LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Networks, instruments and data centres: what does your seismic (meta-) data really mean?

Joachim Wassermann (LMU Munich)

Quest Workshop, Hveragerdi 2011

Seismic Networks: Data Exchange

Why an issue?

- many different data formats are existing, but uniform standard exists to send the data to DCs
- meta data of special importance!
- possibility to form "virtual networks" - especially important for regional events or earthquakes located close to a border region
- increasing the value of the network owners (more use gives more credits)
- simulating instruments is sometimes easier than correcting real data to true ground motion (relevant for synthetics)

What is SEED ?

- SEED is an international standard for the exchange of digital seismological data
- SEED was designed for use by the earthquake research community, primarily for the exchange between institutions of unprocessed earth motion data
- SEED is a format for digital data measured at one point in space and at equal intervals of time.

SEED in Practice

- recordings of digital time-series data (seismic waveforms)
- exchange of waveform data (real-time, archive)
- archiving of digital waveform data (IRIS-DMC, ODC, EIDA...)
- storage of meta-data (information about the data, e.g. station information, sensor)
- end user (analysis software)
- **not for non-time series data**
- **not for unequal time-interval sampled data (except logs)**
- **not designed for processed or synthetic data, but possible (IRIS already use it!)**
- parametric data possible (e.g. phase readings) but never used; IASPEI Seismic Format (ISF)

SEED Structure

control headers

dataless SEED

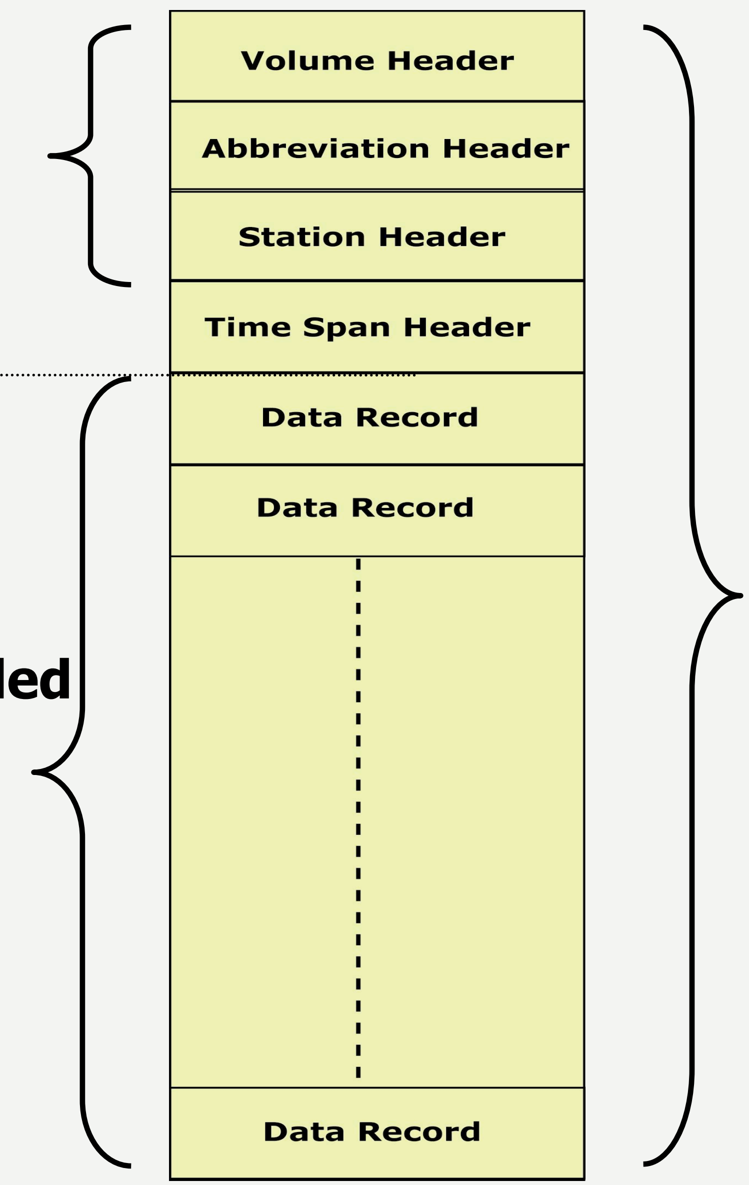
ascii

waveform data

raw data and embedded auxiliary information

mini-SEED

binary (+ ascii)



(full) SEED volume

SEED: Metadata and System Response

- **All site characteristics:**
  - Latitude, longitude, elevation
- **All instrument characteristics:**
  - Detailed responses - calibration, transfer functions
    - Sensor
    - External Preamp and Filter
    - Datalogger
  - Orientation angles and depth of emplacement
  - Serial numbers
  - Instrument type
- **Effective date/time**

System Response or:
Filters and Their Description

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F. Scherbaum (Univ. Potsdam)

From source to receiver...

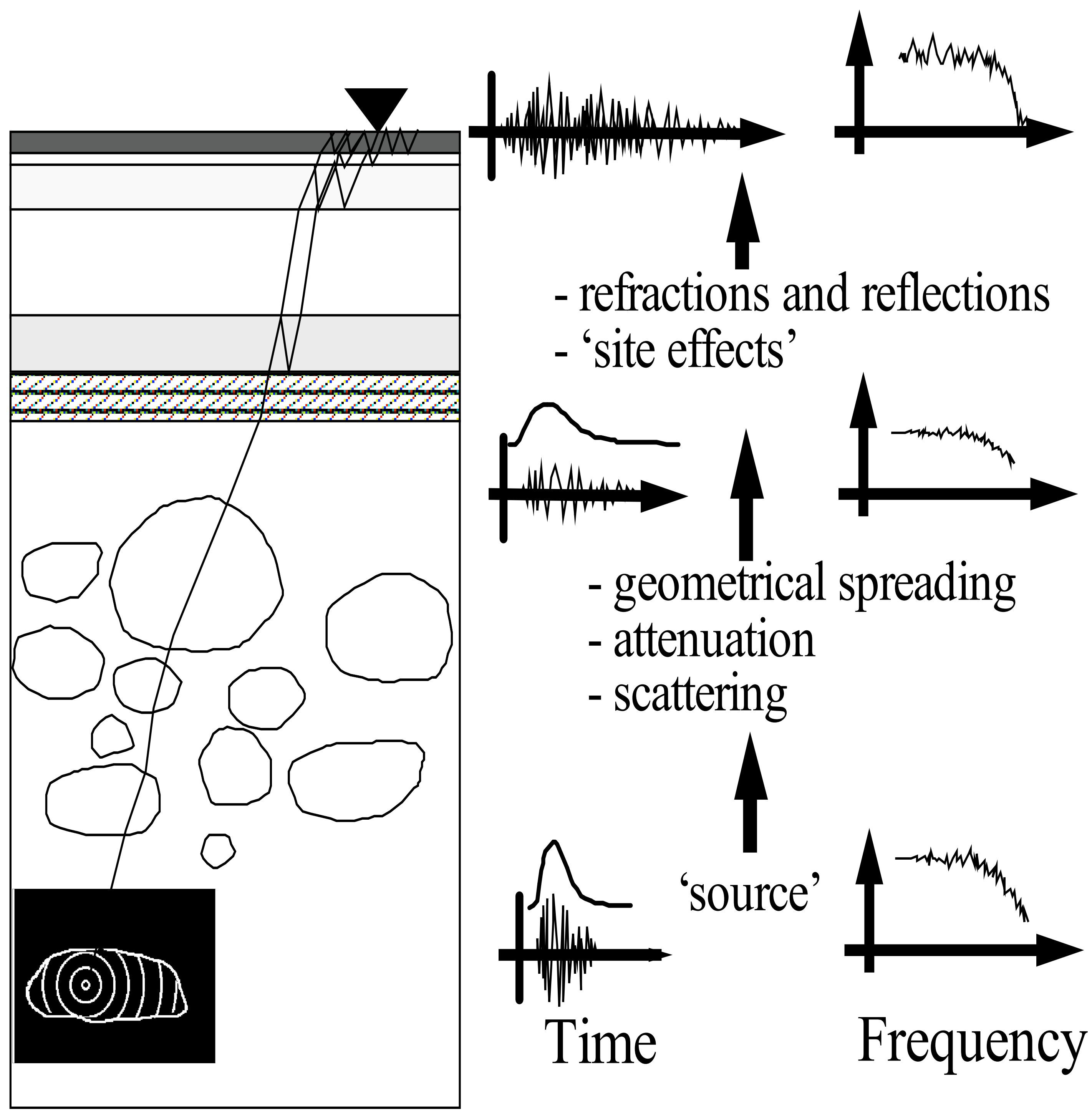


Fig. 1.1 Signal distortion during wave propagation from the earthquake source to the surface.

Influence of recording system

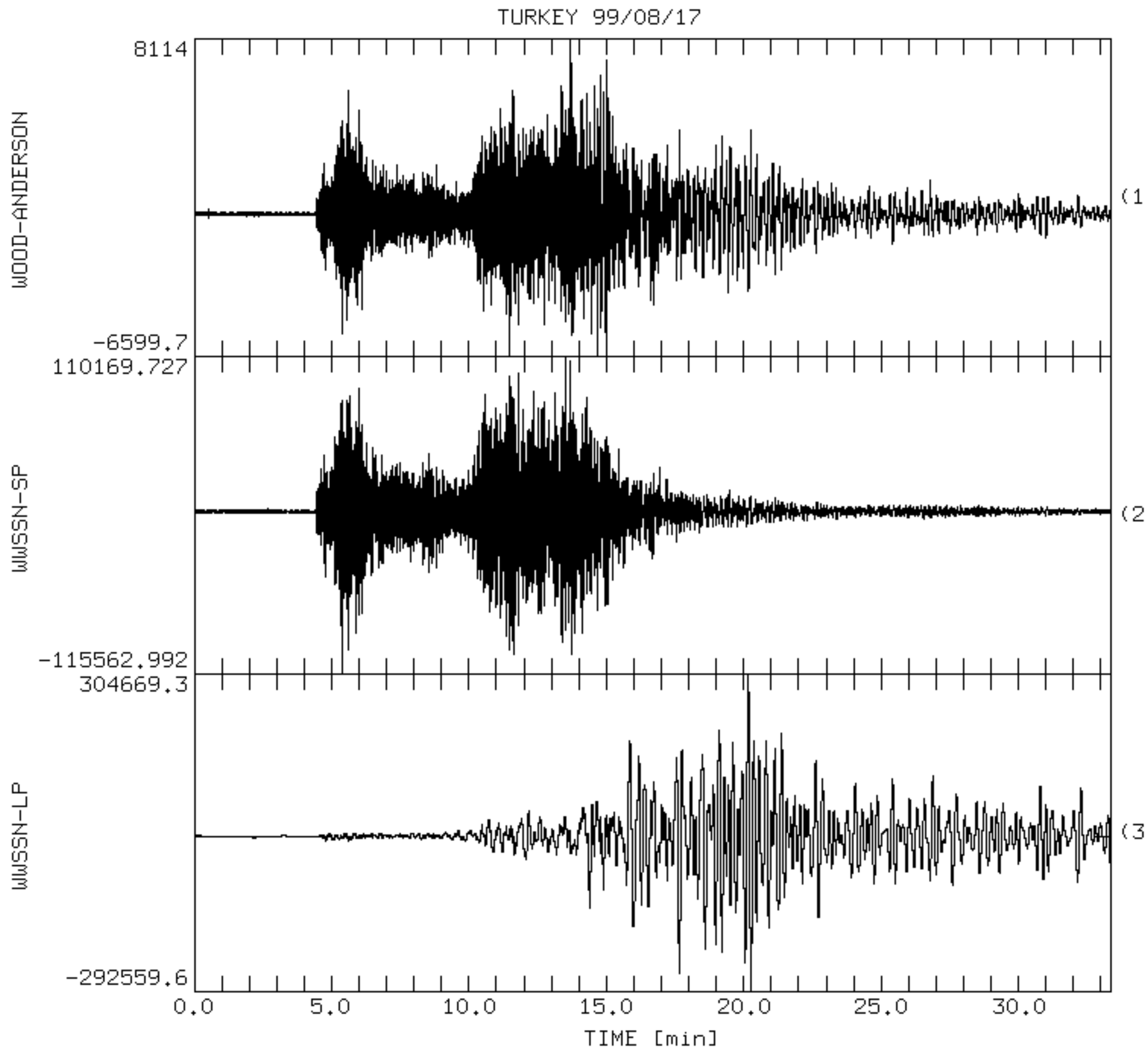


Fig. 1.2 Vertical component record of the Izmit earthquake in Turkey (1999/08/17) recorded at station MA13 of the University of Potsdam during a field experiment in Northern Norway. Shown from top to bottom are the vertical component records for a: Wood-Anderson, a WWSSN SP, and a WWSSN LP instrument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

Sampling process

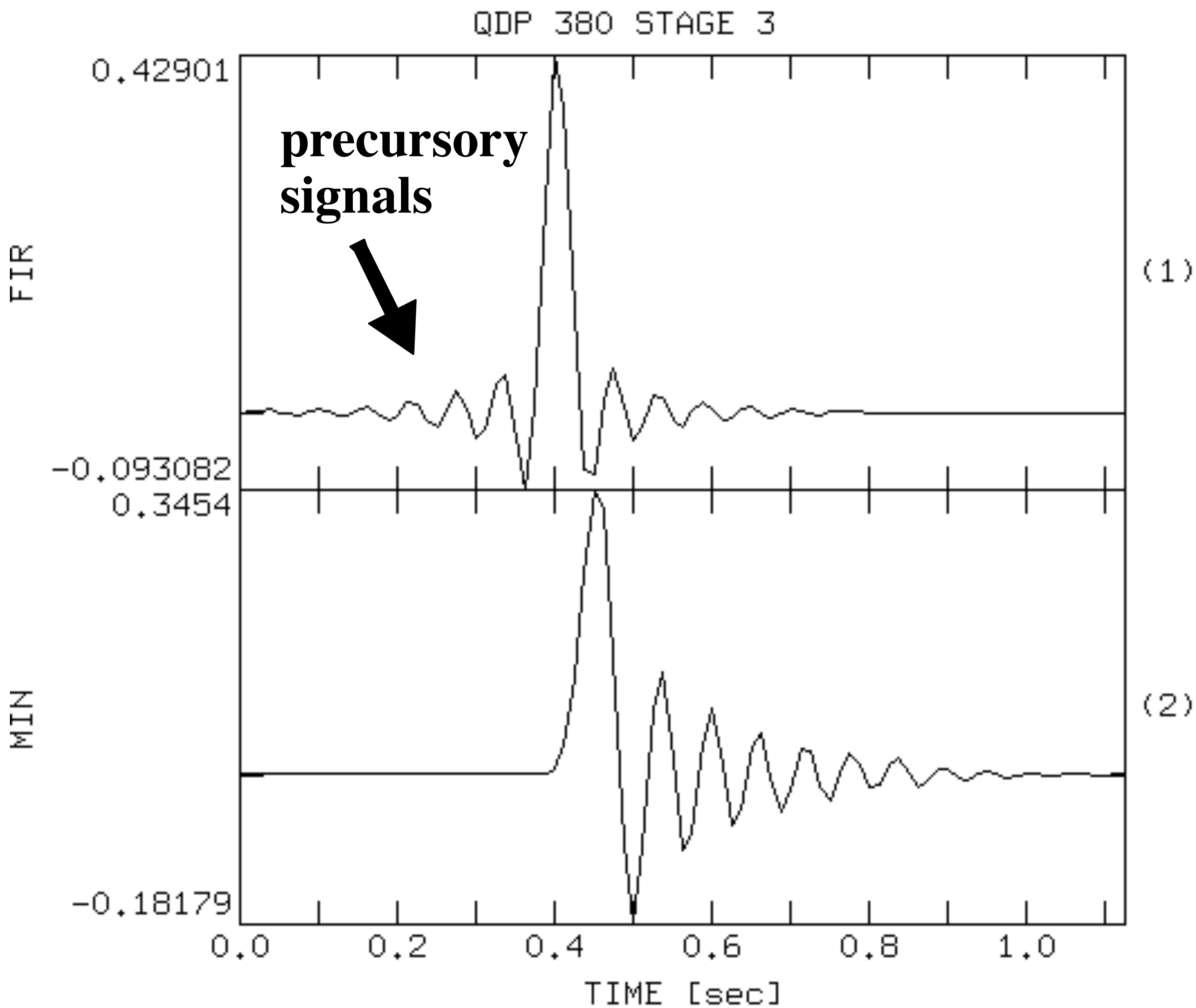


Fig. 1.3 Impulse response of stage 3 of the two-sided decimation filter incorporated in the Quanterra QDP 380 system (top trace). The bottom trace shows a filter response with an identical amplitude but different phase response.

