What Can We Learn from High Quality Instrumentation in Structures?

<< Structural Health Monitoring & The Case of Millikan Library >>

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23 November 2007

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Presentation Outline

ETH

Part I - Motivation

- Existing health monitoring - simple theory
- Bandwidth of modern sensors

Part II - Millikan Library

- Instrumentation at Caltech
- Continuous monitoring
- Transfer Functions
- Movies of earthquakes

Part III - Future Directions

- Factor Building
- ANSS
- European Testbeds
- PQLX noise monitoring

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Simple Dynamics - SDOF

ETH

Part I - Motivation

- Existing health monitoring - simple theory
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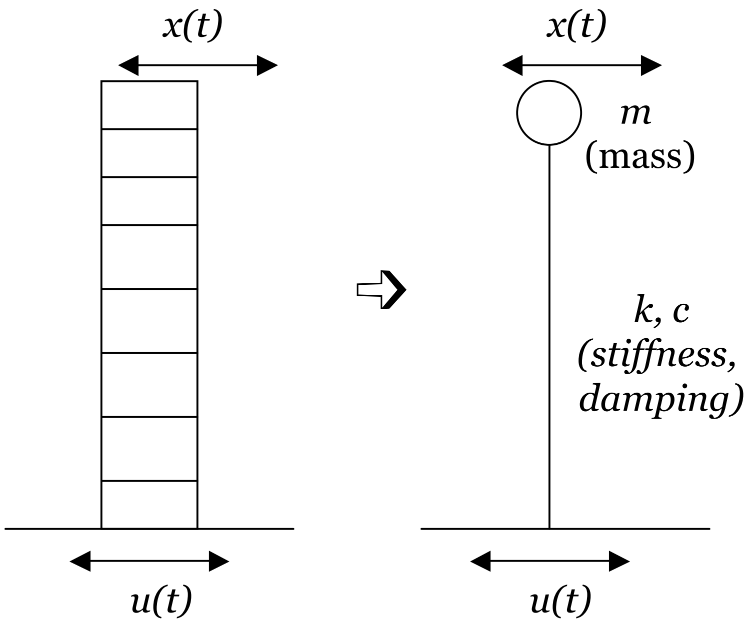


equation of motion of SDOF:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = -m\ddot{u}(t)$$

$$\ddot{x}(t) + 2\zeta\omega_0\dot{x}(t) + \omega_0^2 x(t) = -\ddot{u}(t)$$

dynamic response of an SDOF:

$$f_0 = 2\pi\sqrt{k/m}$$

f_o: natural frequency, *Hz*
($T(s)=1/f_o$; $\omega_o=2\pi f_o$)

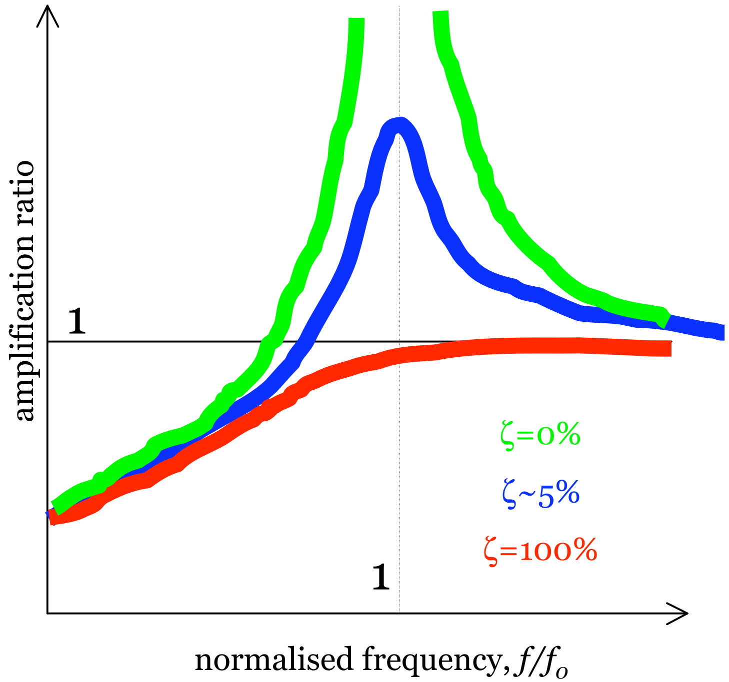
$$\zeta = c/\sqrt{mk}$$

ζ: % of critical damping

Simple Dynamics - SDOF

Frequency response of SDOF

(with f_o const., varying ζ)



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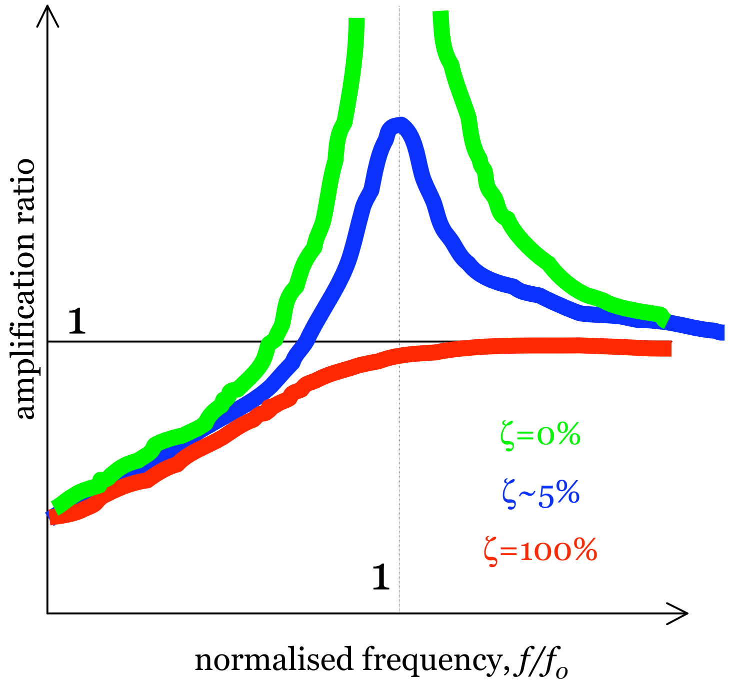
Simple Dynamics - SDOF

Frequency response of SDOF

(with f_o const., varying ζ)



What happens if an SDOF is damaged?

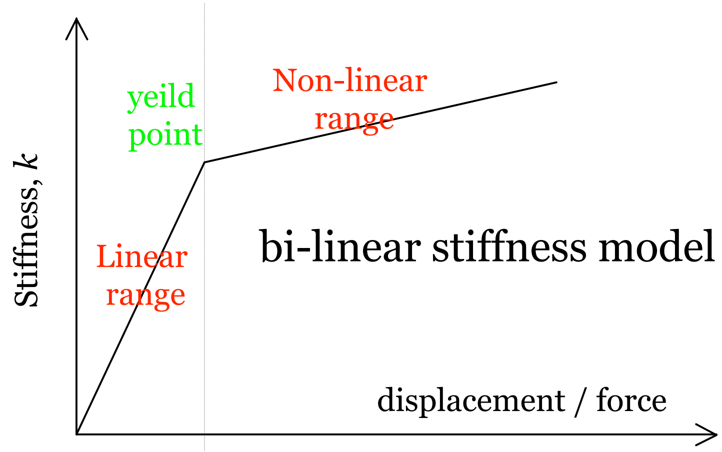
damage is caused by loss in stiffness $\Rightarrow k\downarrow$

so as $f_0 = 2\pi\sqrt{k/m}$, $f_o\downarrow$

[as $f_o \downarrow \Rightarrow k \downarrow\downarrow$]

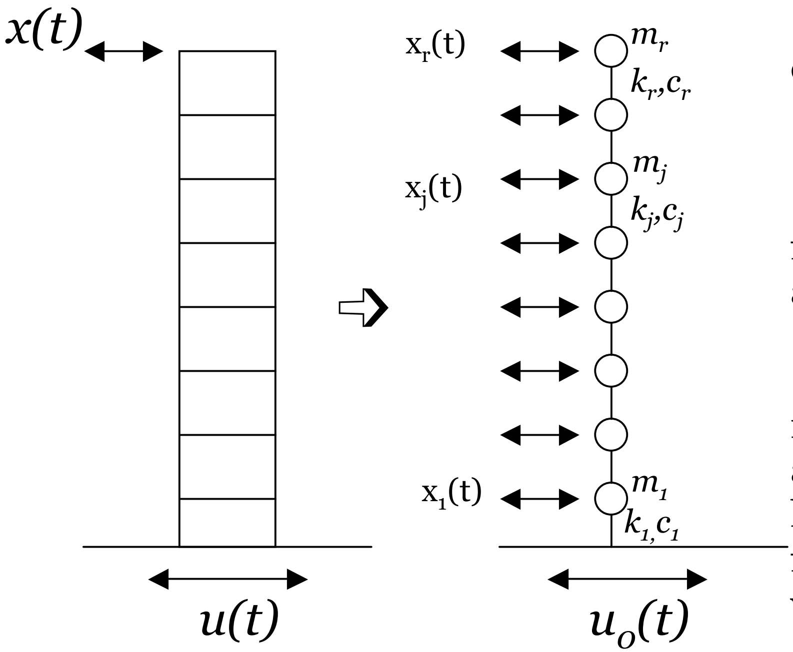
and as $\zeta = c/\sqrt{mk}$, $\zeta\uparrow$

- this is the motivation for looking at natural frequencies



Simple Dynamics - MDOF

a more realistic representation of a real structure is



equation of motion of MDOF:

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = -[M]\{\ddot{u}(t)\}$$

- *n* floor system has *n* natural frequencies (*eigenvalues*) and *n* associated modeshapes (*eigenvectors*)

more realistic models (FEM) take into account the actual beams and columns: have same number of natural frequencies as DOF's in model (very very many)

The earthquake response of most structures can be described by fundamental natural frequencies, and a small number of overtones, because:

1. participation factor of these lowest modes is very dominant

2. damaging energy from earthquakes unfortunately tends to occur between 10s-10Hz, matching the typical frequency range of these modes

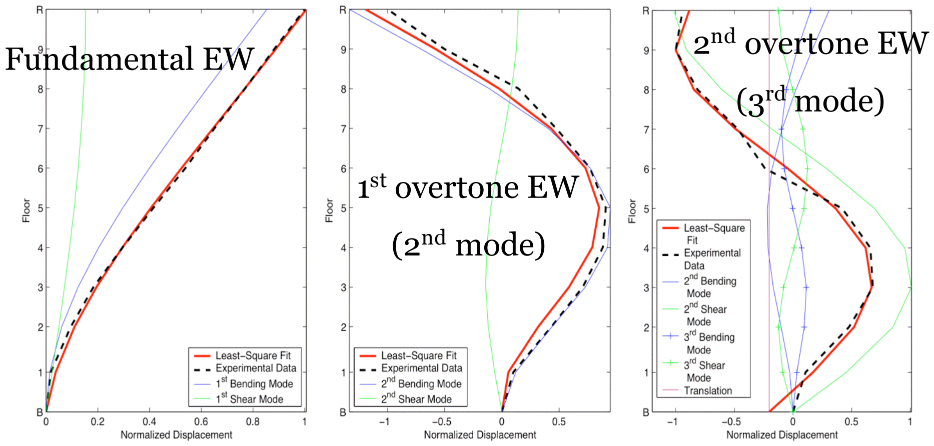
Simple Dynamics - MDOF

mode shapes:

- the horizontal displacement at each floor gives the modeshapes
- in a linear system, the modeshapes will be constant.
- if damage occurs, it will be isolated to a particular region in the structure

⇒a change in natural frequency indicates damage occurs - a change in modeshape can locate the region of damage

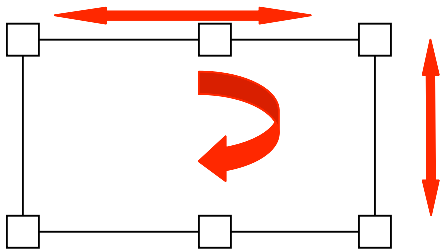
this is the motivation for looking at modeshapes



Millikan Library modeshapes

<< Note: buildings are typically rectangular in plan

⇒ 3 primary orientations for motion (2 horizontal, 1 torsion about vertical)



>>

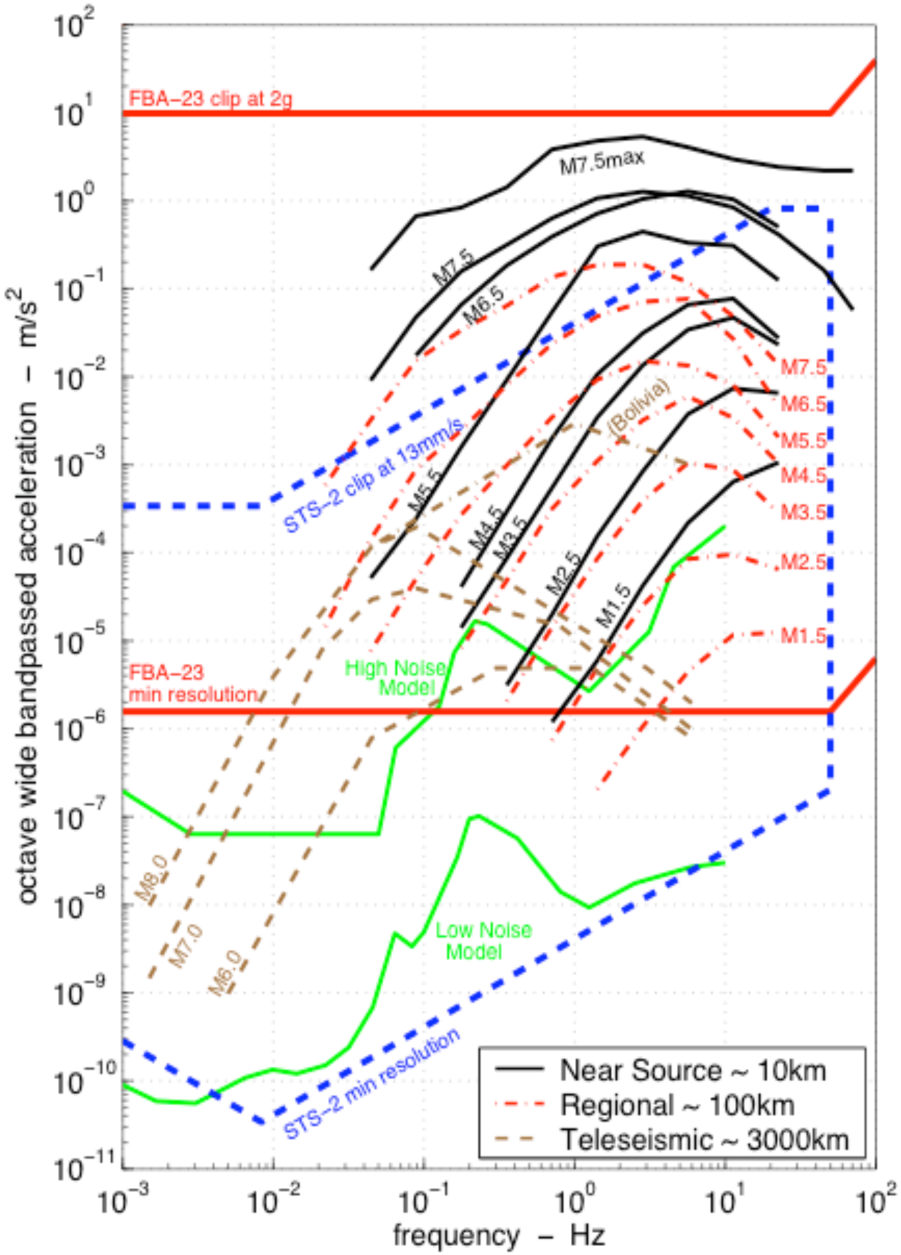
how to we get the dynamic properties?

- Code formulae:
    - •Initial : $T=H/10$ *H: # stories*
    - •UBC (1997) : $T=C_t h_n^{3/4}$ C_t *=.035(SMRF)/ .03 (RCMRF)/.02(else) ; h:ht (ft)*
    - •Eurocode 8 : $T=.75h^{3/4}$ *h:ht(m)*
- MDOF modeling
- FEM modelling
- •Observations
    - •Single observation (ambient and/or forced)
    - •Campaign observations (ambient and/or forced)
    - •Triggered events
    - •Continuous with single sensor
    - •Continuous with multiple sensors

Increasing complexity, cost and accuracy

Typical Seismic Station Range

- dynamic and frequency ranges of the typical 24bit/144dB sensors overlain on a bandpassed signal amplitude plot
- include Peterson (1992) Low and High noise
- a combination of 2 sensors theoretically covers the entire spectrum of expected ground motions <from the low noise model to the strongest recorded earthquake motions>.
- what do we need to cover all ground motions inside a building?



