Long-term monitoring of the STS-2 self-noise: an experiment in the Conrad Observatory, Austria.

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ABSTRACT

At low frequencies (e.g. below 0.1 Hz) in the seismic spectrum the instrumental noise of seismic recording systems increases like in any other active electronic component and may dominate the seismic signal. For any study using low frequency seismic signals it is therefore important to have accurate knowledge about the instrumental noise. Self-noise can be estimated by determining the mutual signal coherency among three similar, collocated instruments. In this presentation we describe an experiment that was conducted for more than 6 months in the Conrad Observatory (Austria) using 4 collocated STS-2 sensors and Q330-HR data-loggers. The Conrad Observatory is a well-equipped, ultra-quiet facility for testing and calibration of seismic instrumentation and acquisition electronics. We investigate the effect of misalignment of sensors and the long-term stability of the sensor self-noise. This research project was grant supported through the EC FP6 project NERIES (Network of Research Infrastructures for European Seismology).
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Key words: self-noise, STS-2, Conrad Observatory, NERIES.

PRESENTER'S BIOGRAPHY

Reinoud Sleeman is seismologist at the Royal Netherlands Meteorological Institute (KNMI) and Director of the ORFEUS Data Center. His interest for seismic recording systems, seismic data and signal processing has lead to a new technique to measure instrumental self-noise based on 3-channel coherency analysis. Results of this technique, which is applied on 3 STS-2 sensors, are presented during the IASPEI General Assembly 2009, Cape Town.

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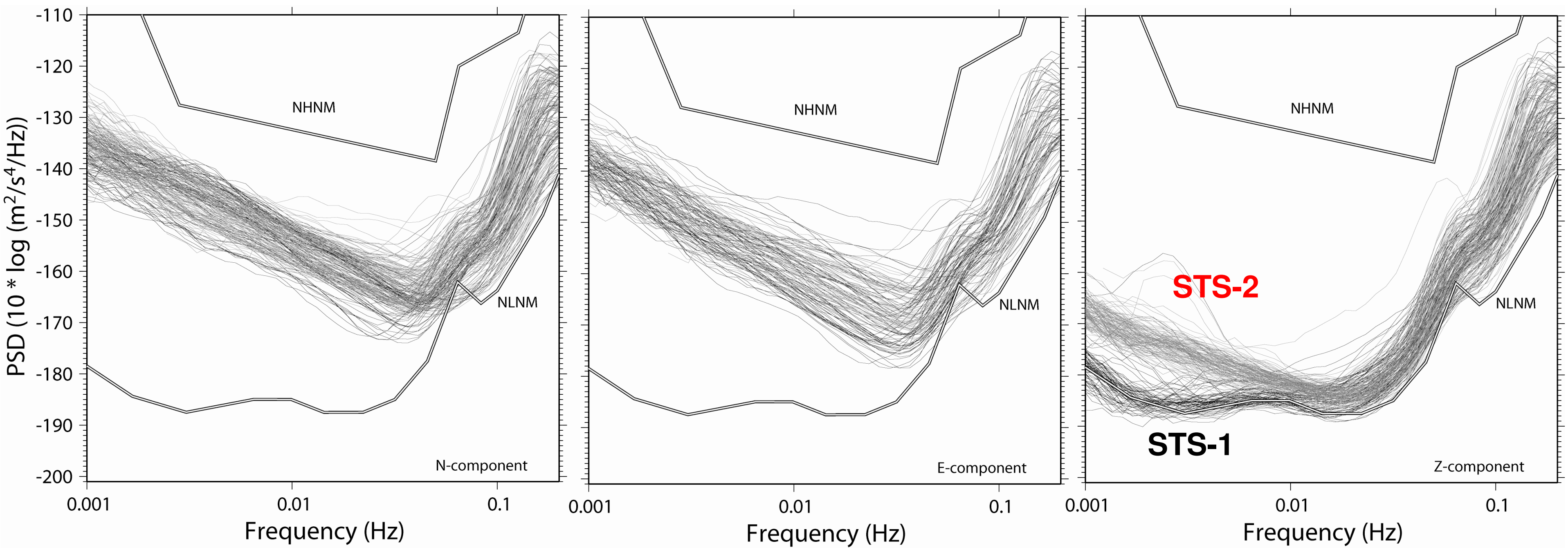
- Introduction and motivation
- Side-by-side correlation technique (2 channels, 3 channels)
- PSD estimate and representation
- Synthetic experiments: exploring the triplet technique
- Potential source of error: sensor mis-alignment
- Initial real experiments, choice of digitizer
- Conrad experiment
- Results
- Conclusions and recommendations

Seismic background noise (m/s^2) power spectral density measured at seismic station Heimansgroeve (HGN), Netherlands during 2002: 302- 309 and 2003: 029 - 043

