Long-Period Seismometry

Jonathan Berger

Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California San Diego

Basics

- Measure motion of Earth's surface relative to some inertial reference frame
- Applied to a mass-on-a-spring suspension, in the Laplace domain:

$$Mass\ Pos(s) = G \frac{1}{s^2 + \frac{{}_0}{Q} s + {}^{2}_{0}} * Ground\ Acceleration(s)$$

$Where$

$G = constant \sim 1$

$and \quad M = mass, \quad {}_0 = 2\#/P_0, \ P_0 = free\ period$

$Q = 1/2 \quad , \quad = damping\ constant$

- For frequencies much smaller than the resonant frequency, ω_0, mass position is proportional to ground acceleration.
- The smaller the resonant frequency the larger the mass motion for a given ground acceleration.

$$Mass\ Pos(s) = \frac{G}{\omega_0^2} * Ground\ Acceleration(s)$$

$$as\ s \rightarrow 0$$

WHAT ARE THE REQUIRMENTS

- What do we want to measure - SIGNALS
- How accurately do we want to measure – RESOLUTION
- Over what frequencies do we want to measure - BANDWIDTH

What Bandwidth is Required

- Gravest Normal Mode – 0.3 mHz
- Top end of Teleseismic signals ~ 1 Hz
- Top end of Regional Signals ~ 10 Hz
- Top end of Strong Motion ~ 30 Hz

WHAT IS THE REQUIRED RESOLUTION?

- WHAT IS THE EARTH'S AMBIENT NOISE FIELD?
- LOOK AT LOWEST OBSERVED NOISE LEVELS TO ESTIMATE REQUIRED RESOLUTION - A MOVING TARGET

NOISE

Brune & Oliver, 1959

"There are virtually no data on noise in the range of periods between 20 seconds and the earth tide periods."

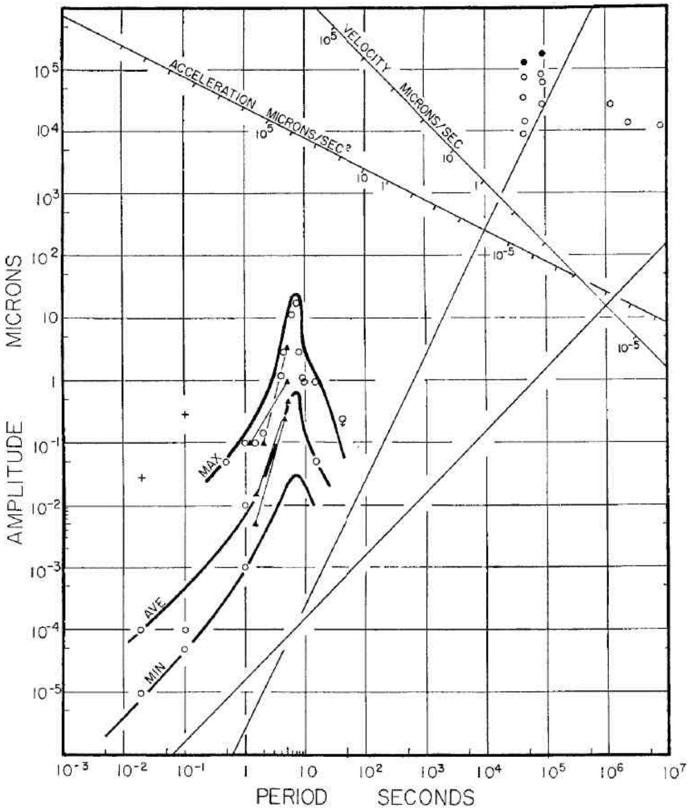
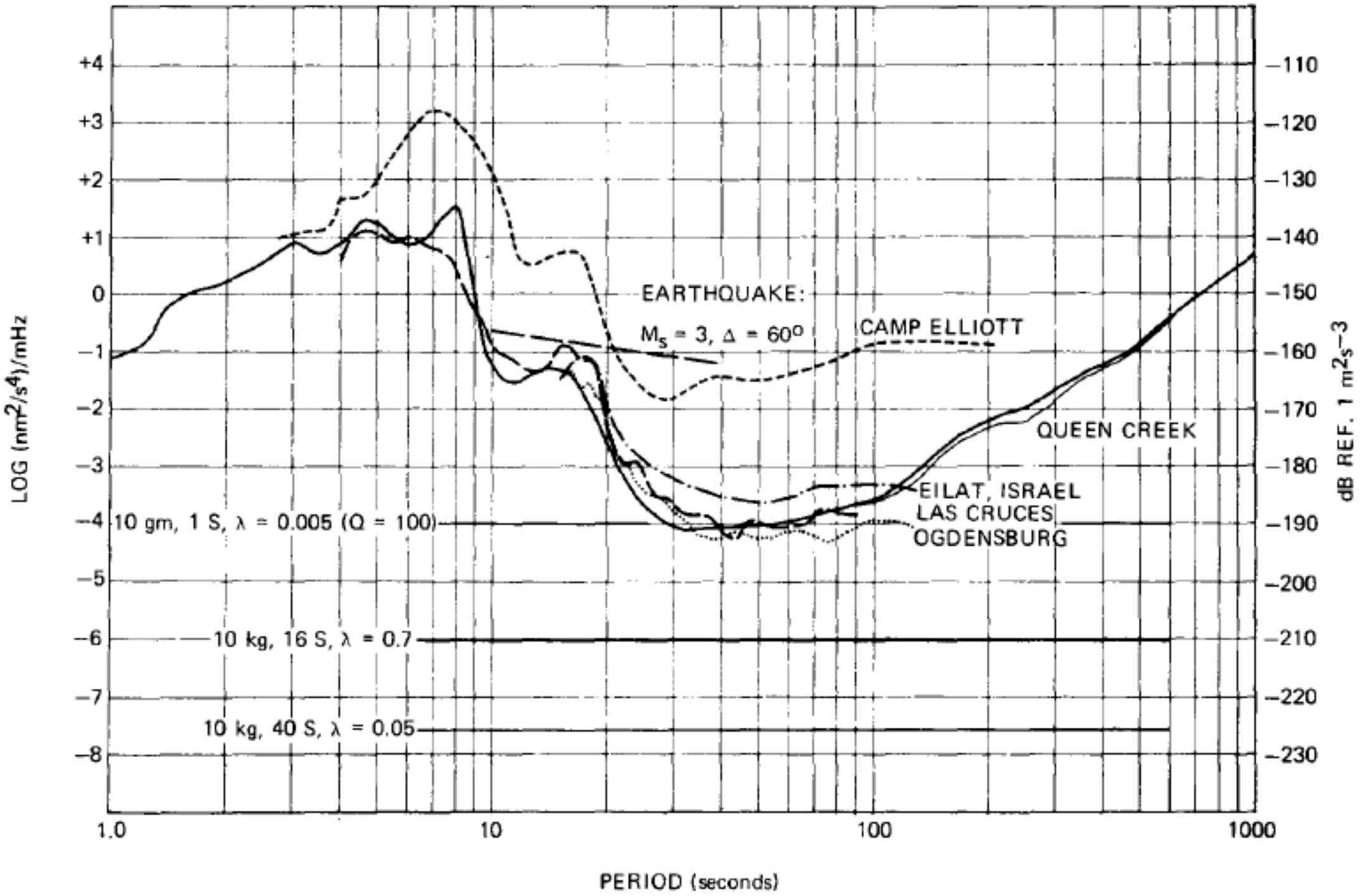


Fig. 1. The seismic noise of the earth's surface.

Melton, 1976



+4
+3
+2
+1
0
−1
−2
−3
−4
−5
−6
−7
−8
LOG (nm^2/s^4)/mHz
−110
−120
−130
−140
−150
−160
−170
−180
−190
−200
−210
−220
−230
dB REF. 1 m^{2}s^{-3}
1.0
10
100
1000
PERIOD (seconds)
EARTHQUAKE:
M_s = 3, Δ = 60°
CAMP ELLIOTT
QUEEN CREEK
EILAT, ISRAEL
LAS CRUCES
OGDENSBURG
10 gm, 1 S, λ = 0.005 (Q = 100)
10 kg, 16 S, λ = 0.7
10 kg, 40 S, λ = 0.05

Agnew & Berger (1978)

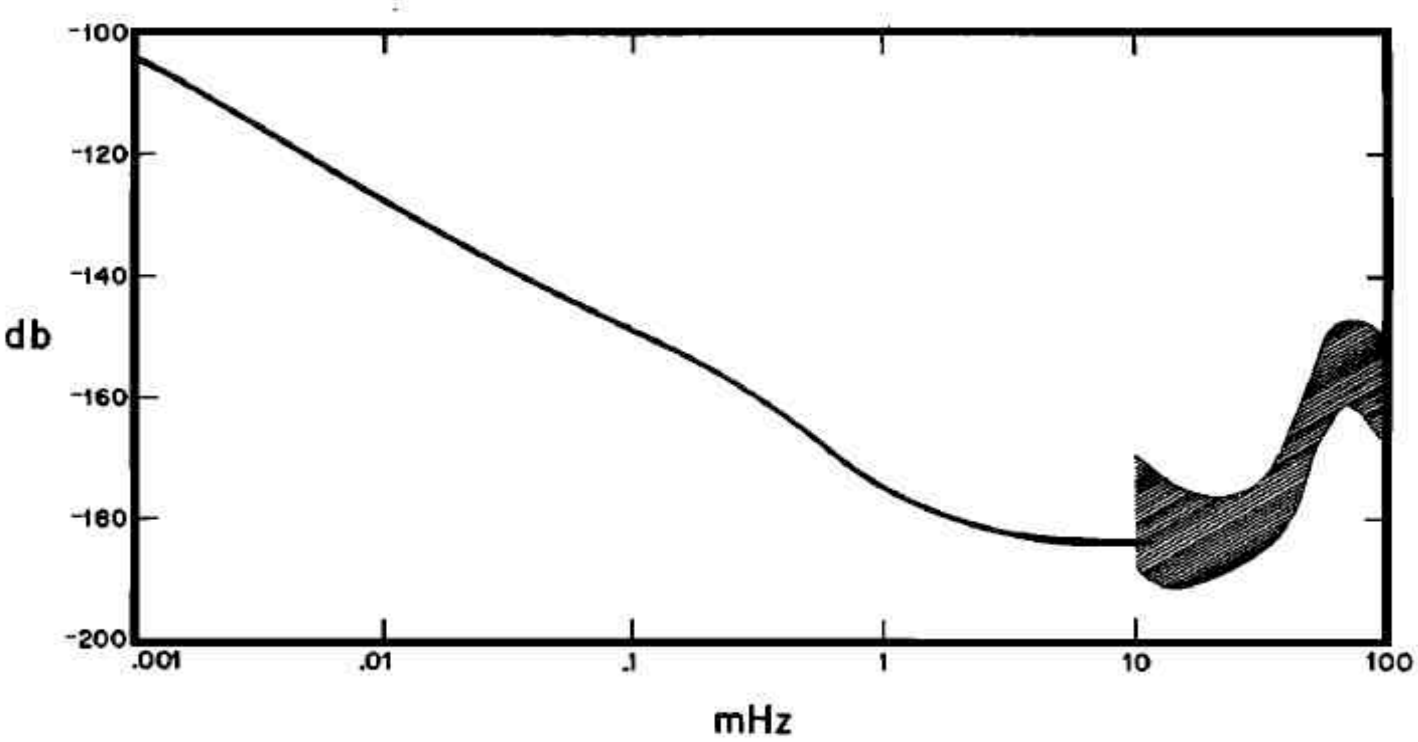
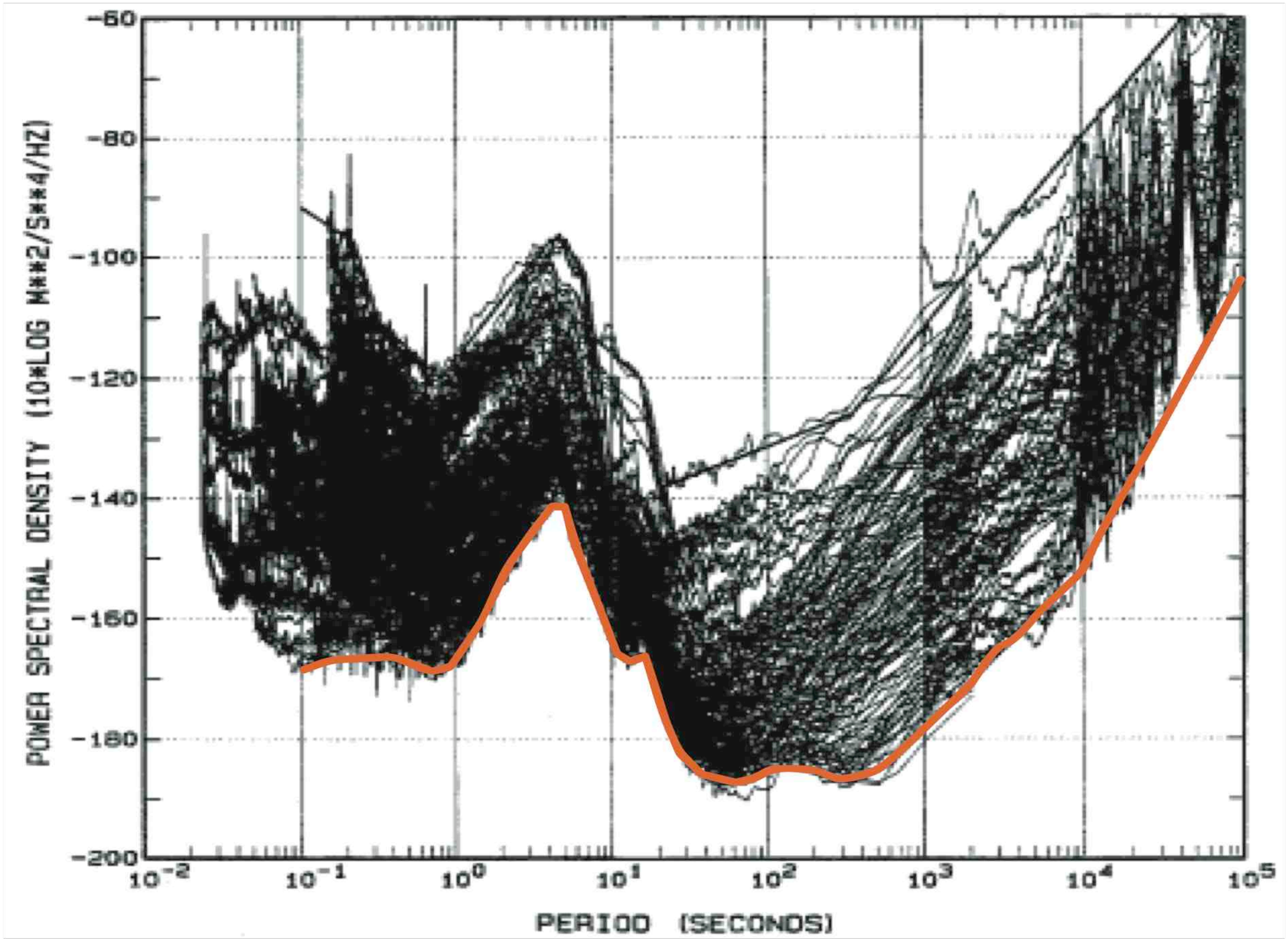
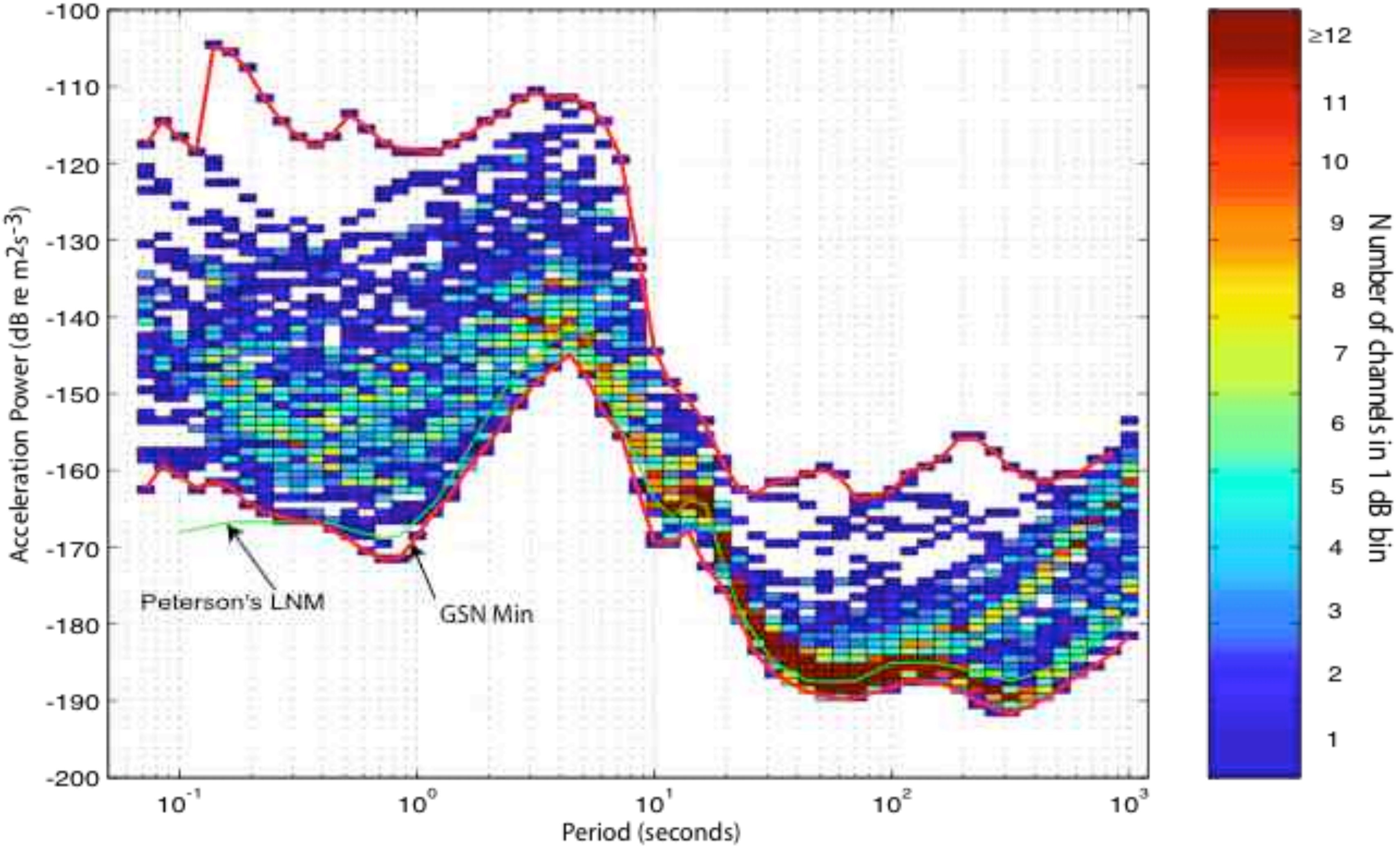