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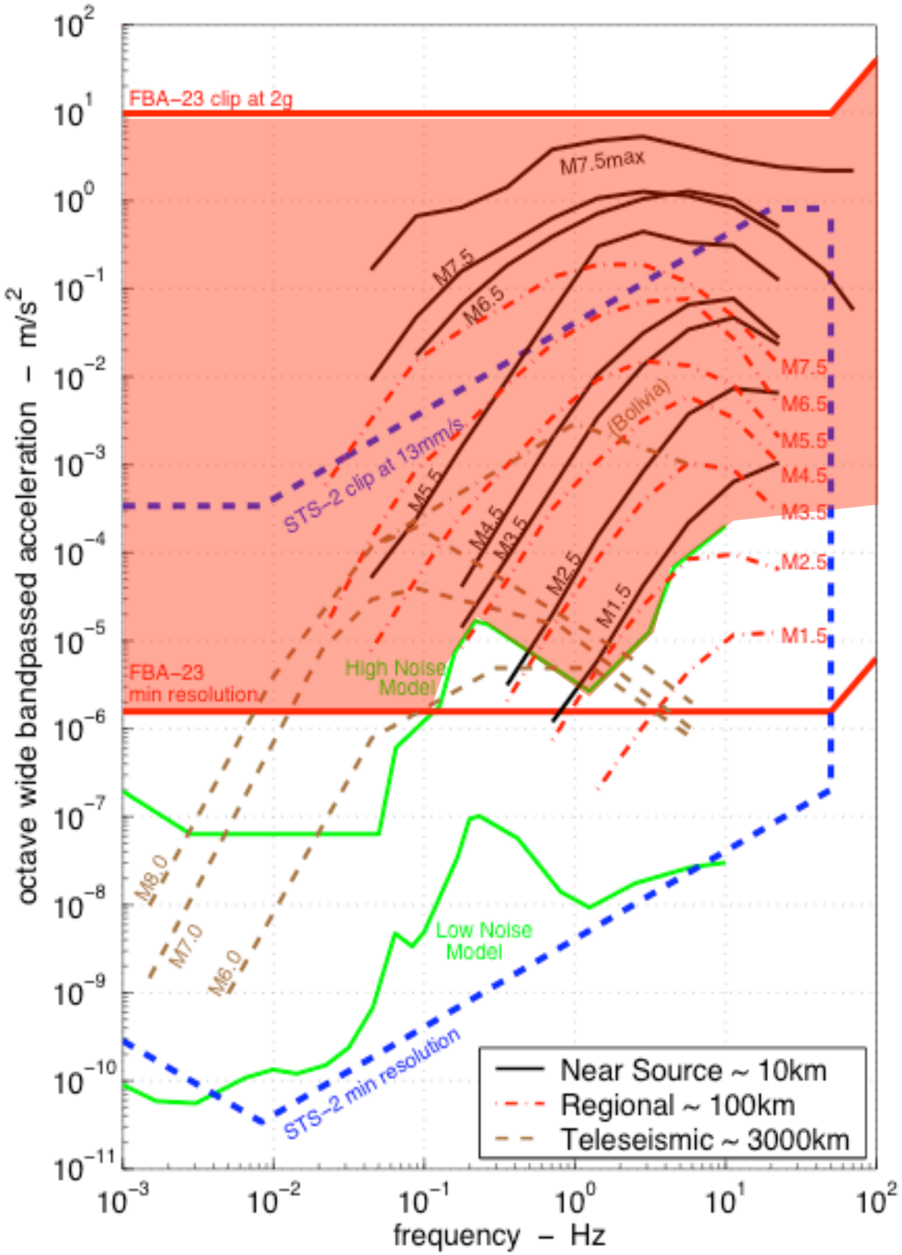

Typical Seismic Station Range

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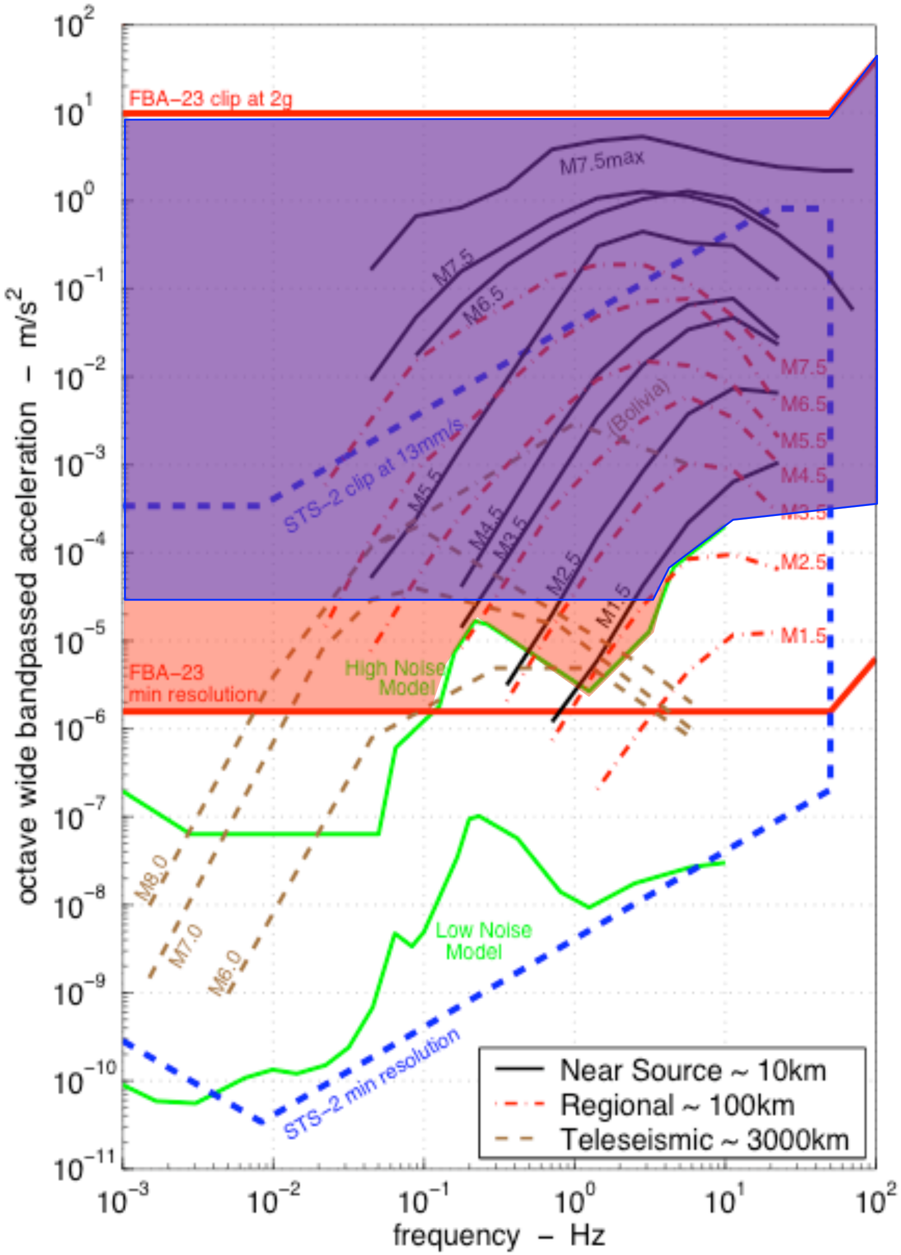
⇨ a single 19-bit accelerometer recording continuously misses ambient noise and small local events!



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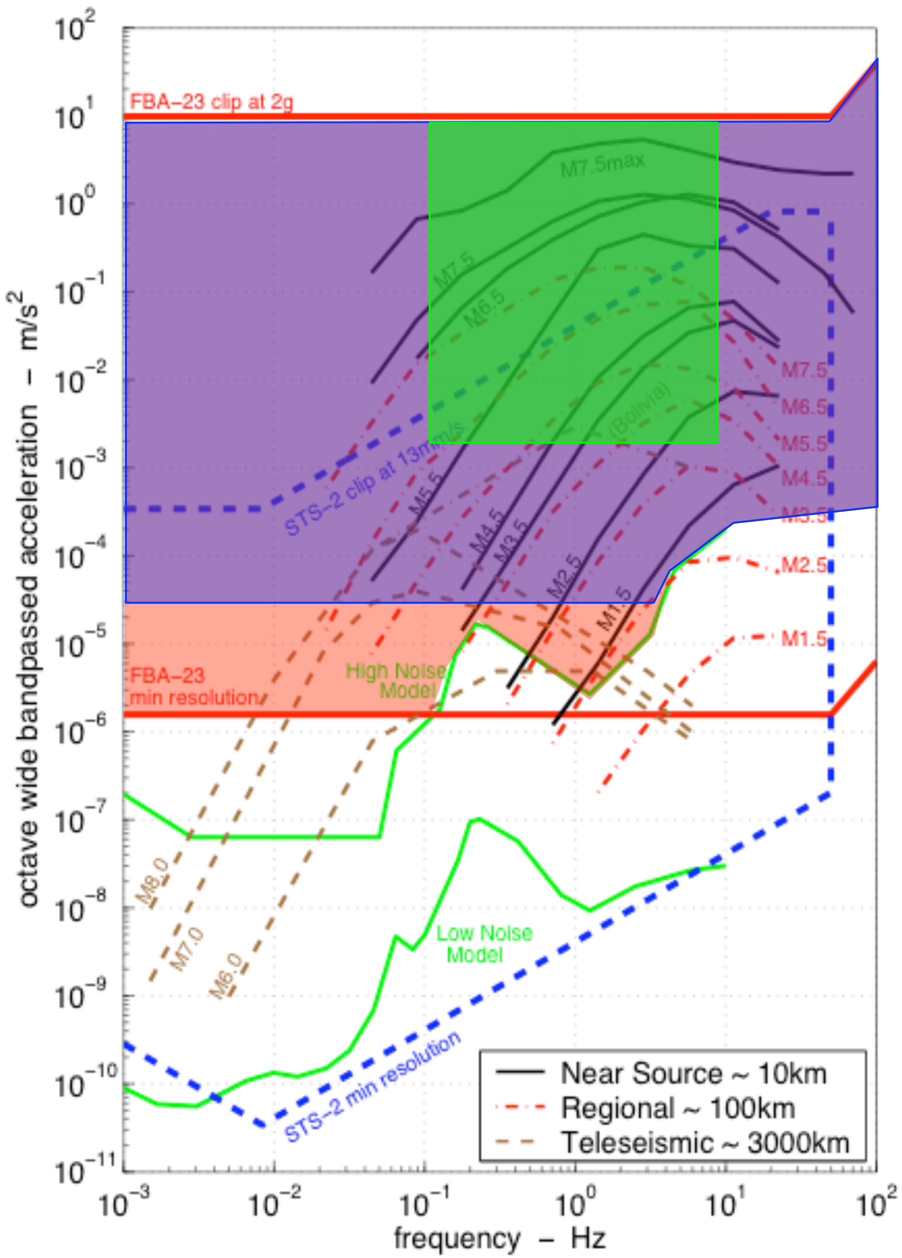
  ⇨ an analogue / 12-bit digital accelerometer recording continuously misses moderate ground motions!



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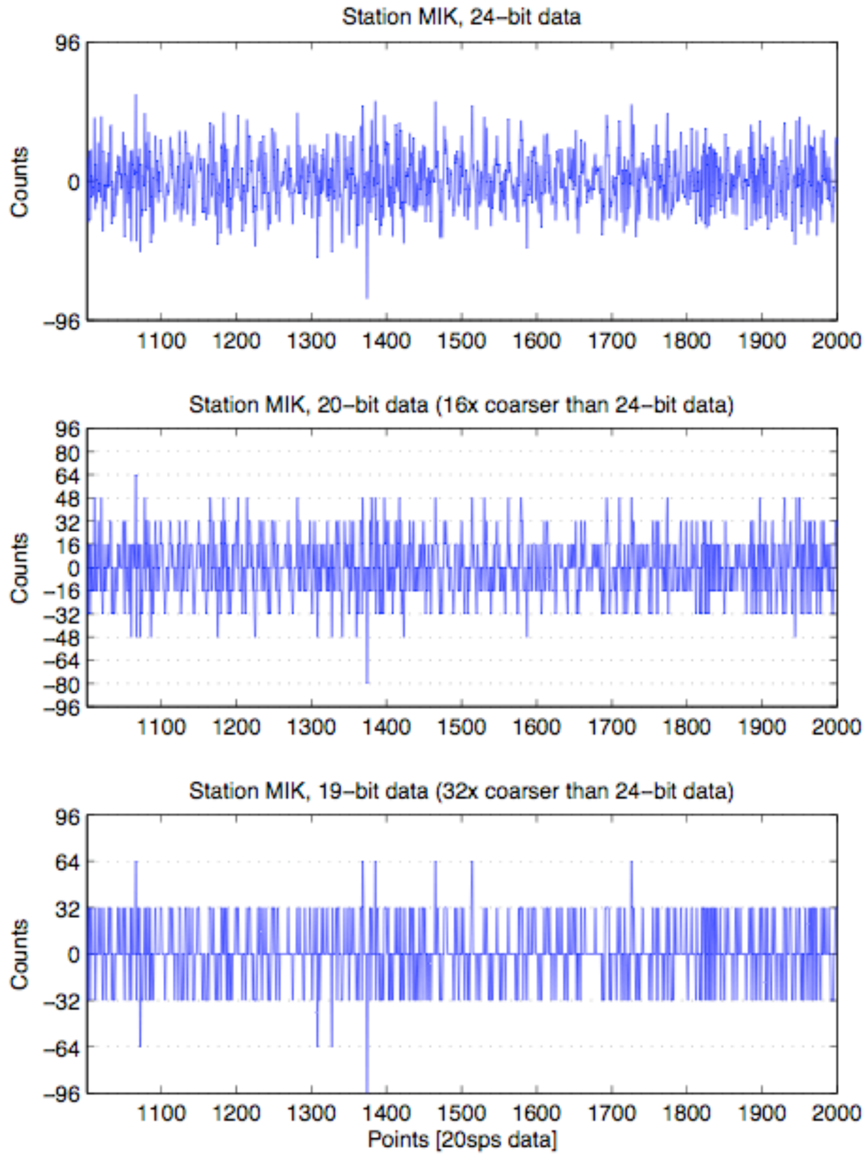

(Bradford, 2006)

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Caltech Campus Instrumentation

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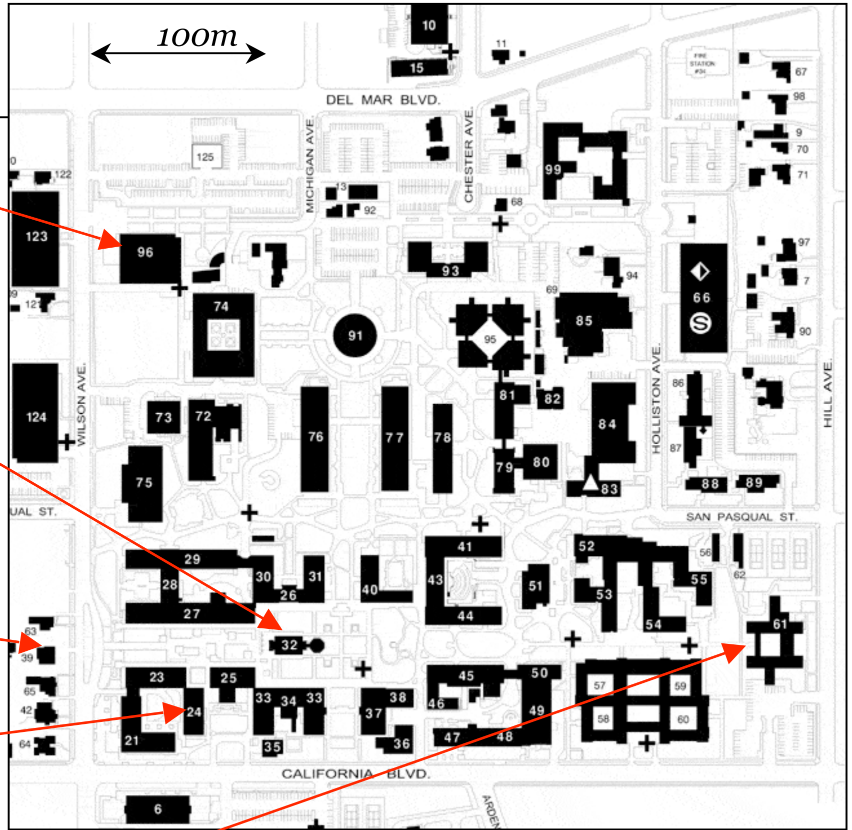
- **Broad Center:**
  CISN Station CBC - 3chan on ground floor,
  5chan on roof, all EpiSensor

- **Millikan Library:**
  CISN Station MIK - 9th floor, 3chan EpiSensor
  USGS 36channel FBA-11 array (triggered)

- **USGS Woodframe**
  CISN Station GSA - basement, 3chan EpiSensor

- **Robinson Pit, Robinson Building**
  CISN Station CRP - 12m deep pit,
  3chan VSE-355G3, 3chan CMG-1T

- **Athenaeum**
  CISN Station CAC - basement, 3chan K-2



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Millikan Library

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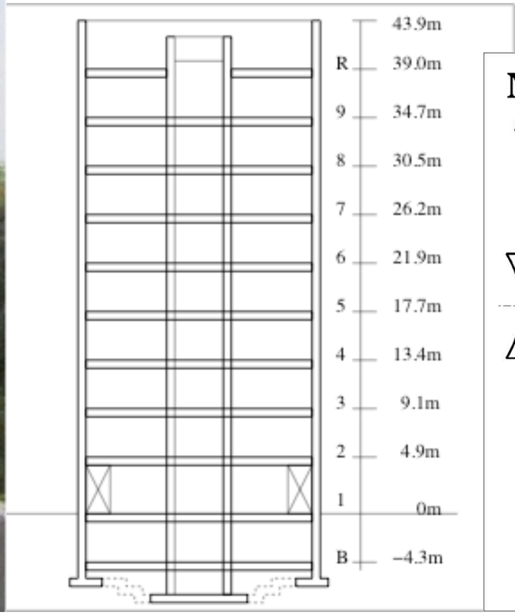
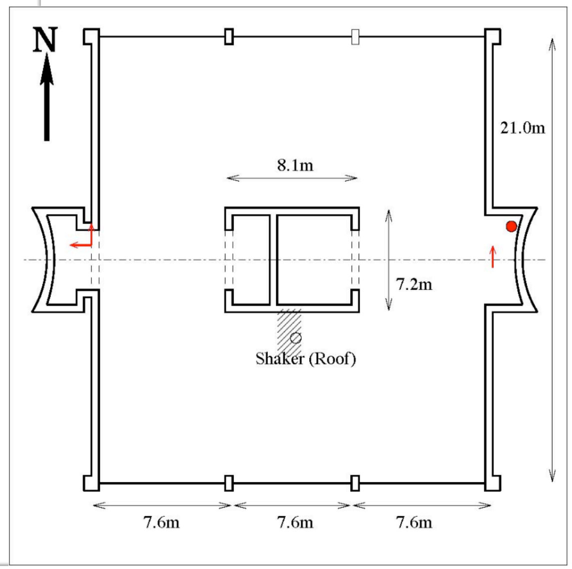
View from NE

