EINSTEIN TELESCOPE SITE SELECTION

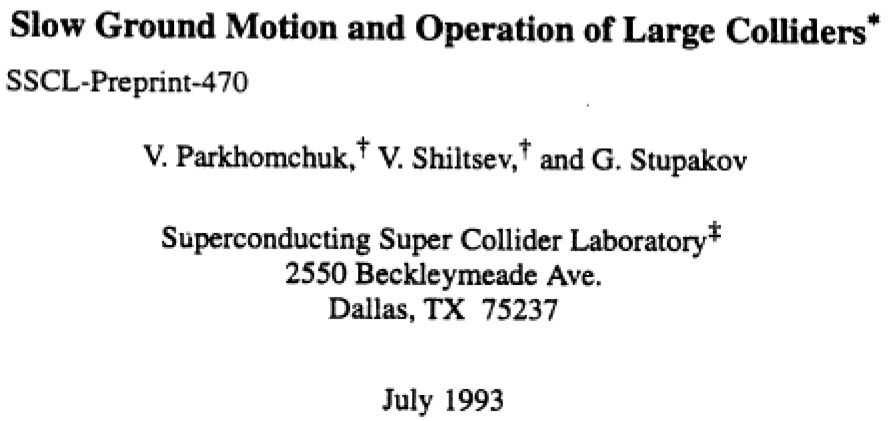
Ambient ground motion

Jo van den Brand, Martin Doets, Mark Beker, Eric Hennis, David Rabeling
Nikhef , Amsterdam

OVERVIEW

- Ambient seismic noise
  - Lowest achievable noise
  - Frequency ranges, coherence, ATL law
  - Depth, geology, geography
- Experience from other fields
  - International linear collider, SSC, LEP, SLAC, Desy, KEK
- Used as guidance for
  - FEA analysis of NN (David Rabeling)
  - Measurements
    - Gran Sasso, Homestake

SLOW GROUND MOTION



Slow Ground Motion and Operation of Large Colliders*

SSCL-Preprint-470

V. Parkhomchuk,† V. Shiltsev,† and G. Stupakov

Superconducting Super Collider Laboratory‡
2550 Beckleymeade Ave.
Dallas, TX 75237

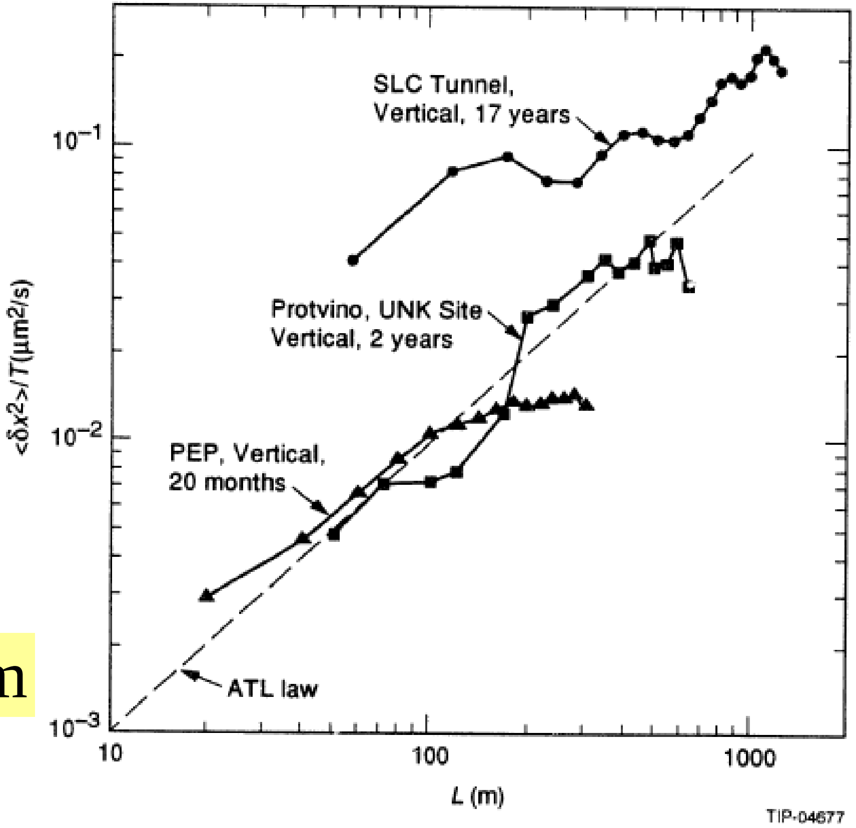
July 1993

Relative rms displacement $<\delta x^2>$ between two points at a distance *L* grows with time *T*

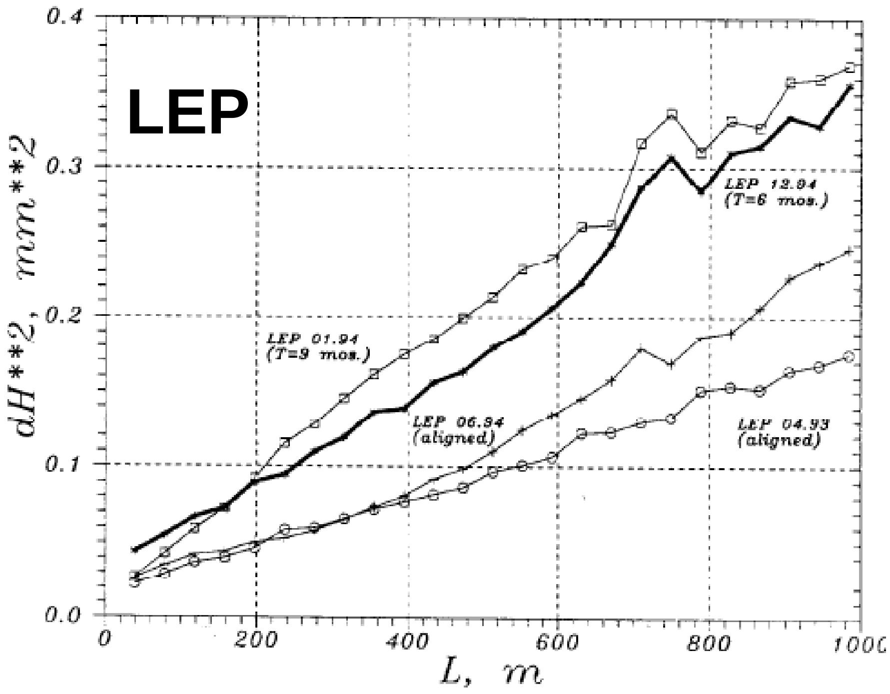
$$\langle \delta x^2 \rangle = ATL$$

$$A = (1.0 \pm 0.5) \cdot 10^{-4}\ \mu\mathrm{m}^2/(\mathrm{m{\cdot}s})$$

$L = 10$ km, $T = 1$ year $\rightarrow \sqrt{< \delta x^2 >} \approx 6\ \mathrm{mm}$



SLOW GROUND MOTION



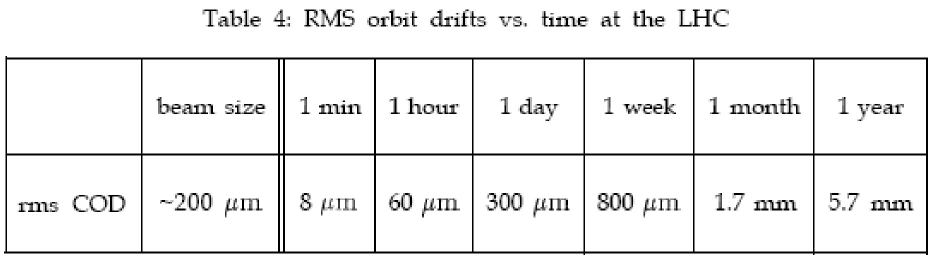
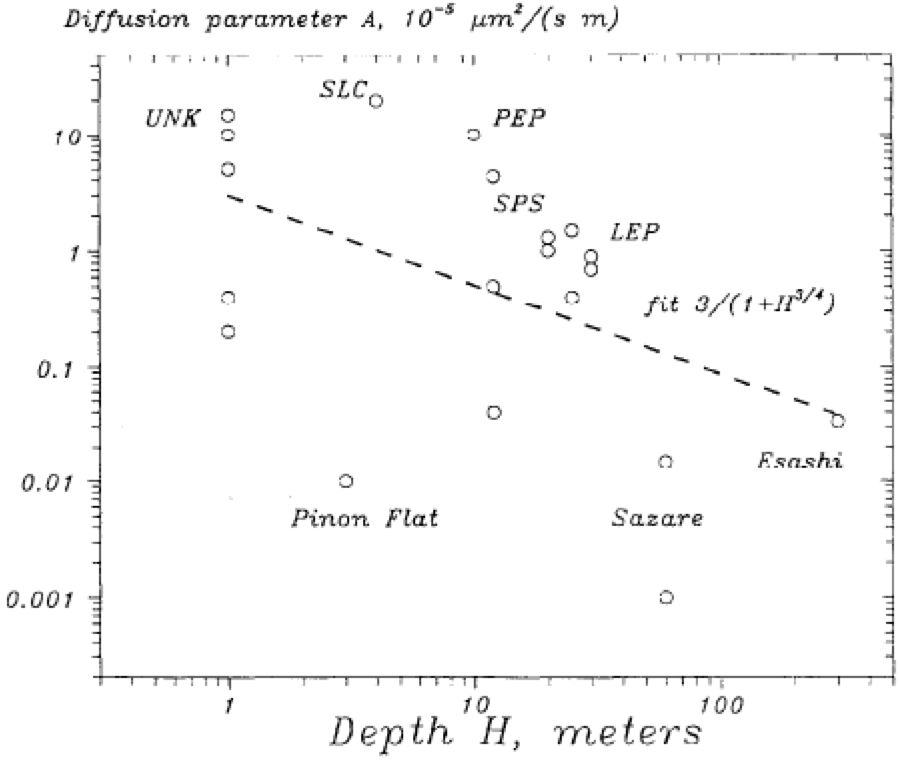


Table 4: RMS orbit drifts vs. time at the LHC

	beam size	1 min	1 hour	1 day	1 week	1 month	1 year
rms COD	~200 μm	8 μm	60 μm	300 μm	800 μm	1.7 mm	5.7 mm

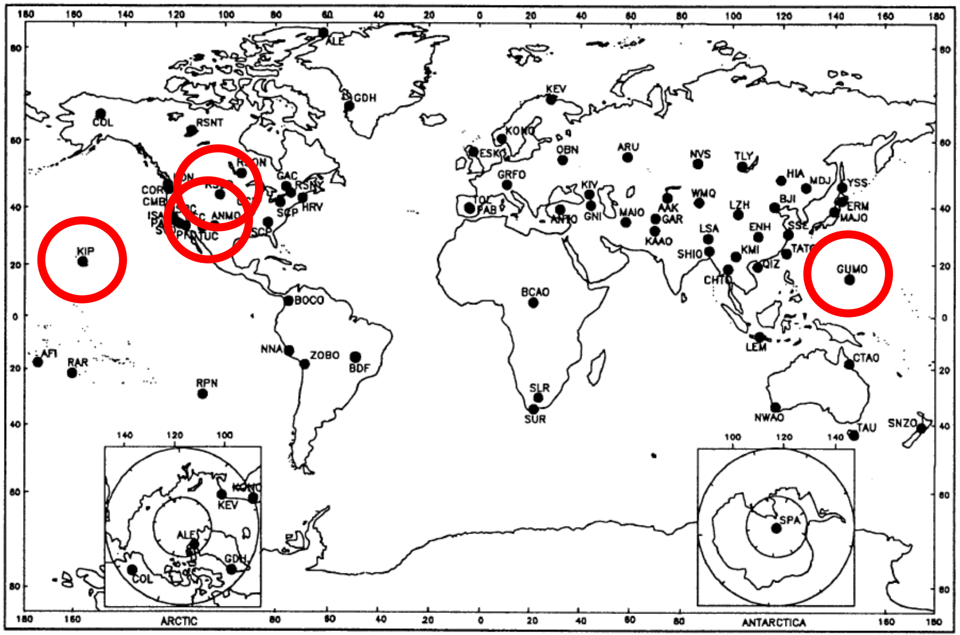
Diffusion versus depth

$$A[\mu m^2/(s \cdot m)] = \frac{3}{1+H^{3/4}}$$



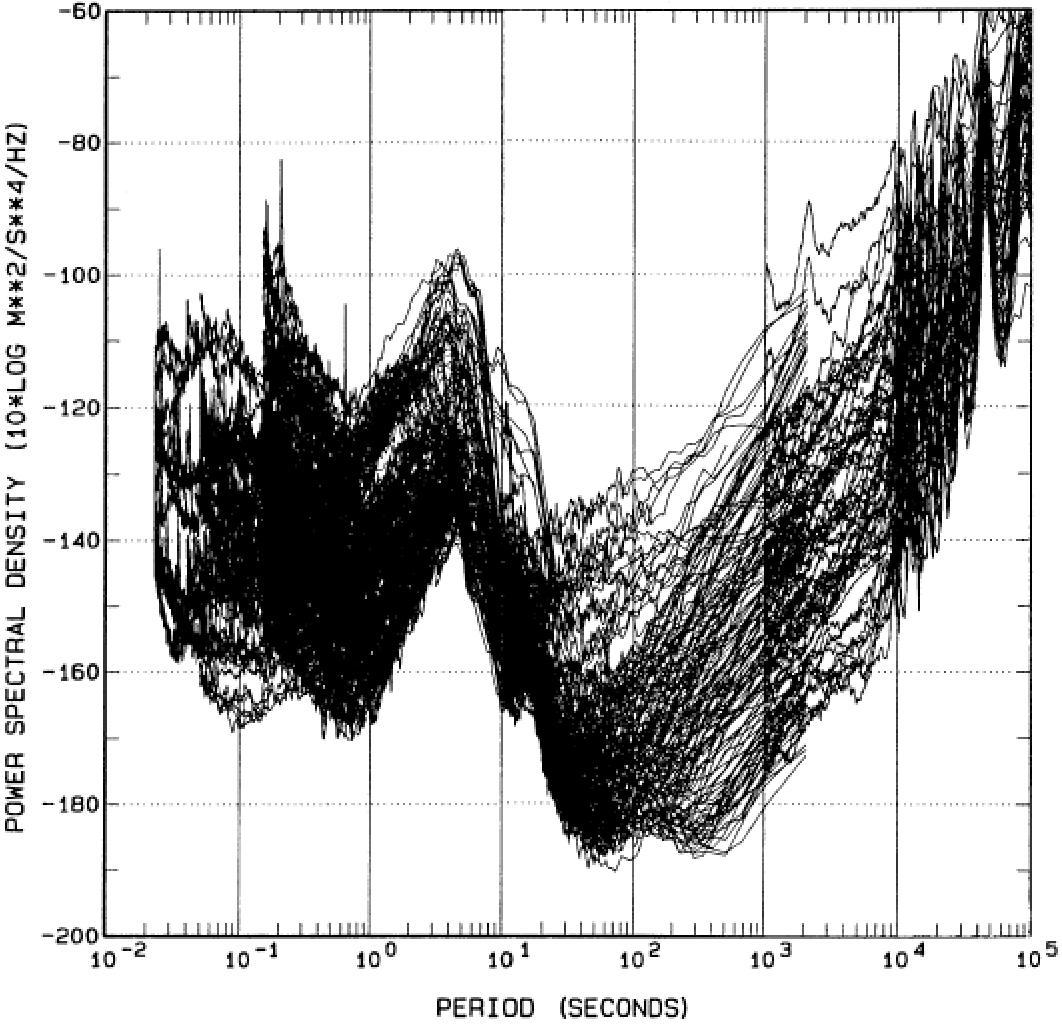
SEISMIC MOTION

- Seismic background noise model
  - Peterson 1993
  - US Department of Interior Seismological Survey
  - Open-File Report 93-322
- Worldwide seismic network
  - Total of 75 surface and borehole sensors (100 – 340 m depth)
  - Then at relatively quiet sites



