Noise Survey and Site Selection

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Outline

1. What is ‘Noise’?

2. Seismic noise

3. Instrumental noise

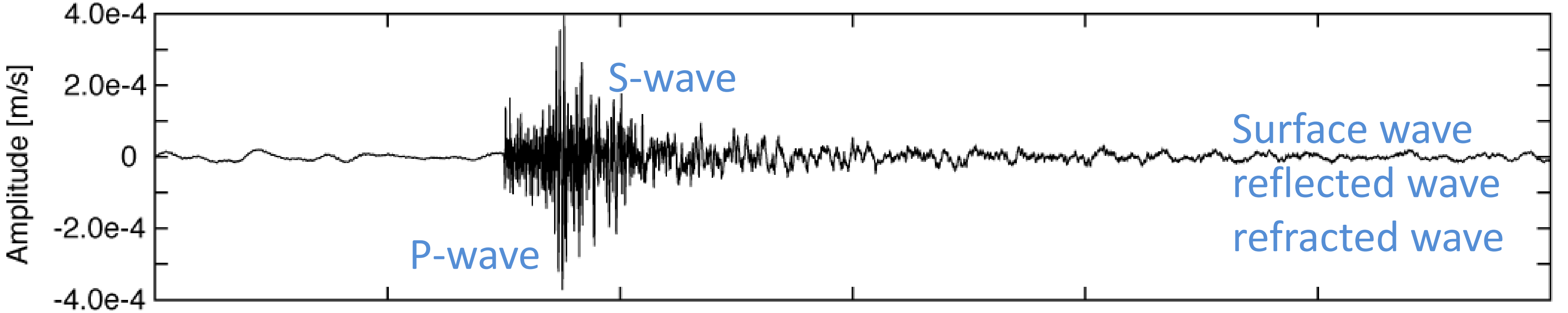
4. Environmental noise

5. Reduction of noise influences on seismic observations

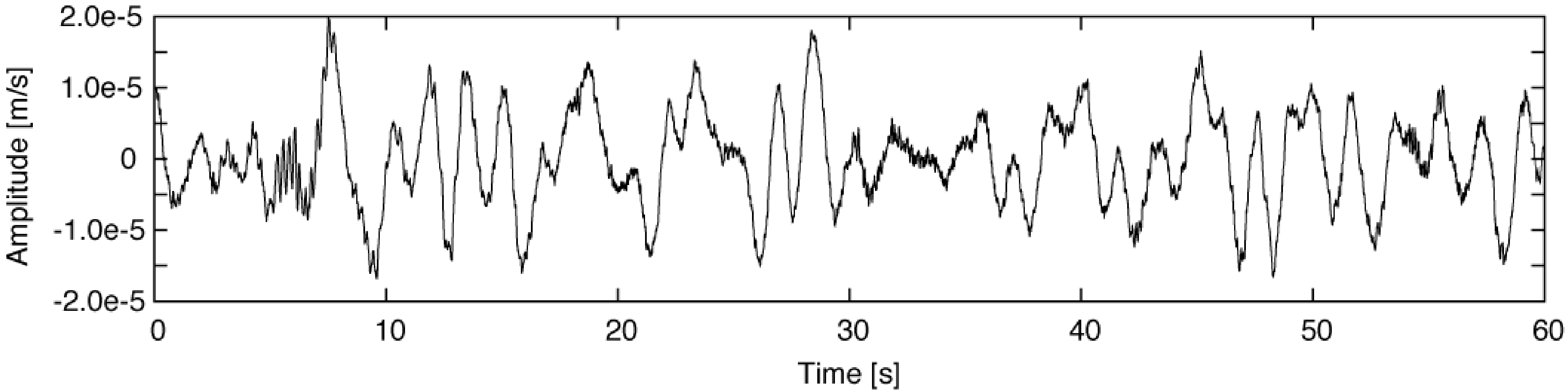
6. Data processing practices

1. What is Noise ?

(a) Earthquake



(b) Noise



Noise : weak motion observed by seismic sensors
during no earthquake

Seismic Noise (ambient noise)
generated by actual phenomena

Instrumental Noise (self-noise)
generated by electrical circuit inside sensors
generated by power supply

Environmental Noise
caused by unsuitable installation

2. Seismic Noise

Microseisms | 1 Hz | Microtremors

Low frequency ⟷ High frequency

Ocean wave

Storm (Air pressure)

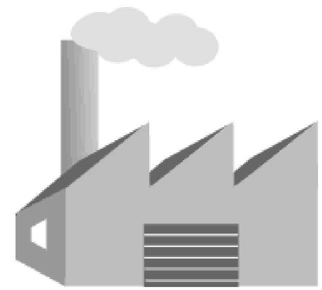
Wind

Natural forces

Surface wave

Walking, Cycling

Factory

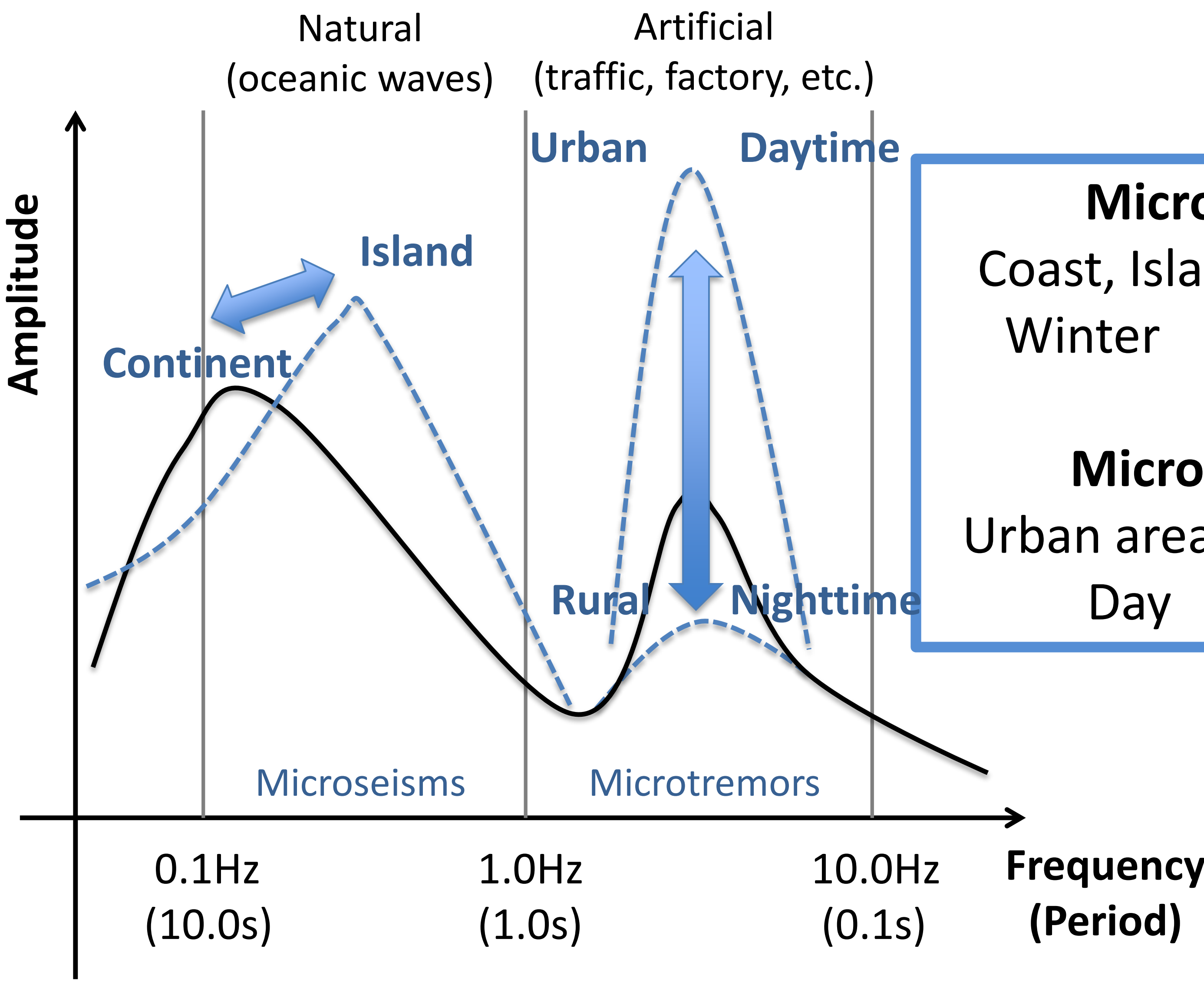


Cars

Human activities

Surface wave + Body wave

2.1 Seismic noise source classification



Microseisms

Coast, Island > Inland

Winter > Summer

Microtremors

Urban area > Rural area

Day > Night

2.2 Temporal change of seismic noise

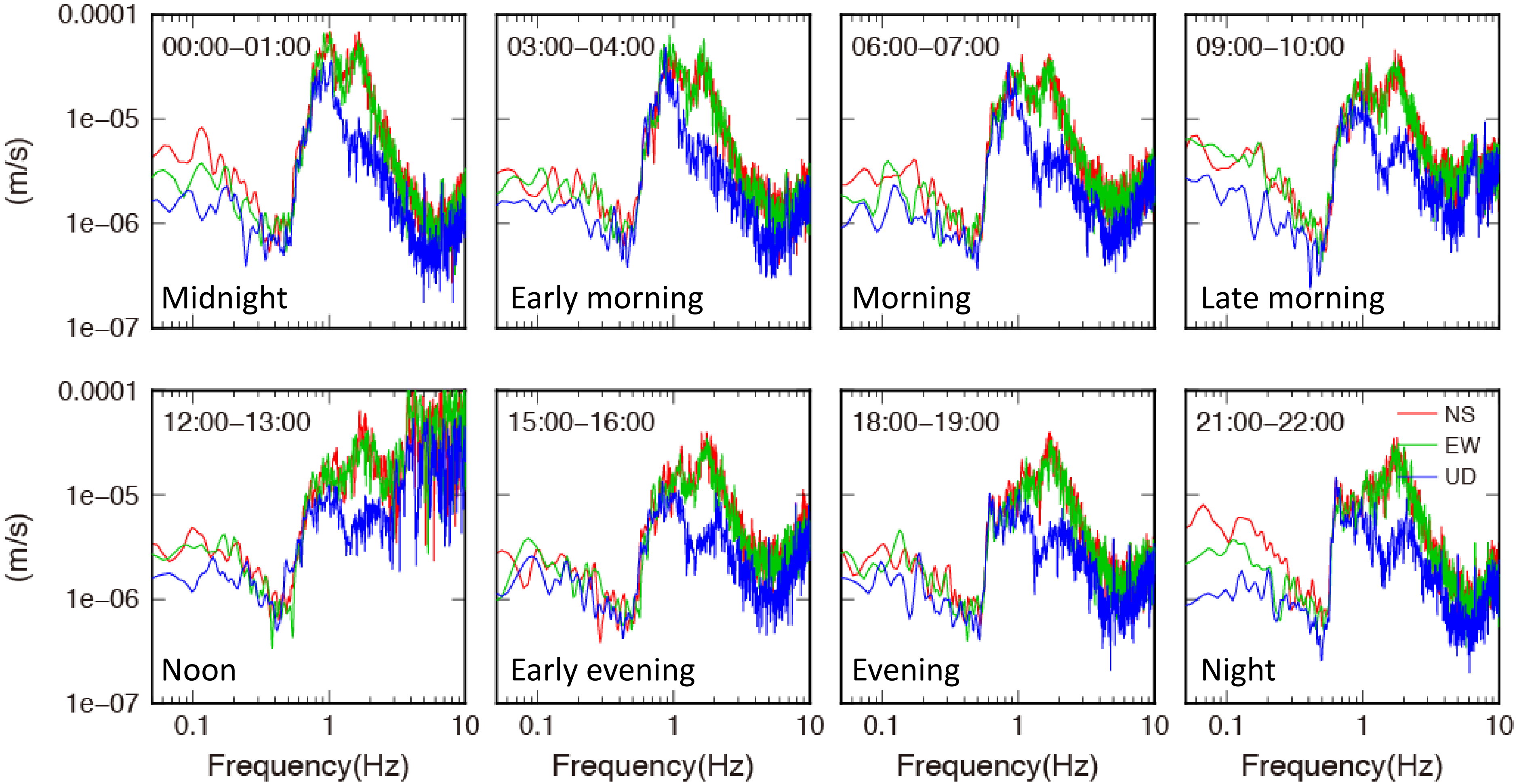
Fourier spectra at IISEE lab.

CMG-40T (Guralp Systems Ltd.)

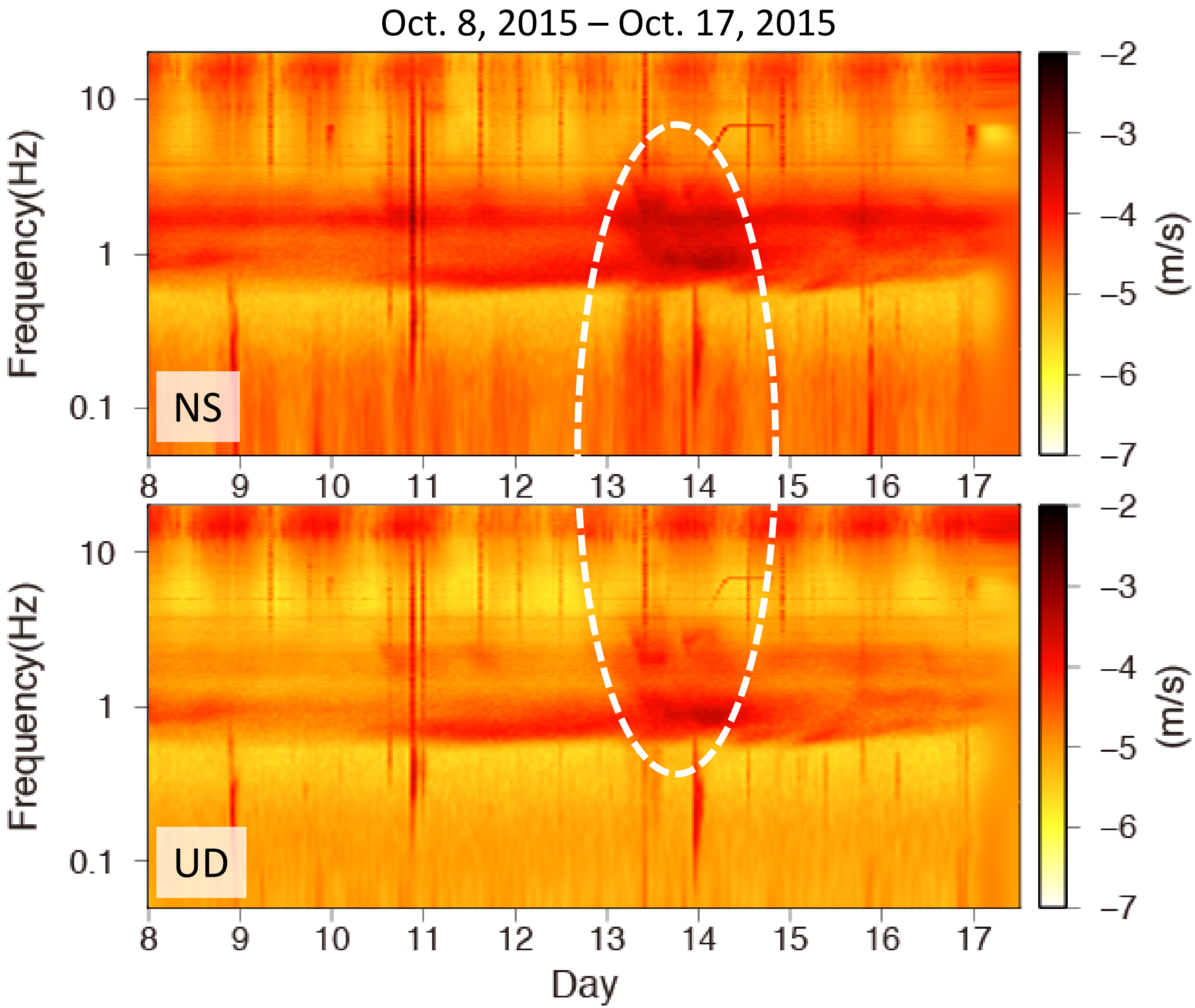
[Procedure]

1. Decimate observed data (100 Hz sampling → 20 Hz sampling)
2. Divide hour-long time series into 5 segments (819.2 sec × 5, overlapping by 75%)
3. Remove DC and linear trend (least-squares fitting)
4. Remove long period trend and apply anti-alias filter (band-pass filter: 0.025-10 Hz)
5. Apply taper using 10% sine function
6. Apply Fast Fourier Transform (FFT)