Seismogram

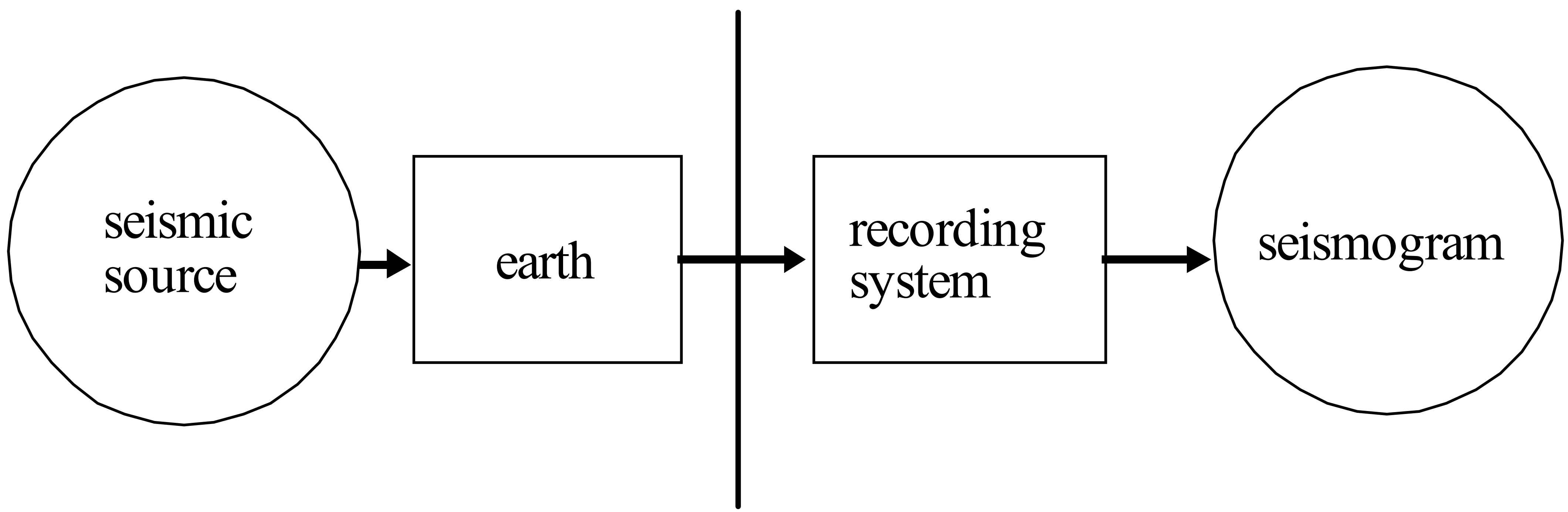
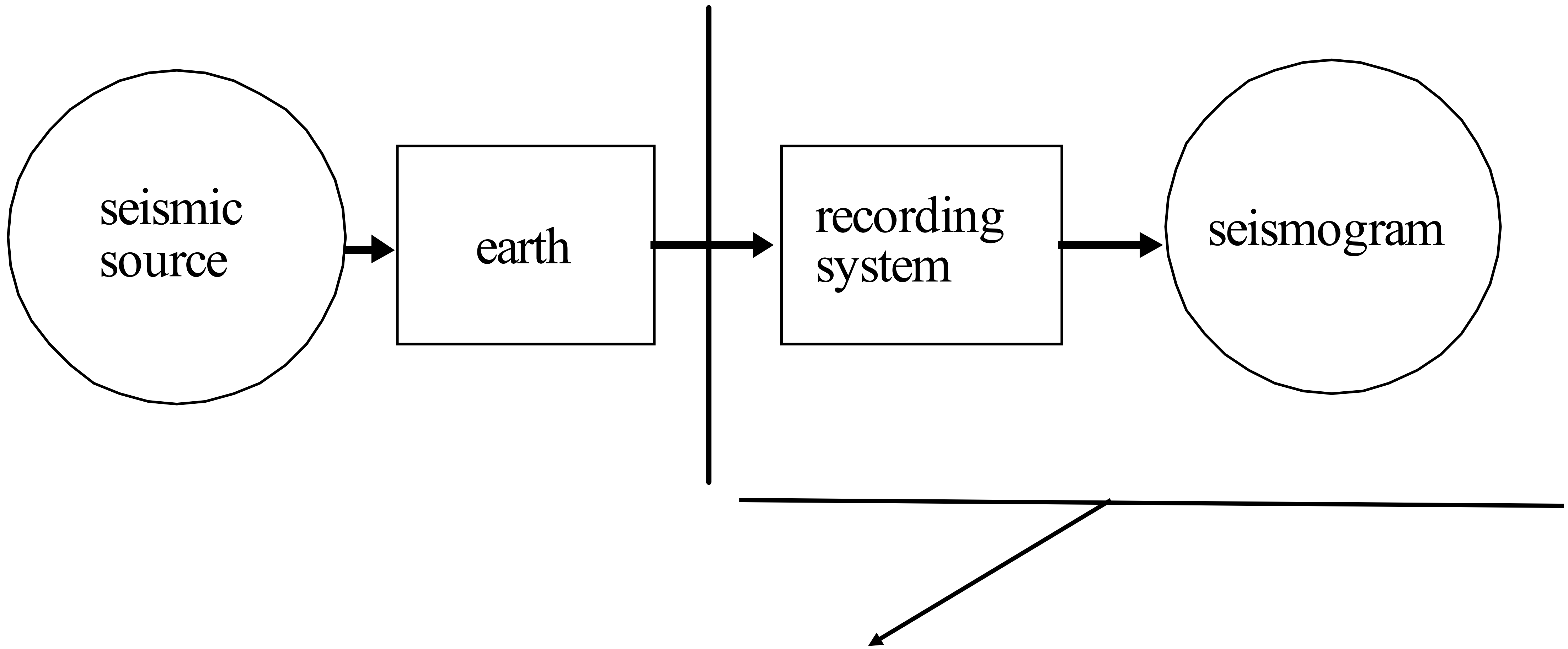


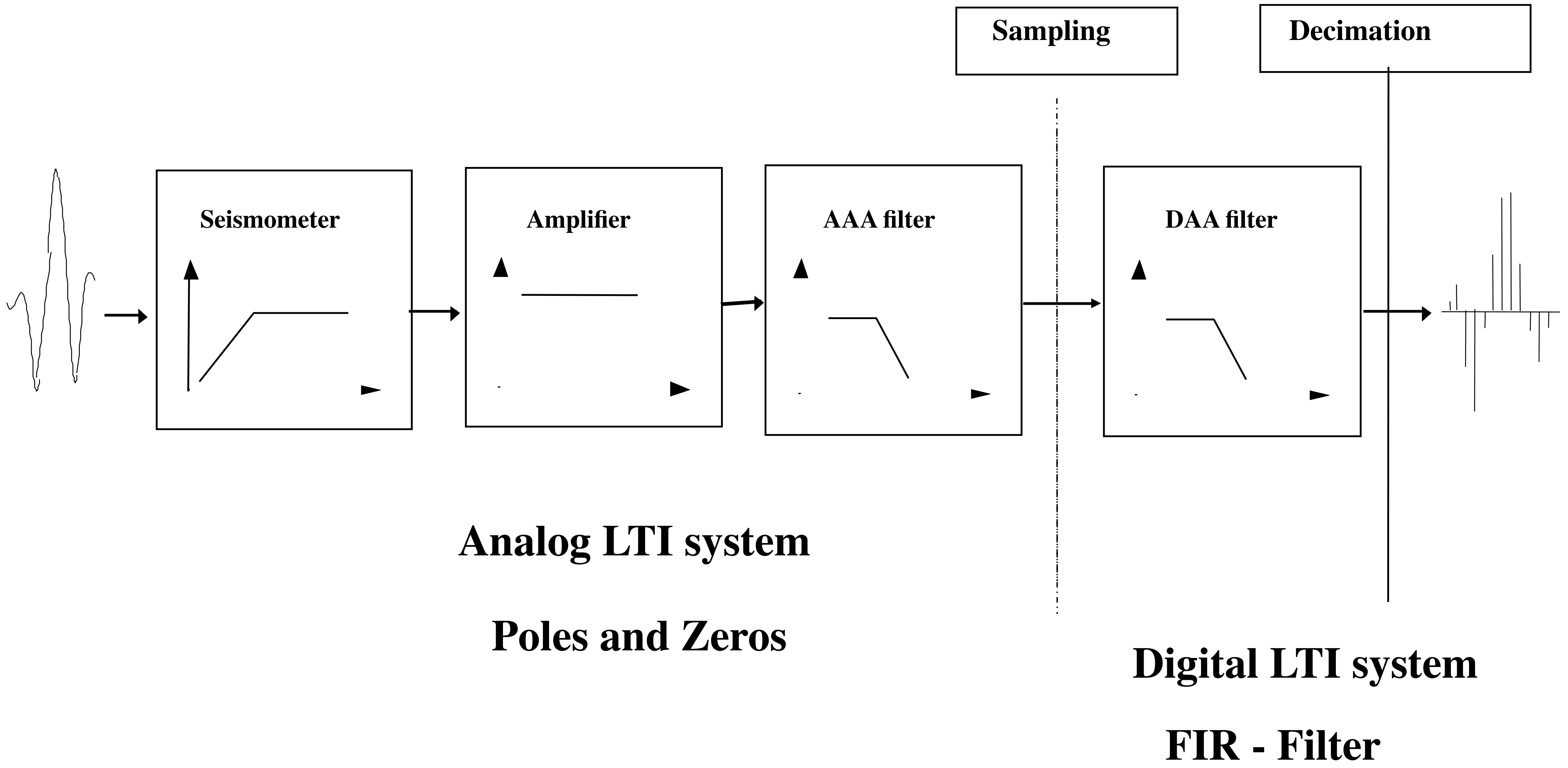
Fig. 1.11 System diagram of a seismogram

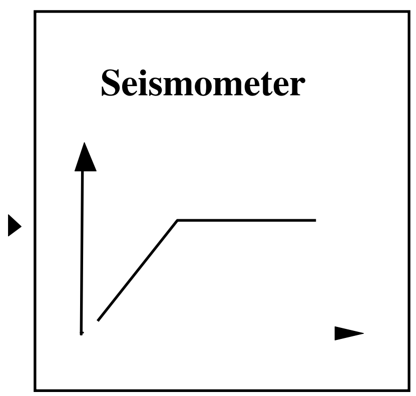
Seismogram



This part is covered by SEED

SEED response information



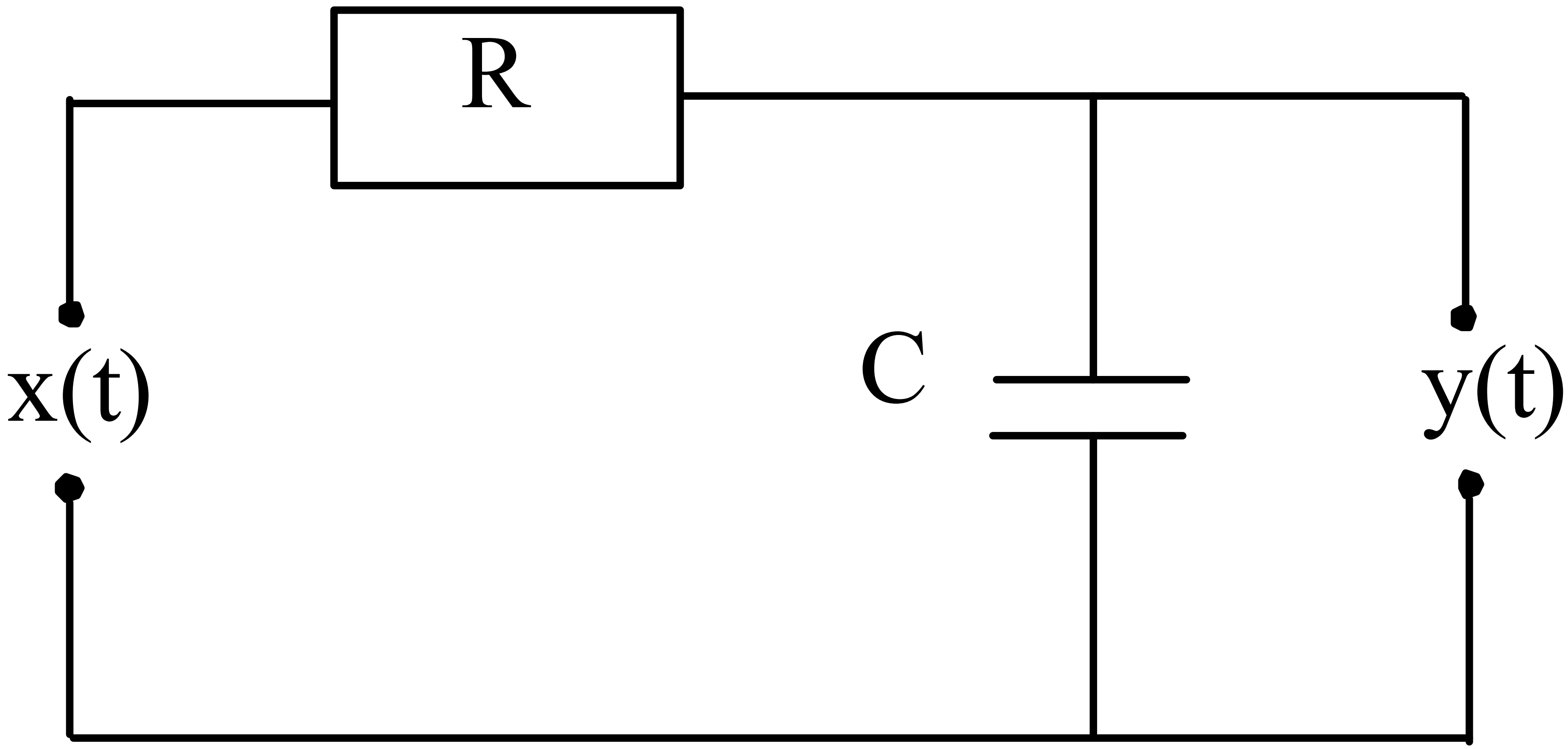



```
#           << IRIS SEED Reader, Release 4.4 >>
#
#           ======== CHANNEL RESPONSE DATA ========
B050F03     Station:     RJOB
B050F16     Network:     BW
B052F03     Location:    ??
B052F04     Channel:     EHZ
B052F22     Start date:  2007,199
B052F23     End date:    No Ending Time
#           =======================================
#           +           +-----------------------------------------+           +
#           +           |  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
```

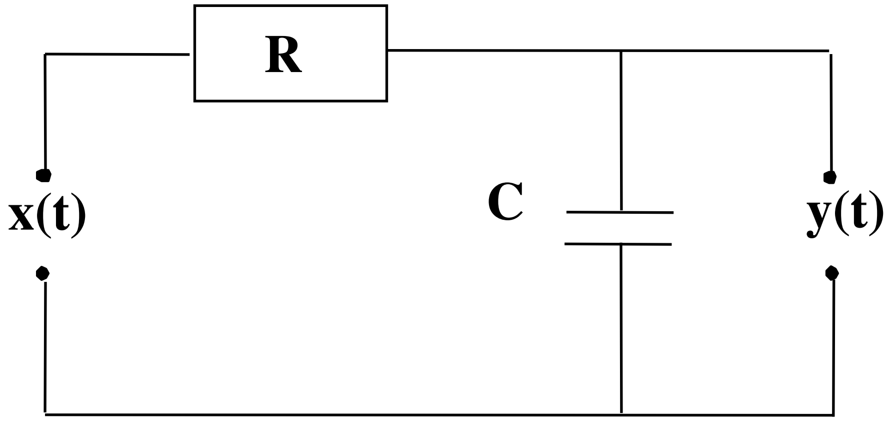
Definition

- Filters or systems are, in the most general sense, devices (in the physical world) or algorithms (in the mathematical world) which act on some input signal to produce a - possibly different - output signal.

RC filter



Differential equation



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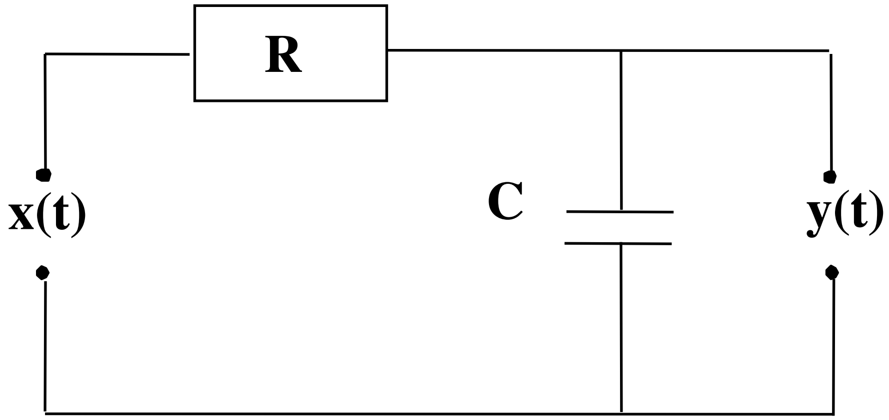
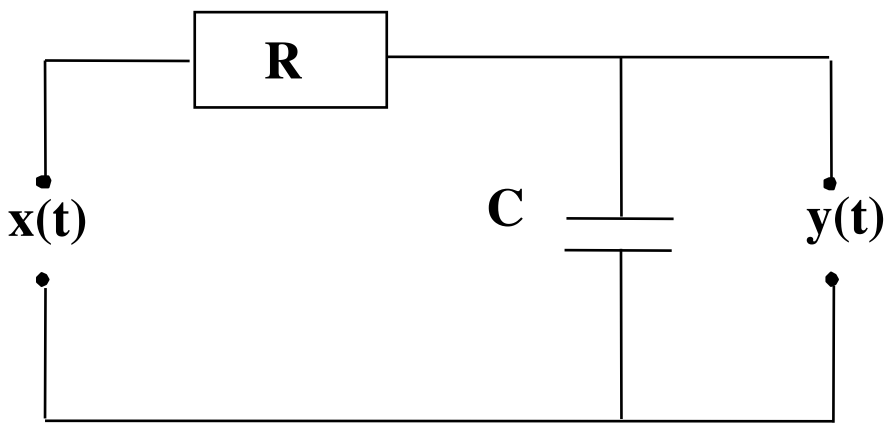


Voltage balance?