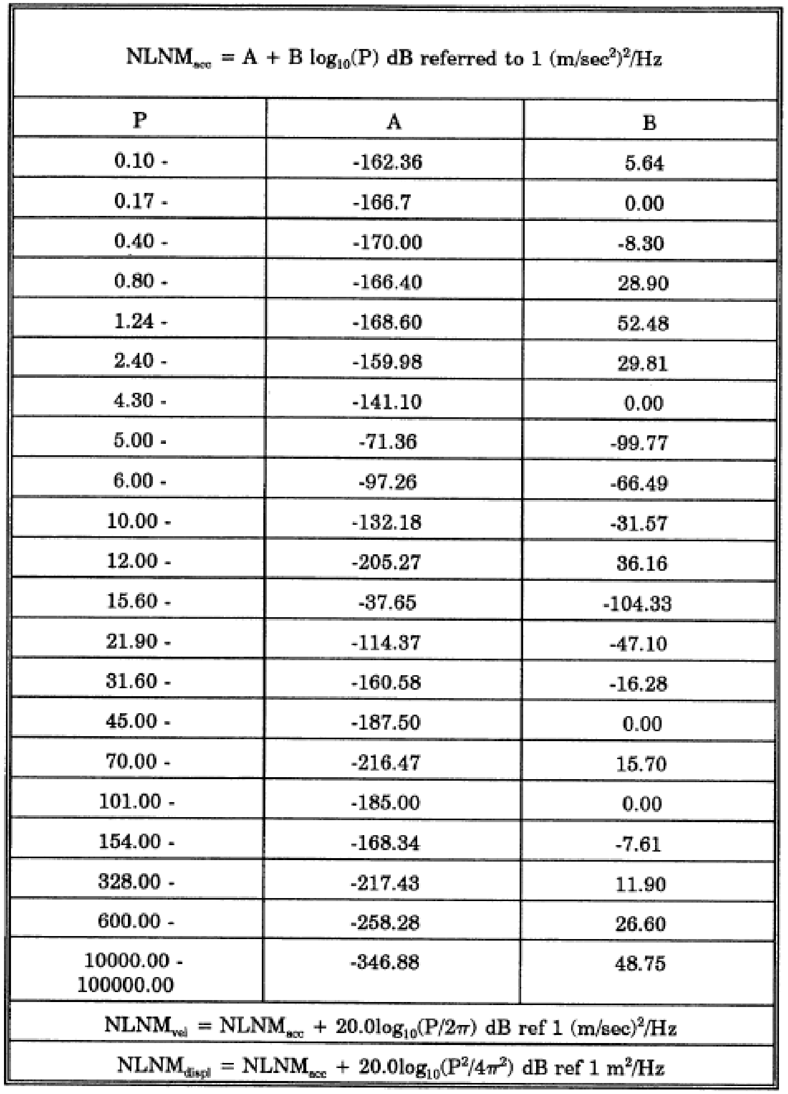
Seismic motion

- Data set
  - Several years of data
  - 12,000 spectra
  - Find representative values of noise at quiet periods
- PSD in decibels
  - Referred to 1 (m/s^2)^2/Hz
  - At 1 Hz: ng/rtHz, < 0.1 nm/rtHz
- Features
  - Microseismism at 5 and 18 s
  - Earth tides
  - Domelike structure at 3 Hz due to STS gain?
  - 90 dB of dynamic range needed between 1 – 100 s
  - Highly variable in 1 – 10 Hz range



NEW LOW NOISE MODEL

- NLNM is composite of different
  - Stations and instruments
  - Geology and geographic regions
  - Not easy to duplicate somewhere
- General observations 1 – 10 Hz lowest noise for
  - Continental sites
  - Hard rock
  - Remote: low cultural noise
  - No wind
  - Borehole instruments
- Lowest noise sites in USA
  - ANMO New Mexico
  - Alaska



$\mathrm{NLNM}_{acc} = A + B\log_{10}(P)$ dB referred to 1 $(\mathrm{m/sec}^2)^2/\mathrm{Hz}$

P	A	B
0.10 -	-162.36	5.64
0.17 -	-166.7	0.00
0.40 -	-170.00	-8.30
0.80 -	-166.40	28.90
1.24 -	-168.60	52.48
2.40 -	-159.98	29.81
4.30 -	-141.10	0.00
5.00 -	-71.36	-99.77
6.00 -	-97.26	-66.49
10.00 -	-132.18	-31.57
12.00 -	-205.27	36.16
15.60 -	-37.65	-104.33
21.90 -	-114.37	-47.10
31.60 -	-160.58	-16.28
45.00 -	-187.50	0.00
70.00 -	-216.47	15.70
101.00 -	-185.00	0.00
154.00 -	-168.34	-7.61
328.00 -	-217.43	11.90
600.00 -	-258.28	26.60
10000.00 - 100000.00	-346.88	48.75

$\mathrm{NLNM}_{vel} = \mathrm{NLNM}_{acc} + 20.0\log_{10}(P/2\pi)$ dB ref 1 $(\mathrm{m/sec})^2/\mathrm{Hz}$

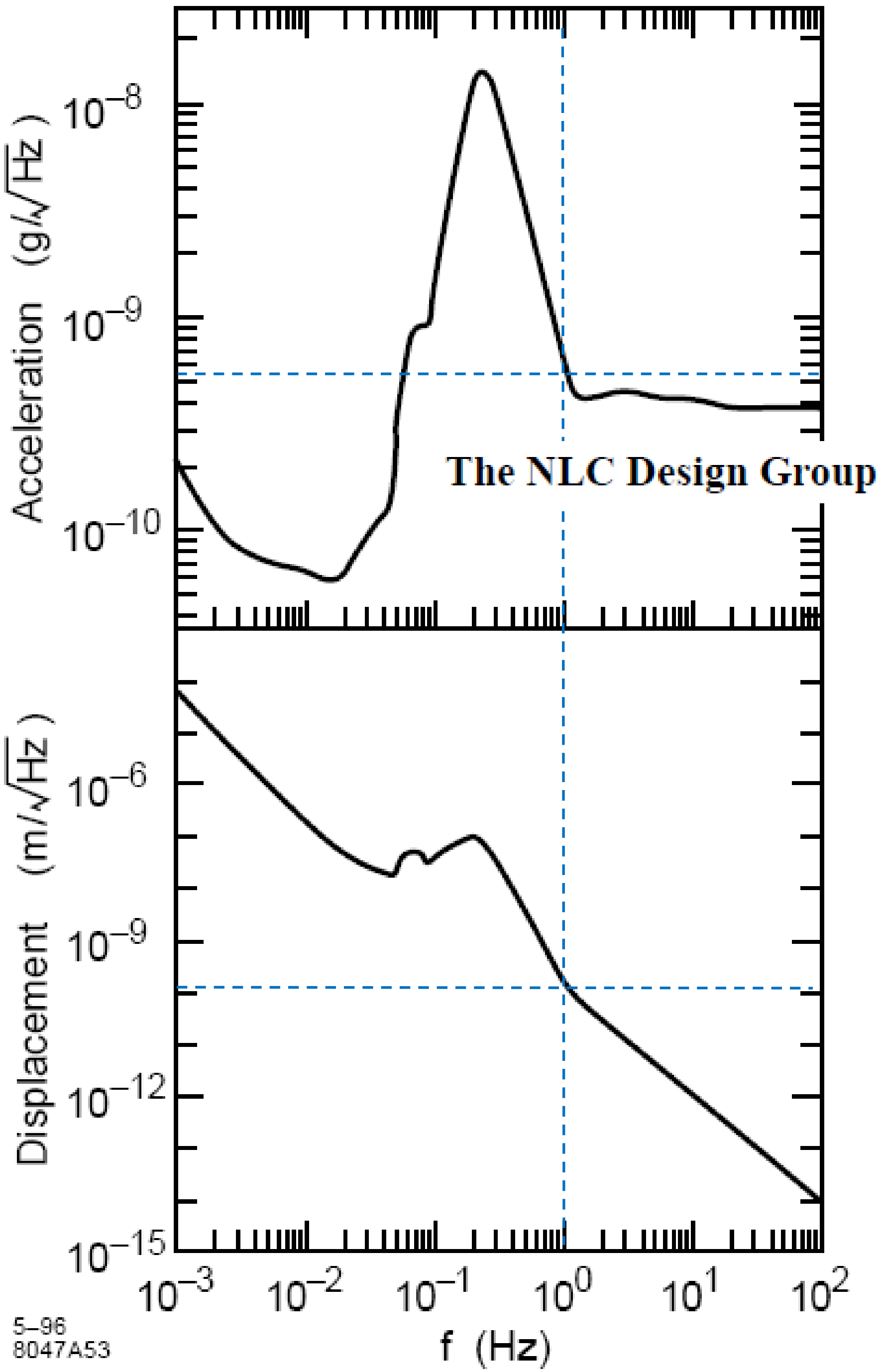
$\mathrm{NLNM}_{displ} = \mathrm{NLNM}_{acc} + 20.0\log_{10}(P^2/4\pi^2)$ dB ref 1 m^2/Hz

USGS NLNM

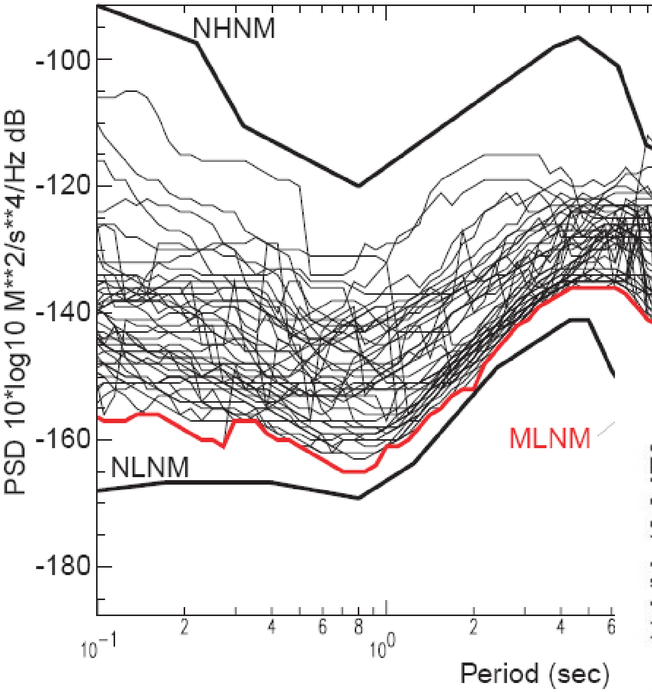
- PSD in Decibels
  - Referred to 1 $(m/s^2)^2/Hz$
  - 168.6 dB/Hz (0.37 ng/rtHz) at 1 Hz
  - Note: 0.55 ng/rtHz at 1 Hz (NLC)
- Displacement
  - About 0.1 nm/rtHz at 1 Hz
- Sometimes amplitude of background noise needed
  - Integration bandwidth → RMS value
  - 1/3 octave: ±10% about center
  - Convert PSD to p2p amplitude
  - Gaussian signal passed through narrow-band filter the absolute peak signals of the filtered signal envelope will have a Rayleigh distribution

$$|\overline{x}_p| = \int_0^\infty \frac{x_p^2}{\sigma^2} e^{\left(-\frac{x_p^2}{2\sigma^2}\right)} dx_p$$