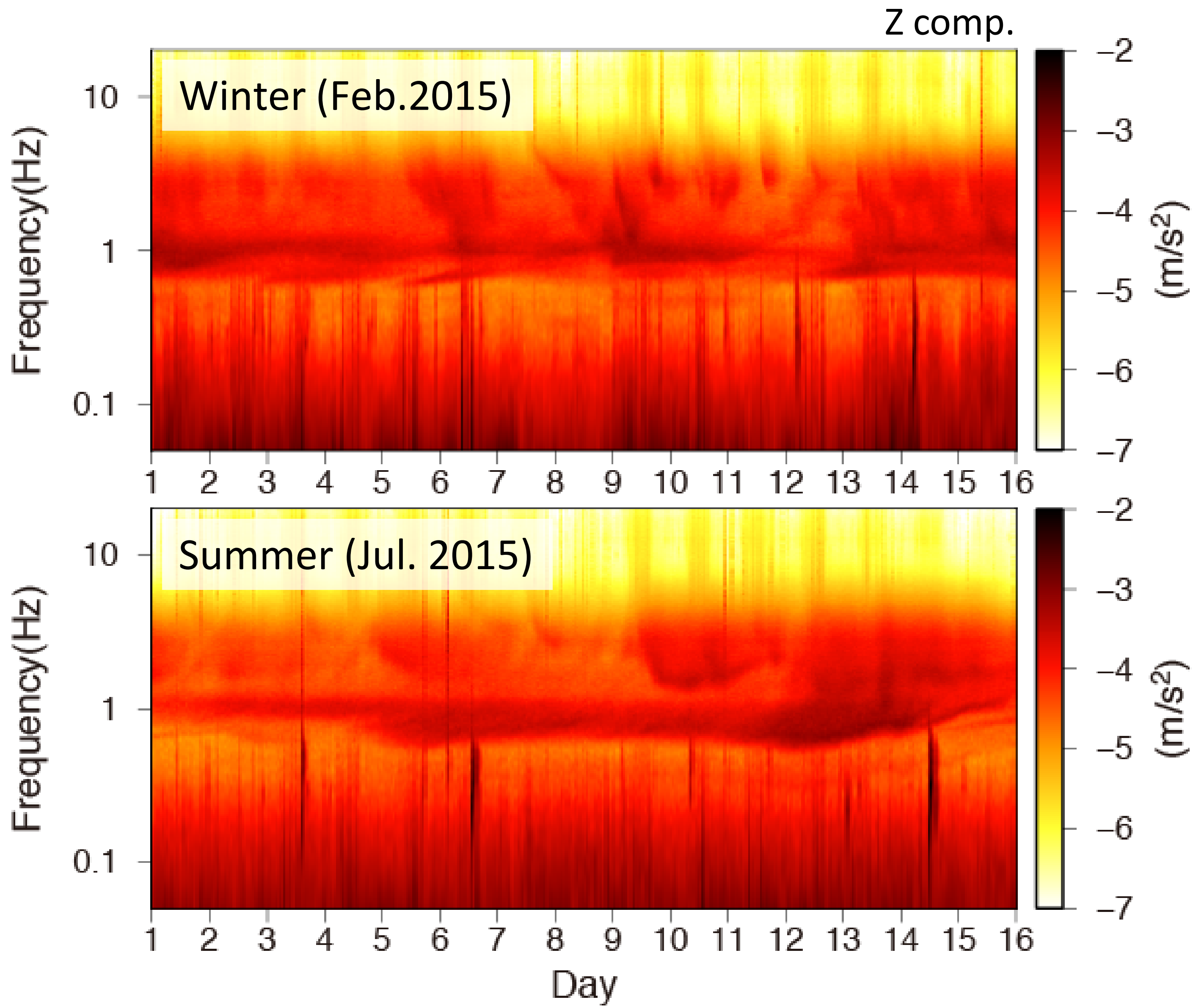
Daily change



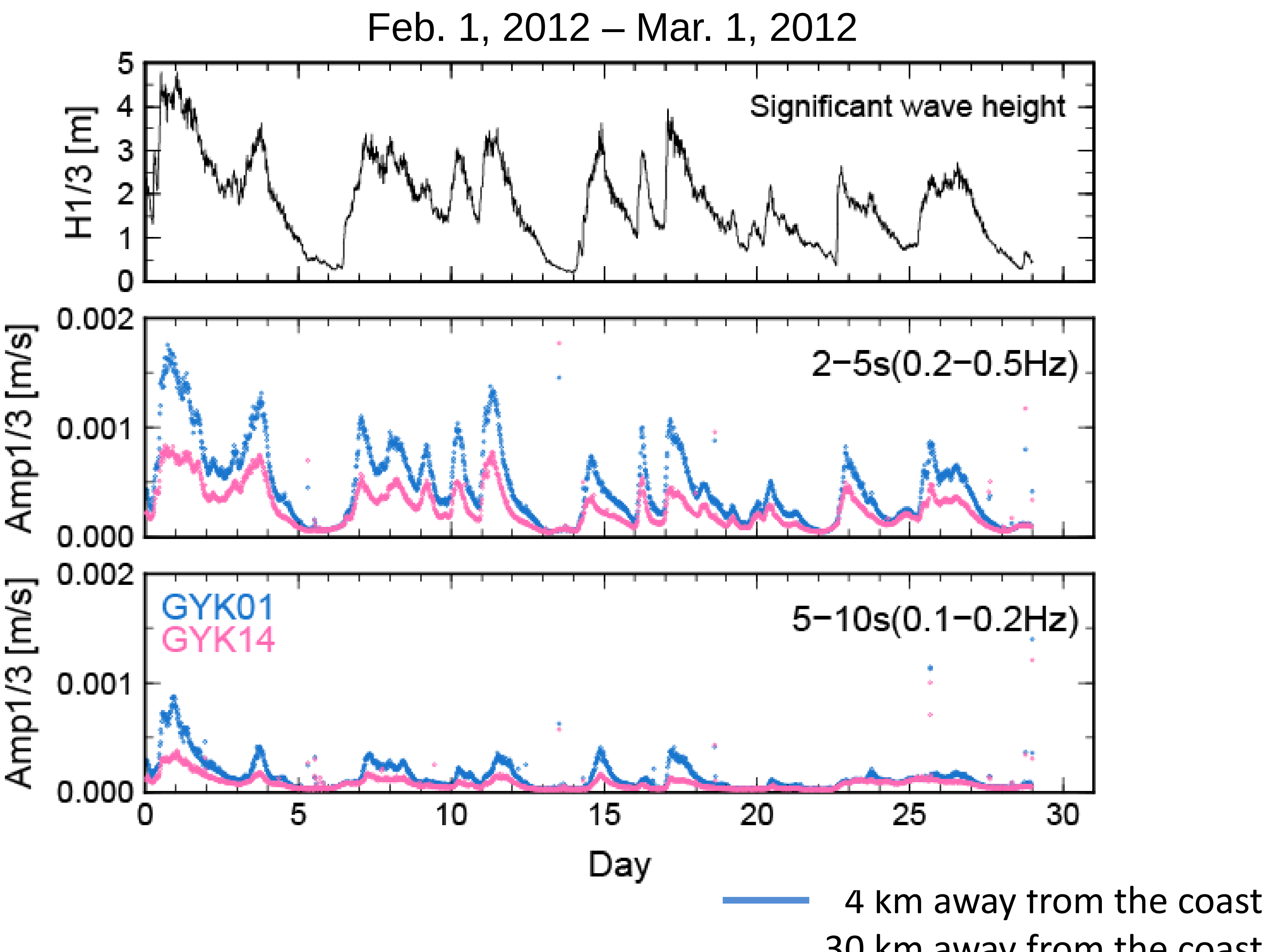
Weekly change

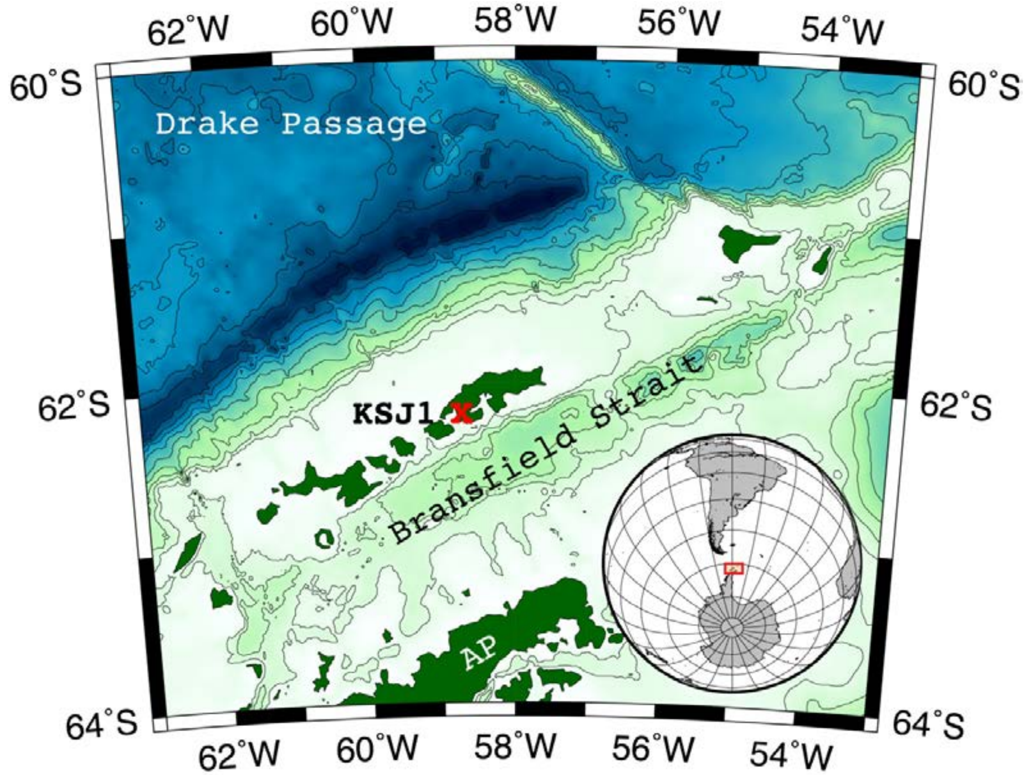


Seasonal change



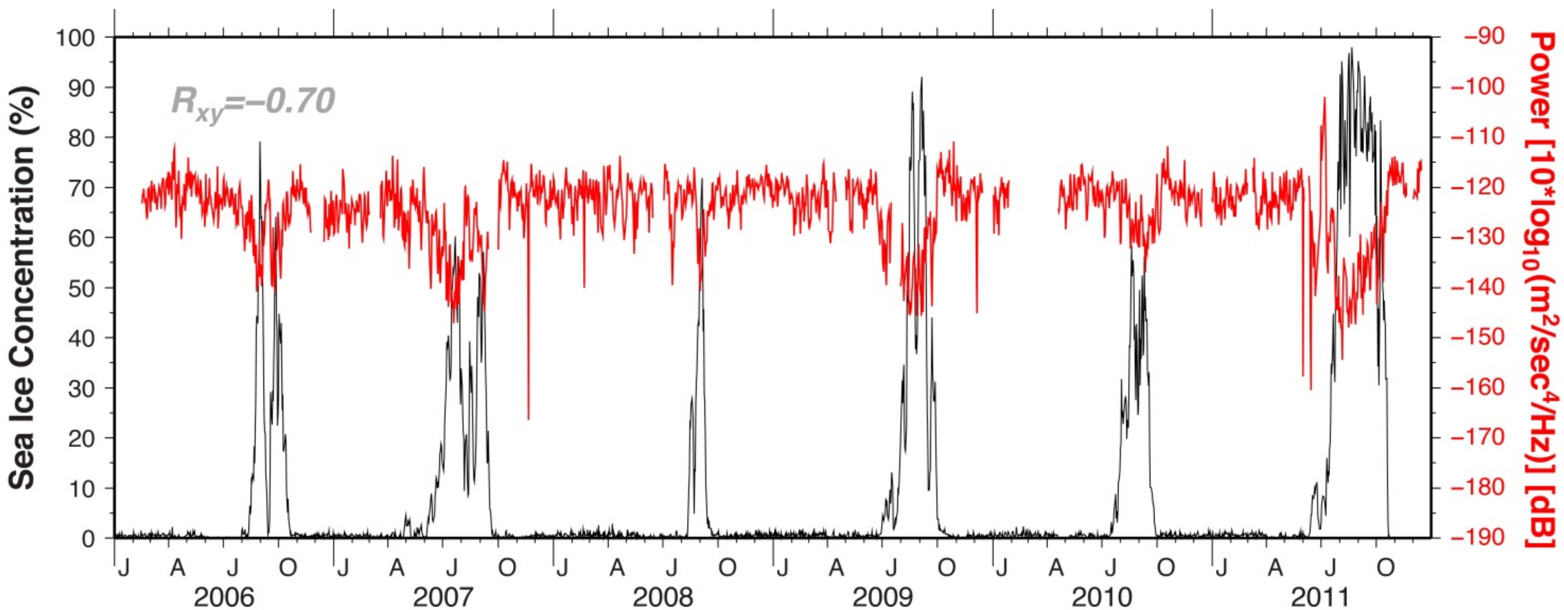
Locational change





Stations near polar areas very quiet in winter when the whole areas are frozen and there are “snow blankets”.

(source: Lee et al., 2013: https://www.researchgate.net/publication/260249639_Lee_etal_2013_InTech)



2.3 Application of Seismic Noise in Earthquake Engineering

Seismological field: "noise"

A nuisance that hampers observations of transient seismic signals.

Of course, nowadays seismologists conduct enormous number of studies using seismic noise.

Earthquake Engineering field: "signal"

An effective tool to investigate underground structures and estimate ground motion characteristics without boreholes.

Microtremor, Microseism = weak ground motion

-> influenced by subsurface structure

(amplification, focusing)

Great discoveries in earthquake engineering

Kanai et al (1961)

- predominant periods of microtremors correspond to those of earthquake ground motions

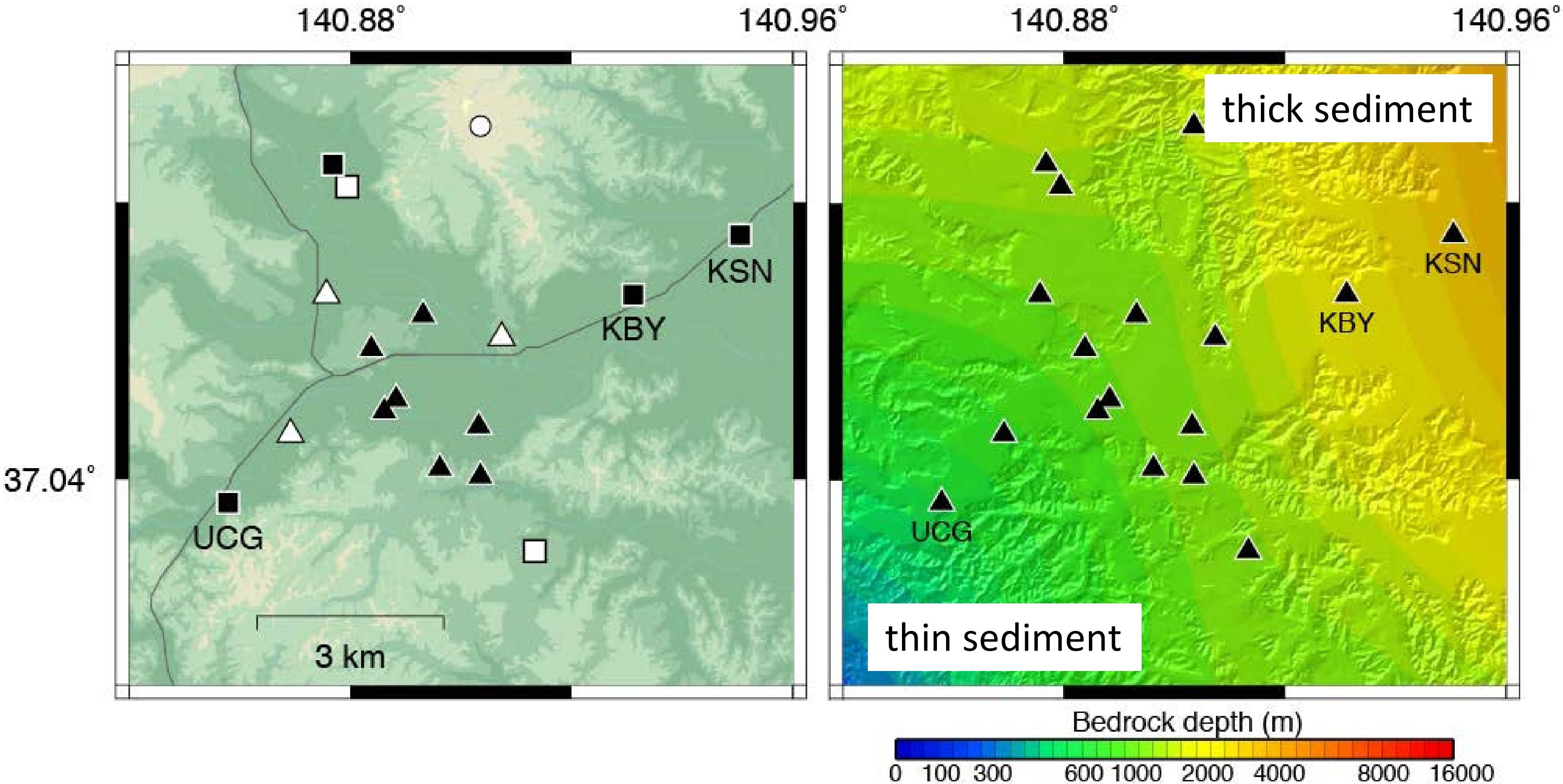
Nakamura (1989)