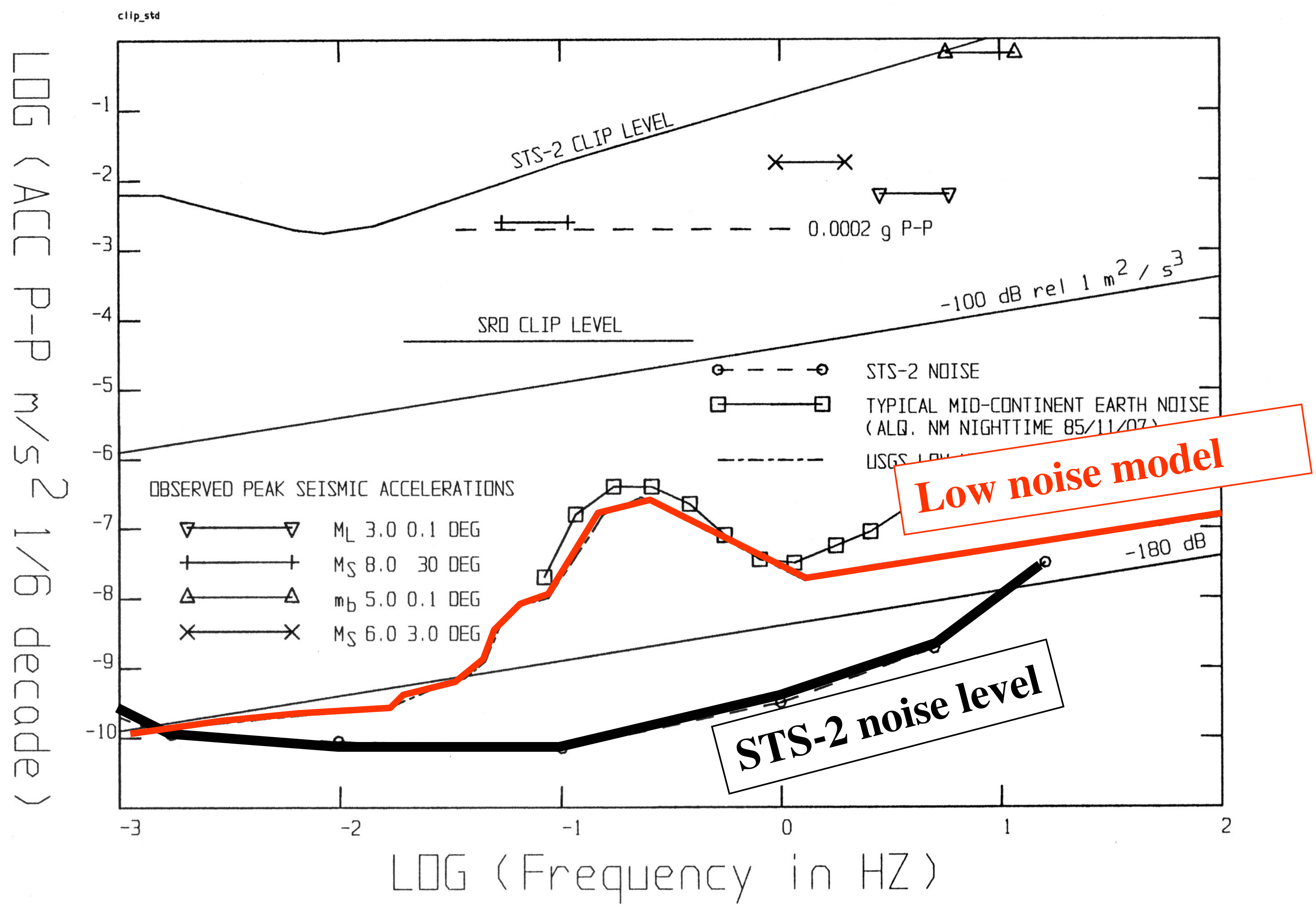


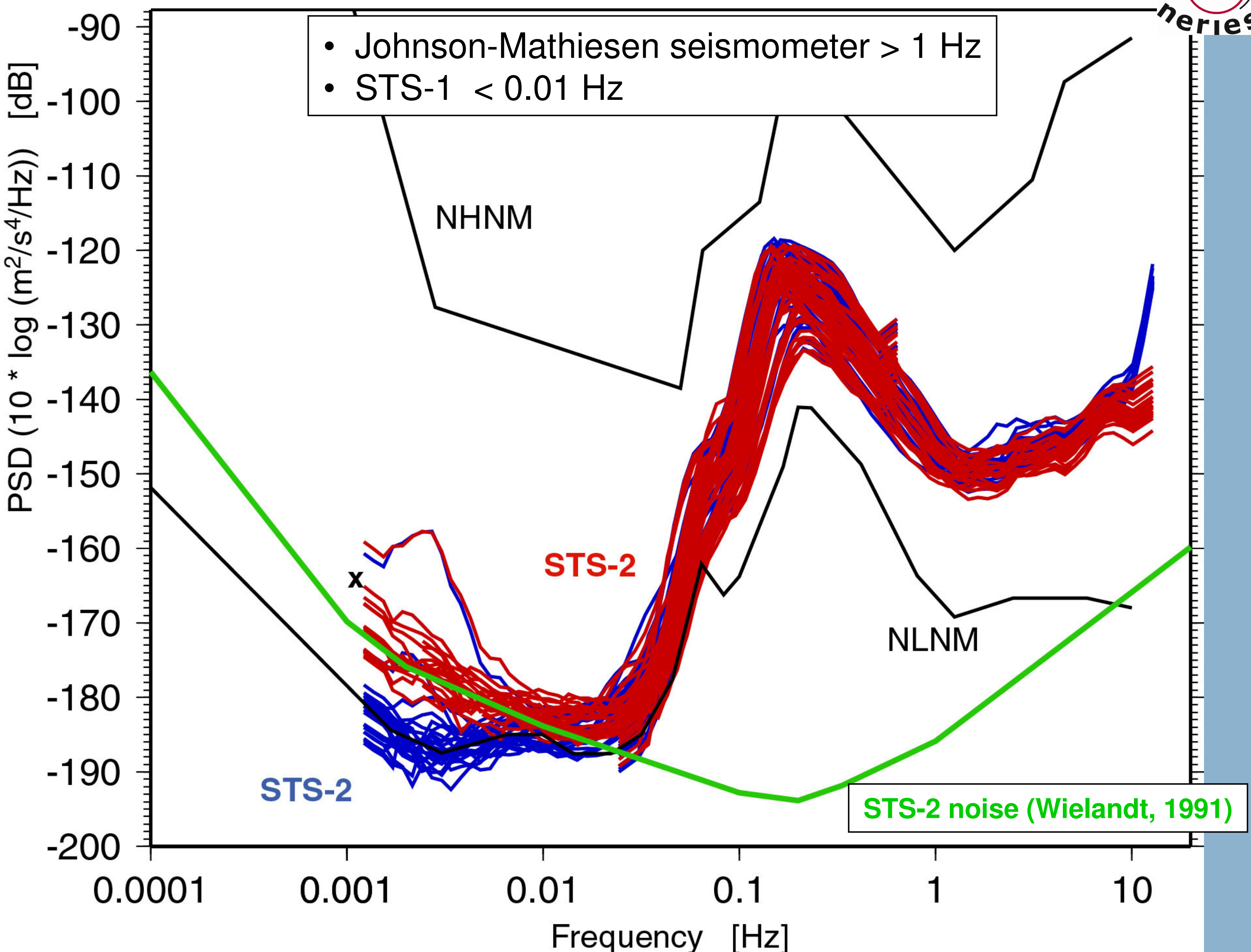
N-S

E-W

Z

from: STS-2 manual





• Johnson-Mathiesen seismometer > 1 Hz
• STS-1 < 0.01 Hz
NHNM
NLNM
STS-2
x
STS-2
STS-2 noise (Wielandt, 1991)
PSD (10 * log (m²/s⁴/Hz)) [dB]
-90
-100
-110
-120
-130
-140
-150
-160
-170
-180
-190
-200
0.0001
0.001
0.01
0.1
1
10
Frequency [Hz]

Motivation for determining instrumental noise:

- bias of data by the recording system
- selection of instrumentation
- improving installation conditions

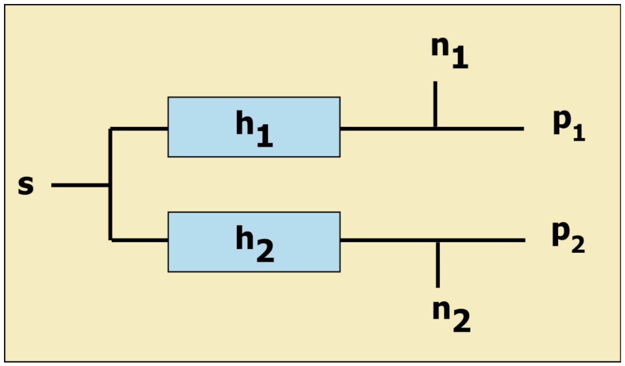
How to determine instrumental noise of digitizers or seismic sensors ?

- digitizer: shorted input recording (e.g. 50 ohm resistor)
- sensor: common input recording (side by side test)
  - coherency analysis of 2 channels (Holcomb, 1989)
  - coherency analysis of 3 channels - triplet (Sleeman et. al., 2006)

Holcomb, L. G., A direct method for calculating instrument noise levels in side-by-side seismometer evaluations.
U.S. Geol. Surv., Open-File Report 89-214 (1989)

Sleeman, R., A. van Wettum and J. Trampert. Three-channel correlation analysis: a new technique to measure instrumental noise of digitizers and seismic sensors.
Bull. Seism. Soc. Am., 96, 1, 258-271 (2006)

Conventional 2-channel correlation



$$p_1 = h_1 \otimes s + n_1$$ time domain

$$P_1 = H_1 \cdot S + N_1$$ frequency domain

notation: $N_{ij} = N_i \, N_j^*$ $\quad P_{11} = P_1 \, P_1^*$

$P_{ss} = S \, S^*$

assumptions: $N_{ij} = 0$ $\quad S \cdot N_i = 0$

$$P_{11} = P_{ss} \cdot H_1 H_1^* + N_{11}$$

$$P_{22} = P_{ss} \cdot H_2 H_2^* + N_{22}$$

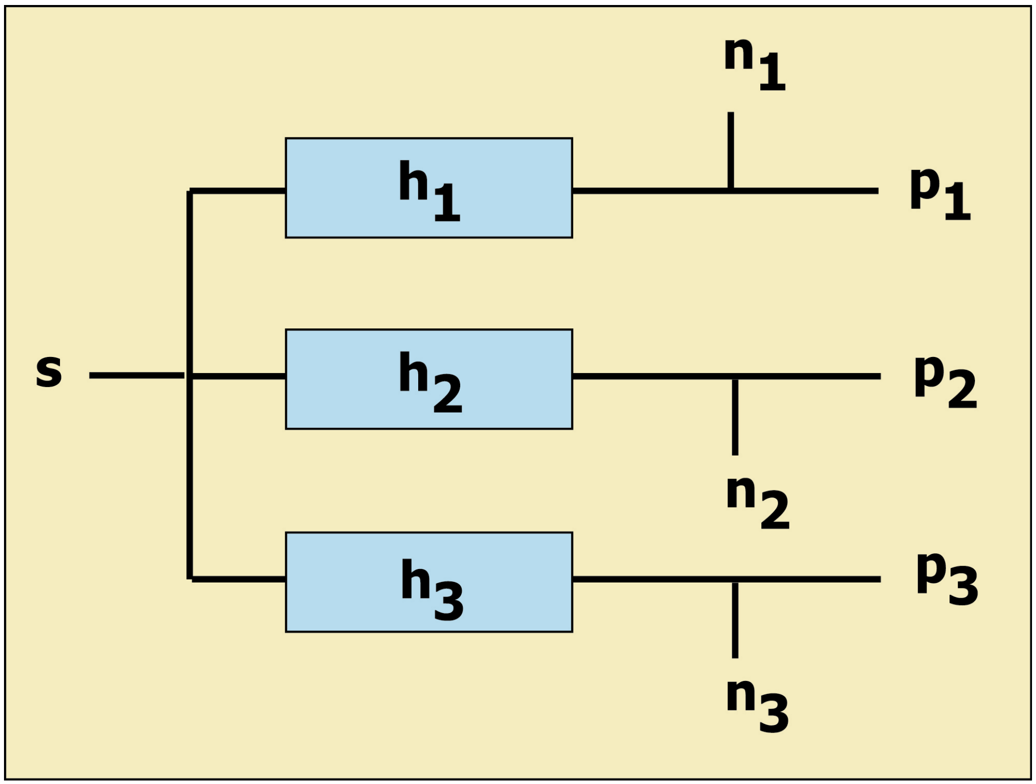
$$P_{12} = P_{ss} \cdot H_1 H_2^*$$

→

$$N_{11} = P_{11} - P_{12} \cdot \frac{H_1^*}{H_2^*}$$

$$N_{22} = P_{22} - P_{12} \cdot \frac{H_2}{H_1}$$

a better approach: 3-channel correlation



$$P_1 = H_1 \cdot S + N_1$$

$$P_2 = H_2 \cdot S + N_2$$

$$P_3 = H_3 \cdot S + N_3$$

Model equations

$$P_{11} = P_{ss} \cdot H_1 H_1^* + N_{11}$$
$$P_{22} = P_{ss} \cdot H_2 H_2^* + N_{22}$$
$$P_{33} = P_{ss} \cdot H_3 H_3^* + N_{33}$$

assumptions: $N_{ij} = 0$ $S \cdot N_i = 0$

$$P_{12} = P_{ss} \cdot H_1 H_2^*$$
$$P_{21} = P_{ss} \cdot H_2 H_1^*$$
$$P_{13} = P_{ss} \cdot H_1 H_3^*$$
$$P_{31} = P_{ss} \cdot H_3 H_1^*$$
$$P_{23} = P_{ss} \cdot H_2 H_3^*$$
$$P_{32} = P_{ss} \cdot H_3 H_2^*$$

→

$$\frac{P_{21}}{P_{31}} = \frac{H_2}{H_3}$$
$$\frac{P_{12}}{P_{32}} = \frac{H_1}{H_3}$$
$$\frac{P_{13}}{P_{23}} = \frac{H_1}{H_2}$$

Relative gains (transfer functions) can be estimated from output cross spectra only !

Model equations

$$P_{11} = P_{ss} \cdot H_1 H_1^* + N_{11}$$
$$P_{22} = P_{ss} \cdot H_2 H_2^* + N_{22}$$
$$P_{33} = P_{ss} \cdot H_3 H_3^* + N_{33}$$

assumptions: $N_{ij} = 0$ $\quad S \cdot N_i = 0$

$$P_{12} = P_{ss} \cdot H_1 H_2^*$$
$$P_{21} = P_{ss} \cdot H_2 H_1^*$$
$$P_{13} = P_{ss} \cdot H_1 H_3^*$$
$$P_{31} = P_{ss} \cdot H_3 H_1^*$$
$$P_{23} = P_{ss} \cdot H_2 H_3^*$$
$$P_{32} = P_{ss} \cdot H_3 H_2^*$$

→

$$N_{11} = P_{11} - \frac{P_{13}}{P_{23}} \cdot P_{21}$$

$$N_{22} = P_{22} - \frac{P_{23}}{P_{13}} \cdot P_{12}$$

$$N_{33} = P_{33} - \frac{P_{32}}{P_{12}} \cdot P_{13}$$

Self-noise PSD can be estimated from output recordings only !

3-channel correlation method (triplet method):

- direct method for estimating system noise and relative transfer functions based on the recordings only

- no *a-priori* information required about transfer functions or their accuracy; method is not sensitive for errors in gain

- reliable technique, up to 120 dB SNR
  no quiet site required (in theory) !

