$\omega_0^2 = \frac{k}{m}; \qquad 2h\omega_0 = \frac{D}{m}$$

$$\boxed{\ddot{x}_r(t) + 2h\omega_0\dot{x}_r(t) + \omega_0^2 x_r(t) = -m\ddot{u}_g(t)}$$

Underdamped ($\omega_0 > \varepsilon$), Result:

$$x_r(t) = \frac{x_{r0}}{\cos\phi} e^{-\varepsilon t} \cos\left(\sqrt{\omega_0^2 - \varepsilon^2}\, t - \phi\right)$$

$$= \frac{x_{r0}}{\cos\phi} e^{-\varepsilon t} \cos\left(\omega t - \phi\right)$$

$$\phi = \arcsin\frac{\varepsilon}{\omega_0}$$

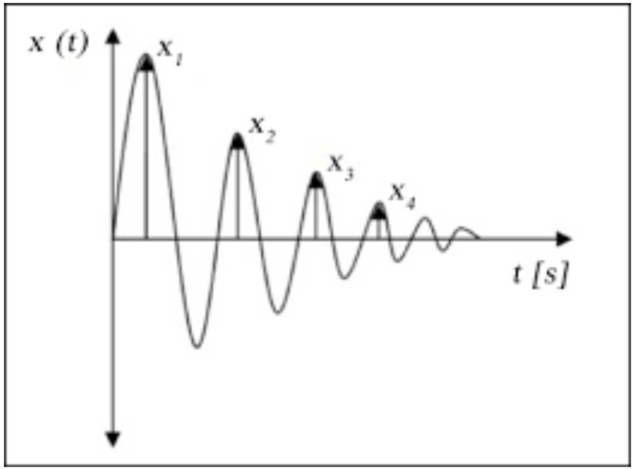
In the underdamped case (h < 1) the seismometer is oscillating with a period of T = 2π/ω. This period is always larger than the undamped free periode T_0.

$$T = \frac{2\pi}{\omega} = \frac{2\pi}{\sqrt{\omega_0^2 - \varepsilon^2}} = \frac{2\pi}{\omega_0\sqrt{1 - \varepsilon^2 / \omega_0^2}} = \frac{2\pi}{\omega_0} \cdot \frac{1}{\sqrt{1 - h^2}}$$

$$= \frac{T_0}{\sqrt{1 - h^2}}$$

Most Simple Calibration

Release Test – Logarithmic Decrement



$$\ln \frac{x_n}{x_{n+1}} = \epsilon T = \Lambda$$

with

$$\Lambda = \epsilon T = \frac{\epsilon T_0}{\sqrt{1 - h^2}}$$

follows:

$$h = \frac{\Lambda}{\sqrt{4\pi^2 + \Lambda^2}}$$

Frequency-Transferfunction

$$\boxed{\ddot{x}(t) + 2h\omega_0\dot{x}(t) + \omega_0^2 x(t) = \ddot{u}_g(t)}$$

$$\Rightarrow \quad -\omega^2 X(j\omega) + j2h\omega_0\omega X(j\omega) + \omega_0^2 X(j\omega) = \omega^2 U(j\omega)$$

$$\frac{X(j\omega)}{U(j\omega)} = \frac{Output}{Input} = \frac{\omega^2}{\omega_0^2 - \omega^2 + j2\epsilon\omega} = T(j\omega)$$

mit

$$|T(j\omega)| = \frac{\omega^2}{\sqrt{(\omega_0^2 - \omega^2)^2 + 4\epsilon^2\omega^2}}$$

Amplitude-Response

$$\Phi(\omega) = \arctan\frac{Im}{Re} = \arctan\left(\frac{-2\epsilon\omega}{\omega_0^2 - \omega^2}\right)$$

Phase-Response

Transfer function

$$\boxed{\ddot{x}(t) + 2h\omega_0\dot{x}(t) + \omega_0^2 x(t) = \ddot{u}_g(t)}$$

$$s^2X(s) + 2sh\omega_0X(s) + \omega_0X(s) = s^2U(s)$$

$$\boxed{T(s) = \frac{X(s)}{U(s)} = \frac{s^2}{s^2 + 2sh\omega_0 + \omega_0^2}}$$

Since a quadratic equation $x^2 + bx + c = 0$ has the roots
in the underdamped case:

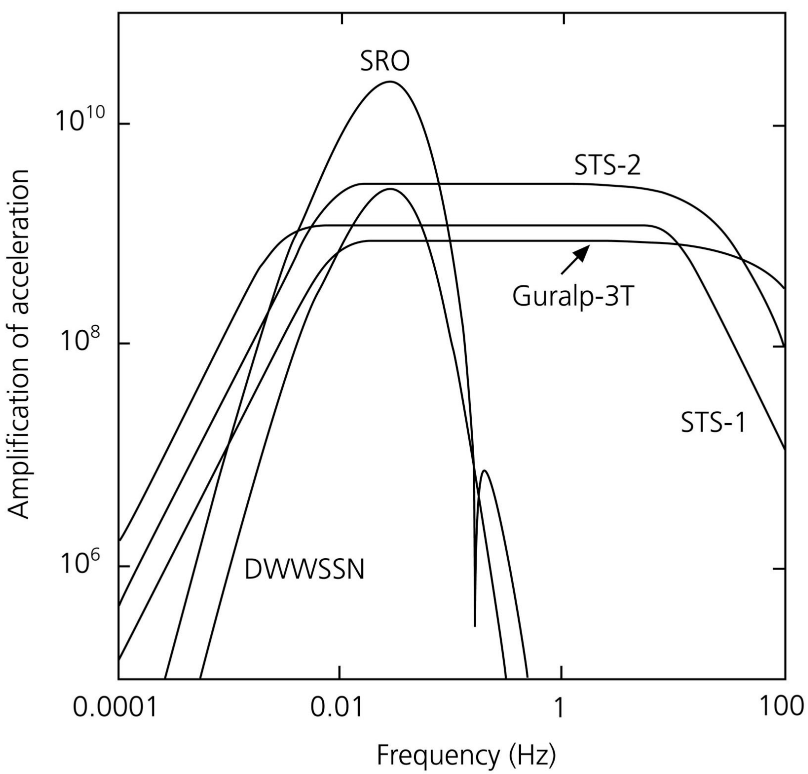
$$p_{1,2} = -(h \pm j\sqrt{h^2 - 1})\omega_0$$

Different Transferfunctions

Routine Data Processing in Earthquake Seismology (2010) J. Havskov & L. Ottemöller, Springer

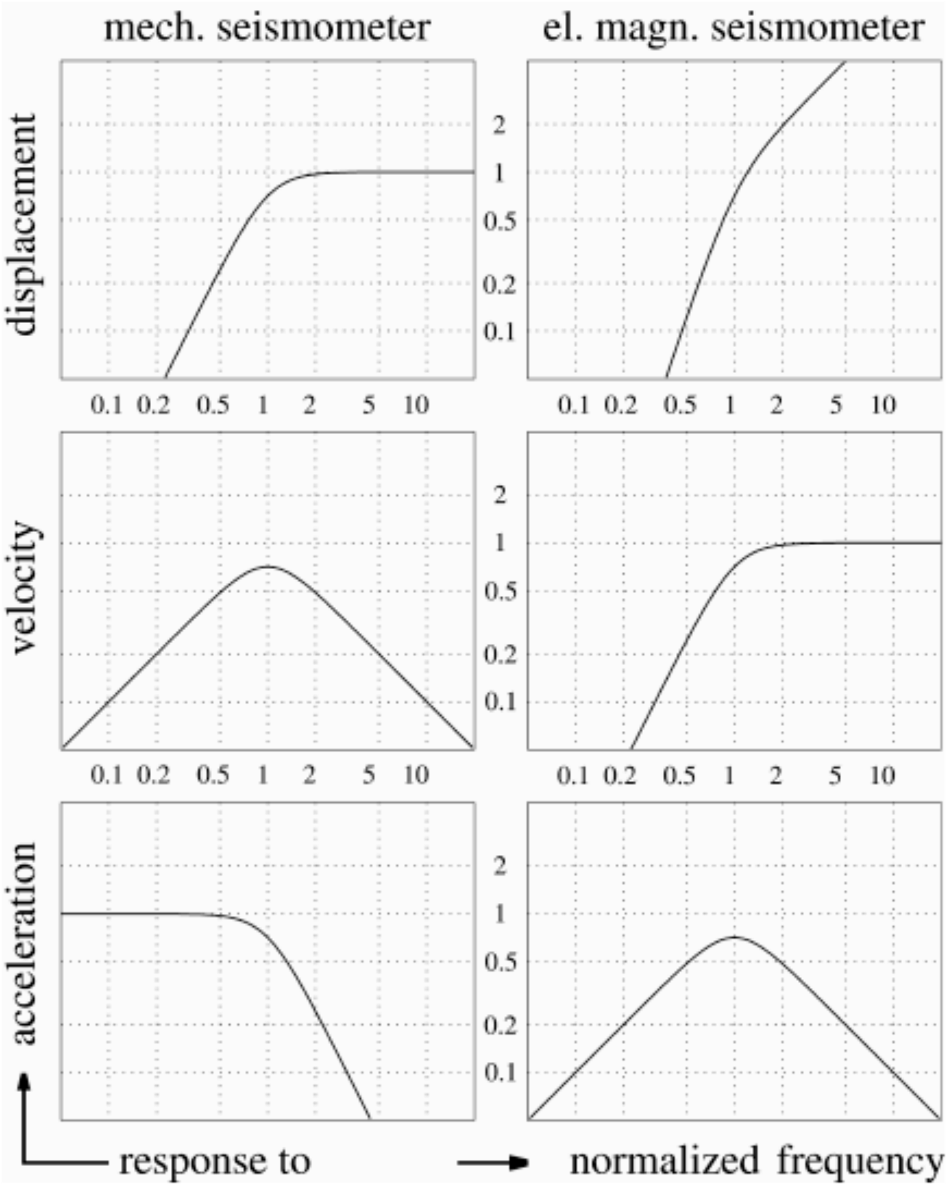
Band code	Band type	Sample rate	Corner period (s)
E	Extremely short period	$\geq$ 80 to < 250	< 10
S	Short period	$\geq$ 10 to < 80	< 10
H	High broadband	$\geq$ 80 to < 250	$\geq$ 10
B	Broad band	$\geq$ 10 to < 80	$\geq$ 10
M	Mid period	> 1 to < 10	
L	Long period	$\approx$ 1	
V	Very long period	$\approx$ 1	
U	Very long period	$\approx$ 0.01	

Introduction to Seismology (2003) Stein & Wysession



The question to be answered determines the seismometer to be used

Displacement, Velocity and Acceleration



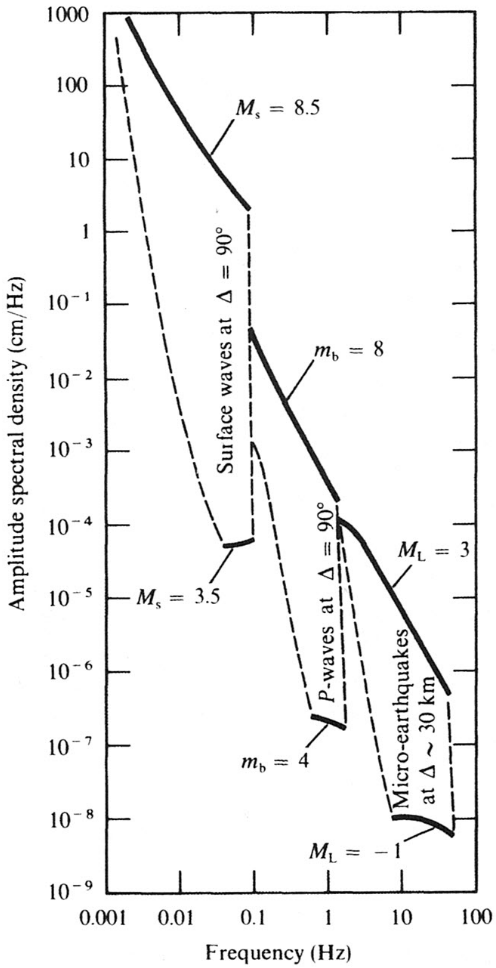
Differences in the building design causes differences in the output

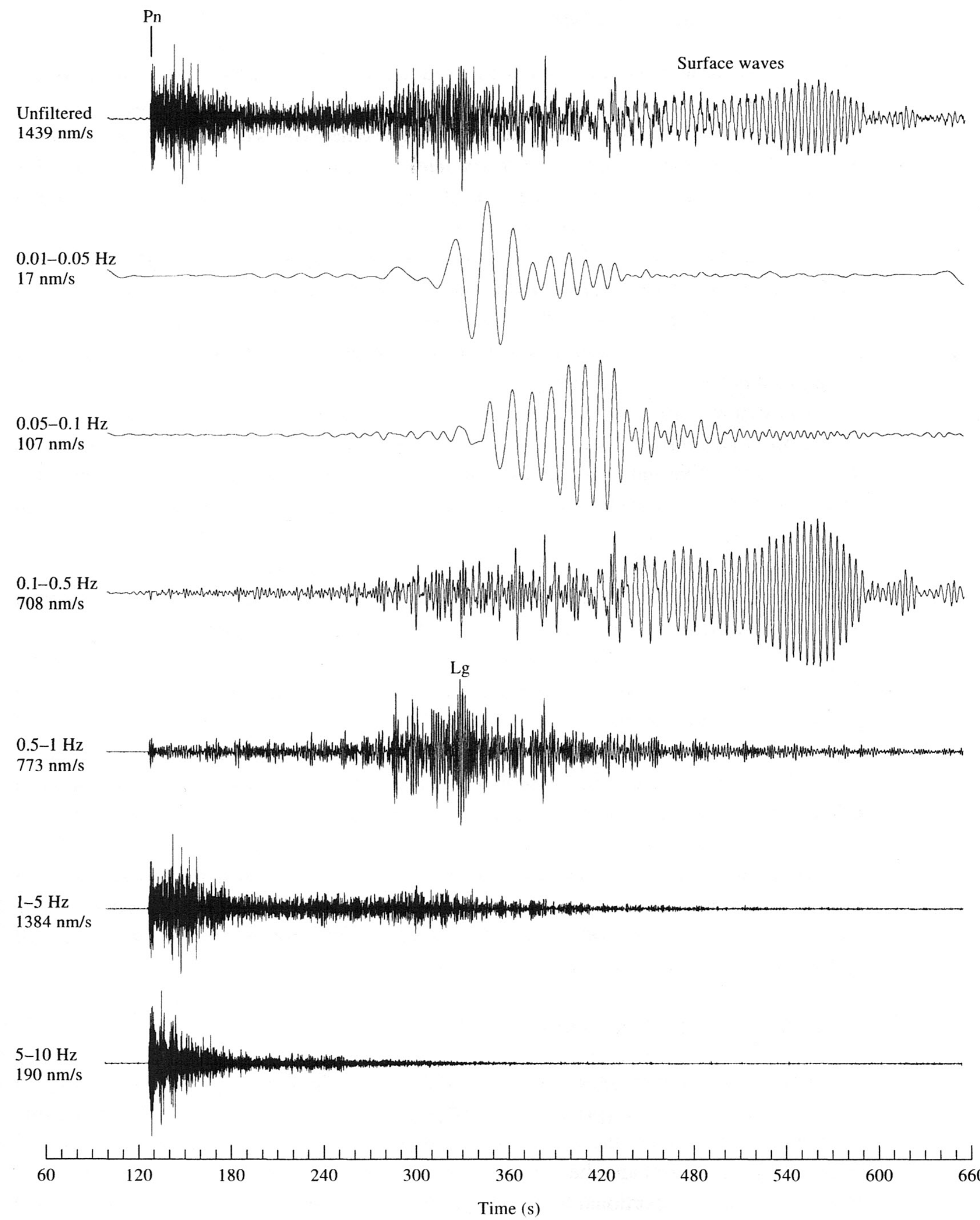
Quelle: NMSOP (2013) P. Bormann (Editor)

Instrument classes

- High frequency teleseismic body waves: SP-instruments (class A)
- LP body waves and teleseismic surface waves: LP-instruments (class B)
- Regional body and surface waves: intermediate band (class C).
- Local magnitude: Wood-Anderson instrument.