- spectral ratio of microtremors between its horizontal and vertical components (H/V) correlates with amplification factor at a site

Aki (1957)

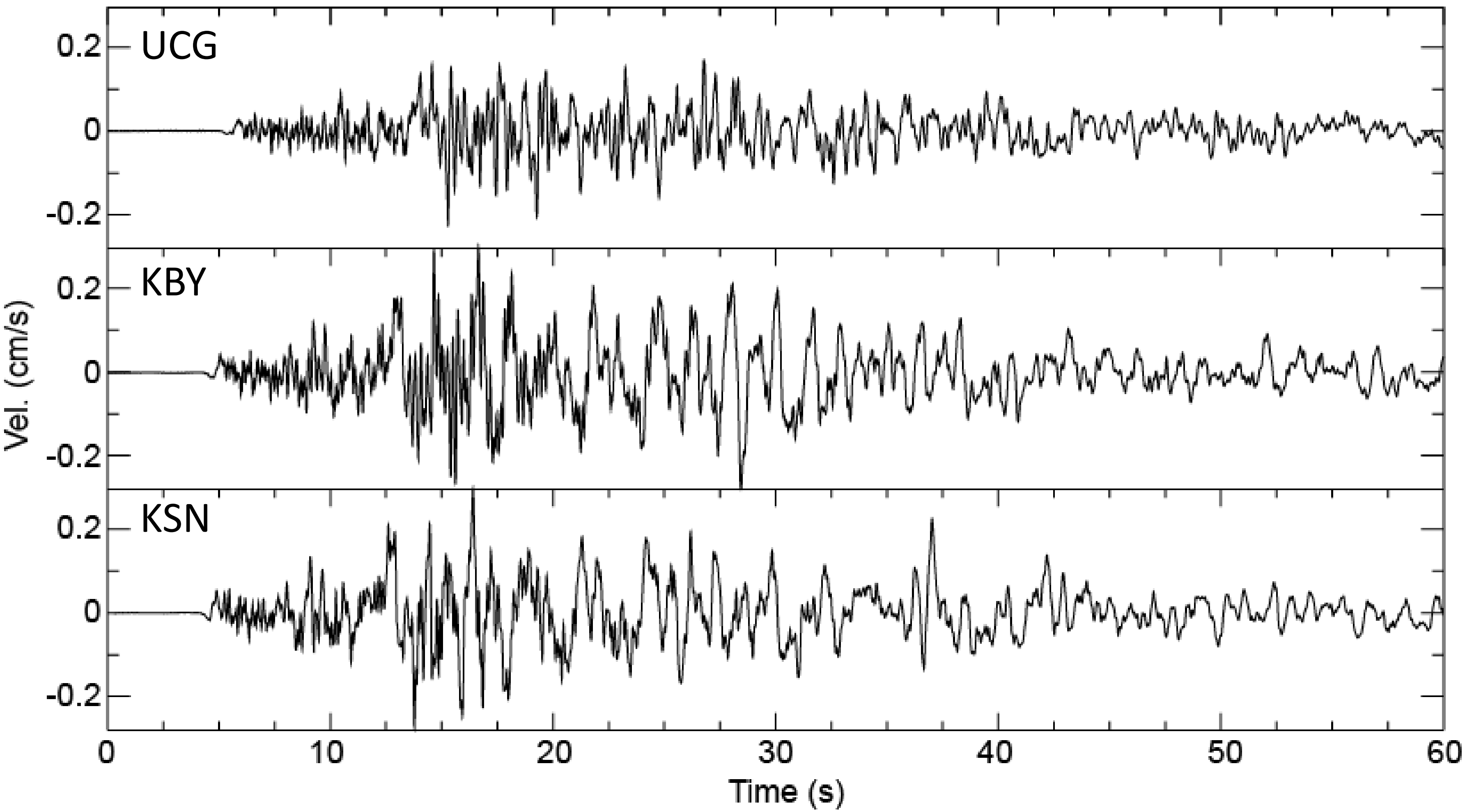
- microtremor records from a circular array of seismic sensors provide information about subsurface S-wave velocity structure

Comparison of observed earthquake and seismic noise data

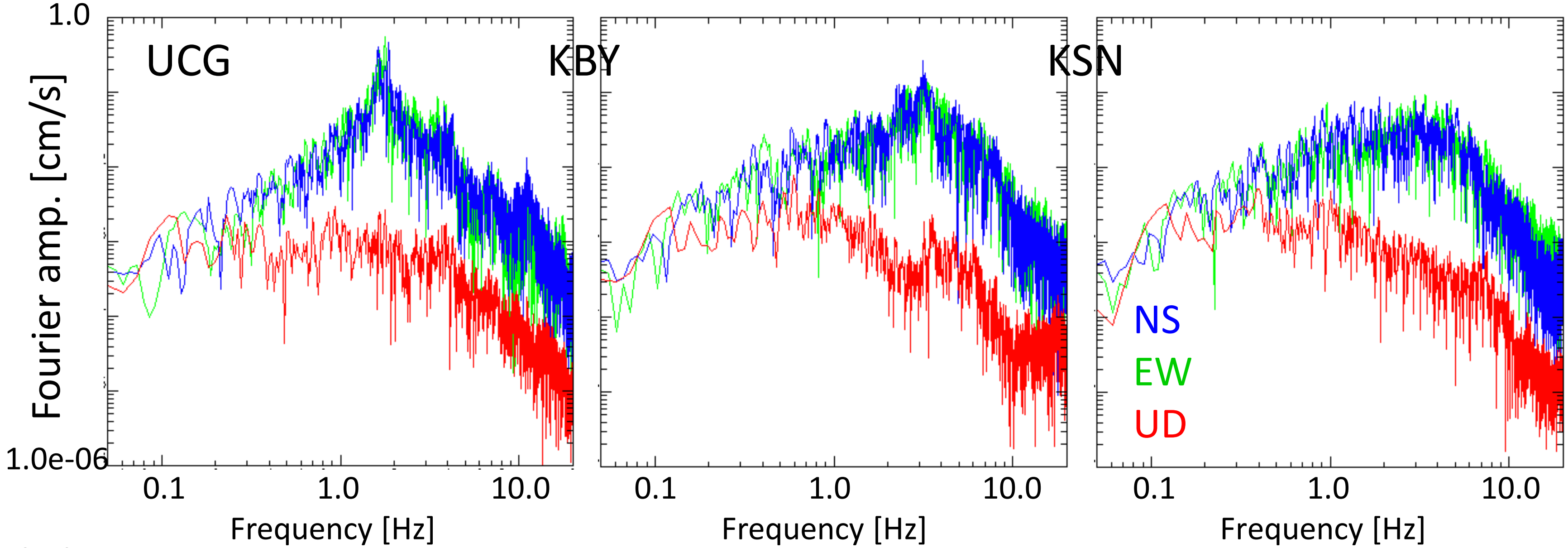


BRI temporary observation network in Iwaki city, Fukushima pref.

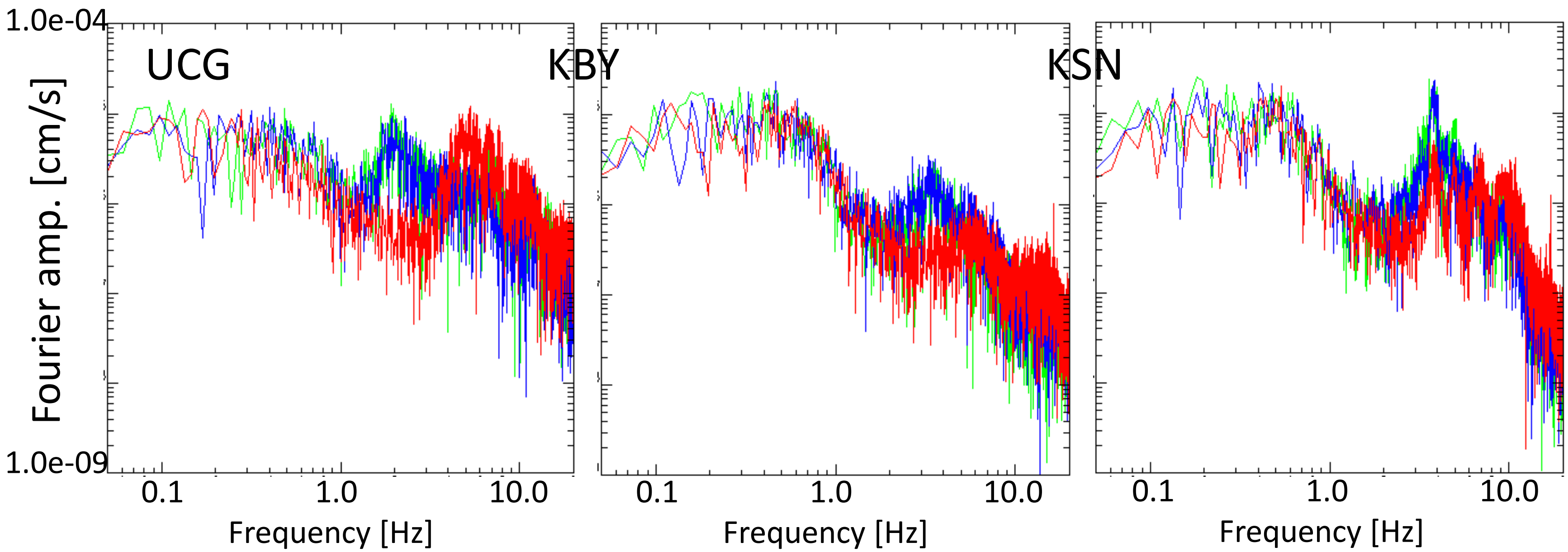
2014/12/25 Depth=36km, M5.6, distance = 70 km UD comp.



(a) Earthquake



(b) Noise



2.4 Validation of seismic noise level

For a discrete time signal whose sampling interval and the number of samples are Δt and N, the duration T is expressed as $T = N\Delta t$.

Provided the finite time series x_{m} ($\mathrm{m} = 0, 1, 2, \ldots, N\text{-}1$), the time of m-th sampling point is $t = m\Delta t$.

A function that has all sampled values can be expressed as a combination of trigonometric functions (assuming k has a finite value $N/2$).

$$x_m = \sum_{k=0}^{N/2}\left[a_k \cos\frac{2\pi km}{N} + b_k \sin\frac{2\pi km}{N}\right]$$

a_k , b_k : Fourier coefficients

The complex Fourier coefficients can be defined as;

$$C_k = \frac{a_k - ib_k}{2}$$

Then,

$$x_m = \sum_{k=0}^{N-1} C_k e^{i(2\pi km/N)} \qquad (m = 0,1,2,\cdots,N-1)$$

Discrete Fourier transform

$$t = m\Delta t$$

$$C_k = \frac{1}{N} \sum_{m=0}^{N-1} x_m e^{-i(2\pi km/N)} \qquad (k = 0,1,2,\cdots,N-1)$$

$$f = k / N\Delta t$$

The Fourier spectrum is defined as,

$$F_k = C_k \Delta t$$

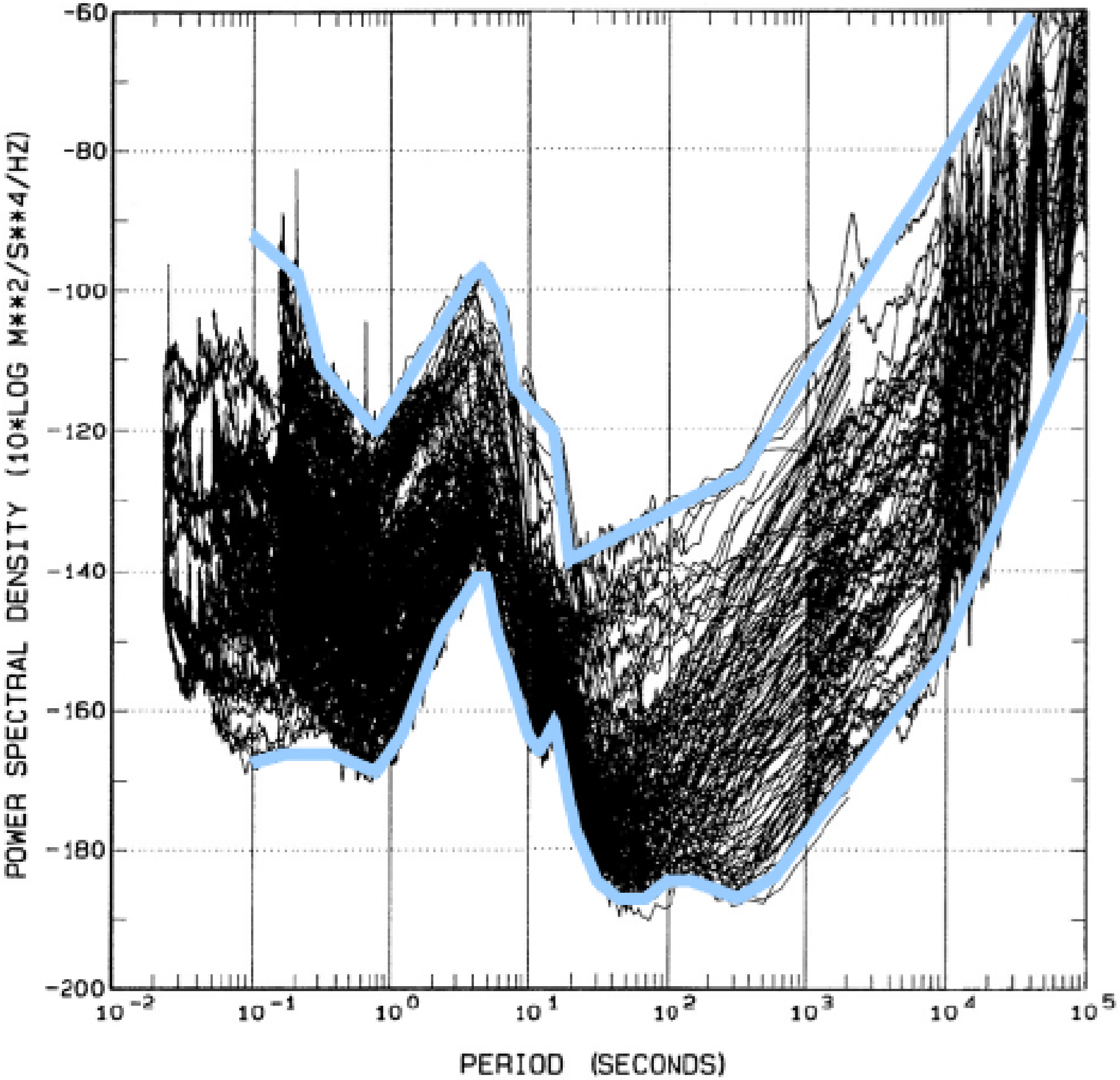
unit: m/s^2 for accelerogram

The power spectral density (PSD) is defined as,

$$P_k = \frac{2}{T} \cdot |F_k|^2 = \frac{2}{N\Delta t} \cdot |C_k|^2 \Delta t^2 = \frac{2\Delta t}{N} |C_k|^2$$

unit: $(m/s^2)^2/Hz$

2.5 Noise model of the Earth

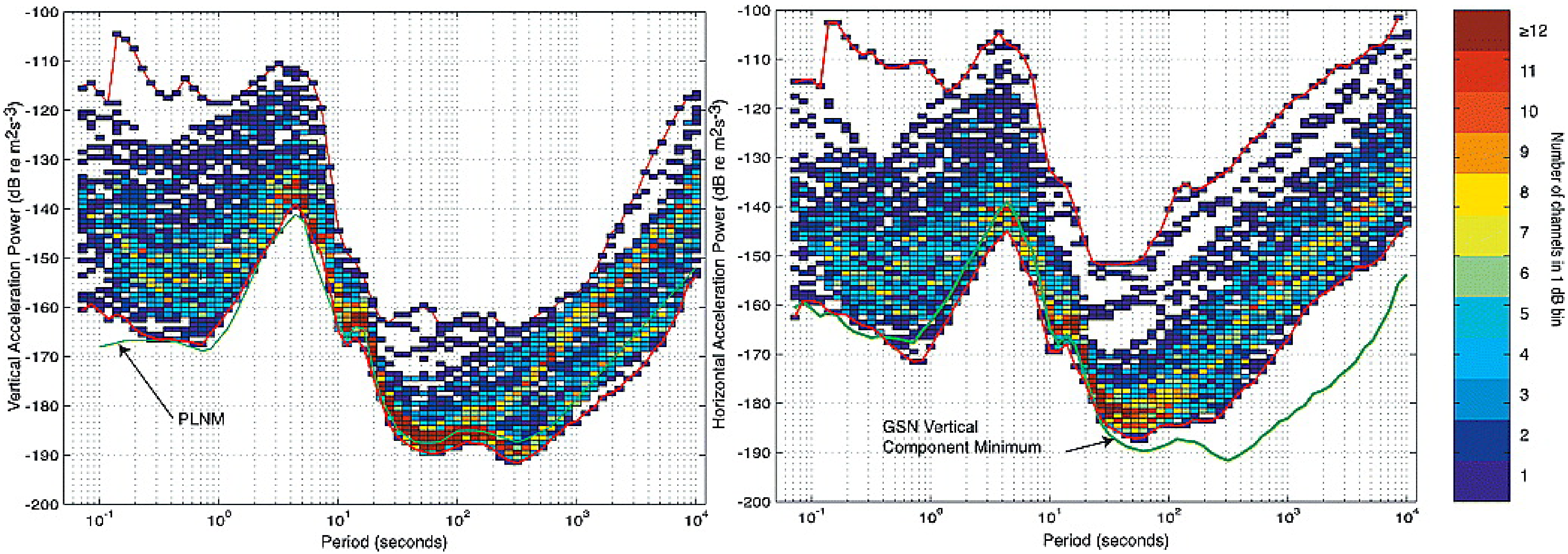


11-20 sec
- from standing waves induced by storms in the deep ocean (primary microseisms)