Fig. 5. Vertical ground noise as a function of frequency. The vertical axis is power spectral density in decibels relativ to $1\ m^2\ s^{-3}$. The shaded area to the right of 10 mHz shows the range of noise found at HGLP stations [*Murphy an Savino*, 1975]. The line to the right shows the ground noise at Piñon Flat, the quietest of the Project IDA stations, base on data from the superconducting and Project IDA gravimeters.

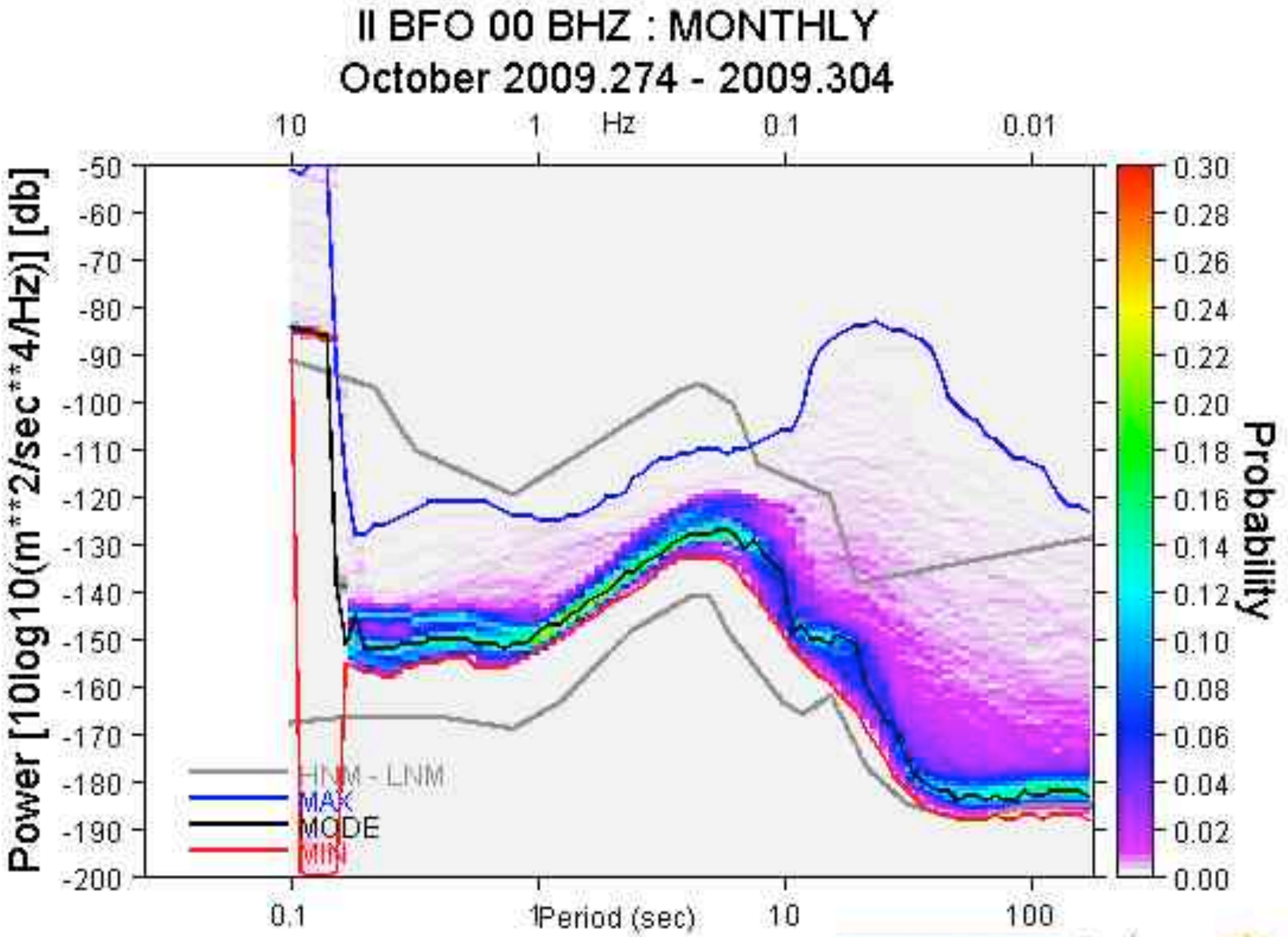
Peterson 1993
(aka USGS NLNM)



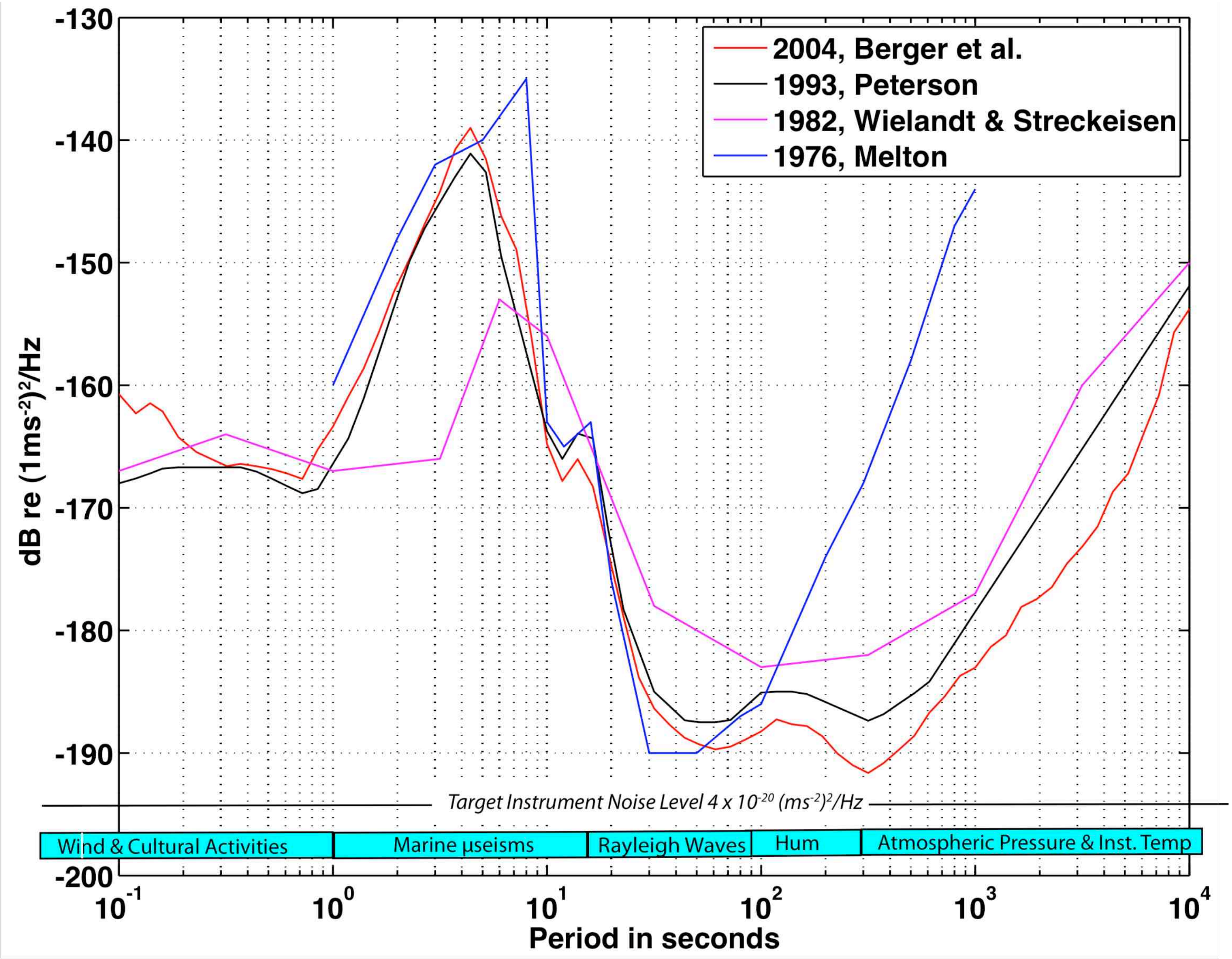
GSN 1st Percentile Noise



Routine Noise Estimation



Evolution of Noise Models



Want to resolve 4 $x10^{-20}(m^2 s^{-4})/Hz$

$$Mass\ Pos(s) = \frac{G}{{}^{2}_{0}} * Ground\ Acceleration(s)$$

$as\ s\ \#\ \ 0$

Which at long periods corresponds to

rms. mass displacement = $5\,x^{-12} * P_0^{\,2}\ m/\sqrt{Hz}$

[Radius of H atom ~ $4x10^{-11}$ m]

Free Period P_0 **Seconds**	**Mass Displacement** **$m/\sqrt{Hz}$**
0.1	**5×10^{-14}**
1	**5×10^{-12}**
10	**5×10^{-10}**

Thermal Issues

- Thermal noise of a damped harmonic oscillator
- Thermal expansion of seismometer suspension
- Thermoelastic effect of seismometer spring
- Environmental protection

$$Thermal\ \ Acceleration = \frac{8\ \ \#T}{mP_0Q} \quad \frac{10^{\%19}}{mP_0Q}(m/s^2)^2/H$$

Where

κ – Boltzmans Constant

T – Temperature in Kelvin degrees ~ 290K°

m – Mass (kg), P_0 – Free Period (s)

Q – Quality Factor of spring (damping)

Example, m= 0.5kg, P_0 = 10s, Q= ½ mP_0Q = 2.5

Thermal Noise = 4 x 10^{-20} $(ms^{-2})^2$/Hz

- Temp coefficient of seismometer "material" > 10^{-5}/C°

- Want to resolve long-period accelerations ~ $10^{-11}\,\partial g/g$
  Implies temperature stability ~ 1 μC°

- How to get μC° temperature stability?
- Thermostating is impractical.