- completed 1967, constant instrumentation since
- 9 story reinforced concrete structure
- 44m high, 21m x 23m in plan
- moment frame with shear walls inner core, and on E & W faces (NS stiffer than EW)
- spread footings
- alluvium to depth of 275m

NS section

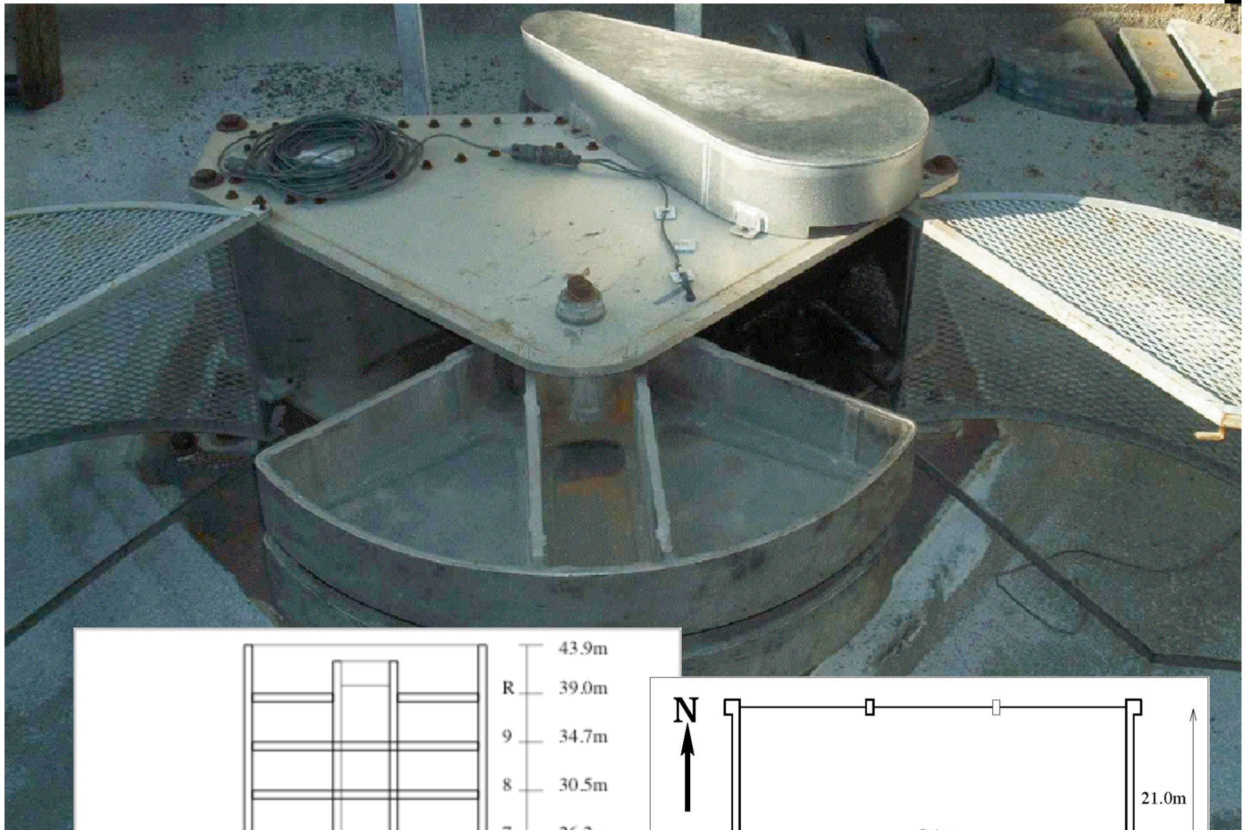


Plan View



Millikan Library - testing facitlities

roof shaker



SENSORS and DATA:

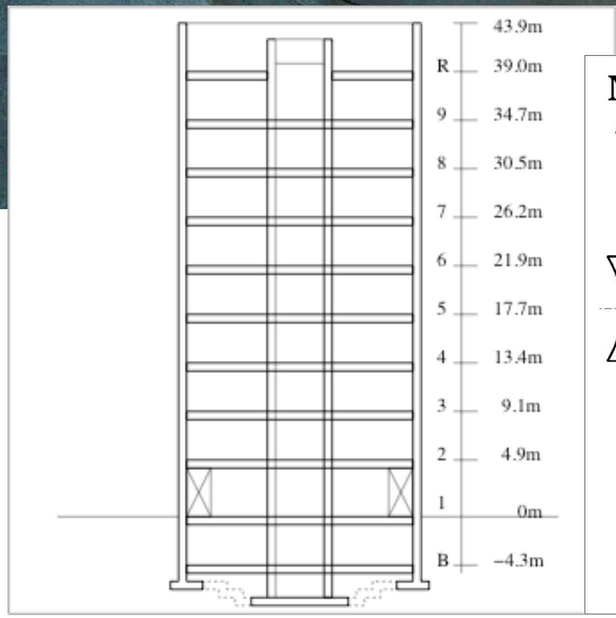
CISN Station MIK - 9th floor,
24-bit, triaxial EpiSensor
(www.data.scec.org)

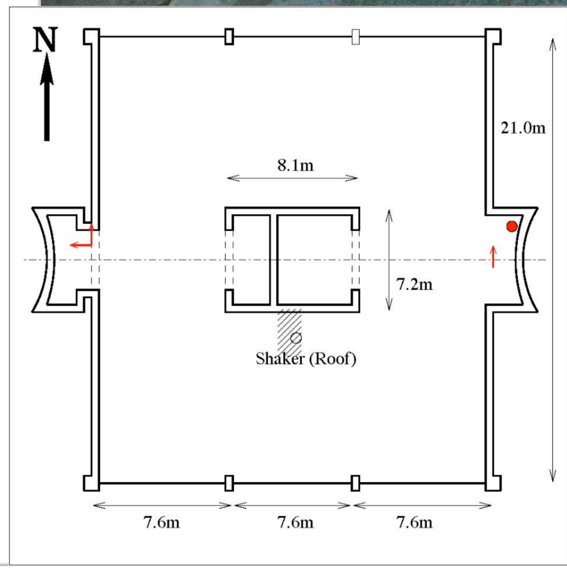
USGS 36channel uniaxial FBA-11 array
19-bit digitiser, triggered
(nsmp.wr.usgs.gov)

EXCITATION SOURCES:

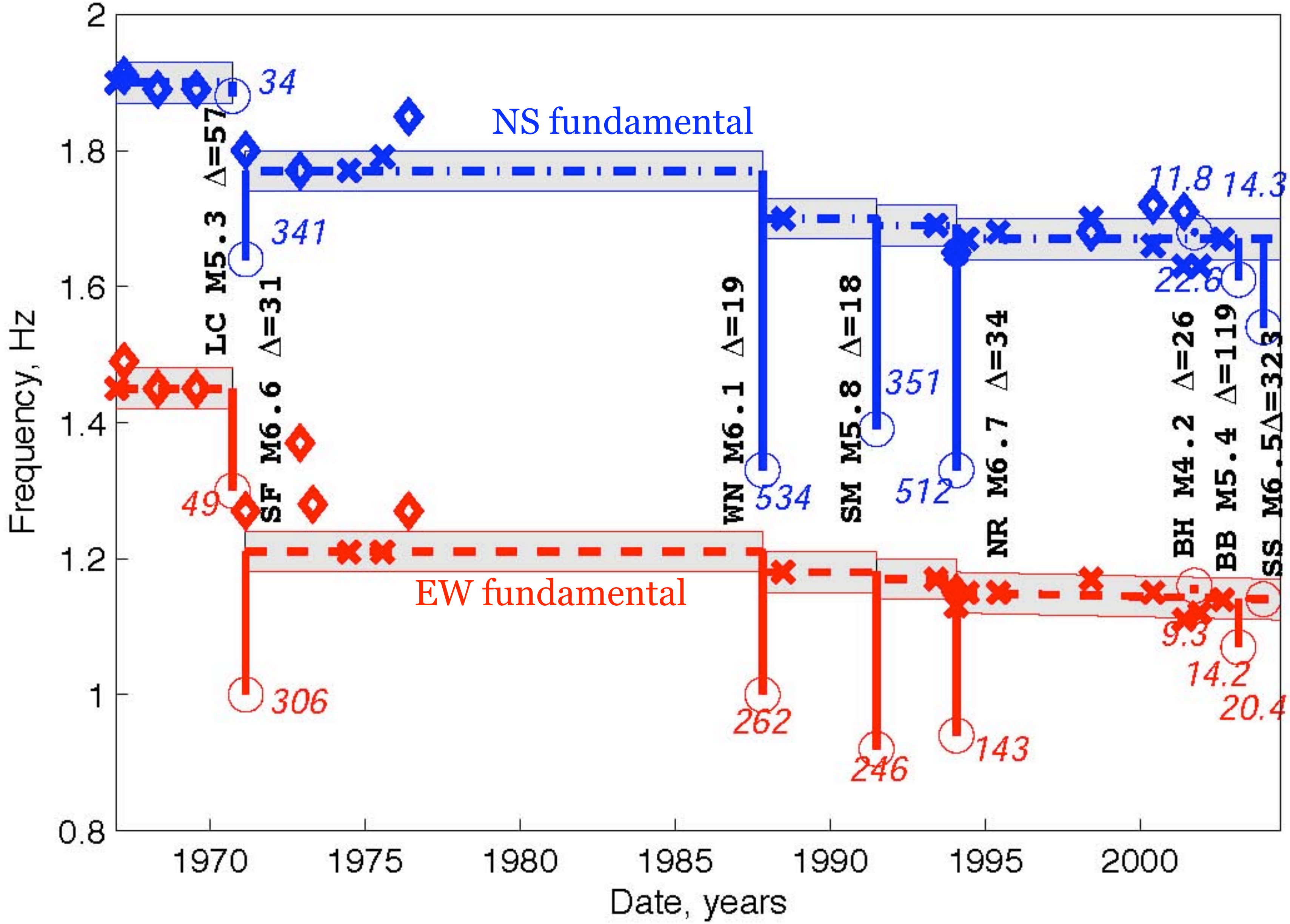
asynchronous shaker
ambient motions
earthquakes
exotic sources

[Results of Millikan Library Forced Vibration Testing, (2004) Bradford et al, EERL-2004-03]





Historical Evidence of Wander of Natural Frequencies



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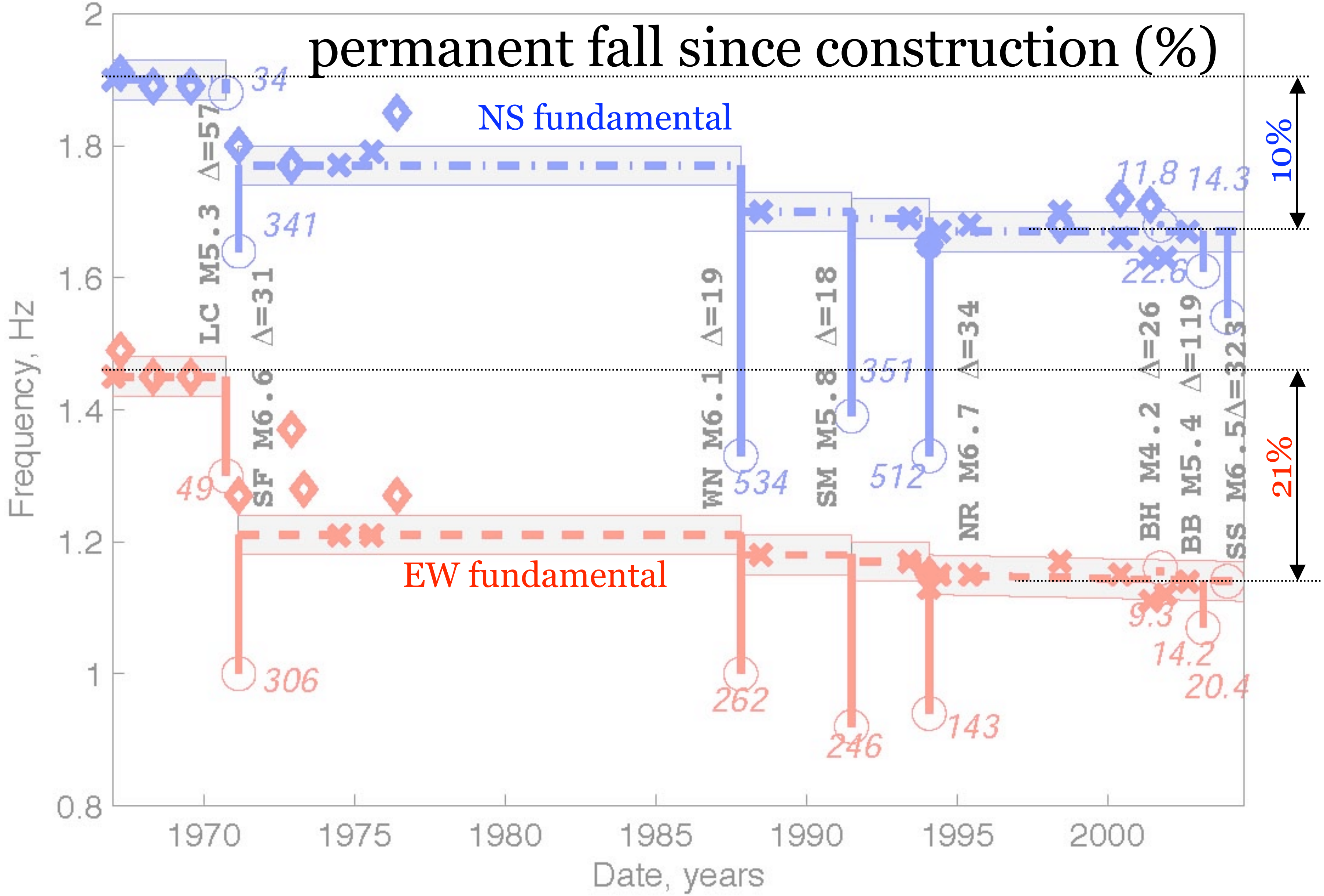
ETH



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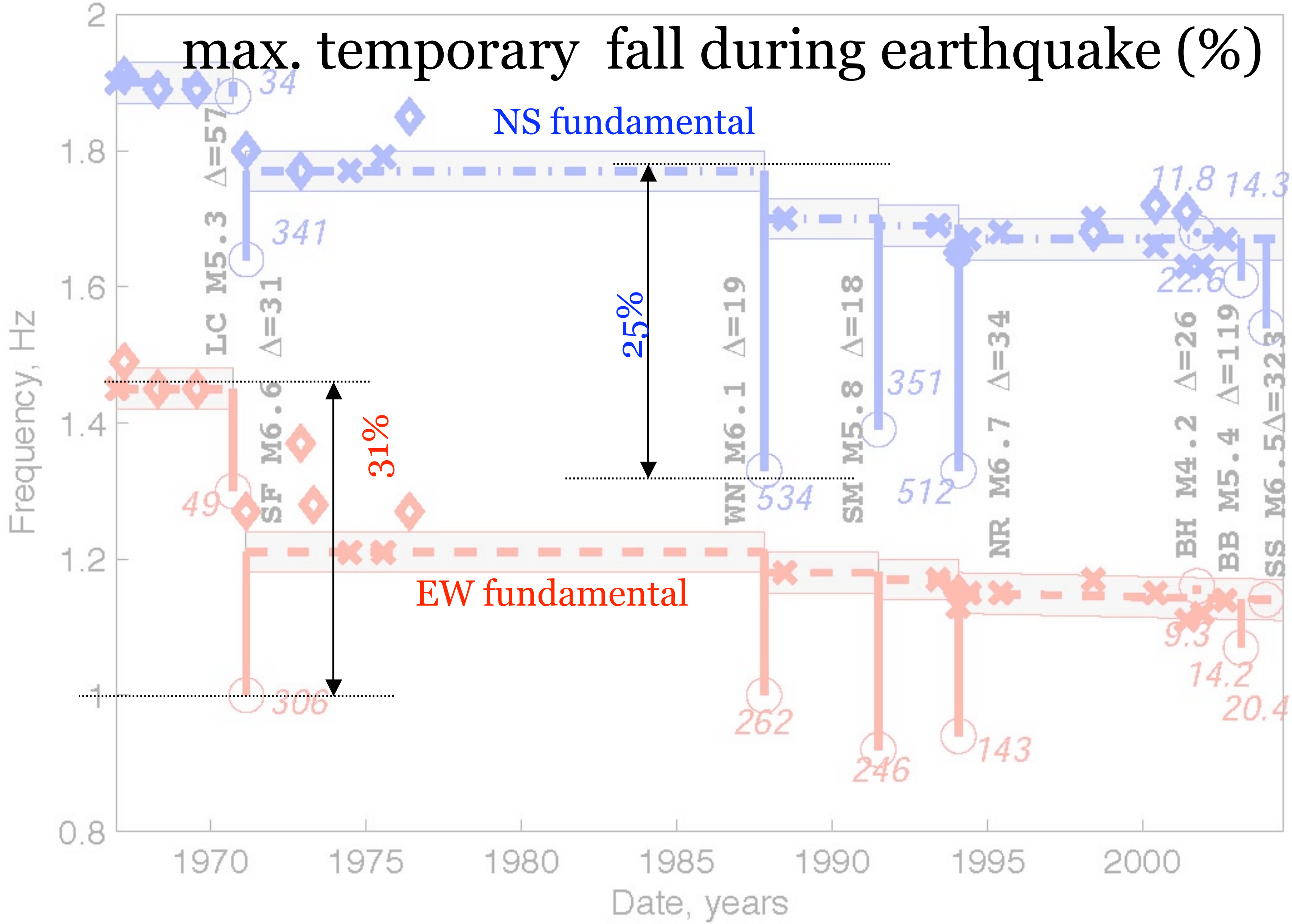