5-10 sec
- from significant wave surf along the coast (secondary microseisms)

lower envelope
→ New Low Noise Model (NLNM)
higher envelope
→ New High Noise Model (NHNM)

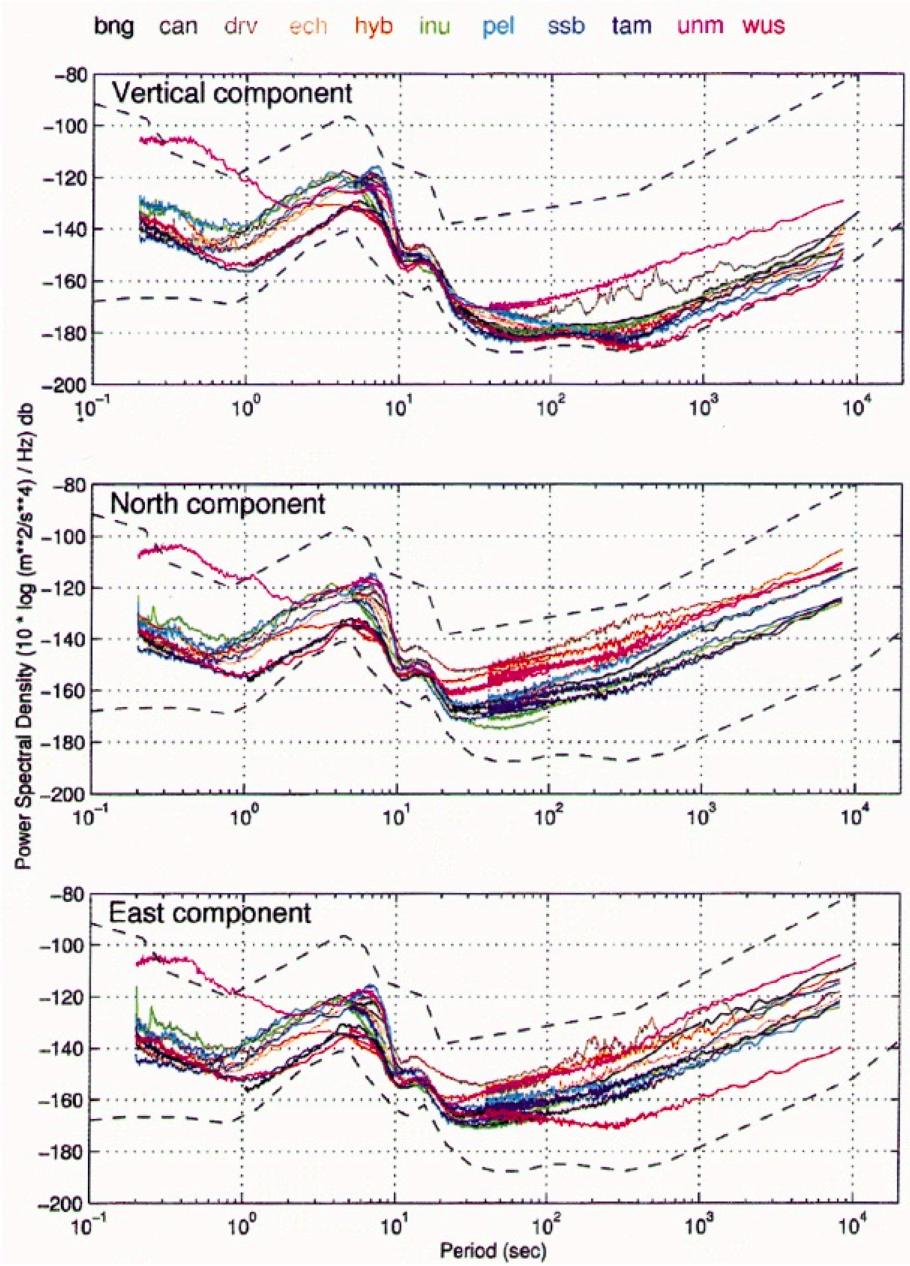
(Source: Peterson, 1993, https://pubs.er.usgs.gov/publication/ofr93322, courtesy of the U.S. Geological Survey) for 118 GSN stations



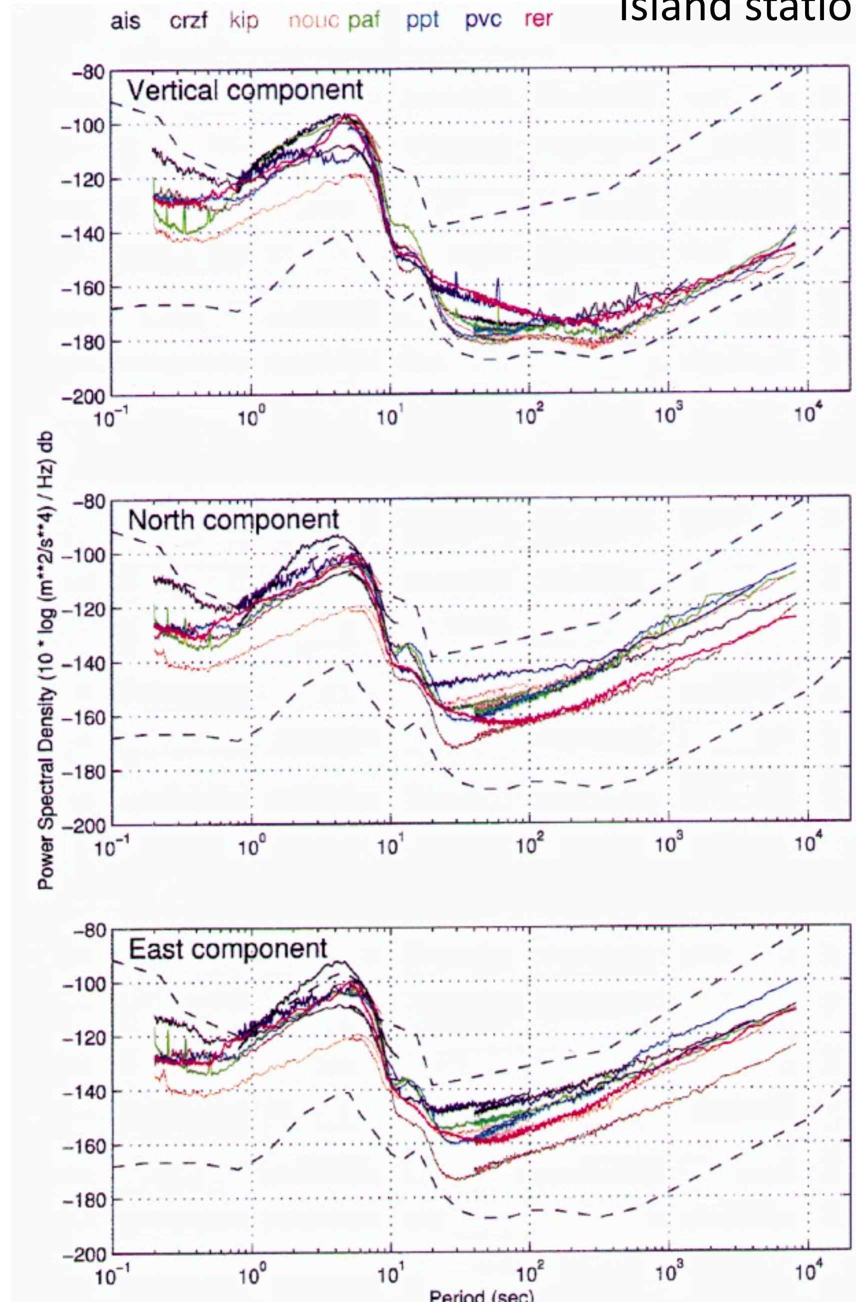
Typical noise levels will vary greatly between different sites and different frequencies.

(Source: Berger et al., 2004, “Ambient Earth noise: A survey of the Global Seismographic Network”, J. Geophys. Res., 109)

Continental stations



Island stations



for 23 GEOSCOPE stations

(Source: Stutzmann et al., 2000, “GEOSCOPE Station Noise Levels”, Bulletin of Seismological Society of America, 90, 3, p690-701, ©Seismological Society of America.)

3. Instrumental Noise

Data logger

input → observation system → **output**

ground motion

voltage change

amplifier
transducer
integrator

3.1 Instrumental noise classification

- Brownian motion for small mass
  → <u>greatly reduced nowadays (no need to consider)</u>

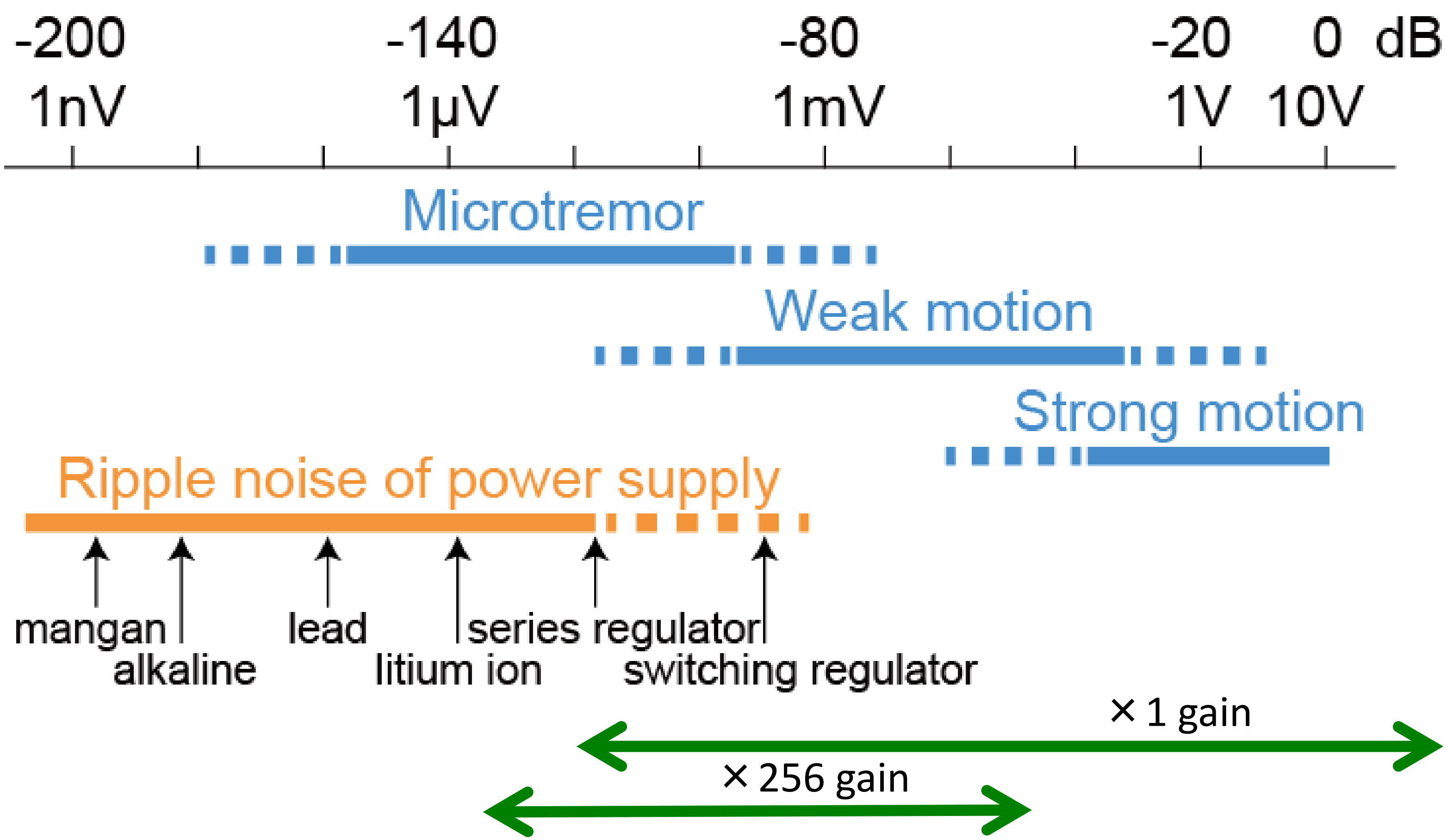
- Switching noise (semiconductor noise)

- Resistor noise
  from electromagnetic transducer (especially for geophones)

- Thermal noise
  from fluctuating self-temperature

- Circuit noise
  - Ripple noise (from fluctuating DC)
  - Flicker noise (from quantity of electron in the device)

3.2 Circuit noise –Ripple noise-

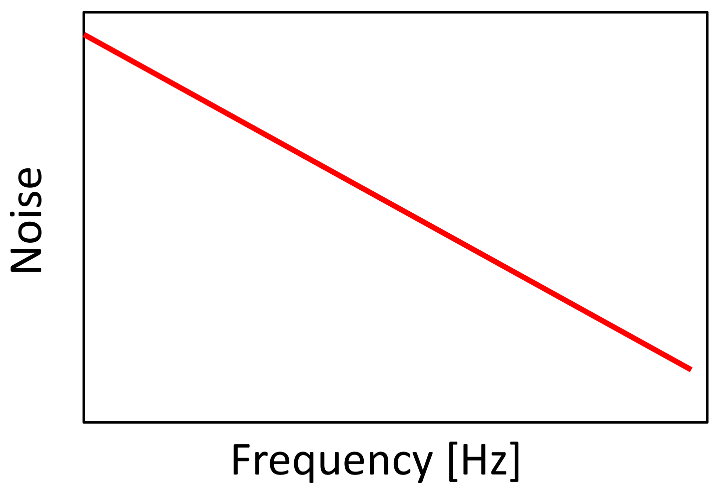


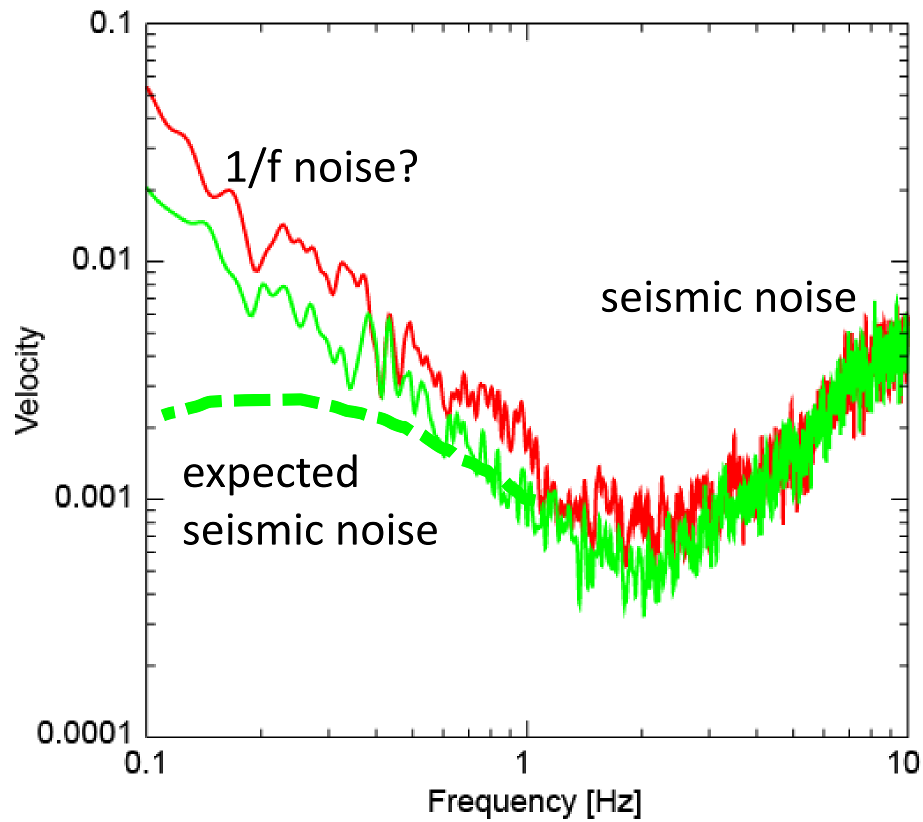
Example of output voltage variations for velocity sensors (sensitivity: 100 V/m/s, A/D converter: 24-bit, Input: ±10V)

3.3 Circuit noise –Flicker noise-

Flicker noise (1/f noise, pink noise) is caused by the quantity of electron in the device. Magnitude of noise is inversely proportional to the number of electron and inversely proportional to frequency.