- Want to minimize seismometer's ability to exchange thermal energy with its surroundings.

- Vault, borehole, enclosure, …

$$\frac{u}{t} = \# \; {}^{2}u = \frac{\%}{\& c_p} \; {}^{2}u$$

Where u = u(t, x, y, z) is temperature as a function of time and space.

α - **Thermal Diffusivity** in $m^2/s = \kappa/\rho\, c_p$

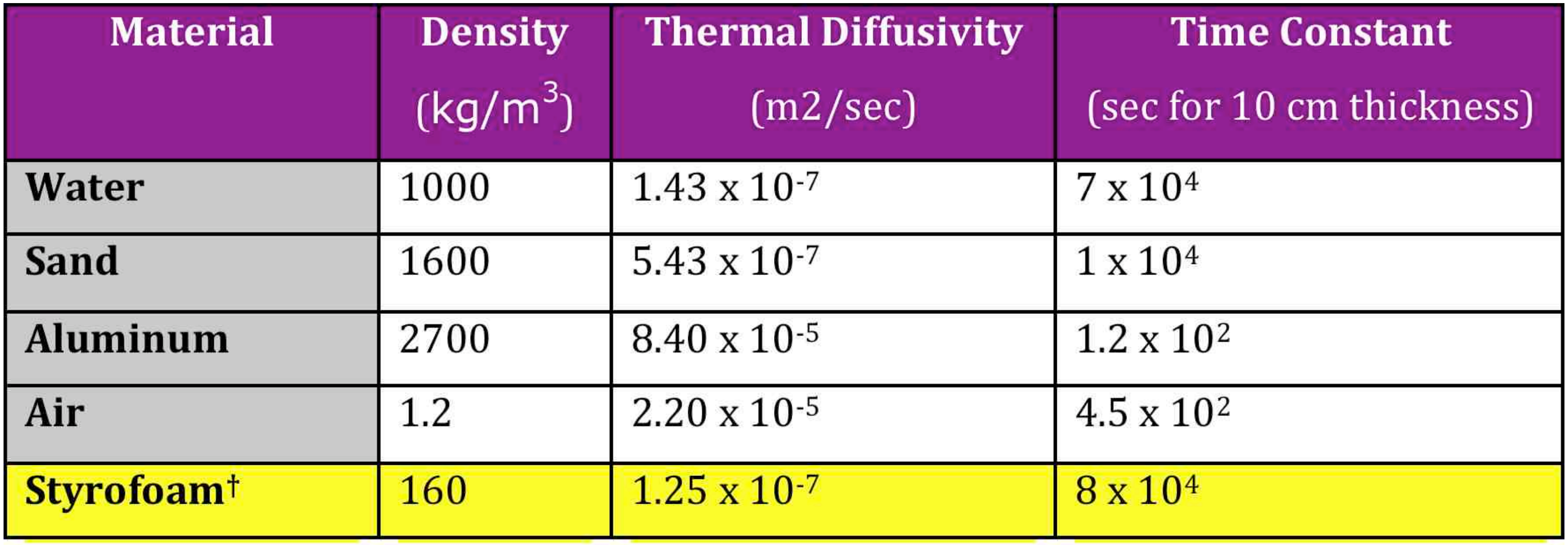
Substances with high thermal diffusivity rapidly adjust their temperature to that of their surroundings, because they conduct heat quickly in comparison to their volumetric heat capacity or 'thermal bulk'.

κ- **Thermal conductivity** in W/m.K°

ρc_p – **Volumetric Heat Capacity** in J/m^3.K°

Thermal Time Constant

The time constant for heat applied at the surface of a 1-D insulating body with thermal diffusivity α to penetrate a distance L



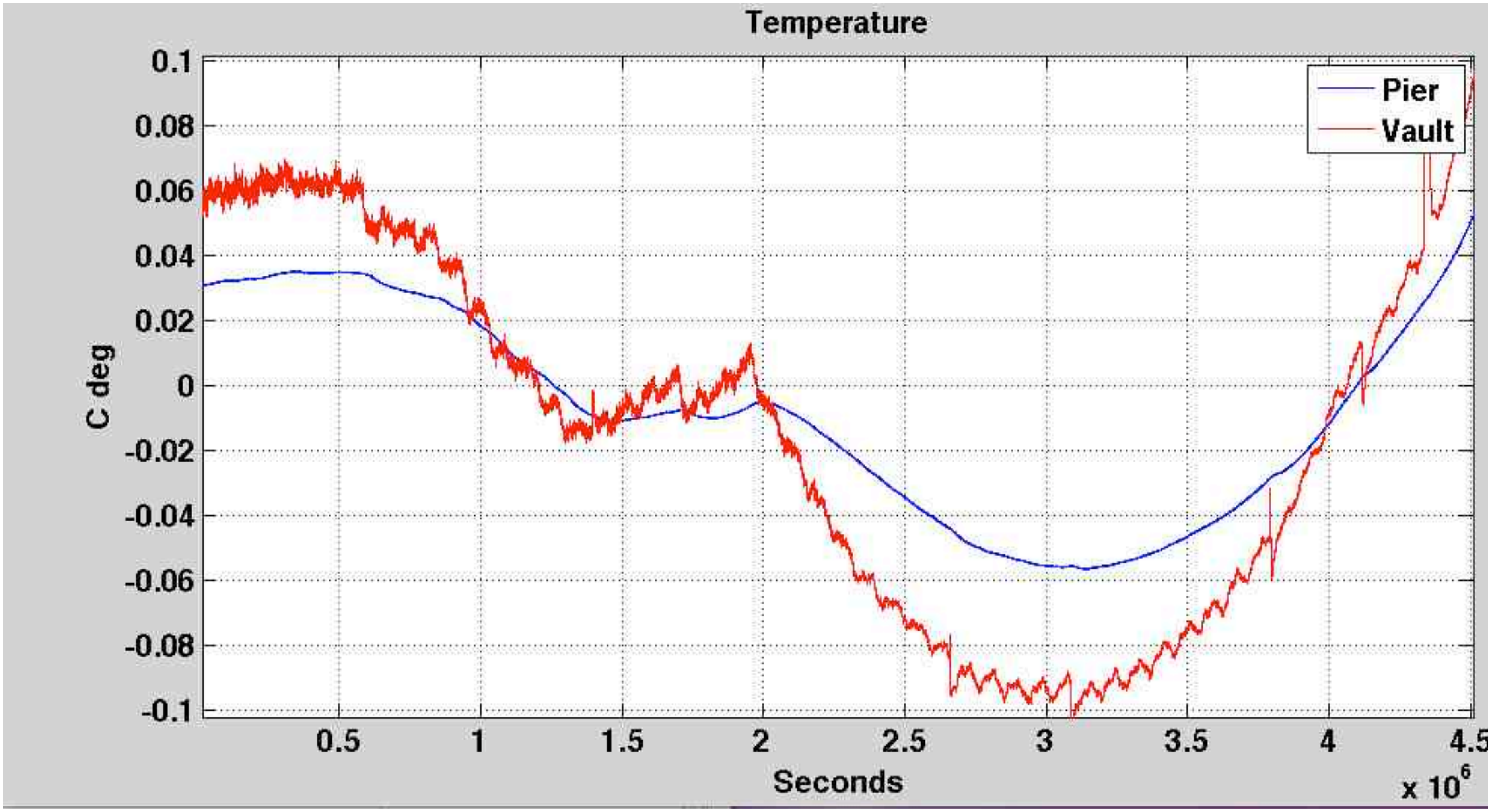
Material	Density (kg/m^3)	Thermal Diffusivity (m2/sec)	Time Constant (sec for 10 cm thickness)
Water	1000	1.43×10^{-7}	7×10^{4}
Sand	1600	5.43×10^{-7}	1×10^{4}
Aluminum	2700	8.40×10^{-5}	1.2×10^{2}
Air	1.2	2.20×10^{-5}	4.5×10^{2}
Styrofoam†	160	1.25×10^{-7}	8×10^{4}

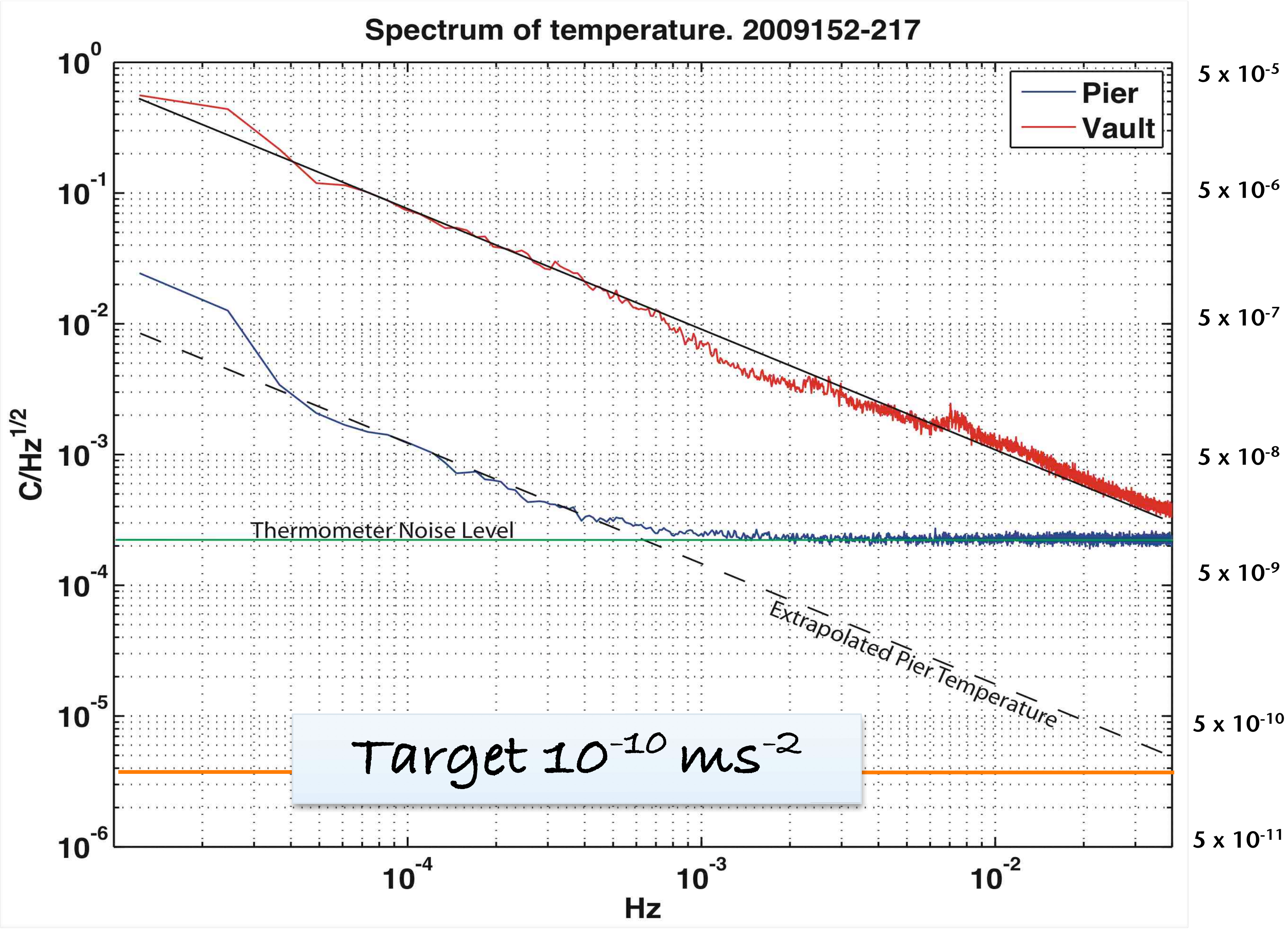
† - LastAfoam 6700

STS1 Suspension

- Spring is a bi-metal structure designed to reduce temperature effects.
- Observed TC of suspension ~ 3.5×10^{-5} m/C° or, with a free period of 20 s ~ 4.5×10^{-6} ms^{-2}/C°
- To resolve long-period rms of 10^{-10} ms^{-2} we nee long-period temperature stability of ~20 µC°