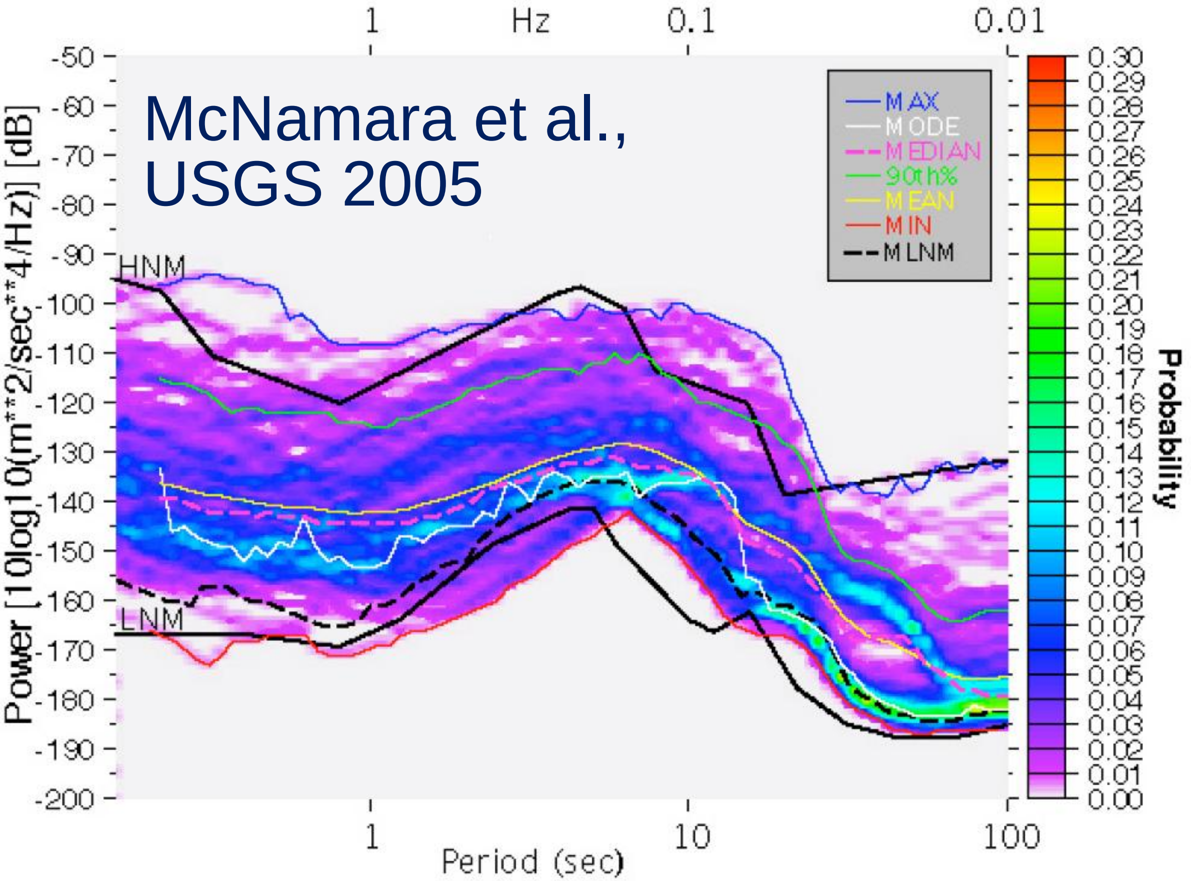
$$= \sqrt{\frac{\pi}{2}}\sigma = 1.253\sigma$$



McNamara & Buland USGS 2004

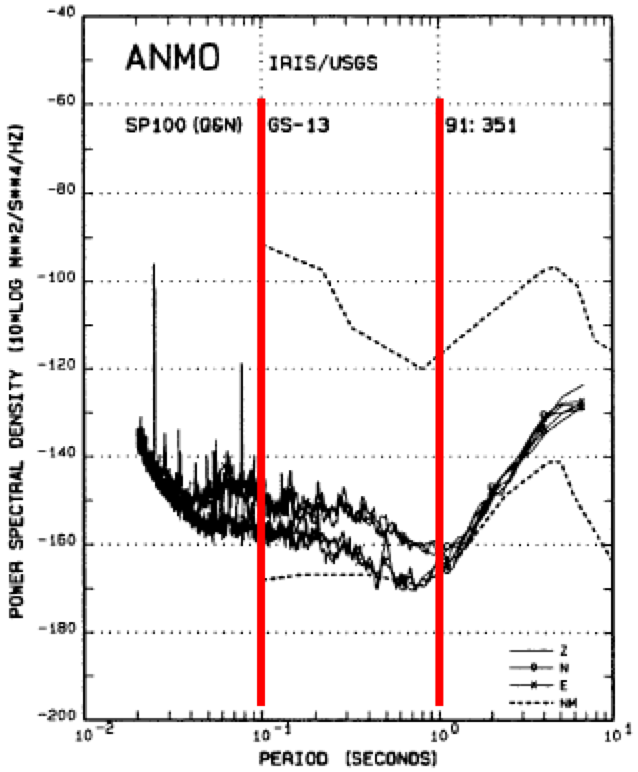


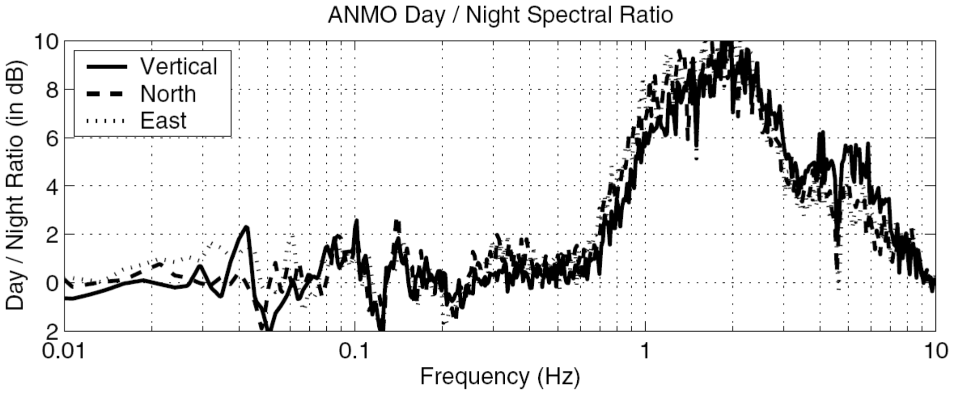
- 159 GSN and ANSS stations
- Lowest noise: Antarctica, QSPA 300 m depth
- Lowest noise has 1 – 2 % probability

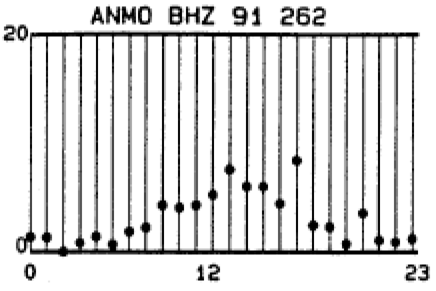

McNamara et al., USGS 2005

Albuquerque New Mexico- USA

- Granite
- Borehole sensor: 100 m
- Elevation: 1740 m
- 1 – 2 dB > NLNM at 0.8 s
- Cultural noise 1 – 10 Hz correlates up to 225 km



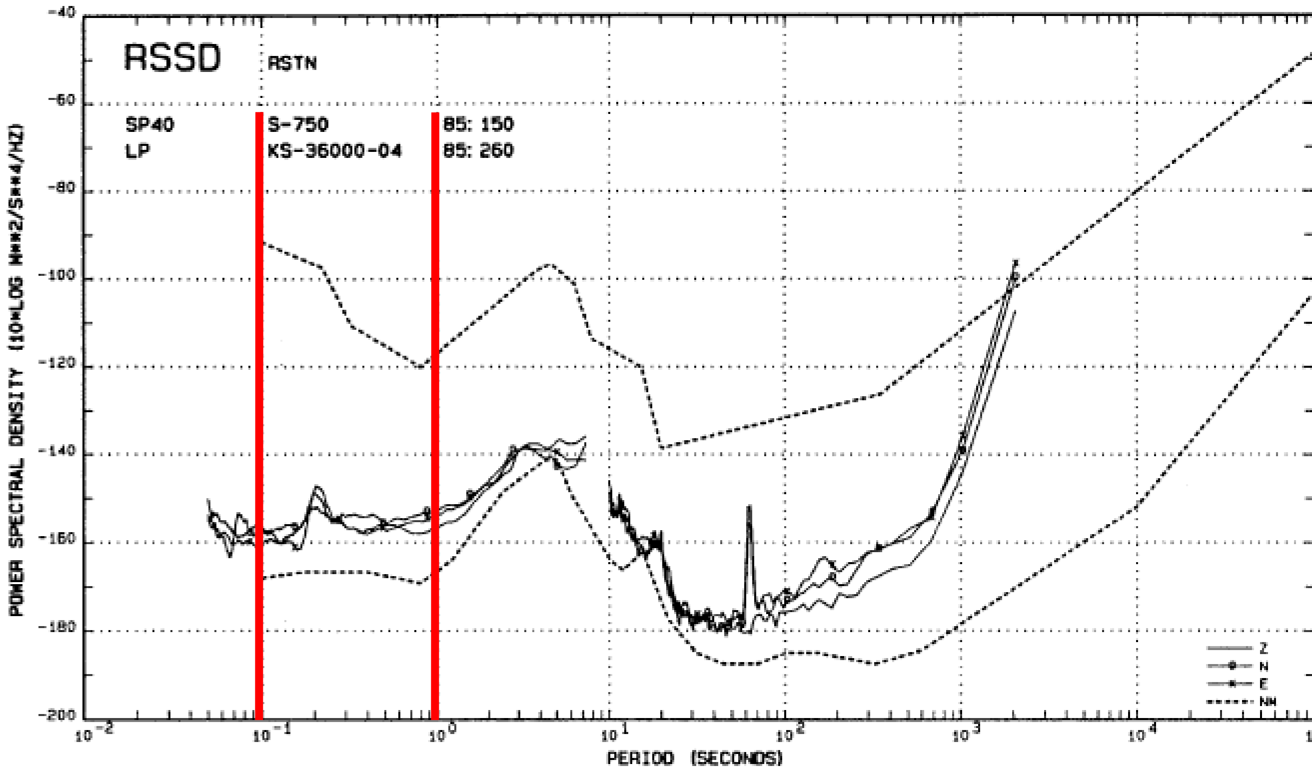




Black Hills South Dakota – USA

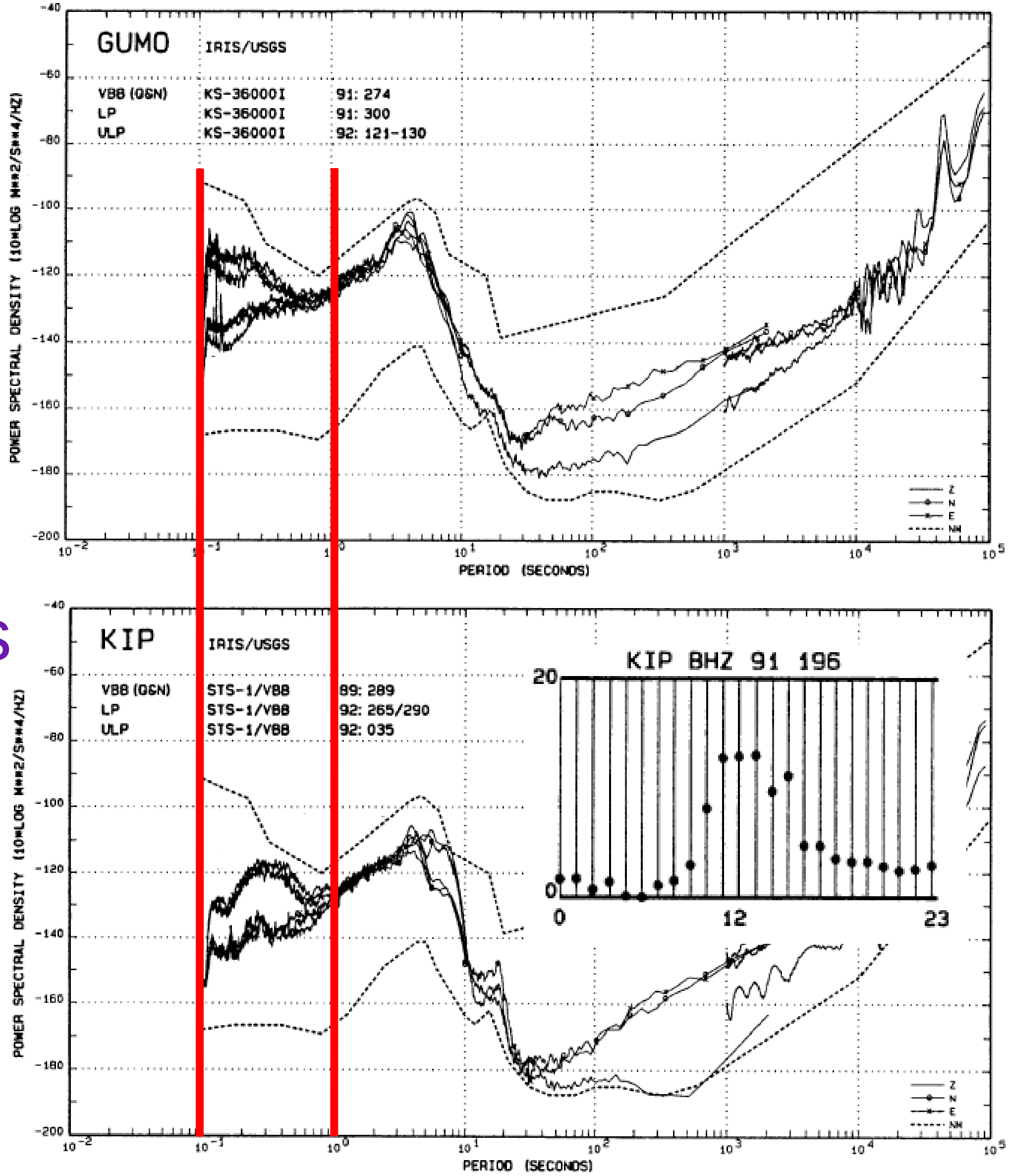
- Limestone
- Borehole sensor: 110 m (elevation: 1950 m)
- 11 – 14 dB > NLNM at 0.8 s

Representative for Dusel / Homestake?