Especially, power-saving observation system tends to cause 1/f noise!

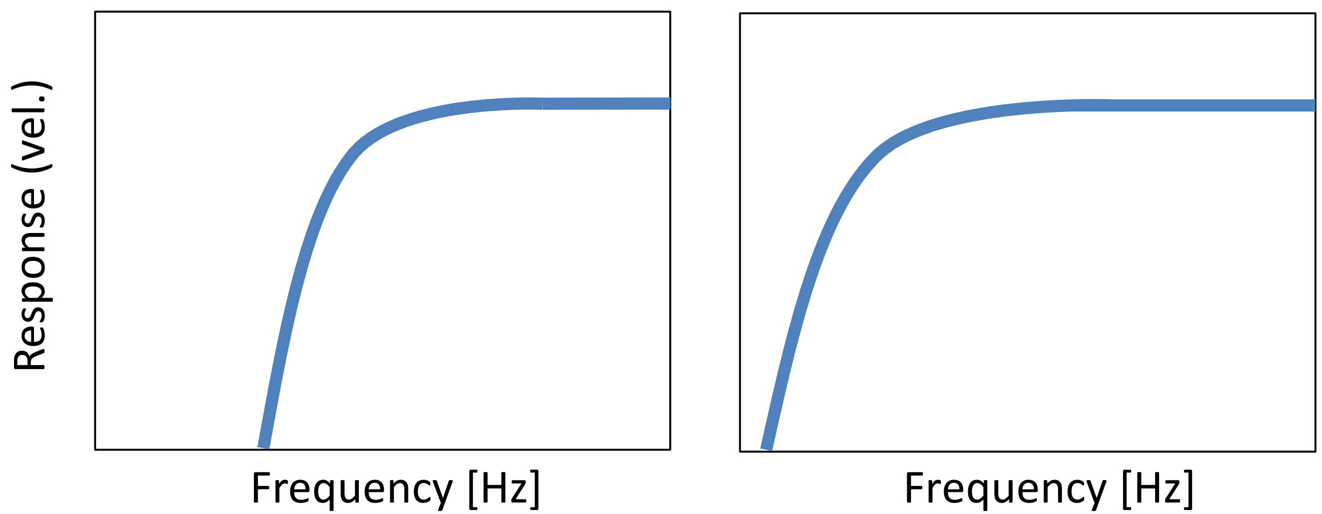


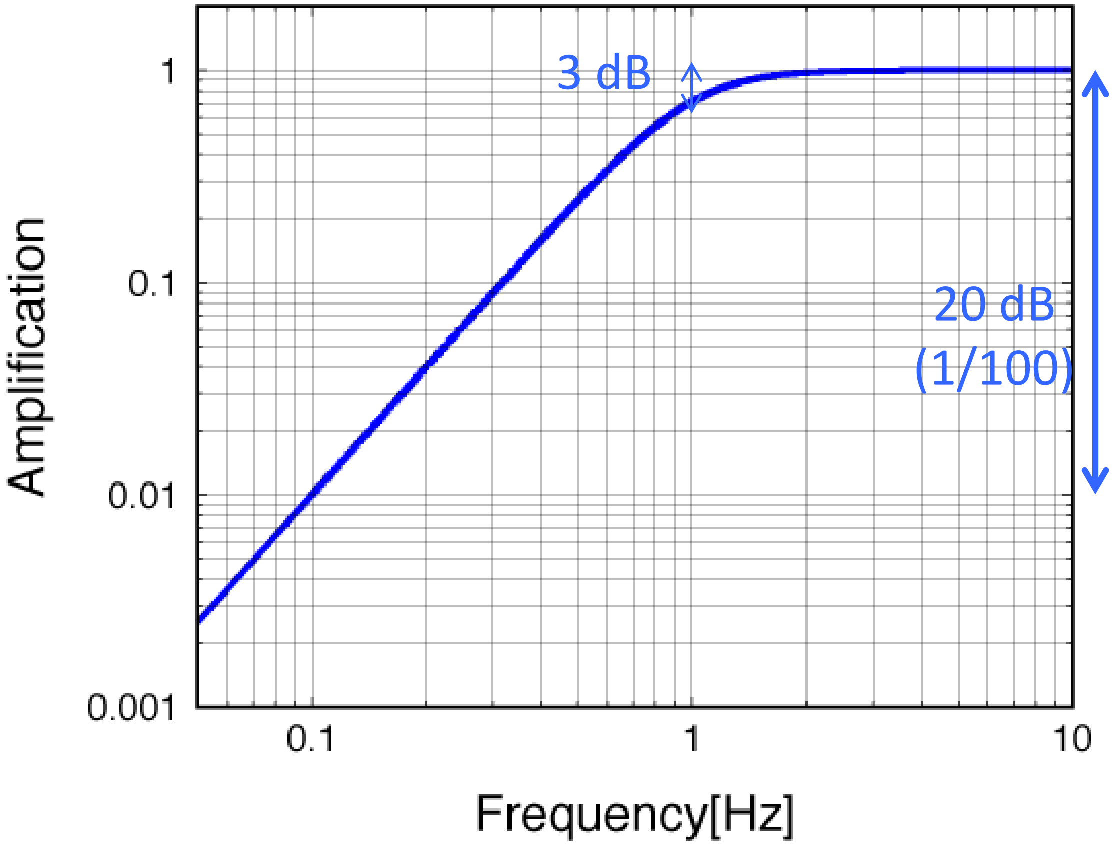


3.4 Moving-coil type seismometer

Conventional electromagnetic seismometer (Moving-coil type)

	Small seismometer	Large seismometer
Weight	Light	Heavy
Natural freq.	High	Low
Freq. range	High frequency	Broadband
Measurement	Stable	Unstable
Treatment	Friendly	Fragile





Sensitivity	: 100 V/m/s
Natural freq.	: 1.0 Hz
Damping factor	: 0.7
Input voltage	: ± 5 V
A/D converter	: 24 bit

When seismic noise level is 1.0×10^{-7} m/s,

sensor output level in the flat range = $100 \times 1.0 \times 10^{-7} = 1.0 \times 10^{-5}$ V (= 10 μV)

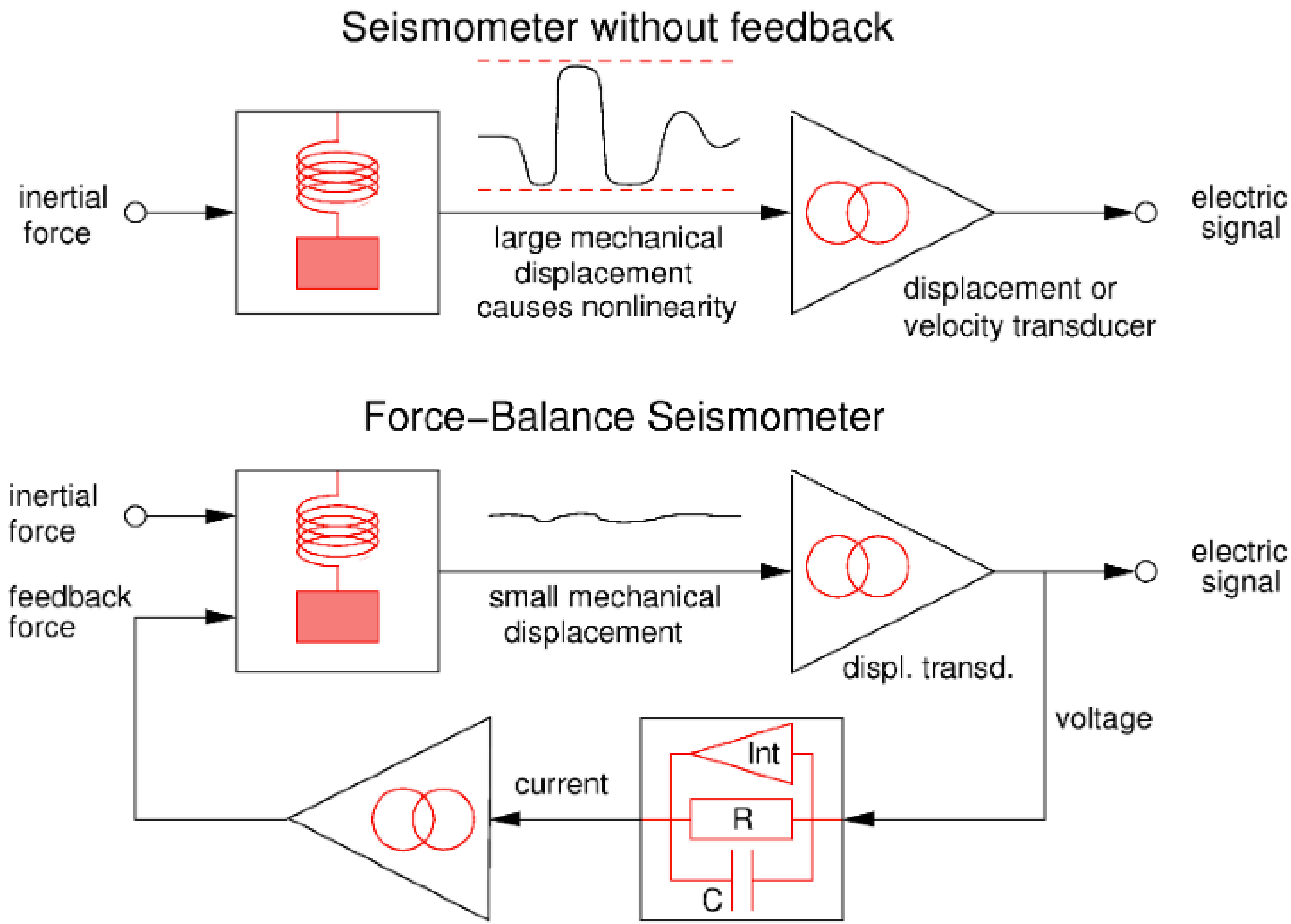
sensor output level at 0.1 Hz = $1.0 \times 10^{-5} / 100 = 1.0 \times 10^{-7}$ V (= 0.1 μV)

When seismic noise level is 1.0×10^{-6} m/s,

sensor output level in the flat range = $100 \times 1.0 \times 10^{-6} = 1.0 \times 10^{-4}$ V (=100 μV)

sensor output level at 0.1 Hz = $1.0 \times 10^{-4} / 100 = 1.0 \times 10^{-6}$ V (= 1.0 μV)

3.5 Feedback seismometer



(Source: Wielandt (2004) from IRIS Website
http://ds.iris.edu/stations/seisWorkshop04/PDF/Wielandt-Design3.pdf)

An feedback circuit enables small seismometers to observe long-period signals. However, additional noise is generated by fluctuations of feedback amplifier.

4. Environmental Noise

- Barometric pressure (especially for the vertical comp.)
- Temperature (especially for the vertical comp.)
- Magnetic fields (DC-powered railway lines)
- Geomagnetic field

  ] Need magnetic shield

- Wind (instrumental vibration : 3-10sec)

  ] Need wind protector

- Ground tilt (human walking, car passing)

5. Reduction of Noise Influences

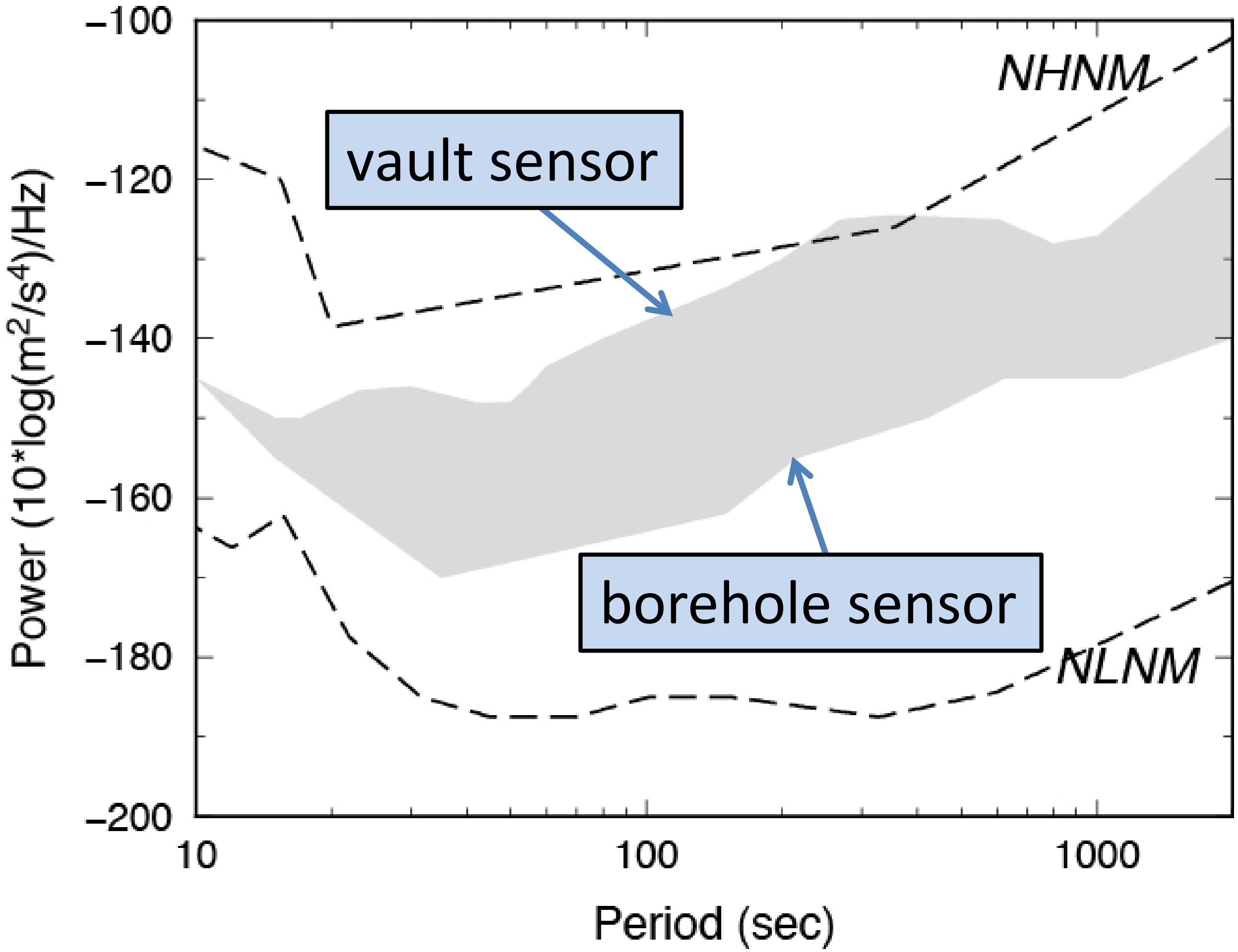
5.1 Site selection

A quiet site is capable of detecting and recording many more earthquakes than a noisy site.

In selecting permanent observation site, we have to consider …

- distance from seismic noise sources
  (should be larger than the thickness of sedimentary layer)
- geological condition
  (solid basement rock is preferable)
- future infrastructure
  (growth of population, expansion of the city)
- possibility of flood
- possibility of cavity underneath the site

Installation of seismometer in urban area / sedimentary basin



Seismic noise reduction can be achieved by using borehole sensors in place of vault sensors.

5.2 Sensor selection

The energy release from earthquakes spans an enormous range. (from several nanometers – several meters)

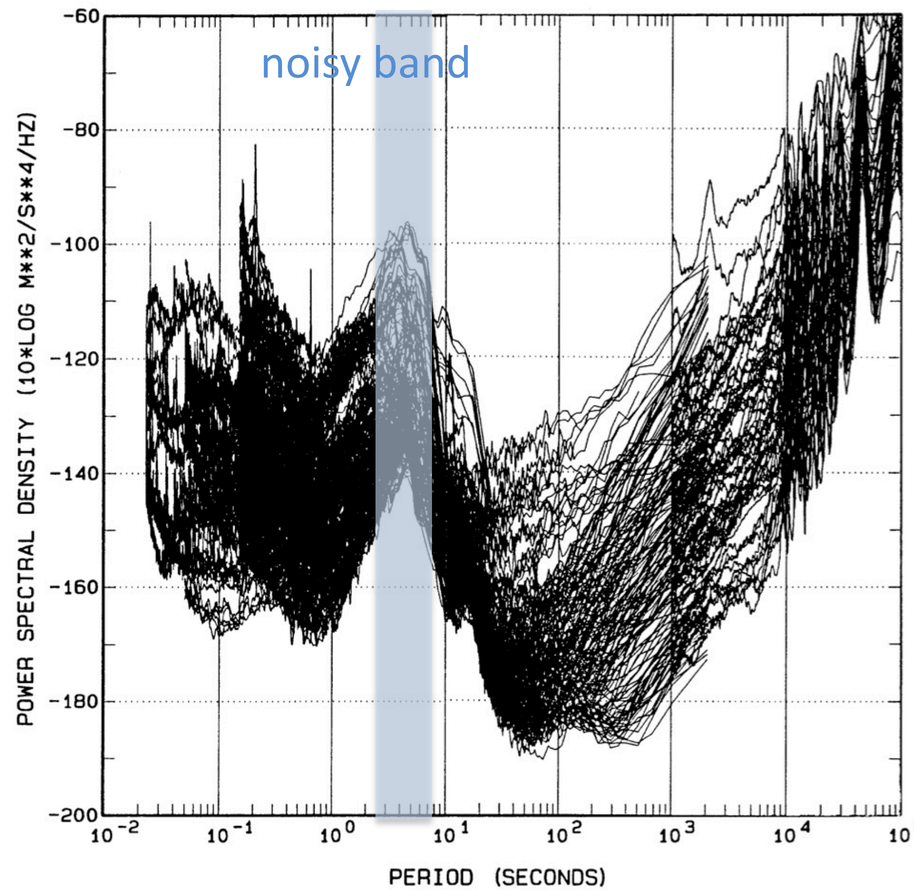
Seismic waves generated by micro-earthquakes or far-field earthquakes may lie below the detection threshold, even if the most sensitive seismometer is used.