Temperature in the Pinon Flat Observatory Vault

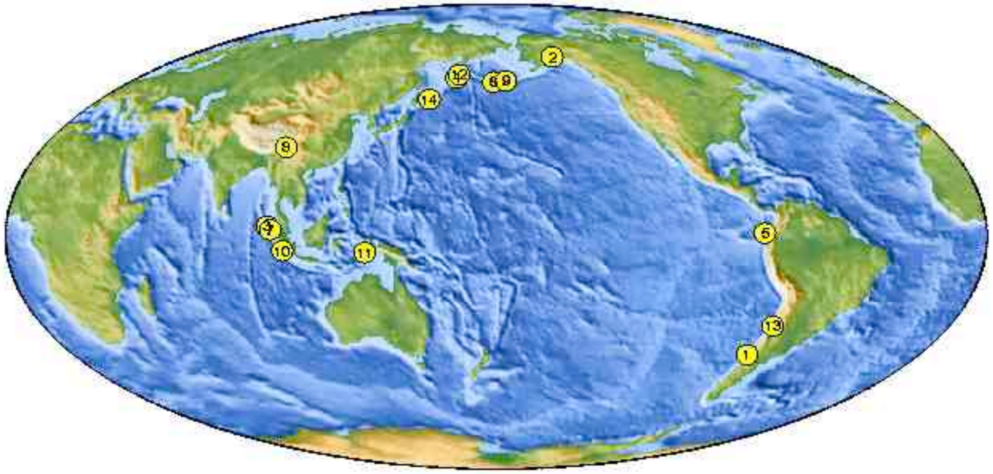




Target 10^{-10} ms^{-2}

SIGNALS

Largest Earthquakes in the World Since 1900

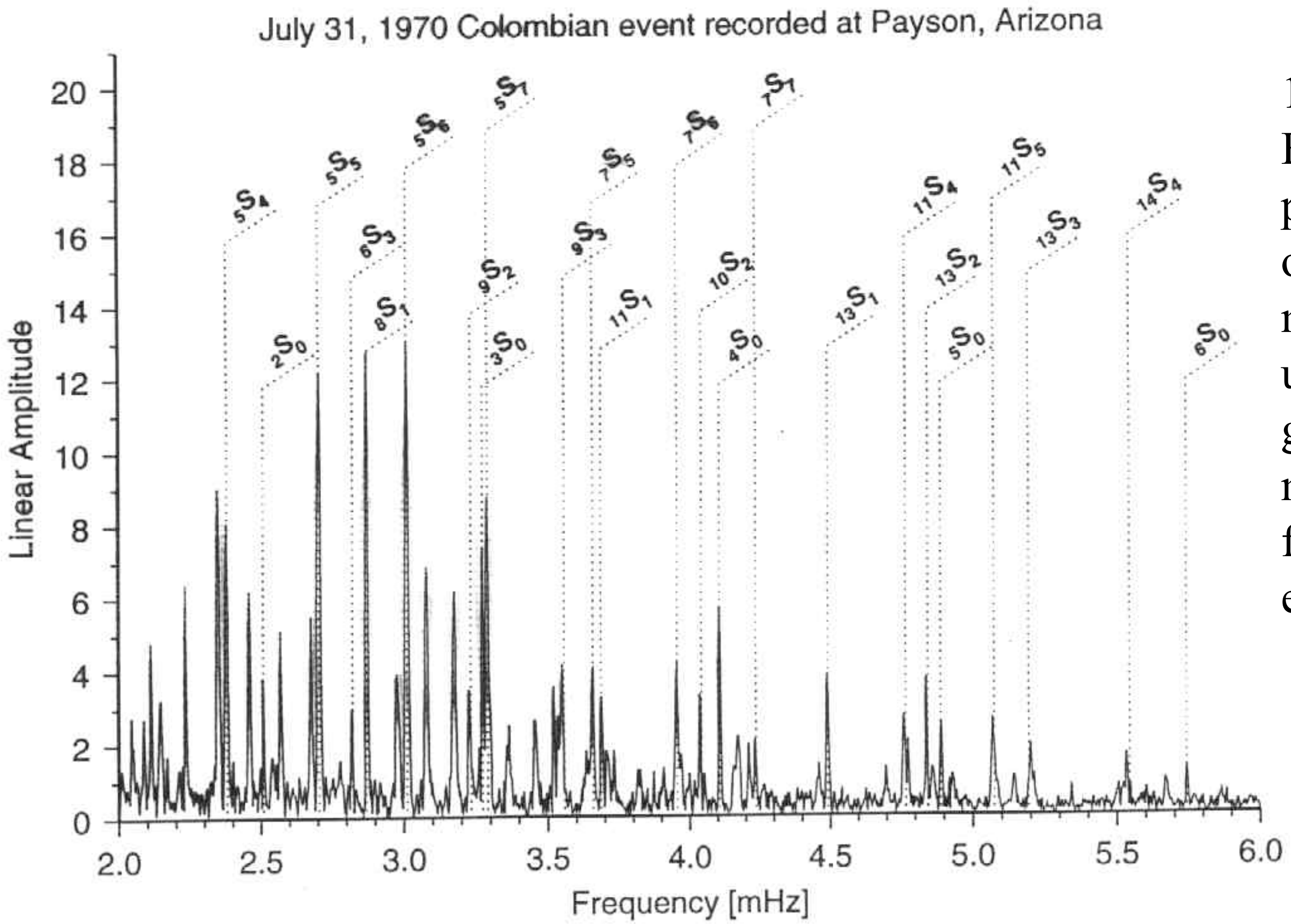


USGS National Earthquake Information Center

Google Earth KML
(requires Google Earth)

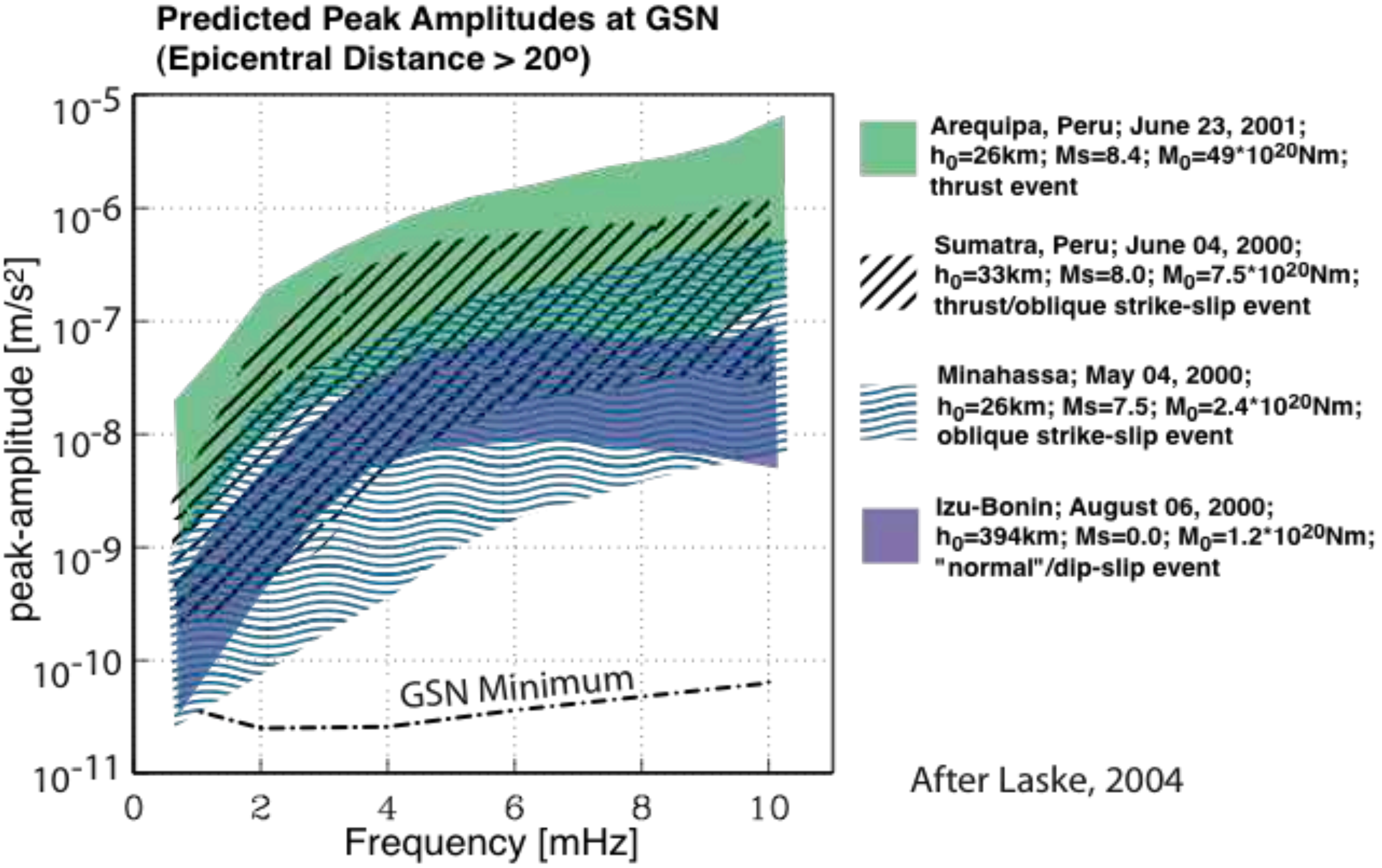
Prior to 1969 there were only a handful of Normal Mode observations, all from earthquakes > Mw 8.5

	Location		Date UTC	Magnitude	Lat.	Long.	Reference
1.	Chile	➡	1960 05 22	9.5	-38.24	-73.05	Kanamori, 1977
2.	Prince William Sound, Alaska	➡	1964 03 28	9.2	61.02	-147.65	Kanamori, 1977
3.	Off the West Coast of Northern Sumatra		2004 12 26	9.1	3.30	95.78	Park et al., 2005
4.	Kamchatka	➡	1952 11 04	9.0	52.76	160.06	Kanamori, 1977
5.	Off the Coast of Ecuador		1906 01 31	8.8	1.0	-81.5	Kanamori, 1977
6.	Rat Islands, Alaska	➡	1965 02 04	8.7	51.21	178.50	Kanamori, 1977
7.	Northern Sumatra, Indonesia		2005 03 28	8.6	2.08	97.01	PDE
8.	Assam - Tibet	➡	1950 08 15	8.6	28.5	96.5	Kanamori, 1977
9.	Andreanof Islands, Alaska	➡	1957 03 09	8.6	51.56	-175.39	Johnson et al., 1
10.	Southern Sumatra, Indonesia		2007 09 12	8.5	-4.438	101.367	PDE
11.	Banda Sea, Indonesia		1938 02 01	8.5	-5.05	131.62	Okal and Reymo
12.	Kamchatka		1923 02 03	8.5	54.0	161.0	Kanamori, 1988
13.	Chile-Argentina Border		1922 11 11	8.5	-28.55	-70.50	Kanamori, 1977
14.	Kuril Islands	➡	1963 10 13	8.5	44.9	149.6	Kanamori, 1977



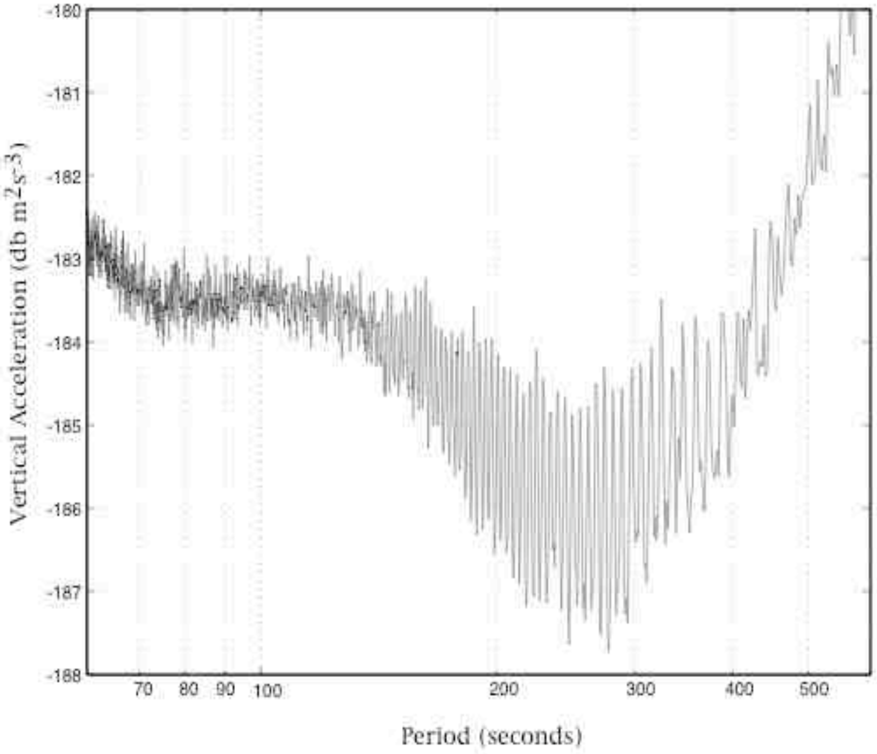
1970 Columbia Earthquake Mw produced first observations of mode overtones using LaCoste gravimeters modified with feedback for electronic record