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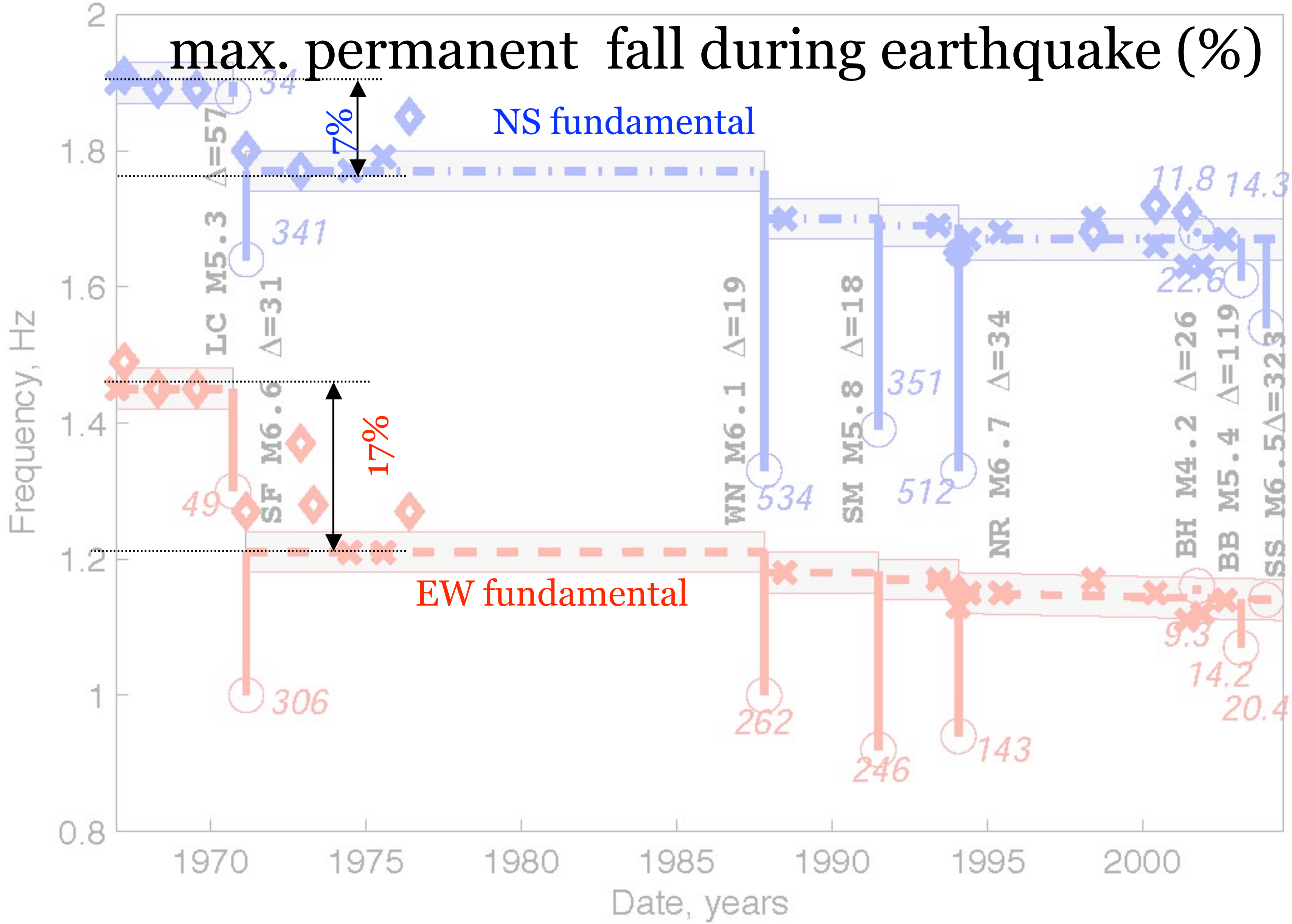
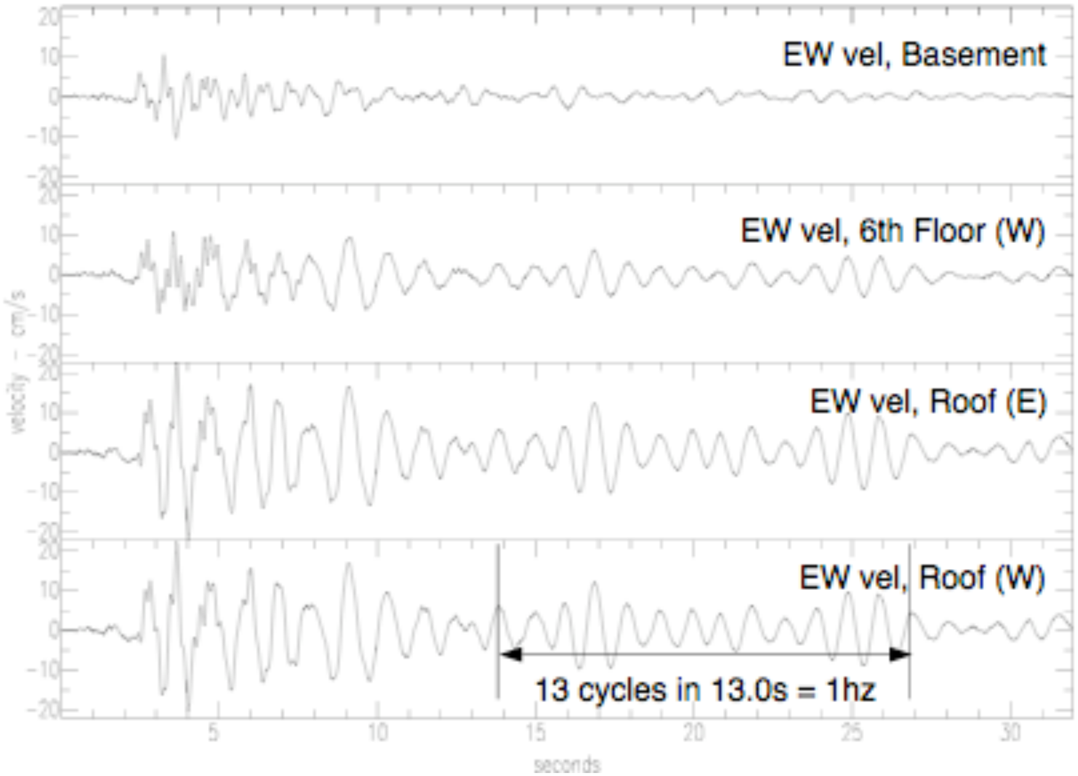
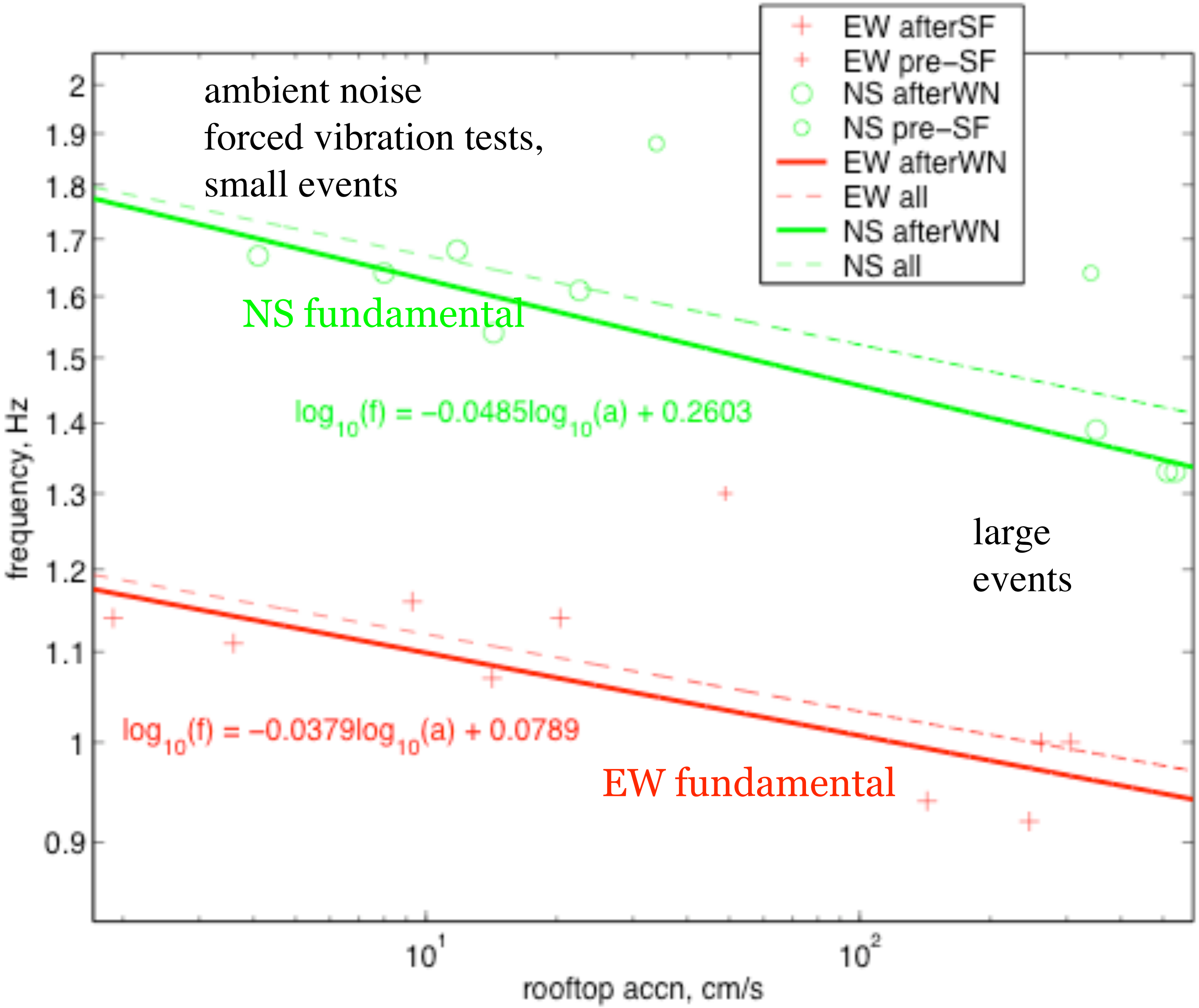


Example of Strong Motion Recording

- 1987 M6.1 Whittier Narrows @ 19km
- EW velocity timeseries



Linearity of Natural Frequency Wander with Excitation Amplitude?



Continuous Monitoring - MIK

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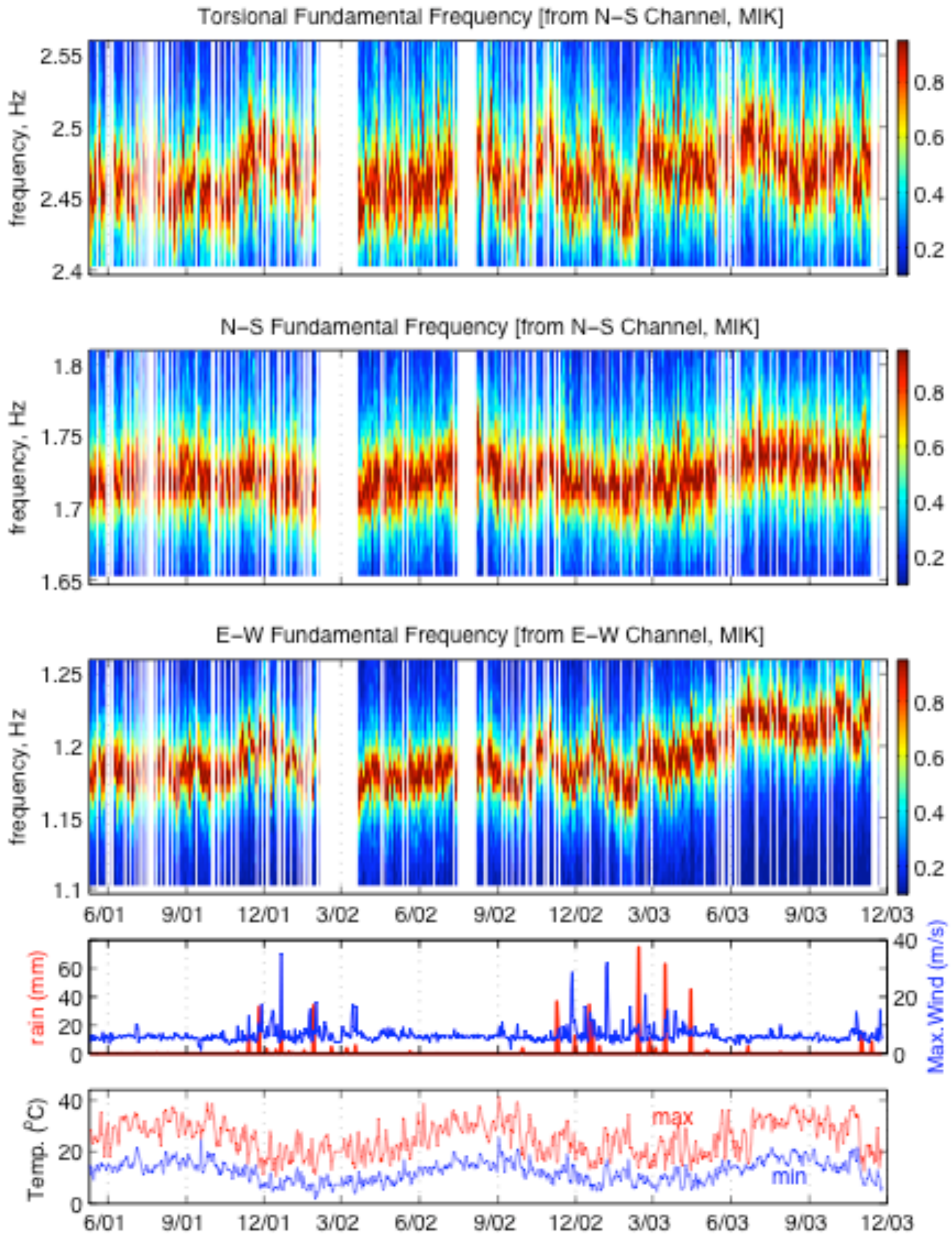
Spectrogram for 2.5 year history of MIK, centred on the fundamental modes

Weather Data from JPL Weather Stations (8km distant)

Little Variation in N-S mode (resistance by massive concrete shear walls), more variation in E-W mode (resisted by concrete moment frame, elevator core).

E-W, torsional rise in Spring 2003 due to installation of partition walls on 3-5 Floors.



Weather Effects - MIK

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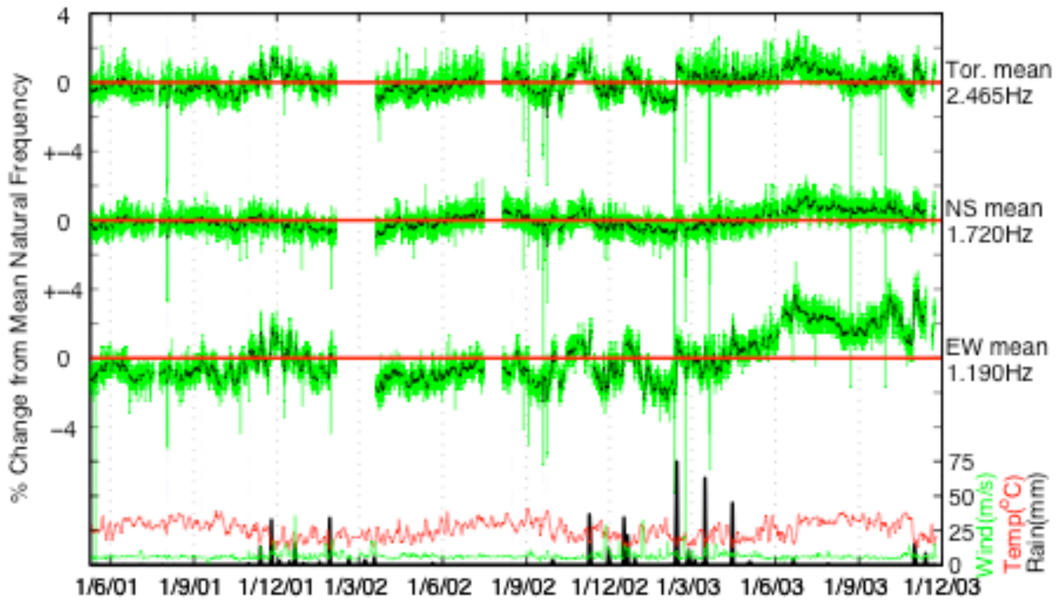
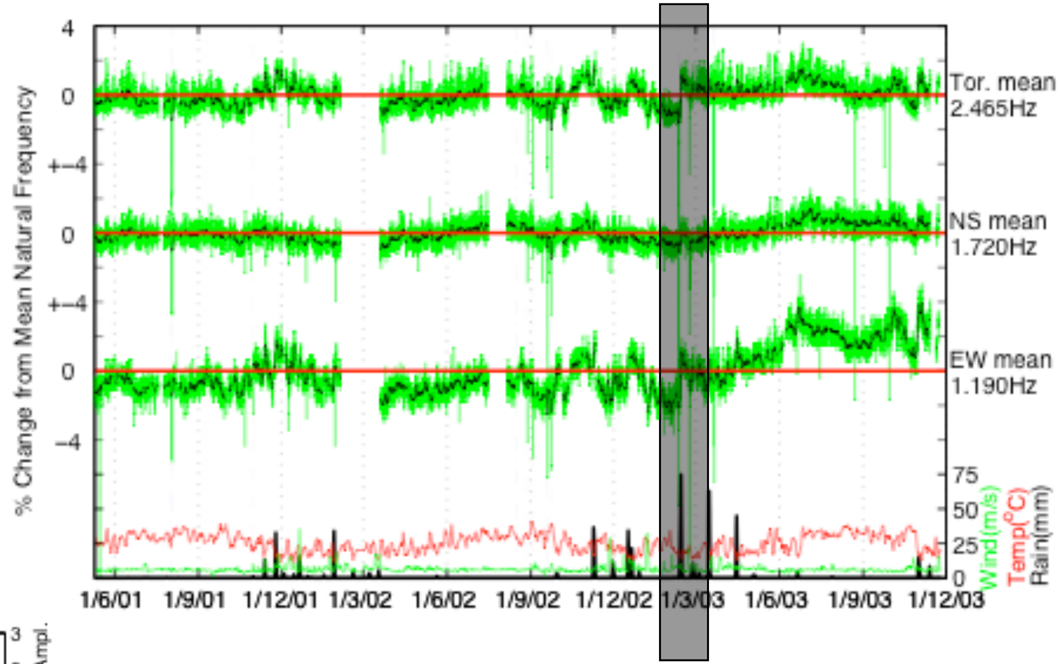