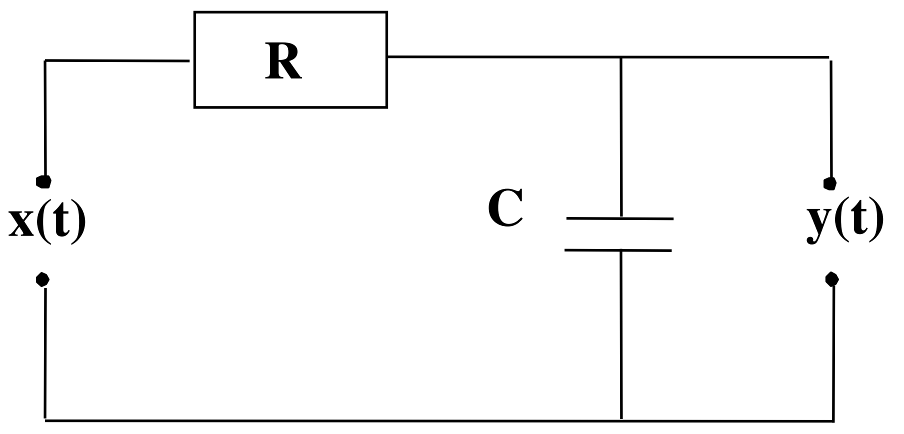
Differential equation



Voltage balance?

$$RI(t) + y(t) = x(t)$$

Differential equation



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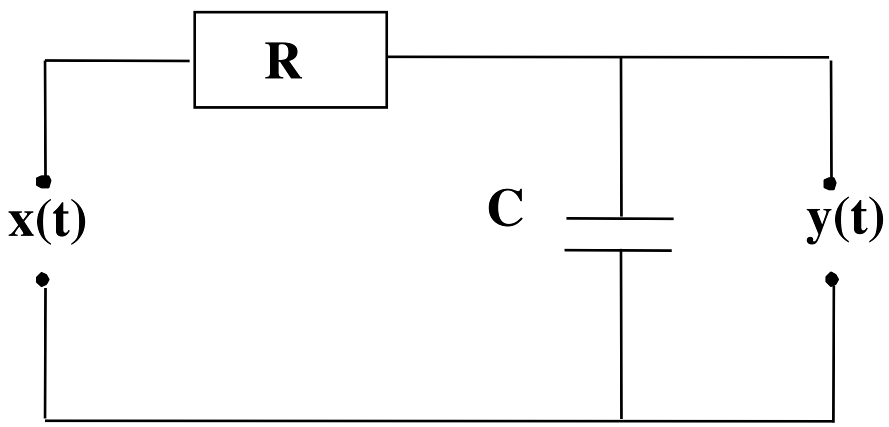

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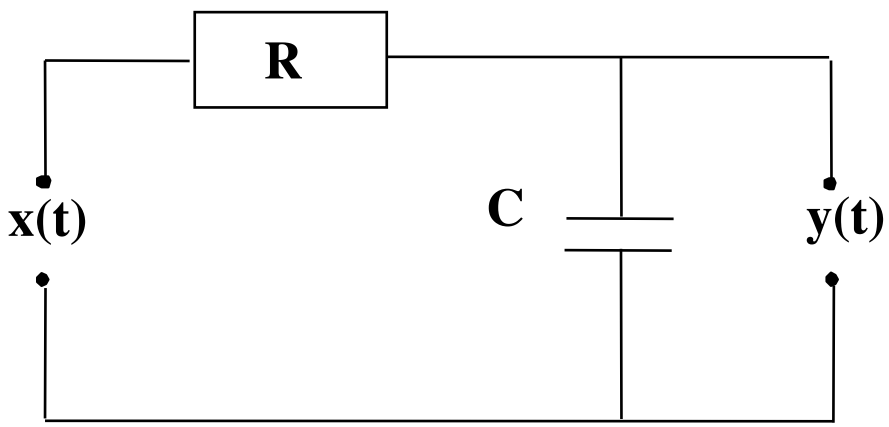

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Current through resistor R and capacitance C:

$$I(t) = C\dot{y}(t)$$

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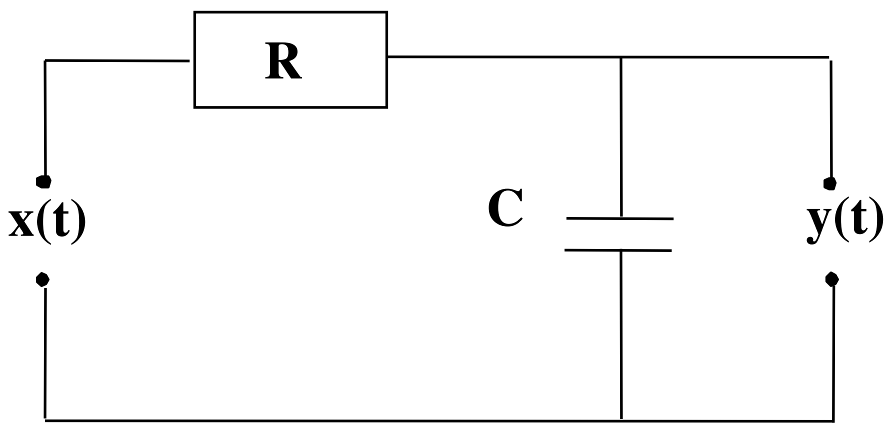
Differential equation



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First order linear differential equation

Harmonic input signals

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Frequency response function

Input/output relation

$$A_o = T(j\omega) \cdot A_i$$

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• ***Definition* —** The frequency response function *$T(j\omega)$* is defined as the Fourier transform of the output signal divided by the Fourier transform of the input signal.

Input/output relation

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• ***Definition* —** The frequency response function *T(jω)* is defined as the Fourier transform of the output signal divided by the Fourier transform of the input signal.

The frequency response function can be measured by comparing output and input signals to the system **without further knowledge of the physics going on inside the filter**!

Transfer function and Laplace transform

Bilateral Laplace transform of *f(t):* $\mathbf{L}\left[f(t)\right] = \int_{-\infty}^{\infty} f(t)e^{-st}dt$

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

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Property: $\mathcal{L}\left[\dot{f}(t)\right] = s \cdot F(s)$

Transfer function and Laplace transform

Transfer function and Laplace transform

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

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$s = -1/\tau$ "pole" of the transfer function

The frequency response function and the pole position

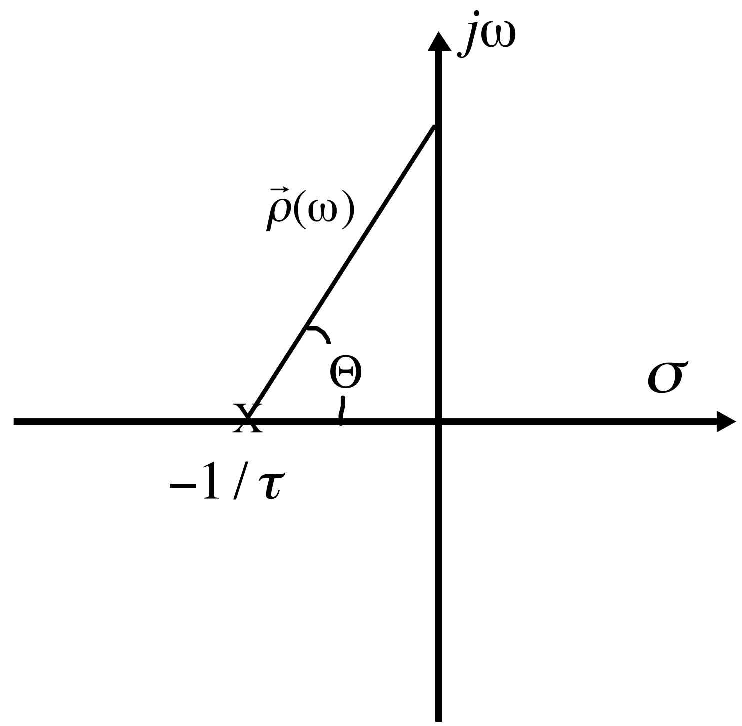

Fig. 2.10 Representation of the RC filter in the s plane. The pole location at $-1/\tau$ is marked by an X.

Transfer function RC filter: $$T(s) = \frac{1}{1+s\tau} = \frac{1}{\tau}\left[\frac{1}{(1/\tau)+s}\right]$$

For $s = j\,\omega$, ω moves along the imaginary axis ⇨ $$T(j\omega) = \frac{1}{\tau}\left[\frac{1}{(1/\tau)+j\omega}\right]$$

$1/\tau + j\omega$ represents the vector $\varrho(j\omega)$

which is pointing from the pole position towards the actual frequency on the imaginary axis.

General linear time invariant systems

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Generalization of concepts

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Generalization of concepts

Rewrite the differential equation for the RC filter:

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

General linear time invariant systems

Generalization of concepts

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$\Longrightarrow$ RC filter special case of Nth order LTI system

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RC filter special case of
Nth order LTI system

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

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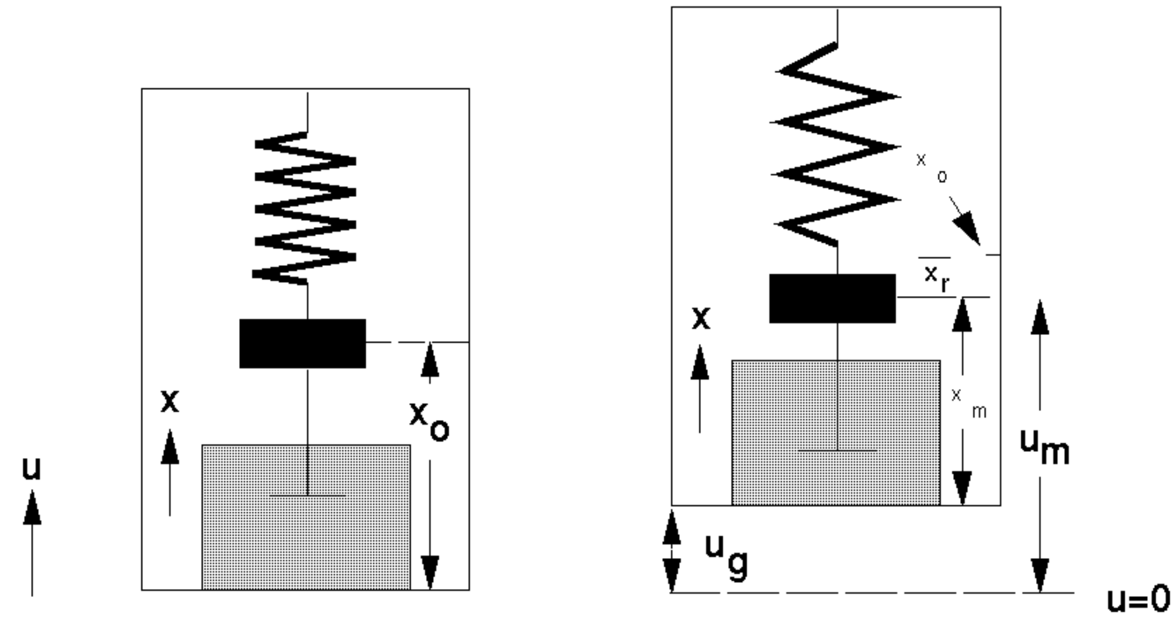
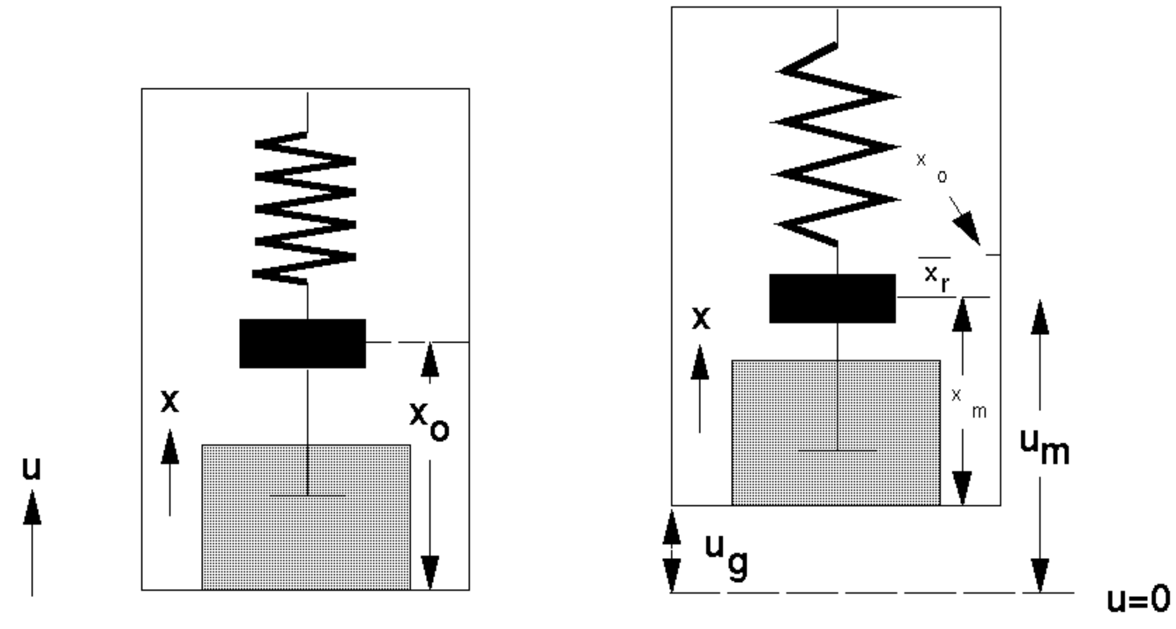
WHAT IS IT GOOD FOR????

Seismometer

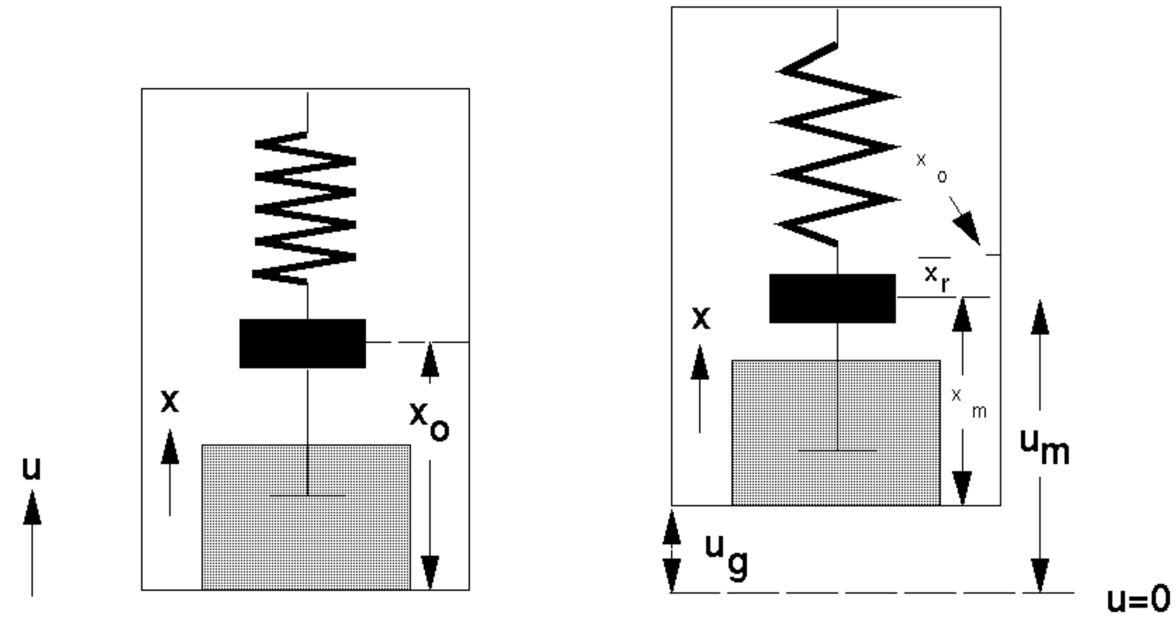


Seismometer



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

Seismometer

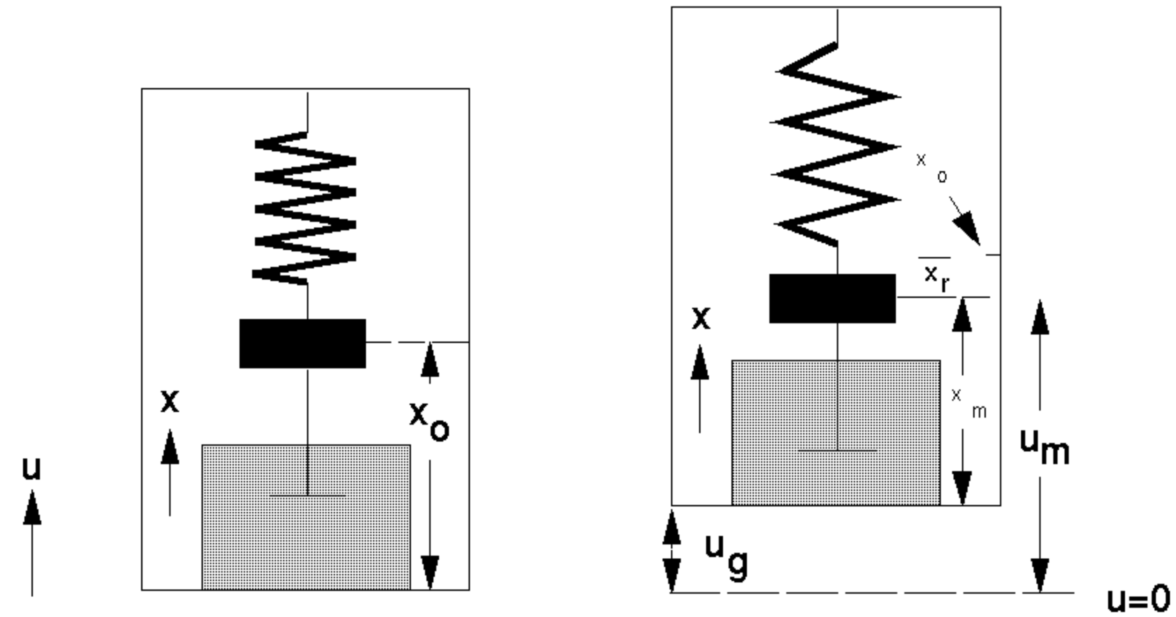


• *The inertia of the mass —* $f_i = -m\ddot{u}_m(t)$

• *The spring —* $f_{sp} = -kx_r(t)$

k = spring constant (strength)