Now routine processing Mw > 6.6



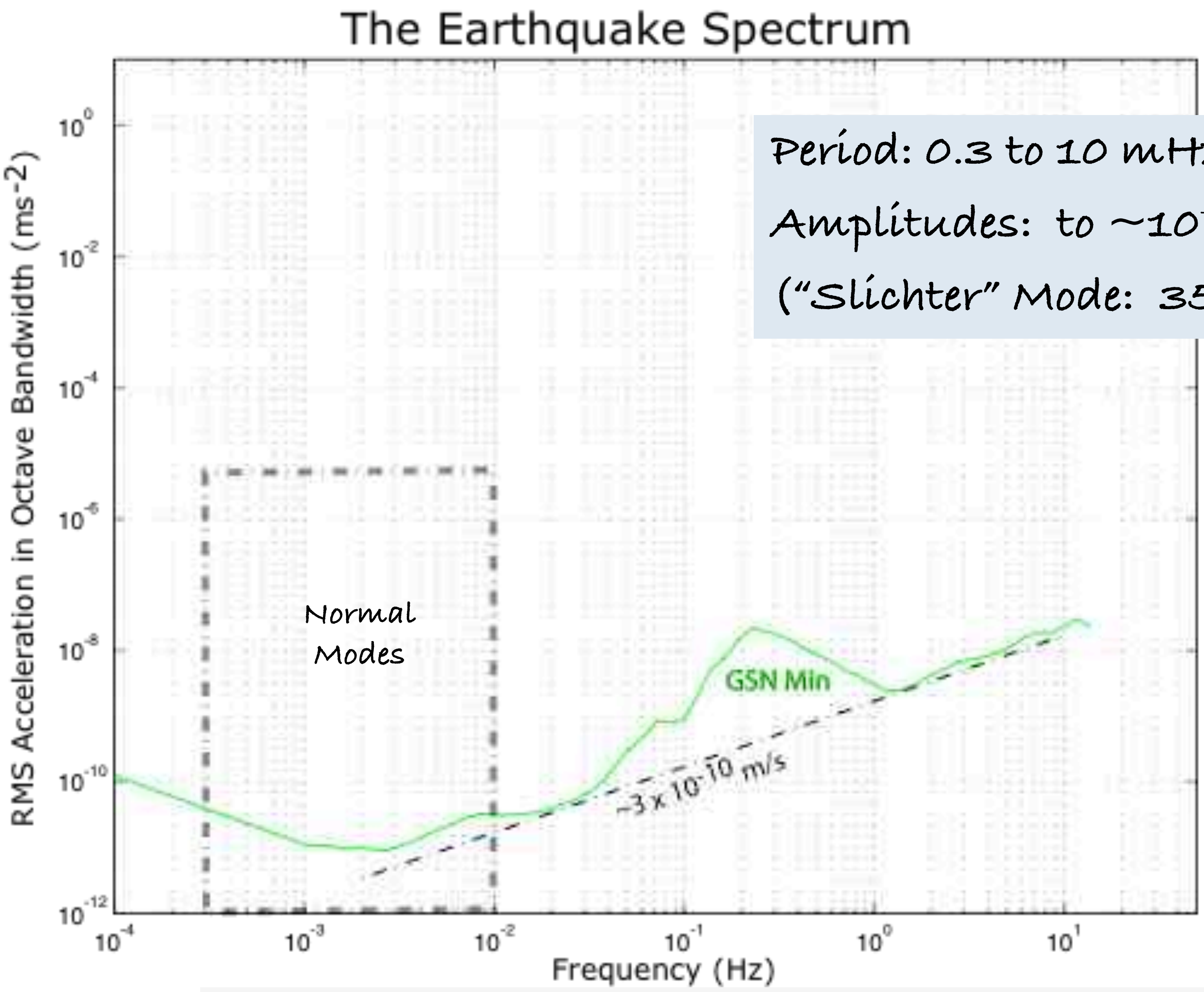
After Laske, 2004

Earth Hummmmm



- In 1998, almost forty years a the initial attempt by Beniof al (1959), continuous free oscillations of the Earth wer finally observed.

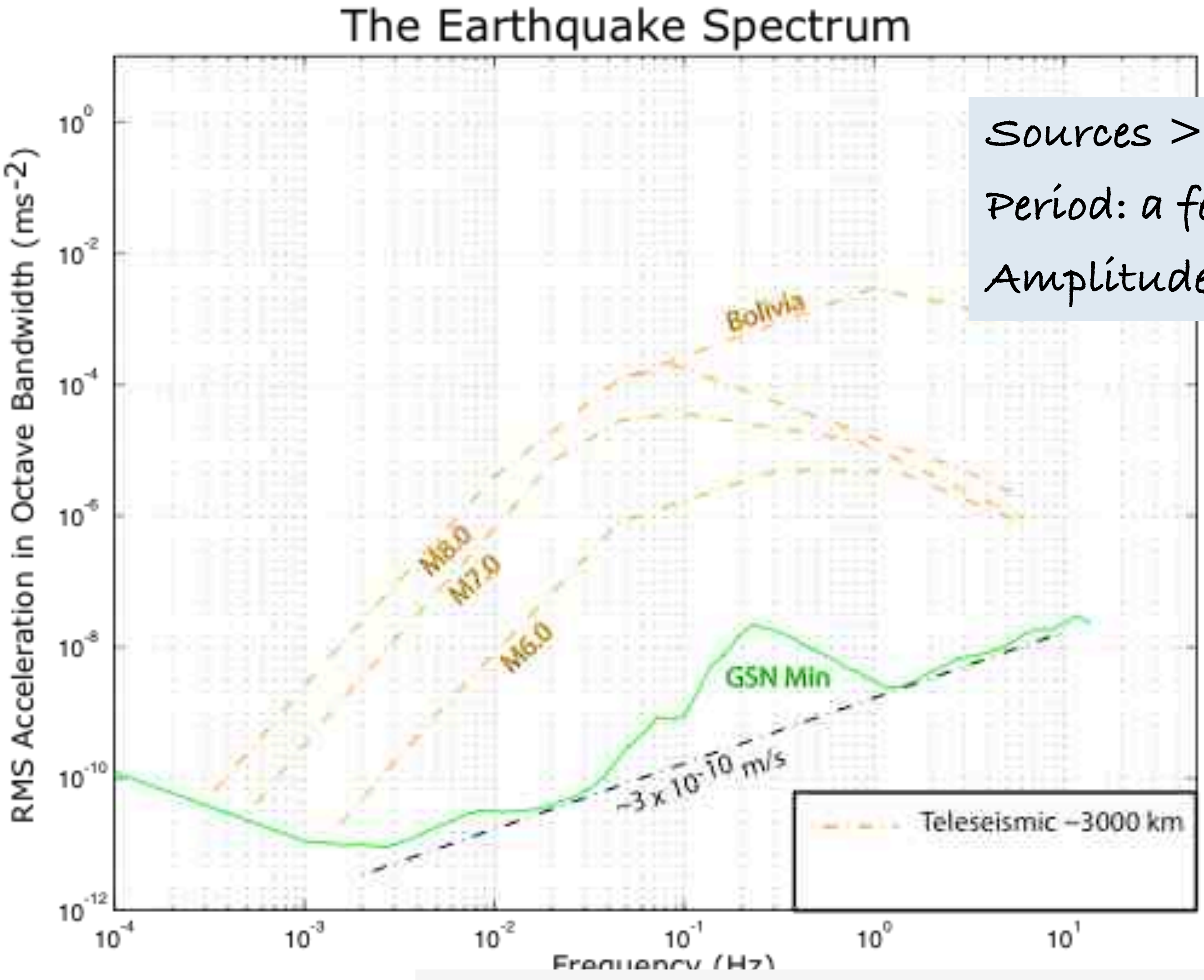
- Earth is constantly excited b spheroidal fundamental mod between about 2 and 7 mHz (from $_0S_{15}$ *to* $_0S_{60}$) with nearl constant acceleration and ar about 3 – 5 x 10^{-12} ms^{-2}.



Period: 0.3 to 10 mHz

Amplitudes: to ~10^{-5} ms^{-2}

("Slichter" Mode: 35 – 70 µHz ?)