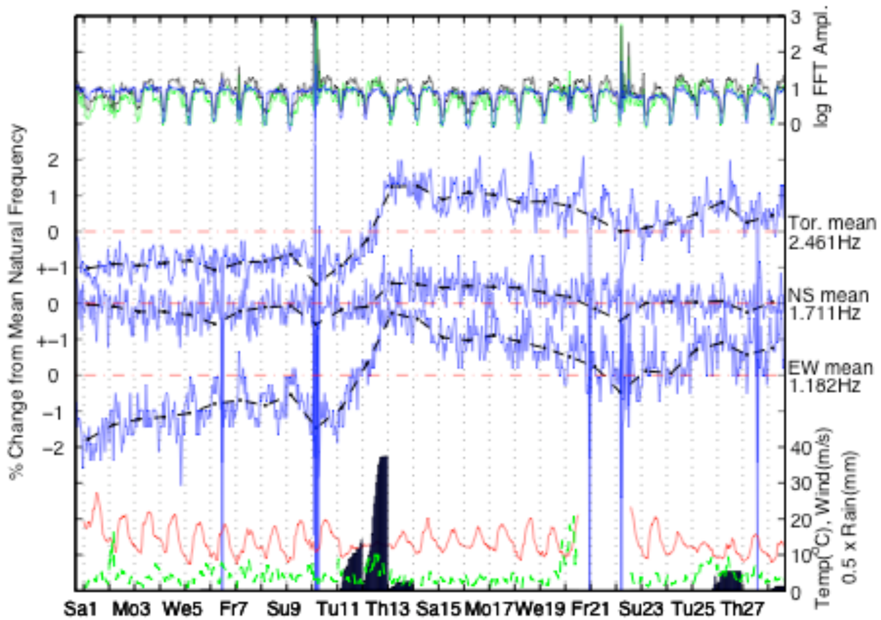
Same figure picking the peaks (daily - black

hourly - green)

Weather Effects - MIK

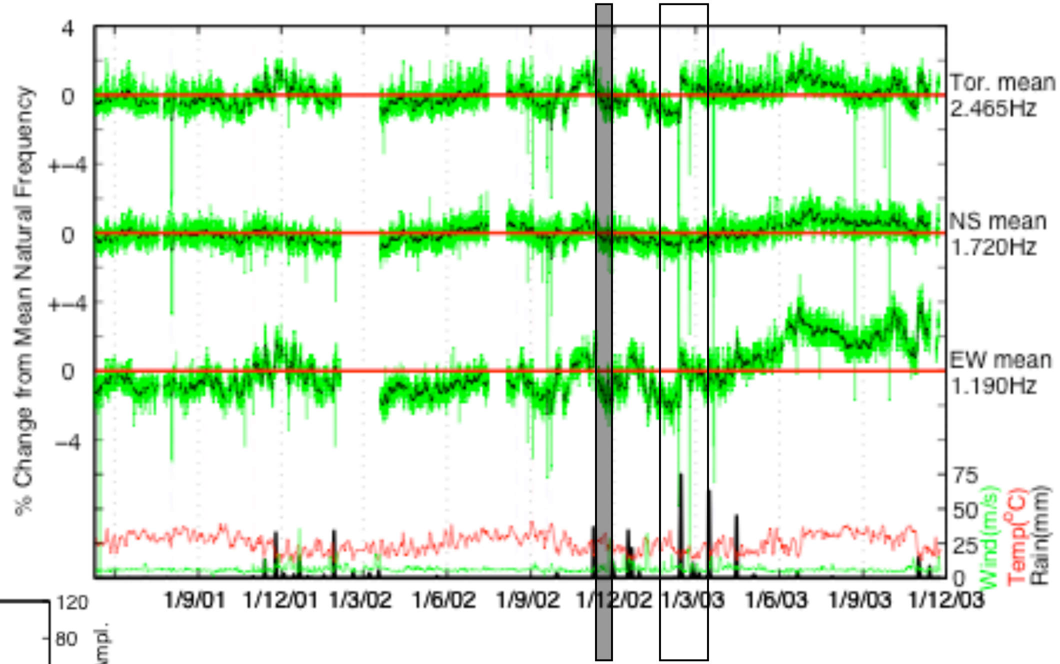
Heavy Rainfall
(28dys, Feb '03)

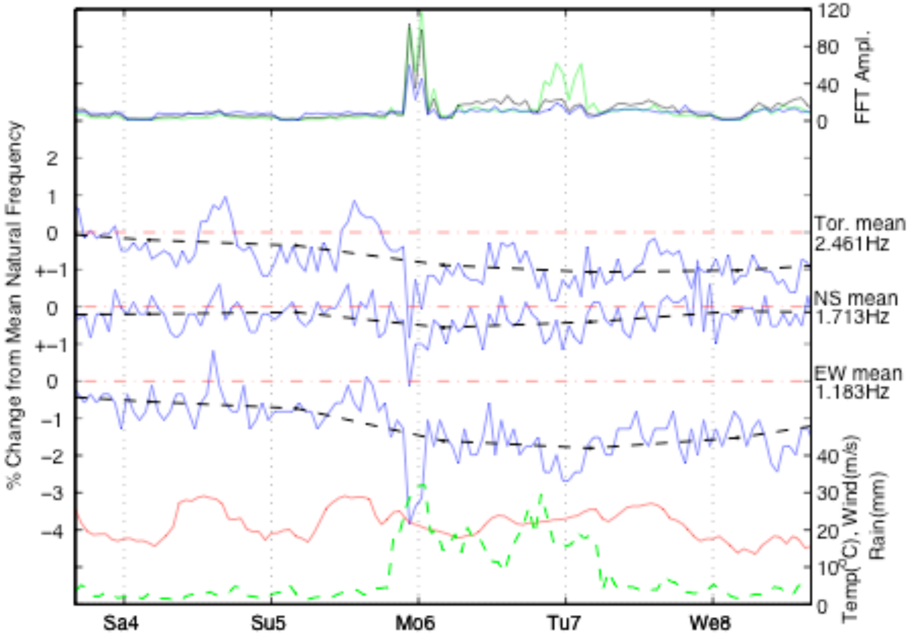




Weather Effects - MIK

Santa Ana windstorm
(5dys, Jan ‘03)





Weather Effects - MIK

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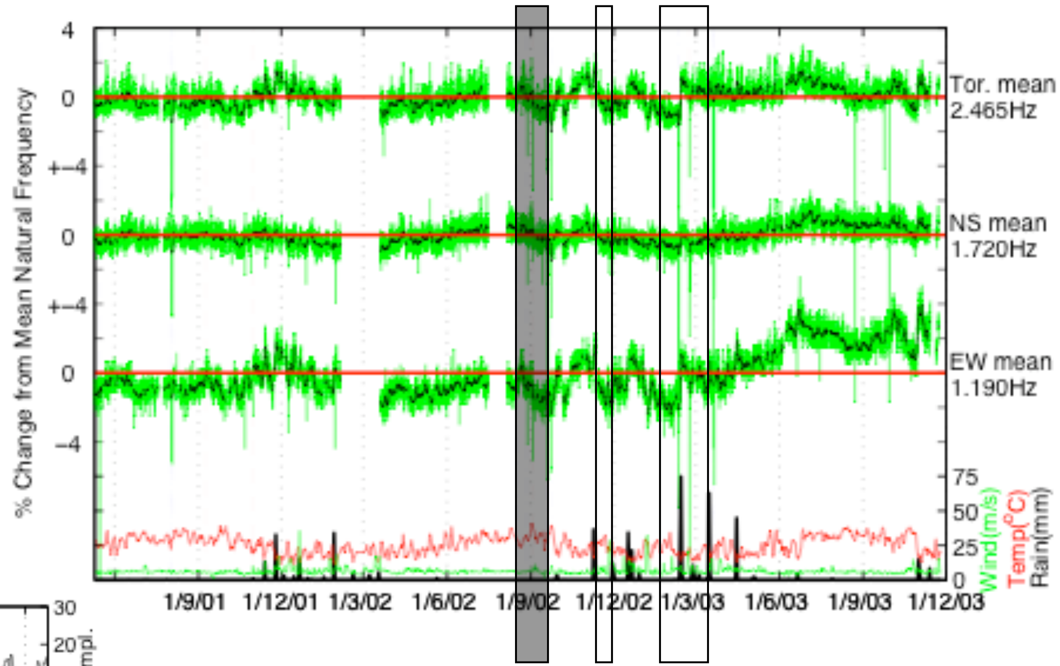
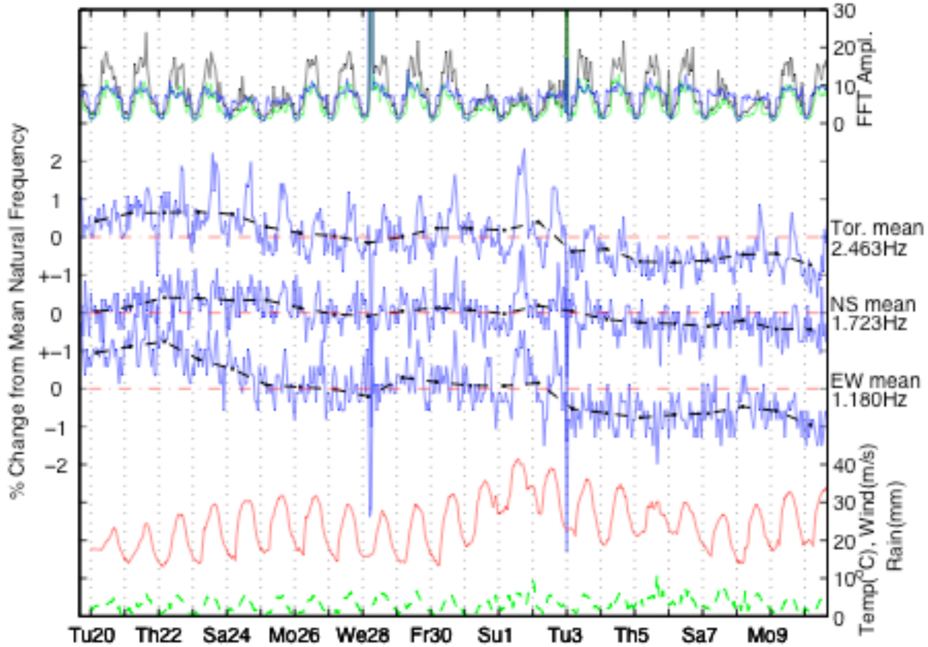
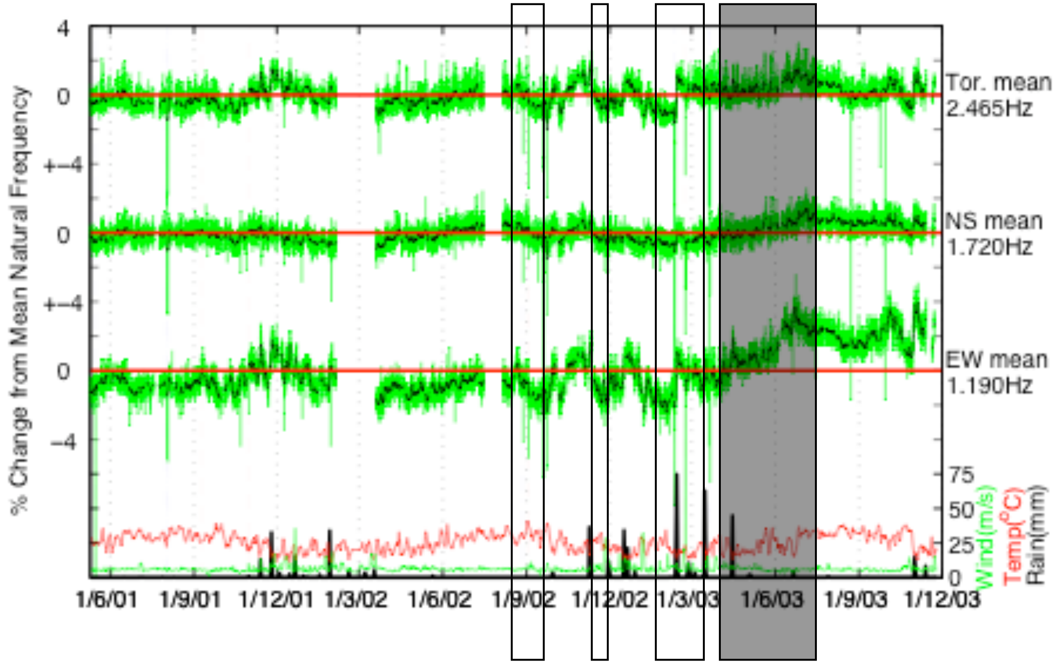
Extreme temperatures
(21dys, Oct '02)





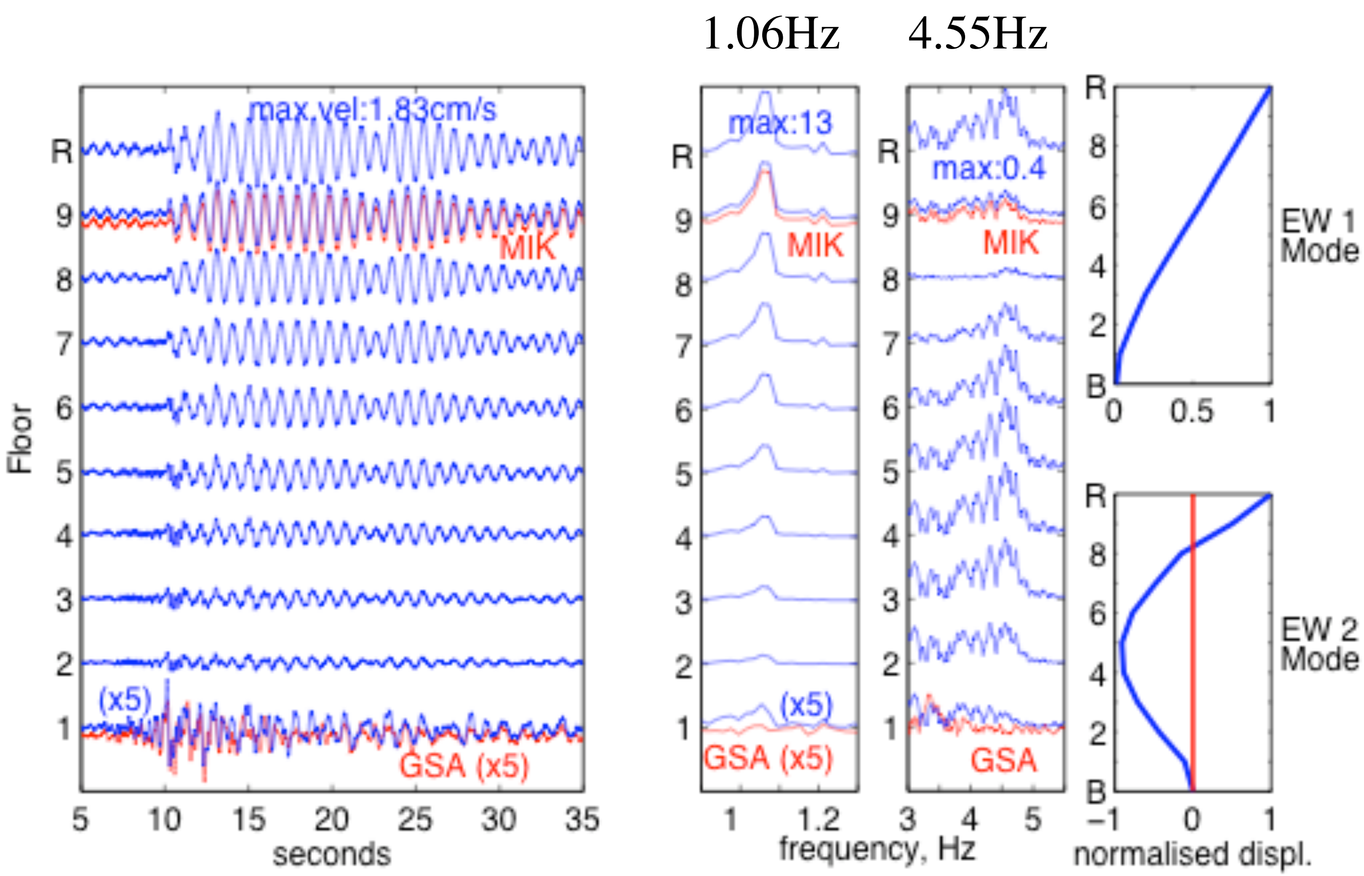
Weather Effects - MIK

change in mass stiffness
(spring 2003)