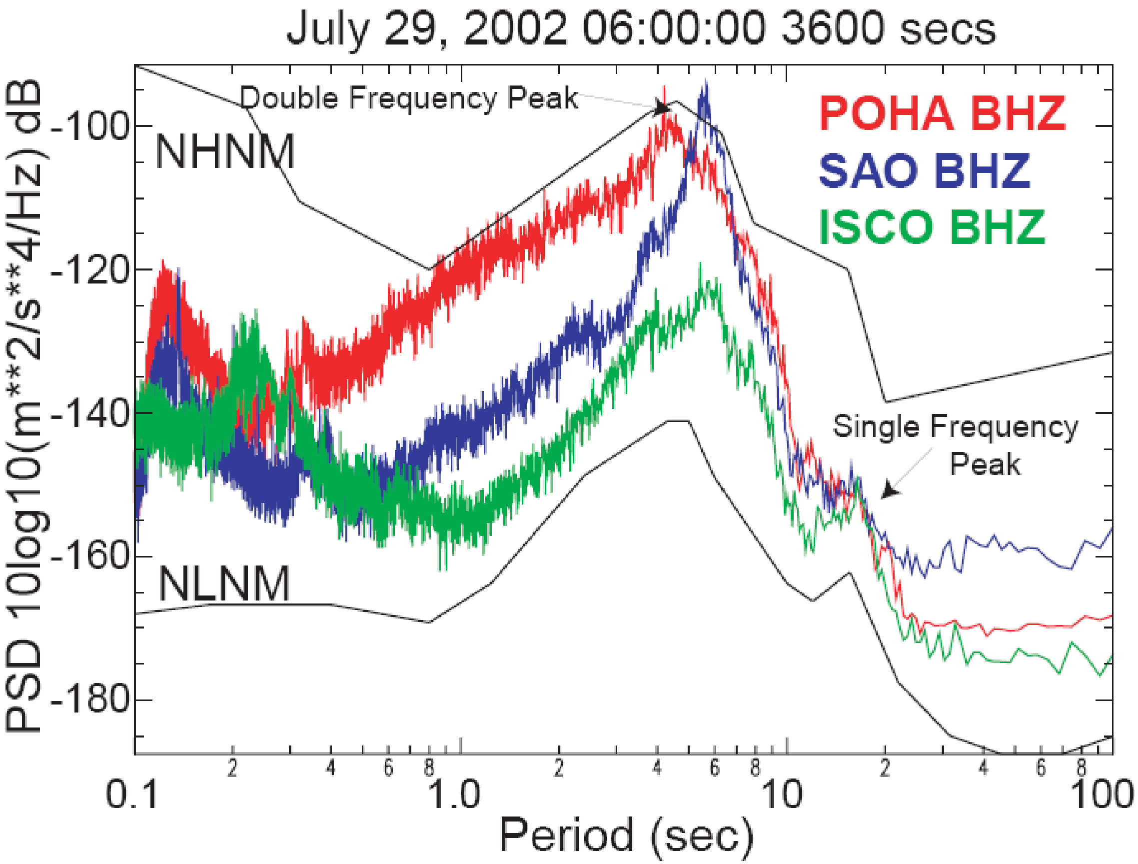
GENERAL OBSERVATIONS 1 – 10 Hz

- Islands
  - Microseismic noise tails
- Two bands visible
  - NLNM
  - NHNM
- Same for coastal stations
- Near lakes
  - Surf noise



MICROSEISMIC NOISE

- Single frequency peak
  - Coastal waves
- Double frequency peak
  - Standing ocean waves
- Seismic stations
  - POHA – Pacific ocean Hawai
  - SAO – California 50 km from coast
  - ISCO – Mine shaft in Colorado



MICROSEISMIC NOISE

- PSD changes up to 30 dB
  - Microseismic minimum vs maximum noise
- Modeling
  - Driver frequency f_0
  - Random phase loss ν

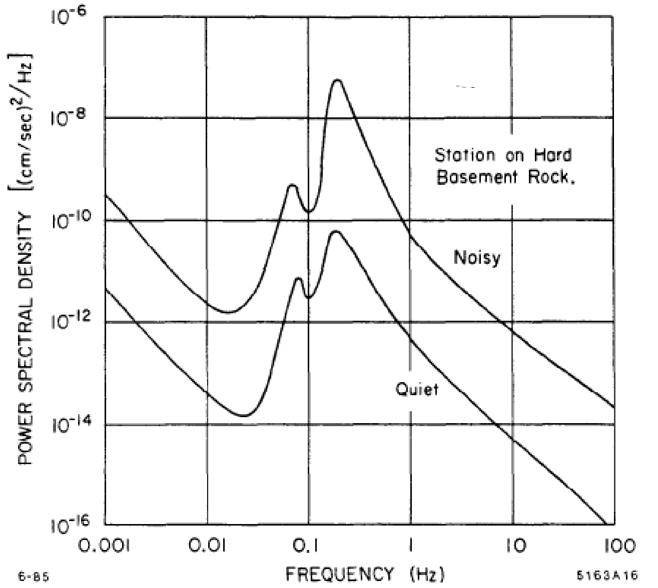
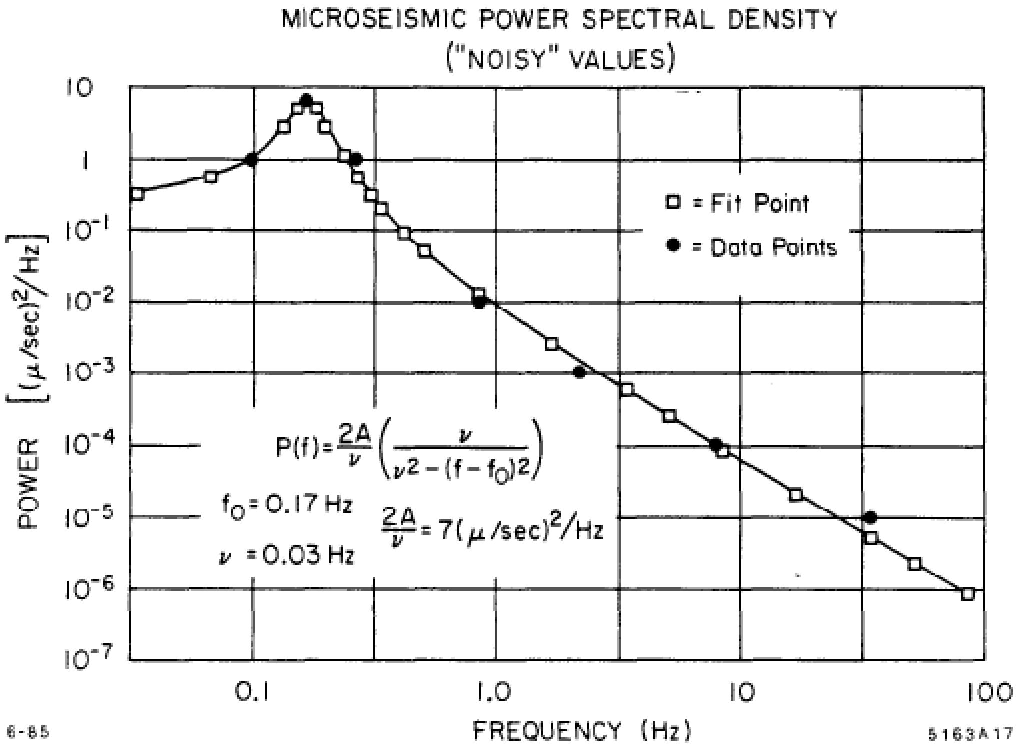
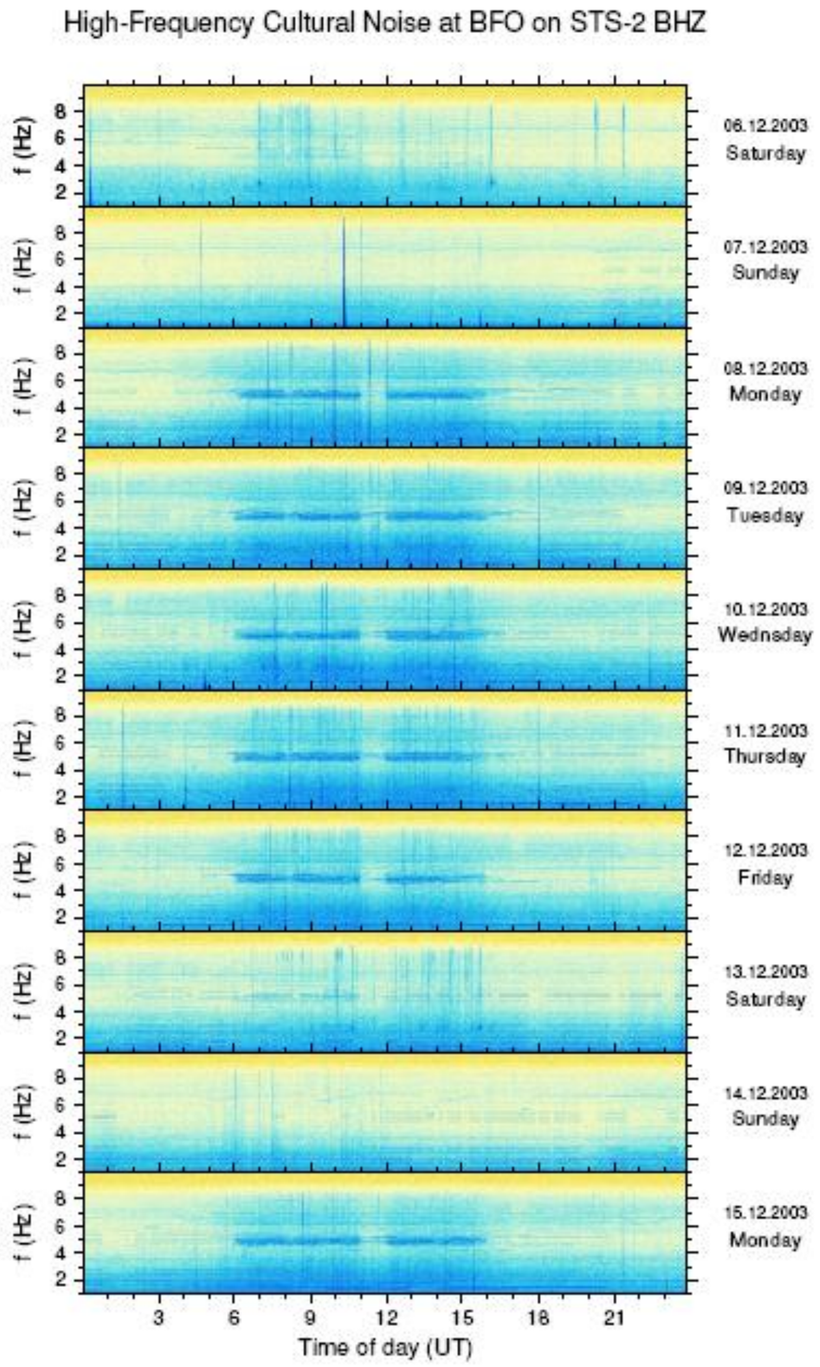


Fig. 4.1. Long Term Averaged "Maximum" and "Minimum" Noise Power Spectra (from Ref. 11).

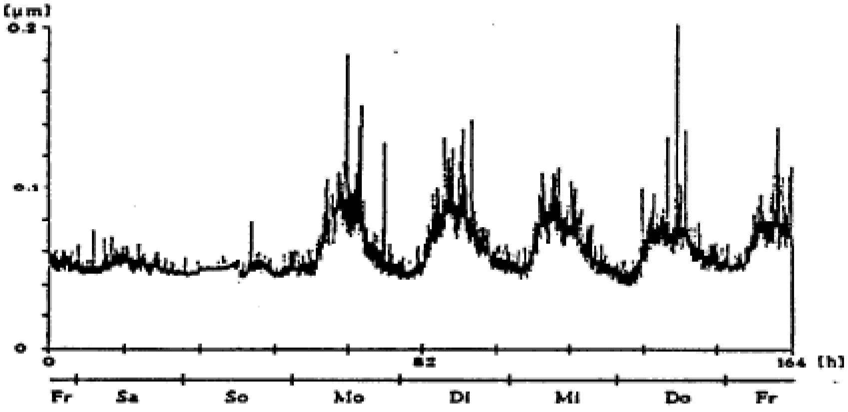


CULTURAL NOISE

- Diurnal variations
  - Binghamton New York:
    - 50 dB long periods
    - 20 dB above 1 Hz
  - ANMO borehole station
    - noise 10 dB above 1 Hz
  - Deep borehole stations see cultural noise up to depths of 2 km
  - BFO station: 180m depth
    - Saw mills



CULTURAL NOISE – DESY, SLAC



RMS Seismic Noise measured in the HERA tunnel at DESY. (From Ref [42])
Vertical 15/9/89 to22/9/89

- Noise sources
  - – Water pumps, water in cooling pipes, cryogenic fluids
  - – Low frequency reciprocating devices
    - – Vacuum pumps
    - – Air, helium, hydrogen compressors
    - – Well defined sharp spectral lines
  - – Implement site policy

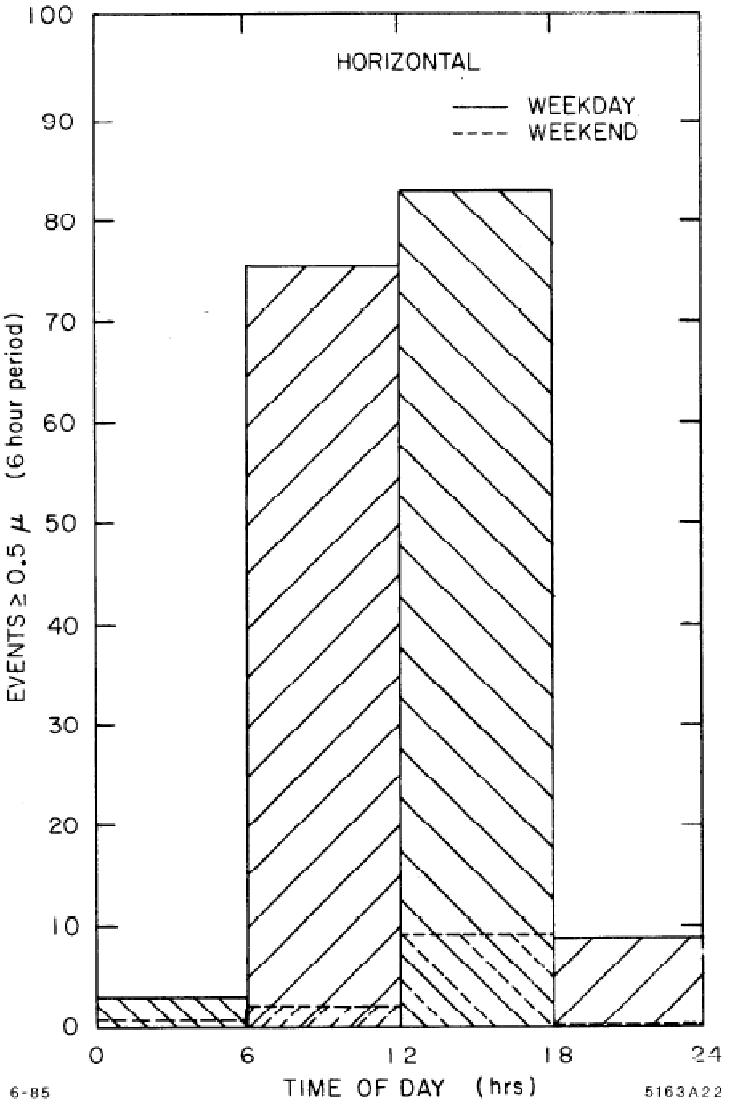
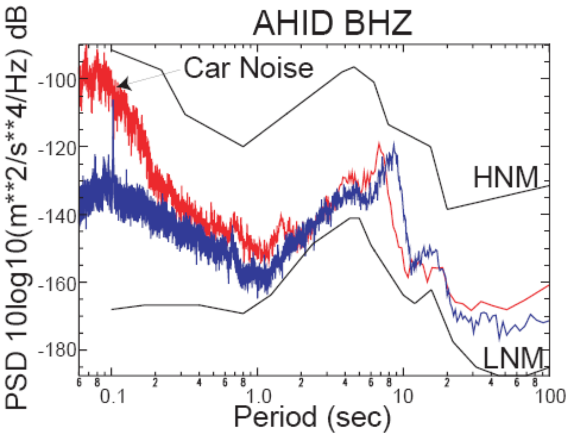


Fig. 1.4. Number of Horizontal Transient Events/6 Hour Interval as a Function of Time of Day.

