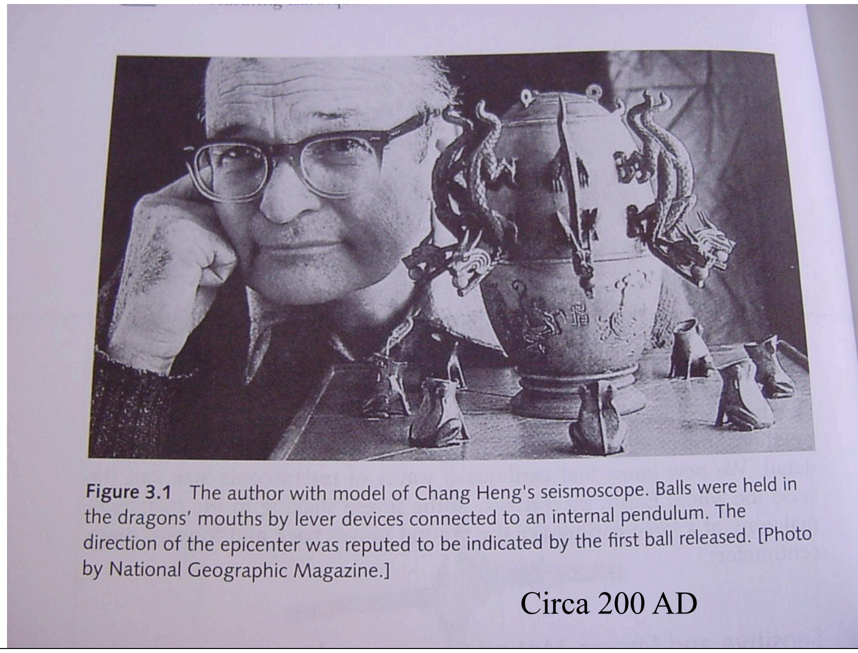
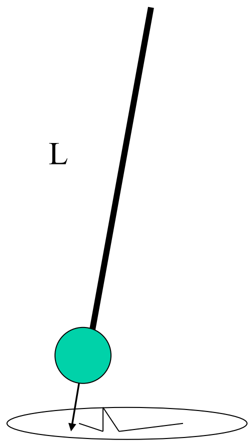
Seismic Instrumentation



- Objective – record transient motions in a moving reference frame
- Needs
  - linear (one-to-one) response
  - Very accurate timing
  - High dynamic range (record small and large motions)
- Major Steps in Development
  - 4th century – **seismoscope**
  - 1751 Bina's simple pendulum seismoscope
  - 1785 Cavalli's mercury-based seismoscope
  - 1875 Cecchi's 1st true **seismograph**
    - Oldest known record Feb 22, 1881
    - First association of a distant earthquake April 17, 1889

Simple Pendulums 1750

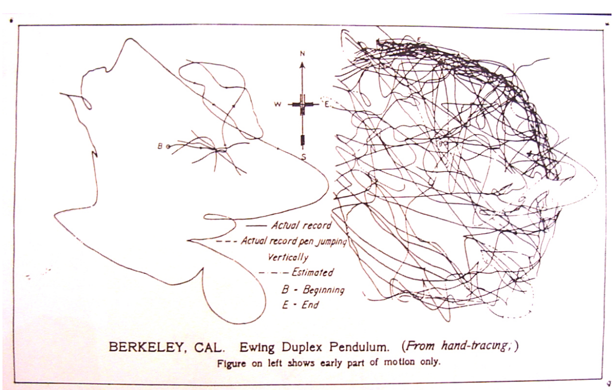


$$T = 2\pi\sqrt{\frac{L}{g}}$$

L=1m

g=9.8 m/s^2

T=2 s



BERKELEY, CAL. Ewing Duplex Pendulum. (From hand-tracing.)
Figure on left shows early part of motion only.

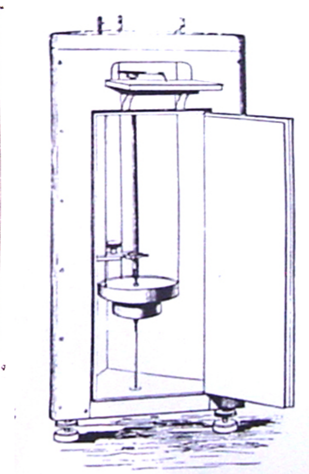


FIG. 2.—DUPLEX PENDULUM SEISMOGRAPH, FOR HORIZONTAL MOTION.

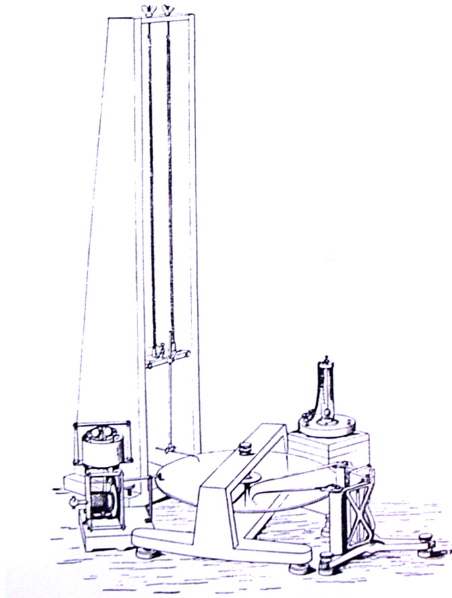
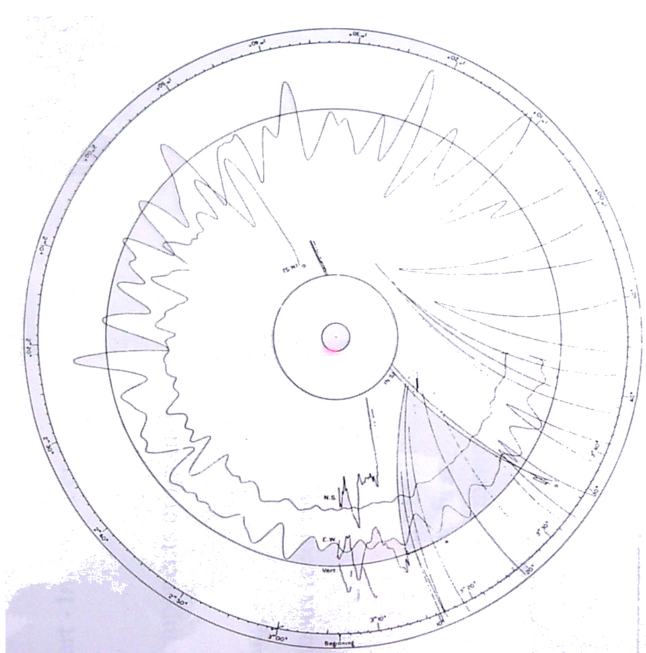