Seismometer



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

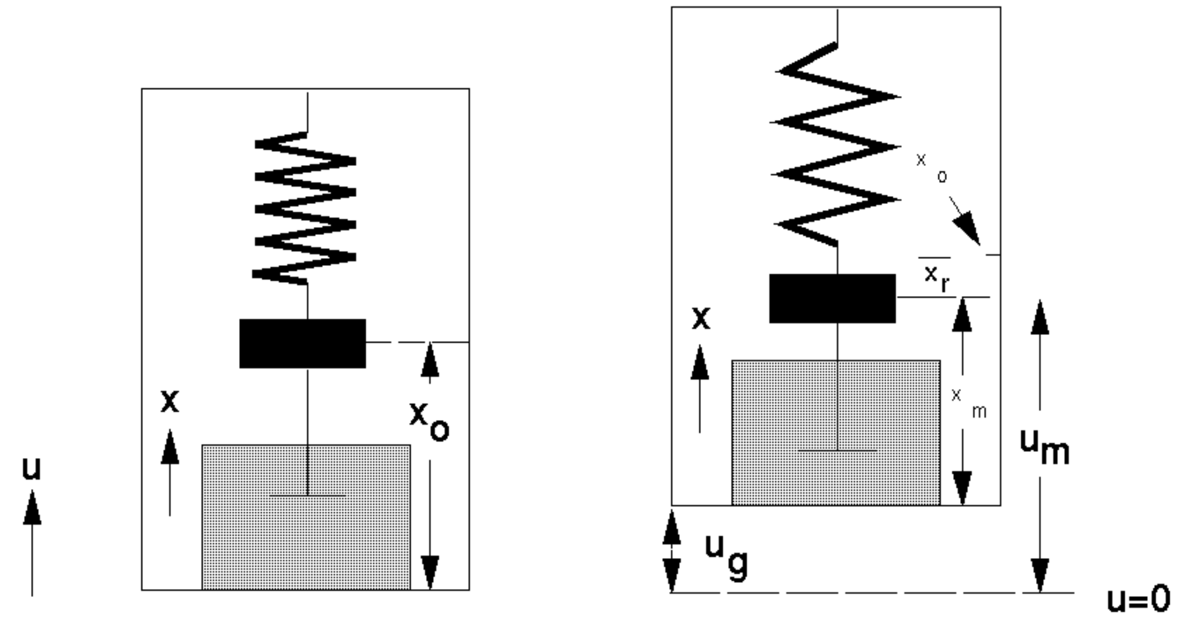
- *The spring* — $f_{sp} = -kx_r(t)$

$k =$ spring constant (strength)

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

$D =$ friction coefficient

Seismometer



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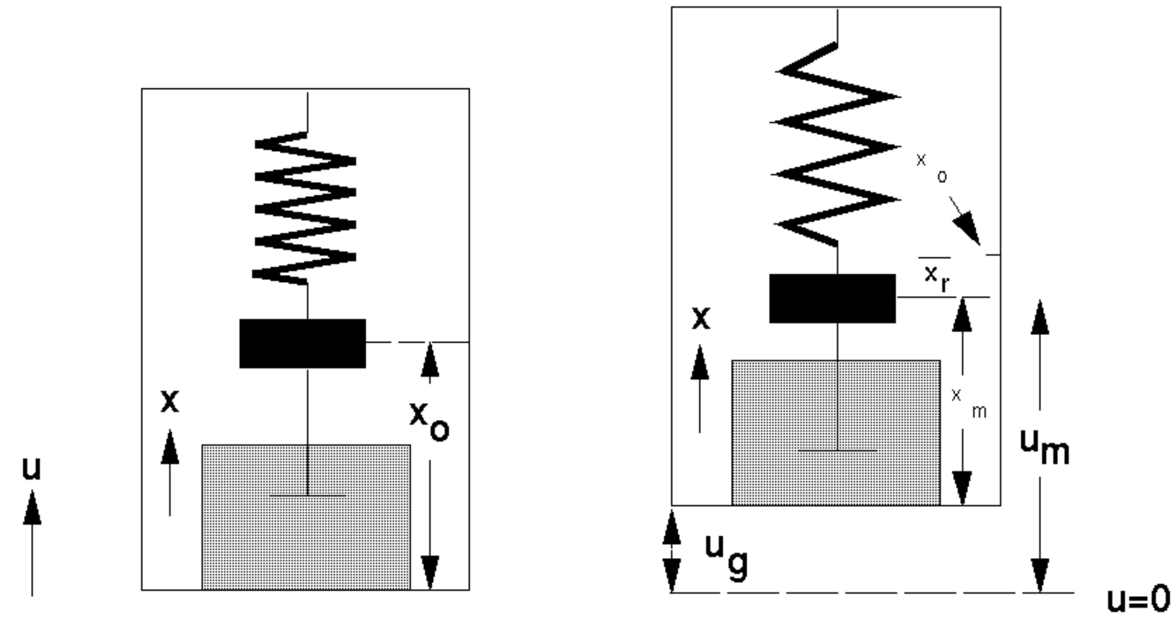
- *The dashpot* — $f_f = -D\dot{x}_m(t)$

D = friction coefficient

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

Seismometer



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2nd order LTI !!

Seismometer Transfer function

Laplace transform of $\ddot{x}_r(t) + 2\varepsilon\dot{x}_r(t) + \omega_0^2 x_r(t) = -\ddot{u}_g(t)$

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Seismometer Transfer function

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Transfer function: $T(s) = \dfrac{X_r(s)}{U_g(s)} = \dfrac{-s^2}{s^2 + 2\varepsilon s + \omega_0^2}$

Seismometer Transfer function

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Transfer function: $T(s) = \dfrac{X_r(s)}{U_g(s)} = \dfrac{-s^2}{s^2 + 2\varepsilon s + \omega_0^2}$

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

$$x_{1,2} = -\frac{b}{2} \pm \sqrt{\frac{b^2}{4} - c}$$

pole positions $p_{1,2}$:

$$p_{1,2} = -\varepsilon \pm \sqrt{\varepsilon^2 - \omega_0^2}$$

$$= -h\omega_0 \pm \omega_0 \sqrt{h^2 - 1}$$

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

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$$p_{1,2} = -\varepsilon \pm \sqrt{\varepsilon^2 - \omega_0^2}$$

$$= -h\omega_0 \pm \omega_0\sqrt{h^2 - 1}$$

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

For the underdamped case ($h < 1$) the pole position becomes

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

pole positions $p_{1,2}$:

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with the pole distance from the origin

$$\left|p_{1,2}\right| = \left|\left(h \pm j\sqrt{1 - h^2}\right)\right| \cdot \left|\omega_0\right| = \sqrt{h^2 + (1 - h^2)} \cdot \left|\omega_0\right| = \left|\omega_0\right|$$

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$$= -h\omega_0 \pm \omega_0\sqrt{h^2 - 1}$$

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Therefore, the poles of an underdamped seismometer are located in the left half of the s plane in a distance of $|\omega_0|$ from the the origin. The quantity $h\,|\omega_0|$ gives the distance from the imaginary axis.

Consequences of transition from single pole to general N-th order system

- No major change in concept
- Zeros in addition to poles
- Can be treated in very similar way

Graphical estimation of the frequency response function

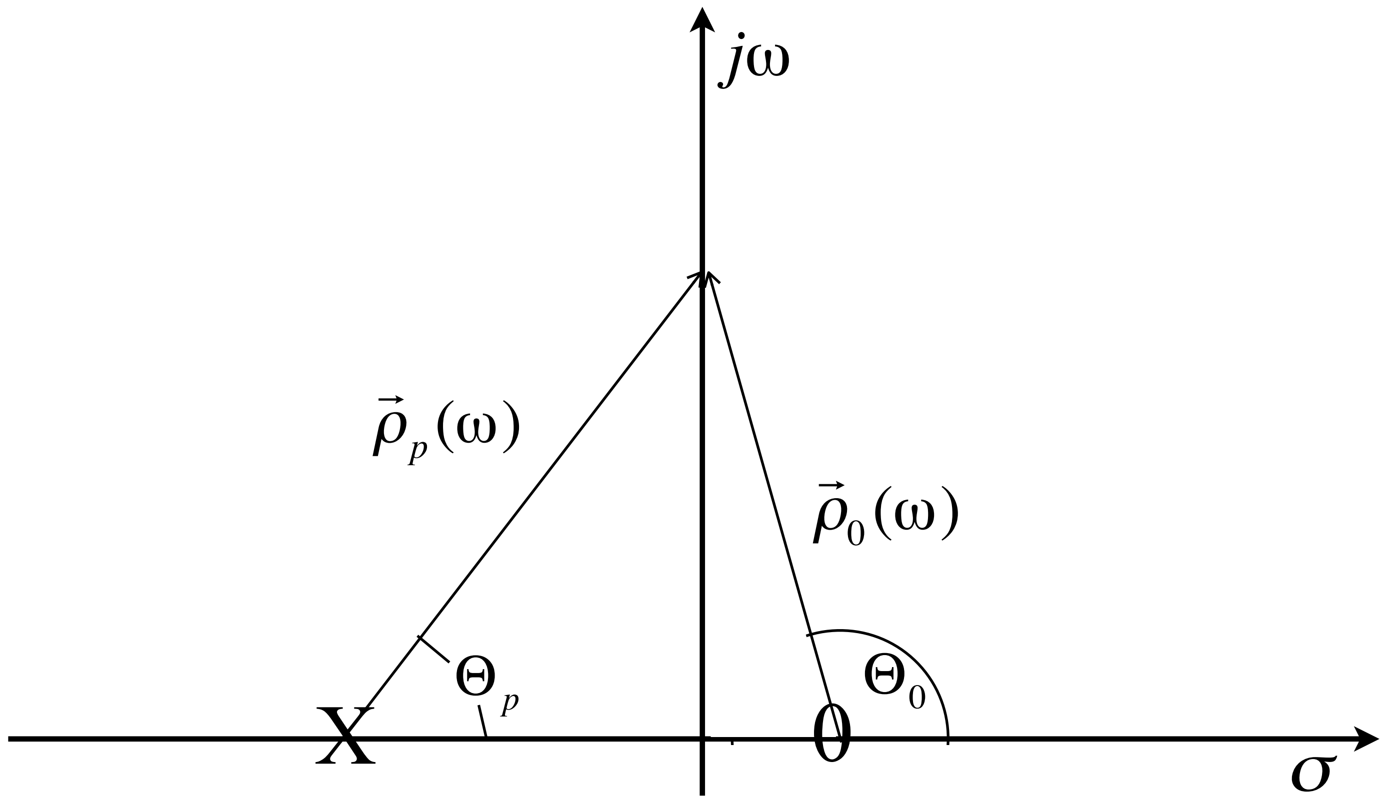


Fig. 3.2 Complex s plane representation of a system with a single pole and zero. The pole and zero locations are marked by an X, and a 0, respectively.

Graphical estimation of the frequency response function

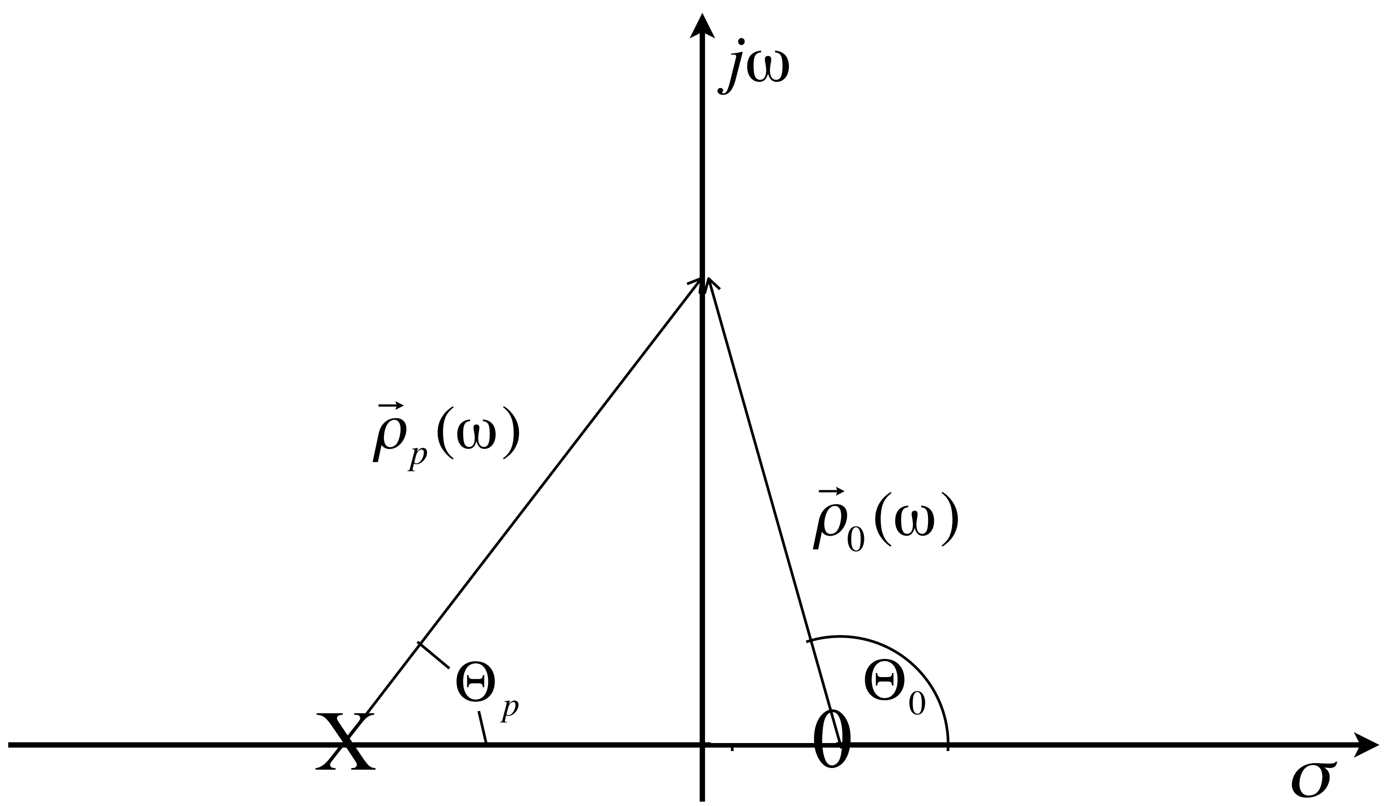
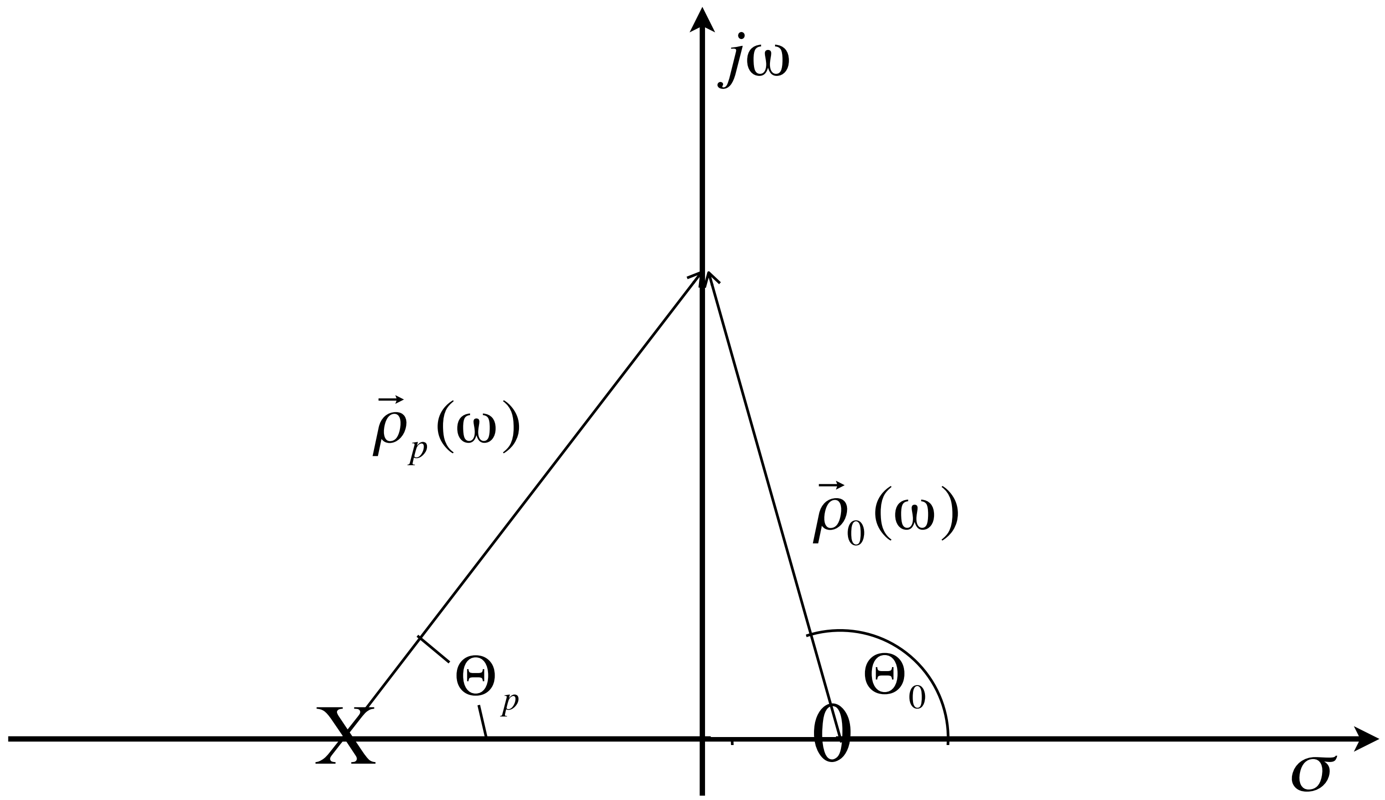


Fig. 3.2 Complex s plane representation of a system with a single pole and zero. The pole and zero locations are marked by an X, and a 0, respectively.