TRAFFIC INDUCED VIBRATIONS

- McNamara & Buland USGS 2004
  - AHID: Auburn Hills, Idaho
  - >30 dB at frequencies: 1 – 10 Hz
  - Attenuation: km’s in distance and depth
- Lombaert and Degrange (2001)
  - Study of peak particle velocities
    - 30 km/h: 5 – 20 Hz
    - 50 km/h: 10 – 30 Hz
    - 70 km/h: 10 – 40 Hz
- Long (2003)
  - Empirical formula for attenuation of seismic road noise
  - Atlanta, GA
  - Steady traffic (15 – 60 cars/min)
  - A rms amplitude of particle velocity, r is distance

Log[A (mm/s)]=0.9 – 1.25 x Log[r (m)]



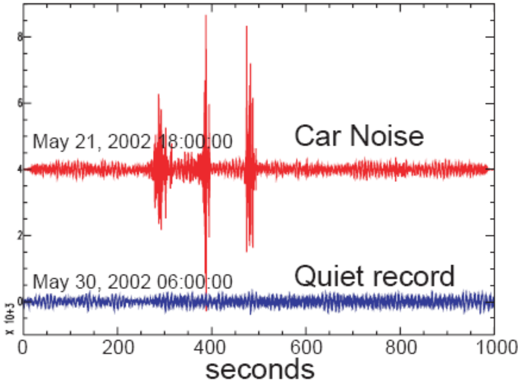


Table 3. Frequency content of road noise.

Study	Location	Frequency range (Hz)
Butler (1975)	Georgia, Alabama	2–50
Coward et al. (2003)	Australia	5–30
Holub (1998)	Czech Republic	3–25
Long (1993)	Georgia	1–50
Schofield et al. (2000)	Washington	1–50; 4–12 peak
Lombaert and Degrande (2001)	The Netherlands (test track)	5–40 (speed dependent)

WIND NOISE

- Withers et al (1996)
  - Datil, New Mexico
    - Remote site, gentle topography
    - Sparse vegetation
    - Nearest road 12 km, lightly traveled
    - Nearest railroad 90 km
  - Depth: 0, 5, 43 and 85 m
  - Reduction 20 dB at 43 m
- Young et al (1996)
  - Amarillo, Texas
  - Depth: 3, 13, 30, 122, 305 m
- Features
  - Broadband noise: 1 – 60 Hz
  - Strong correlation with wind
  - 34 dB at 3 m, 10 dB at 305 m above LNM
  - Threshold increases with depth

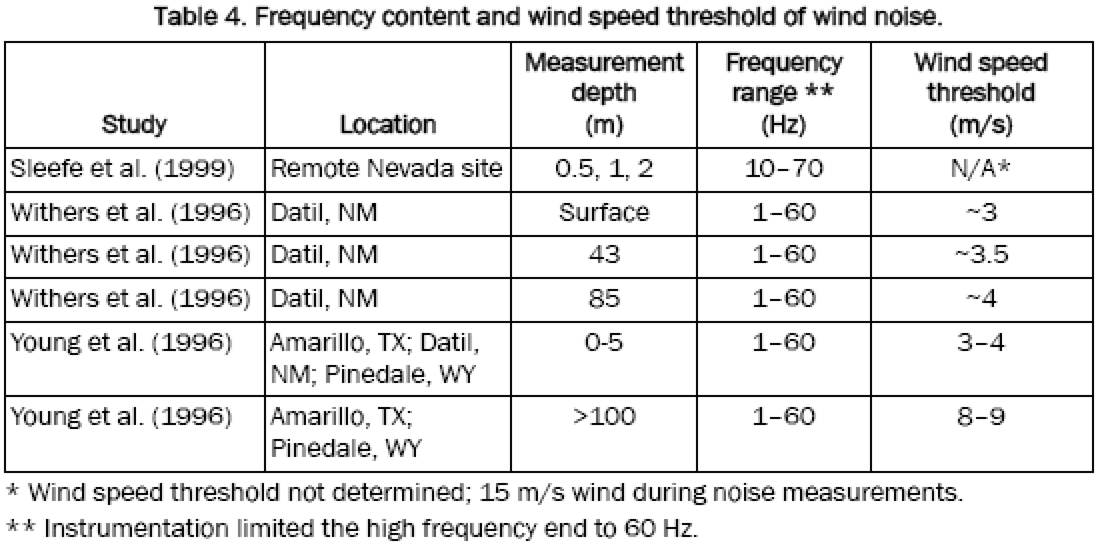


Table 4. Frequency content and wind speed threshold of wind noise.

Study	Location	Measurement depth (m)	Frequency range ** (Hz)	Wind speed threshold (m/s)
Sleefe et al. (1999)	Remote Nevada site	0.5, 1, 2	10–70	N/A*
Withers et al. (1996)	Datil, NM	Surface	1–60	~3
Withers et al. (1996)	Datil, NM	43	1–60	~3.5
Withers et al. (1996)	Datil, NM	85	1–60	~4
Young et al. (1996)	Amarillo, TX; Datil, NM; Pinedale, WY	0-5	1–60	3–4
Young et al. (1996)	Amarillo, TX; Pinedale, WY	>100	1–60	8–9

* Wind speed threshold not determined; 15 m/s wind during noise measurements.

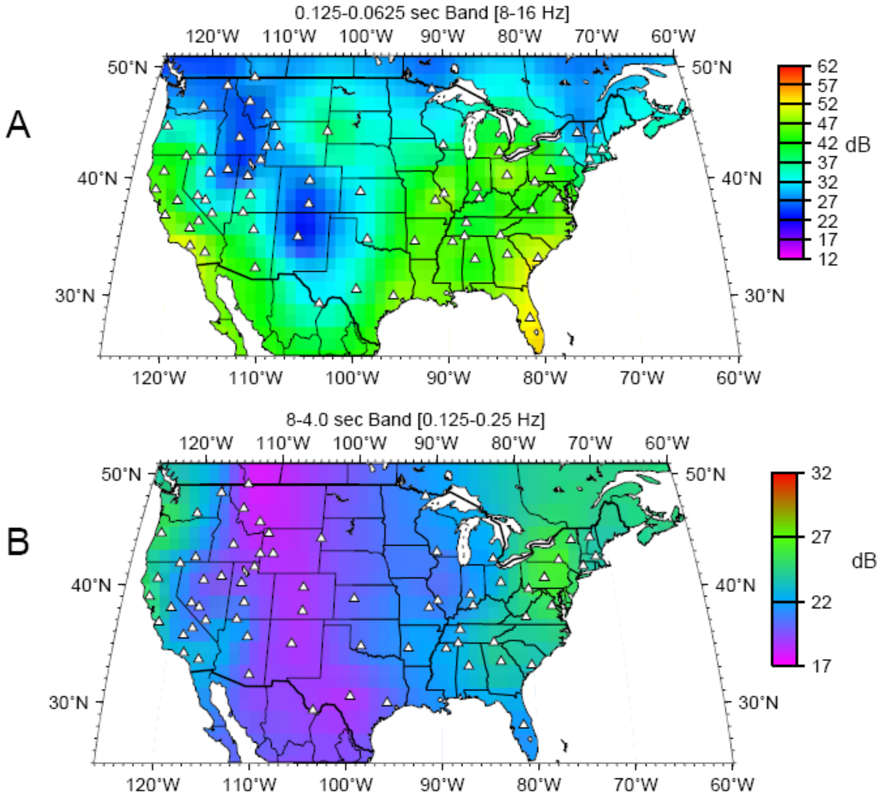
** Instrumentation limited the high frequency end to 60 Hz.

Young, C.J., E.P. Chael, M.M. Withers, and R.C. Aster. 1996. A comparison of the high-frequency (>1 Hz) surface and subsurface noise environment at three sites in the United States. *Bulletin of the Seismological Society of America* 86: 1516–1528.

Withers, M.M., R.C. Aster, C.J. Young, and E.P. Chael. 1996. High-frequency analysis of seismic background noise as a function of wind speed and shallow depth. *Bulletin of the Seismological Society of America* 86: 1507–1515.

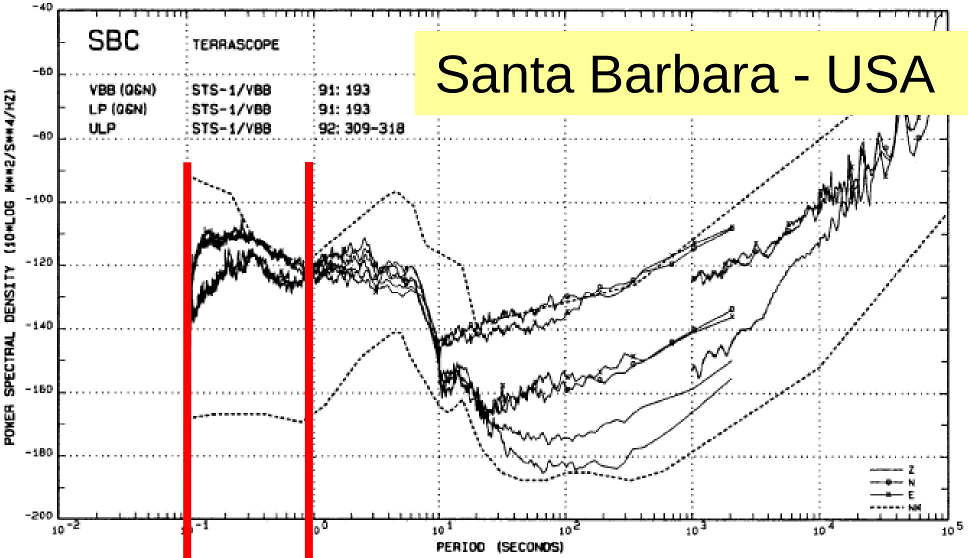
GEOGRAPHIC VARIATIONS

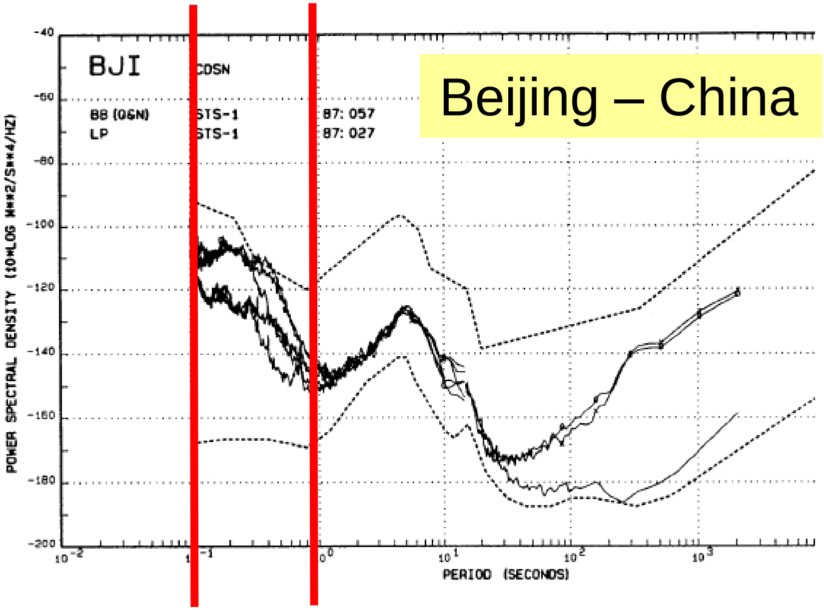
- McNamara & Buland USGS 2004
  - Strongest geographical dependence > 1 Hz (diagram A)
  - East coast up to 50 dB above NLNM (Cultural noise)
  - Microseismism along coast (diagram B)
  - Continental interior NLNM +10 dB