FIG. 1.—COMPLETE THREE-COMPONENT SEISMOGRAPH, FOR MOTIONS IN ALL DIRECTIONS.



MT. HAMILTON, CAL. Ewing Three-Component Seismograph
(From hand-tracing; reduced 1:2.)

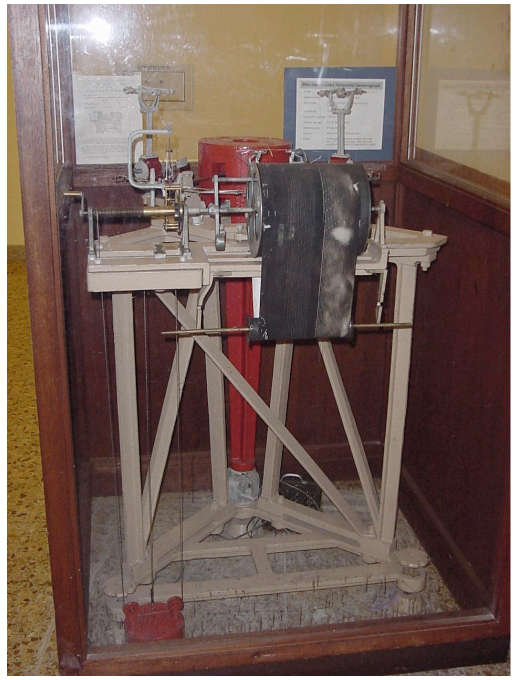
Weichert - Inverted Pendulum

*two components of ground motion

*damping

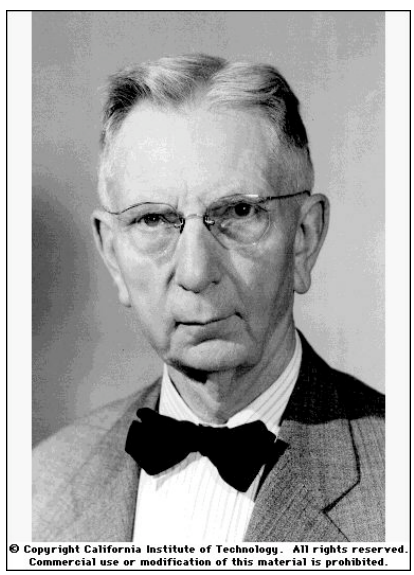
*continuous recording

An earlier version of this instrument was the first installed in North America by Berkeley in 1887.

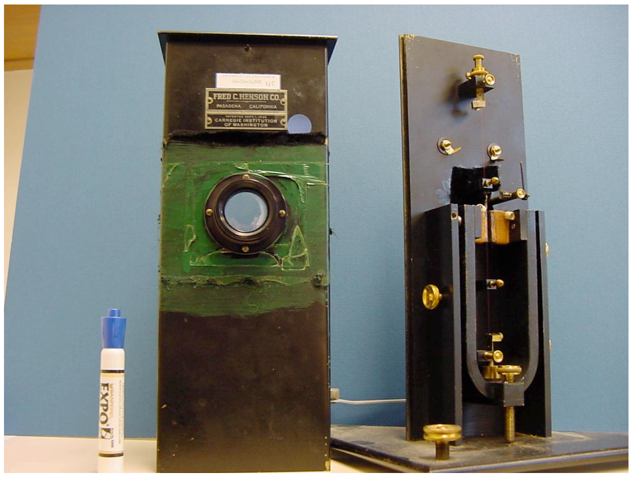


Harry Wood

John Anderson



Wood-Anderson Torsion Seismometer



*Work horse of local/regional monitoring

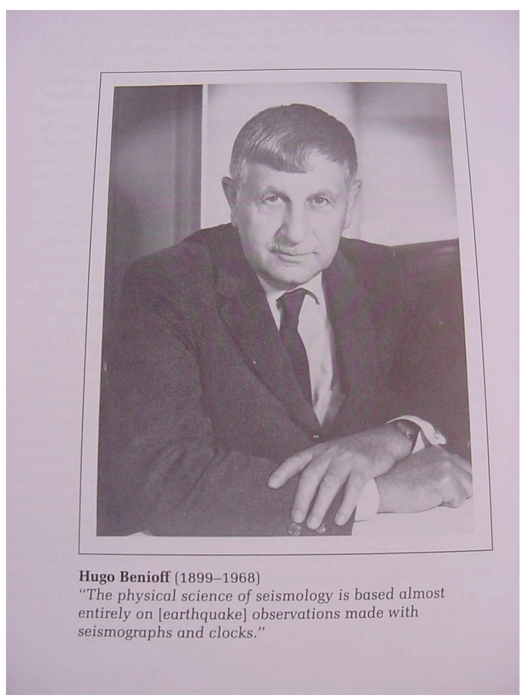
*Instrument behind the development of the Richter Scale

*Makes use of electro-magnetic damping, and optical magnification and recording

*Circa 1920-1980s

Co-discoverer of deep earthquakes - an observation that ultimately contributed some of the most persuasive evidence of Plate Tectonic Theory

Developer of seismic instrumentation



100kg "Baby Benioff"

*Electro-magnetic design

*One of two instruments comprising the bulk of the first global seismic monitoring network - Circa 1960s