Examples

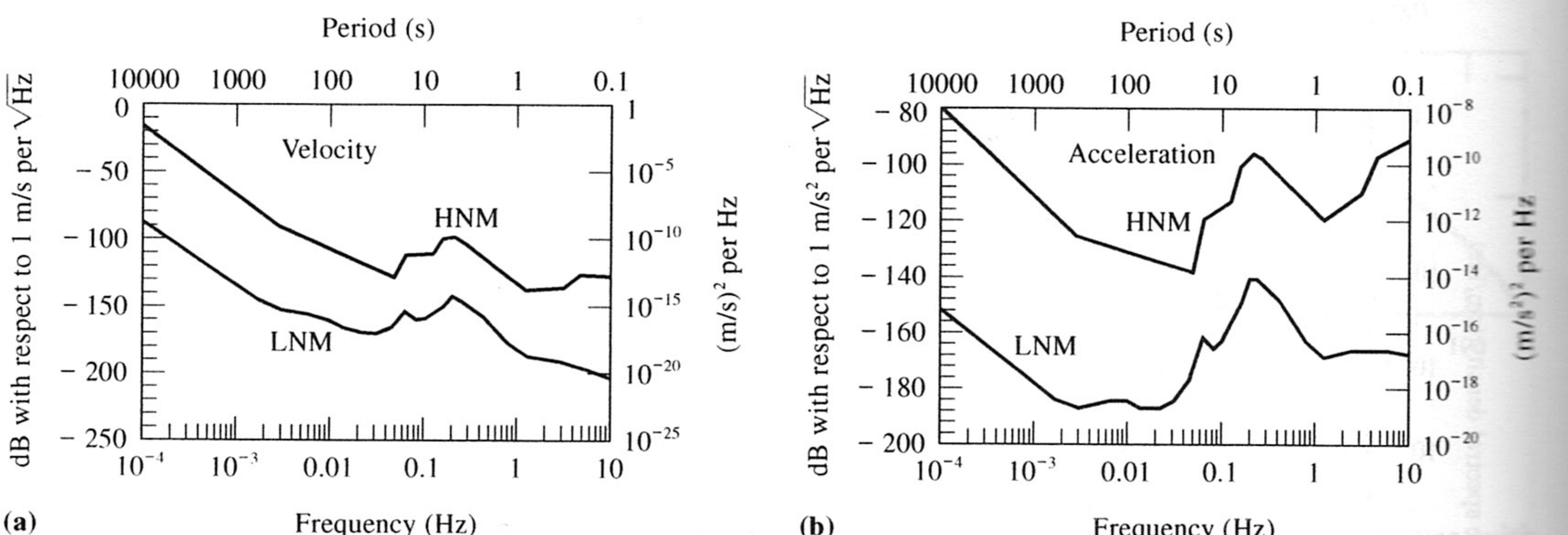




Quelle: Quantitative Seismology (2009) Aki & Richards

Noise

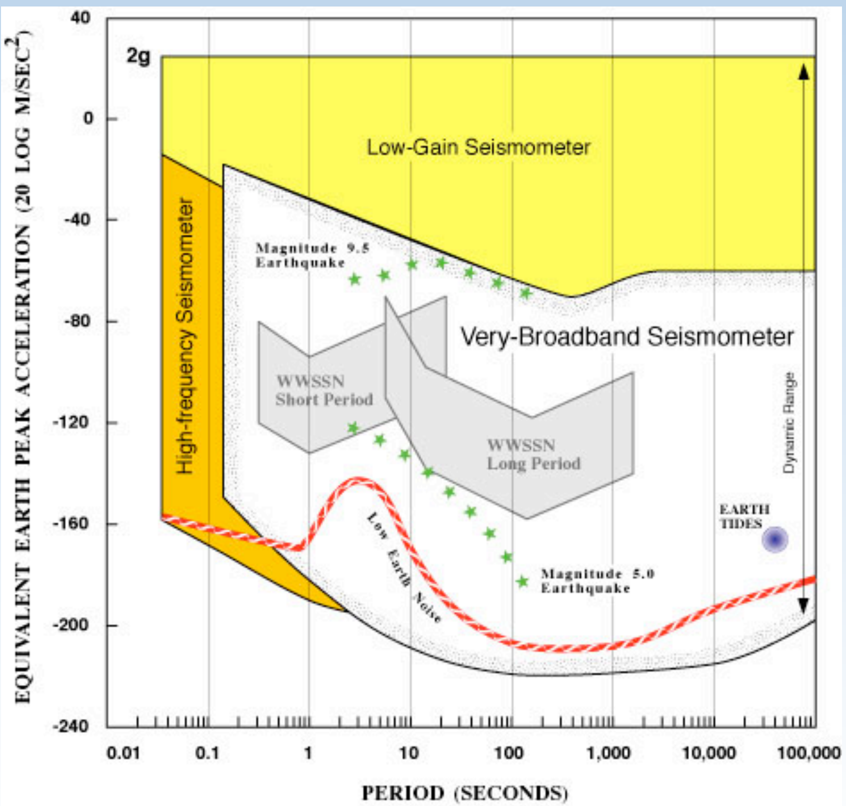
Low Noise Model / High Noise Model
Global average for comparing seismometer locations

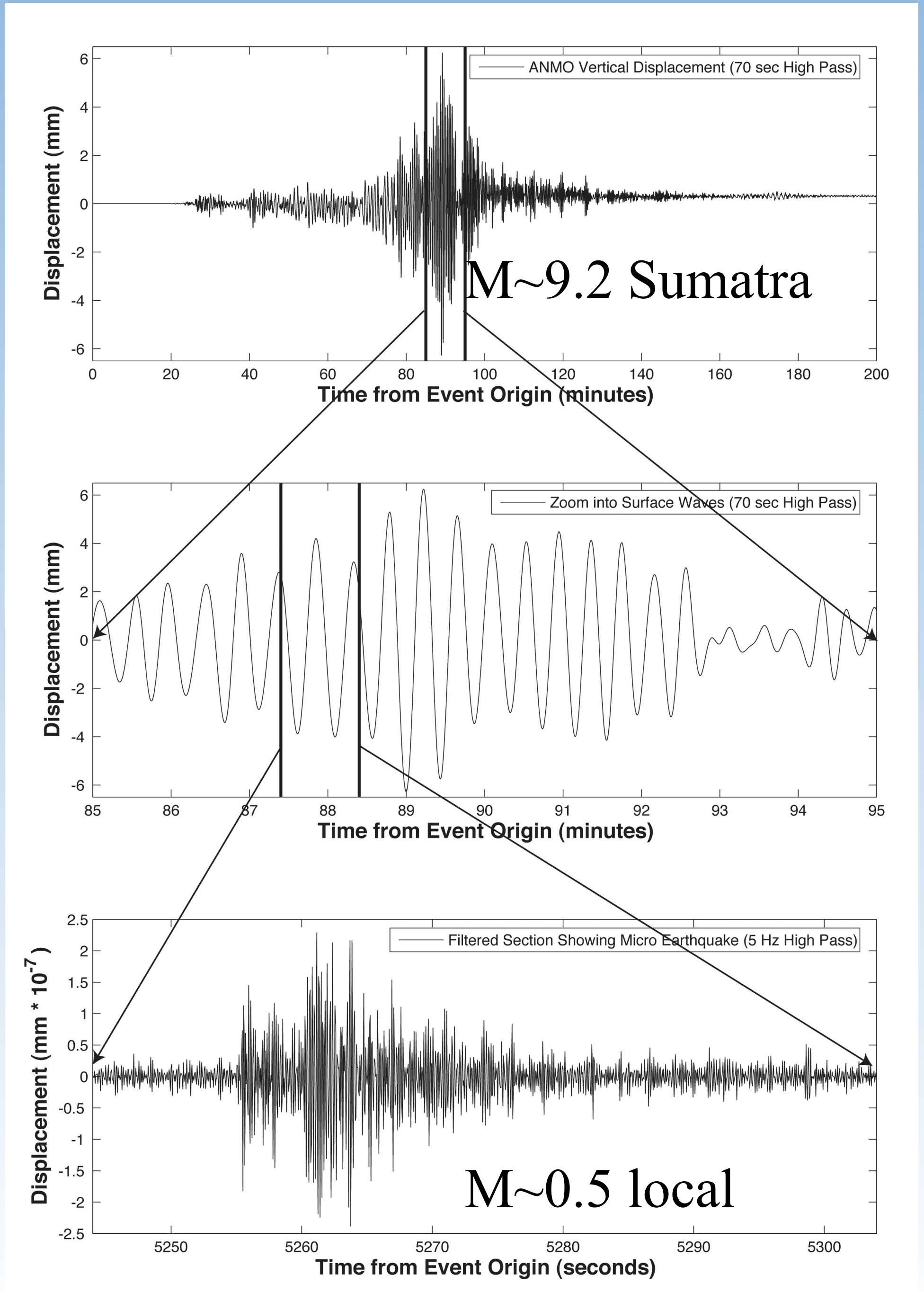


1. Microseisms - Peak: ~ 12-20 s

2. Microseisms - Peak : ~ 5-10 s

Bandwidth & Dynamic

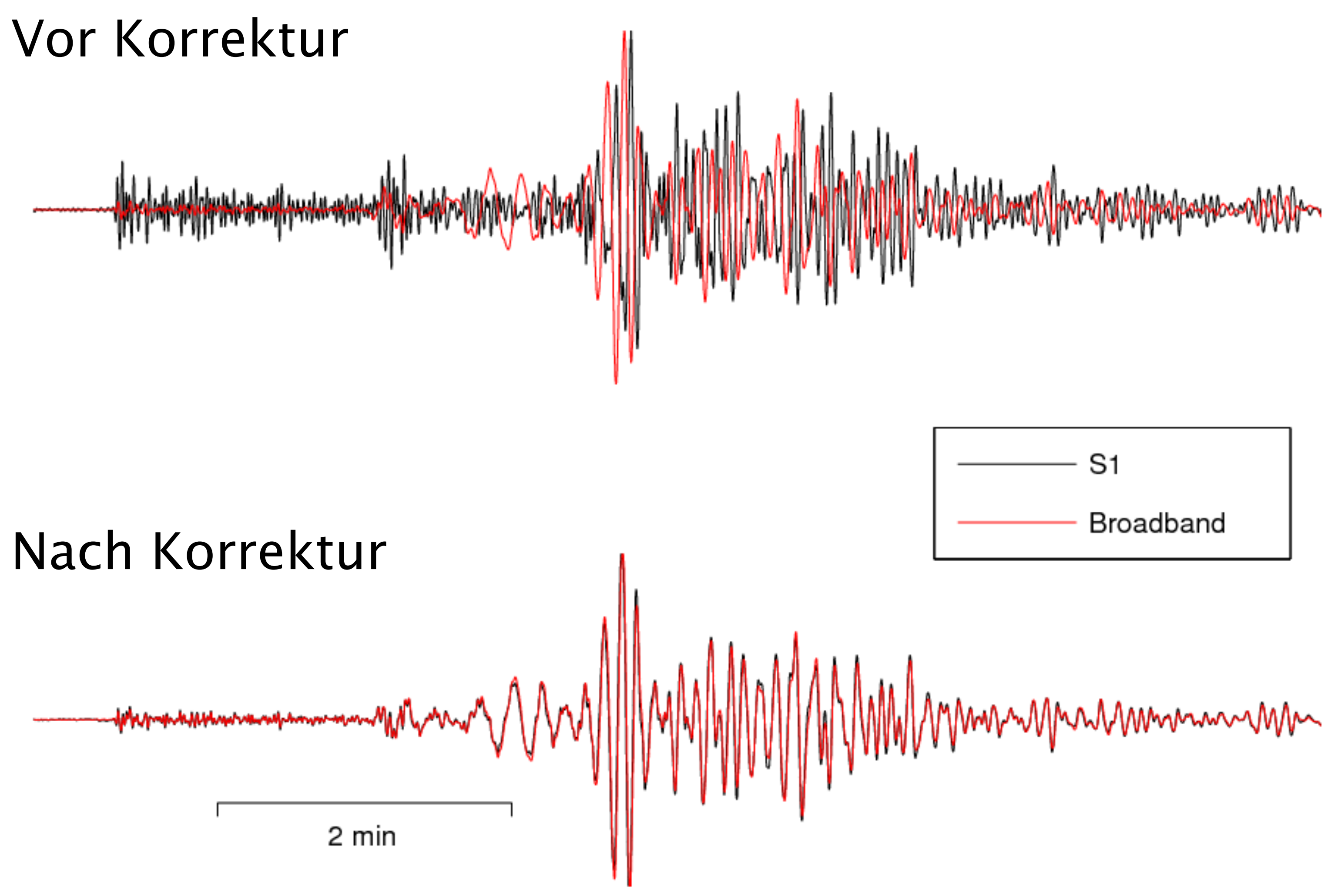




Inverse and simulation filtering of digital seismograms

NEXT: From filter problem to the simulation problem - the conversion of digital (broad-band) records into those from different seismograph systems.

REASON: Signal amplitudes or onset time determination in a manner consistent with other observatories. Simulated systems will most commonly belong to the standard classes of instruments described by Willmore (1979) because there is no single, optimum class of instruments for the detection and analysis of different types of seismic waves.


Vor Korrektur
S1
Broadband
Nach Korrektur
2 min

Simulation = Deconvolution + Filtering

$$Y_{sim}(z) = \frac{T_{syn}(z)}{T_{act}(z)} \cdot Y_{act}(z) = T_{sim}(z) \cdot Y_{act}(z)$$

$T_{act}(z)$ = transfer function of actual recording system

$T_{syn}(z)$ = transfer function of the instrument to be synthesized

$Y_{act}(z)$ = z- transform of the recorded seismogram

$Y_{sim}(z)$ = z- transform of the simulated seismogram

The concept of instrument simulation

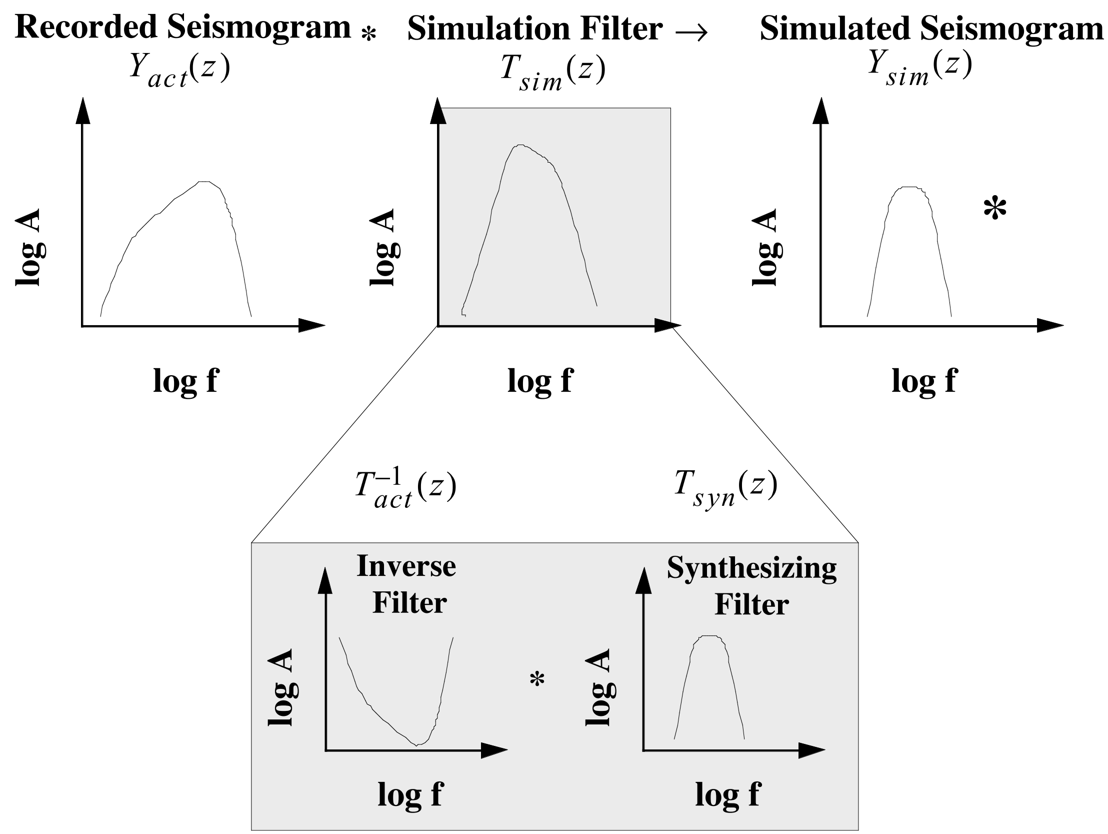


Fig. 9.2 The simulation of digital seismographs. The simulation filter can be thought of as a combination of an inverse filter for the actual recording system and a synthesizing filter for the simulated recording system. Displayed are schematic sketches of the amplitude frequency response functions of the contributing subsystems.