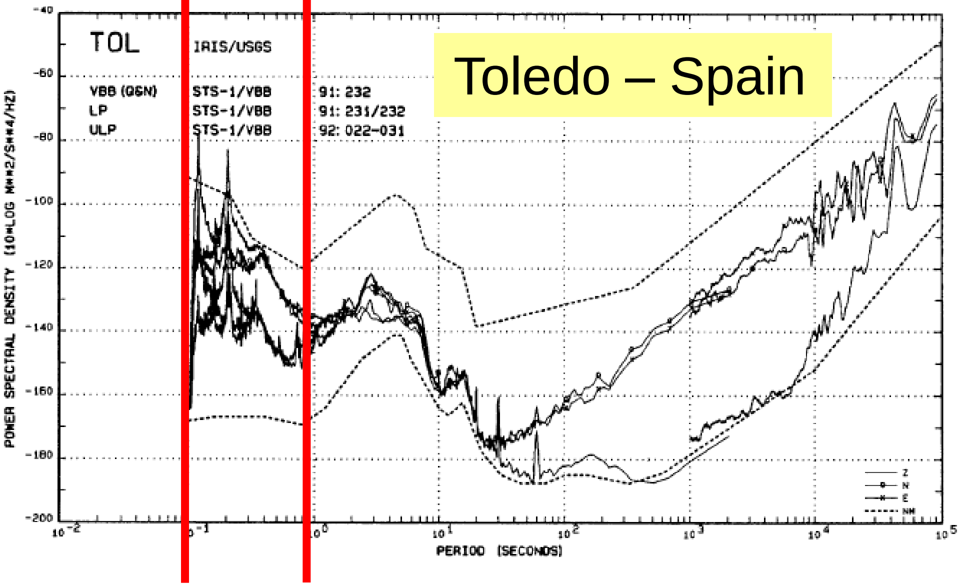


GENERAL OBSERVATIONS 1 – 10 Hz

- Alluvium
  - PSD larger by about 40 dB compared to hard rock


Santa Barbara - USA

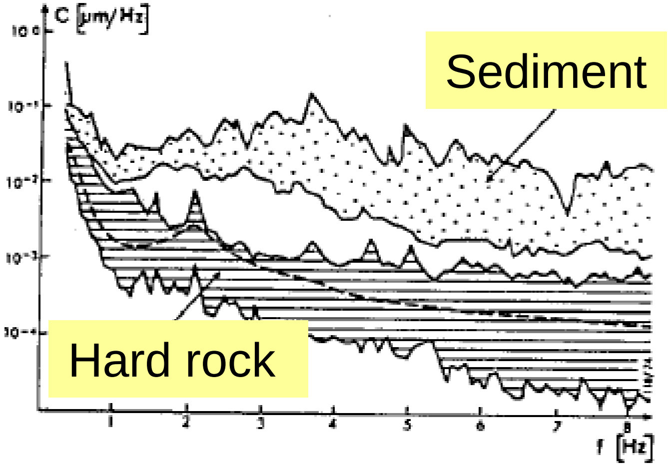

Beijing – China


Toledo – Spain

STEINWACHS (HANNOVER PHD THESIS 1969)

From Fischer at SLAC

Vertical seismic noise in Fed. Rep. Germany

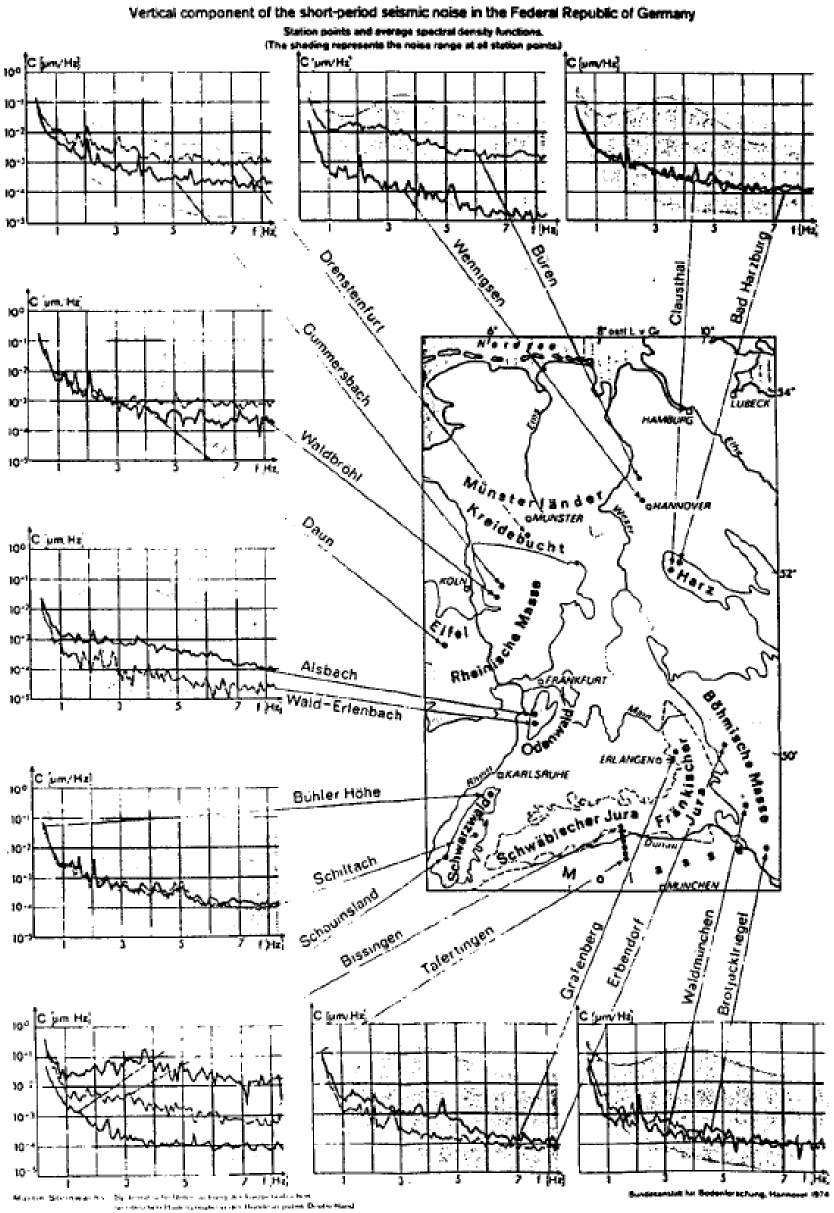


Sediment

Hard rock

Abb. 25: Bereiche der spektralen Dichtefunktionen von Stationspunkten auf Lockersedimenten und auf Festgestein. Zum Vergleich zeigt die unterbrochene Linie das typische Bodenunruhespektrum einer guten kontinentalen Erdbebenstation nach BERCKHEMER (1970).

Fig. 25: Ranges of the spectral density functions for station points located on unconsolidated sediments and bedrock. In comparison the dashed line characterizes the typical noise spectrum at a good continental station after BERCKHEMER (1970).



STEINWACHS (1969)

Vertical seismic noise in Fed. Rep. Germany

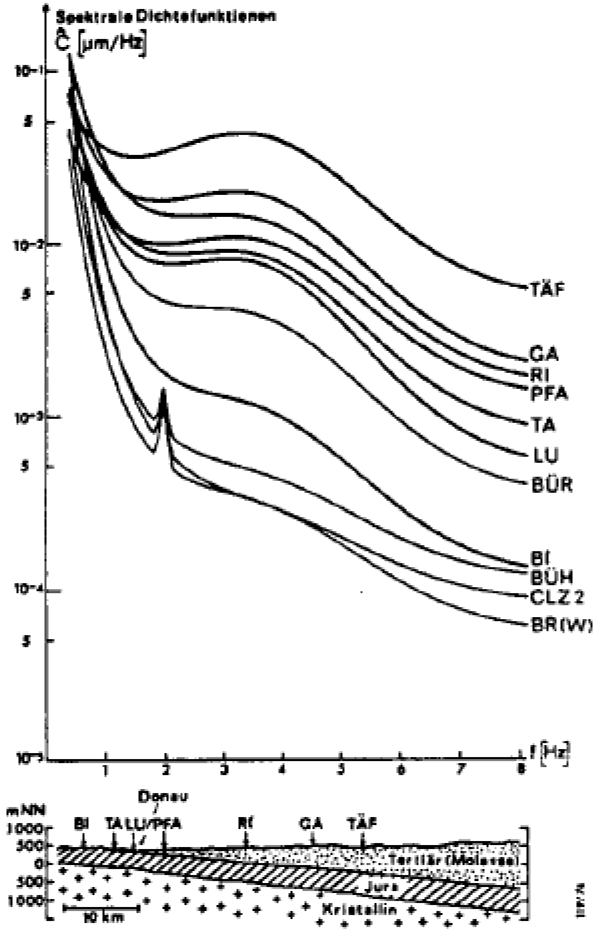
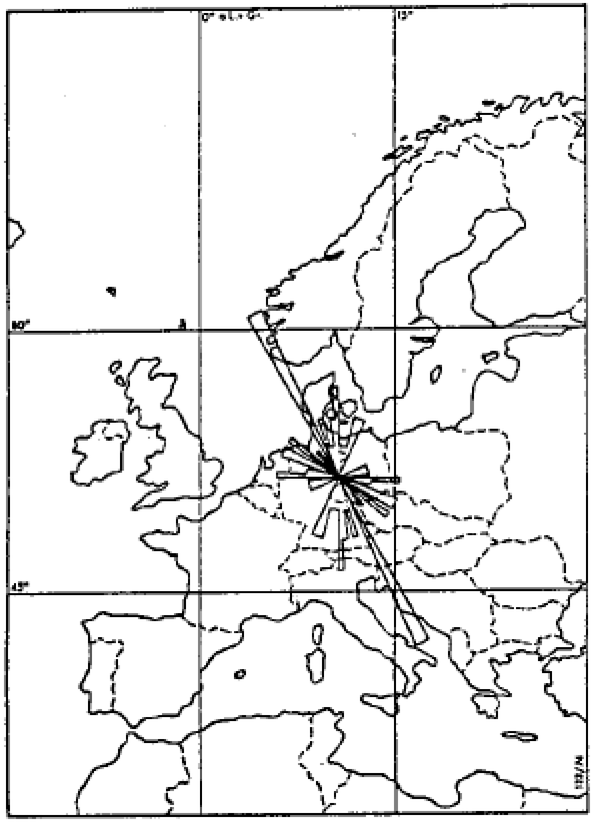


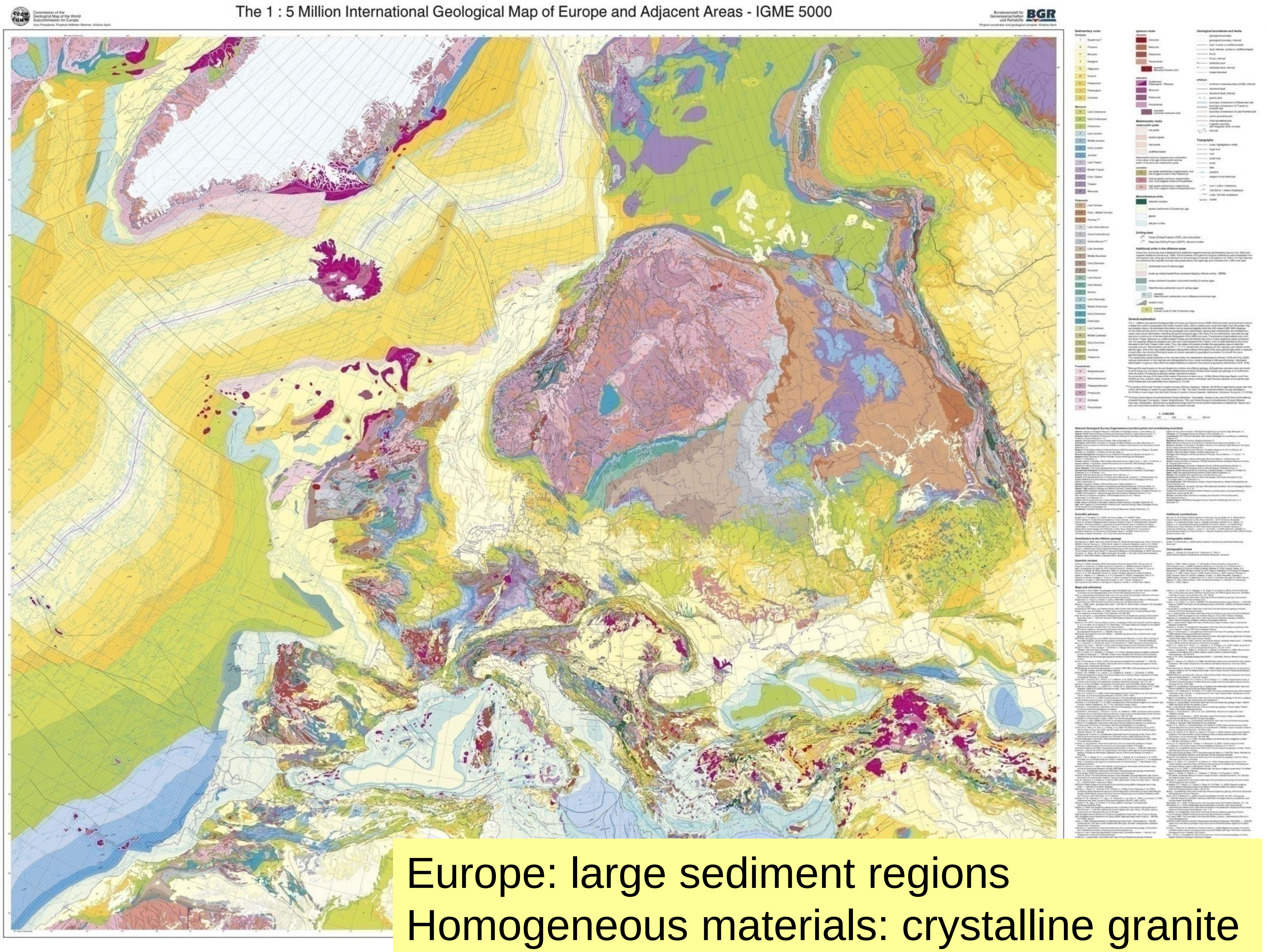
Fig. 126: Average spectral density of the vertical seismic noise along a profile in the Molasse. (The curves are fitted with exponential functions because of the strong oscillations of the spectral density functions.)

Directional analysis 2 Hz noise



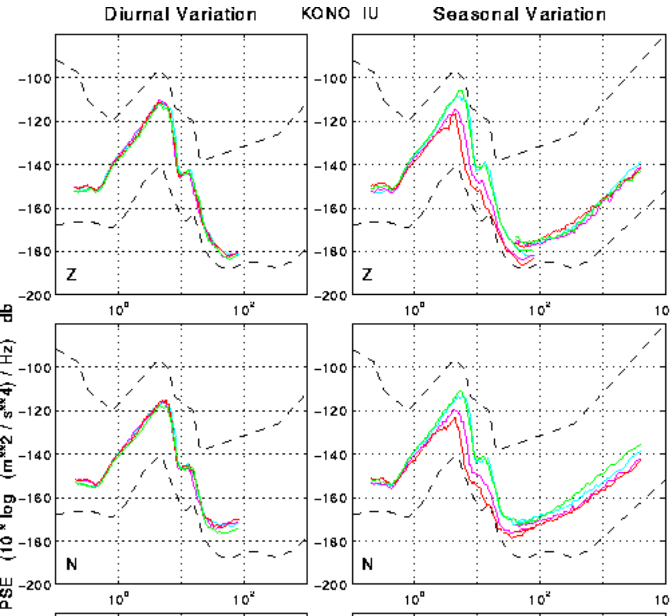
29: Peilungsfigur der horizontalen 2-Hz-Unruhe (20. 3. 69, 20.30 Uhr, Waldmünchen).