Earthquake Effects - USGS Array

22 Feb 2003
M5.4 Big Bear
@ 120km,
USGS Array



- Both EW fundamental and 1st overtone excited, peaks significantly lower than from ambient shacking just prior to event
- 1st overtone modeshape shows small amplitude at MIK (9th floor)

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Earthquake Effects - MIK

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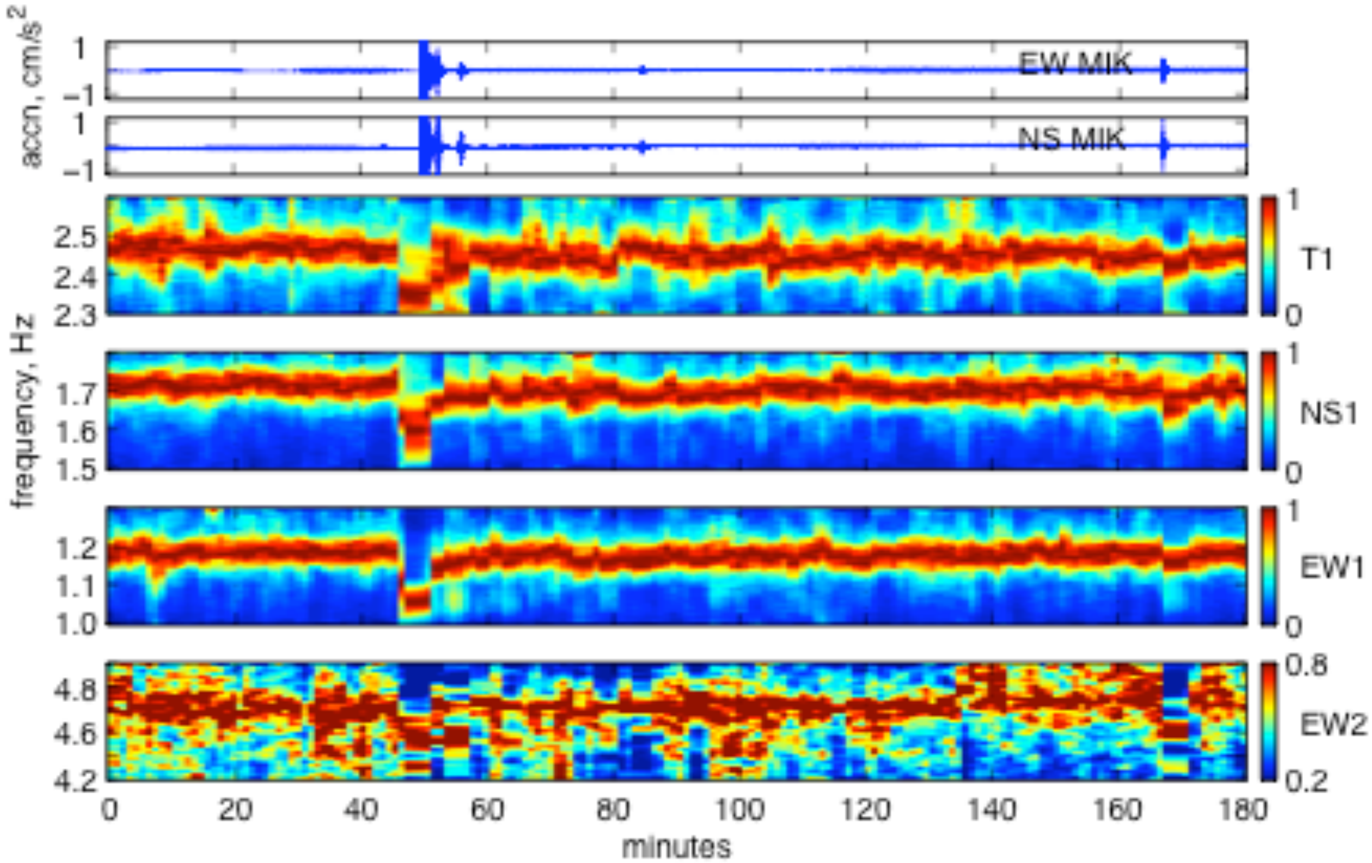
22 Feb 2003 M5.4 Big Bear @ 120km, Millikan Library MIK : spectrograms from continuous data

3hours data,
5min window



- All natural frequencies observed to drop > 5% during strong motions (max. ~$15 cm/s^2$)
- Recovery to pre-event stiffness within minutes at this level of excitation

  [contradicts previous investigations during larger motions (eg 1971 San Fernando) which indicate strength returns slowly over course of months]

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Linear Transfer Functions : from GSA to MIK

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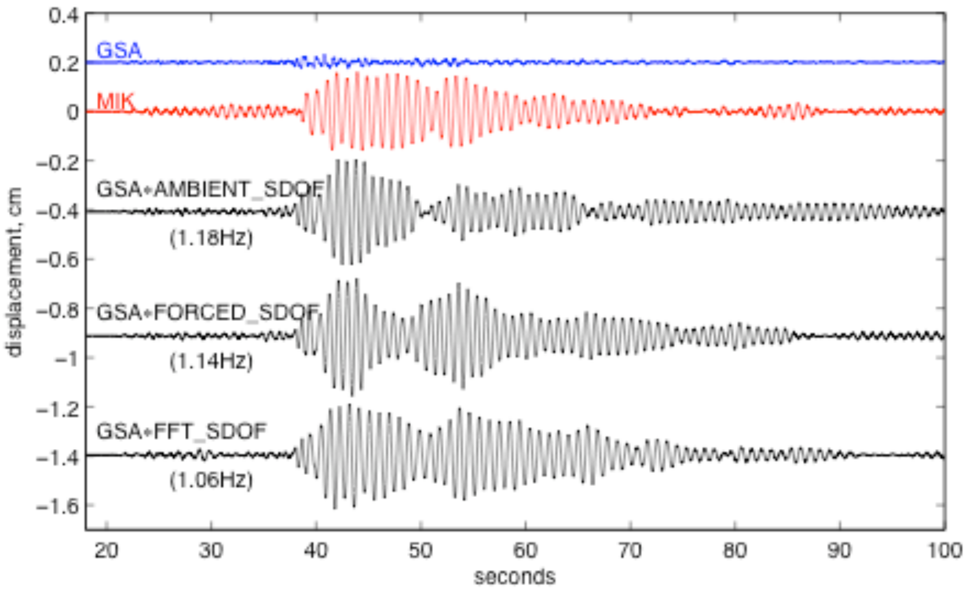
• We attempt to model MIK displacement, U_{MIK}, using GSA displacement, U_{GSA}, convolved with the SDOF impulse response equivalent to Millikan Library:

$$\ddot{U}_{MIK} = \ddot{U}_{GSA} + (\ddot{U}_{GSA} * SDOF_{MIK})$$

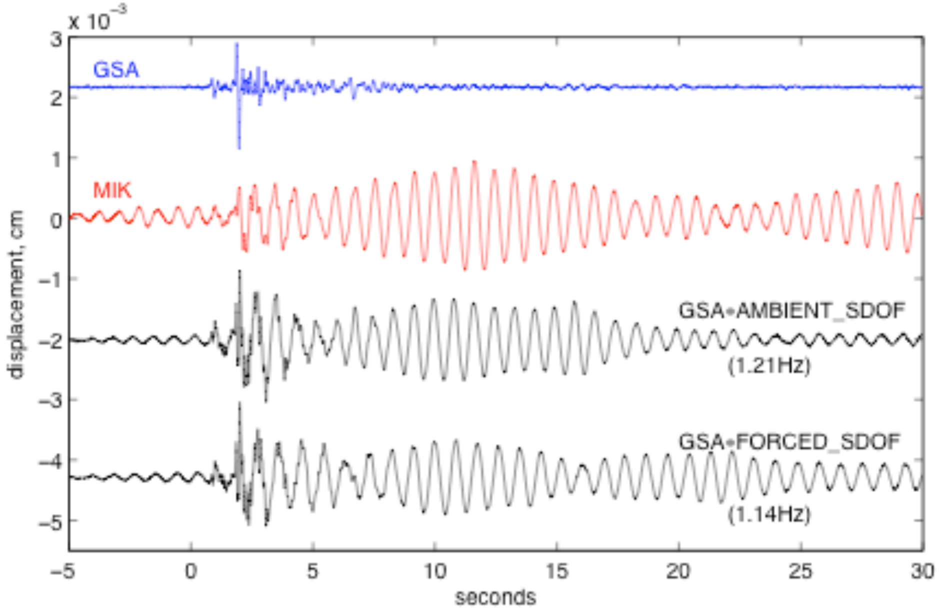
• Amplitude amplification is determined from the participation factor of the first mode, assuming mass matrix of equal floor mass, and modeshapes as determined from forced vibration tests

• During small amplitude excitation, buildings are expected to behave as linear systems…

M5.4 Big Bear



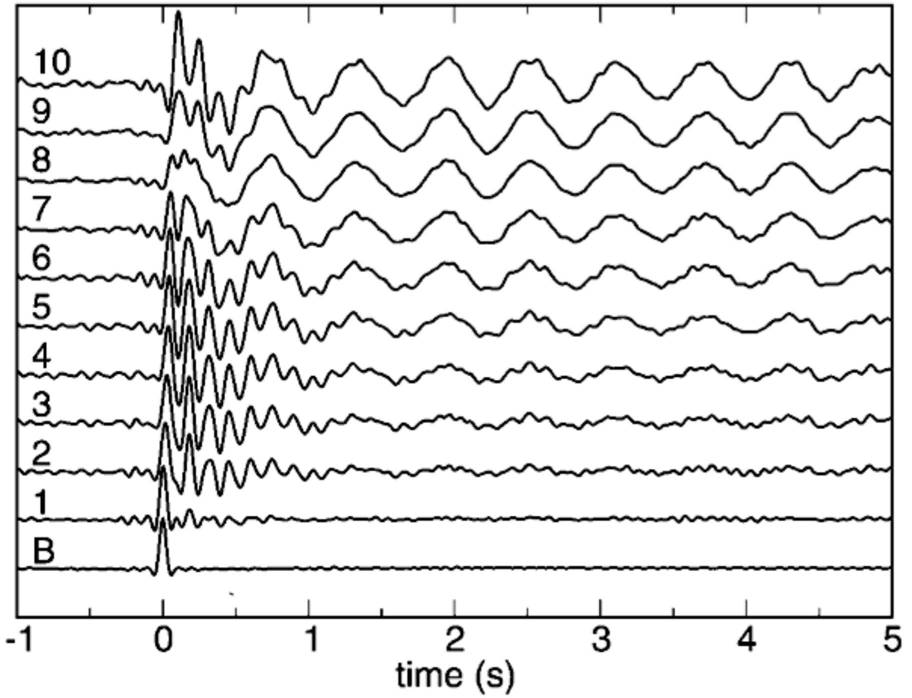
M2.0 Pasadena



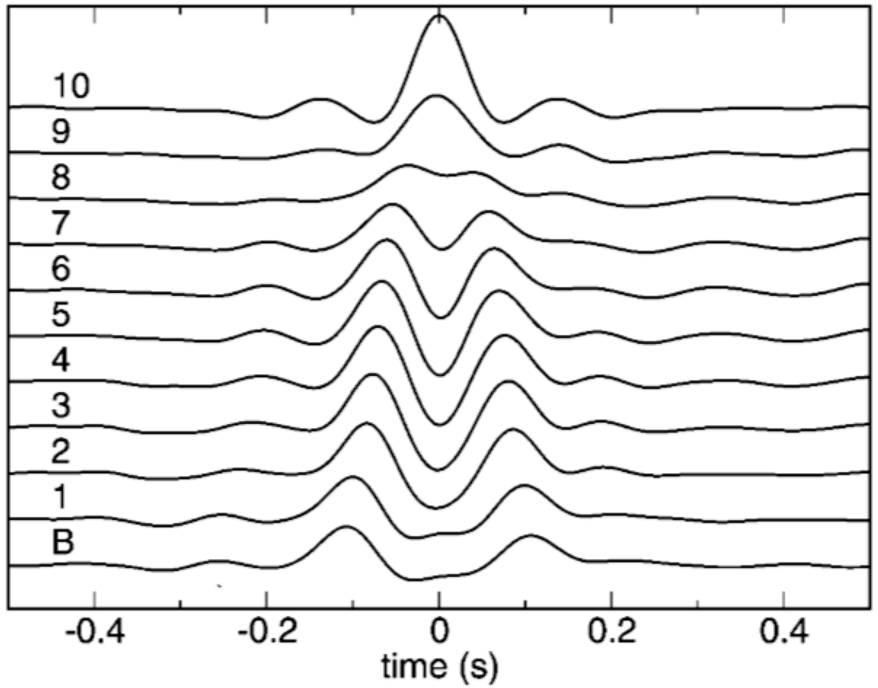
Linear Transfer Functions : Deconvolution

- a transfer function is a way to observe waves travelling through the building
- deconvolve the motion from the one record from upper floors to show building response only
- ideally suited for indicating structural damage

Big Bear, EW array, deconvolve with basement record



Big Bear, EW array, deconvolve with roof record



(Sneider and Safak, BSSA 2006)

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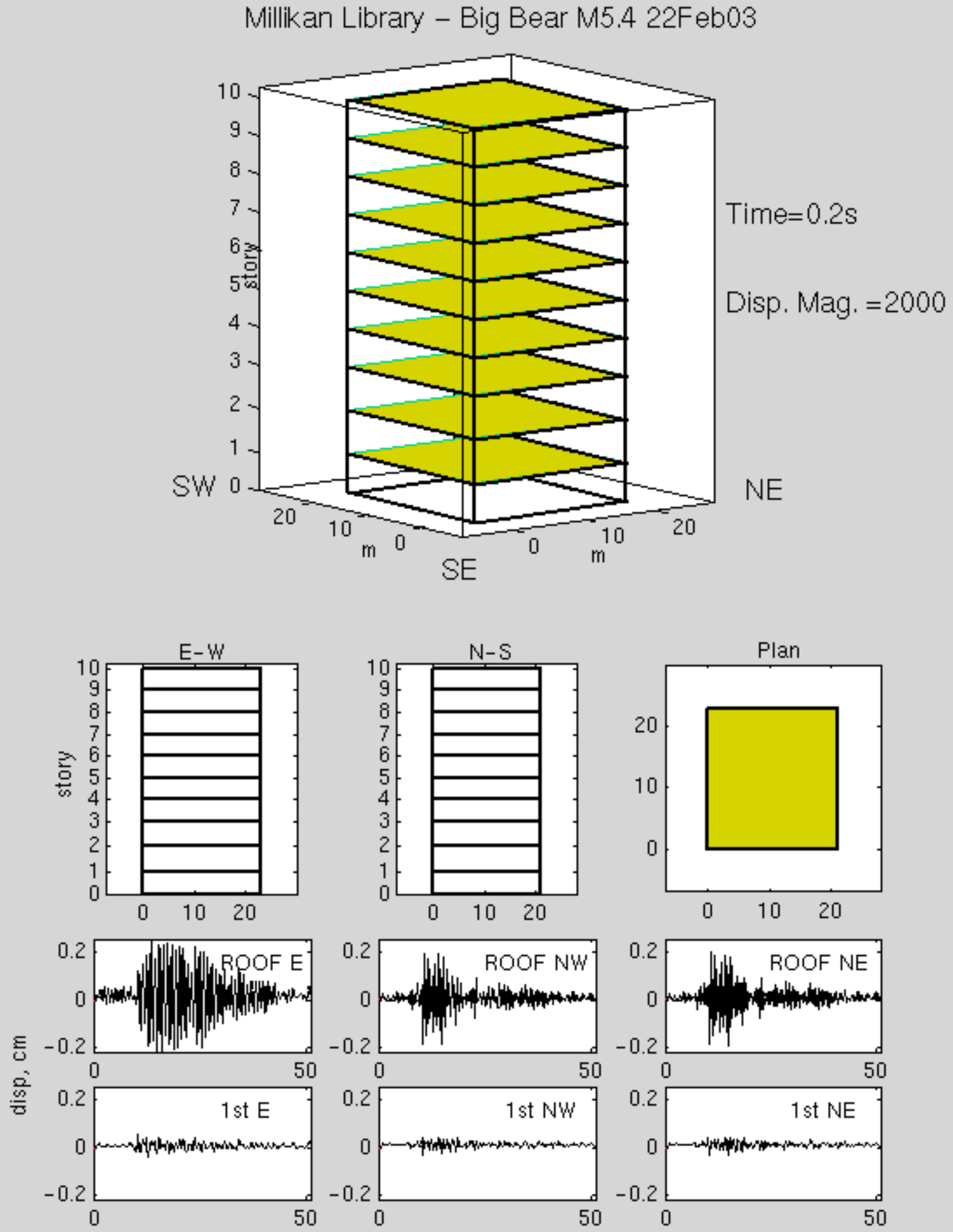
M5.4 Big Bear @ 120km

3-D movie of Millikan Library motion using all USGS horizontal accelerometers (3 per floor)