Transfer function: $$T(s) = \frac{s - s_0}{s - s_p}$$

s_0 and s_p: position of the zero and the pole, respectively.

Graphical estimation of the frequency response function



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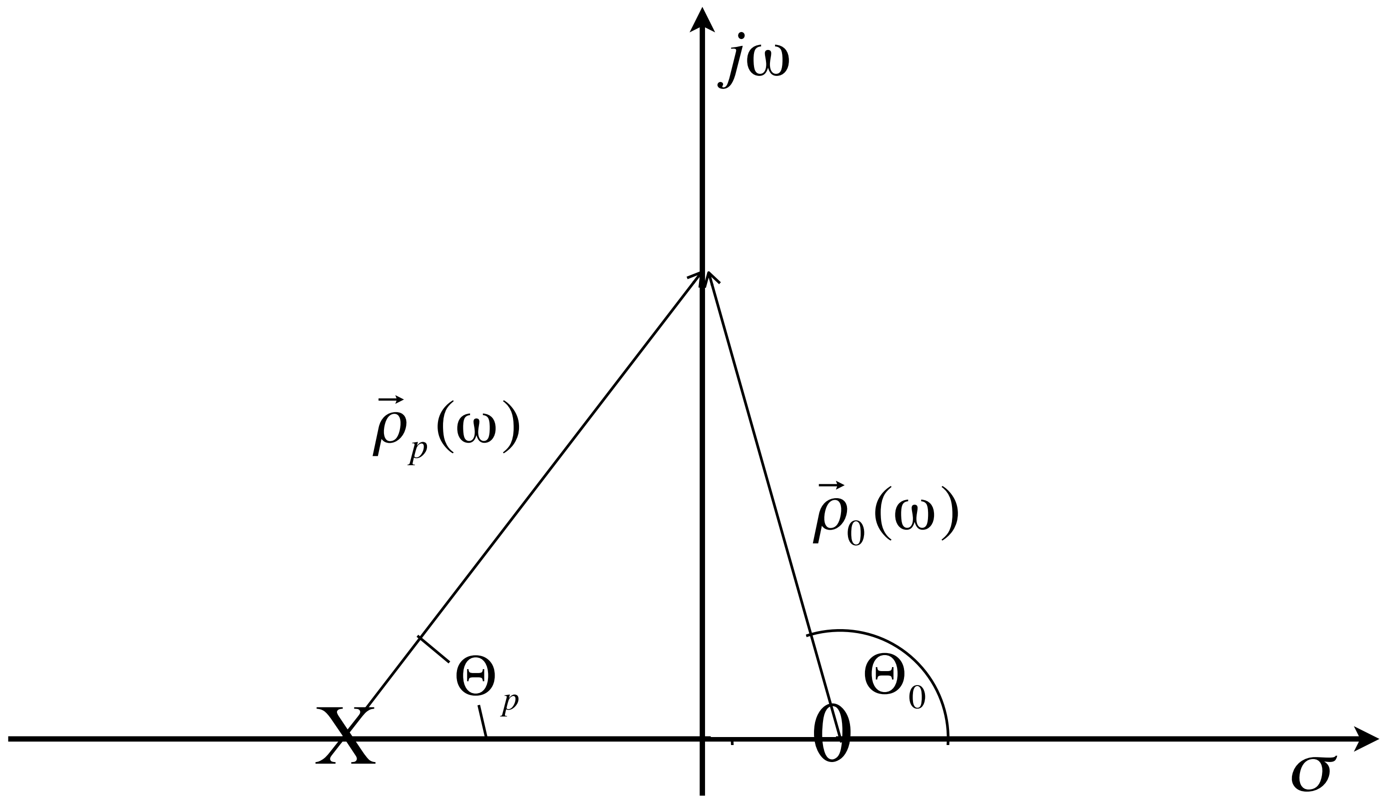
Graphical estimation of the frequency response function



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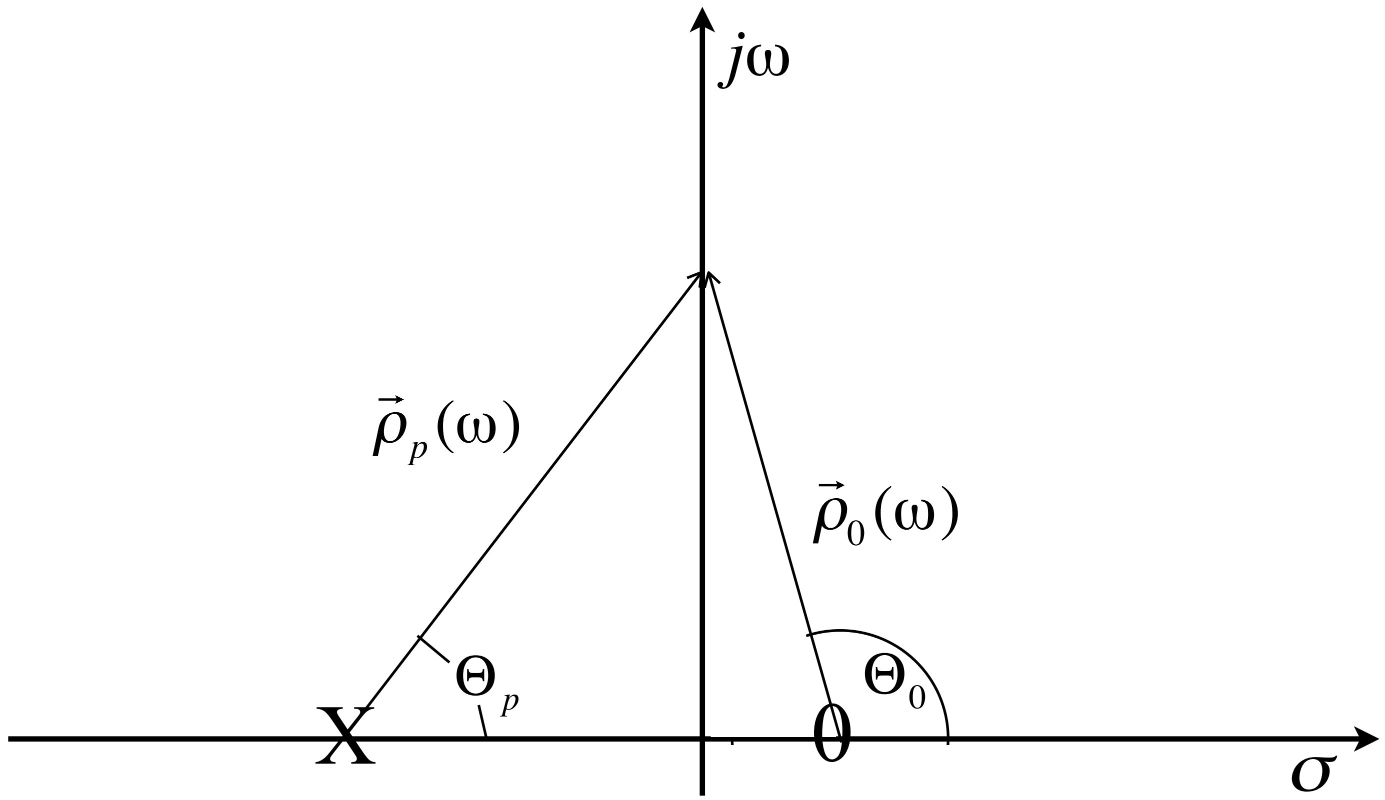
$j\omega - s_p \rightarrow$ vector $\vec{\rho}_p(\omega)$

$j\omega - s_0 \rightarrow$ vector $\vec{\rho}_0(\omega)$

Graphical estimation of the frequency response function



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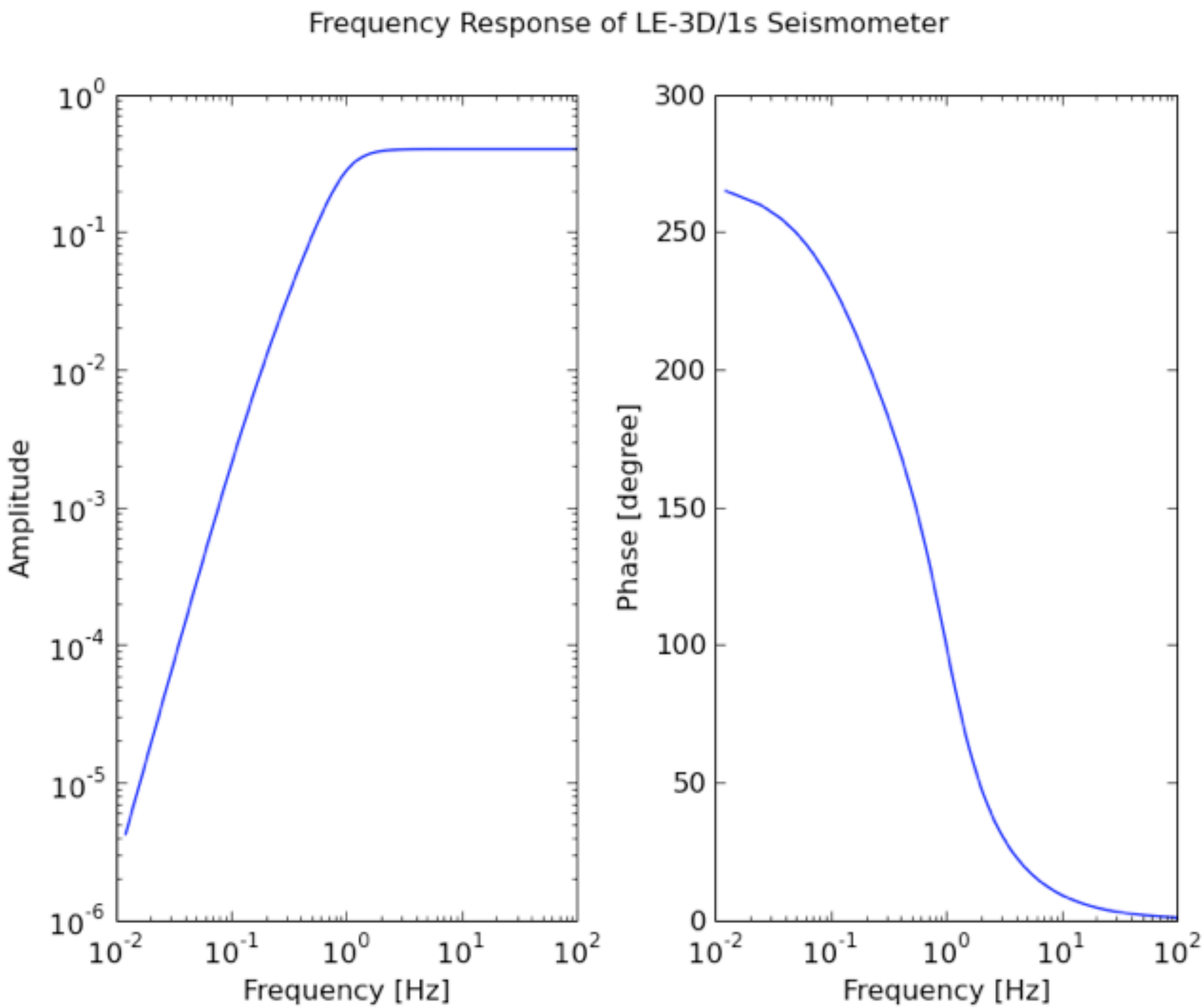
$j\omega - s_p \rightarrow$ vector $\vec{\rho}_p(\omega)$

$j\omega - s_0 \rightarrow$ vector $\vec{\rho}_0(\omega)$

$$T(j\omega) = \left|\rho_0(\omega)\right| e^{j\Theta_0} \frac{1}{\left|\rho_p(\omega)\right|} e^{-j\Theta_p}$$

Simulation Process



Inverse and simulation filtering of digital seismograms

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.

Inverse and simulation filtering of digital seismograms

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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. The different seismic magnitude definitions are based on different instruments!

Stability problems

Noise free situation

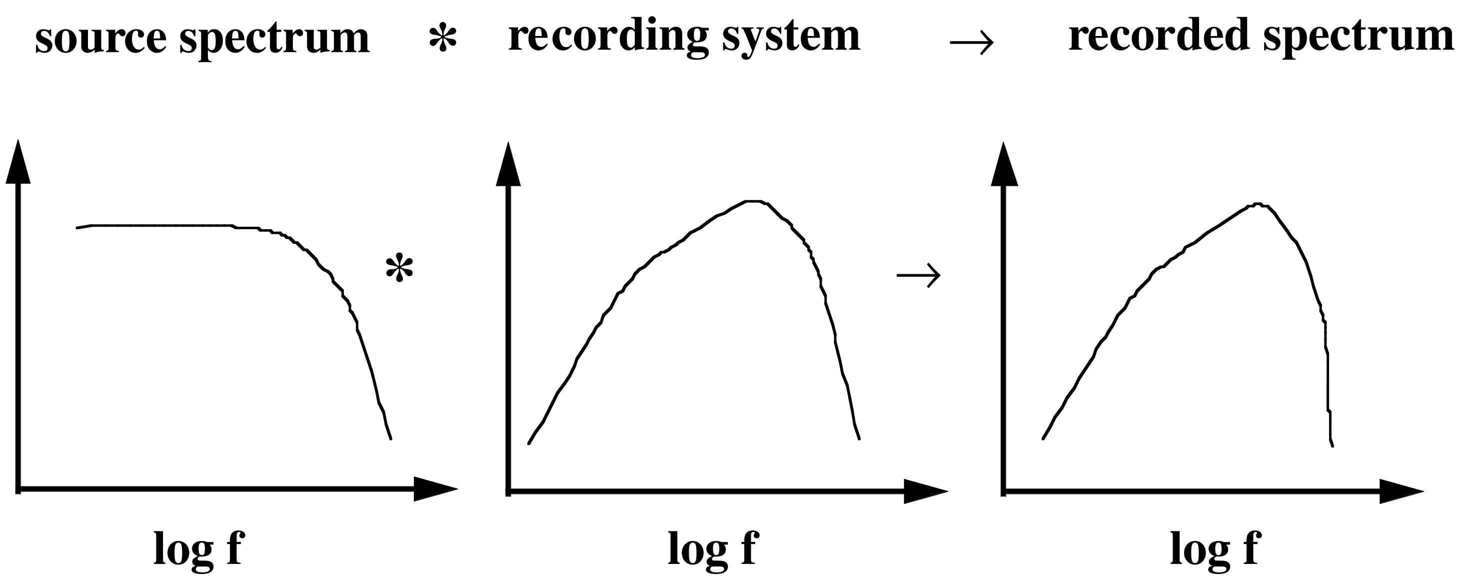


Fig. 9.3 Recording the displacement spectrum of an idealized earthquake source.

Recovery of source spectrum:

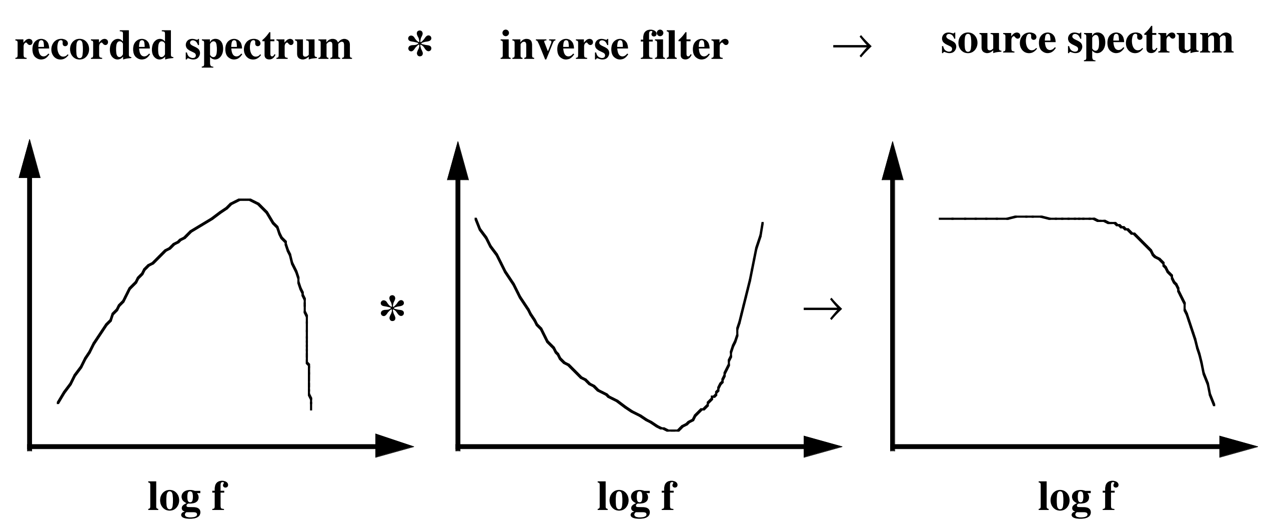


Fig. 9.4 Recovering the source spectrum by inverse filtering in the noisefree case.