Large earthquakes in the immediate vicinity produce very strong ground motion that may go off-scale.

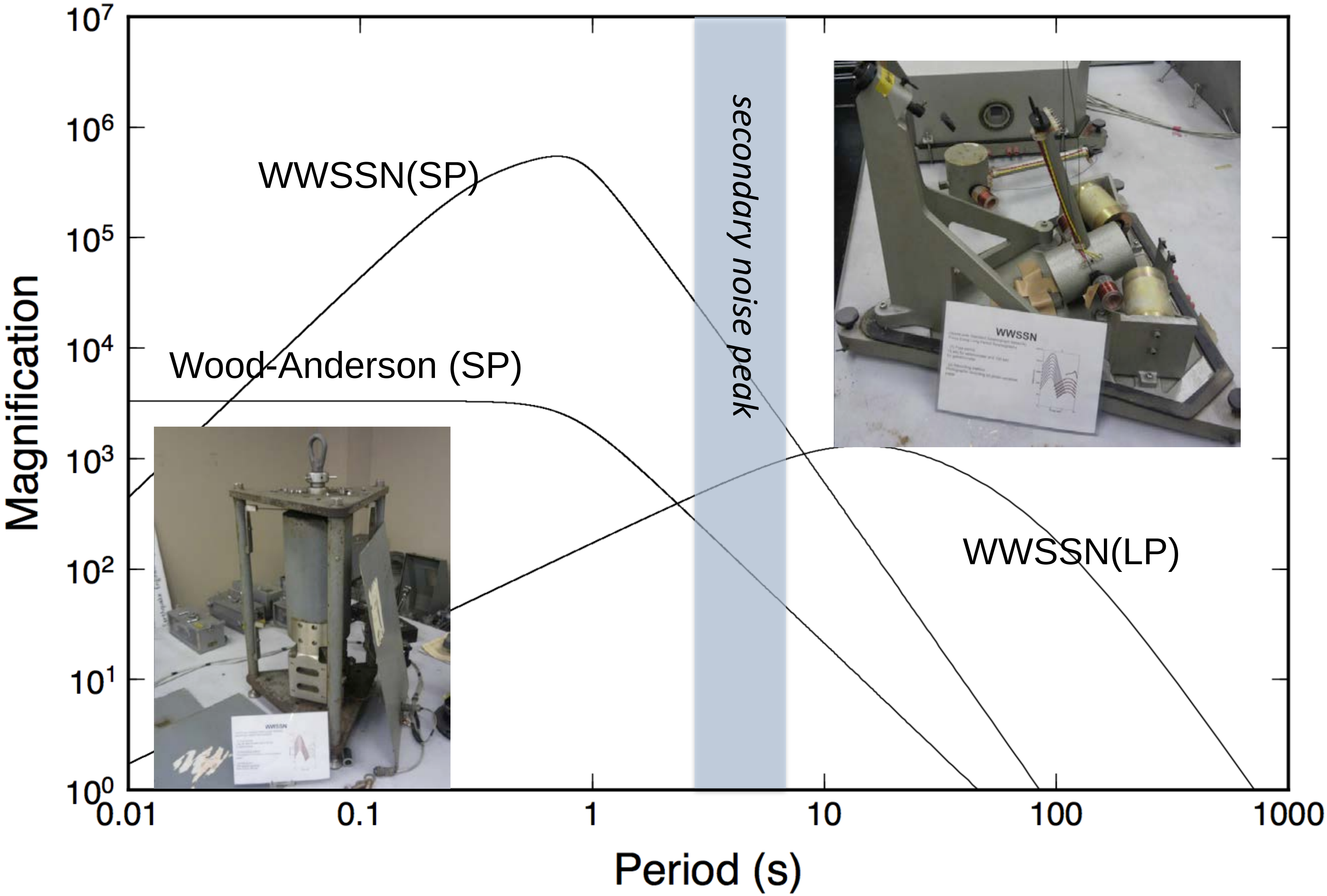
-> Thus, a seismic recording system requires a large dynamic range to cope with the range of conditions.

For the analogue recording systems, it is difficult to achieve adequate dynamic range to cope with the whole range of systems.

To avoid overlapping of the record from medium size events with seismic noise around the secondary microseisms peak, two different instruments (short-period and long-period seismometers) were co-located to detect the signal from the two sides of the noise peak.

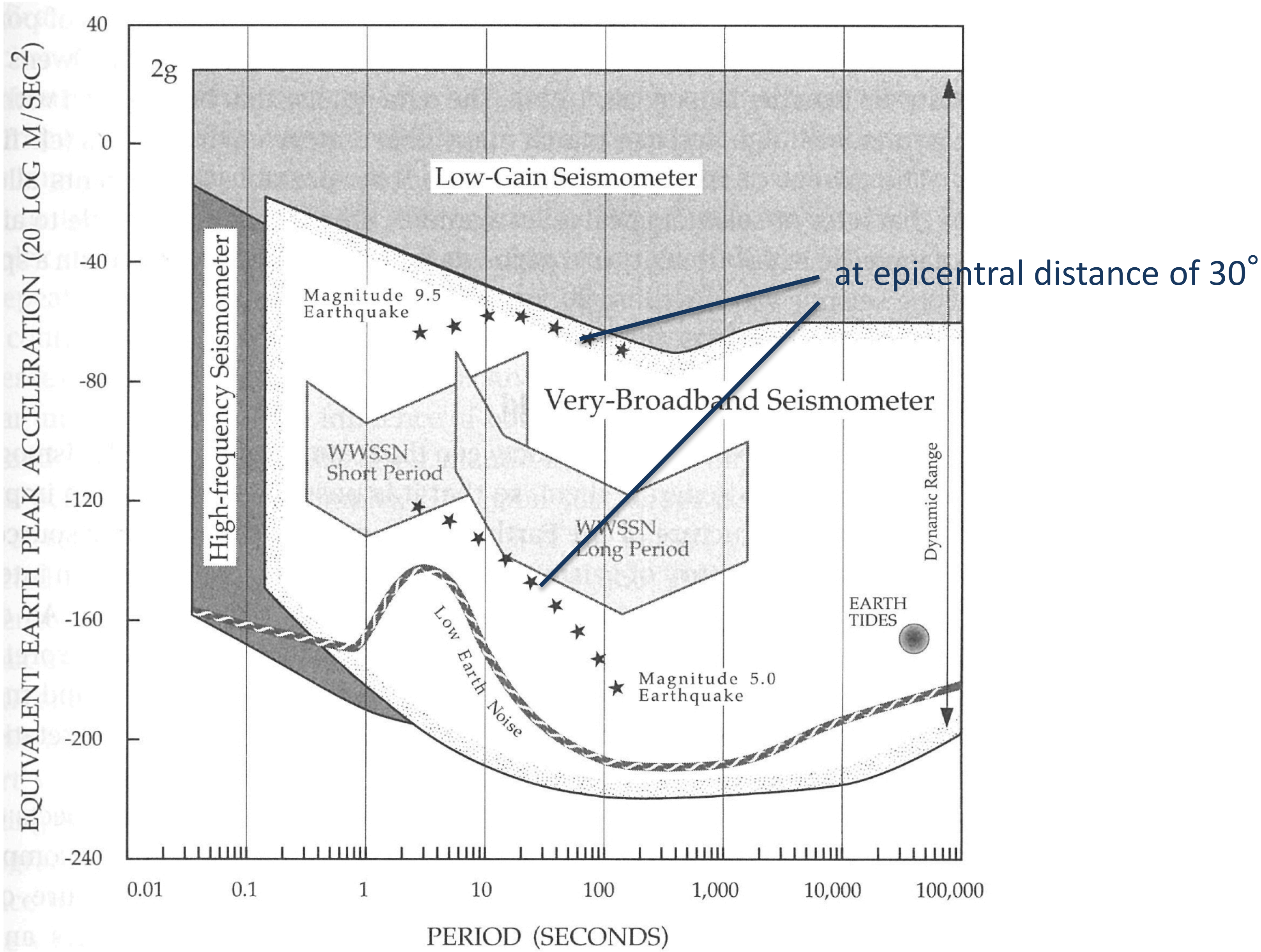


(Source: Peterson, 1993, https://pubs.er.usgs.gov/publication/ofr93322, courtesy of the U.S. Geological Survey)



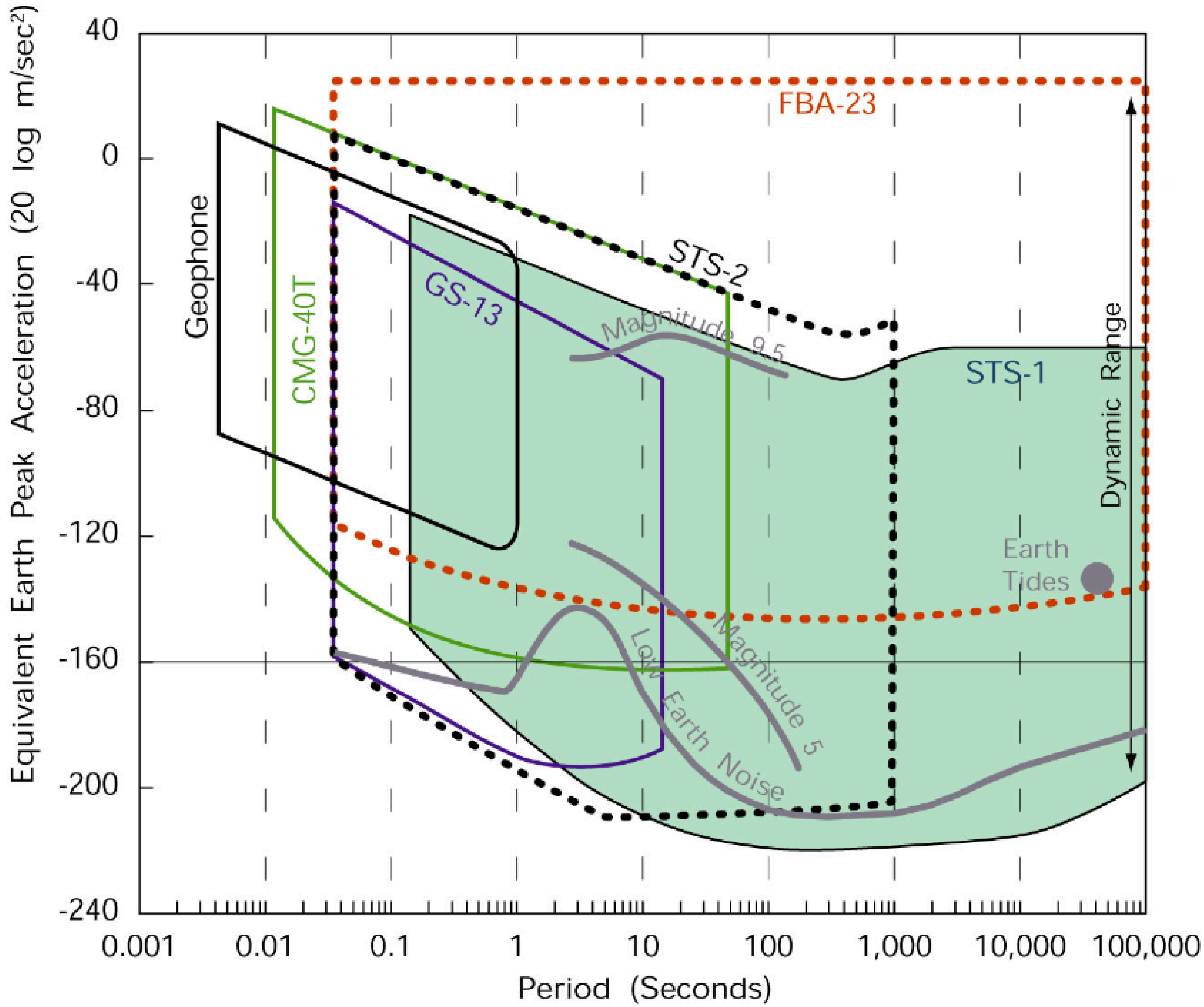
Instrument response curves for classical short- and long-period seismometers

Dynamic ranges of current observation systems and the WWSSN instruments.



(Source: Kennett (2001), The Seismic Wavefield: Volume 1. Introduction and Theoretical Development, Cambridge University Press)

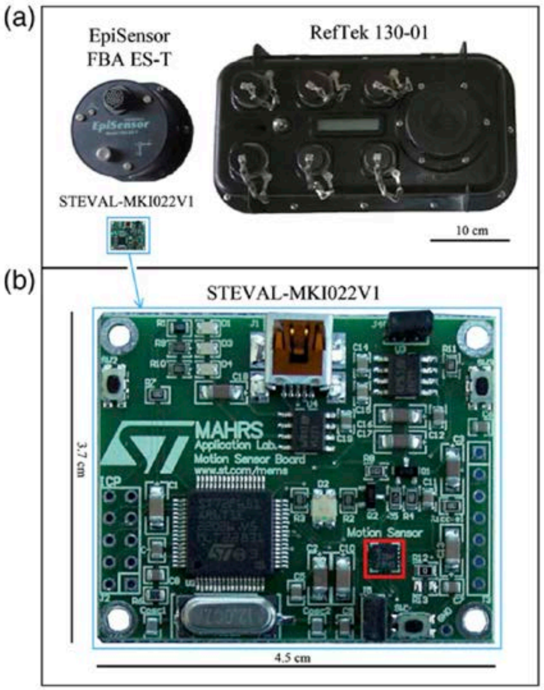
Dynamic ranges of current observation systems



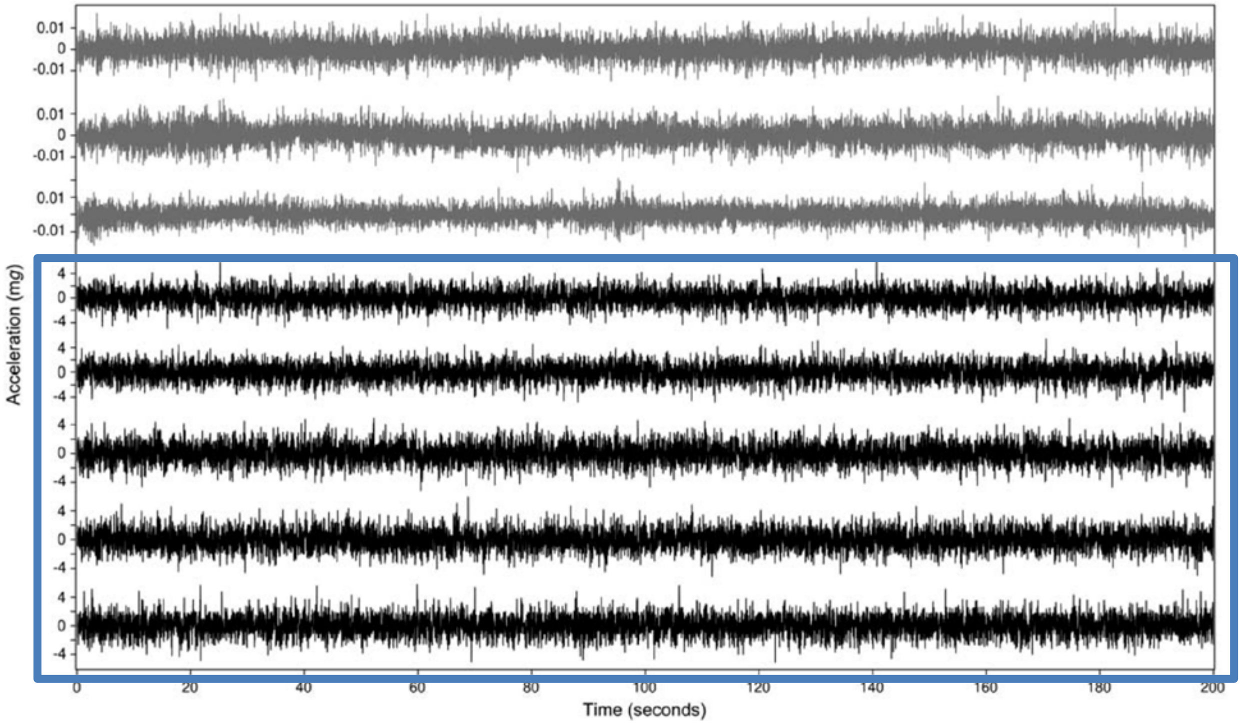
(Source: IRIS (2004)
https://ds.iris.edu/media/workshop/2004/03/broadband-seismometer-workshop/files/VBBworkshop.pdf)