WWSSN

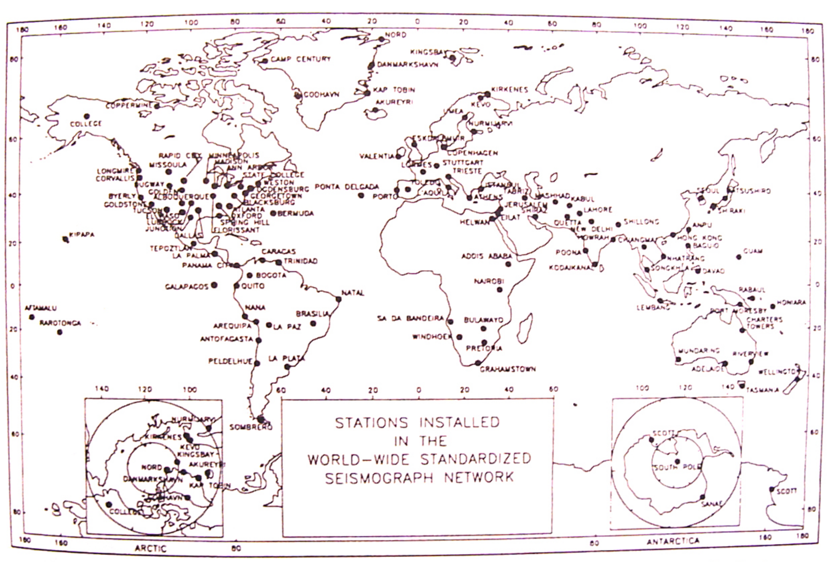
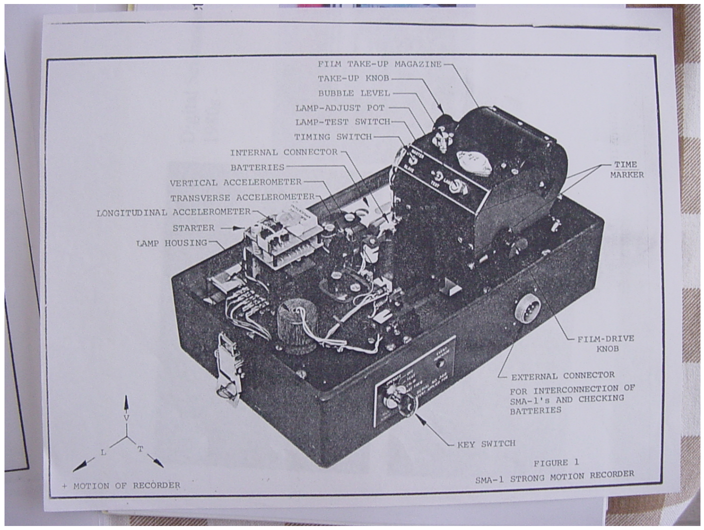


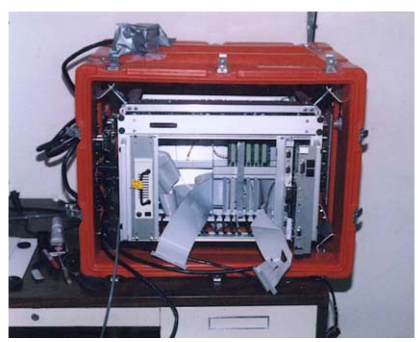
FIGURE 5.7 Global map indicating the locations of stations of the World Wide Standardized Seismograph Network (WWSSN). (Courtesy of the U.S. Geological Survey.)

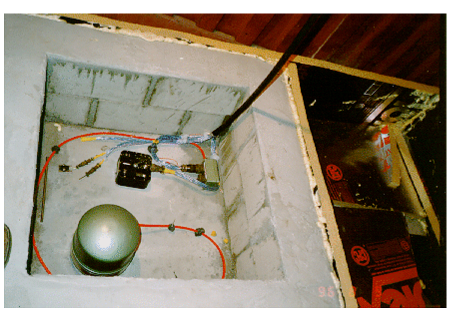
Accelerometers

Developed in 1930 by the USCGS to obtain onscale records of large earthquakes. In 1933 the M6 Long Beach EQ provided the first accelerogram