Noisy situation

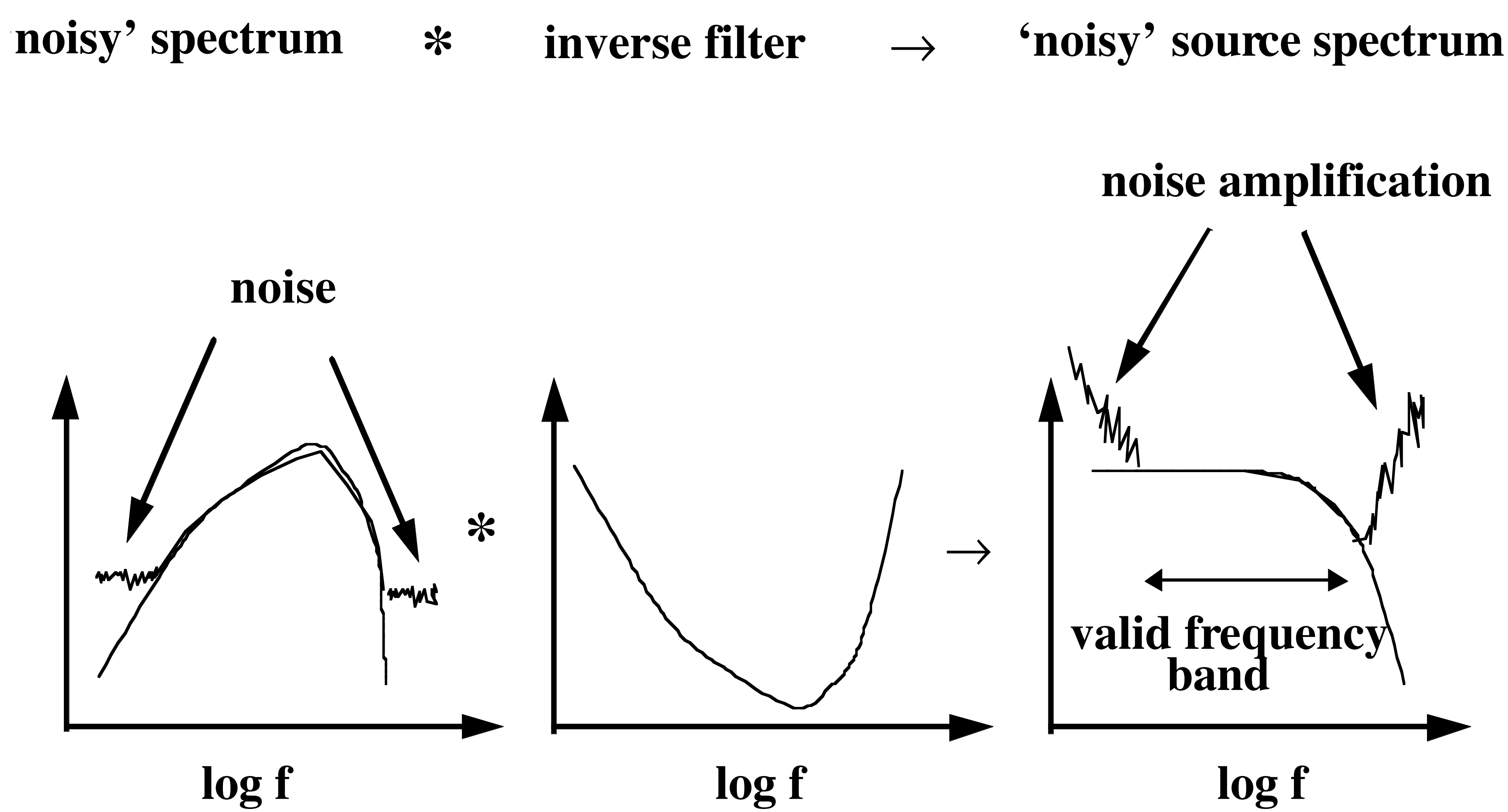


Fig. 9.5 Noise amplification by inverse filtering. The solid line in the left panel shows the signal plus noise while the noisefree signal is shown by the dashed line.

Noisy situation

Noisy situation

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!).

Noisy situation

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.

Example

Station Pruhonice (PRU) of the Czech Academy of Sciences.

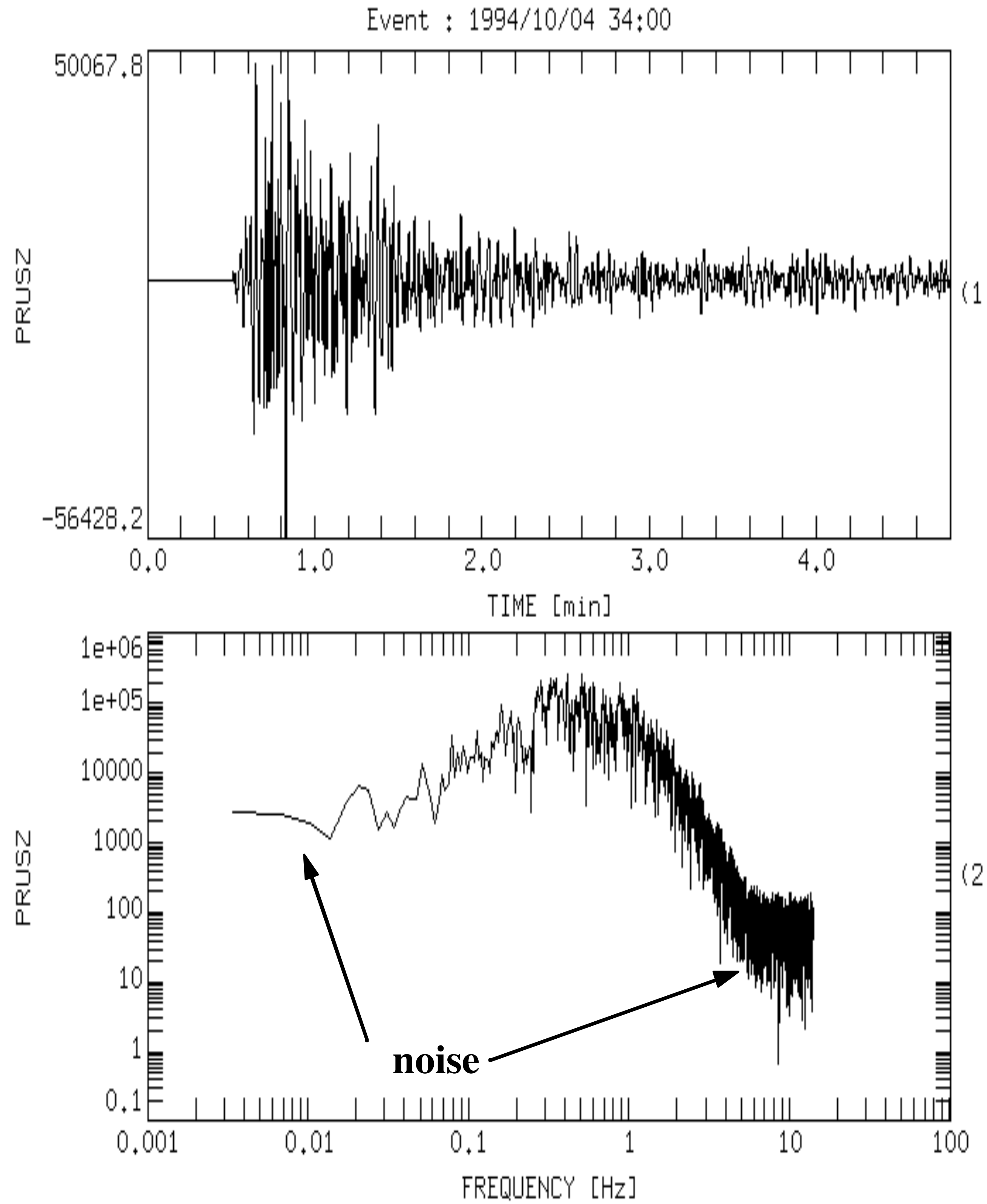


Fig. 9.6 Vertical component record of an mb = 7.5 earthquake (1994 April 4) in the Kurile islands (upper panel). The units are counts with offset removed. The lower panel shows the corresponding amplitude spectrum. Notice the noise at both the low frequency and high frequency ends of the amplitude spectrum.

Amplitude spectrum and displacement frequency response function of the recording system.

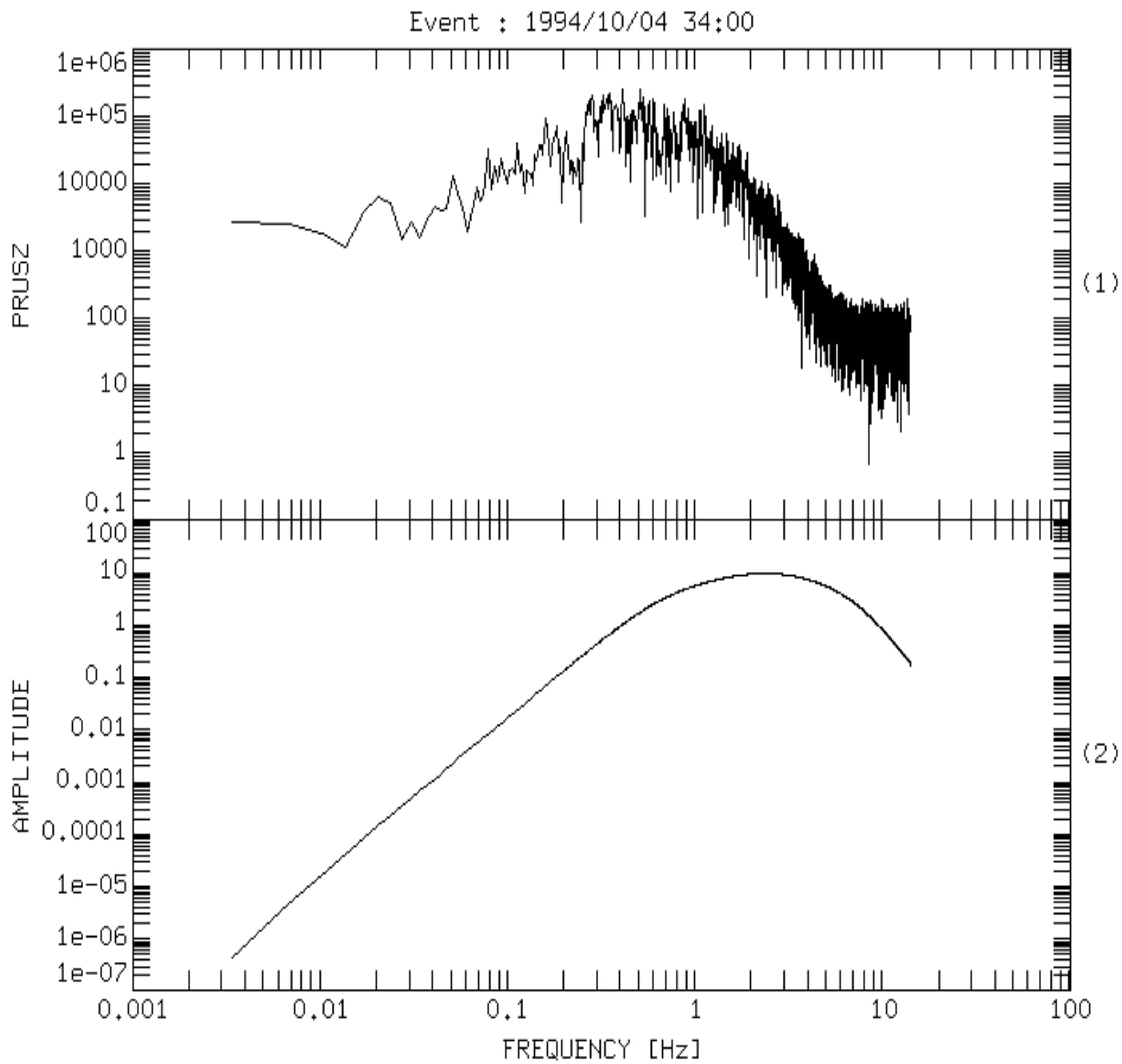


Fig. 9.7 Amplitude spectrum from Fig. 9.6 compared to the modulus of the displacement frequency response function at station PRU (lower panel).

Frequency domain results

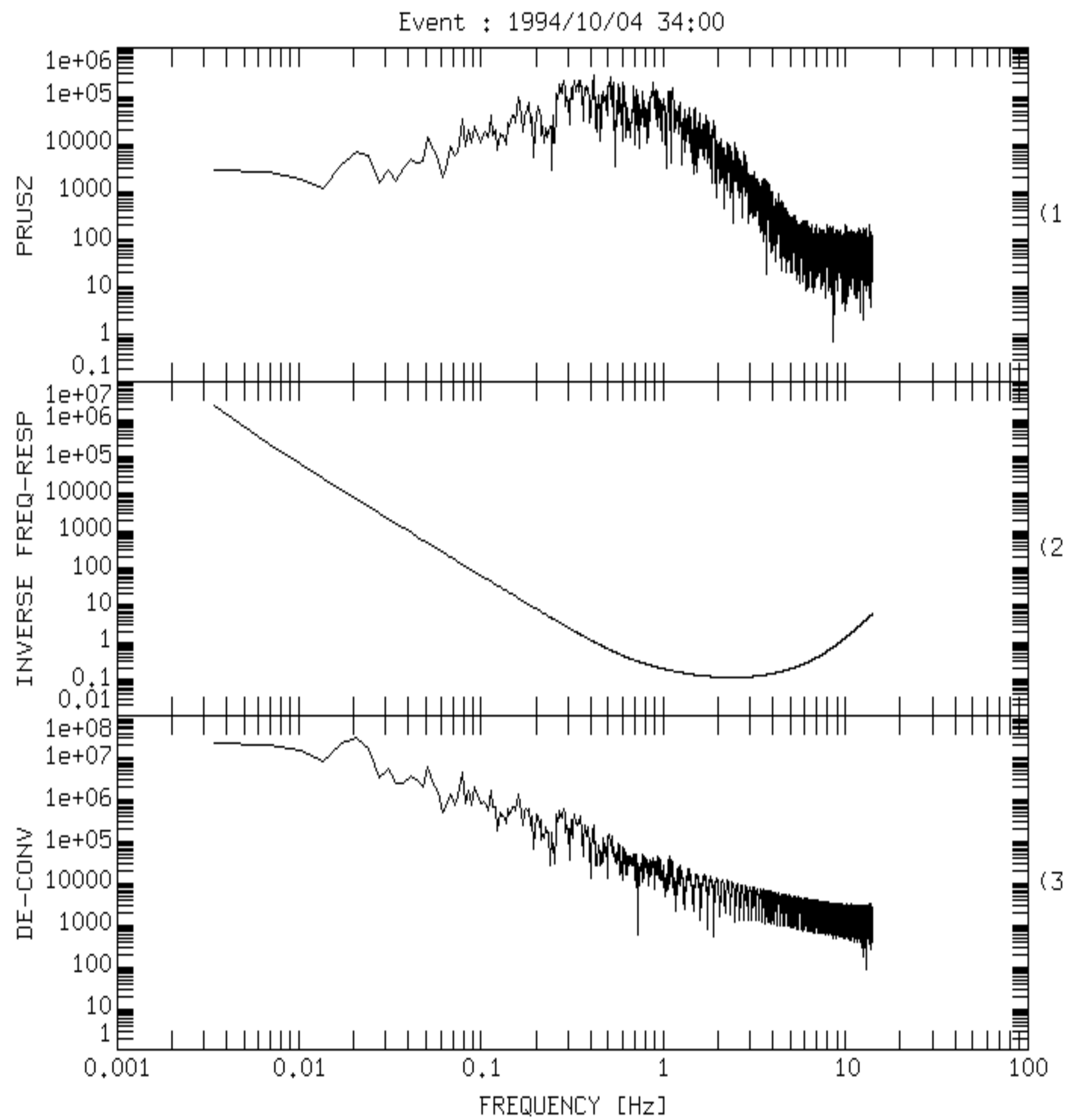


Fig. 9.9 Deconvolution illustrated in the frequency domain. From top to bottom, the amplitude spectrum of the observed trace, the frequency response function of the inverse filter, and the amplitude spectrum of the deconvolved trace are displayed.