Sources $>\_$ 3000km

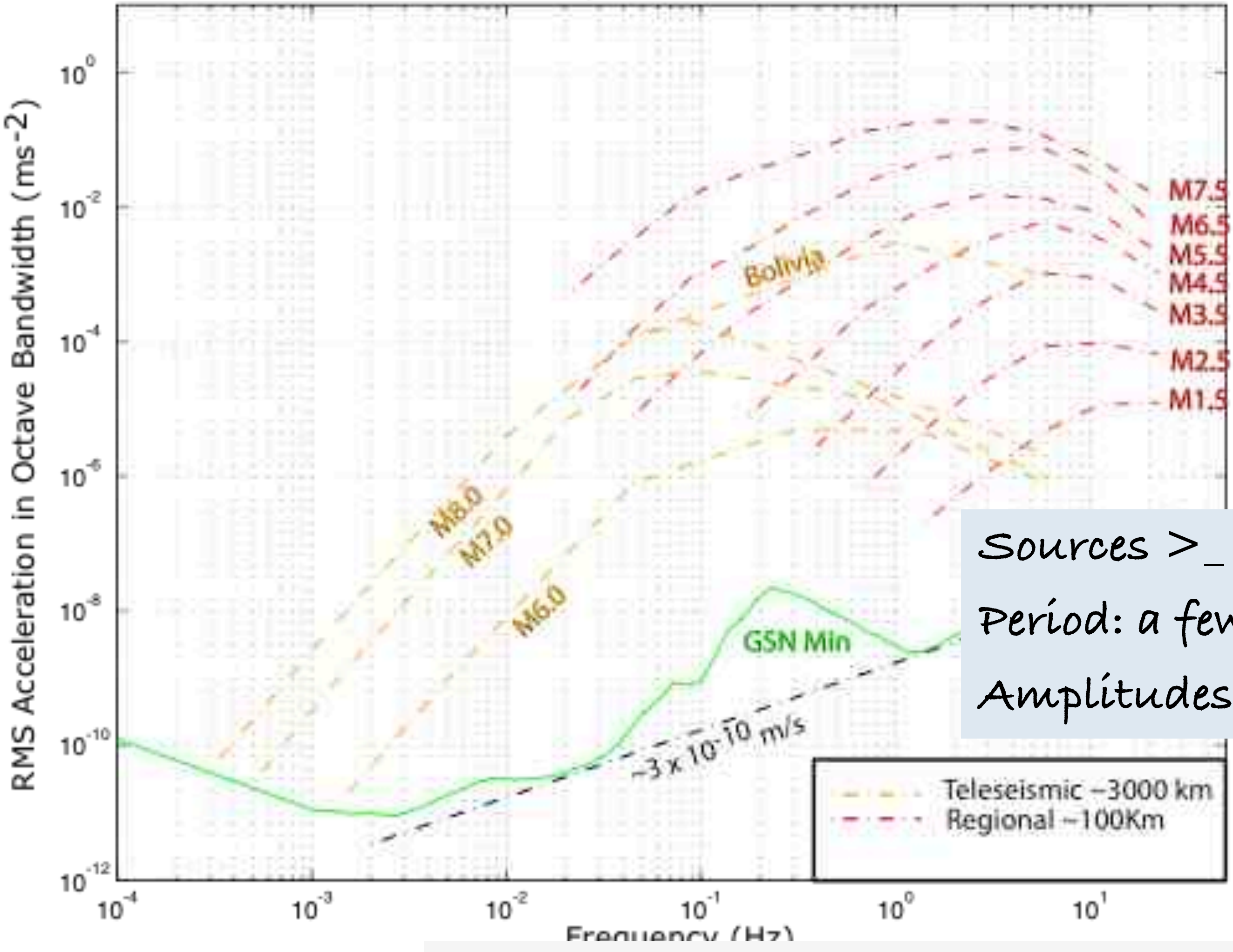
Period: a few mHz to several H

Amplitudes: to $\sim 10^{-3}$ ms^{-2}

Af

To convert: pow

The Earthquake Spectrum



Sources >_ 100km

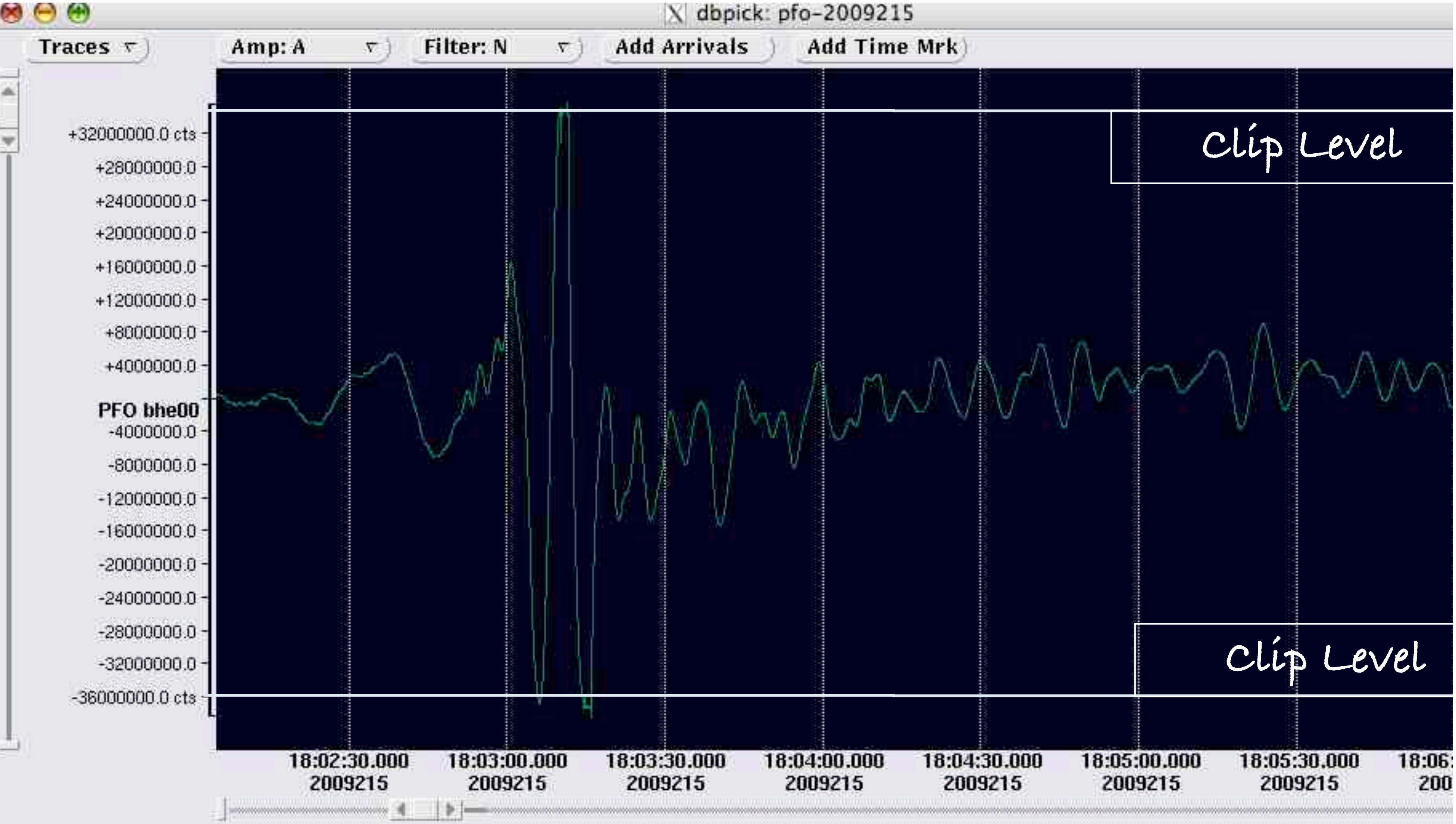
Period: a few 10's s to ~10 Hz

Amplitudes: to ~10^{-1} ms^{-2}

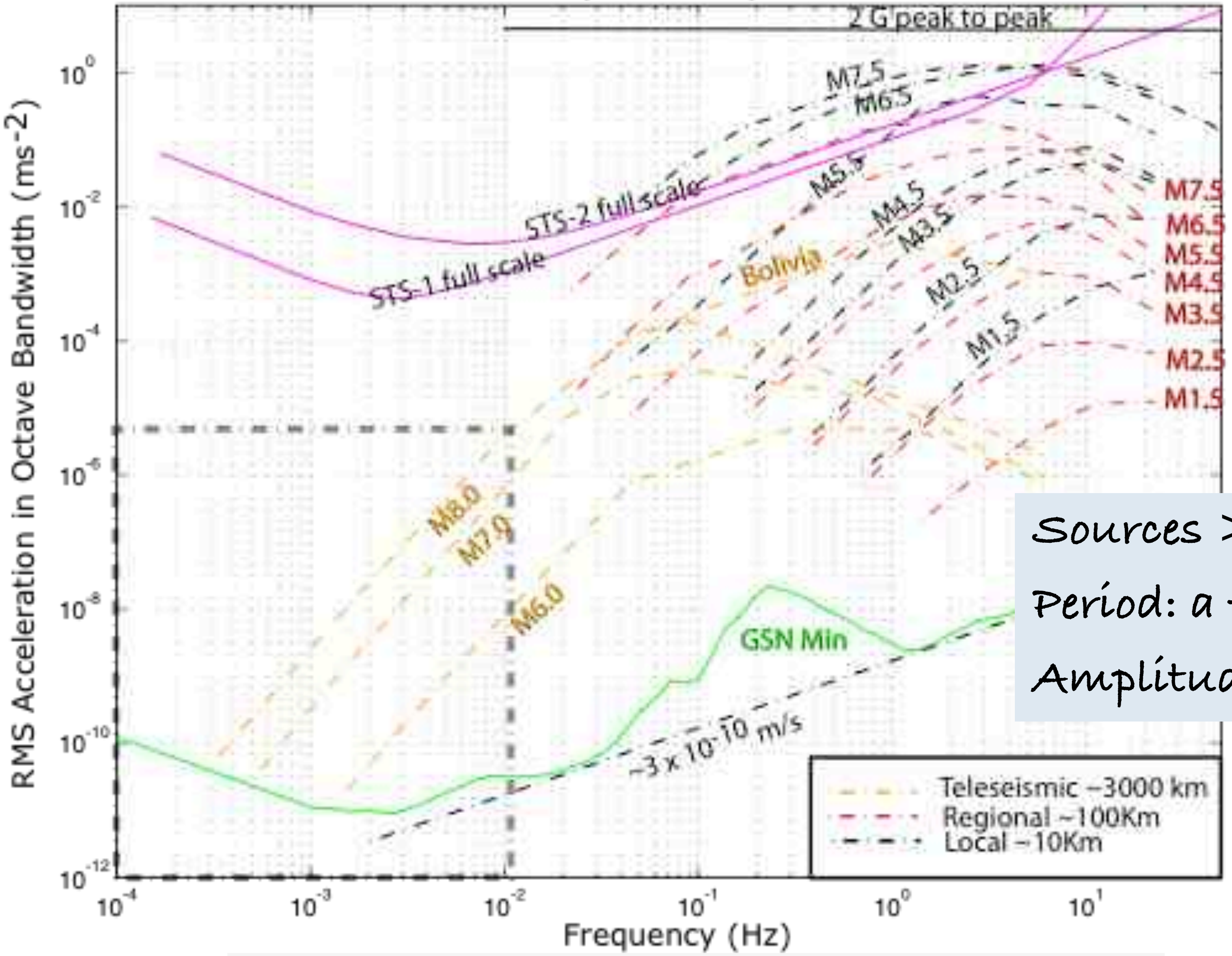
Af

To convert: pow

Lg Phase observed at PFO, M6.9, Distance 630Km



The Earthquake Spectrum

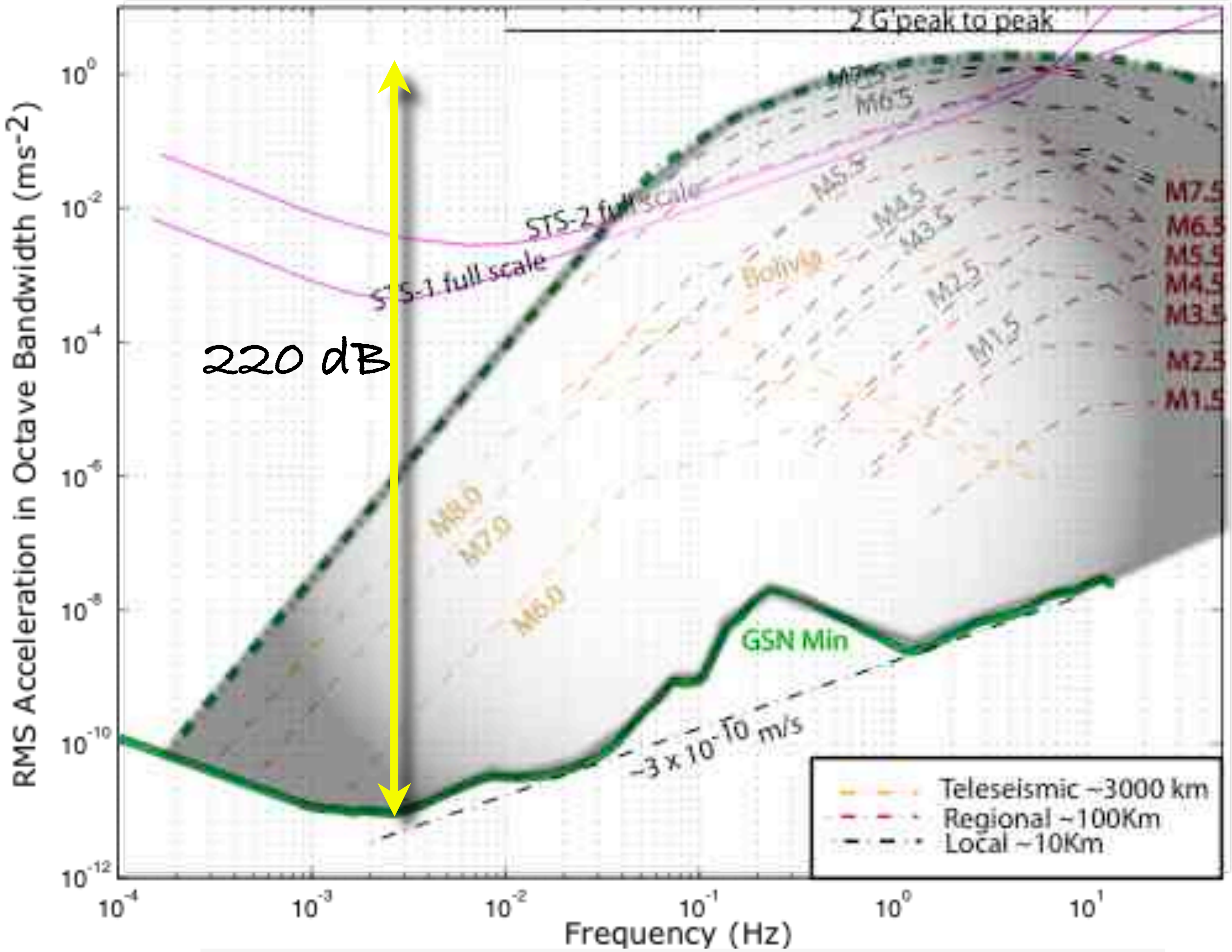


Sources >~10km

Period: a few seconds to ~3

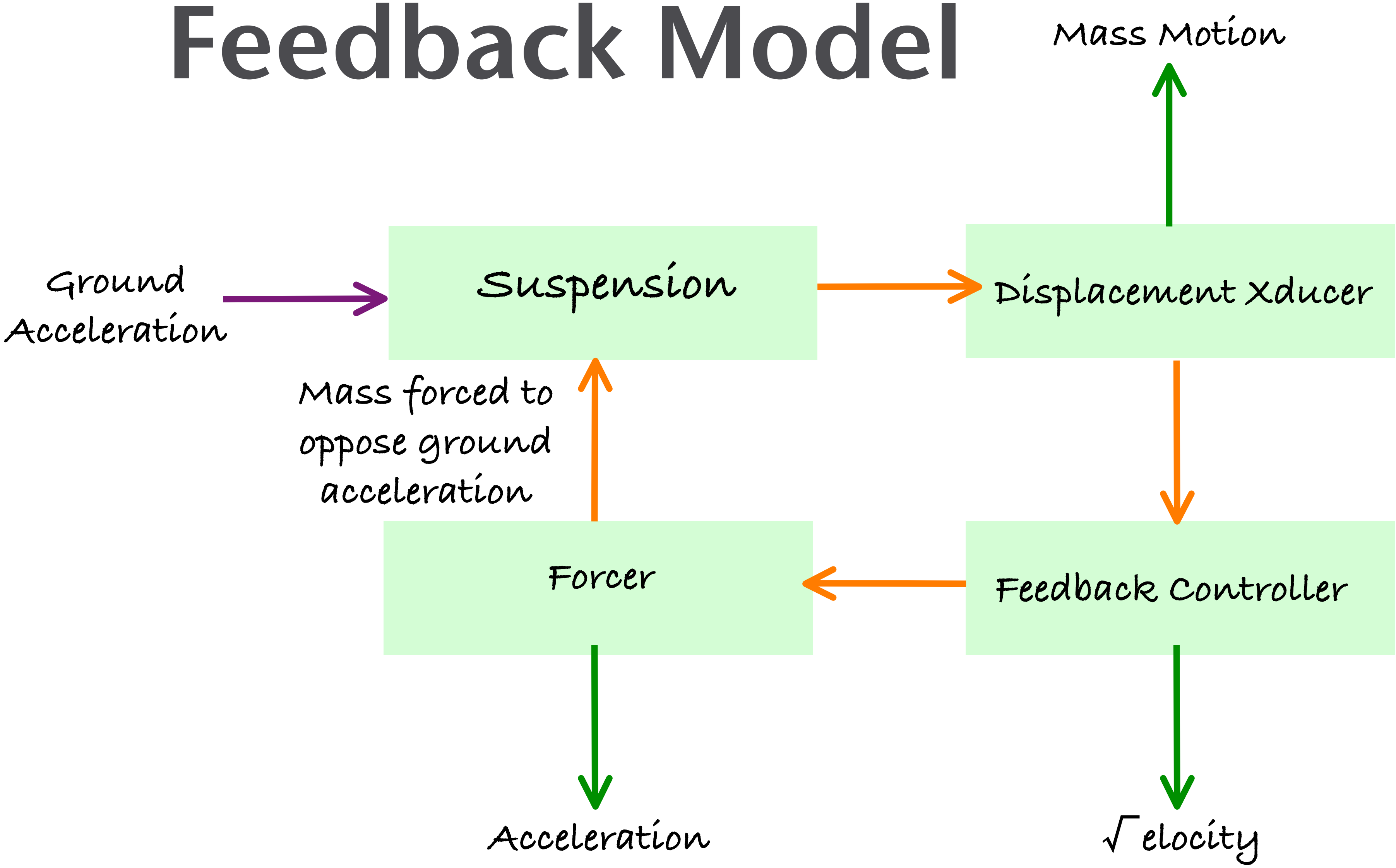
Amplitudes: to ~10 ms^{-2}

The Earthquake Spectrum



Instruments

Feedback Model



Mass Motion

Ground Acceleration

Suspension

Displacement Xducer

Mass forced to oppose ground acceleration

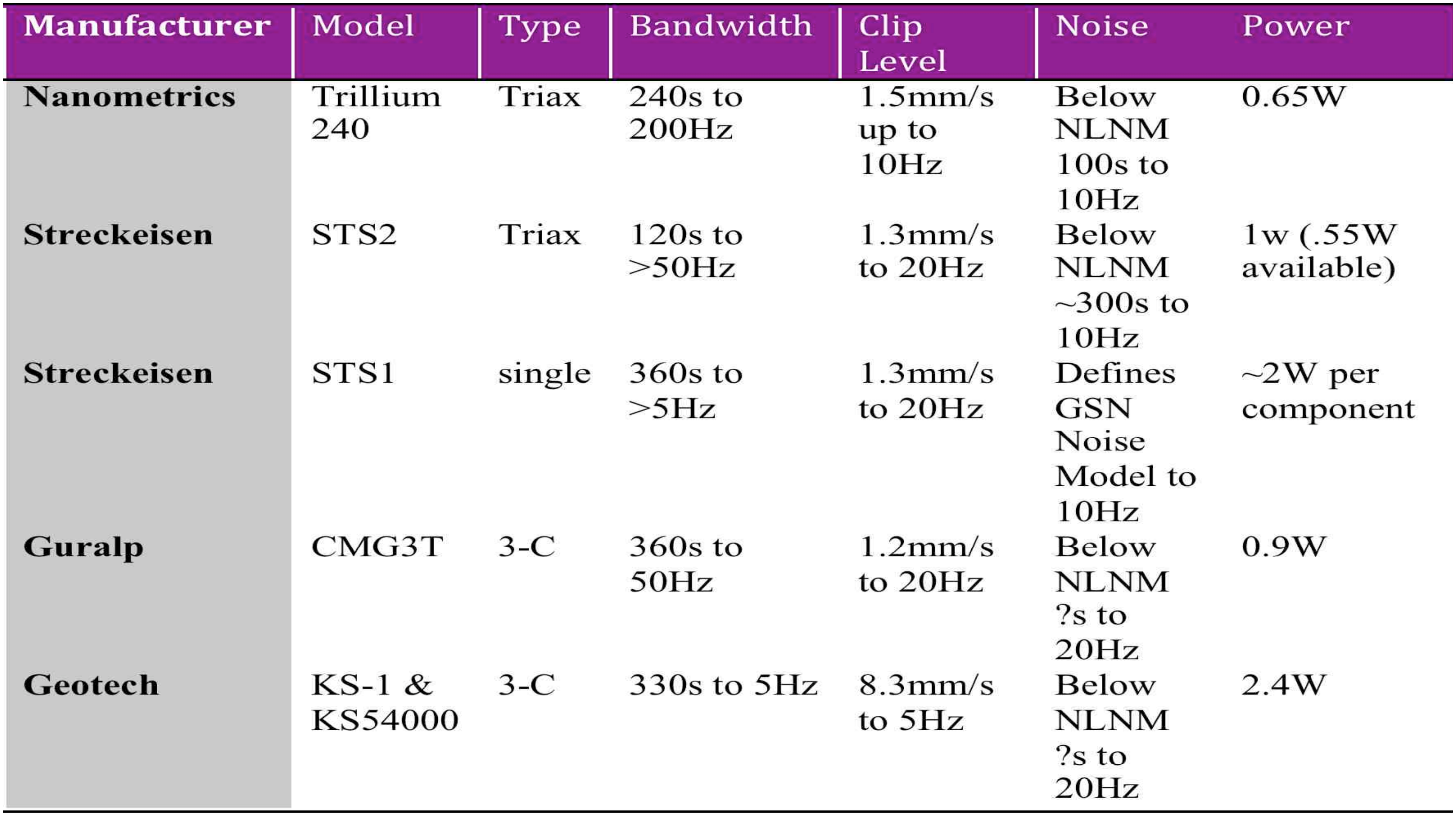
Forcer

Feedback Controller

Acceleration

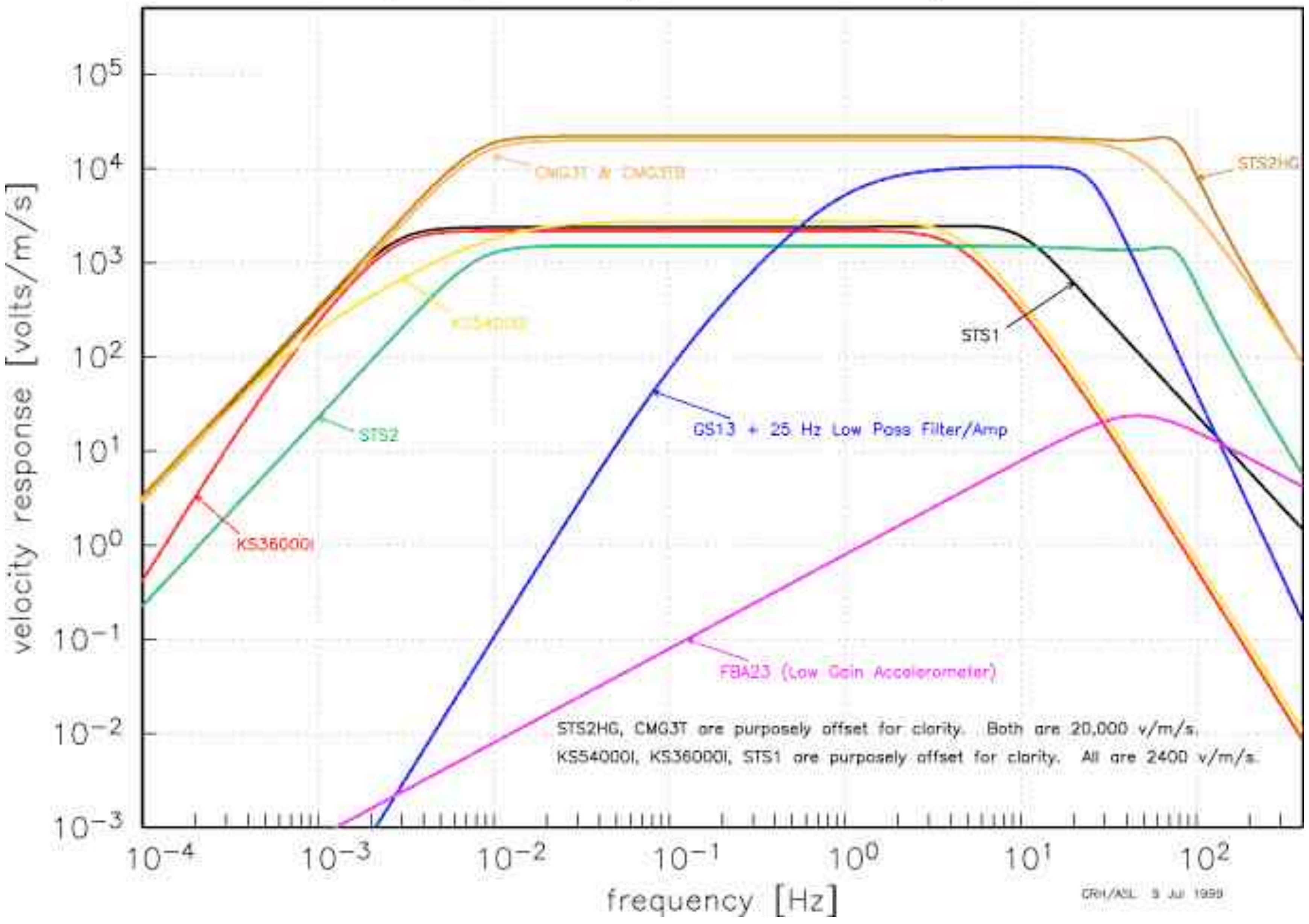
Velocity

Commercial Broadband Seismomete



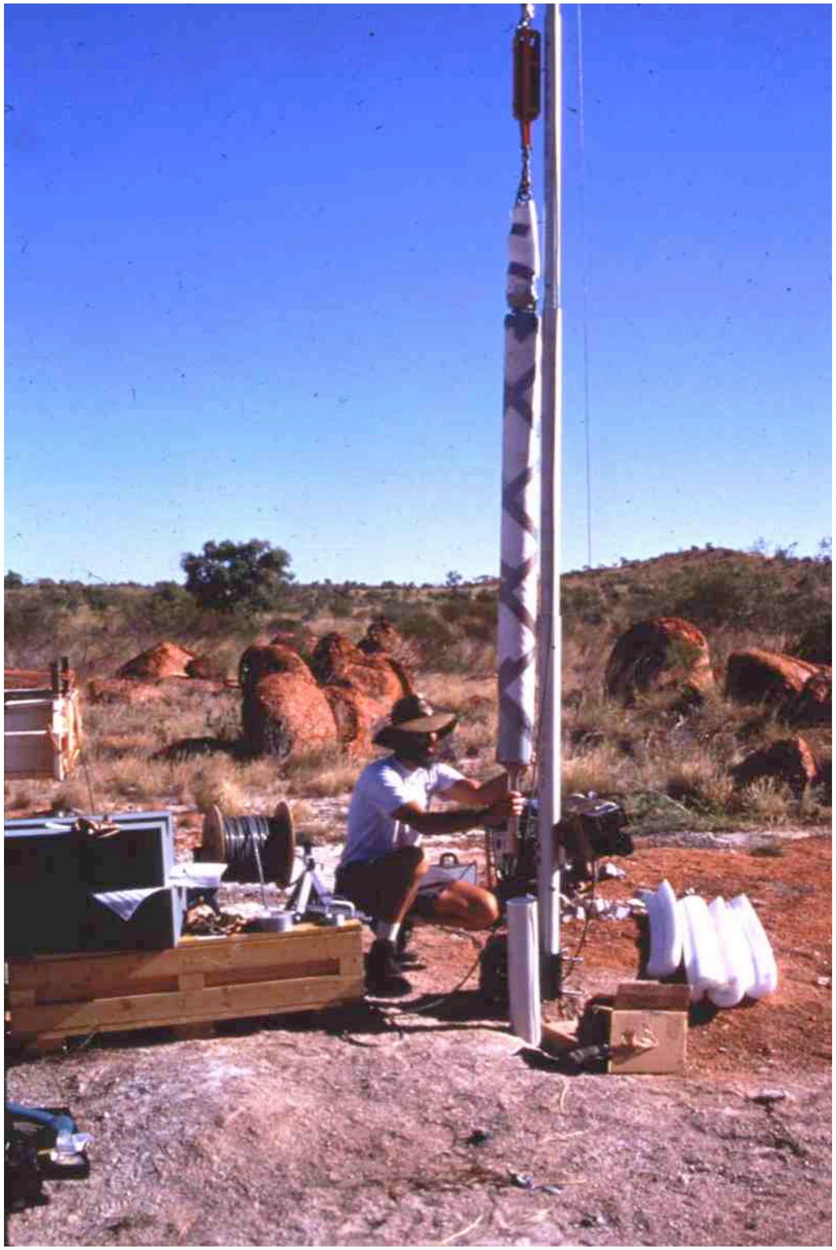
Manufacturer	Model	Type	Bandwidth	Clip Level	Noise	Power
Nanometrics	Trillium 240	Triax	240s to 200Hz	1.5mm/s up to 10Hz	Below NLNM 100s to 10Hz	0.65W
Streckeisen	STS2	Triax	120s to >50Hz	1.3mm/s to 20Hz	Below NLNM ~300s to 10Hz	1w (.55W available)
Streckeisen	STS1	single	360s to >5Hz	1.3mm/s to 20Hz	Defines GSN Noise Model to 10Hz	~2W per component
Guralp	CMG3T	3-C	360s to 50Hz	1.2mm/s to 20Hz	Below NLNM ?s to 20Hz	0.9W
Geotech	KS-1 & KS54000	3-C	330s to 5Hz	8.3mm/s to 5Hz	Below NLNM ?s to 20Hz	2.4W

Velocity Response Comparison of IRIS/USArray Instruments