Digital Seismometry - 1980s -

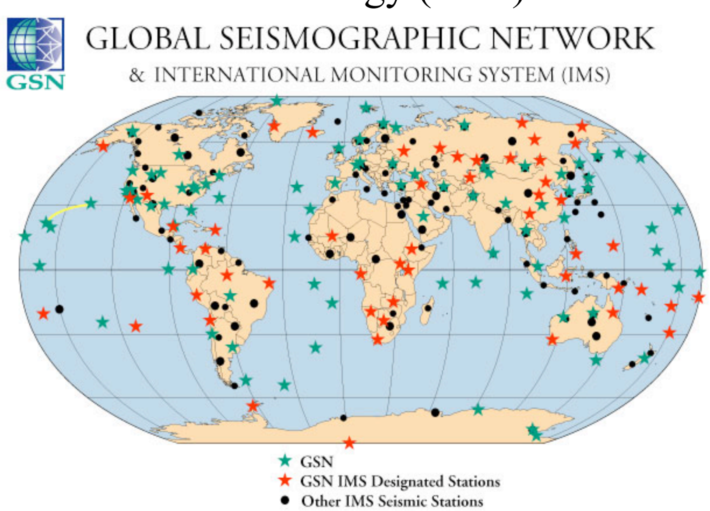




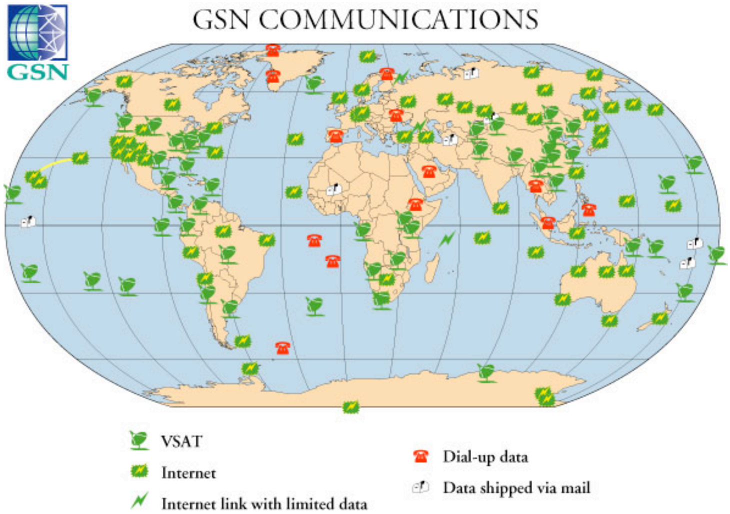
Recording Objectives

Gravitational tides	~0 Hz to ~70 microHz (periods of 4+ hours)
Earth's eigenvibrations	~0.3 mHz to ~0.1 Hz
Surface wave analysis	~2 mHz to ~2 Hz
Regional earthquakes	~10 mHz to ~10 Hz
Local earthquakes	~10 mHz to ~400+ Hz
Strong motion	~0.05 Hz to ~10 Hz (frequency band which usually causes structural damage during strong ground shaking)

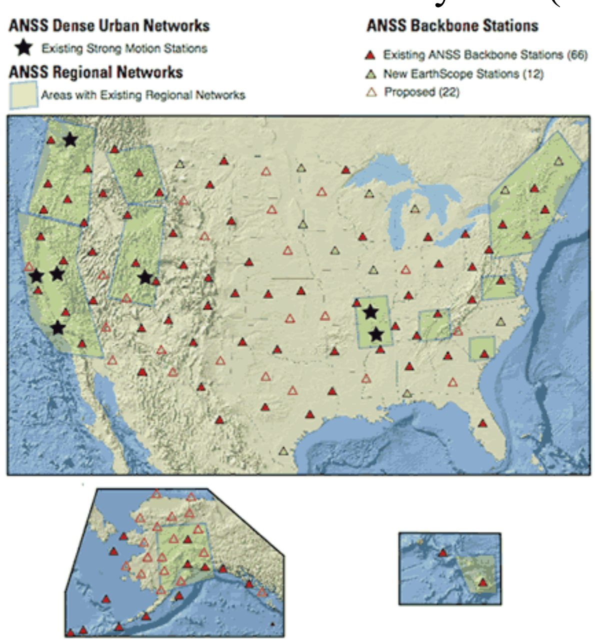
Incorporated Research Institutions for Seismology (IRIS)



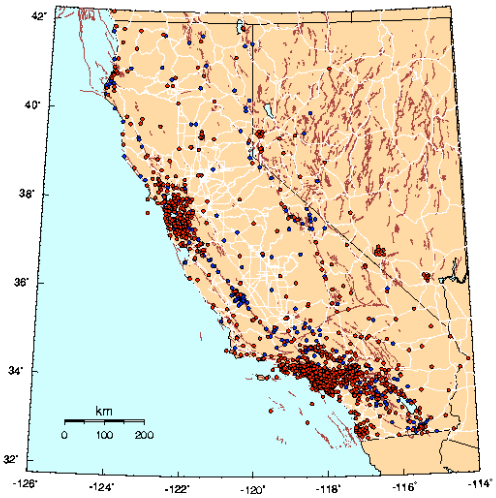
Incorporated Research Institutions for Seismology (IRIS)



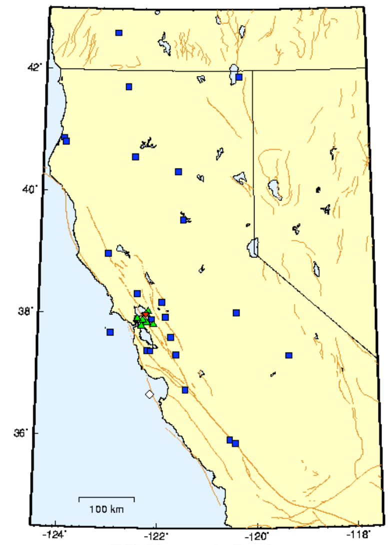
Advanced National Seismic System (ANSS)



California Integrated Seismic Network (CISN)