Waterlevel correction

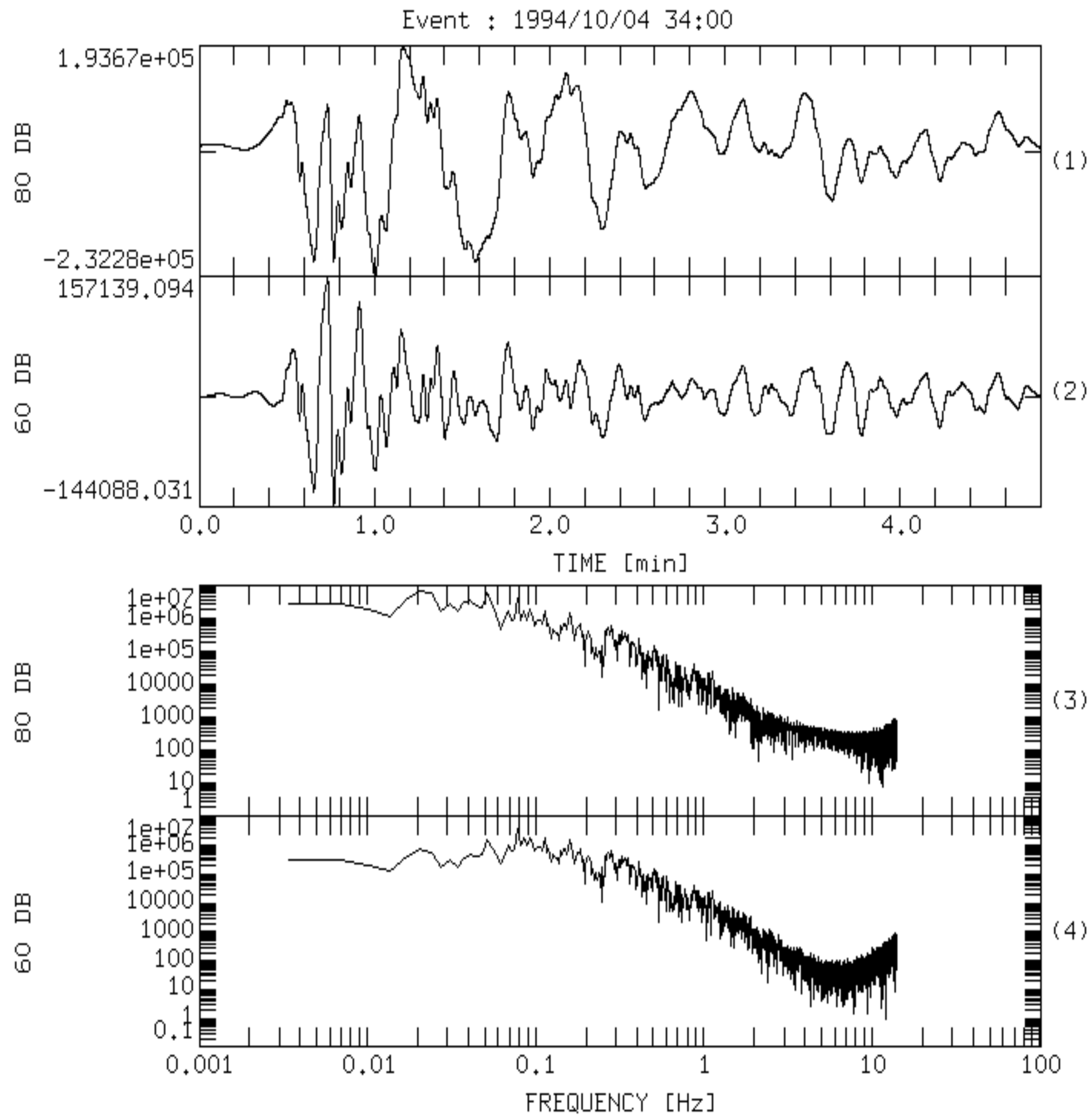


Fig. 9.10 Deconvolution by spectral division using a waterlevel stabilization of 80 dB (top trace) and 60 dB (second trace) of the signal shown in Fig. 9.6. The corresponding amplitude spectra are shown in the two bottom traces.

Simulation = Deconvolution + Filtering

Be aware that in the digital world you have to change from s- to z-transform

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

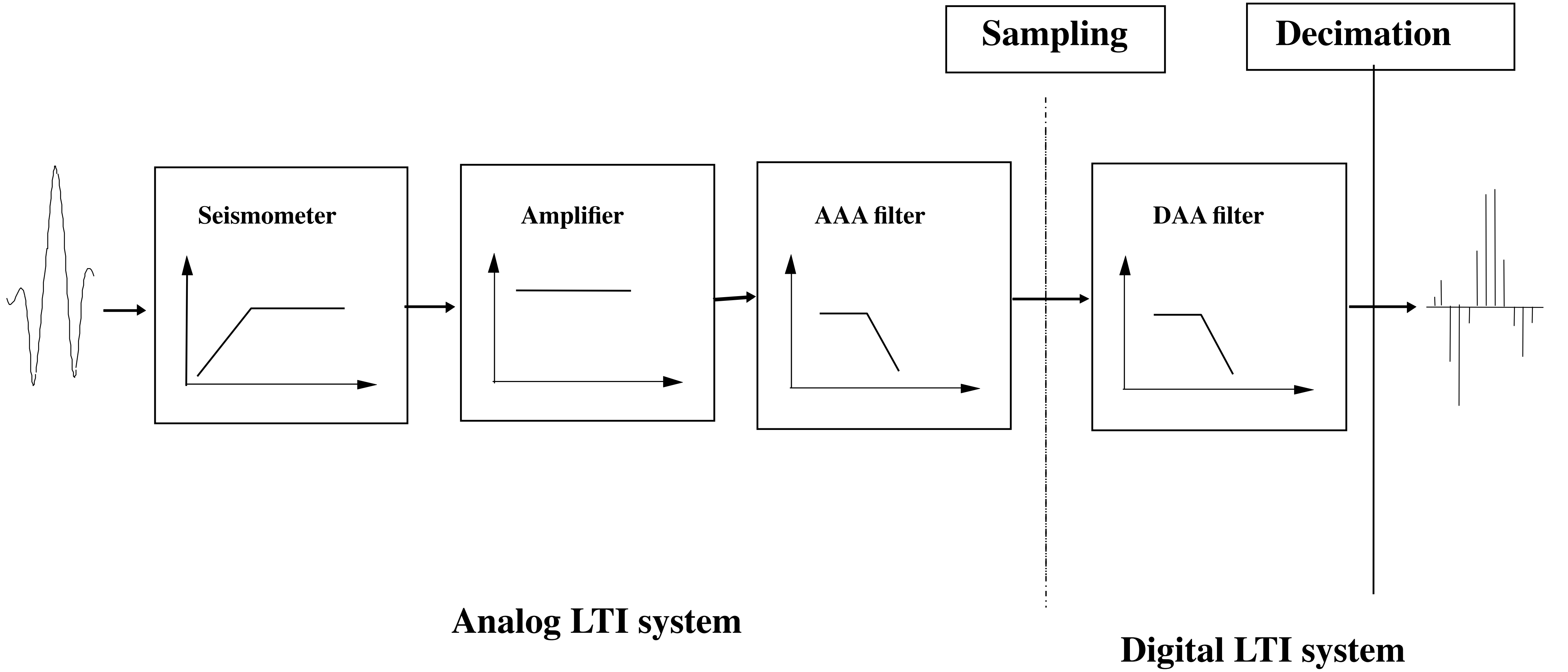
$T_{act}(z)$ = transfer function of actual recording system