STS2HG, CMG3T are purposely offset for clarity. Both are 20,000 v/m/s.

KS54000I, KS36000I, STS1 are purposely offset for clarity. All are 2400 v/m/s.



STS1 with bell jar

KS54000 ready to go down WRAB Borehole

CMG-3T

Trillium 240

STS-2

Some Features of the New version STS-1

- Non-Galperin: Separate H and V Sensor Designs
- Factory-Leveled: Plug and Go in Leveled Package
- 360 Second to 15 Hz Passband
- Self-Noise Comparable to Original Sensors
- Incorporates Wielandt/ASL "Warpless Baseplate" Design
- Three Aluminum Vacuum Chambers on Single Baseplate; All-Metal Valve
- Integrated Magnetic Shield for V Sensor
- Galvanic Isolation from Pier

See Poster by VanZandt

Interferometric Seismometer

- Interferometric Displacement Transducer
- Large Bandwidth & Dynamic Range
- No Feedback; No enclosed electronics; No Electrical Connections
- Capable of operating in extreme temperatures

See Poster by Otero *et al.*

Station Requirements for Long Period Observations

- Good thermal stability
- Solid rock foundations for local tilt suppression
- Far from coast (Yet island stations are required)
- Human Factor ....

The GSN Station PALK
100m, steel-cased, Borehole

The GSN Station AAK
The tunnel entrance

The GSN Station AA
One of the vaults

DGAR - Vault under construction

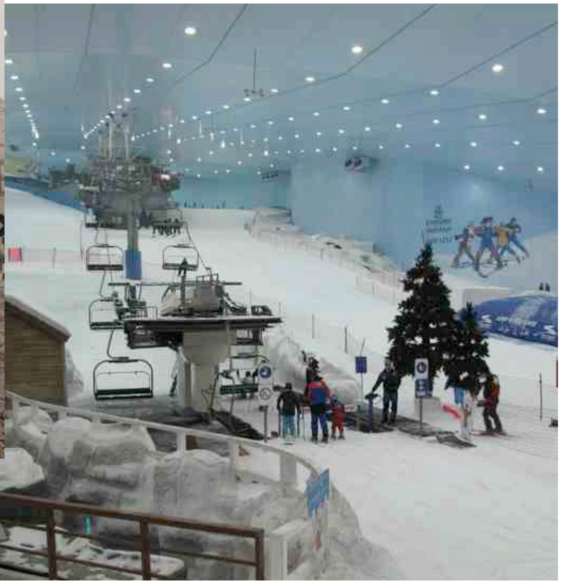
Final Thoughts

- Modern Broadband Seismometer are pretty good. What more would we like?
- Additional Bandwidth – long period end
- Reduced long-period noise – small market
- Improved environmental protection
- Long-term, telemetered, Ocean-bottom instruments