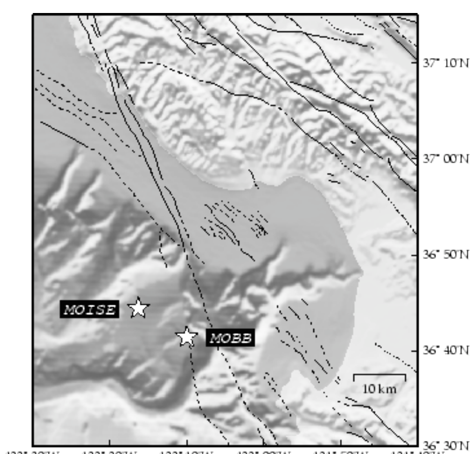
Berkeley Stations

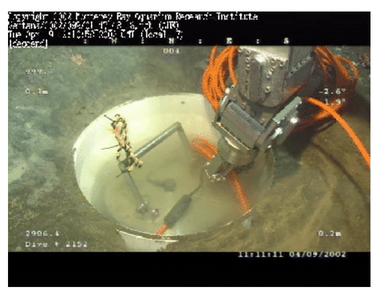


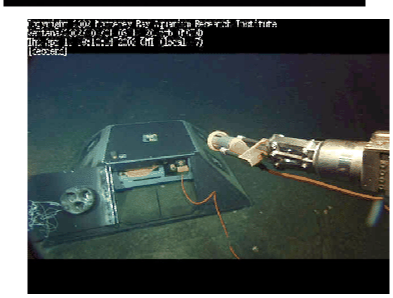
BK Network Stations

BDSN NHFN MPBO MOBB

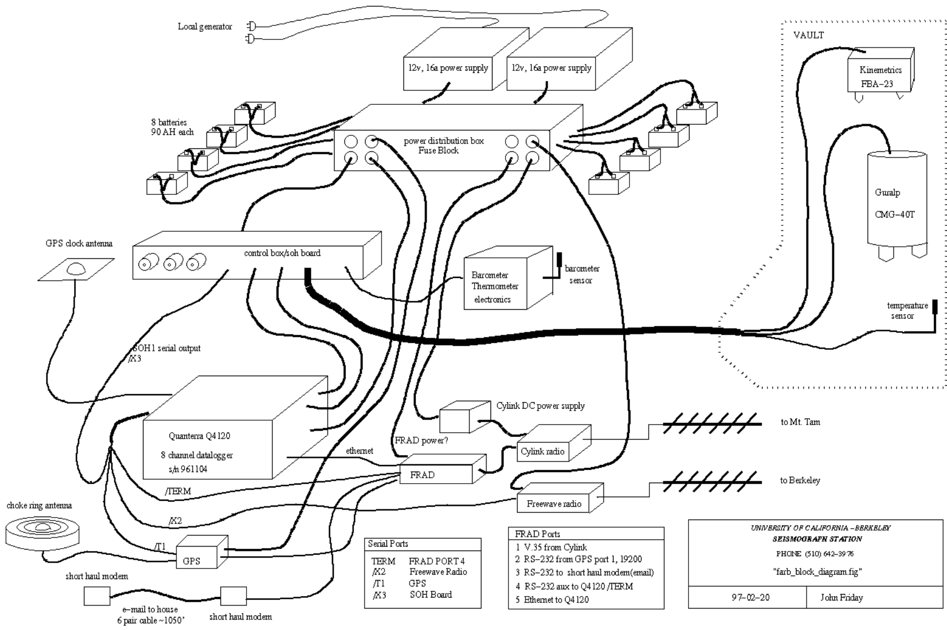
Ocean Bottom Seismometry – BSL/MBARI partnership





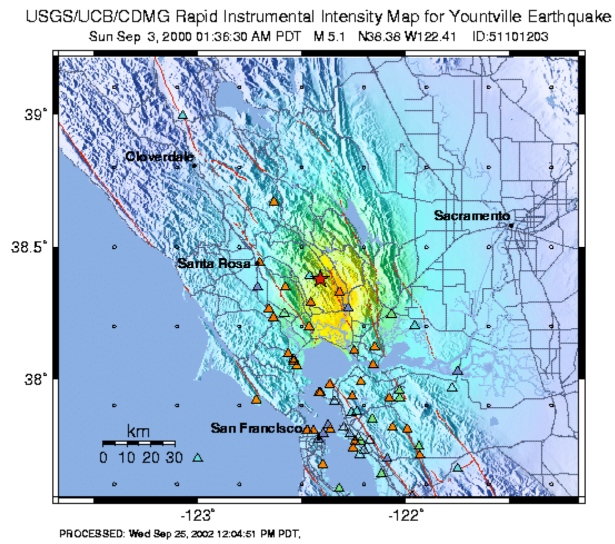


Farallon Islands Installation



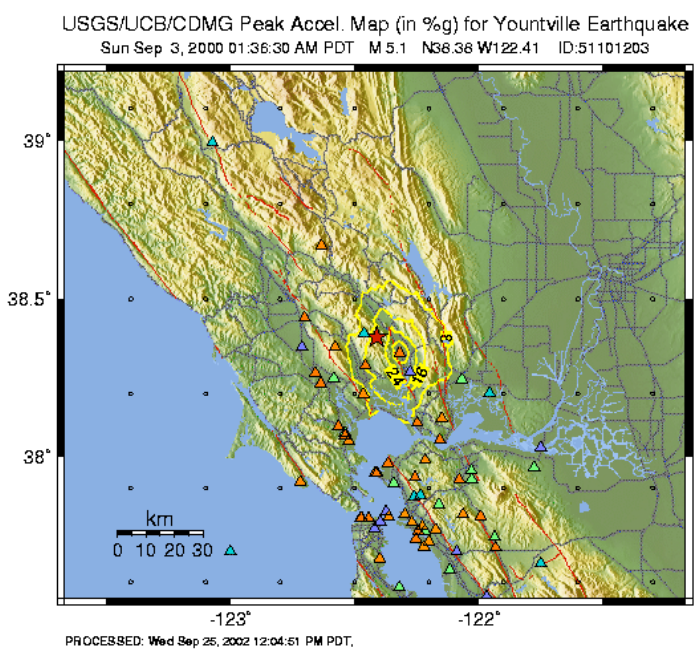
Specifications of the Berkeley Digital Seismic Network (BDSN)

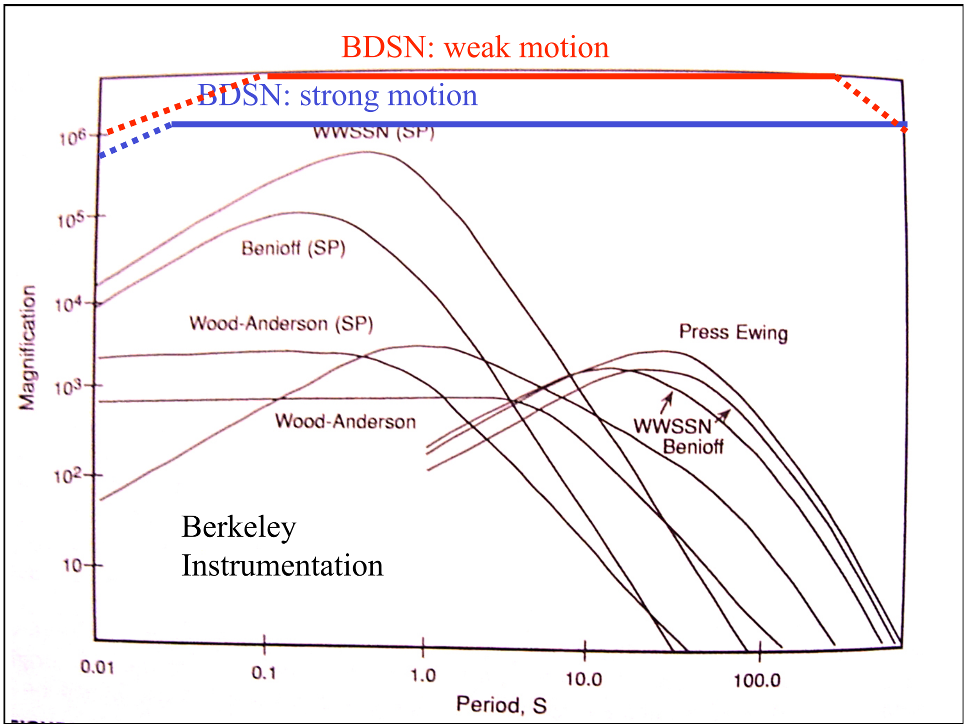
- Broadband
  - Velocity 0.0028 to 10 Hz (360s to 0.1s period)
  - Acceleration 0. to 40 Hz
- High Dynamic Range
  - 24-bit recording nominally 10^{10} in amplitude range
  - +- 2 g acceleration to background noise
- Realtime Telemetry
  - Continuous over telephone, microwave, radio and satellite networks
- Backup Power
  - Three days of battery at all sites. Some are solar powered