$T_{syn}(z)$ = 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

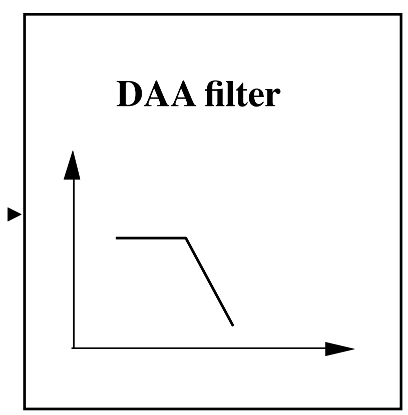
FIR - Filter Effects



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.




```
#          +              +------------------------------+              +
#          +              |  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

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

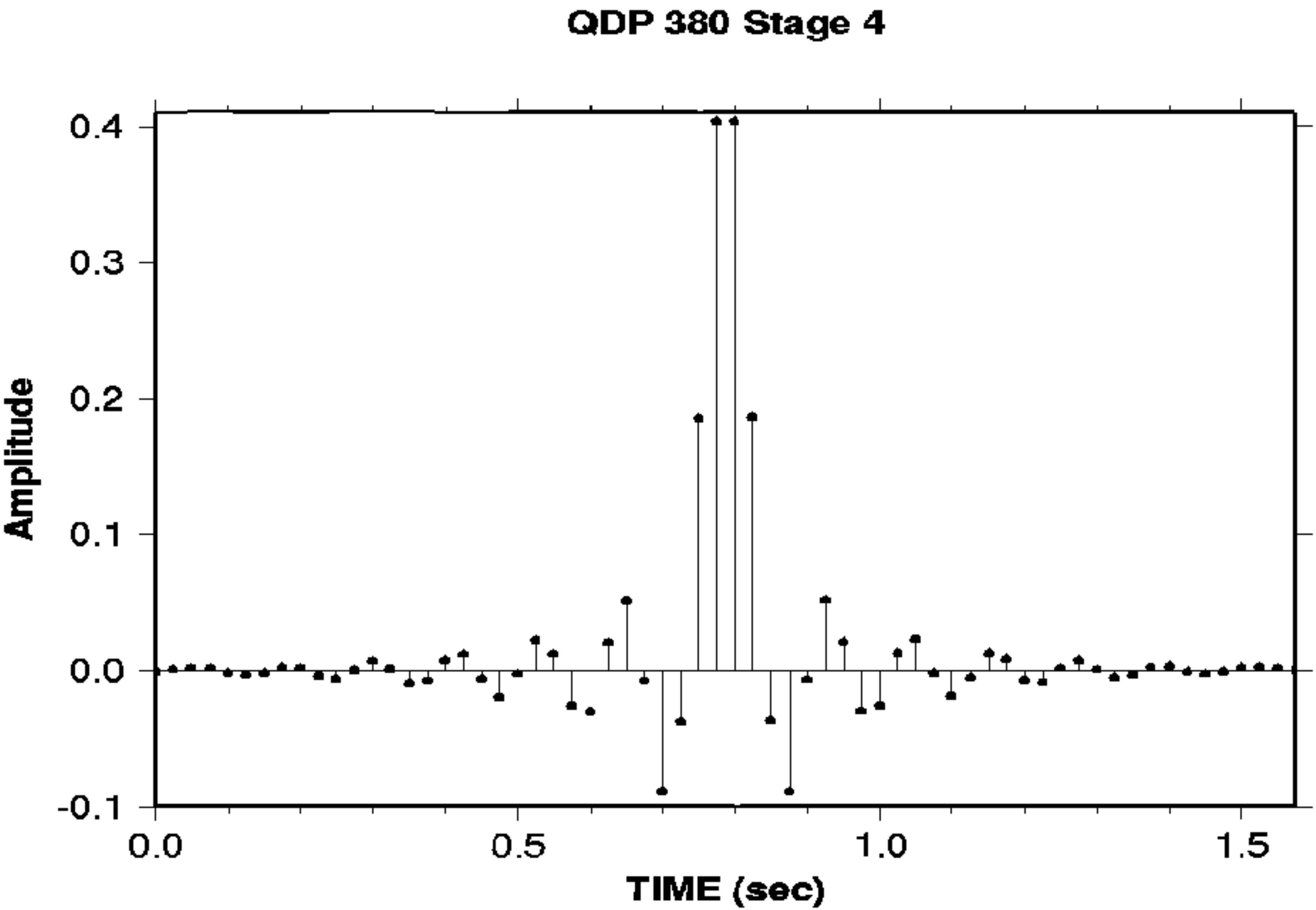
Infinite Impulse Response: $a_k \neq 0$
Finite Impulse Response: $a_0 = 1$; $a_{k \neq 0} = 0$

- FIR filters :

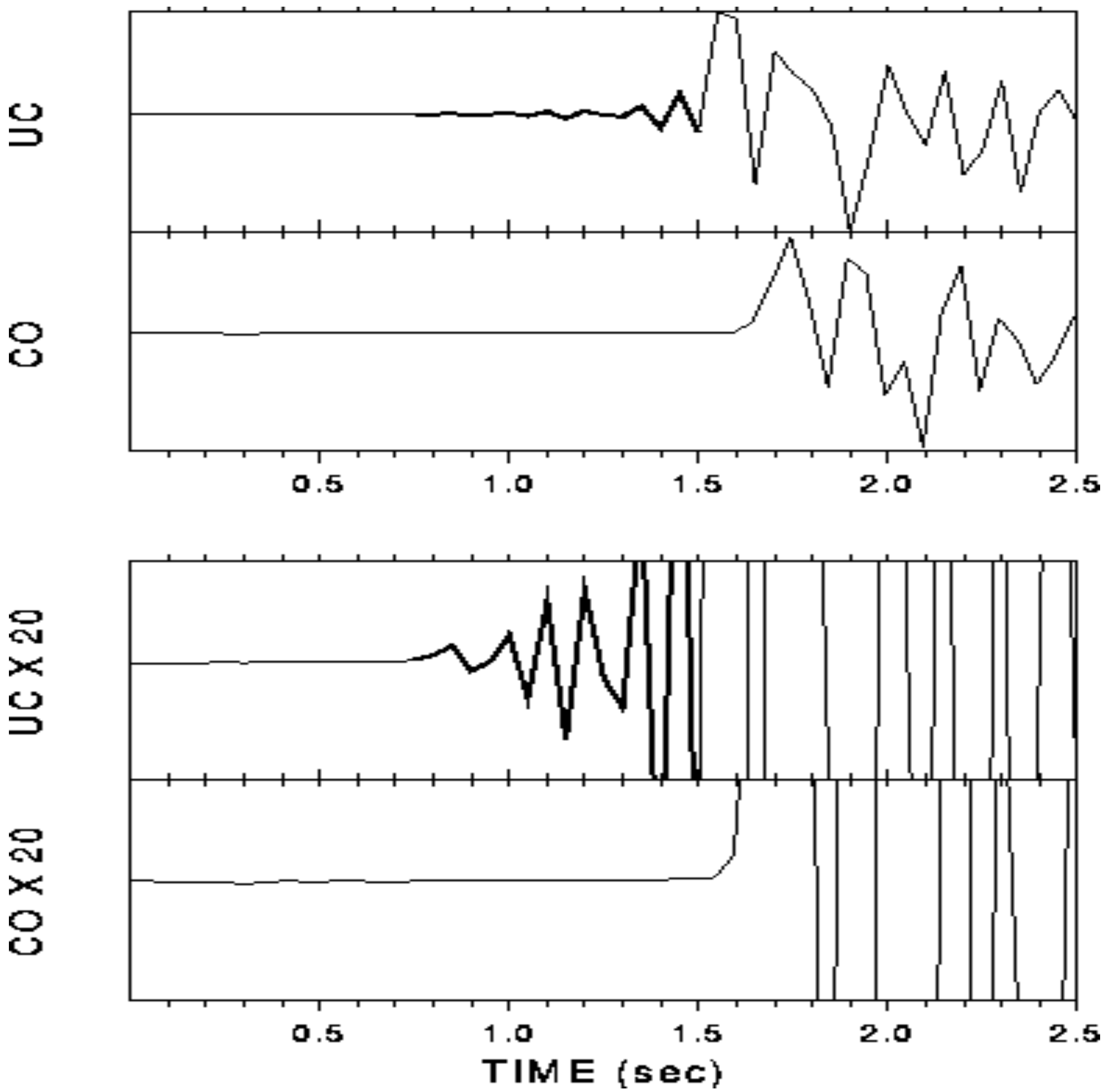
+ Always stable.
- Steep filters need many coefficients.
+ Both causal and noncausal filters can be implemented.
+ Filters with given specifications are easy to implement!

- IIR filters :

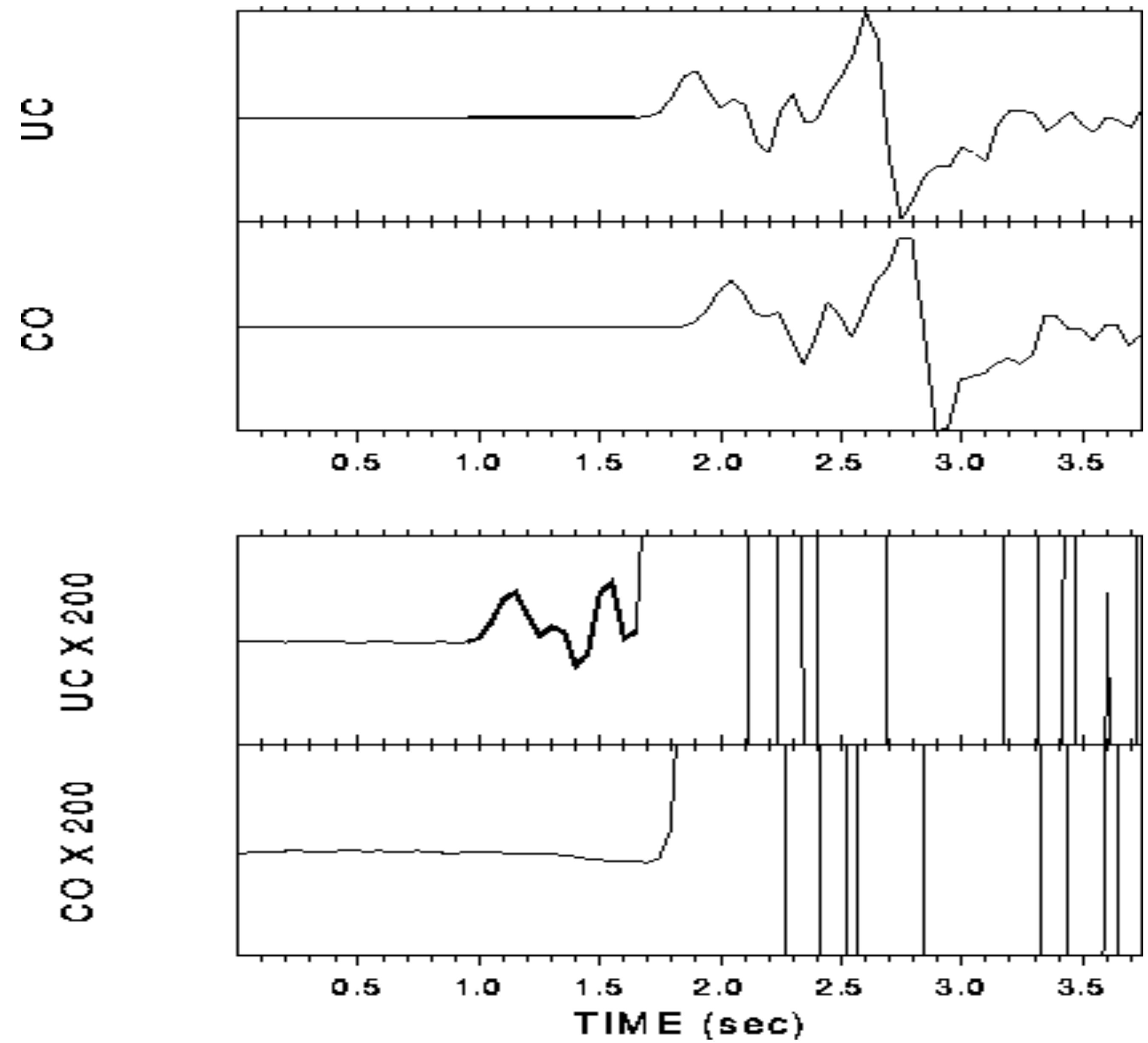
- Potentially unstable and subject to quantization errors.
+ Steep filters can easily be implemented with a few coefficients. Speed.
- Filters with given specifications are in general, difficult, if not impossible, to implement *exactly(!)*.



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

a)


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

b)

Routine Quality Control at DCs

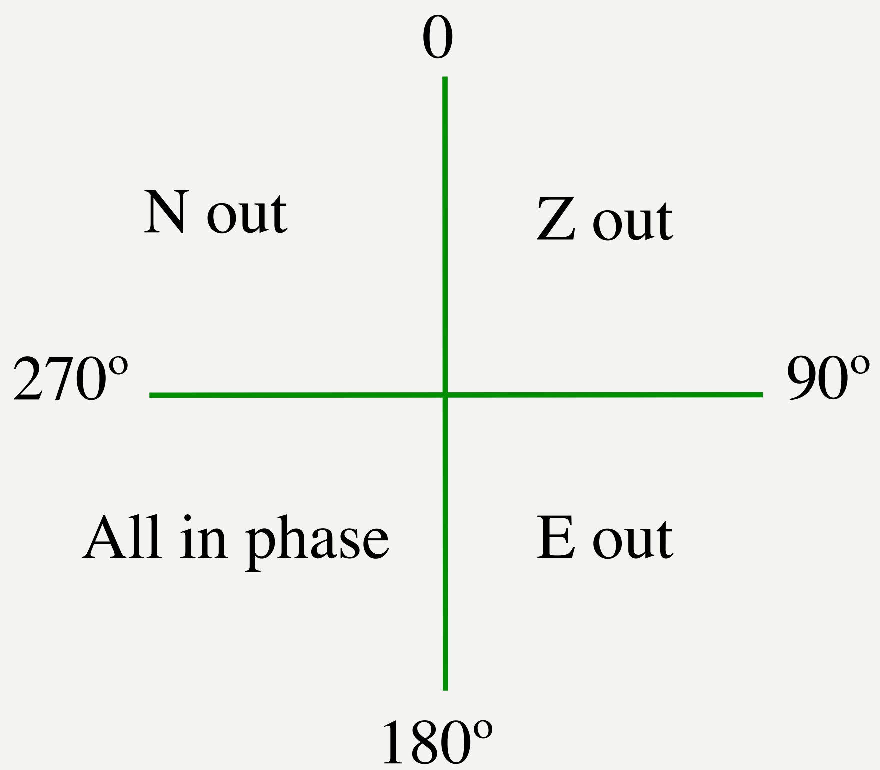
Why Routine Control?

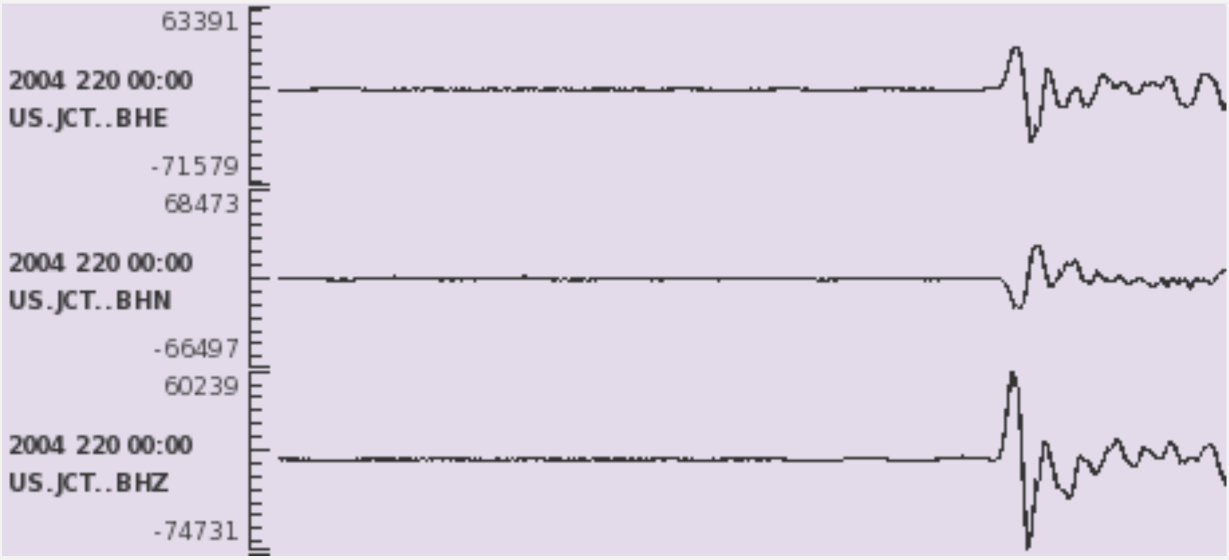
- The sooner problems are detected the sooner they can be fixed
- Sensor malfunctions, misconfigurations, aging
- Digitizer & recorder malfunctions
- Vault problems: tilting, settling, etc
- Cable & connection problems
- Telemetry issues
- Timing problems
- Many, many other potential issues

Quick Checks: Polarization

The “quadrant method” allows an analyst to perform a rough check of 3-component sensor horizontal polarity.

Compare the P wave first motion of a relatively large event between the 3 components to determine back azimuth:





Aluetian Island event :: Texas, USA station (BA: ~317°)

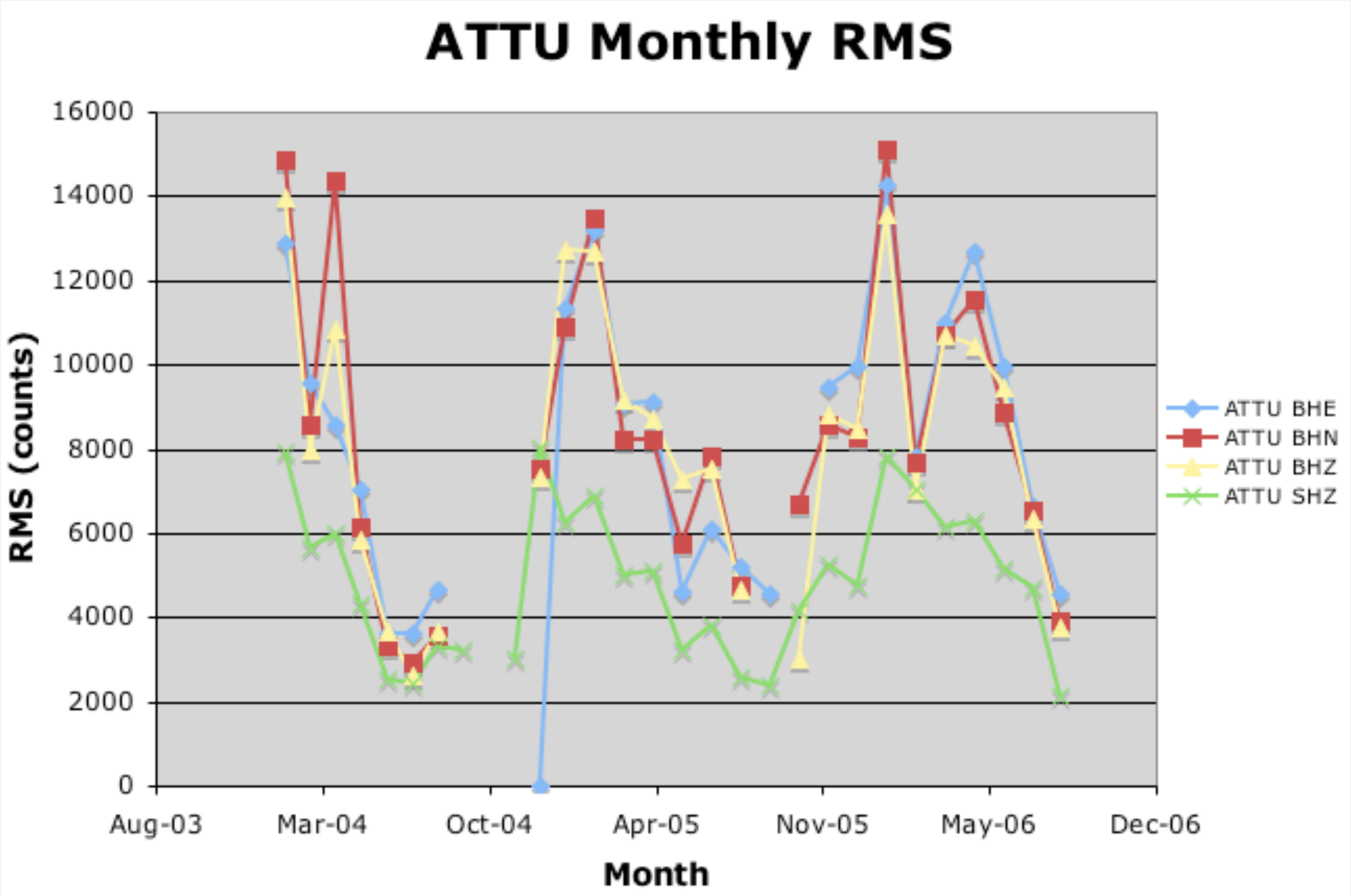
* Assumes Z component polarity is correct.

Quack (IRIS DMC)

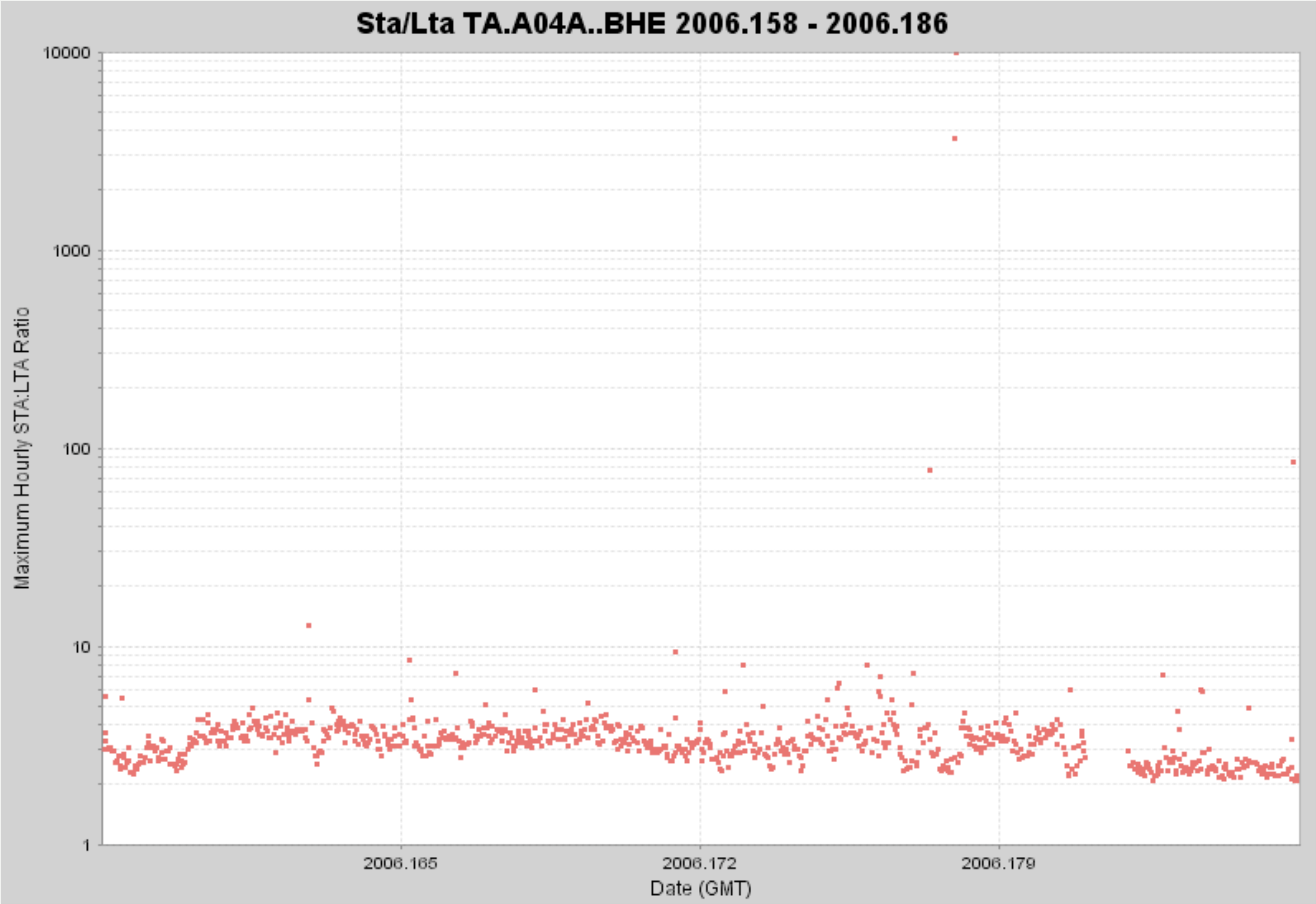
Automated QC measurements for incoming real-time data at the DMC:

- Tracks a number of simple parameters (signal RMS, mean, gaps, overlaps, etc.) in addition to more complicated analyses (PSD/PDF, STA/LTA)
- Generates daily reports, using thresholds to control what information is included in the report in order to reduce the number of issues that need attention

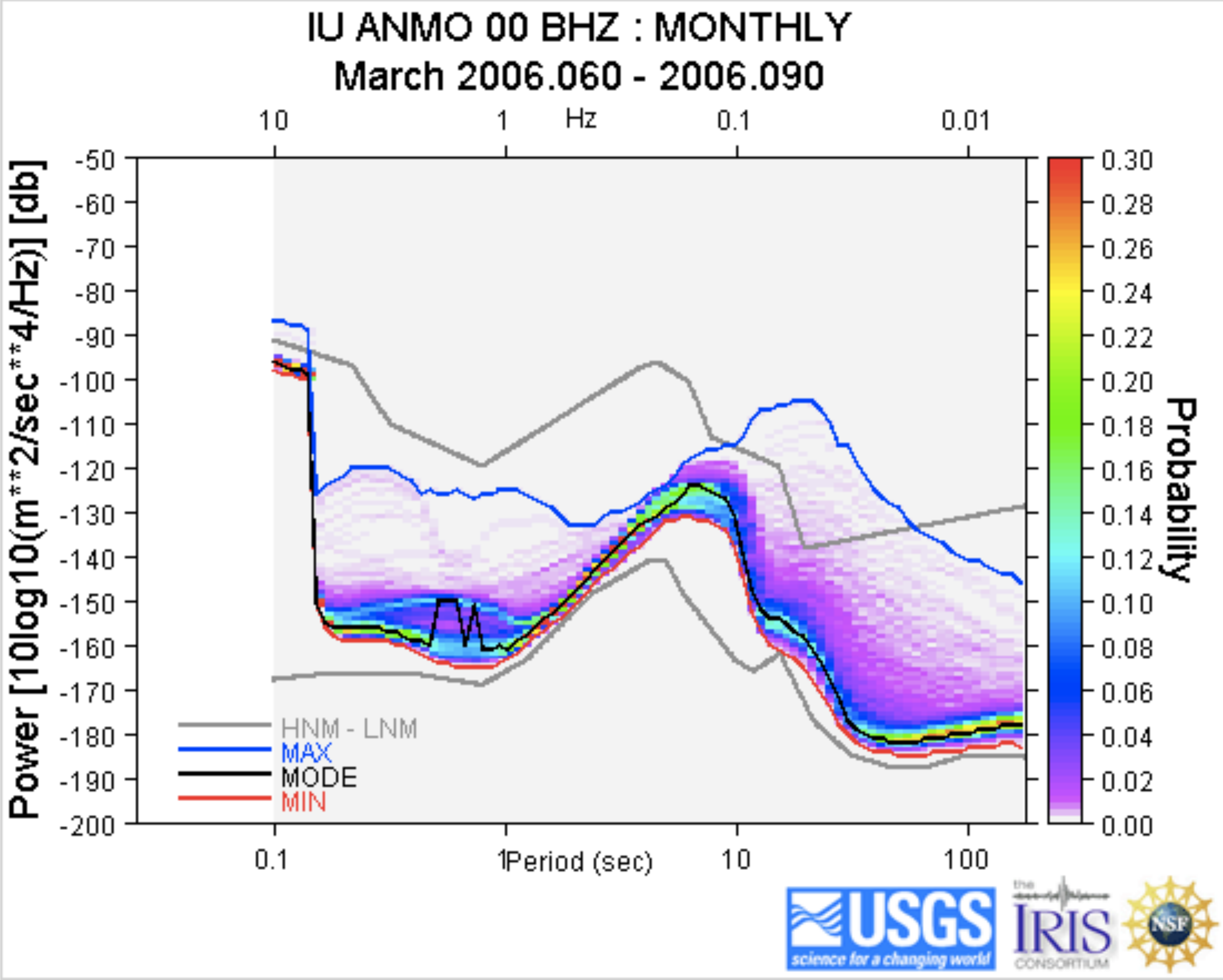
RMS values


ATTU Monthly RMS
RMS (counts)
16000
14000
12000
10000
8000
6000
4000
2000
0
Aug-03
Mar-04
Oct-04
Apr-05
Nov-05
May-06
Dec-06
Month
ATTU BHE
ATTU BHN
ATTU BHZ
ATTU SHZ

STA/LTA


Sta/Lta TA.A04A..BHE 2006.158 - 2006.186
Maximum Hourly STA:LTA Ratio
10000
1000
100
10
1
2006.165
2006.172
2006.179
Date (GMT)

Prob. Density of Power Spectra



Missing: Timing Problems

- problem if digitizer don't report (GPS) timing problems
- miniSEED has only restricted possibilities for reporting timing problems

➡ Way out by stacked cross correlation of noise between distant stations (by-product of cross correlating diffusive wave field)

Two Stations CrossCorrelation