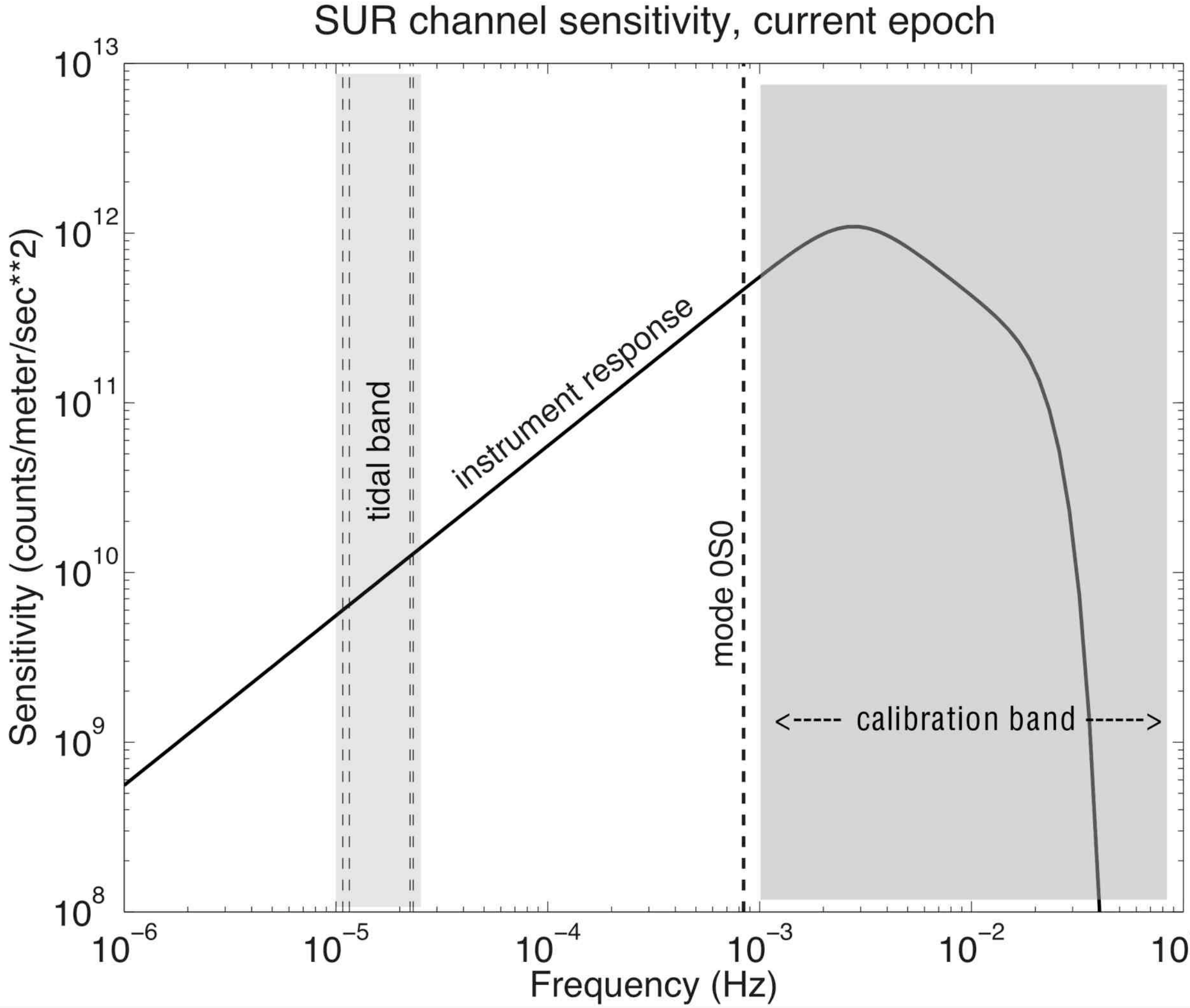
GSN Station **UOS**

Tunnel entrance as seen from the recording building

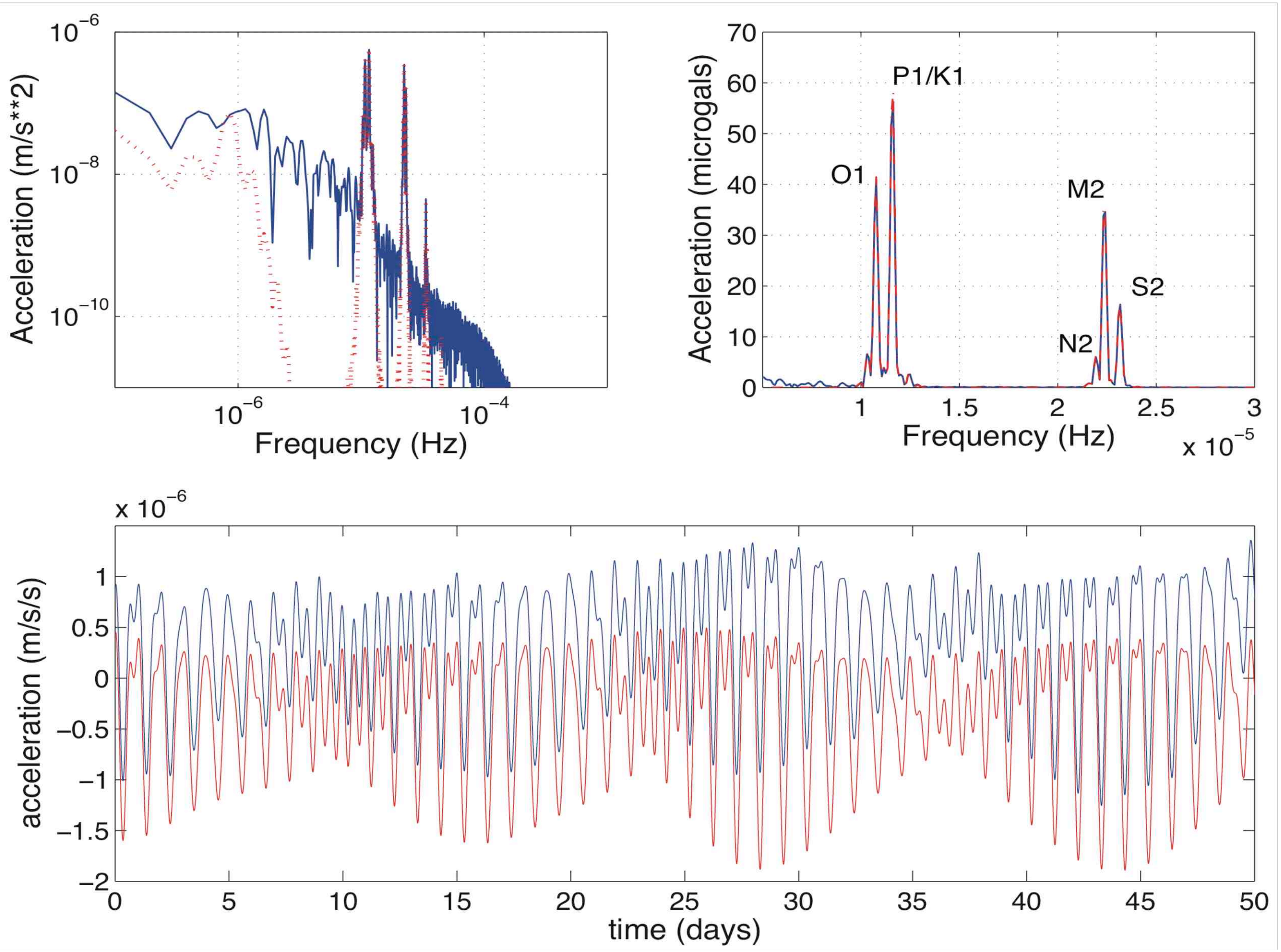
tunnel hallway, looking from the entrance to the instrument room



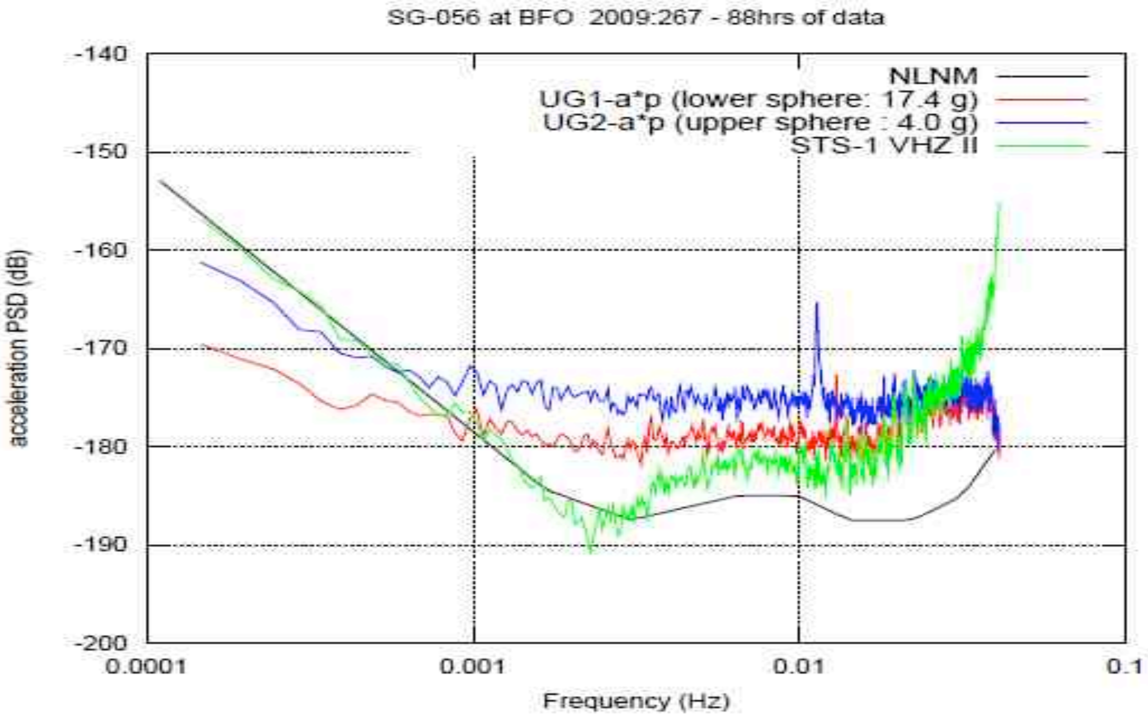
Nature's Calibration Signal: Earth Tides



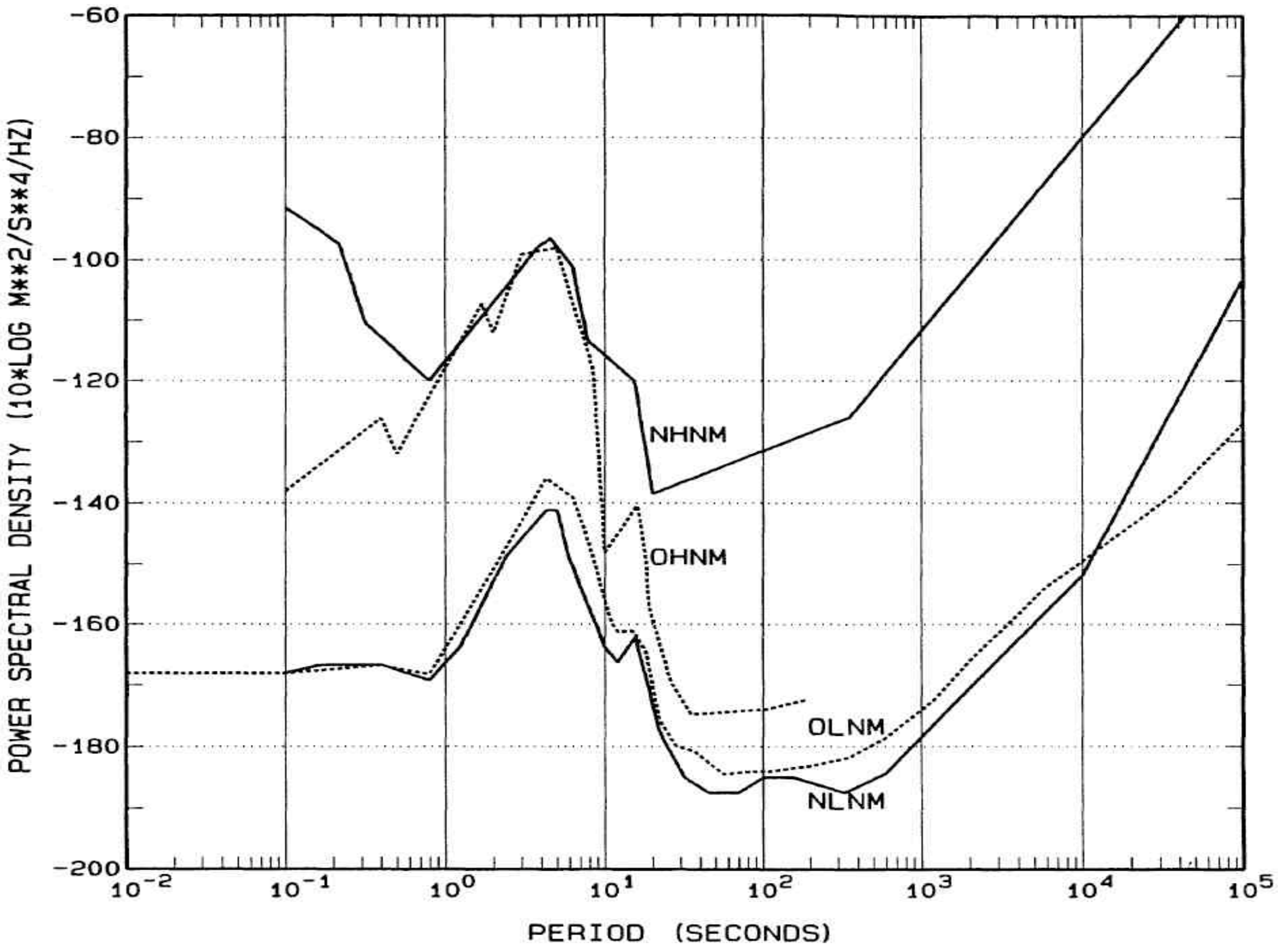
BFO 2006,090 - 2006,180



Effect of increasing mass i
Superconducting Gravimete



USGS Old (1980) & New(199
Noise Mode



DGAR - Inside the Vault

Berger *et al.*, 2003

- 118 GSN Stations of the IU and II networks for the year July 2001 through June 2002.
- Each station-channel data segmented into hourly, 1 to 11 hour segments.
- noise estimated in 50% overlapping 1/7 decade ($\partial f/f=0.33$, ~1/2 octave) bands.

Features of Feedback

- Limits the dynamic range and linearity requirements of the displacement transducer as the test-mass displacement is reduced by gain of feedback loop
- Can easily shape overall response to compensate for suspension free period and Q
- Can provide electrical outputs proportional to displacement, velocity, or acceleration