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

http://www.cisn.org/shakemap/nc/shake/51101203/intensity.html





Response of Different Instruments

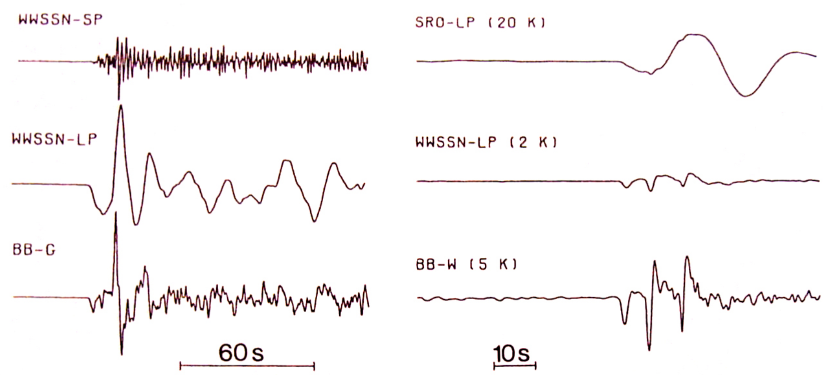
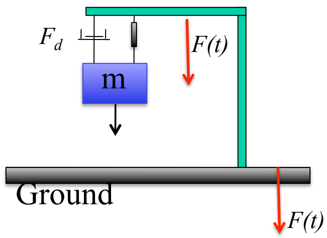


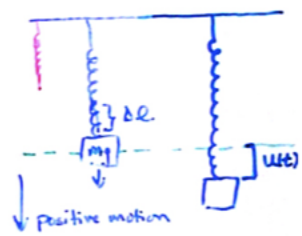
FIGURE 5.12 Comparison of seismograms with varying instrument responses for the same ground motion. The records on the left compare a teleseismic *P* wave from the March 4, 1977 Bucharest event, as it would appear on WWSSN short- and long-period seismograms, with the broadband signal (proportional to ground velocity) actually recorded at station A1 of the Gräfenberg seismic array in Germany. The broadband recording contains much more information than either WWSSN recordings alone or combined. The example on the right compares GDSN (SRO-LP), WWSSN-LP, and broadband ground-displacement recordings for a *P* wave from the April 23, 1979 Fiji earthquake that has traversed the Earth's core. The broadband recording contains much more information that can reveal details of the core structure. (Modified from Harges *et al.*, 1980.)



Physical behavior of seismic instrumentation

Forces in the system

1) $F_g = mg = K\Delta l$



2) Fs: spring restoring force

for $\frac{\Delta l}{l} << 1$ $\quad F \propto \Delta l$

$F_S = -K(u(t) + \Delta l) > \varnothing$

if $u + \Delta l > \varnothing$ force is directed upward

if $u + \Delta l < \varnothing$ force is directed downward

3) Fd: damping force $\quad F_d = -C\frac{du}{dt} \quad$ for small $\left|\frac{du}{dt}\right|$

4) Applied forces F(t)

Governing Equation Newton's law: F = m a

Substituting

$$mg + F_s(t) + F_d(t) + F(t) = m\ddot{u}$$
$$mg - K(u(t) + \Delta l) - C\dot{u}(t) - F(t) = m\ddot{u}(t)$$
$$m\ddot{u}(t) + C\dot{u}(t) + Ku(t) = -F(t) = -m\ddot{z}(t)$$
$$\ddot{u}(t) + \frac{C}{M}\dot{u}(t) + \frac{K}{M}u(t) = -\ddot{z}(t)$$

Defining

$$\omega_0 = \left[K/m\right]^{1/2} \qquad \left[\frac{N/m}{Kg}\right]^{1/2} \rightarrow 1/s$$
$$f_0 = w/(2\pi) \qquad T_0 = \frac{2\pi}{\omega_0} = 2\pi\left[\frac{m}{K}\right]^{1/2}$$

Defining

$$2\xi = \frac{C}{\omega_0 m} = \frac{C}{\sqrt{Km}} \rightarrow \xi = \frac{C}{2\sqrt{Km}}$$

Indicator Equation

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

Homogeneous equation solutions

$$\ddot{u}(t) + 2xw_0\dot{u}(t) + w_0^2 u(t) = 0$$

if $\xi = 0$ there is no damping and the motion is harmonic

$$u(t) = A\sin(\omega_0 t) + B\cos(\omega_0 t)$$

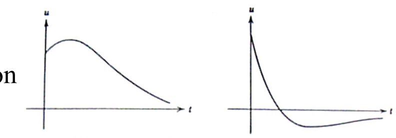


FIGURE 3.4 Overdamped or critically damped motions.