Stability problems

Noisefree situation

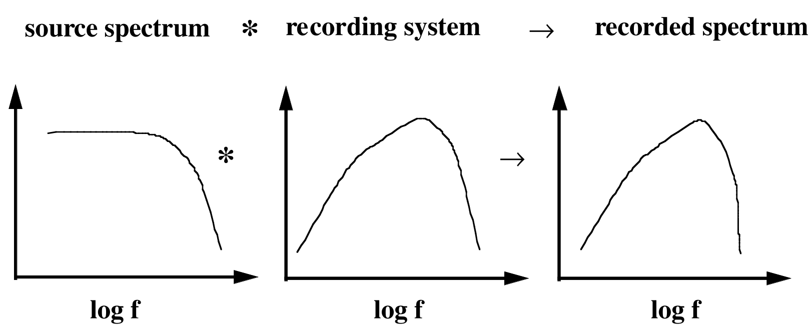


Fig. 9.3 Recording the displacement spectrum of an idealized earthquake source.

Recovery of source spectrum:

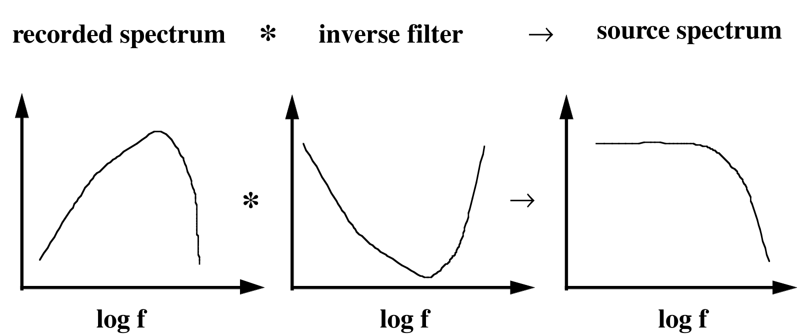


Fig. 9.4 Recovering the source spectrum by inverse filtering in the noisefree case.

Noisy situation

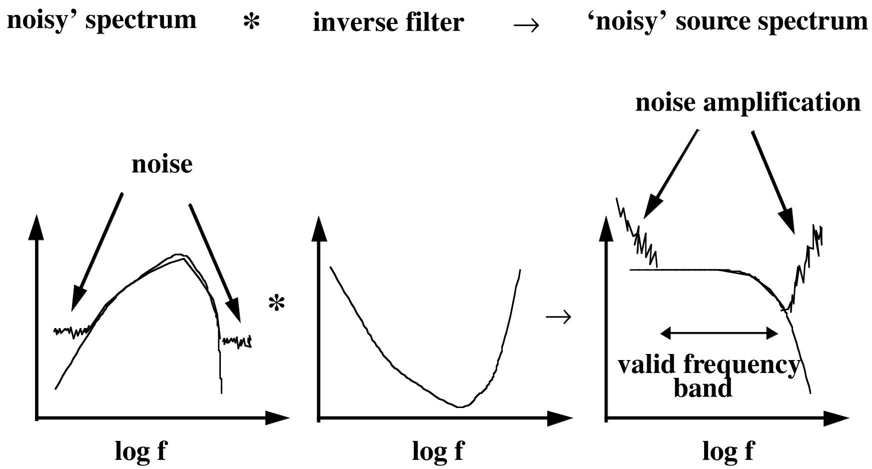


Fig. 9.5 Noise amplification by inverse filtering. The solid line in the left panel shows the signal plus noise while the noisefree signal is shown by the dashed line.

Problem:

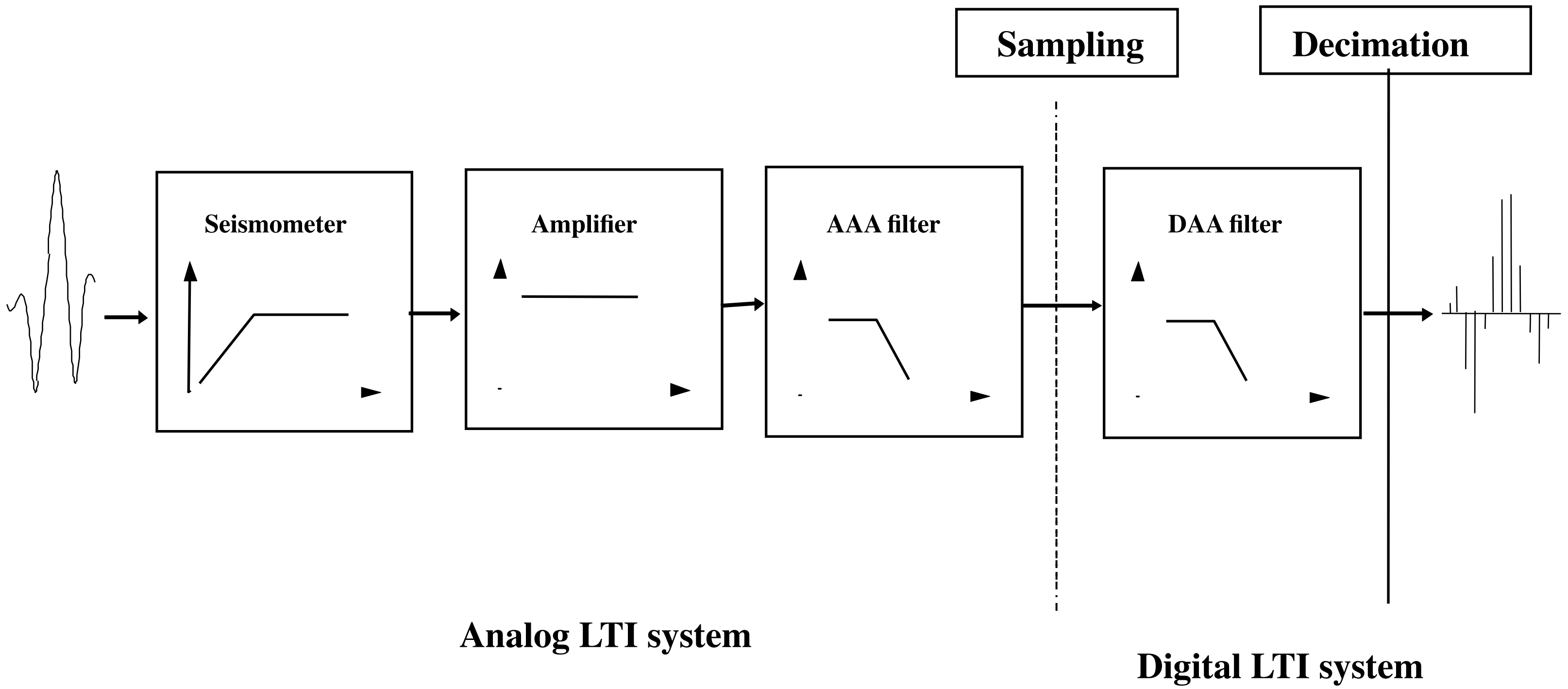
- Decrease of signal-to-noise ratio (SNR) outside the pass-band of the recording instrument

- magnification of the inverse filter is largest where SNR is smallest. Thus, noise in this frequency band will be amplified (instability!).

Consequence:

- The instrument response can only be deconvolved within a certain *valid frequency band* in the presence of noise. The valid frequency band depends on both the signal-to noise ratio and the slope of the frequency response function of the recording systems.

FIR - Filter Effects

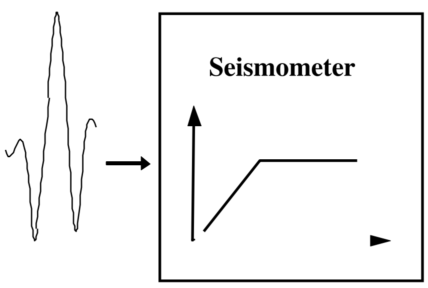


Why bothering?

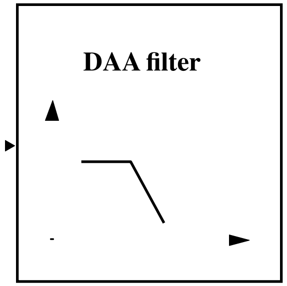
What is the reason for doing FIR filtering and decimating?

Nearly all seismic recorders use the oversampling technique to increase the resolution of recordings. In order to achieve an optimum valid frequency band, the filters are very steep.

Besides its advantages this also bears new problems.




```
#           << IRIS SEED Reader, Release 4.4 >>
#
#           ======== CHANNEL RESPONSE DATA ========
B050F03     Station:     RJOB
B050F16     Network:     BW
B052F03     Location:    ??
B052F04     Channel:     EHZ
B052F22     Start date:  2007,199
B052F23     End date:    No Ending Time
#           =======================================
#           +          +-------------------------------------------+          +
#           +          |  Response (Poles & Zeros),  RJOB ch EHZ  |          +
#           +          +-------------------------------------------+          +
#
B053F03     Transfer function type:            A [Laplace Transform (Rad/sec)]
B053F04     Stage sequence number:               1
B053F05     Response in units lookup:            M/S - Velocity in Meters per Second
B053F06     Response out units lookup:           V - Volts
B053F07     A0 normalization factor:             6.0077E+07
B053F08     Normalization frequency:             1
B053F09     Number of zeroes:                    2
B053F14     Number of poles:                     5
#           Complex zeroes:
#             i  real          imag          real_error    imag_error
B053F10-13    0  0.000000E+00  0.000000E+00  0.000000E+00  0.000000E+00
B053F10-13    1  0.000000E+00  0.000000E+00  0.000000E+00  0.000000E+00
#           Complex poles:
#             i  real          imag          real_error    imag_error
B053F15-18    0 -3.700400E-02  3.701600E-02  0.000000E+00  0.000000E+00
B053F15-18    1 -3.700400E-02 -3.701600E-02  0.000000E+00  0.000000E+00
B053F15-18    2 -2.513300E+02  0.000000E+00  0.000000E+00  0.000000E+00
B053F15-18    3 -1.310400E+02 -4.672900E+02  0.000000E+00  0.000000E+00
B053F15-18    4 -1.310400E+02  4.672900E+02  0.000000E+00  0.000000E+00
```




```
#            +                  +--------------------------------+                  +
#            +                  |  FIR response,  RJOB ch EHZ  |                  +
#            +                  +--------------------------------+                  +
#
B061F03    Stage sequence number:              3
B061F05    Symmetry type:                  A
B061F06    Response in units lookup:           COUNTS - Digital Counts
B061F07    Response out units lookup:          COUNTS - Digital Counts
B061F08    Number of numerators:               96
#          Numerator coefficients:
#            i, coefficient
B061F09      0  3.767143E-09
B061F09      1  5.277283E-07
B061F09      2  2.184651E-06
B061F09      3 -5.639535E-06
B061F09      4 -1.233773E-06
B061F09      5  9.386712E-06
B061F09      6  4.859924E-06
B061F09      7 -1.644319E-05
…
#
#            +                  +------------------------------+                  +
#            +                  |  Decimation,  RJOB ch EHZ  |                  +
#            +                  +------------------------------+                  +
#
B057F03    Stage sequence number:              4
B057F04    Input sample rate:               1.000000E+03
B057F05    Decimation factor:               5
B057F06    Decimation offset:               0
B057F07    Estimated delay (seconds):          1.490000E-01
B057F08    Correction applied (seconds):        0.000000E+00
```

Linear Difference Equation

$$\sum_{k=0}^{N} a_k y[n-k] = \sum_{l=0}^{M} b_l x[n-l]$$

Infinite Impulse Response: $a_k \neq 0$

Finite Impulse Response: $a_0 = 1$; $a_{k \neq 0} = 0$

- <u>FIR filters</u> :

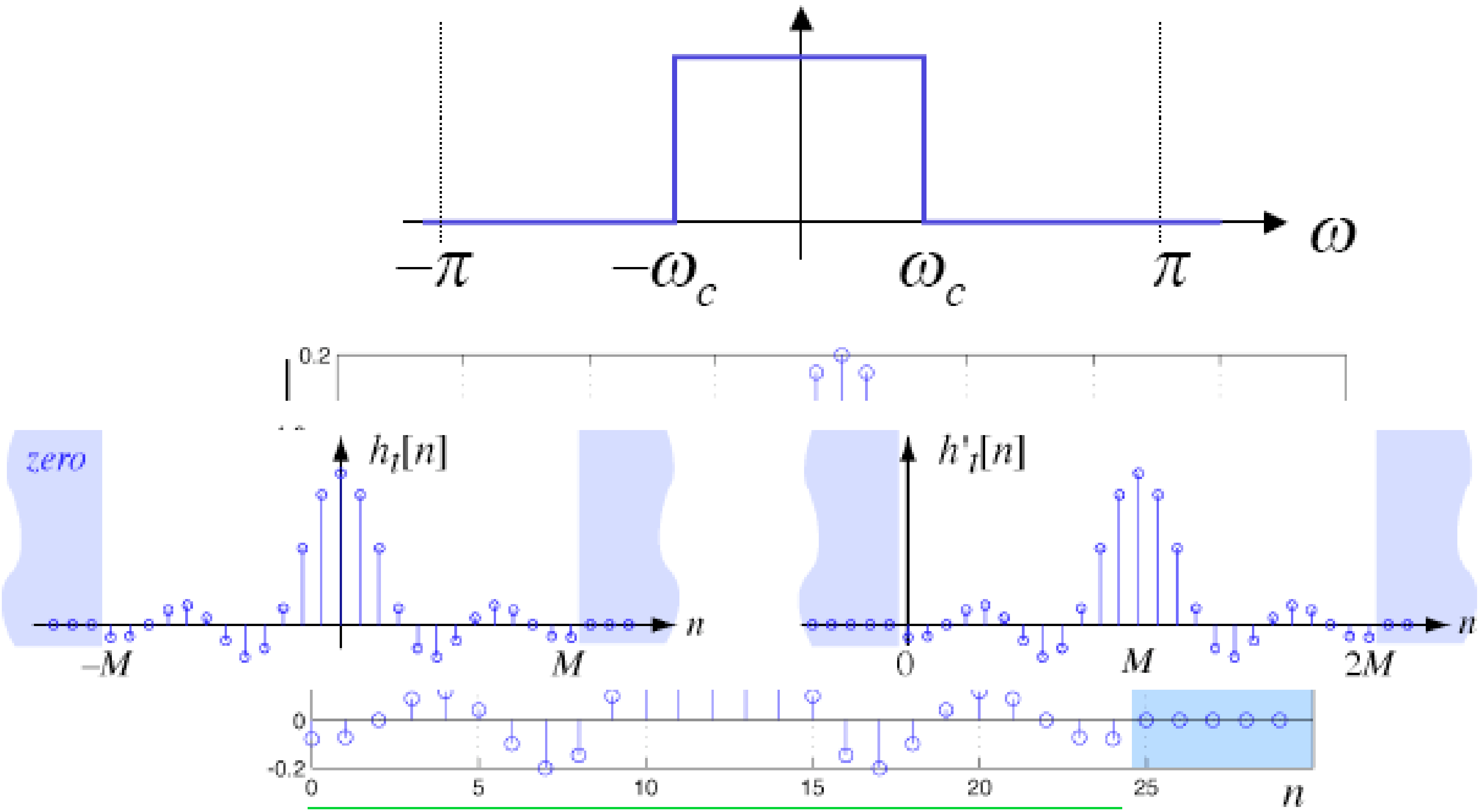
+ Always stable.
- Steep filters need many coefficients.
+ Both causal and noncausal filters can be implemented.
+ Filters with given specifications are easy to implement!