Instrumental self noise is non-deterministic, stochastic signal ⇨
Power Spectral Density

Powers Spectrum Density (PSD) estimation (Welch, 1978)

- 50 % overlapping time sections
- tapering (Hanning window)
- autocorrelation
- Fourier transform
- averaging over the number of time sections
- one-sided PSD (USGS noise models)
- instrument response deconvolution (to acceleration)
- PSD smoothing over 1/10-th of a decade

common input: seismic recording

self noise: white noise (rms = 1)

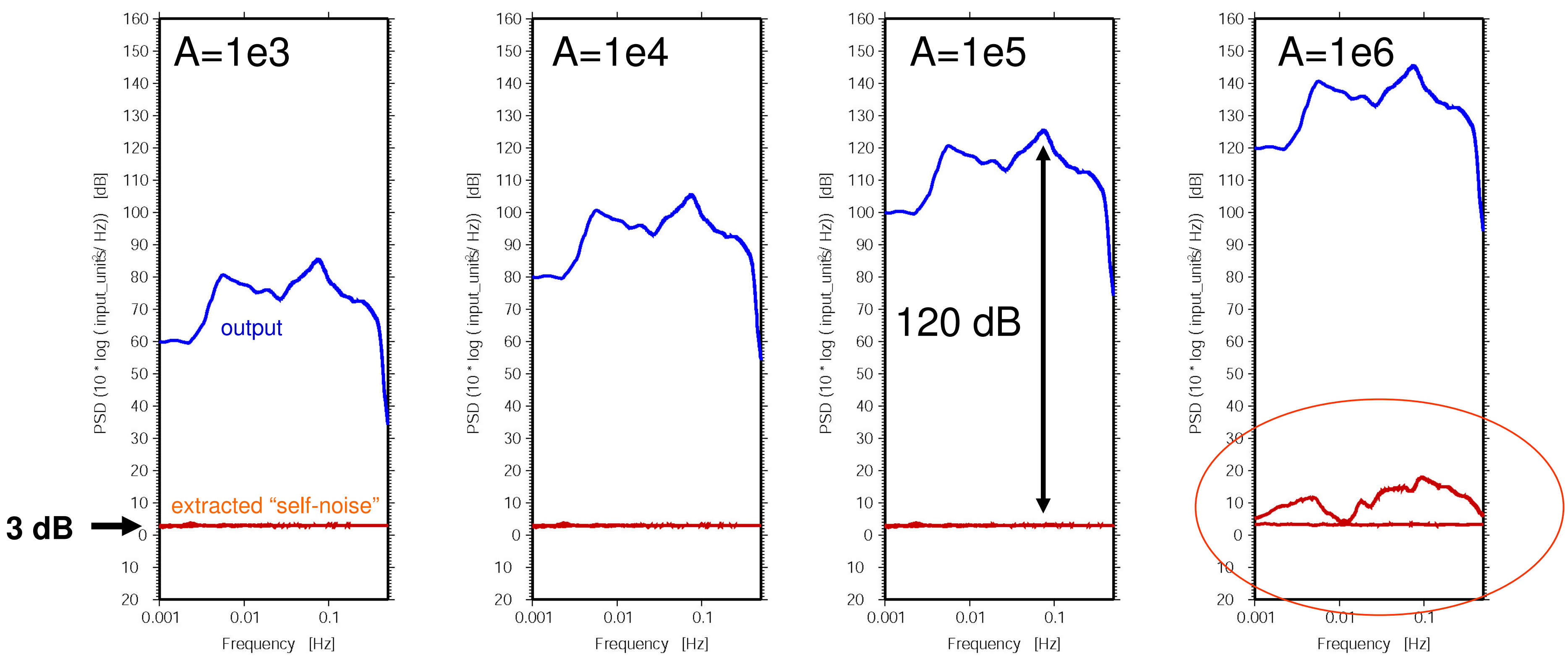
sampling rate: 1 sps

⇨ **theoretical self noise: 3 dB**

output — gain — self noise

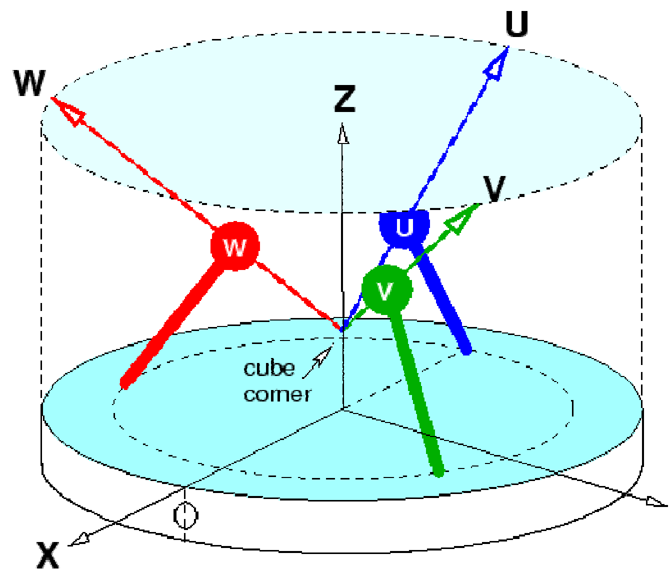
$$y_i = A_i \otimes x + n_i$$

common input



Self noise extraction possible up to about 120 dB SNR !

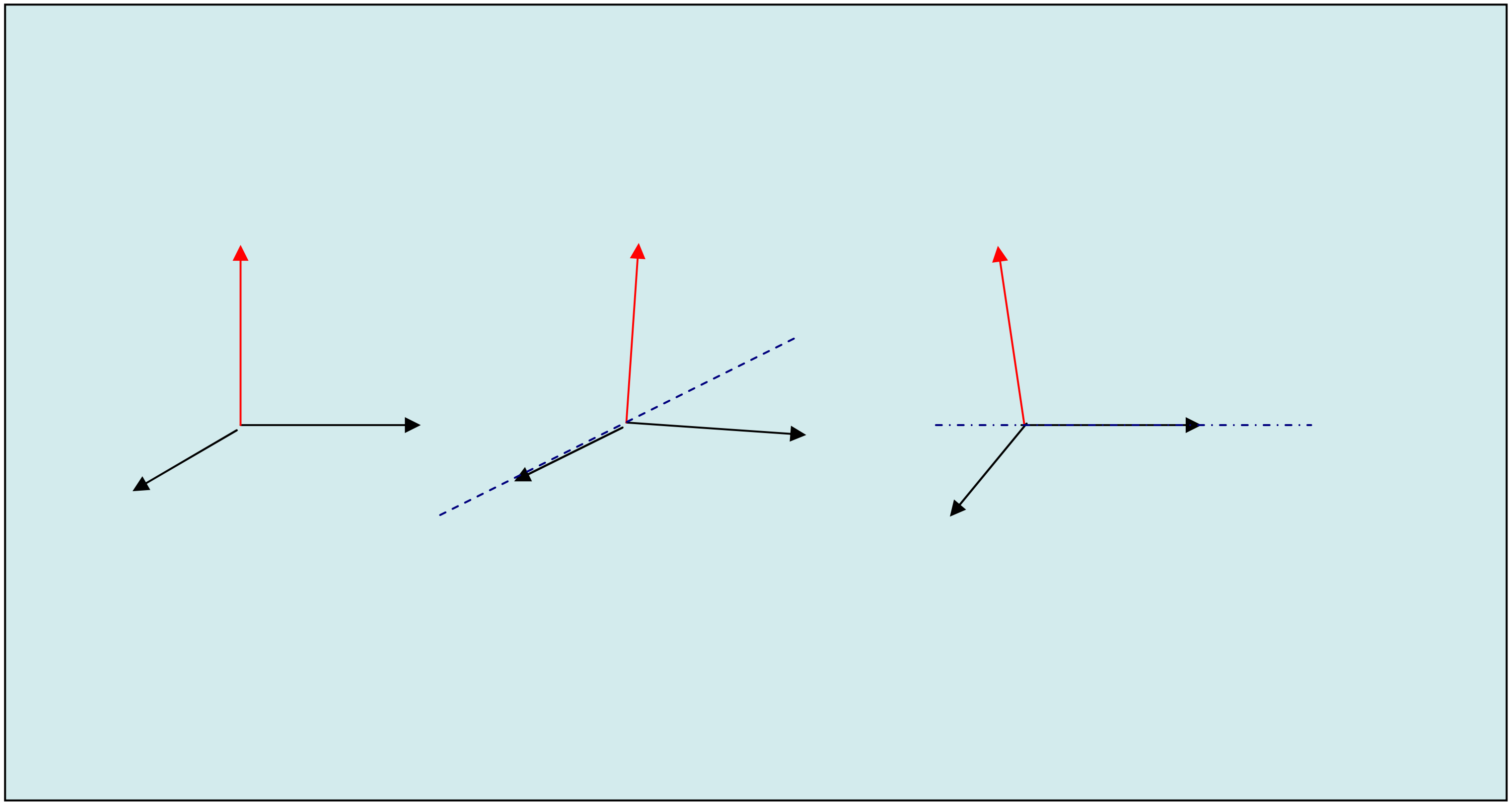
3-channel coherency analysis requires identical alignment and levelling of the 3 sensors



STS-2 sensor

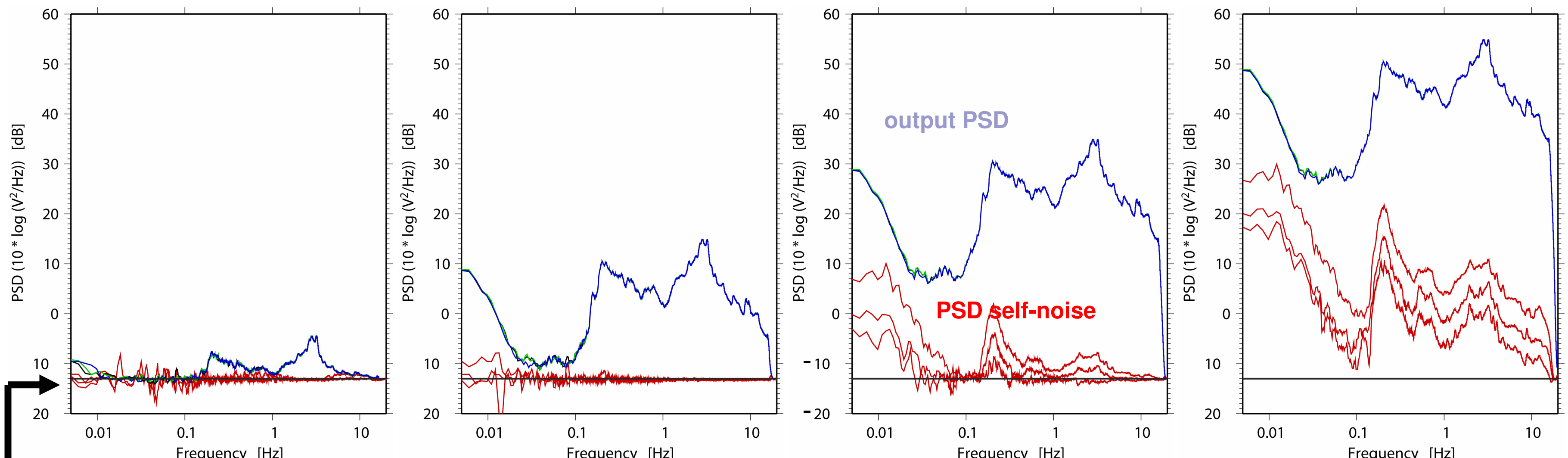
$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \frac{1}{\sqrt{6}} \begin{pmatrix} -2 & 1 & 1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ \sqrt{2} & \sqrt{2} & \sqrt{2} \end{pmatrix} \begin{pmatrix} U \\ V \\ W \end{pmatrix}$$

Synthetic experiment sensors with alignment and/or levelling errors



Sensor misalignment

for small alignment/tilting errors:
self noise extraction possible only up to about ~40-60 dB SNR !