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if $\xi = 1$ Response is critically damped

$$u(t) = (A + Bt)e^{-\omega_0 t}$$

---

if $\xi > 1$ Response is over damped

$$u(t) = Ae^{-\omega_0 \xi t + \omega_0\sqrt{\xi^2 - 1}t} + Be^{-\omega_0 t(\xi + \sqrt{\xi^2 - 1})}$$

---

if $\xi < 1$ Response is under damped

$$u(t) = Ae^{-\xi\omega_0 t}\sin(\omega_0 \mu t) + Be^{-\xi\omega_0 t}\cos(\omega_0 \mu t)$$

$$\mu = \sqrt{1 - \xi^2}$$

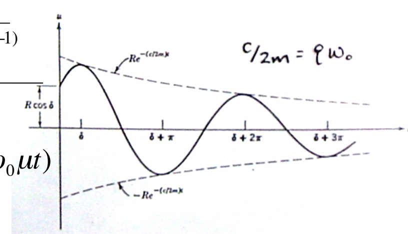
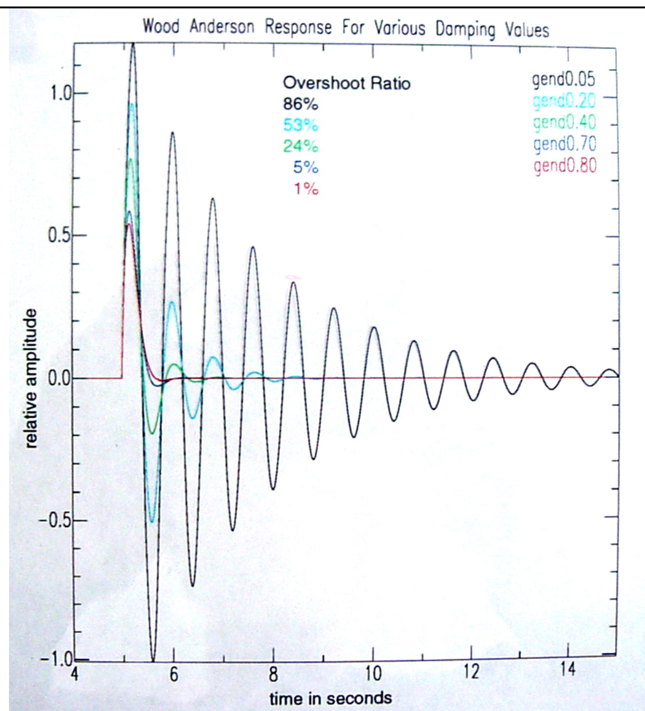
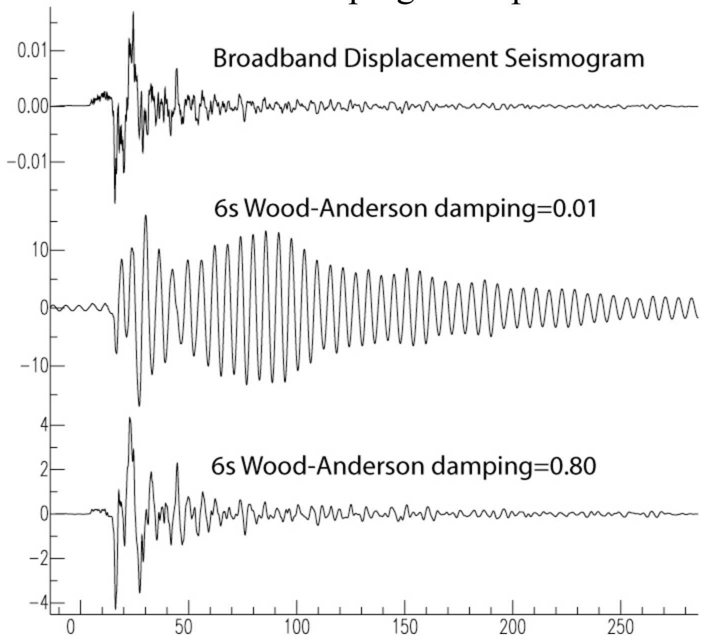


FIGURE 3.5 Damped vibration.

Used in seismometry to describe damped vibratory motion



Yountville Damping Example



Fourier Analysis

Box 5.1 Time and Frequency Domain Equivalence

In seismometry and many other aspects of seismology, it is often useful to represent transient time functions by equivalent functions in the frequency domain. This is possible using Fourier transforms, which are integral relationships that state that for an arbitrary function, $f(t)$, a set of harmonic terms exists such that

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)e^{i\omega t}\,d\omega, \qquad (5.1.1)$$

where

$$F(\omega) = |A(\omega)|e^{i\phi(\omega)} = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}\,dt. \qquad (5.1.2)$$

These transform pairs correspond to a mapping from the time domain to the frequency domain, where ω is angular frequency, $A(\omega)$ is the amplitude of each harmonic component, and $\phi(\omega)$ is the corresponding phase shift (see Figure 5.B1.1). The integral in (5.1.1) is simply a sum, so this theorem states that an

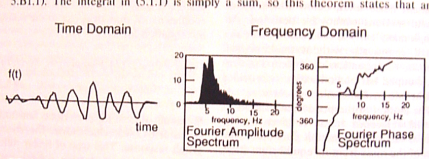


FIGURE 5.B1.1 A signal that is a function of time, as shown on the left, may be equivalently represented by its Fourier spectrum, as shown on the right. The amplitude and phase spectra are both needed to provide the complete time series.

arbitrary ground-motion time series, even an impulsive one, can be expressed as a sum of monochromatic periodic functions (Figure 5.B1.2). This is possible if the amplitude and phase alignment of the harmonic terms are chosen appropriately and the sum is over a continuous distribution of harmonic functions. Destructive and constructive interference between the harmonics is balanced so that they add up exactly to the original time series. The functions are called the signal spectrum and define the frequency-domain representation of the time-domain trace. Fourier spectra are determined using computers and digital, discretized versions of Fourier transforms. This text will often represent seismological observations by their spectra, which contain all of the information of the original seismogram, as long as both amplitude and phase are considered.

continues

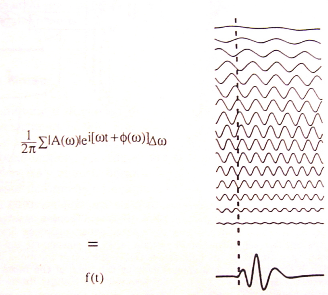


FIGURE 5.B1.2 A discretized version of Eq. (5.1.1), showing how a sum of harmonic terms can equal an arbitrary function. The amplitudes of each harmonic term vary, being prescribed by the amplitude spectrum. The shift of the phase of each harmonic term is given by the phase spectrum.