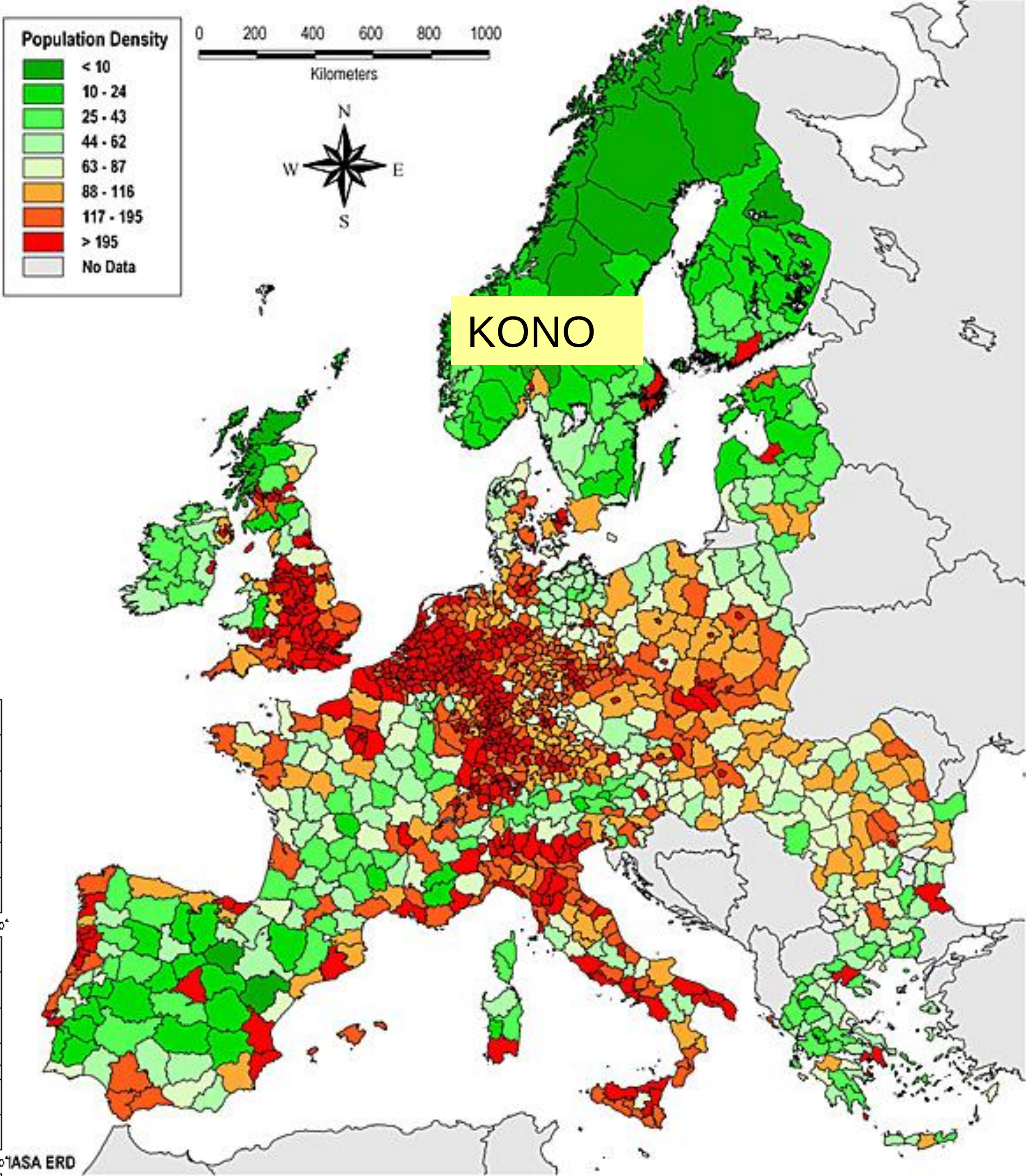
29: Characteristic of the directions of the horizontal 2-Hz seismic noise (20 March 1969, 20:30, Waldmünchen).



Europe: large sediment regions
Homogeneous materials: crystalline granite

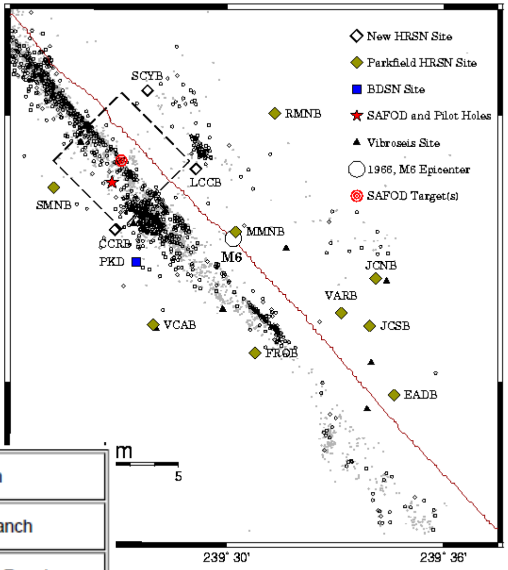
Kongsberg, Norway
Silver mine, 340 m depth



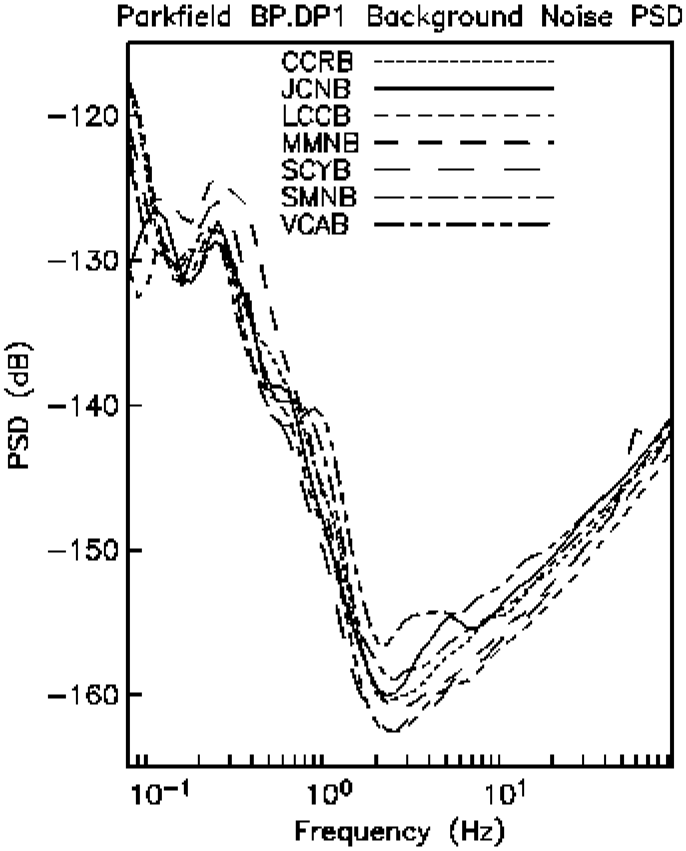


PARKFIELD AND SAFOD BOREHOLES

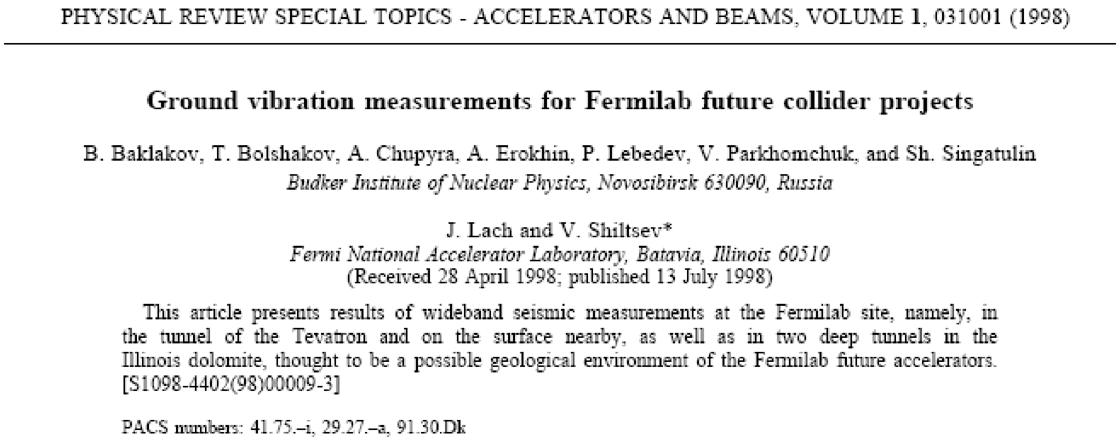
Depth: 63 – 572 m
At 1 Hz: ~1 nm/rtHz



Site	Net	Latitude	Longitude	Surf. (m)	Depth (m)	Date	Location
EADB	BP	35.89525	-120.42286	499	245	01/1988 -	Eade Ranch
FROB	BP	35.91078	-120.48722	542	284	01/1988 -	Froelich Ranch
GHIB	BP	35.83236	-120.34774	433	63	01/1988 -	Gold Hill
JCNB	BP	35.93911	-120.43083	559	224	01/1988 -	Joaquin Canyon North
JCSB	BP	35.92120	-120.43408	487	155	01/1988 -	Joaquin Canyon South
MMNB	BP	35.95654	-120.49586	731	221	01/1988 -	Middle Mountain
RMNB	BP	36.00086	-120.47772	1198	73	01/1988 -	Gastro Peak
SMNB	BP	35.97292	-120.58009	732	282	01/1988 -	Stockdale Mountain
VARB	BP	35.92614	-120.44707	511	572	01/1988 -	Varian Well
VCAB	BP	35.92177	-120.53424	790	200	01/1988 -	Vineyard Canyon
CCRB	BP	35.95716	-120.55161	601	251	05/2001 -	Cholame Creek



Tunnels and mines



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 1, 031001 (1998)

Ground vibration measurements for Fermilab future collider projects

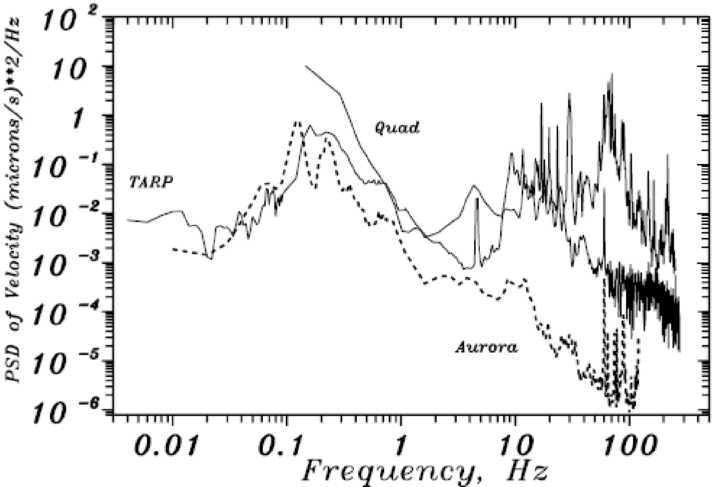
B. Baklakov, T. Bolshakov, A. Chupyra, A. Erokhin, P. Lebedev, V. Parkhomchuk, and Sh. Singatulin
Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

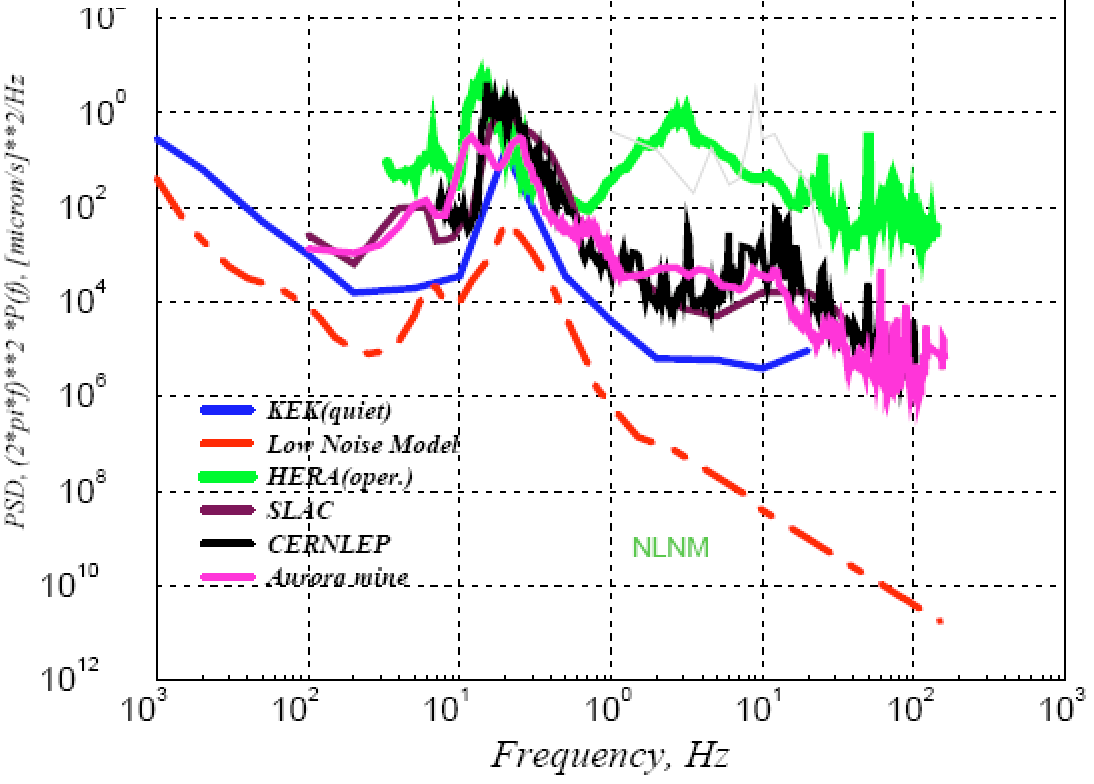
J. Lach and V. Shiltsev*
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(Received 28 April 1998; published 13 July 1998)

This article presents results of wideband seismic measurements at the Fermilab site, namely, in the tunnel of the Tevatron and on the surface nearby, as well as in two deep tunnels in the Illinois dolomite, thought to be a possible geological environment of the Fermilab future accelerators. [S1098-4402(98)00009-3]