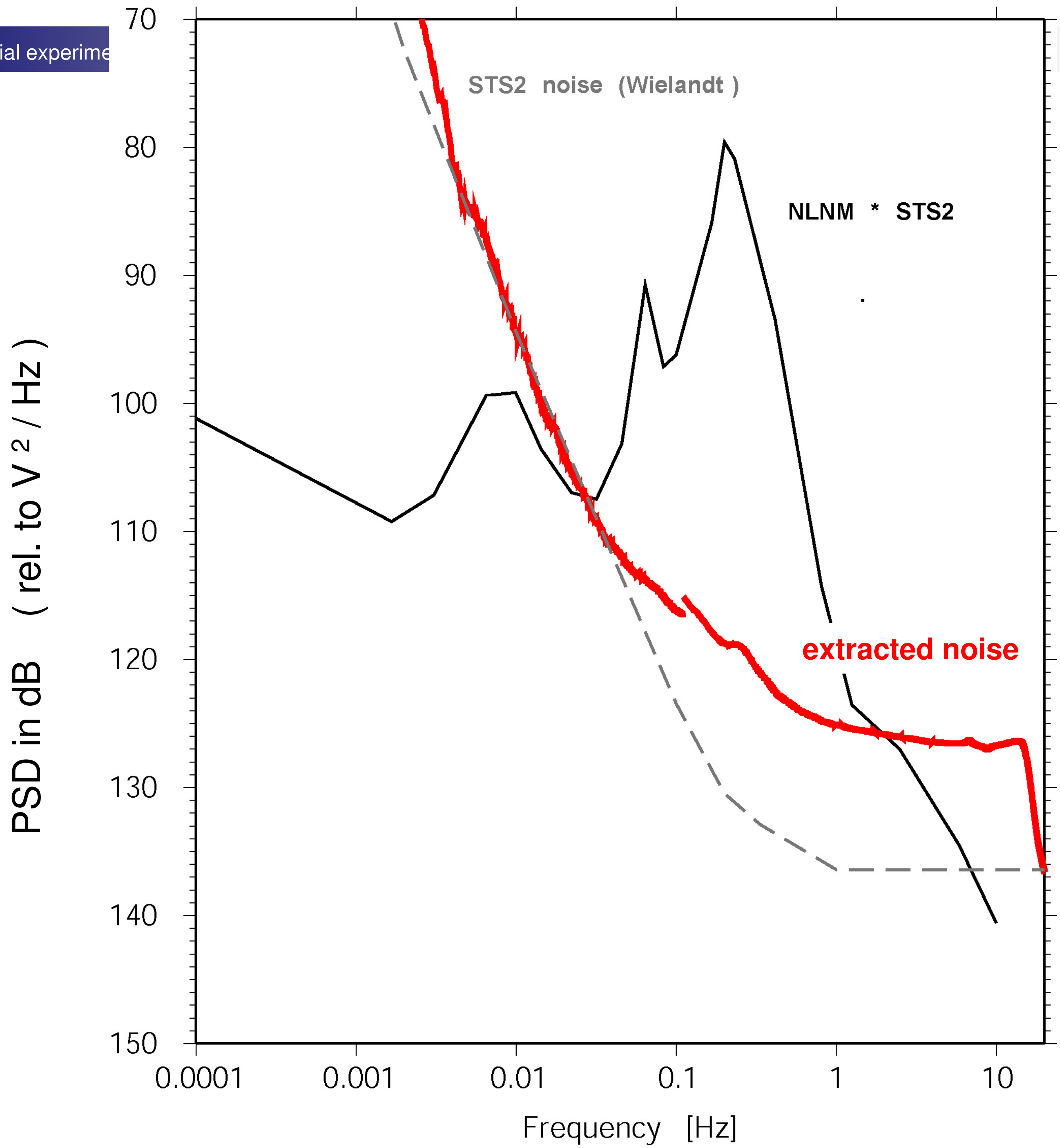
alignment or tilting error (~1^0)

theoretical self-noise

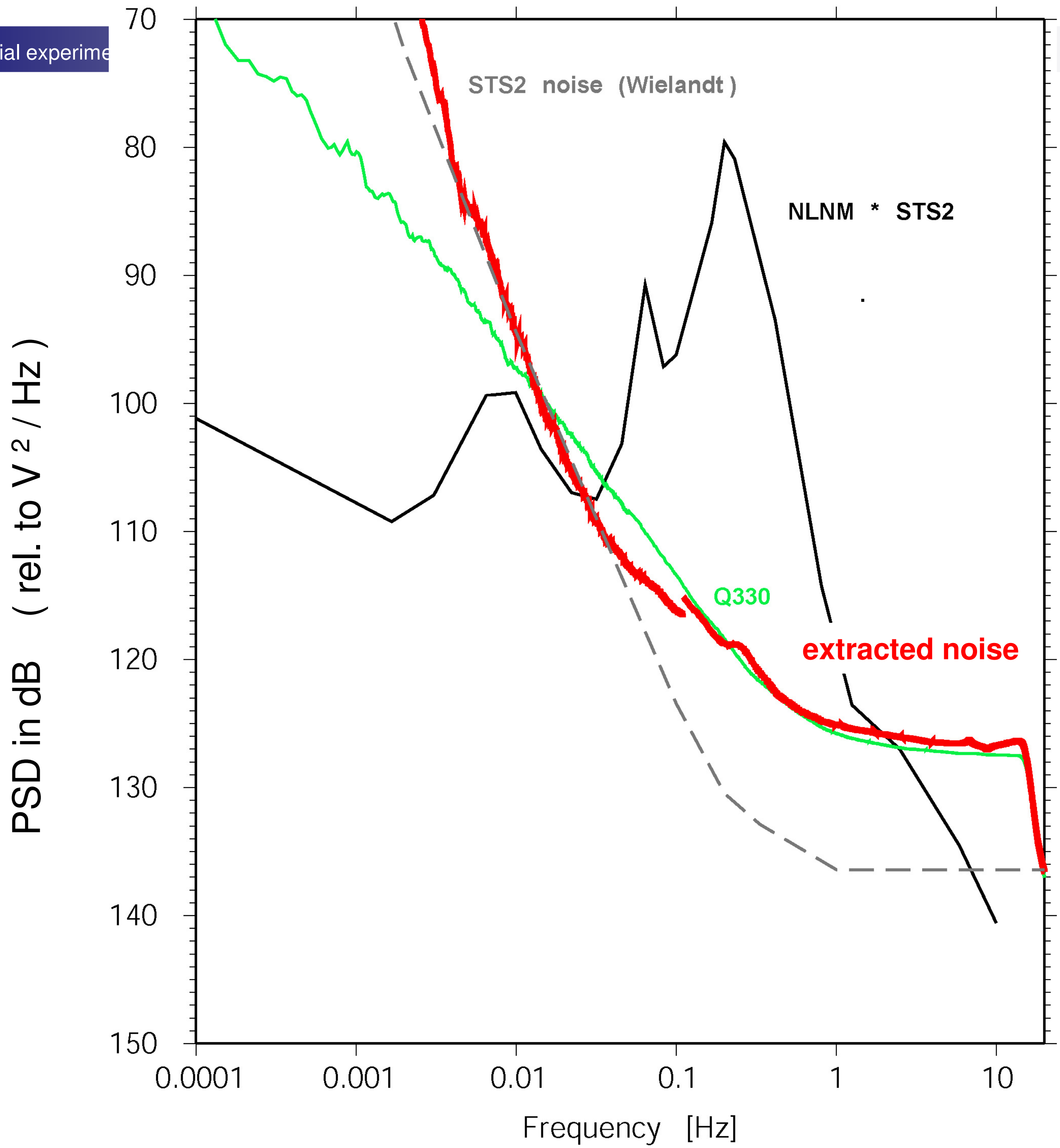
- Initial experiments in De Bilt (KNMI) showed that sites with high background noise levels are not suitable for self-noise measurements, using the 3-channel technique.

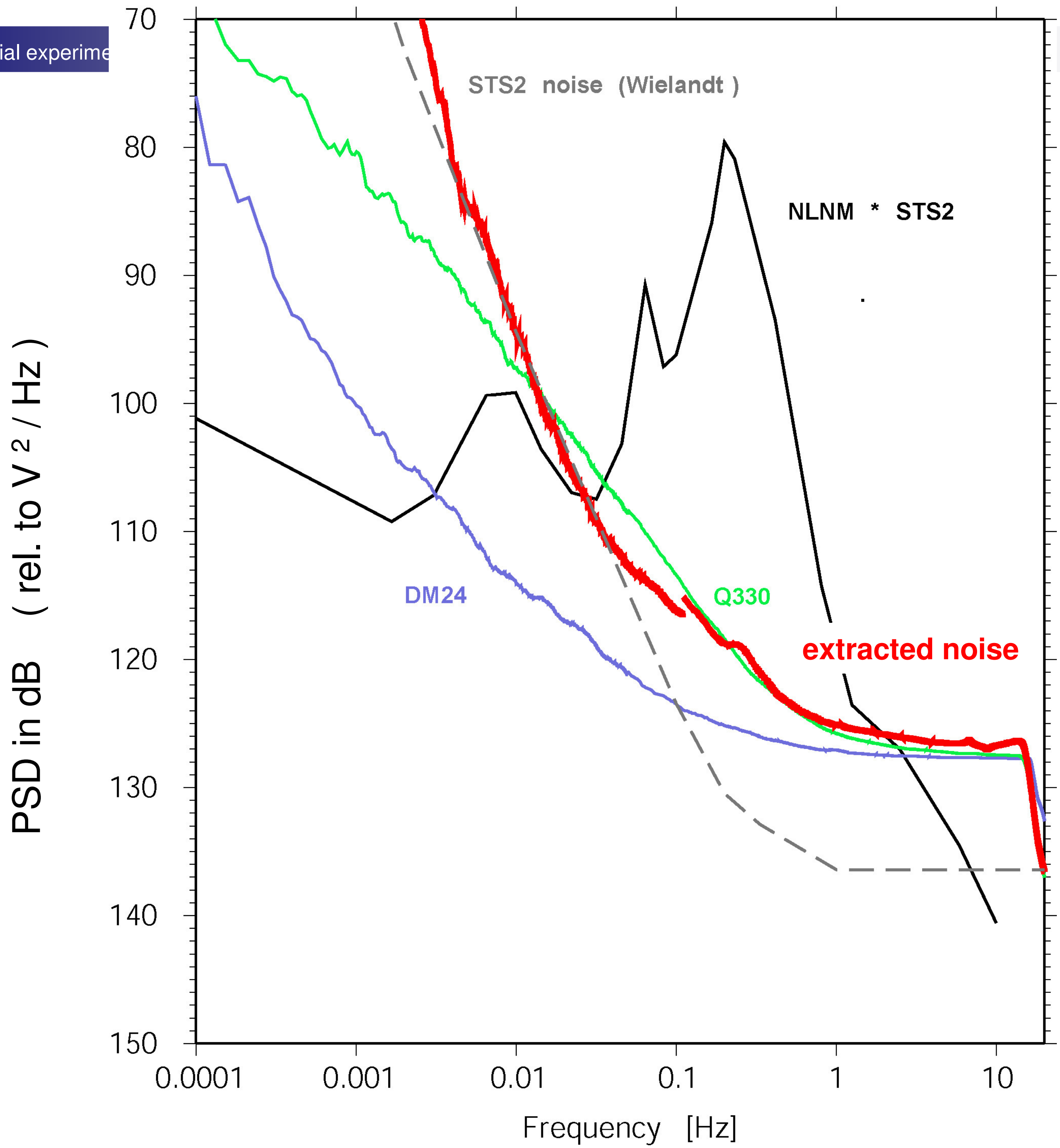
Which datalogger is suitable for measuring the STS-2 self-noise ?