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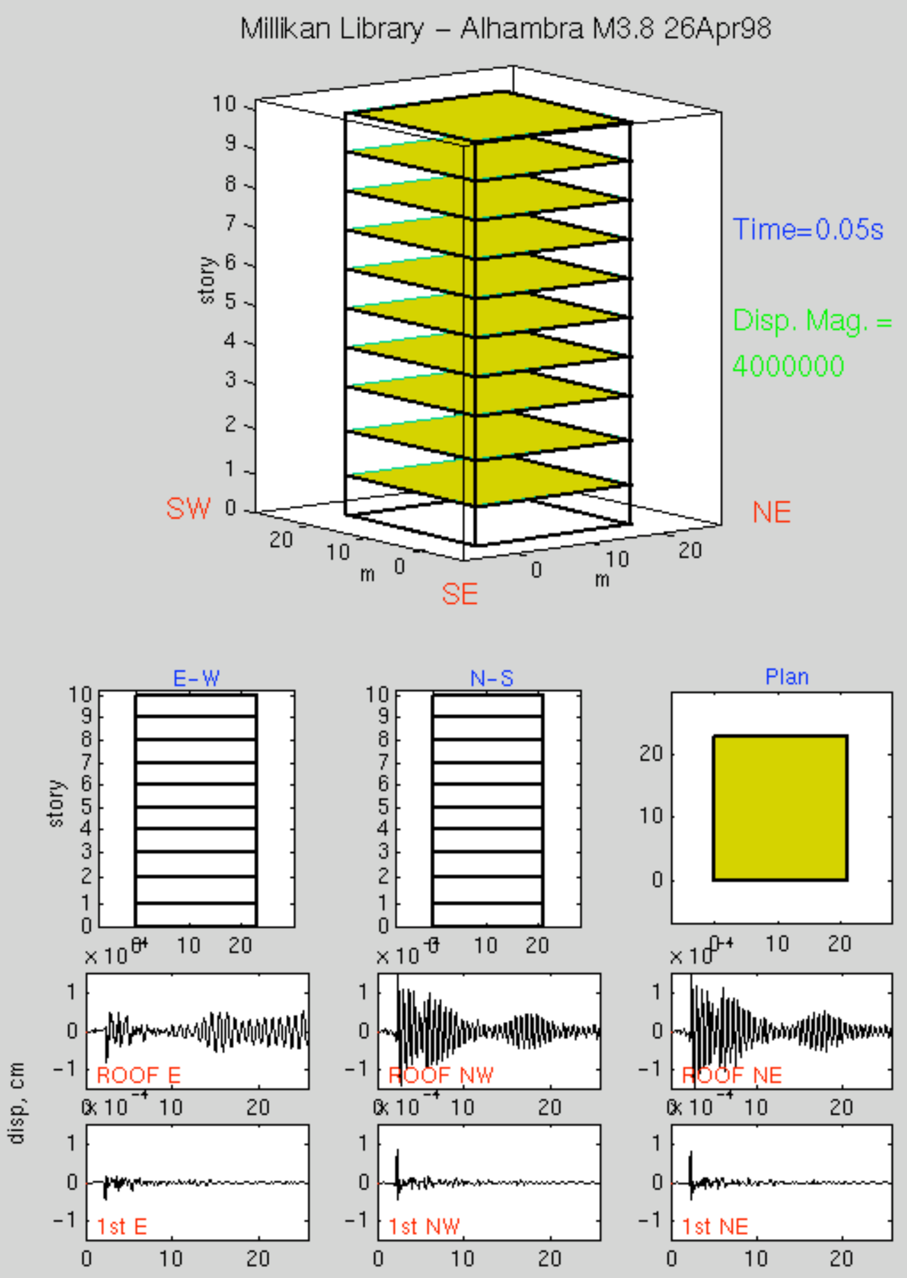
M3.8 Alhambra @ 7km

3-D movie of Millikan Library motion using all USGS horizontal accelerometers (3 per floor)



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Millikan Summary

ETH

Observe:	|Effect| (EW)	Mechanisms?
Over 30 years f↓	21%	loss of stiffness in non-structural elements soil-structure changes
ground motion amplitude↑ f↓	17% permanent 31% during	soil-structure interaction rocking at basement degradation of non-structural elements
day : f↑ night : f↓	1%	heating / cooling of cladding? internal noise
rainfall↑ f↑	3% for weeks	expansion of wet concrete soil-structure interaction
wind↑ f↓	3% inst.	non-white noise excitation? loosening of cladding?
temperature↑ f↑	3% inst.	expansion of cladding / moment frame stiffens system
changing usage f↑	2% permanent	remove mass, add stiffness (partition walls)

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Broad Center

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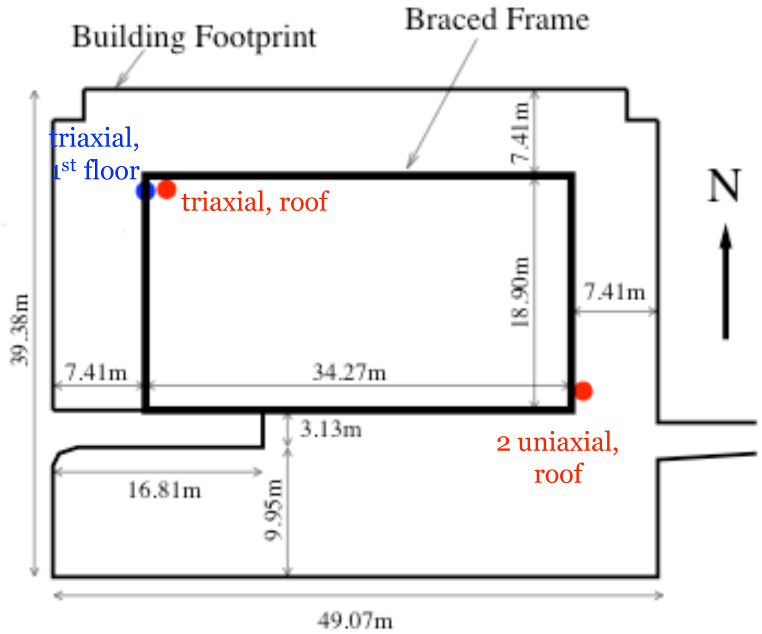
view from SW

- completed and instrumented in 2003
- 3 story steel moment frame with stiff unbonded braces
- 2 deep concrete shear wall basements
- irregular floor plan
- 8channel SCSN station CBC



typical section

Continuous Monitoring - CBC

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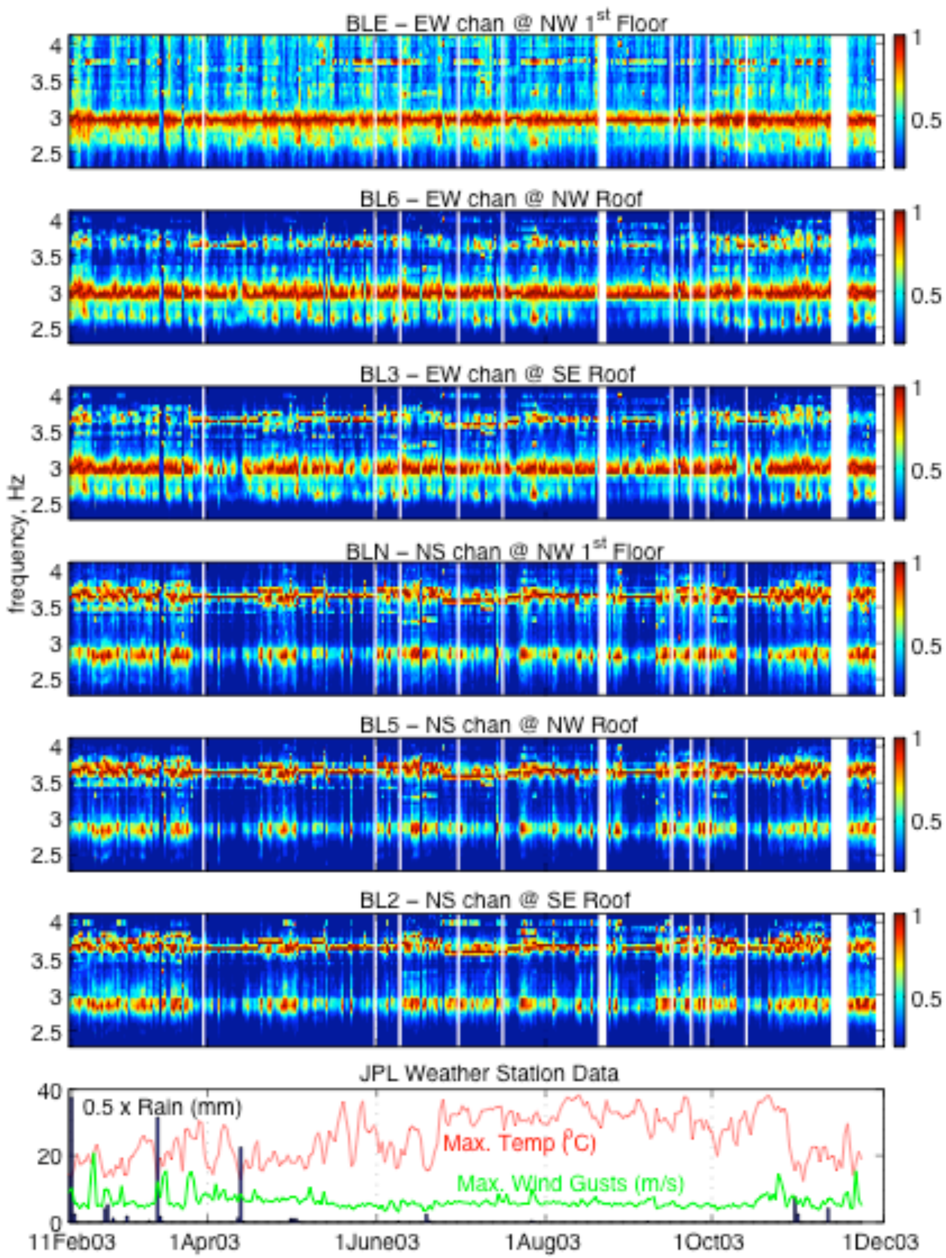
Spectrogram for 10month history of CBC, for each of the EW / NS channels, from 2.4-4.2Hz

Weather Data from JPL Weather Stations (8km distant)

Apparently 2 E-W modes at 2.65, 3.0Hz, 2 N-S modes at 2.43Hz, 2.8Hz, Torsional at 3.65Hz.

Significant building noise seems to drive natural frequencies

Some wander of lowest translational modes



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Presentation Outline

ETH

Part I - Motivation

- Existing health monitoring
- Bandwidth of modern sensors
- Continuous monitoring and small amplitude studies

Part II - Millikan Library

- Instrumentation at Caltech
- Continuous monitoring
- Transfer Functions
- Movies of earthquakes

Part III - Future Directions

- Factor Building
- ANSS
- European Testbeds
- PQLX noise monitoring

Factor Building, UCLA

72 sensor system
continuous, real-time
Data available from IRIS

65m high
15 story
Steel moment frame
Concrete spread footings

>100m deep borehole

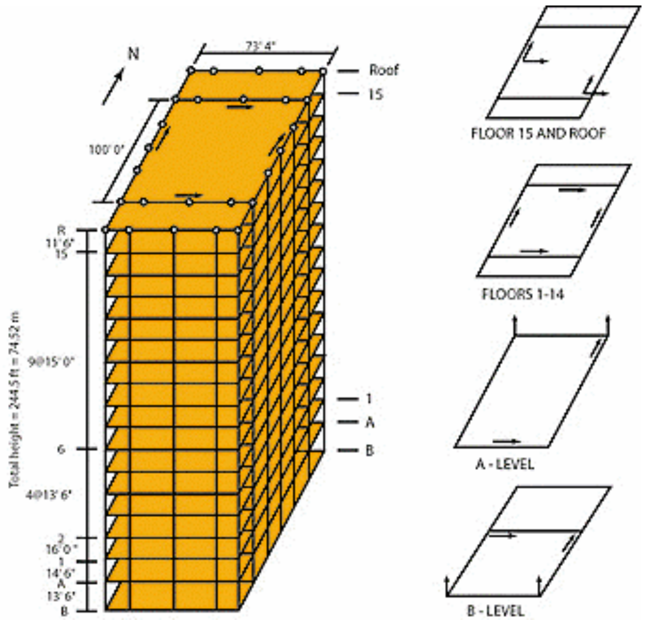


photo from factor.gps.caltech.edu

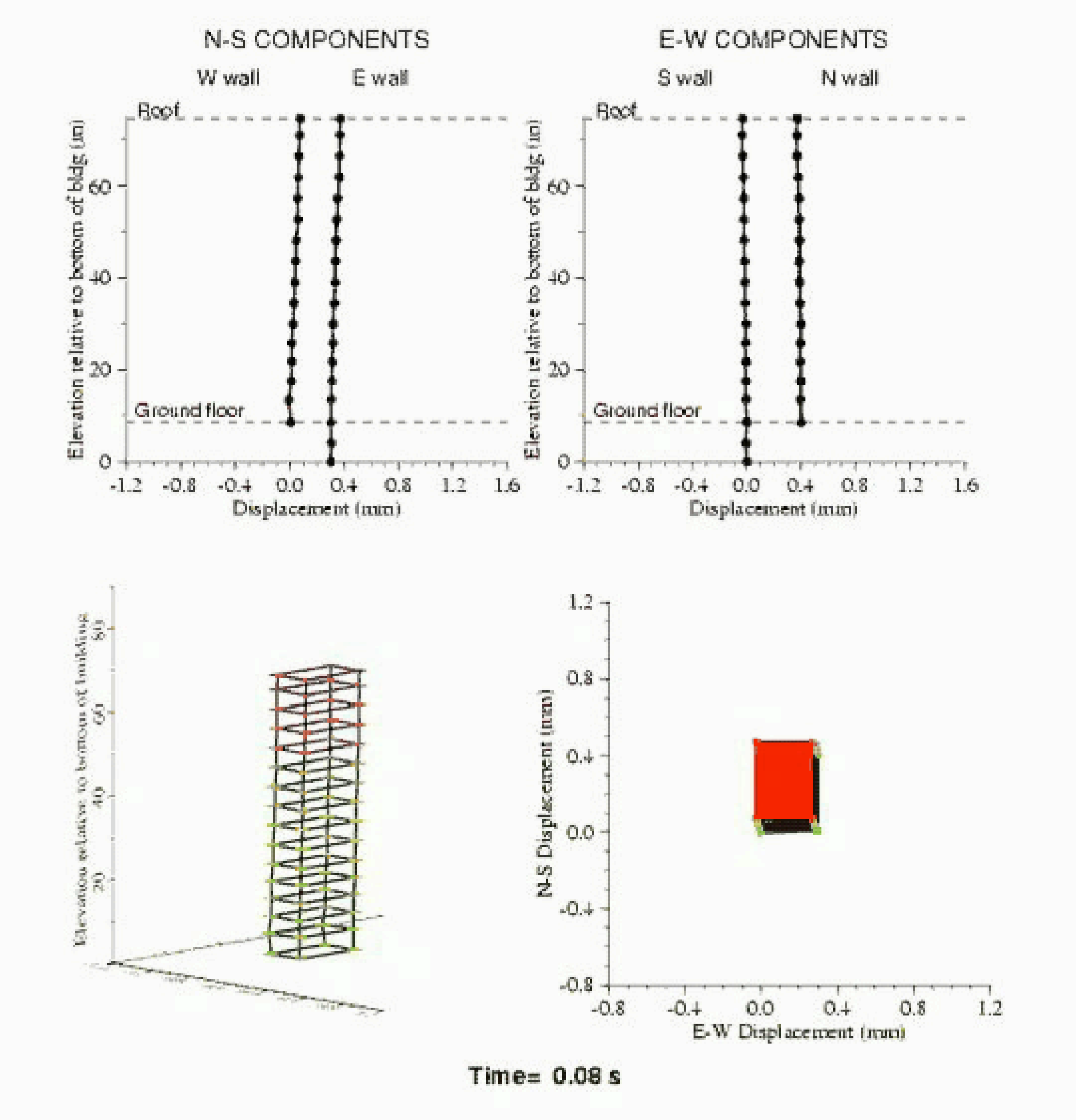
Fac

Swiss Seismological Service

72 sensor system
continuous, real-time
Data available from IRIS

3-D movie of Factor Building motion using all USGS accelerometers (4 per floor)

28/10/04 Ml6.0 Parkfield @270km



factor.gps.caltech.edu

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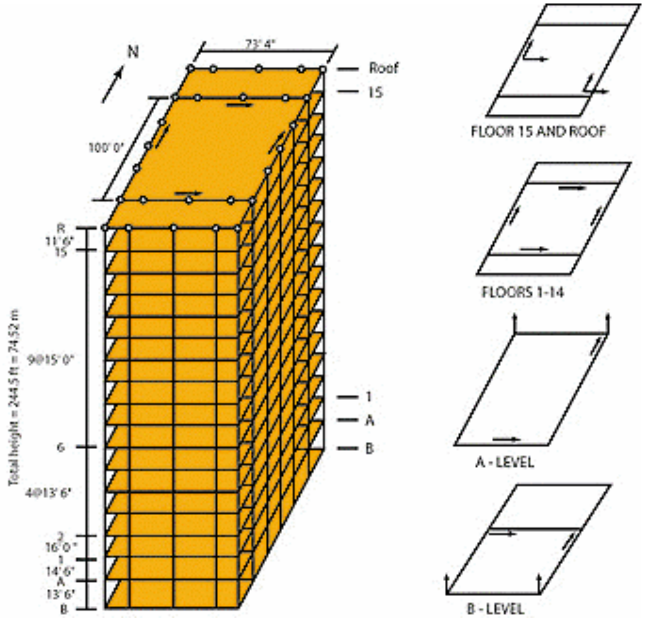
Factor Building, UCLA