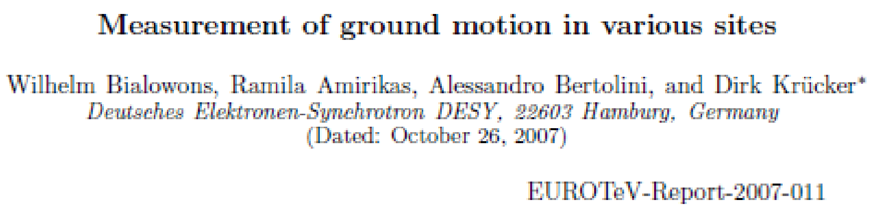
PACS numbers: 41.75.–i, 29.27.–a, 91.30.Dk

Aurora mine: near Fermilab, 80 m depth
At 1 Hz: ~1 nm/rtHz





ACCELERATOR SITE SPECTRA

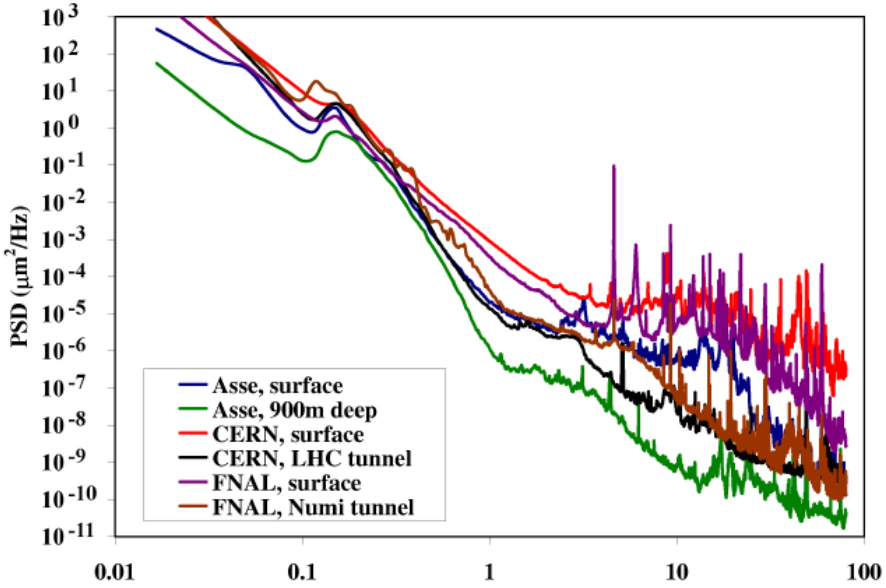


Measurement of ground motion in various sites

Wilhelm Bialowons, Ramila Amirikas, Alessandro Bertolini, and Dirk Krücker*
Deutsches Elektronen-Synchrotron DESY, 22603 Hamburg, Germany
(Dated: October 26, 2007)

EUROTeV-Report-2007-011

At 1 Hz:
Hiidenvesi cave: <1 nm/rtHz
Moxa station: 0.5 nm/rtHz
Asse 900 m: 0.5 nm/rtHz



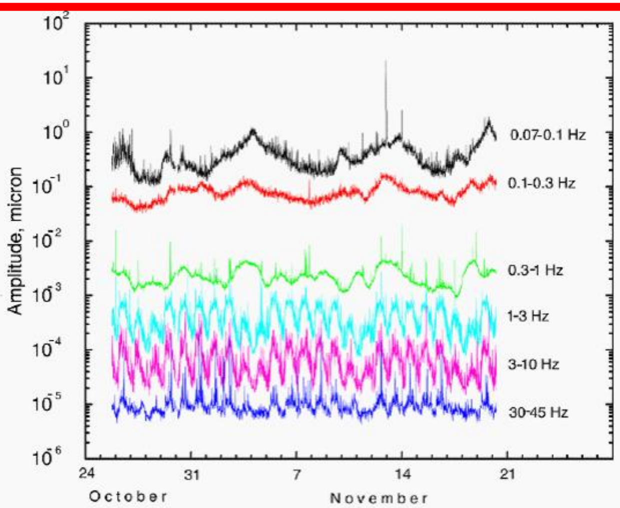
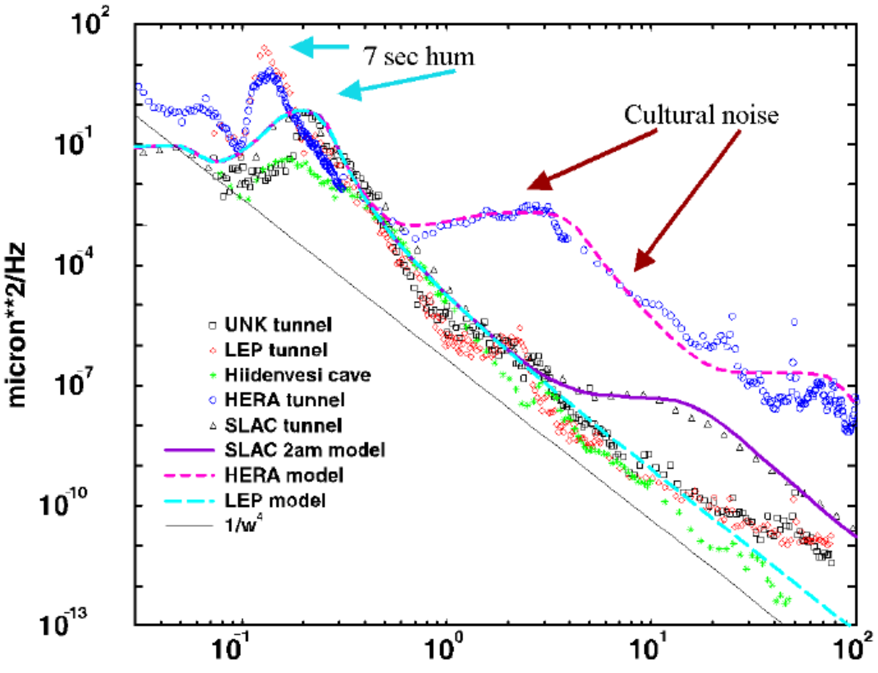
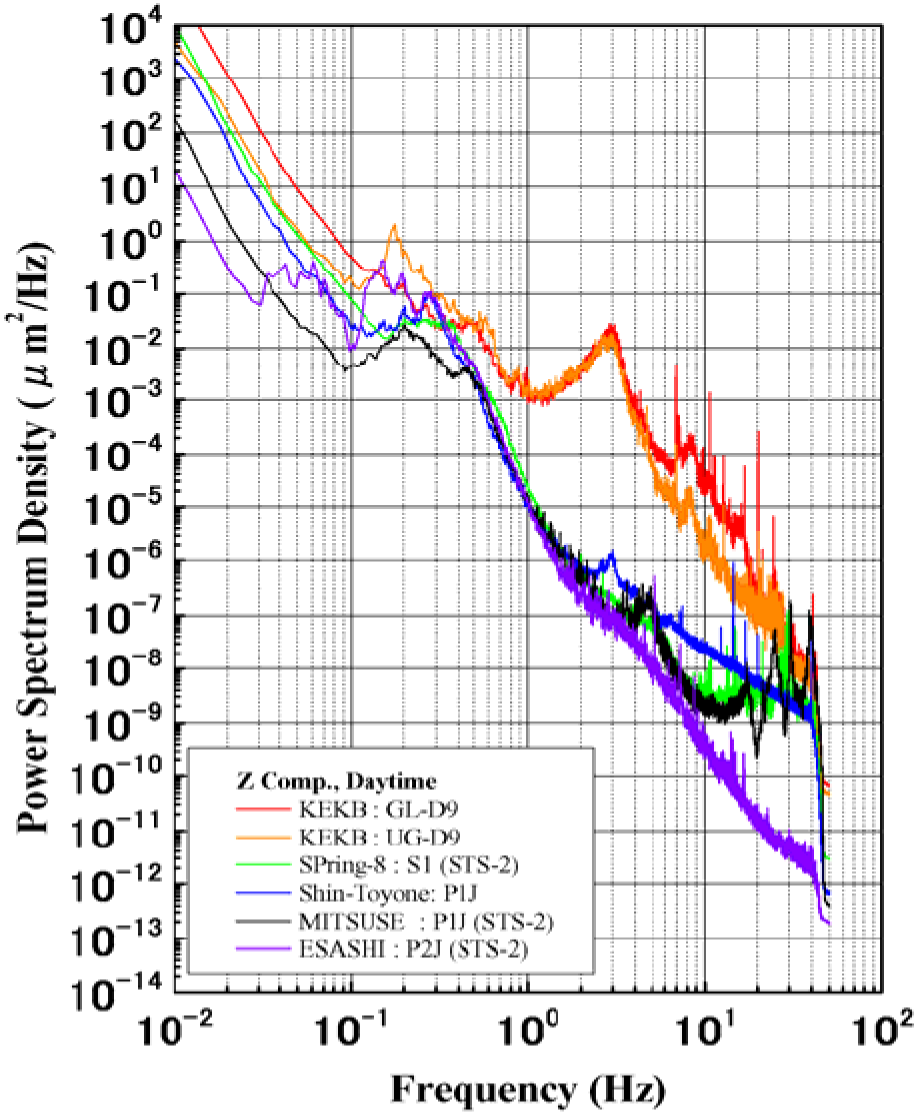
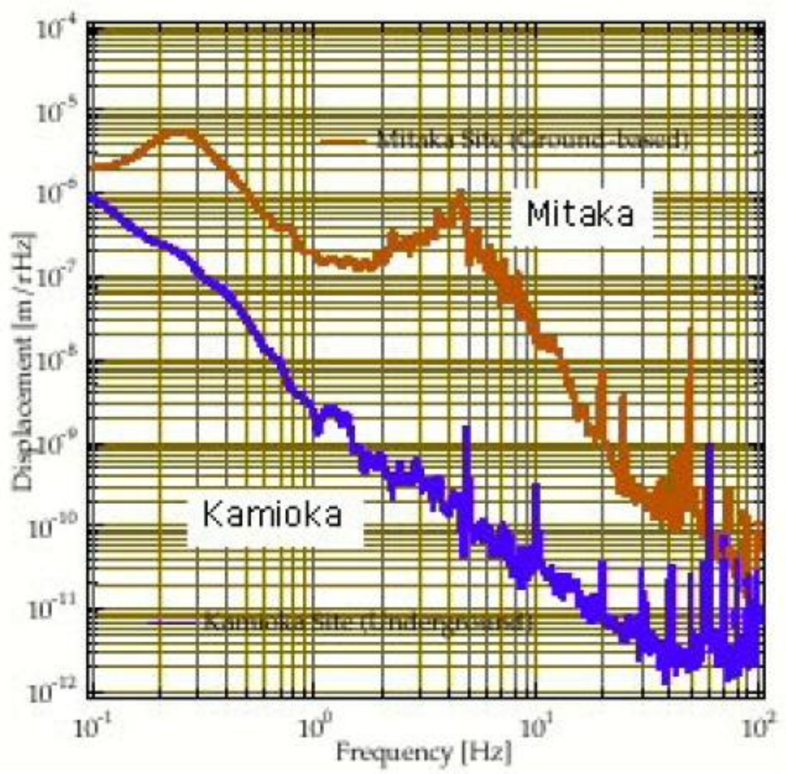


Figure 1: Ground motion measured in a typical quiet underground location: Hiidenvesi cave. RMS amplitude is shown in different frequency bands [10]. Natural ground motion is very low at high frequencies.



JAPANESE SITE SPECTRA





At 1 Hz:
Kamioka: 2 nm/rtHz
Shin-Toyone: 3 nm/rtHz

Compilation of sites (noise ≥ 1 Hz)

Site location	Average rms (nm)	σ (nm)	Day rms (nm)	Night rms (nm)
ALBA, Barcelona, Spain	18.8	9.5	42	9.1
ANMO Albaquerque NM	**0.3**			
APS, Argonne, U.S.A.	10.7	1	11	9.8
Asse, Germany (salt mine)	0.6	0.1	0.7	0.5
Aurora FNAL, USA (mine)	1			
BESSY, Berlin, Germany	75	28.1	140.7	53.1
BFO Black Forest	1			
BNL, Upton, U.S.A.	89.6	30.2	135.3	29.1
CERN LHC, Geneva, Switzerland	1.9	0.8	2.8	0.9
DESY HERA, Hamburg, Germany	53.3	18.9	77	34.8
DESY XFEL, Osdorf, Germany	29.1	11.9	48.4	19.5
DESY XFEL, Schenefeld, Germany	41.1	16.6	70	35.1
DESY, Zeuthen, Germany	64.4	40.4	75.6	88.5
Ellerhoop, Germany (TESLA IP)	18.2	8.4	35.9	9.3
ESRF, Grenoble, France	74	34.9	137.2	40.2
FNAL, Batavia, U.S.A.	3	0.9	4	2.2
Hiidenvesi (cave), Finland	0.5			
IHEP, Beijing, China	8.5	0.5	9	8.1
Kamioka, Japan	2			
KEK, Tsukuba, Japan	80.5	36	125.1	38
LAPP, Annecy, France	3.6	1.6	7	1.9
Moxa, Germany (seismic station)	0.6	0.1	0.9	0.5
QSPA Antarctica	0.1			
RSSD Blackhill SD	1			
Shin-Toyone, Japan (tunnel)	3			
SLAC, Menlo Park, U.S.A.	4.9	1.2	7.4	4.1
Spring-8, Harima, Japan	2	0.4	2.5	1.8
SSRF, Shanghai, China *	292	164	444	102

For ILC database:
see vibration.desy.de

Various suitable sites exist (in principle)

SUMMARY

- Site selection
  - Possible sites feature
    - Ambient seismic noise around 1 nm/rtHz at 1 Hz
    - For frequencies > 1 Hz noise depends on $1/f^2$
    - (Use as input for FEA)
  - Avoid the following locations
    - Islands, seacoast with violent storms
    - Sites near heavy industrialization
    - Sites with large population concentrations
  - Use hard geology
    - Good quality rock: e.g. granite
- Implement site policy
  - Care with continuously reciprocating machinery, (cryogenic) fluids
    - Replace above by high rpm machines, vibration isolated
  - Minimize traffic noise: good roads, speed limits, stop signs