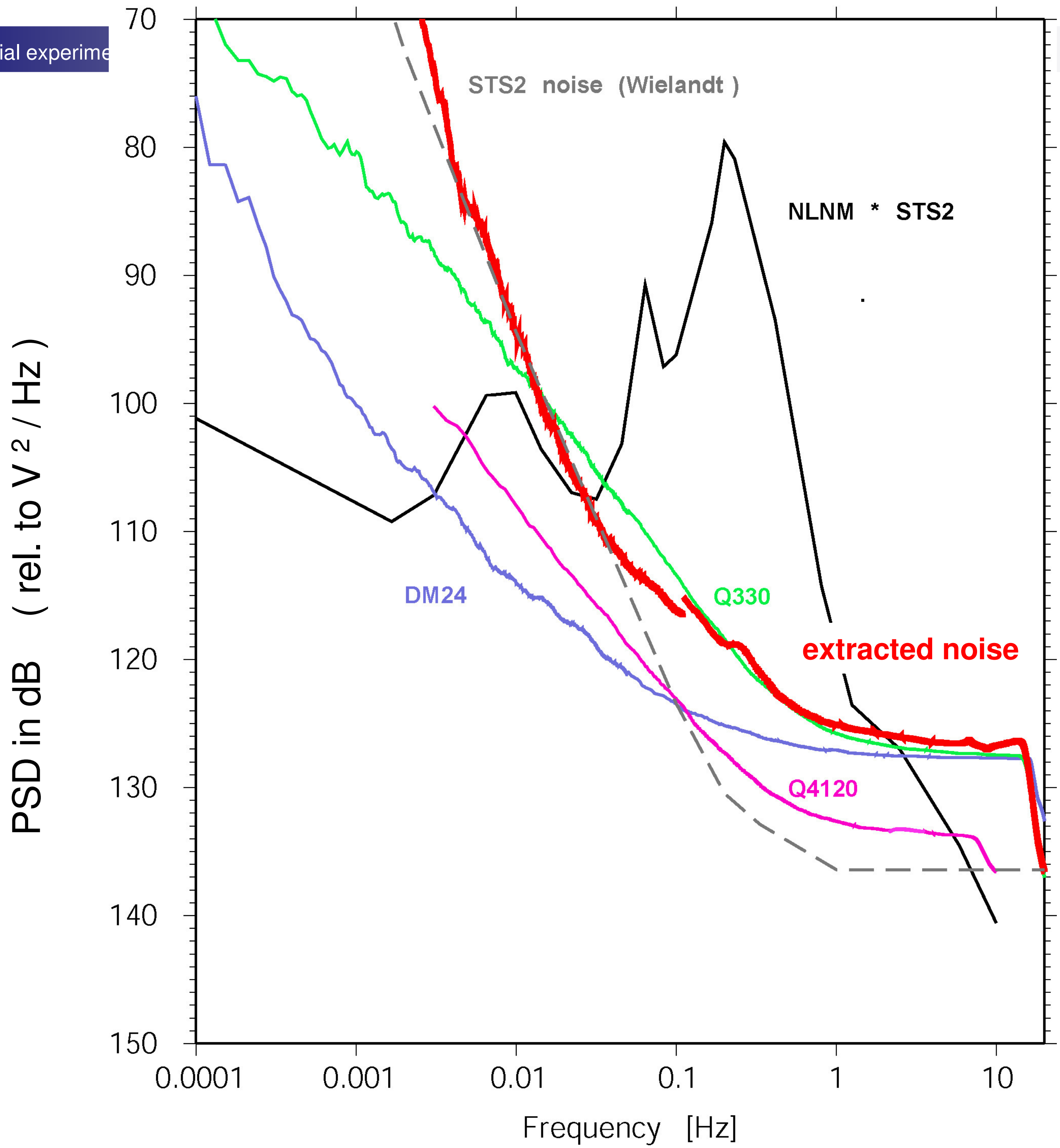
Initial experiment with STS-2 + Q330 dataloggers

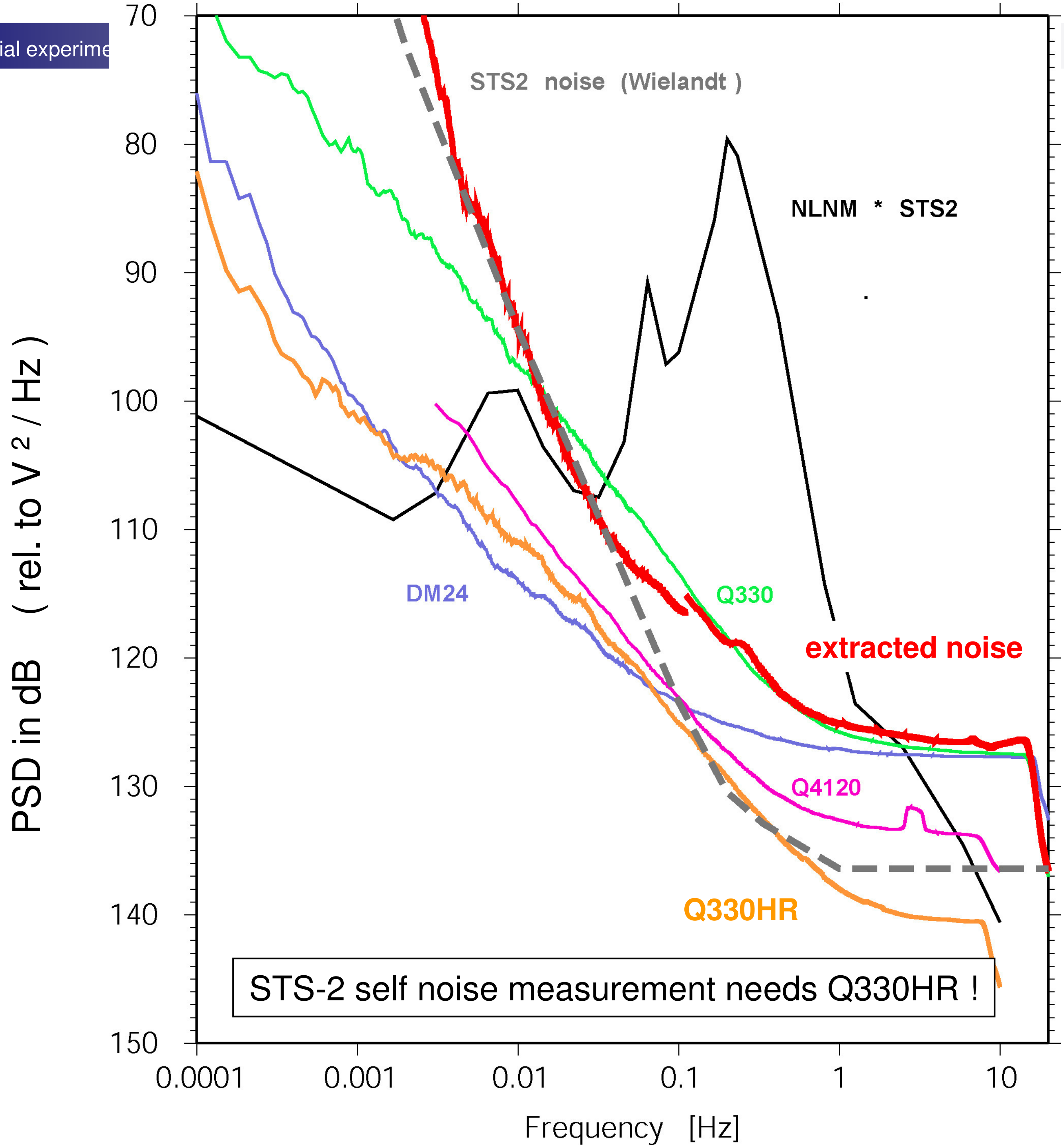

STS2 noise (Wielandt)
NLNM * STS2
extracted noise
PSD in dB (rel. to V 2 / Hz)
Frequency [Hz]
70
80
90
100
110
120
130
140
150
0.0001
0.001
0.01
0.1
1
10