- <u>IIR filters</u> :

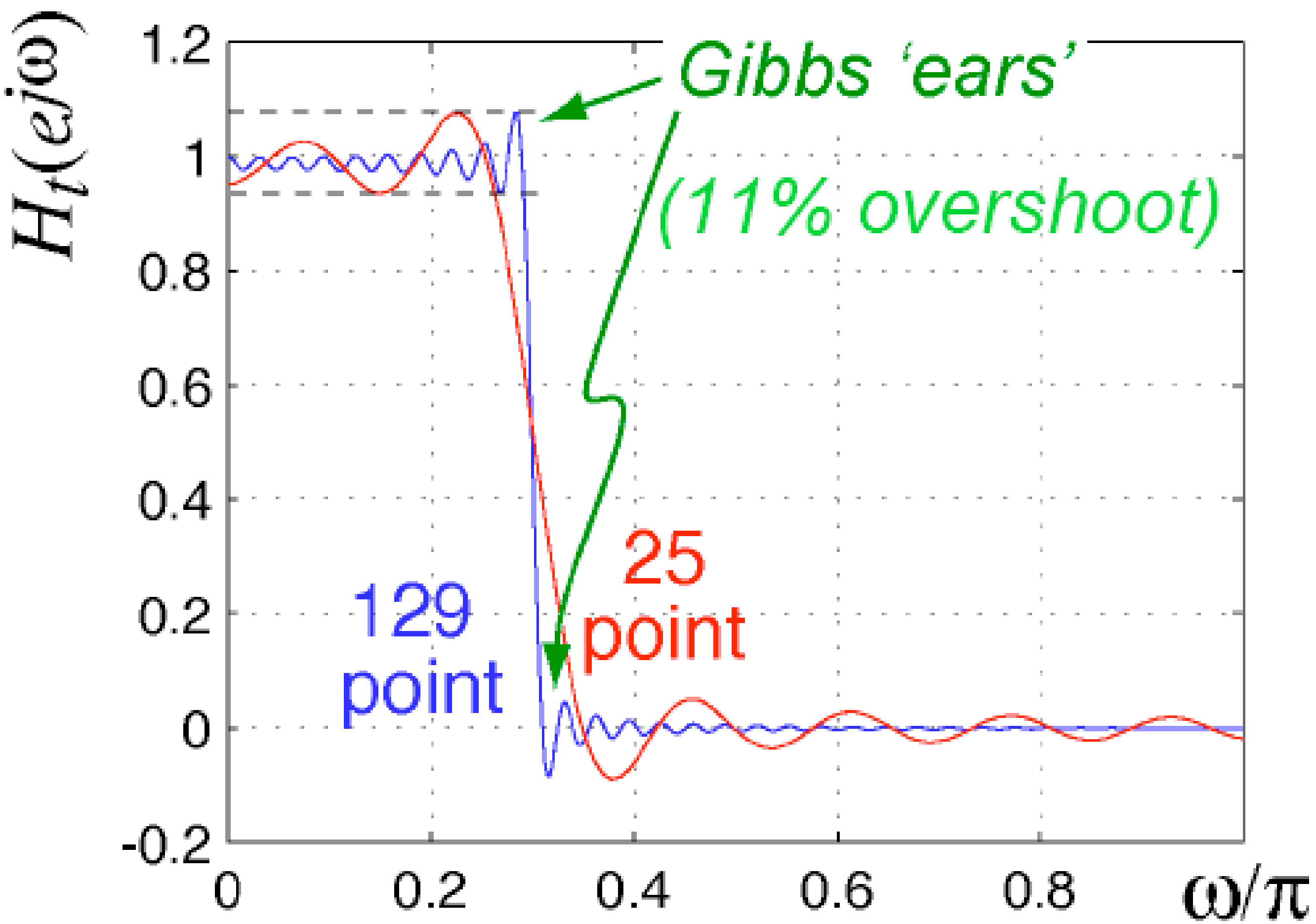
- Potentially unstable and subject to quantization errors.
+ Steep filters can easily be implemented with a few coefficients. Speed.
- Filters with given specifications are in general, difficult, if not impossible, to implement *exactly(!)*.

In SEED the impulse response of the decimation filters are given. But how to construct FIR filters?

Easiest way: inverse DFT with selected spectral shape and phase and truncate the (infinite) sequence to form a finite impulse response



Filter length vs. steepness

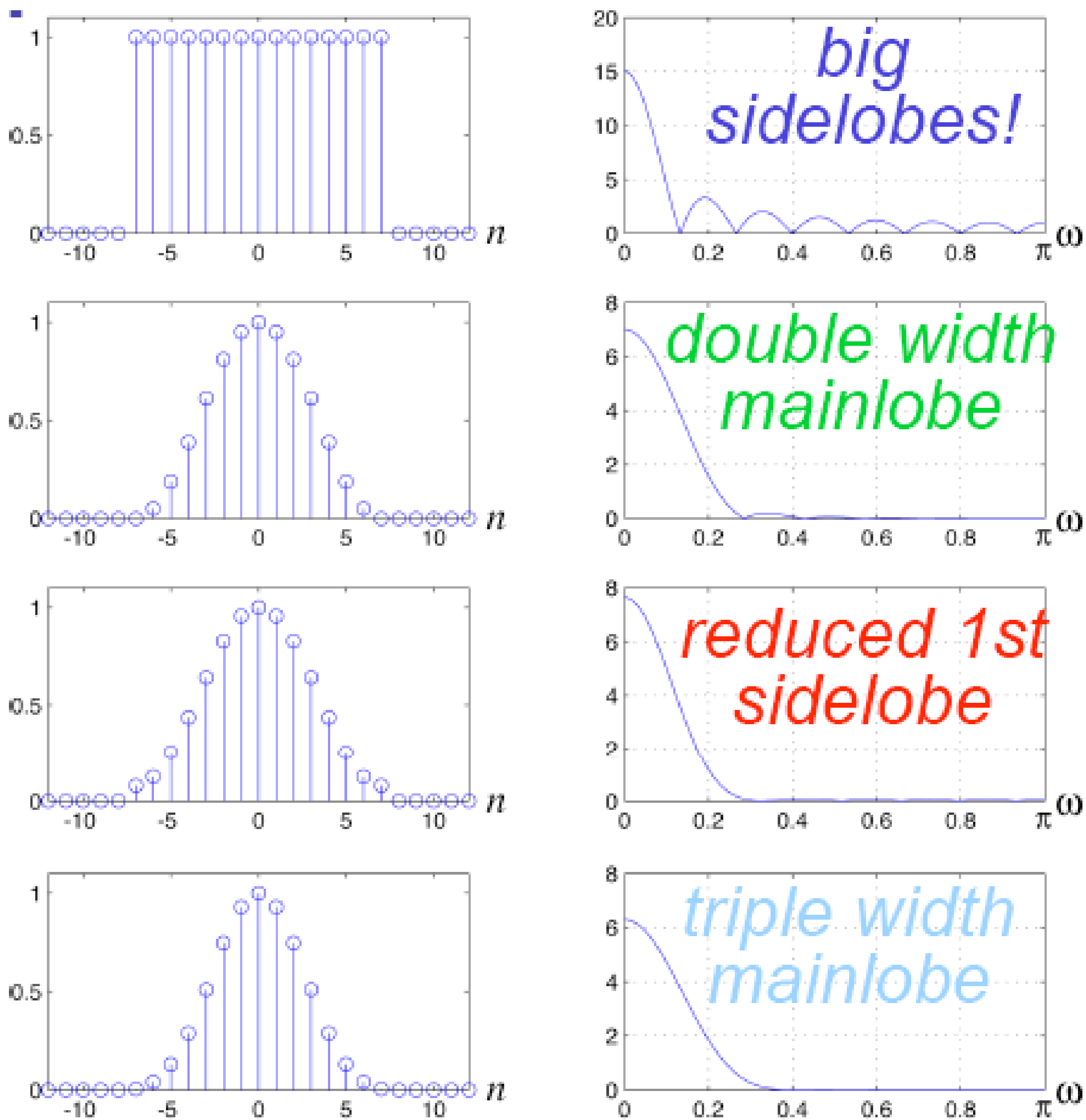


Rectangular

Hanning

Hamming

Blackman



Windowed FIR Filter Example:

1. Get ideal filter impulse response:

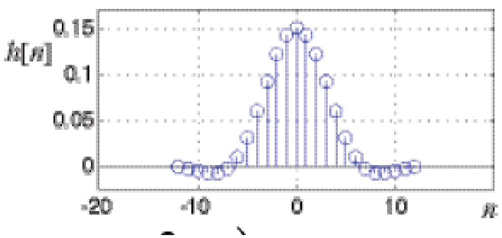
$$\omega_c = 0.15\pi \qquad \Rightarrow h_d[n] = \frac{\sin 0.15\pi n}{\pi n}$$

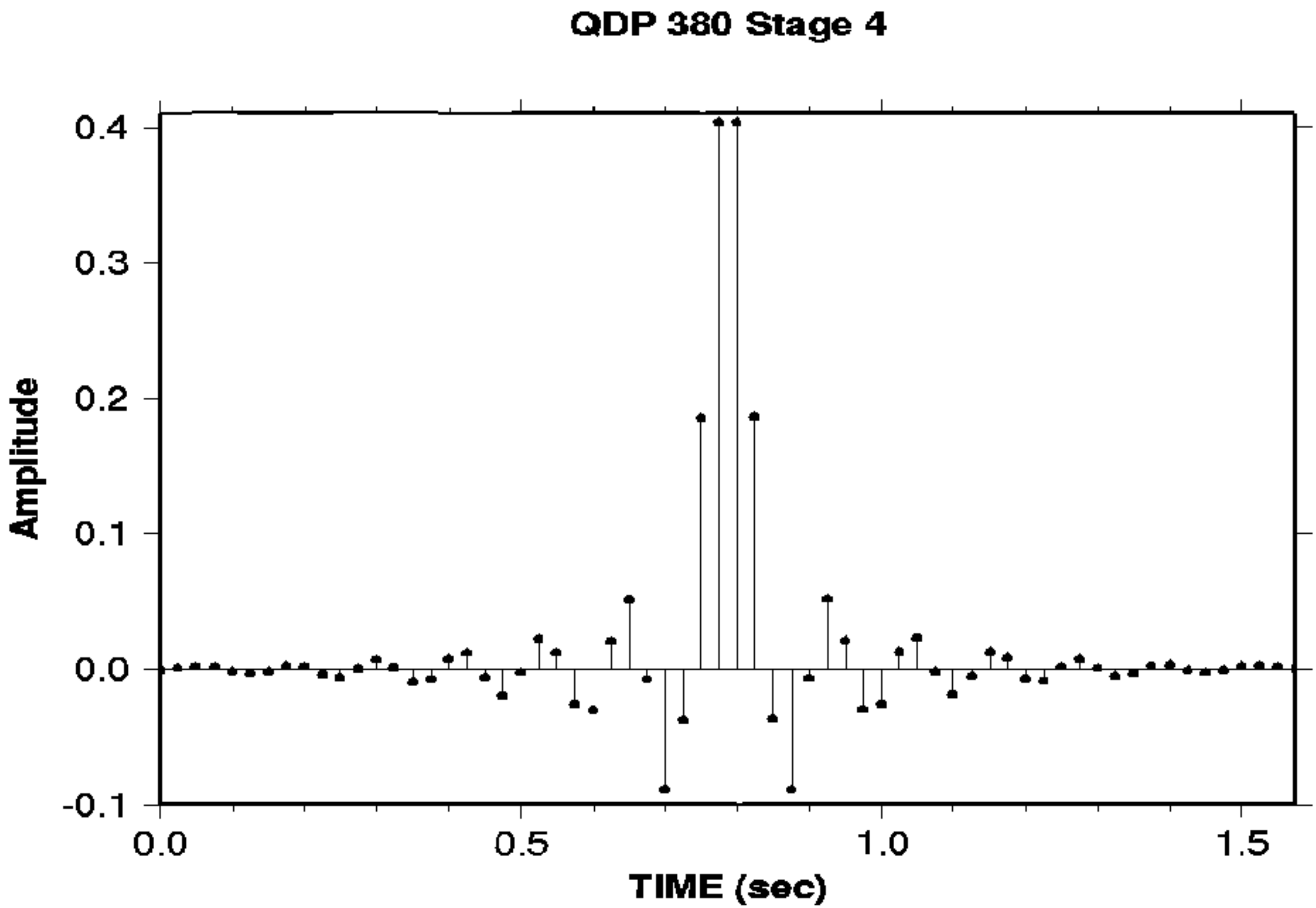
2. Get window function for truncation:

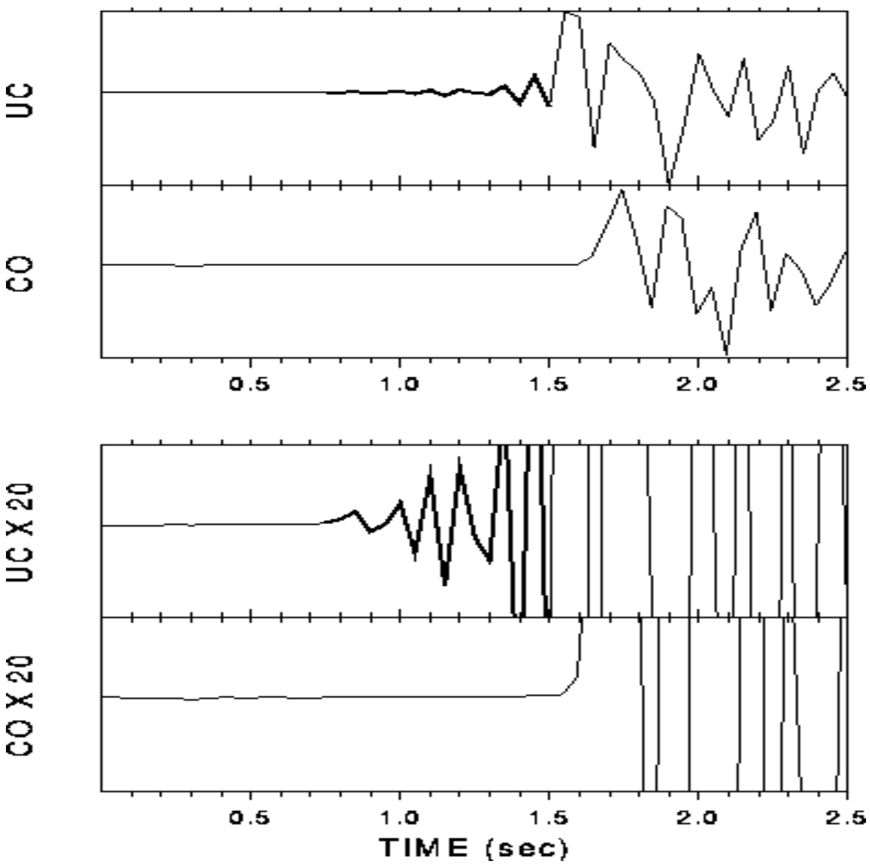
$$N = 25 \rightarrow M = 12 \quad \text{(N=2M+1)}$$
$$\Rightarrow w[n] = 0.54 + 0.46\cos\left(2\pi\frac{n}{25}\right) \quad -12 \le 12$$

3. Apply window:

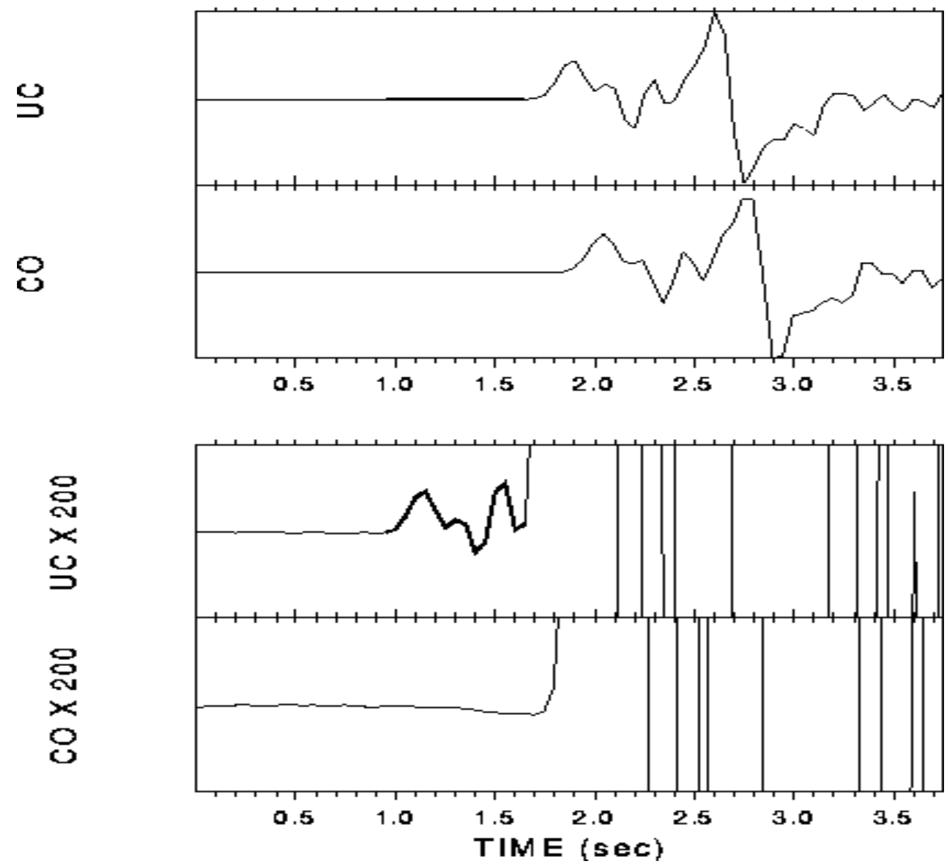
$$h[n] = h_d[n]w[n]$$
$$= \frac{\sin 0.15\pi n}{\pi n}\left(0.54 + 0.46\cos\frac{2\pi n}{25}\right) \quad -12 \le 12$$