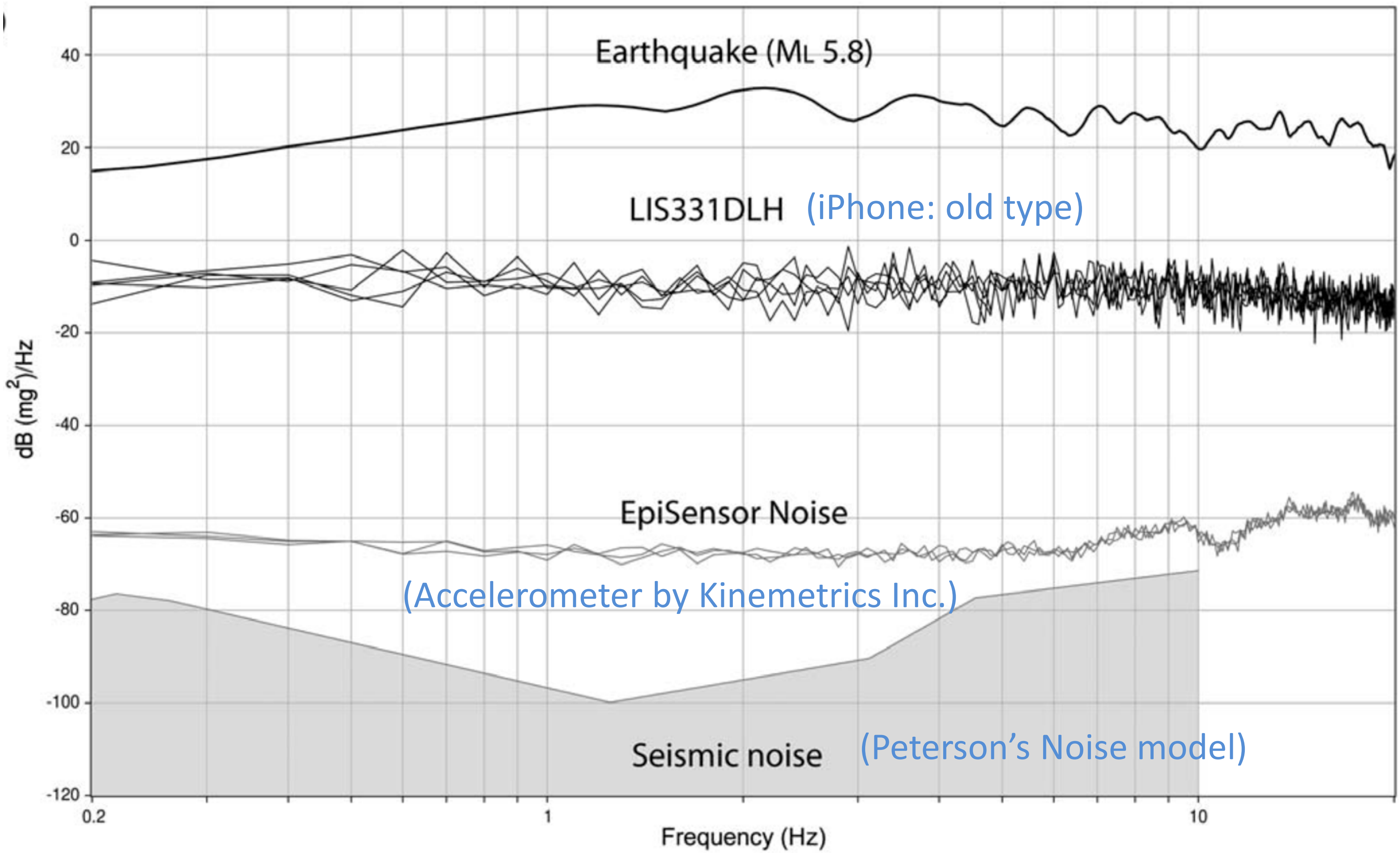
Digression: suitability of a smartphone accelerometer

(by D'Alessandro and D'Anna (2013), "Suitability of Low-Cost Three-Axis MEMS Accelerometers in Strong-Motion Seismology: Tests on the LIS331DLH (iPhone) accelerometer", Bull. Seismological Society of America, 103, p2906-2913.©Seismological Society of America)



Noises of LIS331DLH (iPhone: old type) accelerometer





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It is desirable to use iPhone accelerometers only in strong motion seismology!

5.3 Indexes of preferable sites/sensors

less than 2 s

- horizontal component > vertical component
- a factor of 10 of the NLNM is preferable

between 2 – 20 s

- similar amplitudes of seismic noise both in the horizontal and vertical components
- seasonal variation of seismic noise (50dB above the NLNM is possible in winter or in island)

between 100 – 300 s

- horizontal component > vertical component
- a site whose horizontal noise fluctuation of ±10dB is preferable

6. Data Processing Practices

6.1 Unit conversion

seismometer

Output: Voltage change (V)

How to convert voltage change to amplitudes of velocity or acceleration?

(a) Unit conversion with given coefficients

$$\underset{\text{voltage change (count)}}{\boxed{\text{Output}}} \times \underset{\text{seismometer}}{\frac{1}{\text{Sensitivity [V/(m/s)]}}} \times \underset{\text{amplifier}}{\frac{1}{\text{Gain}}} \times \underset{\text{digitizer}}{\text{Bit-weight (V/count)}} \rightarrow \text{(m/s)}$$

where

$$\text{Bit-weight (V/count)} = \frac{\text{Input data logger range (V)}}{2^{\text{*Digitizer resolution}}}$$

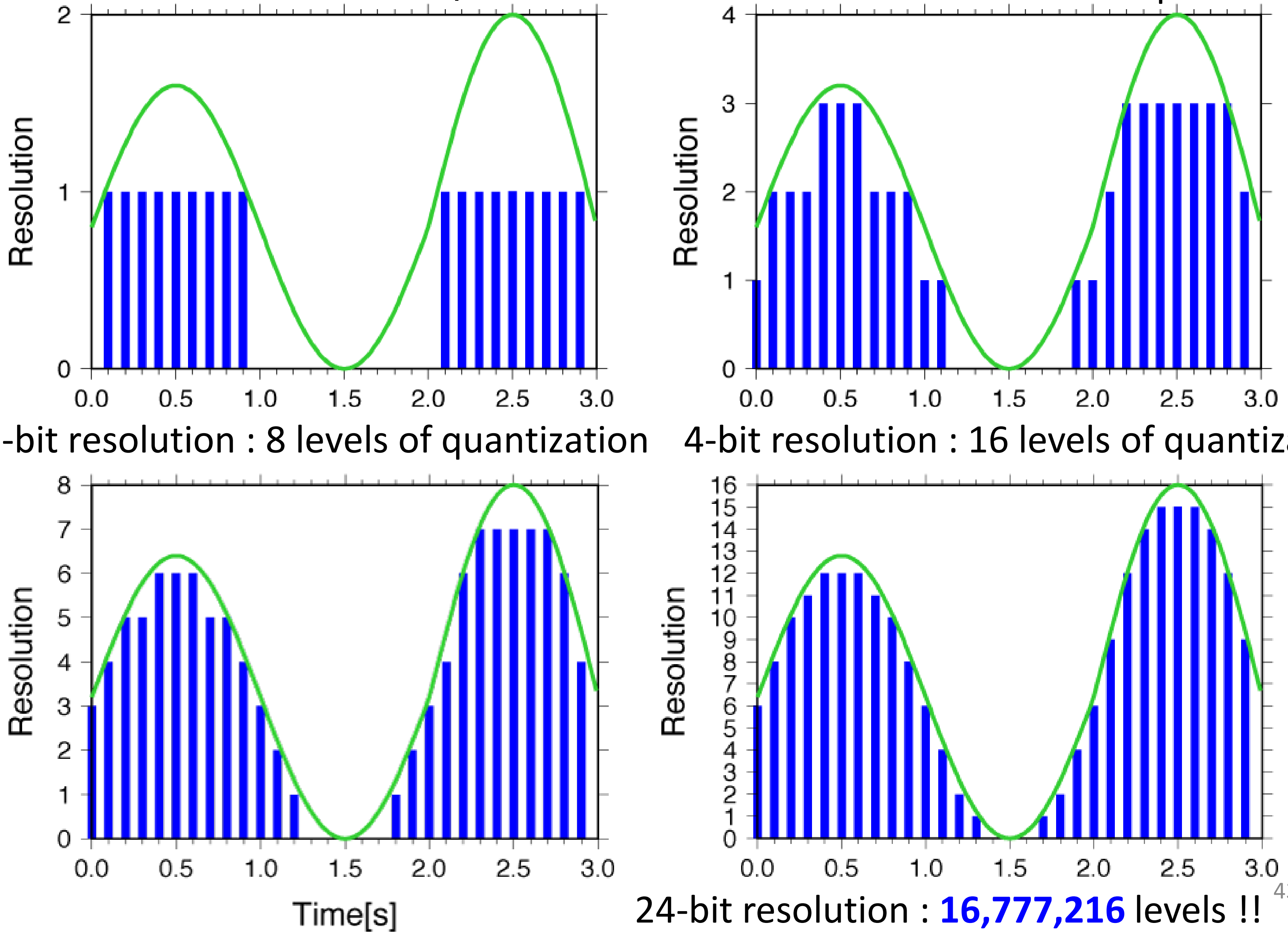
＊Digitizer resolution

1-bit resolution : 2 levels of quantization

2-bit resolution : 4 levels of quantization

3-bit resolution : 8 levels of quantization

4-bit resolution : 16 levels of quantization



24-bit resolution : **16,777,216** levels !!

(b) Unit conversion with a response file

Normalizing Factor (A0) -0.314
Sensitivity (V/m/s) 804
Normalizing Frequency (Hz) 1.0

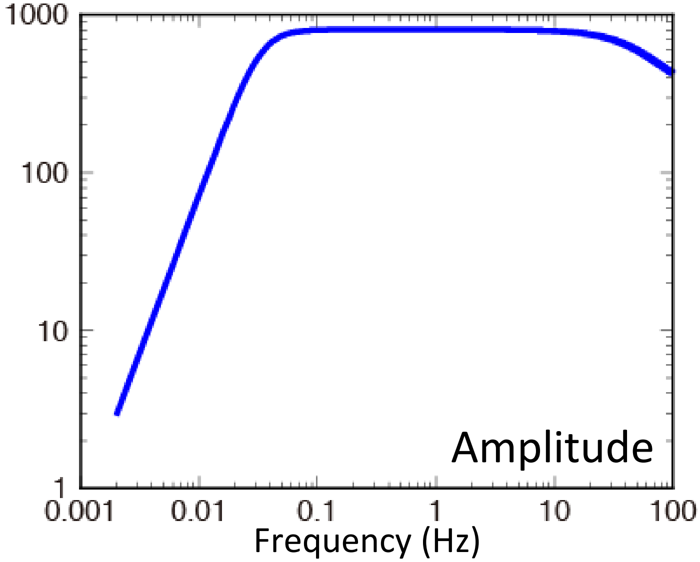
Zeros(rad/sec) 3

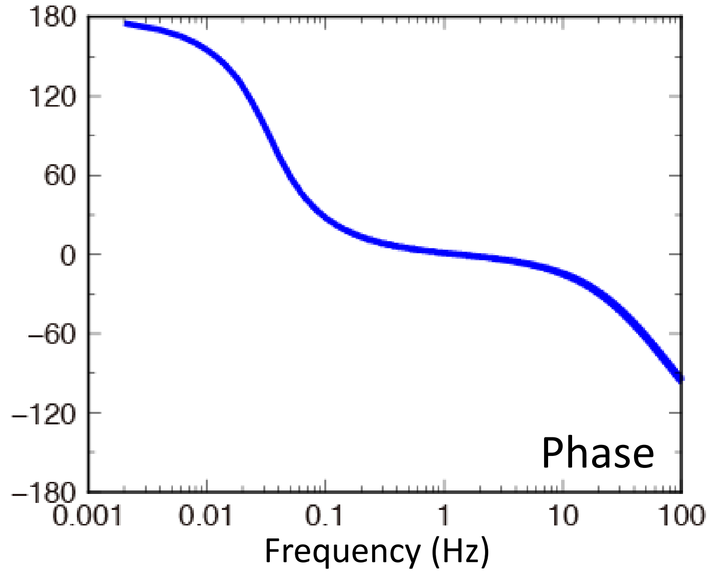
	Real Part	Imaginary Part
0	0.00E+00	0.00E+00
1	0.00E+00	0.00E+00
2	9.99E+02	0.00E+00

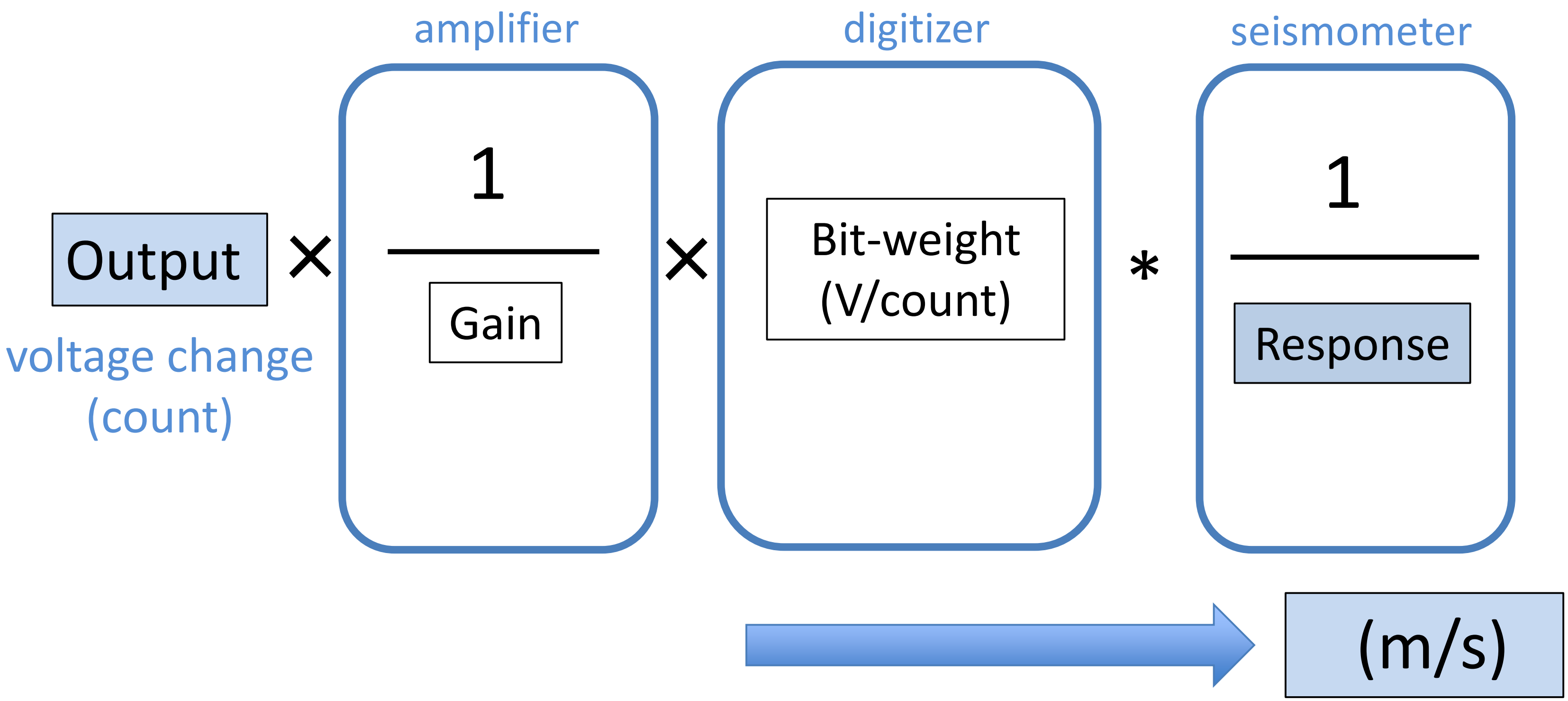
Poles(rad/sec) 3

i	Real Part	Imaginary Part
0	-1.480E-01	1.480E-01
1	-1.480E-01	-1.480E-01
2	-3.140E+02	0.00E+00

For CMG-40T
(Güralp Systems Limited)






Output
voltage change
(count)
×
amplifier
1
Gain
×
digitizer
Bit-weight
(V/count)
*
seismometer
1
Response
(m/s)

6.2 Procedure to apply FFT to given time series
(a) Removal of DC Component and linear trend

When the time series has a DC component or a linear trend, FFT can not estimate Fourier Transform correctly, because of the assumption of periodicity.