Initial experime



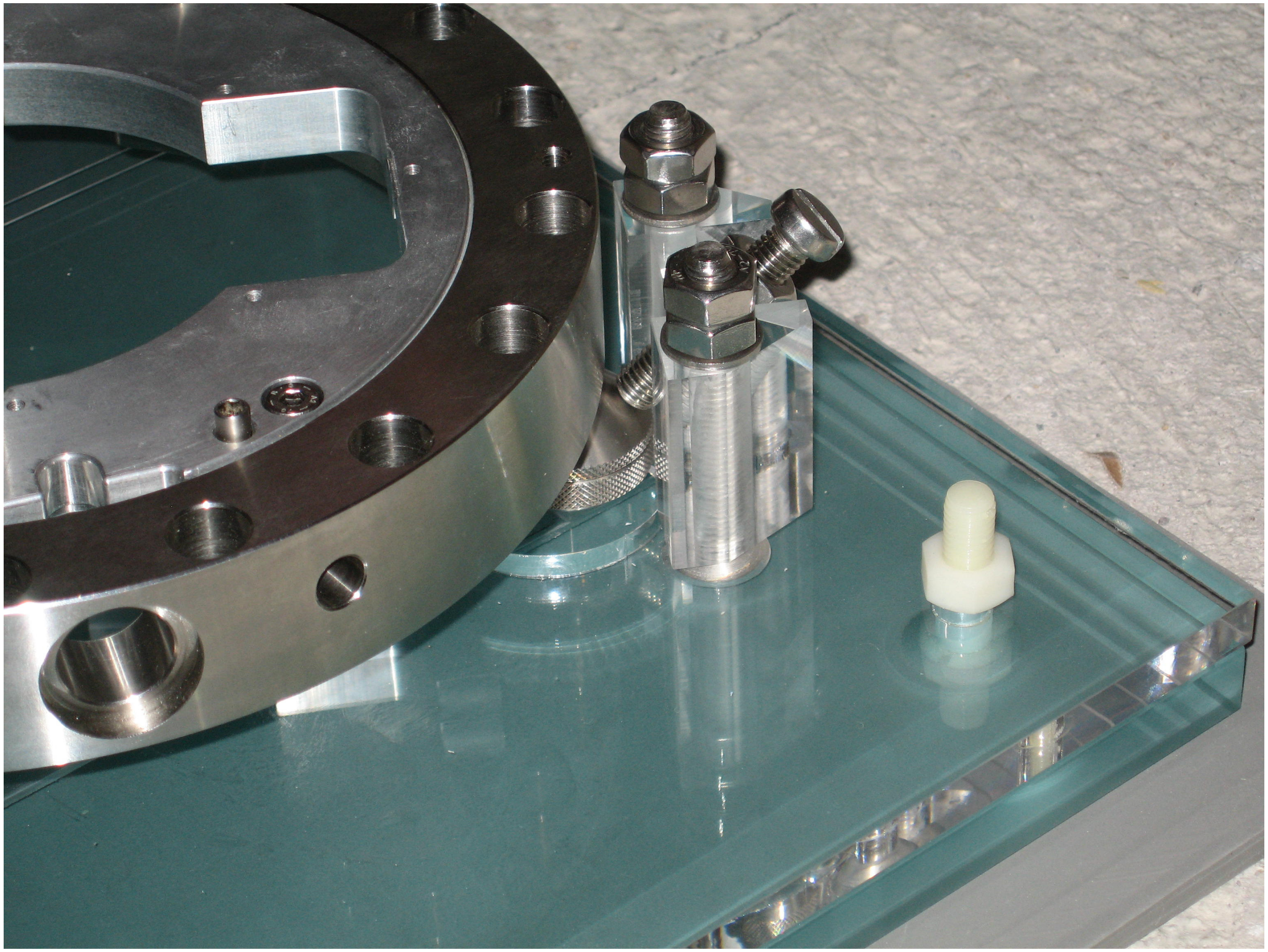

STS2 noise (Wielandt)
NLNM * STS2
DM24
Q330
extracted noise
PSD in dB (rel. to V 2 / Hz)
Frequency [Hz]
70
80
90
100
110
120
130
140
150
0.0001
0.001
0.01
0.1
1
10

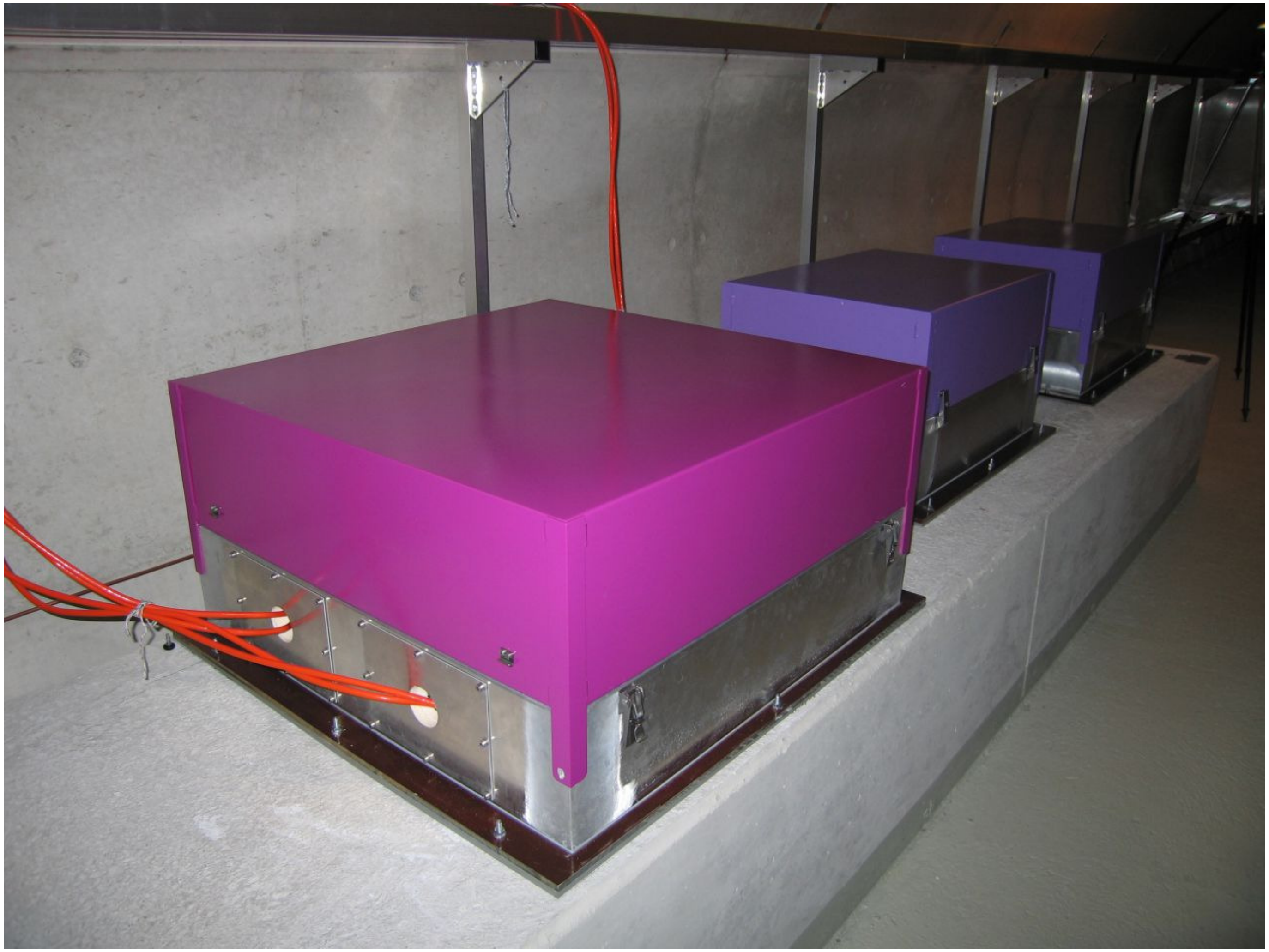

STS2 noise (Wielandt)
NLNM * STS2
DM24
Q330
extracted noise
Q4120
70
80
90
100
110
120
130
140
150
PSD in dB (rel. to V 2 / Hz)
0.0001
0.001
0.01
0.1
1
10
Frequency [Hz]


STS2 noise (Wielandt)
NLNM * STS2
DM24
Q330
extracted noise
Q4120
Q330HR
STS-2 self noise measurement needs Q330HR !
PSD in dB (rel. to V 2 / Hz)
70
80
90
100
110
120
130
140
150
0.0001
0.001
0.01
0.1
1
10
Frequency [Hz]