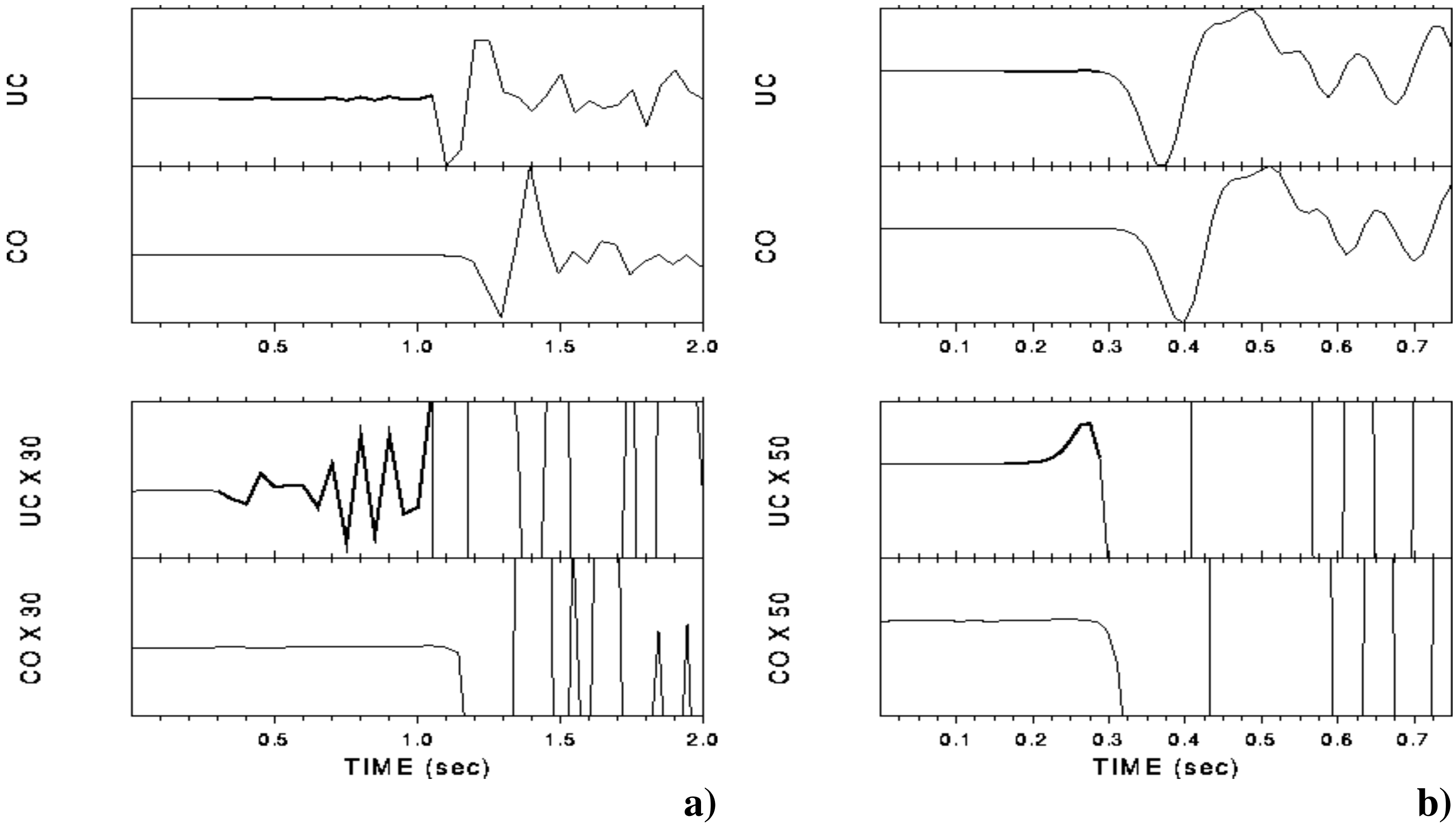

QDP 380 Stage 4
Amplitude
0.4
0.3
0.2
0.1
0.0
-0.1
0.0
0.5
1.0
1.5
TIME (sec)


UC
CO
0.5
1.0
1.5
2.0
2.5
UC X 20
CO X 20
0.5
1.0
1.5
2.0
2.5
TIME (sec)

a)


UC
CO
0.5
1.0
1.5
2.0
2.5
3.0
3.5
UC X 200
CO X 200
0.5
1.0
1.5
2.0
2.5
3.0
3.5
TIME (sec)

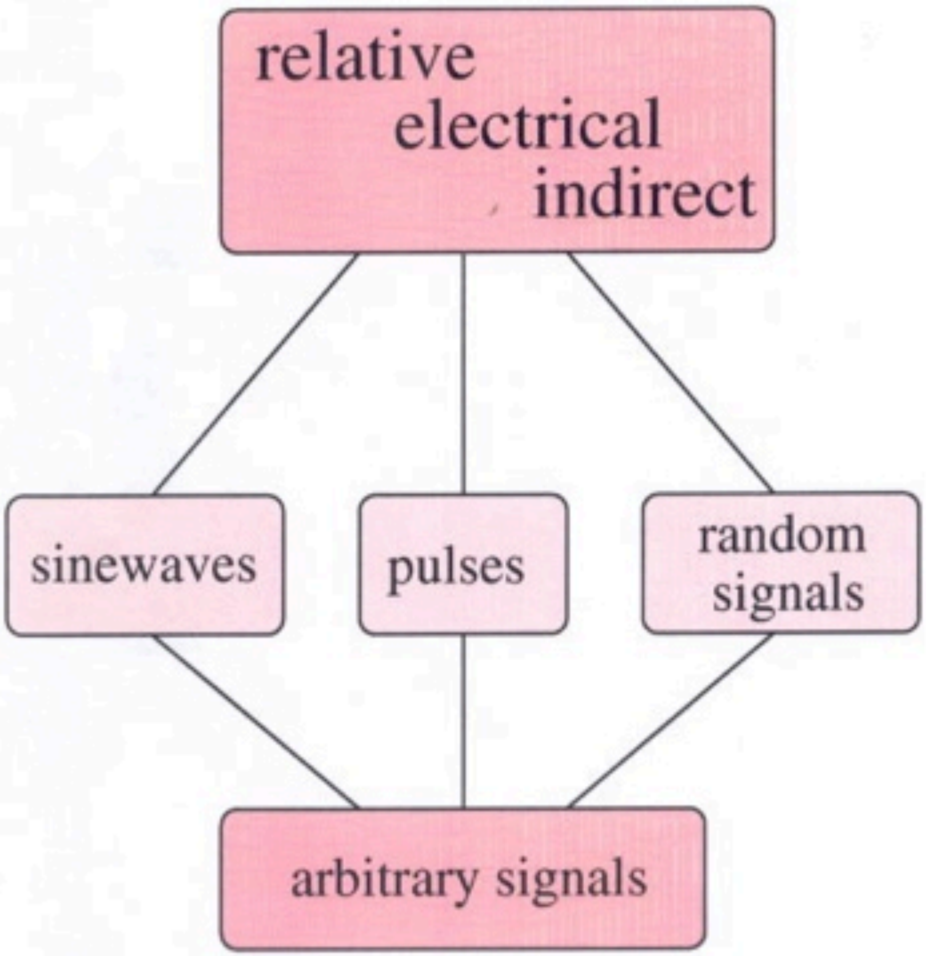
b)

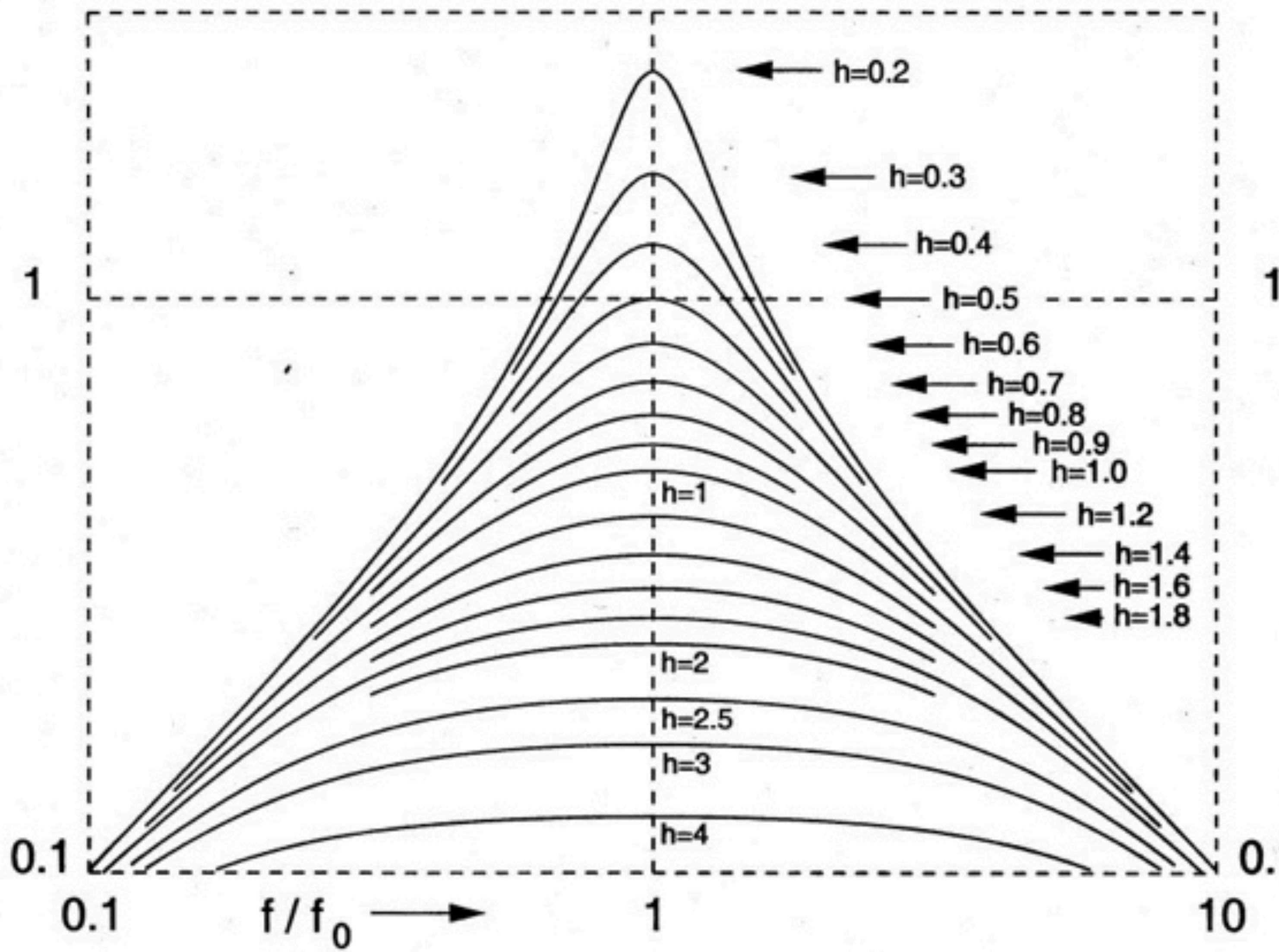

UC
CO
0.5
1.0
1.5
2.0
UC X 30
CO X 30
TIME (sec)
a)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
UC X 50
CO X 50
b)

Modern Seismometers Calibration

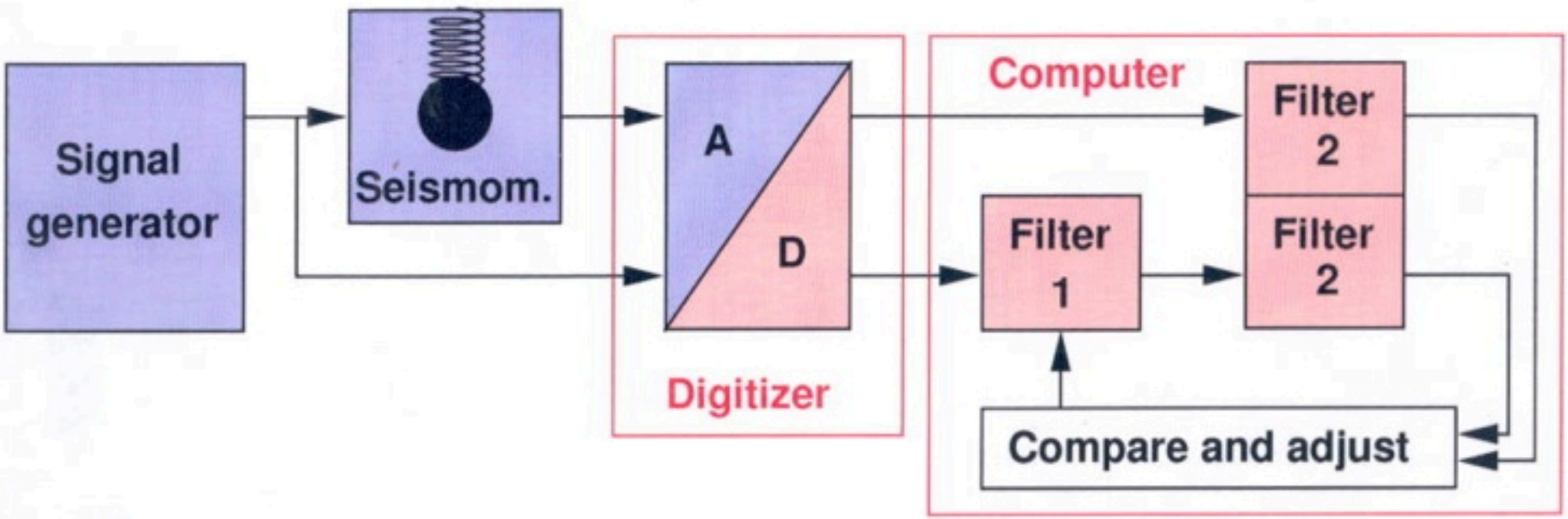
(Material of E. Wielandt)