Fitting function

$$x_n = at_n + b + r_n$$

t_n: time (n-th data points)
x_n: data at t_n
r_n: residual

Error Function

$$S = \sum_{n=1}^{N} (r_n)^2 = \sum_{n=1}^{N} \left\{ x_n - (at_n + b) \right\}^2$$

Find coefficients *a* and *b* using least square method

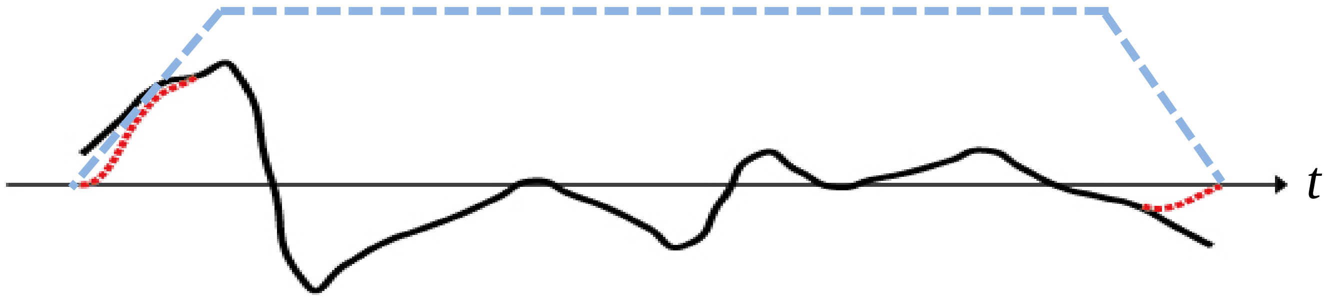
$$\frac{\partial S}{\partial a} = 0, \frac{\partial S}{\partial b} = 0 \Rightarrow \begin{cases} a\left(\sum_{n=1}^{N} n^2\right)\Delta t + b\left(\sum_{n=1}^{N} n\right) = \sum_{n=1}^{N}(nx_n) \\ a\left(\sum_{n=1}^{N} n\right)\Delta t + bN = \sum_{n=1}^{N} x_n \end{cases}$$

(b) Tapering or Windowing

Usually a time series starts with an actual value (≠0) and ends with another value (≠0).

→ This causes unexpected jump or step (bad influence) due to the implicit assumption of periodicity by FFT

A way to prevent for this artificial effect is tapering or windowing that makes the time series start with zero and end with zero.



(c) Zero Padding

FFT has its efficiency when the number of data *N* is 2^n (n: integer)
When the number of the data points is less than 2^n, zeros must be padded up to the nearest 2^n.

6.3 Plotting waveforms using SAC

1. Start SAC in earth2 server

```
% sac

 SEISMIC ANALYSIS CODE [06/08/2007 (Version 101.0)]
 Copyright 1995 Regents of the University of California
```

2. Type as follows

```
SAC> qdp off                  <-  Avoids 'quick and dirty plot'
SAC> r (SAC file name)        <-  Reads data file
SAC> bd x                     <-  Sets output device (x:window)
SAC> p                        <-  Plots time series
```

In the above case, one trace is shown in a window.

```
SAC> r (SAC file name) (SAC file name) (SAC file name)
SAC> p1
```

In the above case, multi traces are shown in a window.

3. Other useful commands

`SAC> bp bu co 0.01 0.5` *<- Applies bandpass filter (Butterworth filter)*

`SAC> hp bu co 1.0` *<- Applies highpass filter (Butterworth filter)*

`SAC> lp bu co 0.5` *<- Applies lowpass filter (Butterworth filter)*

`SAC> xlim 10 20` *<- Determines the plot limits for the x axis.*

`SAC> ylim all` *<- Scales y limits to the minimum and maximum of all files in memory.*

```
SAC> rmean
SAC> int t
```

<- Performs integration using the trapezoidal rule. (acceleration -> velocity)

```
SAC> rmean
SAC> dif
```

<- Differentiates data in memory. (velocity -> acceleration)

6.4 Plotting Fourier spectrum using SAC

Start SAC and type as follows

```
% sac

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SAC> qdp off
SAC> cut 0 819.15                      <-  Defines how much of a data
SAC> r (SAC file name)                     file is to be read (power of 2).
SAC> cut off
SAC> rmean                             <-  Removes the DC component
SAC> rtrend                            <-  Removes the linear trend
SAC> taper type cosine width 0.1       <-  Applies a symmetric taper.
SAC> fft                               <-  FFT
SAC> psp am                            <-  Plots amplitude spectrum
```

If you want to create a spectral files (amplitude and phase spectra), please type as follows.

```
SAC> wsp
```

.> (SAC file name).am and (SAC file name).ph will be created

```
SAC> r (SAC file name).am
SAC> loglog
SAC> xlim 0.001 50
SAC> p
```

In the above case, one trace is shown in a window.

```
SAC> r (SAC file name).am (SAC file name).am …
SAC> p1
```

In the above case, traces are shown separately in a window.

```
SAC> r (SAC file name).am (SAC file name).am …
SAC> p2
```

In the above case, traces are shown on top of each other.

```
SAC> color red inc
```

In the above case, traces are shown on top of each other in different colors.

6.5 Calculation of PSD for broadband station

- IU.ANMO.00.BH1.M.SACdata (SAC format, NS comp.)
- IU.ANMO.00.BH2.M.SACdata (SAC format, EW comp.)
- IU.ANMO.00.BHZ.M.SAC data (SAC format, UD comp.)

- SAC_PZs_ANMO.BH1 polezero file (NS comp.)
- SAC_PZs_ANMO.BH2 polezero file (EW comp.)
- SAC_PZs_ANMO.BHZ polezero file (US comp.)

- noise.dat numerical data of NLNM and NHNM

- calpsd.f90 Fortran90 program to calculate PSD
- plotpsd Gnuplot script to plot power spectral density

Compilation

```
$ gfortran -o calpsd.exe calpsd.f90 /usr/local/sac/lib/sacio.a
```

```
$ sac

 SEISMIC ANALYSIS CODE [06/08/2007 (Version 101.0)]
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SAC> qdp off
SAC> r IU.ANMO.00.BH1.M.SAC
SAC> p                              ←  Plot 1-hour waveform
SAC> cut 100 919.15                 ←  Select time window (T=819.2 s)
SAC> r ANMO.BHZ                     ←  Read file again
SAC> cut off
SAC> rmean                          ←  Removes the DC component
SAC> rtrend                         ←  Removes the linear trend
SAC> transfer from polezero s ANMO.BHZ to vel freq 0.01 0.02 8 9
SAC> rmean                          ↑  Remove instrumental response
SAC> rtrend
SAC> w vel.sac
SAC> q                              ←  Save file


$ ./calpsd.exe
$ gnuplot plotpsd                   ←  A postscript file "psd.ps" will be generated.
```

Report subject

(1) Investigate noise levels of IRIS stations using MUSTANG (http://service.iris.edu/mustang/)

- at two different sites (island, continent, coast, etc.)
- for three-component broadband seismometers
- for different seasons (e.g. winter and summer)
- plot probability density functions for 1 week data

(2) Compute power spectral densities of observed noise data in Tsukuba (on February 1).

- for three-component long-period seismometer
- for three-component NIED broadband data

* You can get SAC format data from a file server
file:¥¥catfish¥share¥lecture¥hayasida¥noisesurvey¥

MUSTANG data quality metrics web service (by IRIS)

(Source: http://service.iris.edu/mustang/)

INCORPORATED RESEARCH INSTITUTIONS FOR SEISMOLOGY

DMC Home

WebServices Home / MUSTANG

IRIS DMC Web Services

Services implementation: MUSTANG

Introduction

*Welcome to the **MUSTANG** data quality metrics web service home page.* MUSTANG has six service interfaces described in the request tools table below, each returning different information related to data quality. Each of the service links can be navigated to for more specific information and usage examples. If you scroll down past the table on this page, you will find a general overview of MUSTANG and contact information.

You can also visit our Quality Assurance home page to get the scoop on how we are using MUSTANG and the processes we use to analyze the quality of the data we receive. In addition to general quality assurance information, you can find MUSTANG tutorials here.

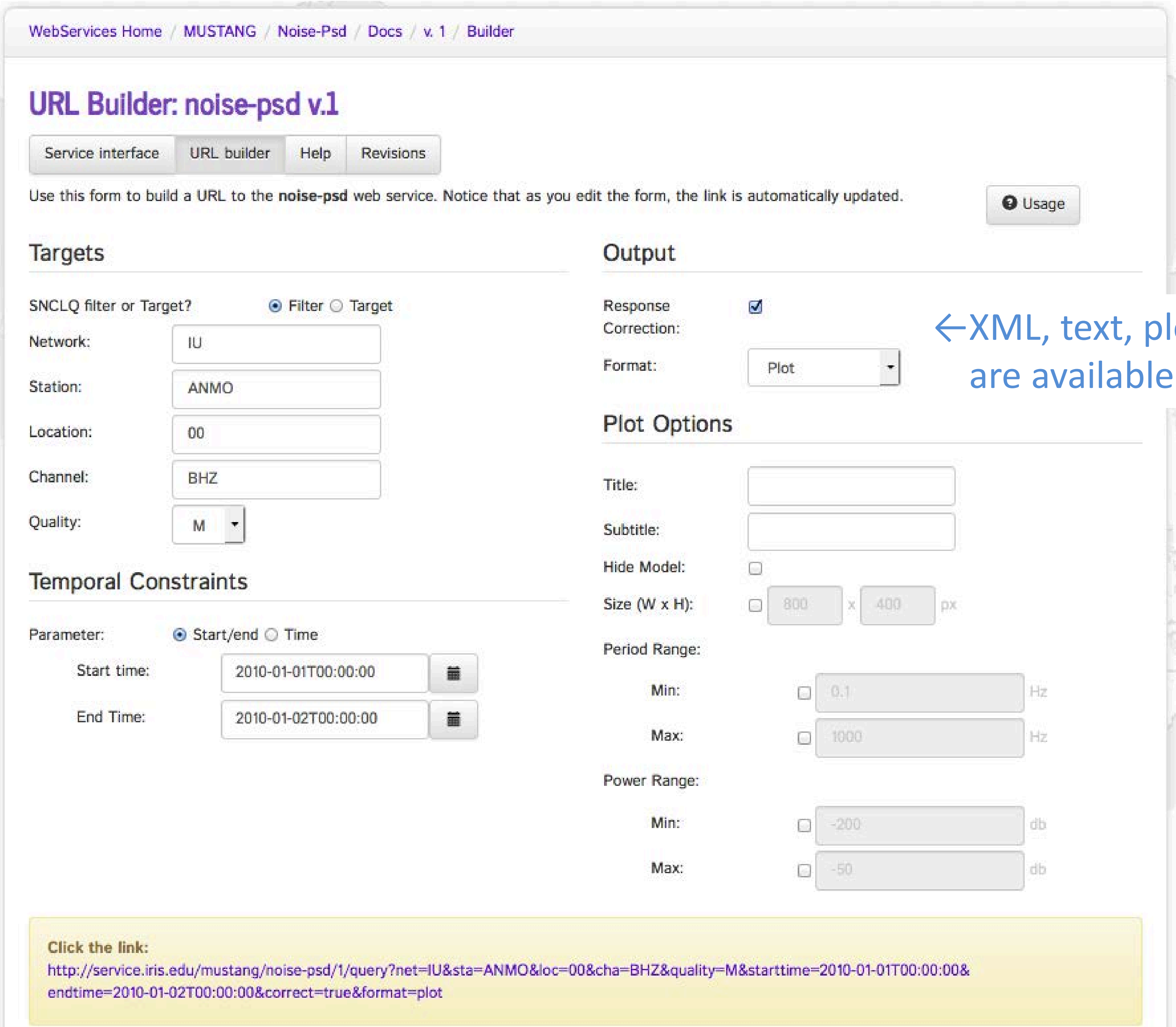
Metrics values are calculated on a daily basis and new features are being added. Feedback from users is appreciated.

Request tools

Service interface	Version	Summary	Return options
measurements	v.1	The main MUSTANG web service returning measurements for metrics relating to station data quality.	• XML (default) • text • CSV • JSON • JSONP
noise-psd	v.1	Returns Power Spectral Density estimates of seismic data and can generate aggregate plots.	• Text – CSV • XML • Plot (PNG)
noise-pdf	v.1	Returns Probability Density Functions in frequency \`bins\` and can generate aggregate plots.	• Text – CSV • XML • Plot (PNG)
noise-mode-timeseries	v.1	Returns PDF Mode Timelines at select frequencies and can generate plots.	• Text – CSV • XML • Plot (PNG)
metrics	v.1	The metrics web service returns a description of available metrics in a variety of formats	• XML • HTML • XSD • JSON

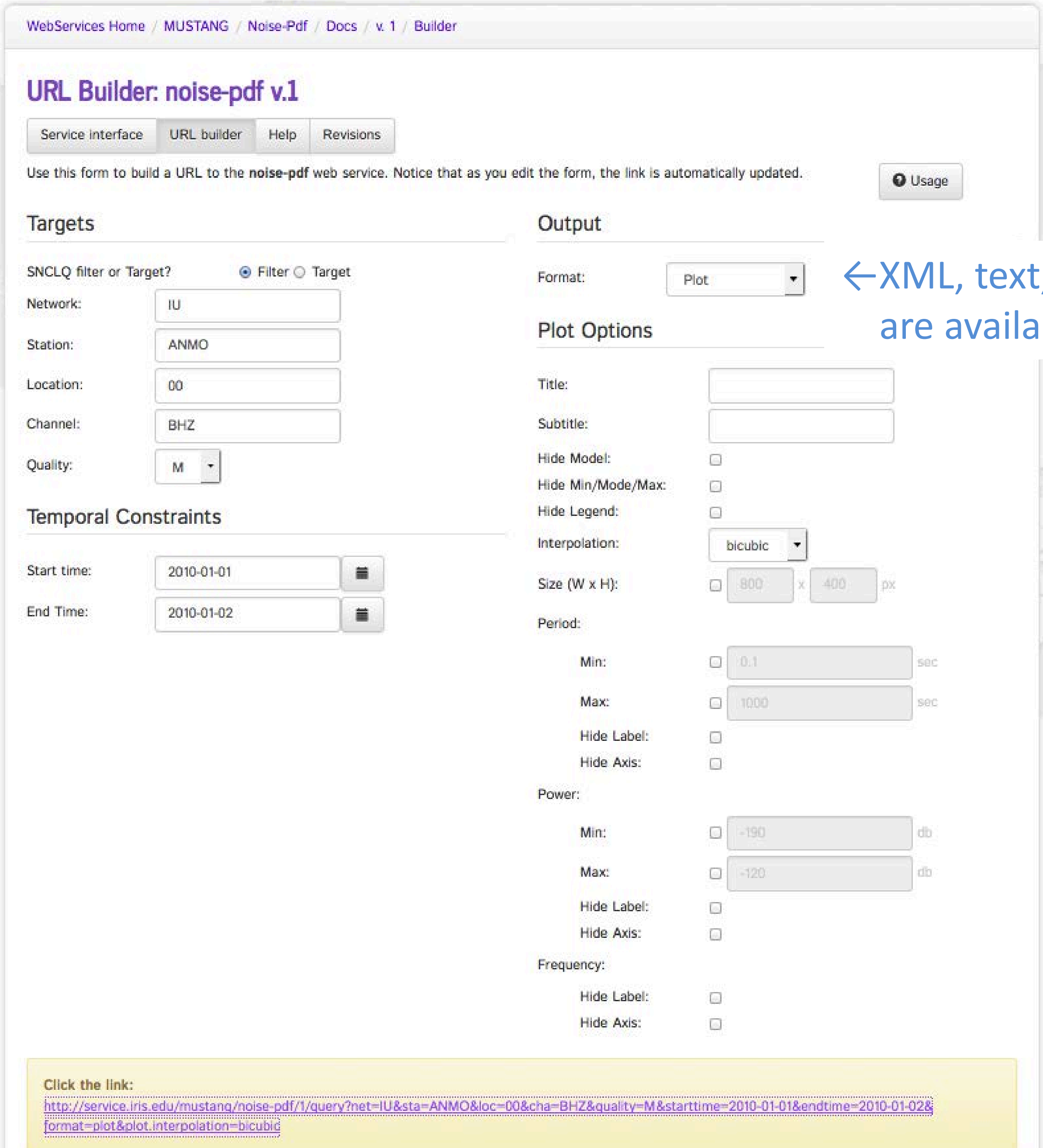
noise-psd (traces of power spectral densities)

(Source: http://service.iris.edu/mustang/noise-psd/docs/1/builder/)



←XML, text, plot (PNG image) are available

noise-pdf (probability density function) (Source: http://service.iris.edu/mustang/noise-pdf/docs/1/builder/)



←XML, text, plot (PNG image) are available

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