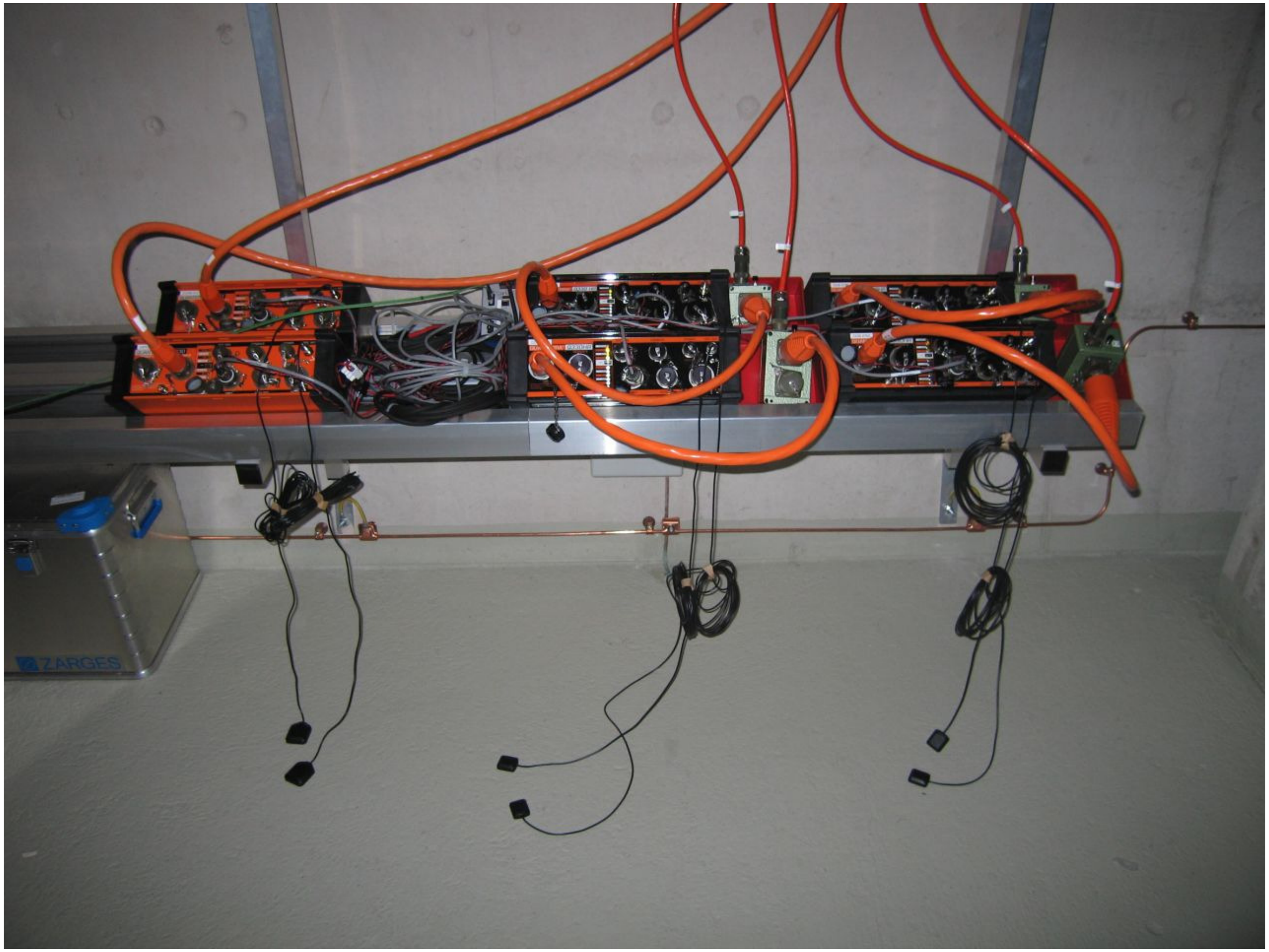
The Conrad Observatory Experiment

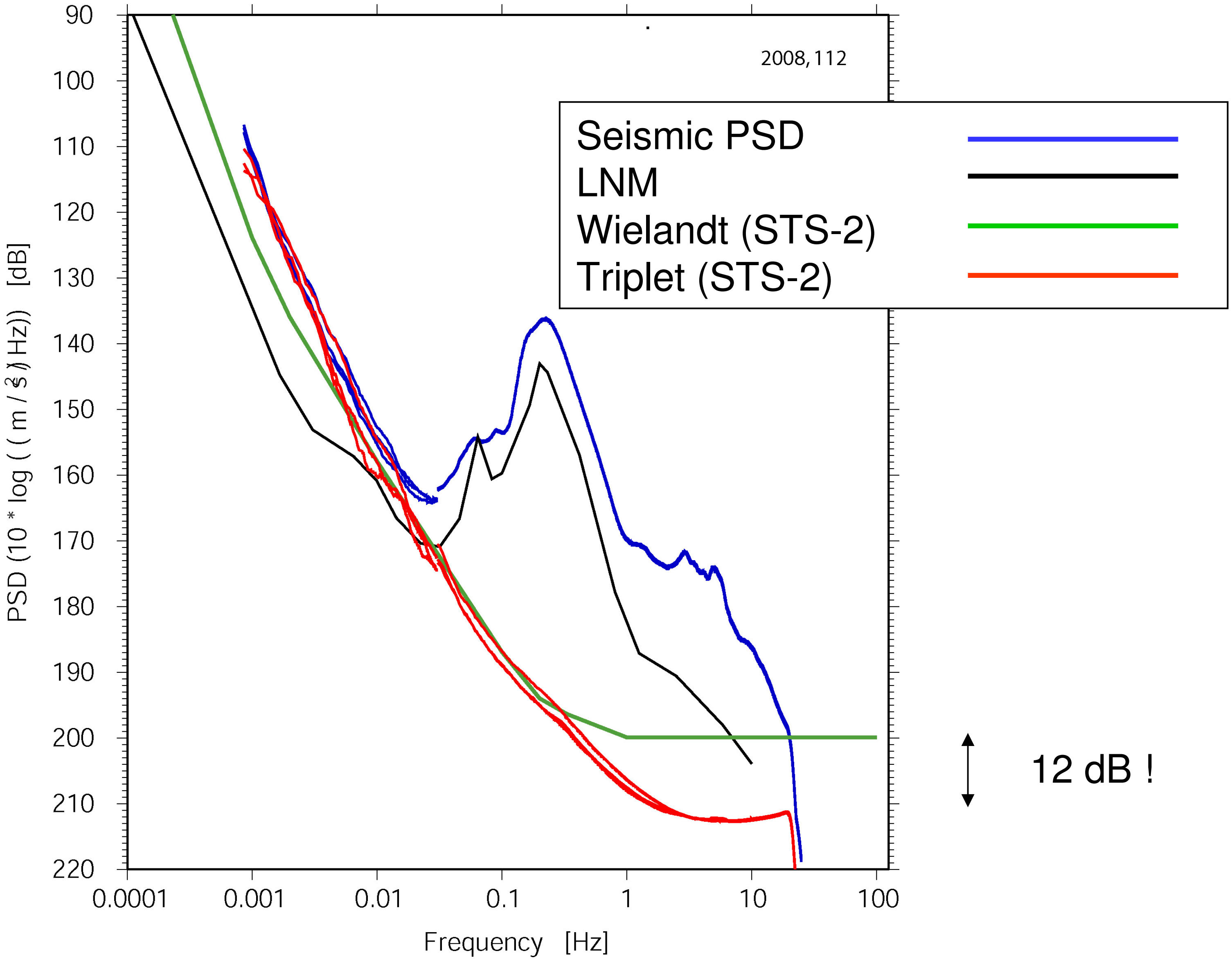
- NERIES framework (TA5) - funding
- Conrad Observatory - quiet conditions
- 4 STS-2 (same generation)
- 3 aligned, 1 mis-aligned (2, 4, 8 degrees)
- 4 Q330-HR, enabled pre-amplifier
- Antelope acquisition

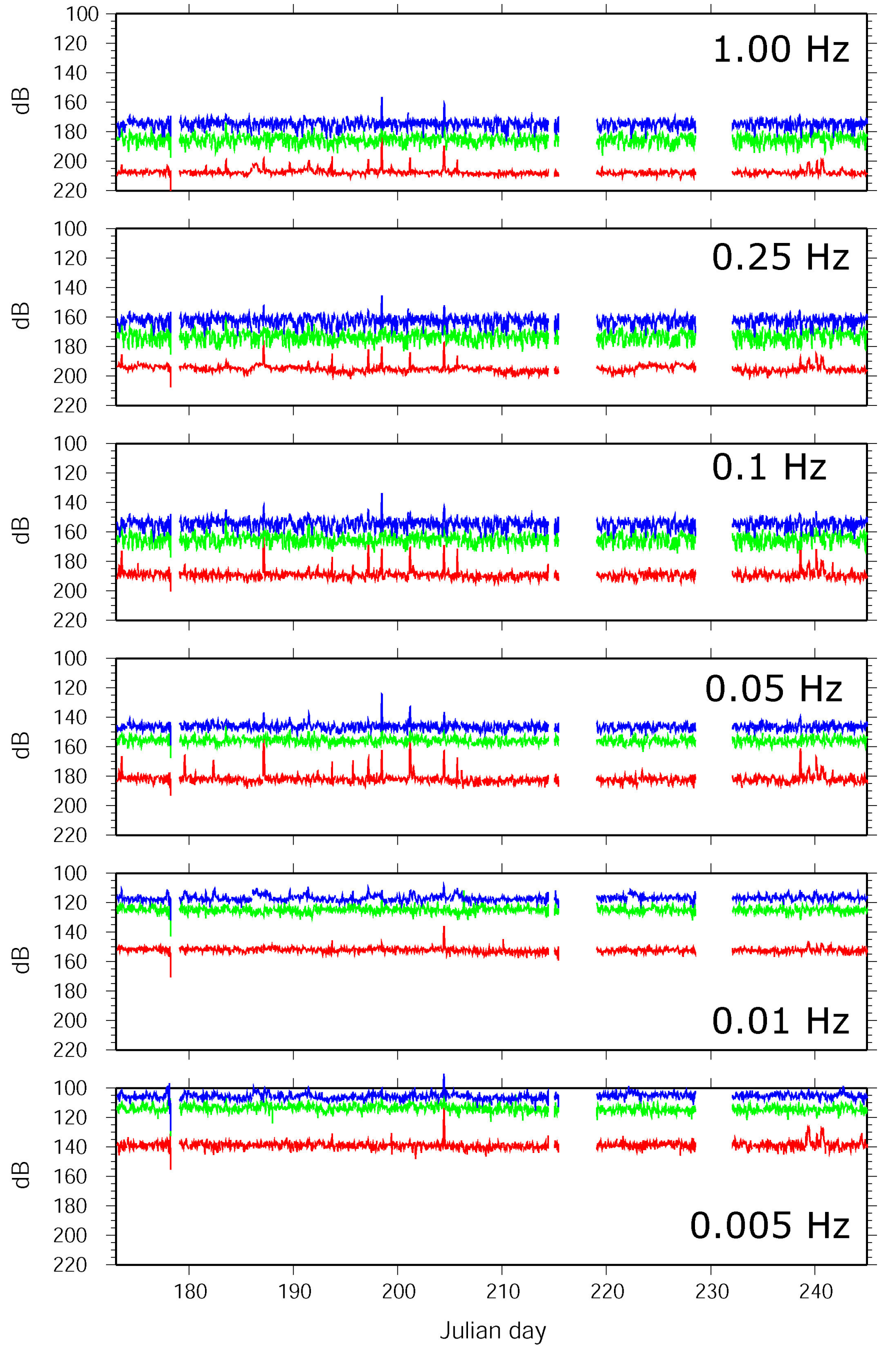




Conrad experiment




2008, 112
Seismic PSD
LNM
Wielandt (STS-2)
Triplet (STS-2)
PSD (10 * log ((m / s²)² / Hz)) [dB]
90
100
110
120
130
140
150
160
170
180
190
200
210
220
0.0001
0.001
0.01
0.1
1
10
100
Frequency [Hz]
12 dB !