Systematics of Seismometer calibration



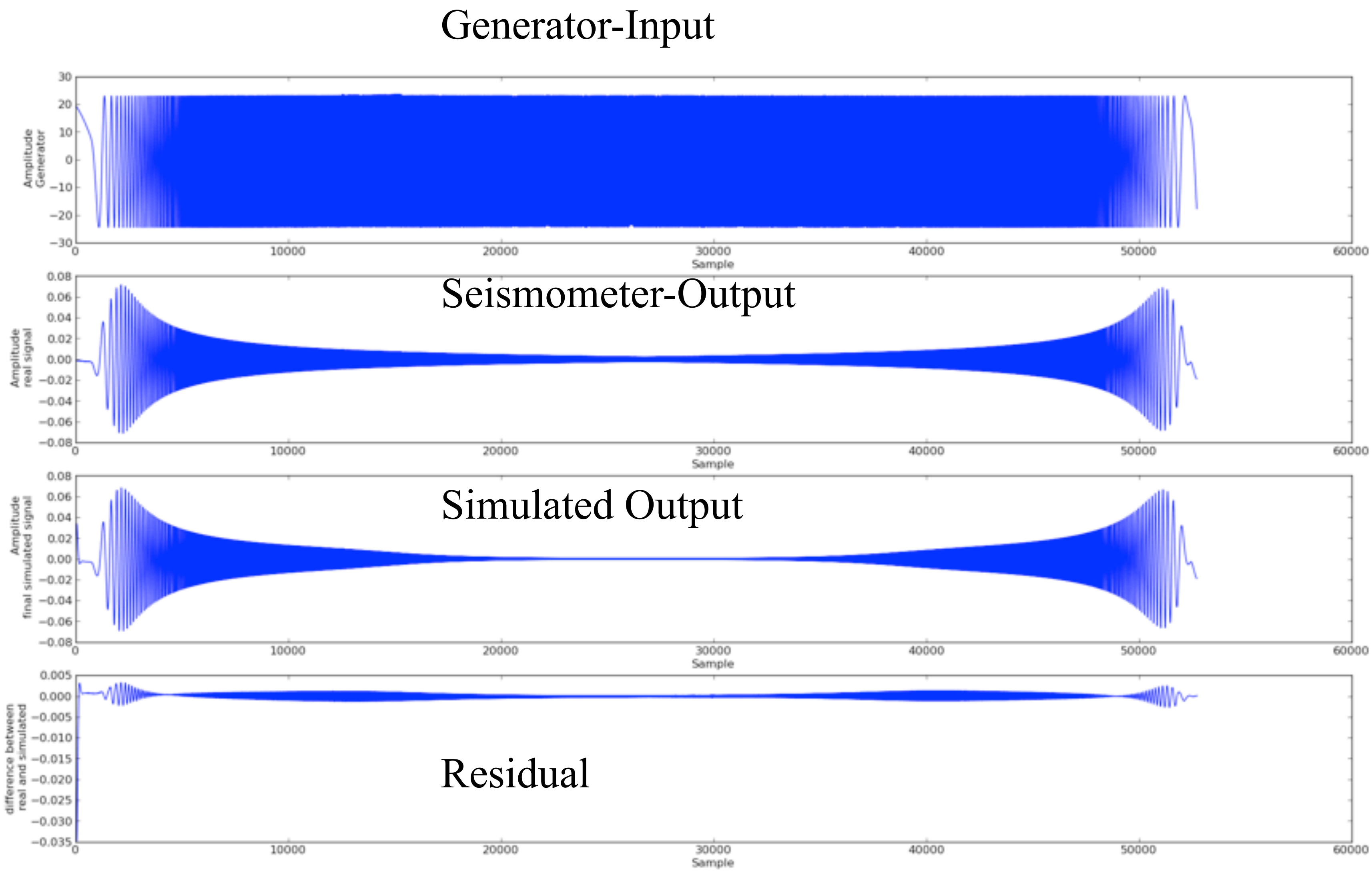

h=0.2
h=0.3
h=0.4
h=0.5
h=0.6
h=0.7
h=0.8
h=0.9
h=1.0
h=1.2
h=1.4
h=1.6
h=1.8
h=1
h=2
h=2.5
h=3
h=4
1
1
0.1
0.1
0.1
f / f_0
1
10

Calibration with arbitrary signals

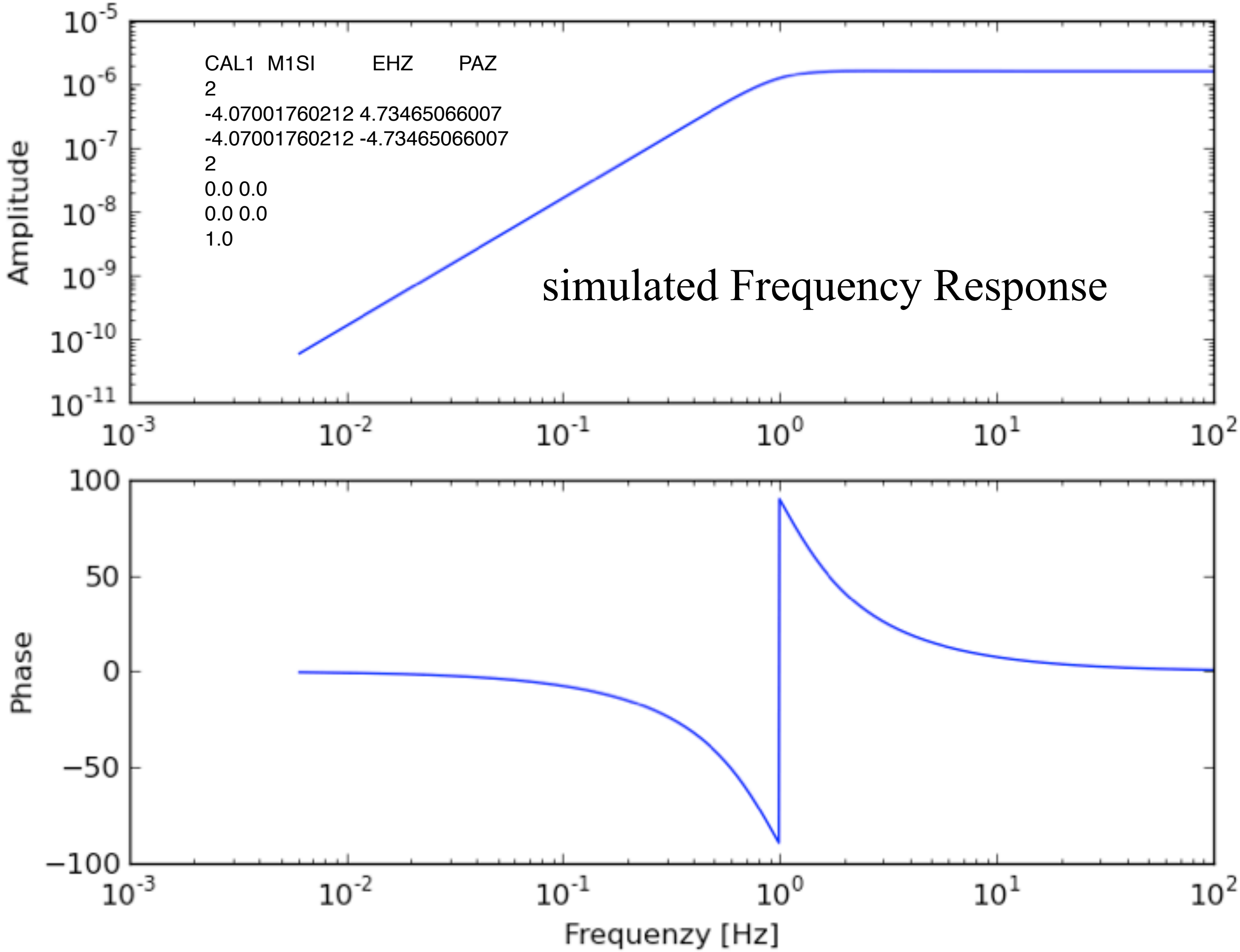


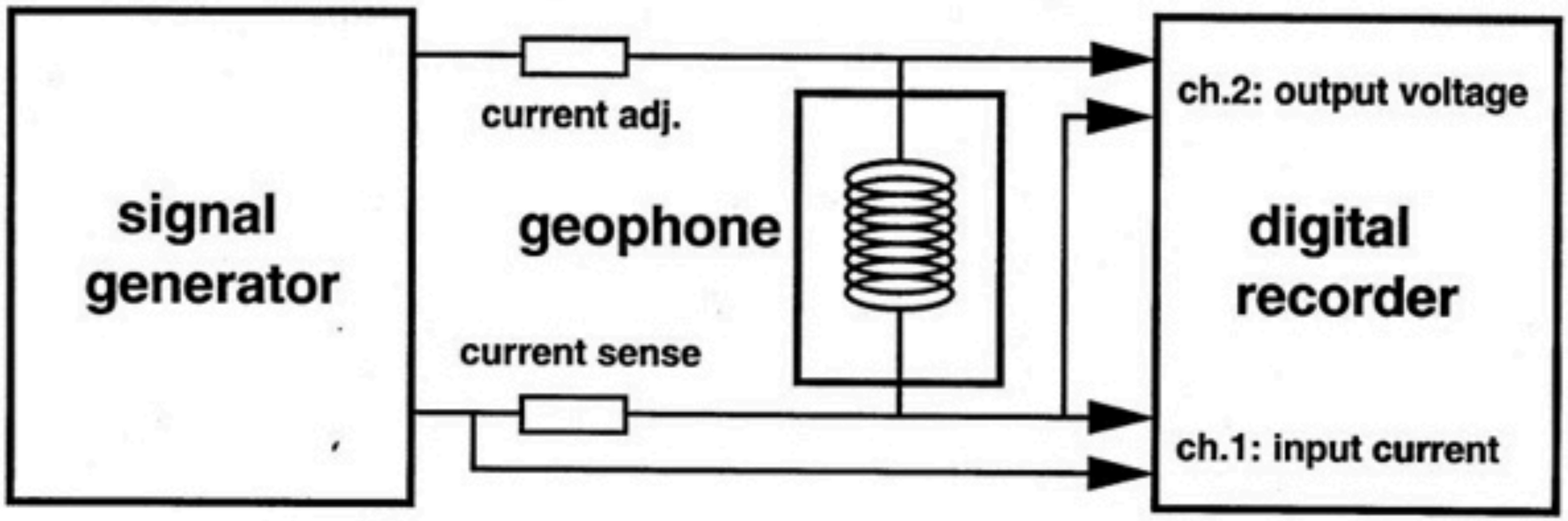
For a perfect fit, filter 1 must be an exact digital representation of the seismometer.
This is only possible when the passband is limited with the anti-alias-filter 2.

CALEX - ObsPy Version



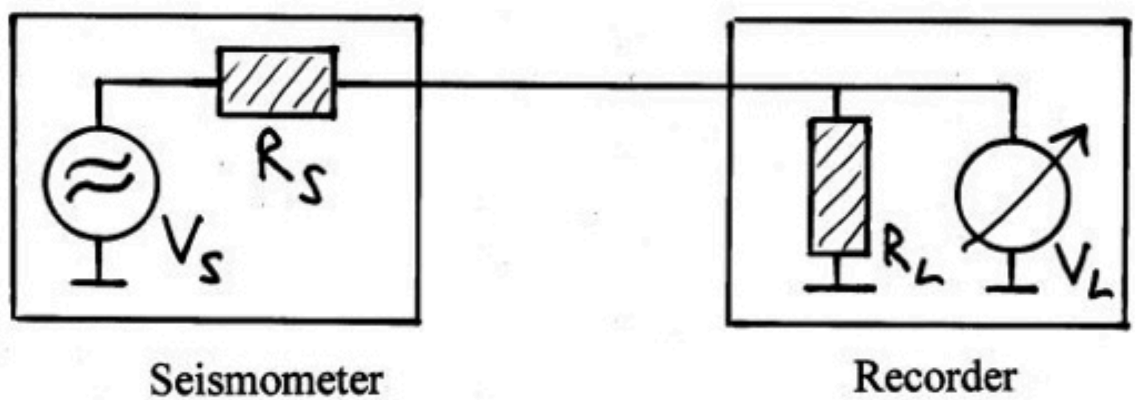
CALEX - ObsPy Version



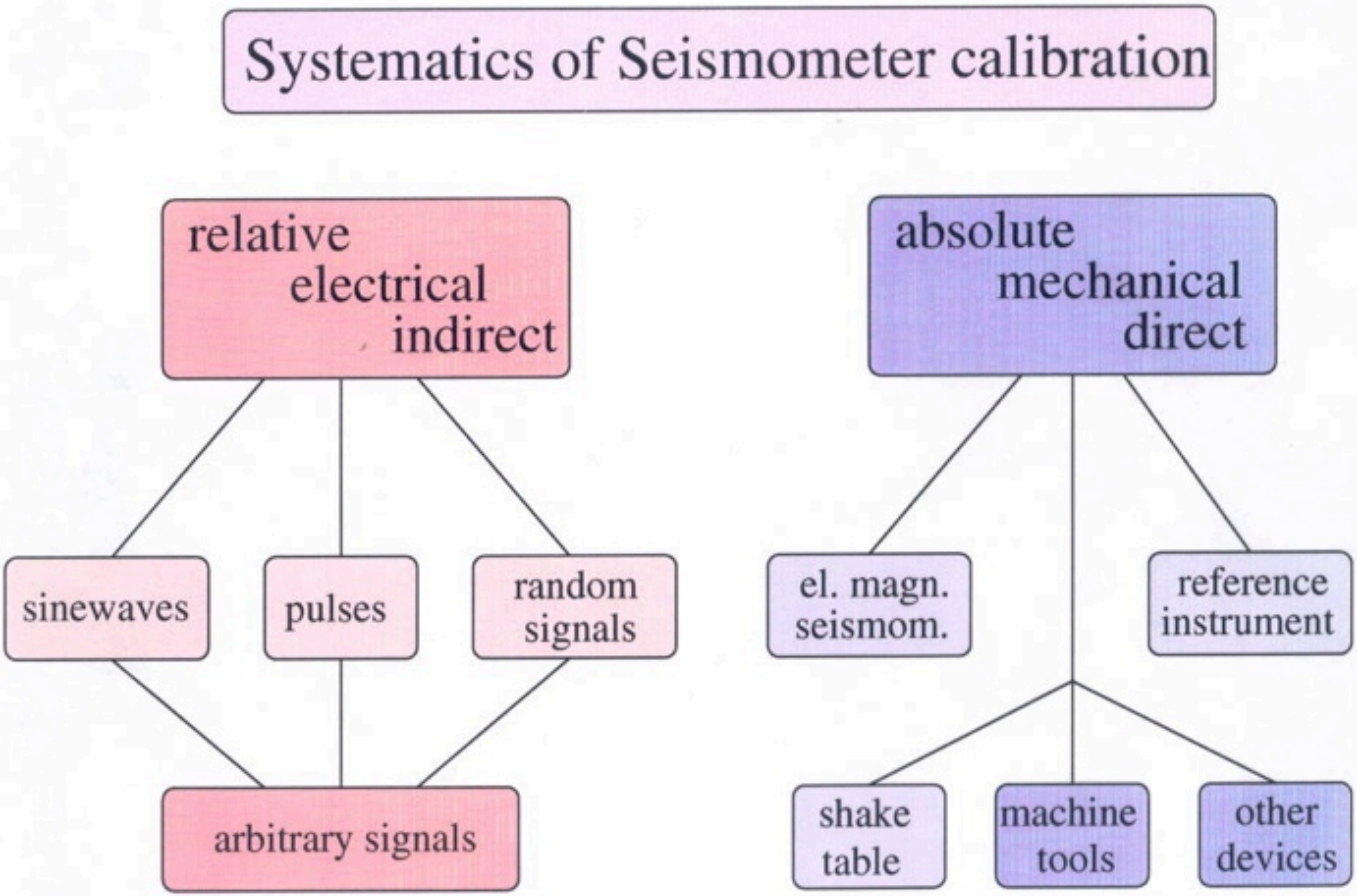

signal
generator
current adj.
geophone
current sense
digital
recorder
ch.2: output voltage
ch.1: input current

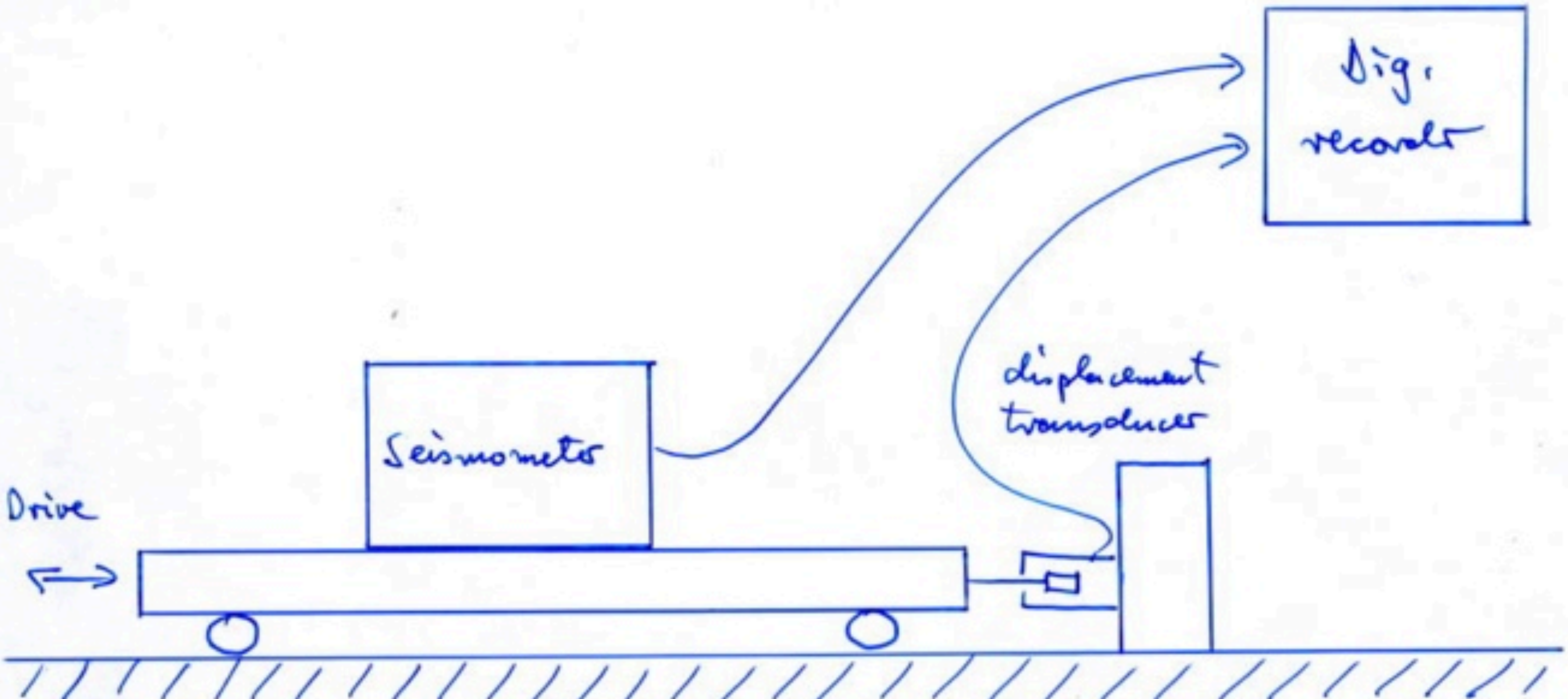
What can easily go wrong without being obvious:

- Polarity reversed
- Only one out of two signal wires connected
- One wire shorted
- One wire interchanged between different channels
- Signal reduction by source / receiver impedance

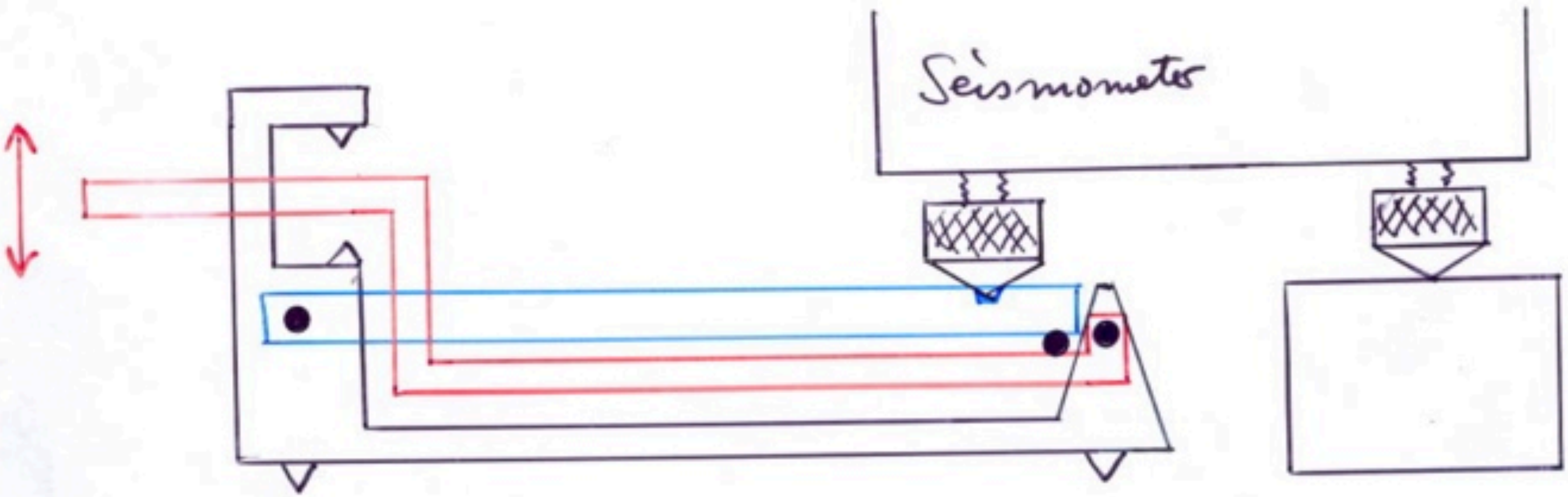


The measured voltage is $V_L = \frac{R_L}{R_L + R_S} V_S$

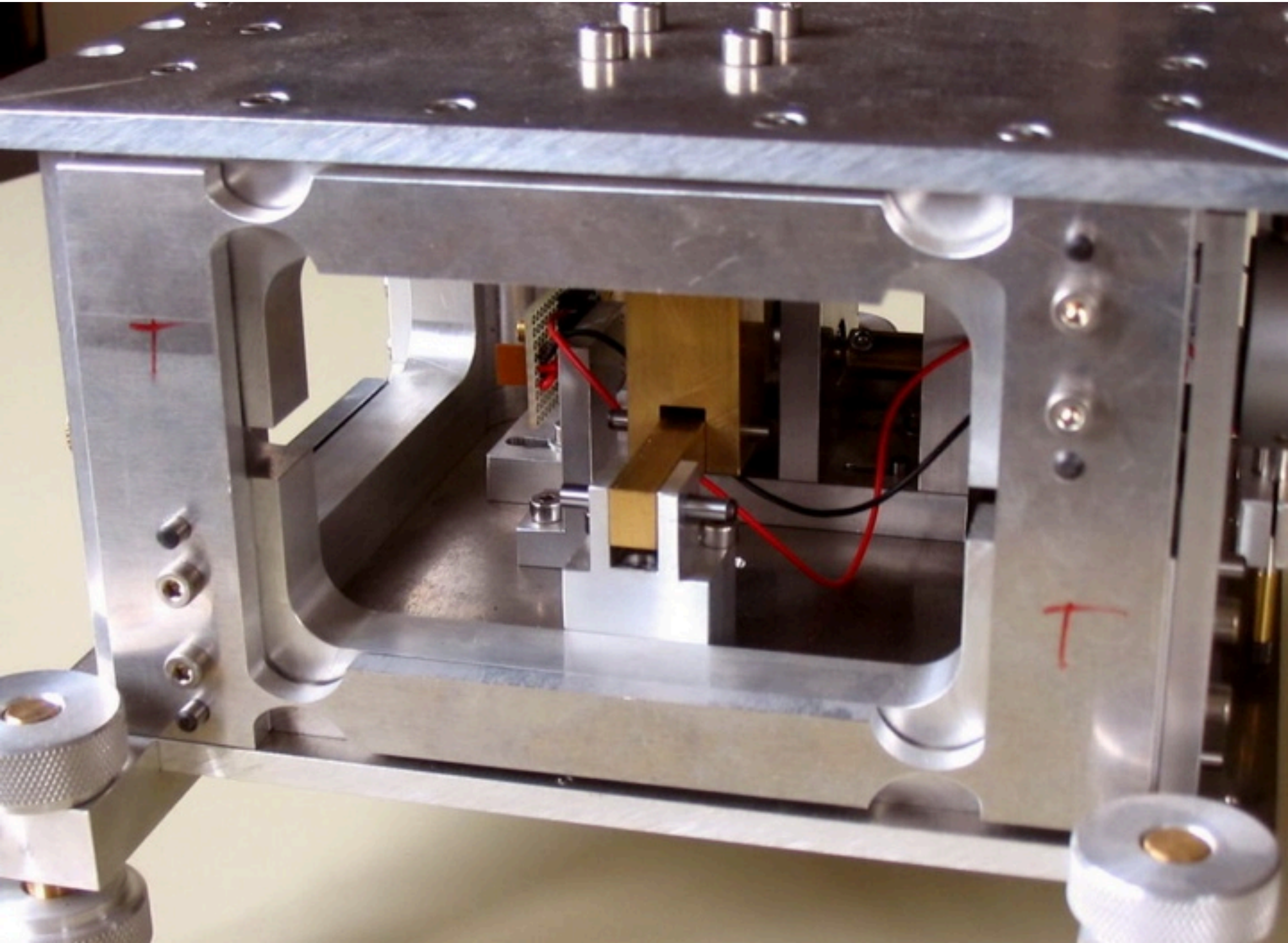

Systematics of Seismometer calibration
relative
electrical
indirect
absolute
mechanical
direct
sinewaves
pulses
random signals
el. magn. seismom.
reference instrument
arbitrary signals
shake table
machine tools
other devices



Shake table

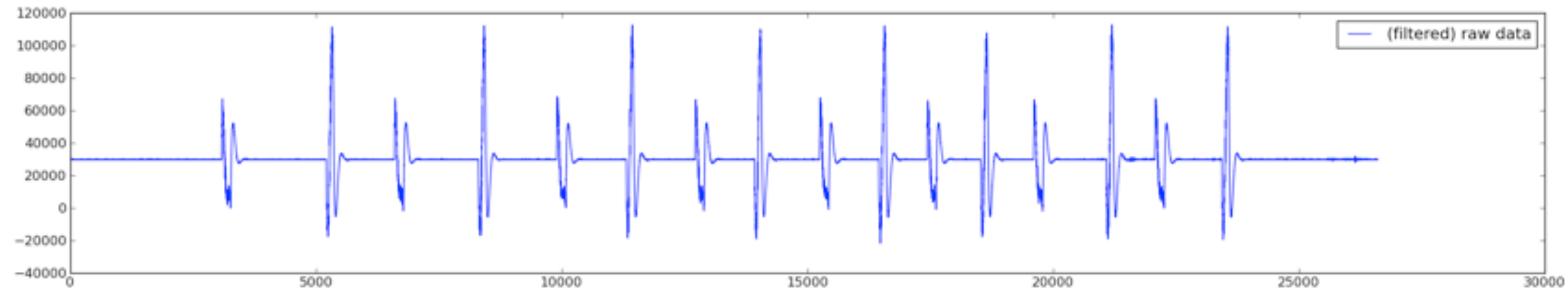


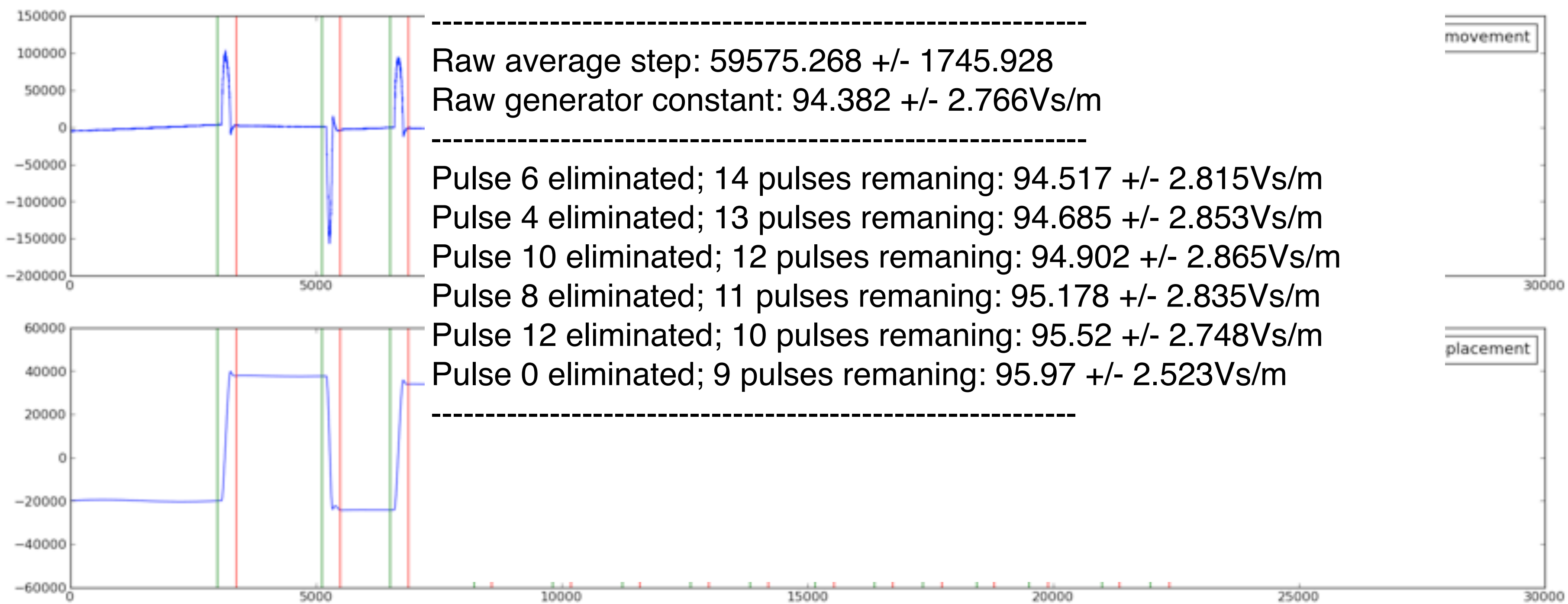
Tilt calibrator




HAHN&KOLB
STOSSGESCHÜTZT
× 0,1 mm
0,001 mm

DISPCAL - ObsPy Version





Raw average step: 59575.268 +/- 1745.928

Raw generator constant: 94.382 +/- 2.766Vs/m

Pulse 6 eliminated; 14 pulses remaning: 94.517 +/- 2.815Vs/m

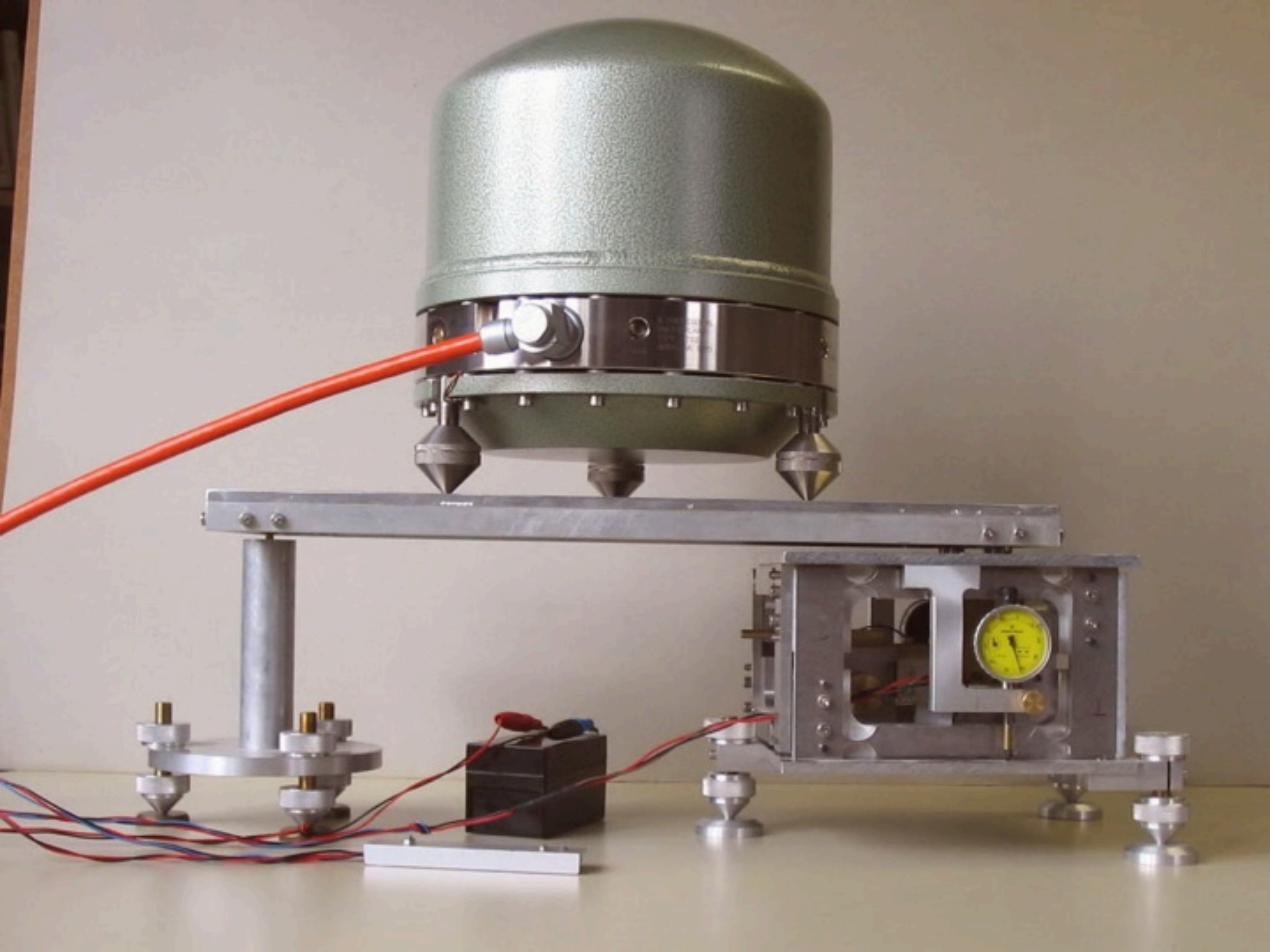
Pulse 4 eliminated; 13 pulses remaning: 94.685 +/- 2.853Vs/m