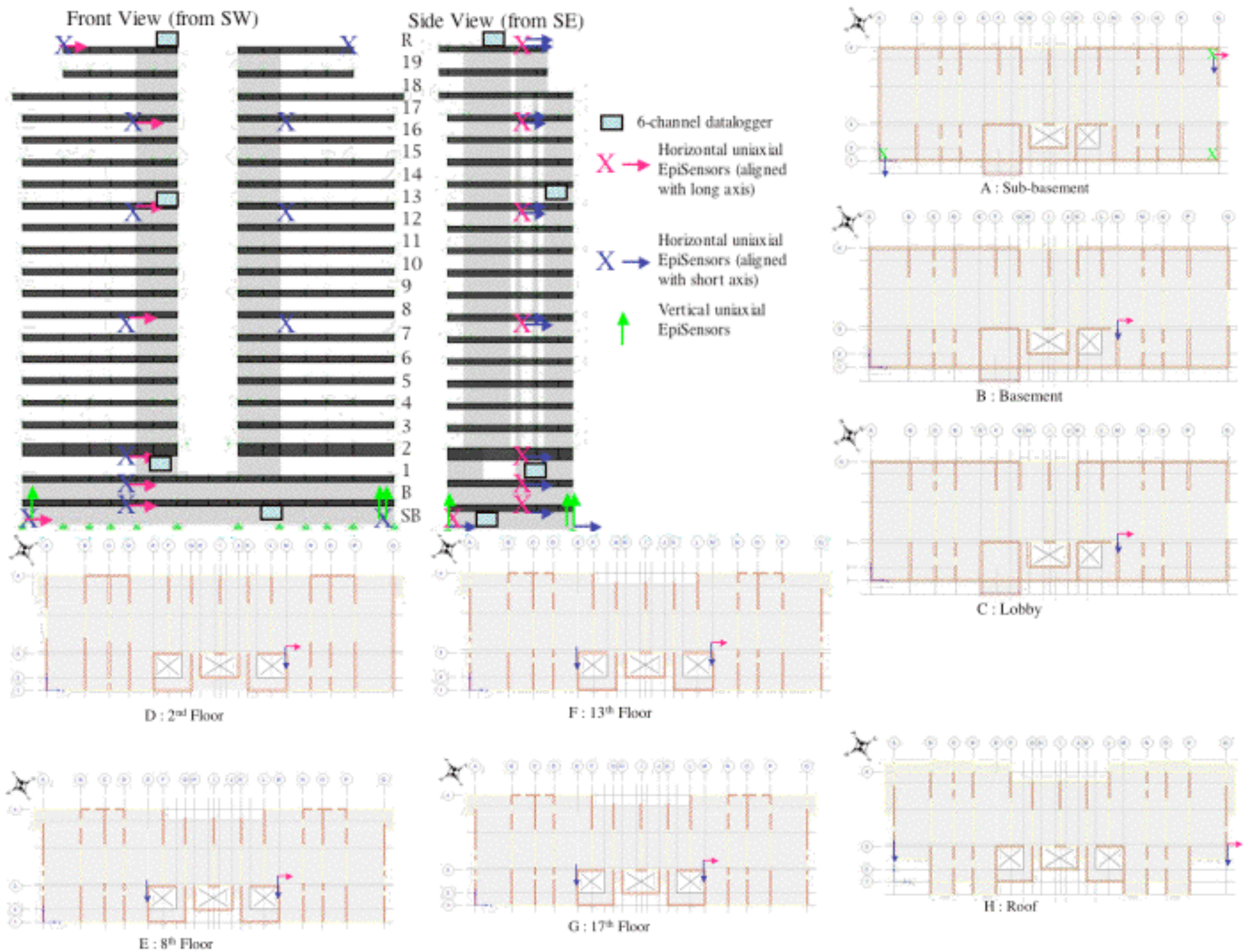
ETH



- Current Research (Heaton, Kohler, Muto) : create library of Green’s functions for potential fracture at column/beam connections:
- Record response at each of the 72 sensors to impulse of energy at each column/beam connection
- Damage in an earthquake will occur at these connections: brittle fracture at these locations will gernerate high frequency energy, radiated from the connection throughout the structure: previous knowledge of green’s fn of this signal can lead to near real-time identification of exact location of structural damage
- Massive consequences for this localised damage recognition : Northridge Earthquake damage costs dominated by attempts to identify this sort of damage in high rise steel moment frame buildings.

El Castillo, Mayagüez, PR

El Castillo, Mayagüez, PR



Lettsome Tower, BVI

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ETH

View from roof towards apron on fill

- completion this year
- 12-channel K2:
  - triaxial free field
  - 6 uniaxial @ base
  - 3 uniaxial @ top
- capture rocking, torsion, liquifaction

View from free field site

HPP @ ETH Hönggerberg

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ETH

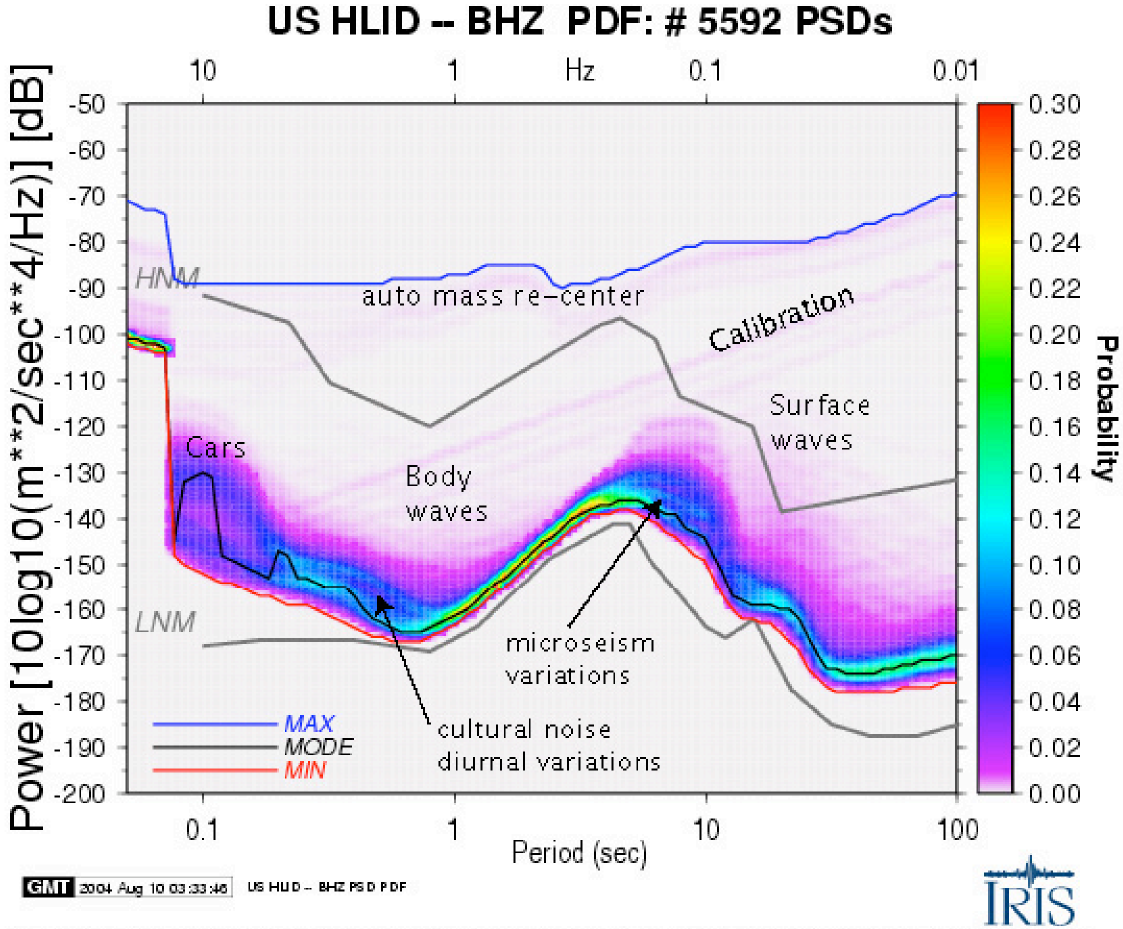
- Geophysics Building at ETH Hönggerberg
- 10 story concrete moment frame with concrete shear walls
- 2 deep basements, founded on rock

- instrumented over Winter 06/07 with Episensor on roof
- weather station beside building

View with weather station in foreground

PQLX noise monitoring

- PQLX software recently installed at SED for ~30 broadband, ~25 strong motion
- Shows PSD's of signals for duration of station in archives
- Can identify problems with stations, metadata, observe earthquakes
- Move and select signals in both time and frequency domain



PDF analysis code by Daniel E. McNamara (USGS-NEIC), Ray Buland (USGS-NEIC) & Richard Boaz (private contractor).

PQLX noise monitoring

Swiss Seismological Service

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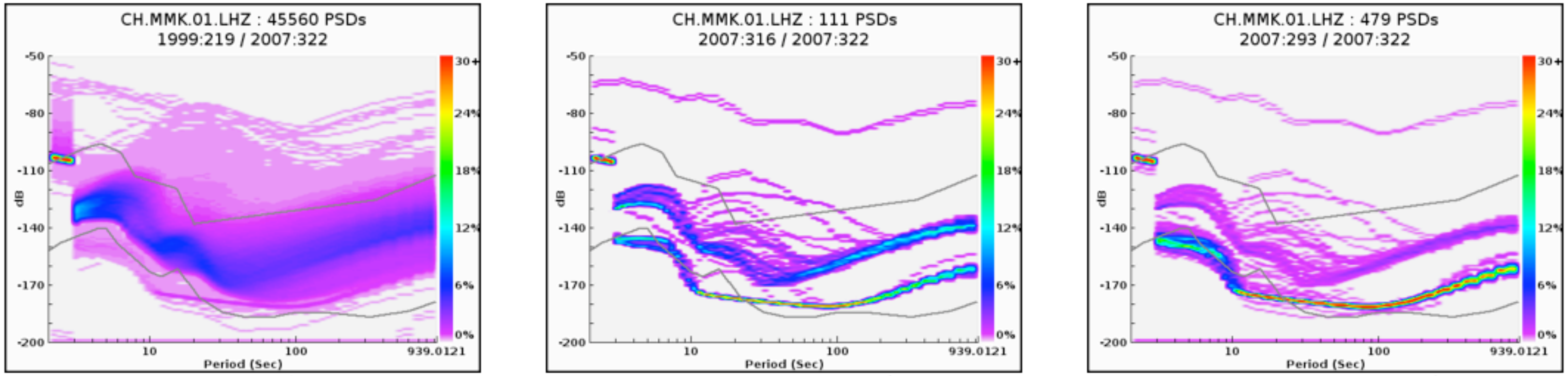
Station MMK



MMK LHZ : ALL
MMK LHZ : Last Week
MMK LHZ : Last Month

Typical SDSnet STS sensor performance over 8 years, plus recent trends : Station MMK Z component

PQLX noise monitoring

Swiss Seismological Service

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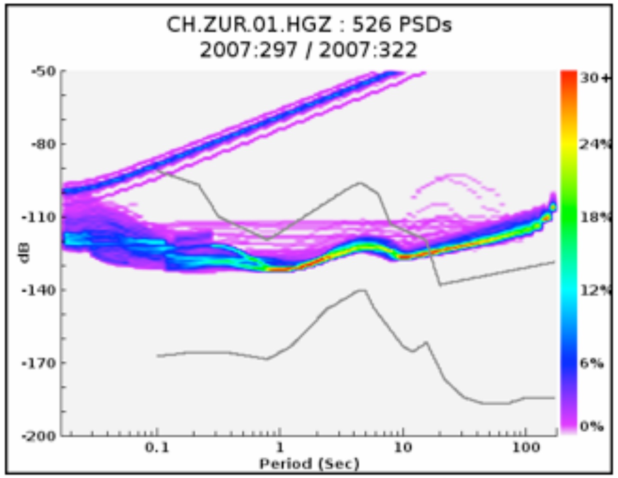
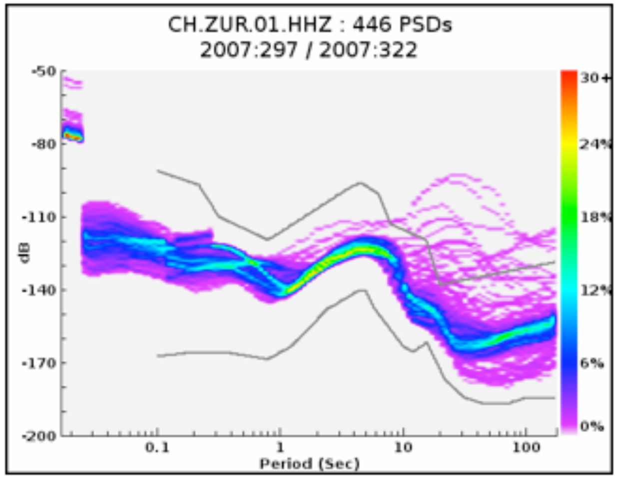


ZUR HGZ : Last Month



ZUR HHZ : Last Month

Comparison of noise from co-located SM and BB sensor : Station ZUR, Z components

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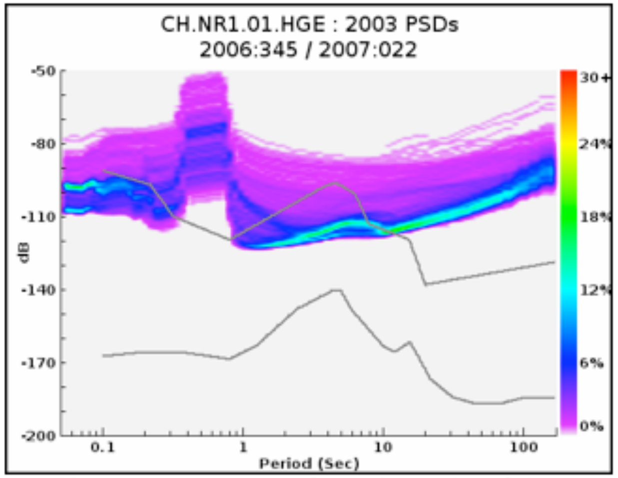
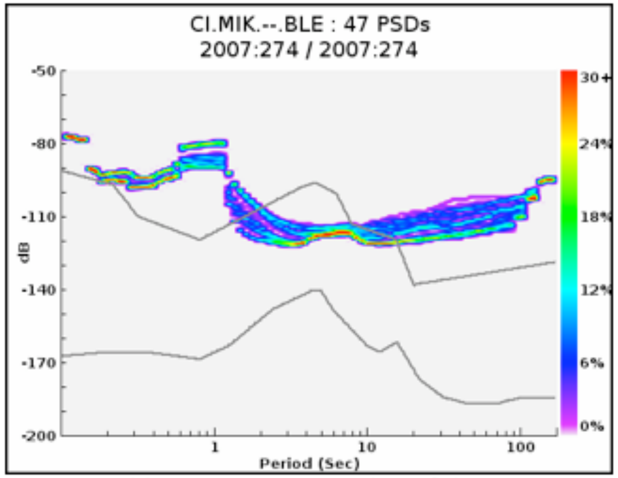


40sps E-W HPP Rooftop : 2months of data



20sps E-W MIK : 1day of data

Traditional PQLX representation of building motion data : HPP@ETHZ, and MIK @Caltech

PQLX noise monitoring

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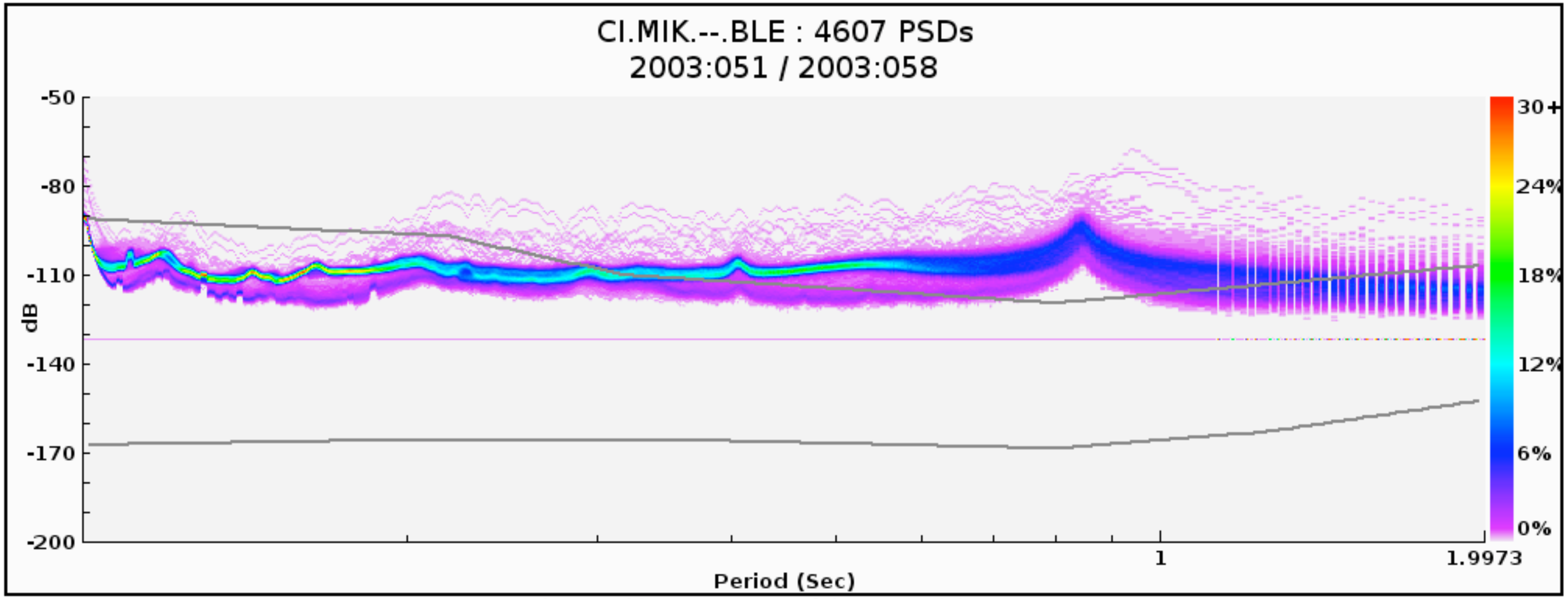

Modified PQLX view of MIK for 7 day period about BigBear Earthquake, 2003

Swiss Seismological Service

Future Directions

ETH

Testbed Installations:

- new structures : dams, bridges
- further investigations of buildings
  - high rise steel structures, wooden structures,
  - particular attention to damping
- boreholes
- novel sensor distribution

Algorithm Development:

- Wigner-Ville time frequency representation
- automation of natural frequency detection
- transfer functions / green’s functions
- realtime and continuous usage of system identification techniques
- PQLX - open source solution to process large datasets, possibly identify damage in near-realtime