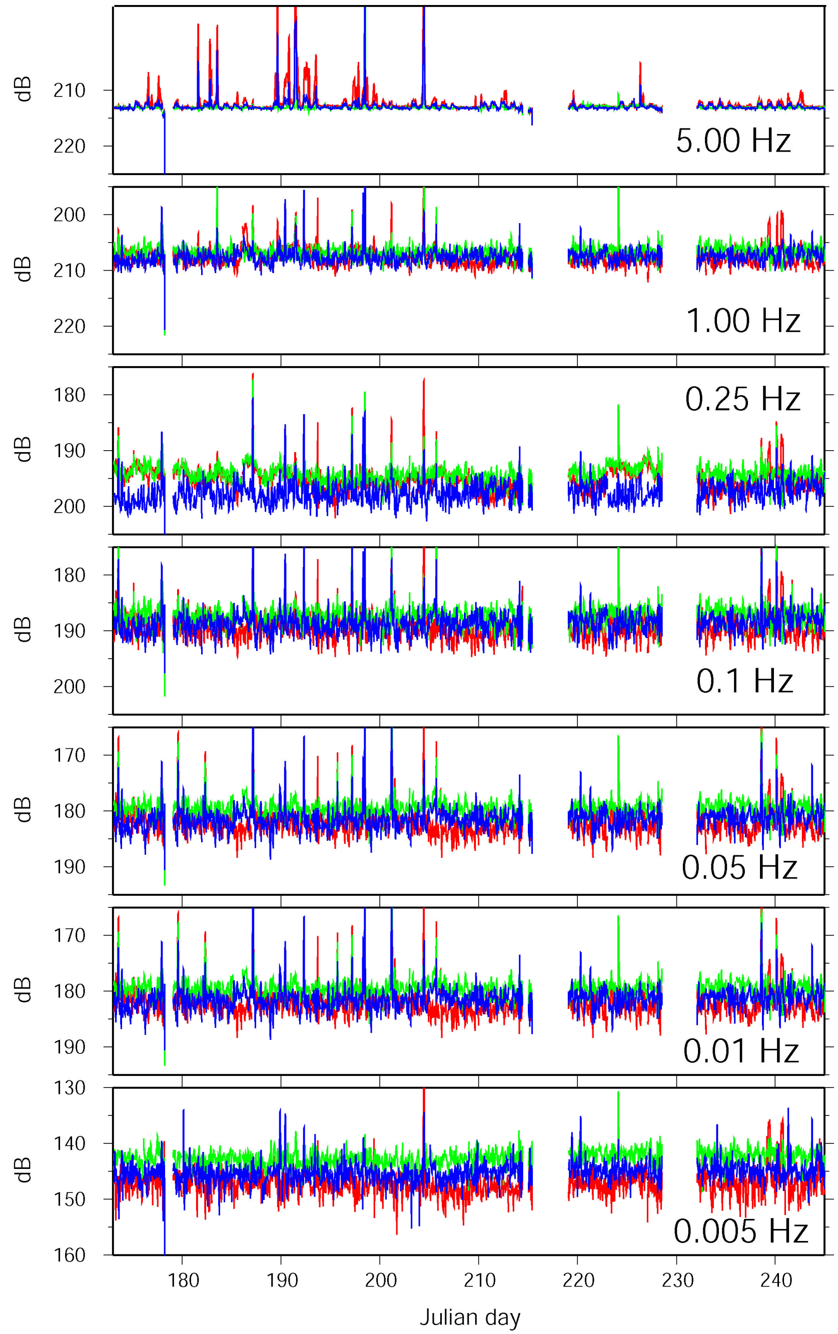


Z comp

N comp

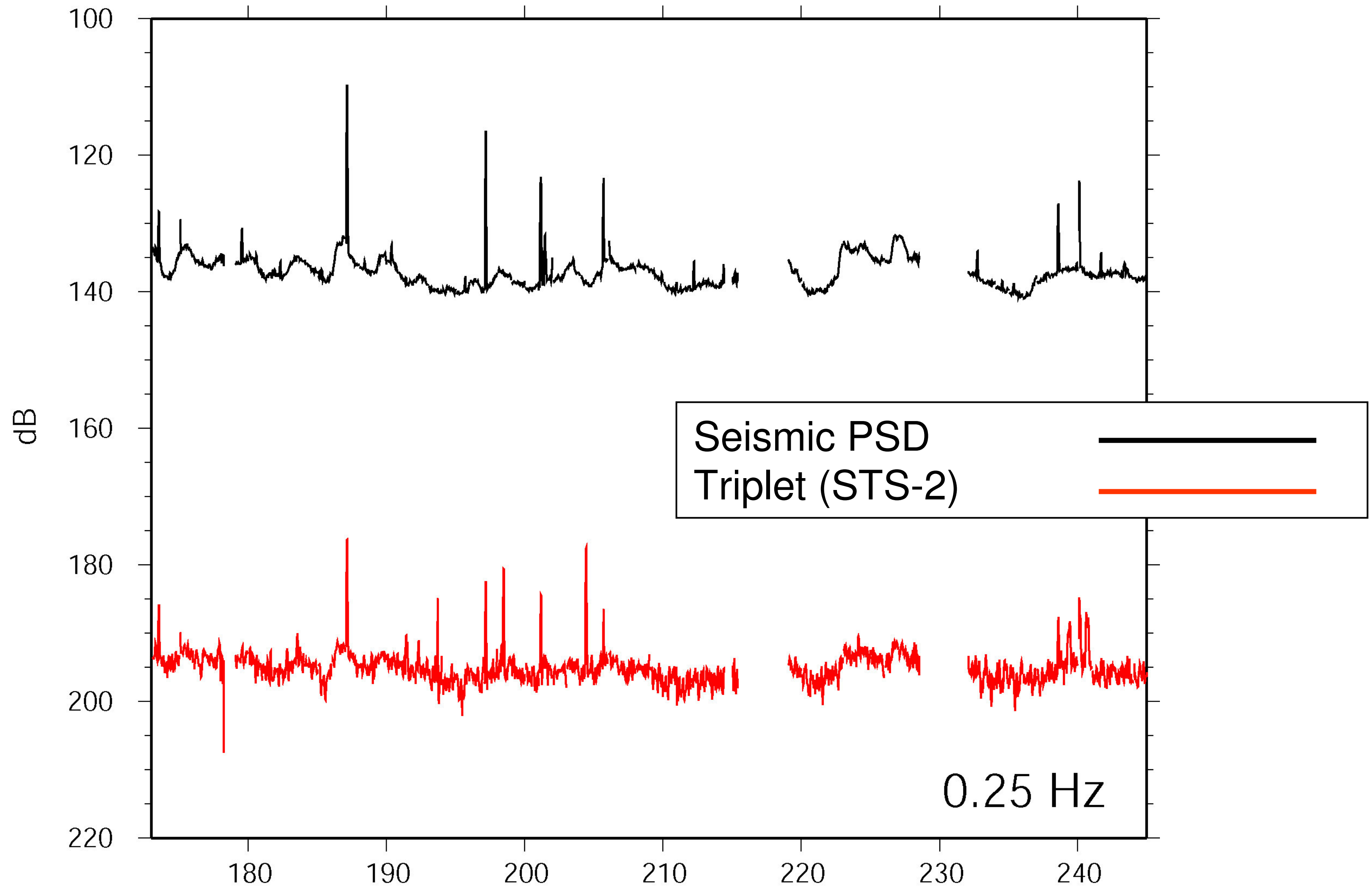
E comp

use vertical component !

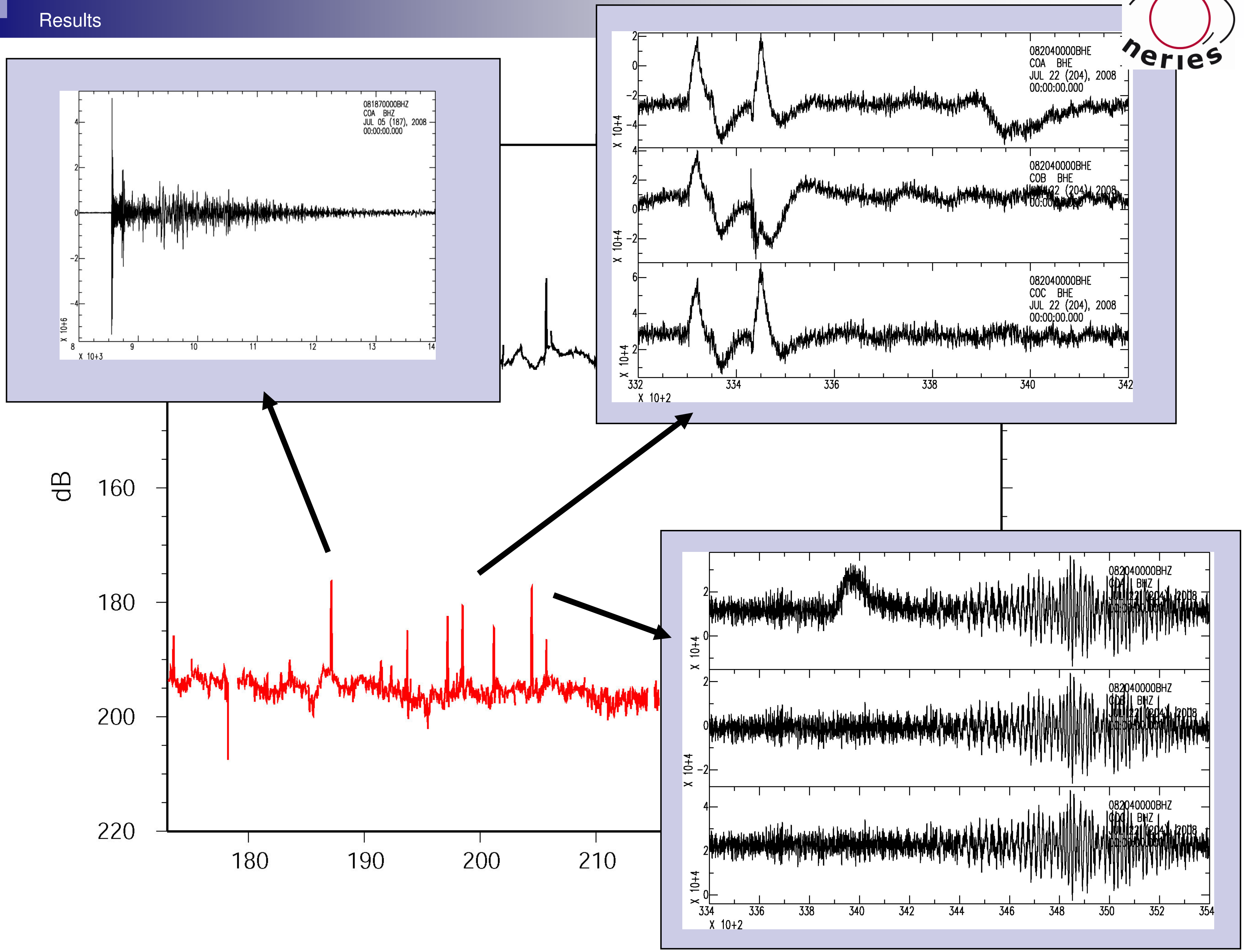


3 Z components

differences up to 5 dB


dB
100
120
140
160
180
200
220
180
190
200
210
220
230
240
Seismic PSD
Triplet (STS-2)
0.25 Hz

Results



dB
160
180
200
220
180
190
200
210
081870000BHZ
COA BHZ
JUL 05 (187), 2008
00:00:00.000
X 10+6
X 10+3
082040000BHE
COA BHE
JUL 22 (204), 2008
00:00:00.000
082040000BHE
COB BHE
082040000BHE
COC BHE
JUL 22 (204), 2008
00:00:00.000
X 10+4
332
334
336
338
340
342
X 10+2
082040000BHZ
334
336
338
340
342
344
346
348
350
352
354

- Q330-HR with enabled pre-amplifier required for estimating the self-noise of the STS-2.
- Quiet site required, only vertical components.
- STS-2 self-noise is ~12 dB below previous estimates (> 1 Hz) and is in agreement with Wielandt between 0.01 and 1 Hz.
- Coherency is lost below 0.05 Hz (in present installation)
- Long-term analysis required instead of window shopping.
- Relatively large differences between individual sensors
- High and low frequency spurious signals.

Possible contributing sources:

- Barometric pressure variations (ground tilt, elastic response)
- Temperature variations
- Humidity (corrosion)
- Installation conditions (mechanical strees in the pier)
- Quantization noise of digitizer
- Sensor self-noise (instrumental noise)

  - Brownian motion of the mass (thermal noise)
  - Displacement transducer noise
  - **Integrator noise** (semi-conductors)
  - Electromagnetic noise of the displacement sensor (LVDT)

:

Effects of temperature variations

- Thermal expansion of leaf spring (and other components)
- Temperature dependence of elasic moduli of leaf spring
- Thermal stresses due to uneven heating
- Thermal stresses due to differing expansion coefficients of different metalic components
- Convection of enclosed air due to dissipated heat from feedback electronics
- Tilting due to uneven heating and expansion of foot screws
- Thermal stresses in pier

=> Privide additional thermal shielding and increase thermal inertia.