Pulse 10 eliminated; 12 pulses remaning: 94.902 +/- 2.865Vs/m

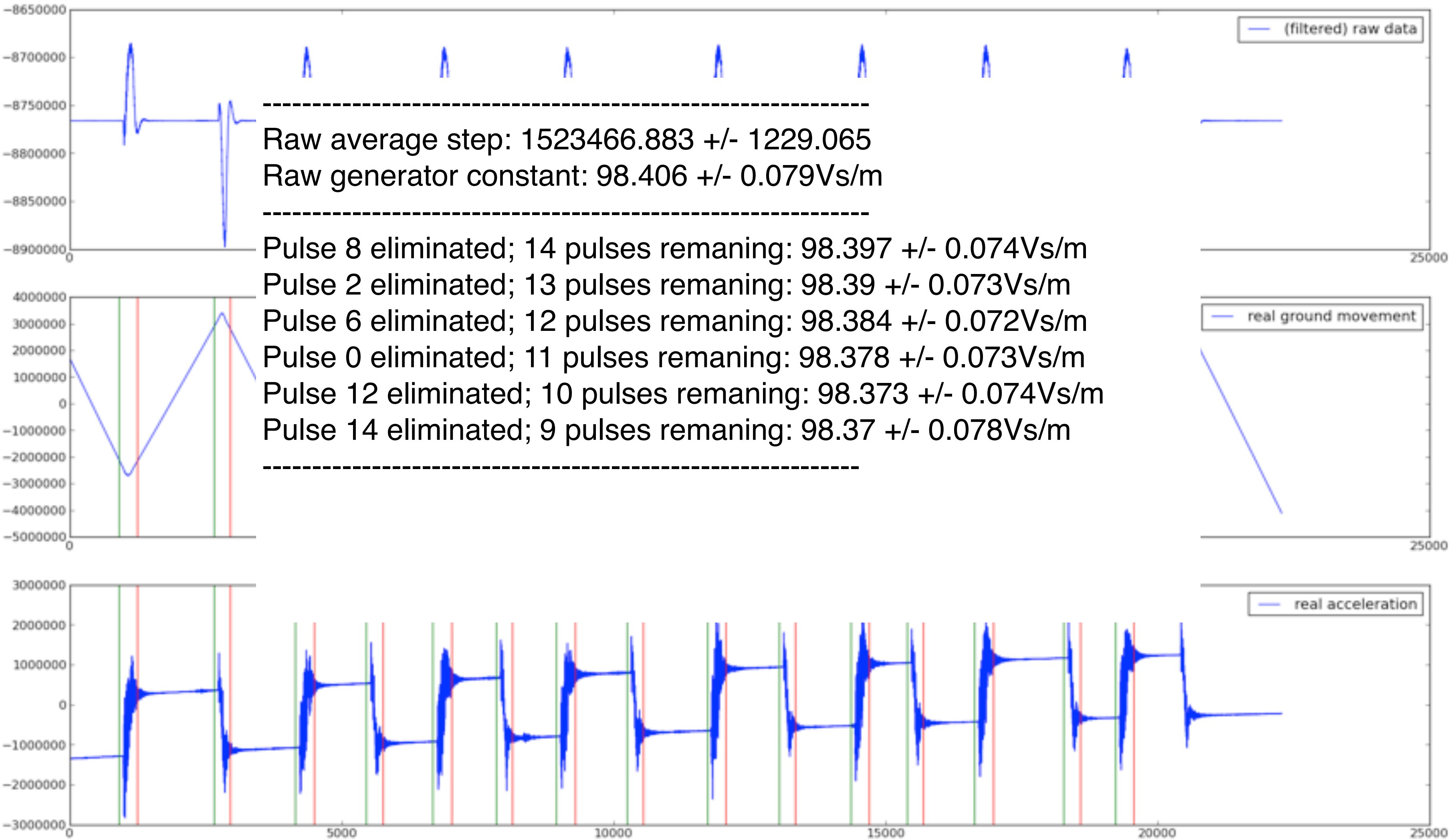
Pulse 8 eliminated; 11 pulses remaning: 95.178 +/- 2.835Vs/m

Pulse 12 eliminated; 10 pulses remaning: 95.52 +/- 2.748Vs/m

Pulse 0 eliminated; 9 pulses remaning: 95.97 +/- 2.523Vs/m



TILTCAL - ObsPy Version



Raw average step: 1523466.883 +/- 1229.065

Raw generator constant: 98.406 +/- 0.079Vs/m

Pulse 8 eliminated; 14 pulses remaning: 98.397 +/- 0.074Vs/m

Pulse 2 eliminated; 13 pulses remaning: 98.39 +/- 0.073Vs/m

Pulse 6 eliminated; 12 pulses remaning: 98.384 +/- 0.072Vs/m

Pulse 0 eliminated; 11 pulses remaning: 98.378 +/- 0.073Vs/m

Pulse 12 eliminated; 10 pulses remaning: 98.373 +/- 0.074Vs/m

Pulse 14 eliminated; 9 pulses remaning: 98.37 +/- 0.078Vs/m

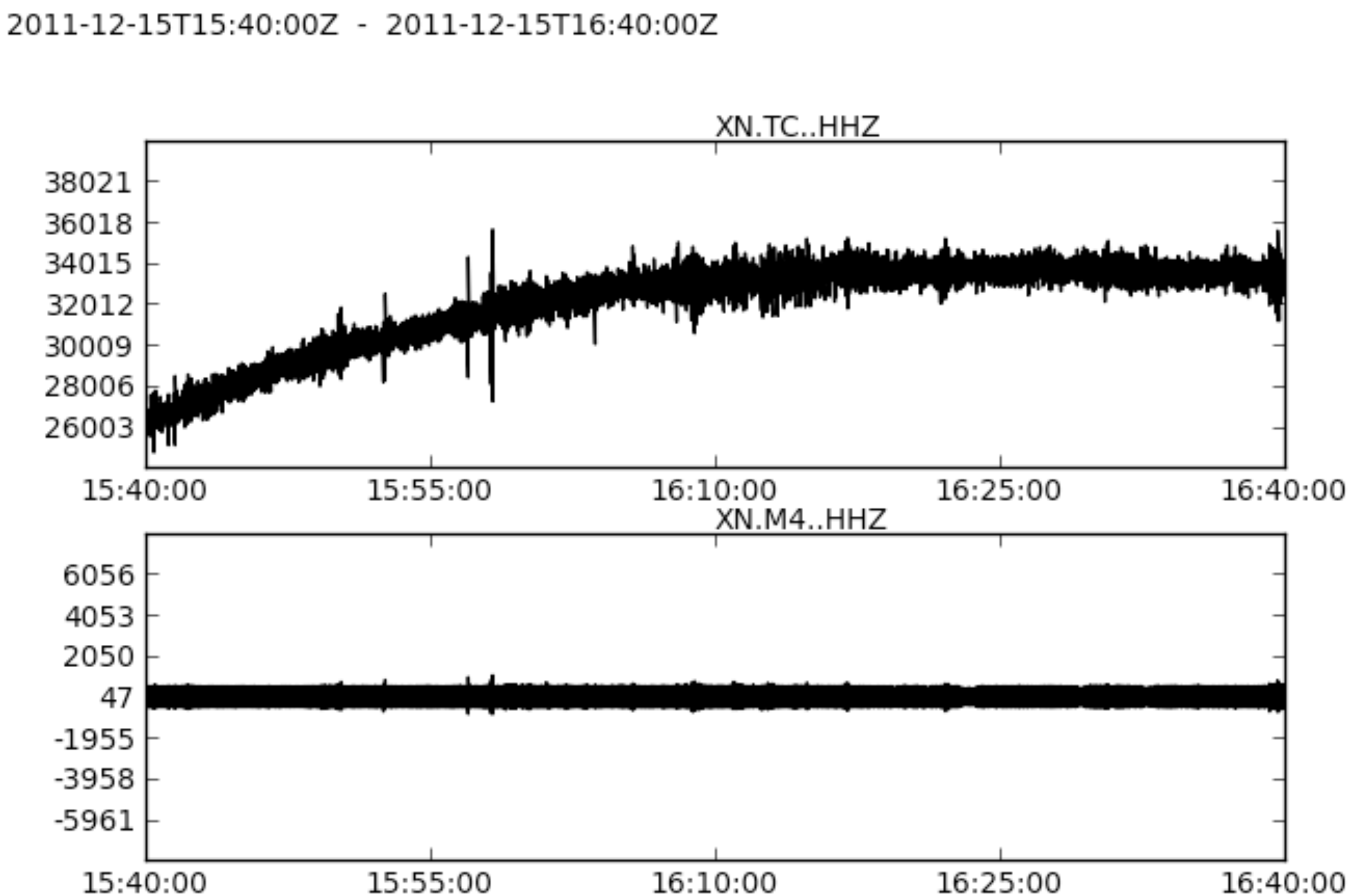
Absolute calibration of seismic sensors by displacement and tilt

Sensor type \	milling machine	balance	tilt lever
Streckeisen STS2 # 99113	X: 1484 +-3 Y: 1490 +-4 Z: 1502 +-6	 Z: 1503 +-4	X: 1481 +-3 X: 1480 +-4 X: 1481 +-6
Sensonics Mk3A	H: 499 +-4		
SM4 geophone 10 Hz		Z: 28.5 +-0.1	

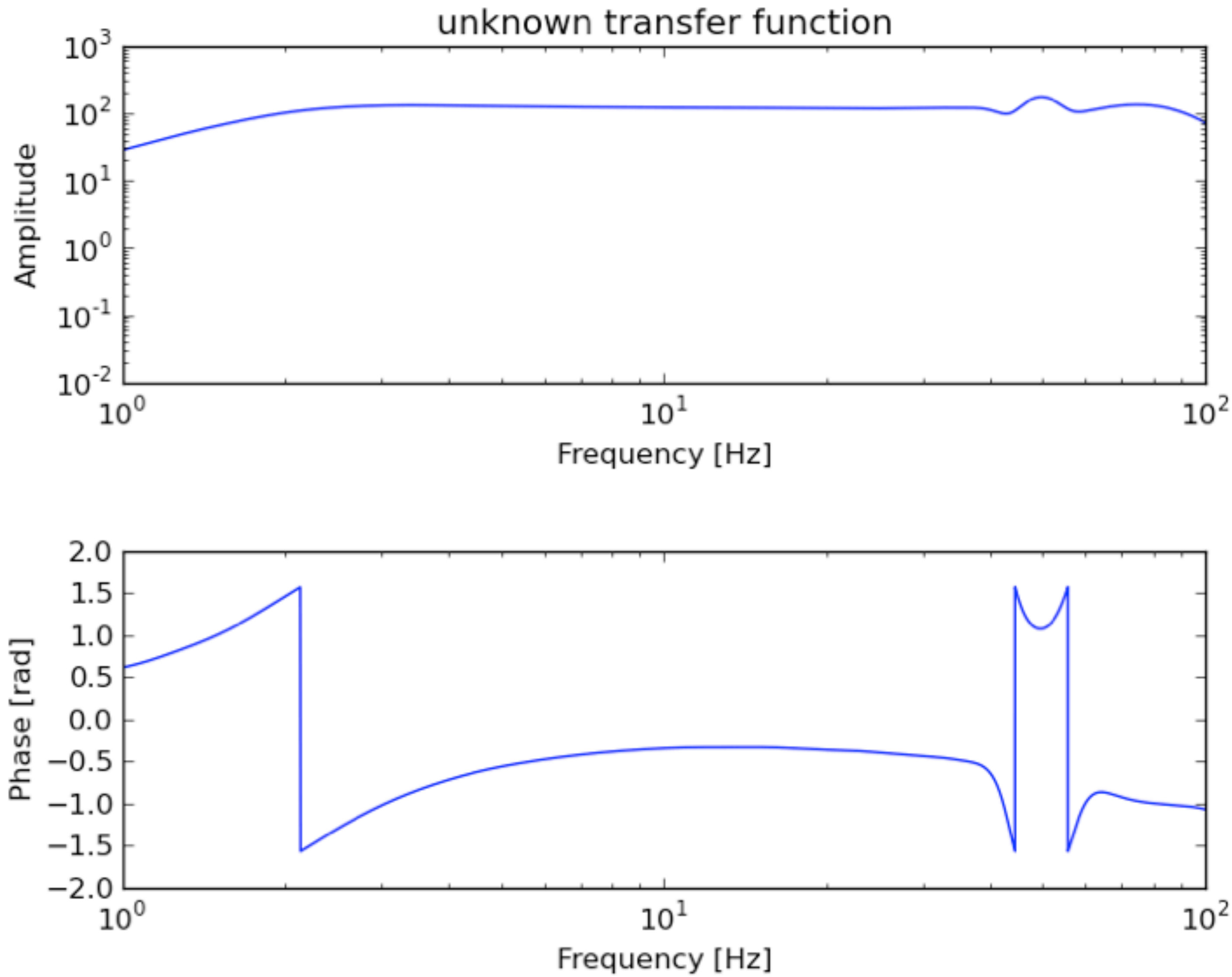
Specs were: STS2 1500 Vs/m   Mk3A 500 Vs/m   SM4 28.8Vs/m


Trillium

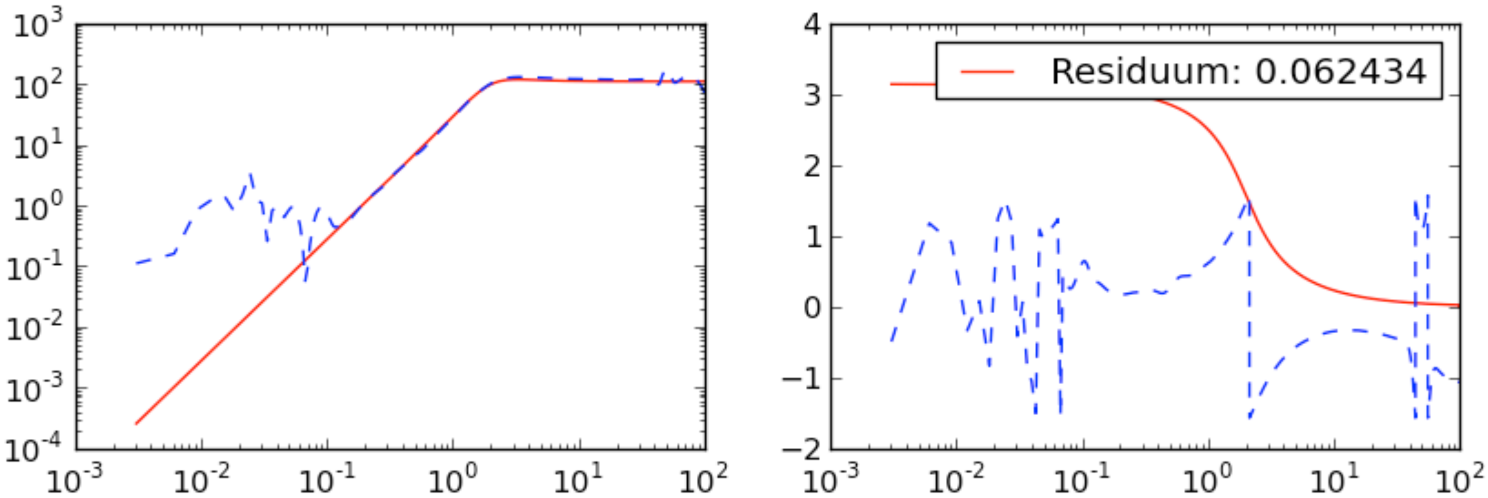
NoiseCalib - ObsPy Version (RELCALSTACK)



NoiseCalib - ObsPy Version (RELCALSTACK)



NoiseCalib - ObsPy Version (PyQt_FitResp)



f_0=2.0 Hz, h = 0.56, G=110V/m/s