Inverse Fourier Transform

$$u(t) = \int_{-\infty}^{\infty} u(\omega) e^{i\omega t} d\omega$$

Inverse FT of derivative of function

$$\dot{u}(t) = \int_{-\infty}^{\infty} [i\omega] \cdot u(\omega) e^{i\omega t} d\omega$$

Indicator Equation

$$\ddot{u}(t) + 2\xi\omega_0 \dot{u}(t) + \omega_0^2 u(t) = -F\ddot{z}(t)$$

FT of indicator equation

$$[-\omega^2 + 2\xi\omega_0 i\omega + \omega_0^2] u(\omega) = F\omega^2 z(\omega)$$

Spectral Response of Instrument

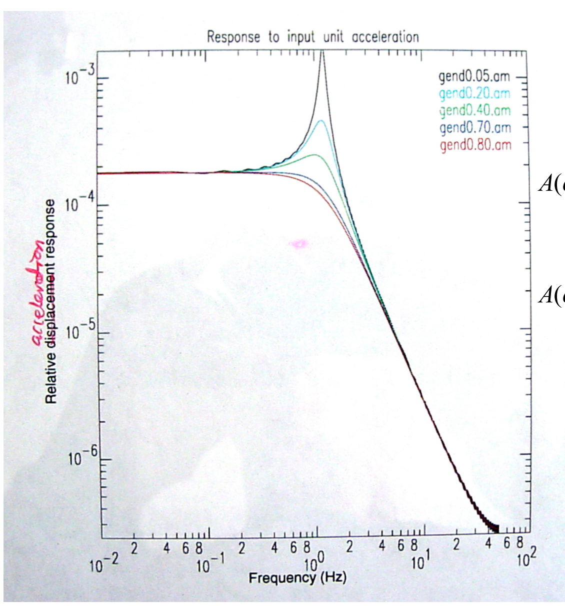
$$u(\omega) = \frac{F\omega^2 z(\omega)}{\omega_0^2 - \omega^2 + 2i\omega\omega_0\xi}$$

Amplitude and Phase Response

$$u(\omega) = F\omega^2 z(\omega) \frac{\omega_0^2 - \omega^2 - 2i\omega\omega_0\xi}{(\omega_0^2 - \omega^2)^2 + 4\omega^2\omega_0^2\xi^2}$$

$$A(\omega) = F\omega^2 \Big/ \sqrt{(\omega_0^2 - \omega^2)^2 + 4\omega^2\omega_0^2\xi^2}$$

$$\Phi(\omega) = \tan^{-1}\left(2\xi\omega\omega_0 \Big/ (\omega^2 - \omega_0^2) \right)$$



$$A(\omega) = F\omega^2 z(\omega) \Big/ \sqrt{(\omega_0^2 - \omega^2)^2 + 4\omega^2\omega_0^2\xi^2}$$

$$A(\omega) = F\ddot{z}(\omega) \Big/ \sqrt{(\omega_0^2 - \omega^2)^2 + 4\omega^2\omega_0^2\xi^2}$$

Instrument Design

if $\omega_0 >> \omega$

$$u(\omega) \approx \frac{F\omega^2}{\omega_0^2} z(w) = \frac{-F}{\omega_0^2} \ddot{z}(\omega)$$

Sensitive to acceleration. Large ω_0 implies a stiff low mass instrument.

if $\omega_0 << \omega$

$u(\omega) \sim Fz(\omega)$

Sensitive to displacement. Small ω_0 requires a large inertial mass instrument.

$$\ddot{u}(t) + 2\xi\omega_0 \dot{u}(t) + \omega_0^2 u(t) = -F\ddot{z}(t)$$

if motion is fast

$$\ddot{u}(t) \propto \ddot{z}(t)$$

$$u(t) \approx z(t)$$

Mass offset corresponds to ground displacement

if motion is slow

$$\omega_0^2 u(t) \approx -\ddot{z}(t)$$

$$u(t) \approx -\ddot{z}(t) / \omega_0^2$$

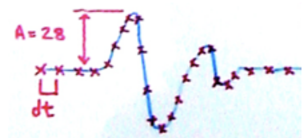
Mass offset corresponds to ground acceleration

Instrument Demonstrations

- Horizontal Sprengnether
- Horizontal Wood Anderson

Recording technologies

- Pre 1910 smocked glass
- Smocked paper
- Photography and electric sensitive paper
- Film
- Magnetic tape
  - Above have limited dynamic range



- Digital recording
  - Analog signal from sensor is converted to digital form by discrete sampling
  - Sampling theorem – a signal is correctly represented to a maximum frequency following $dt=1/(2f_m)$
  - Data loggers over sample data in the kHz range and decimate to 100 Hz or less.

- Each sample is represented as a binary word

- Assuming an 8-bit word
  - 1-bit is used for sign
  - 7-bits are used for amplitude
  - *<u>Example:</u>* If the amplitude in the preceding example is 28 then in binary

28=10011100

i.e. 28=**1** $0 \times 2^6 + 0 \times 2^5 + 1 \times 2^4 + 1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 0 \times 2^0$

What is the binary code for -31? -31=00011111

Why is this so important?

- Dynamic range is the ratio of the maximum to the minimum amplitude that can be meaningfully stored

$dB = 10 . \log(E/E_0)$ since $E \, \alpha \, A2$

$dB = 20 . \log(A/A_{min}) = 20 . \log(2^{(n-1)}) \approx 6 . (n-1)$

where n is the number of bits

- Galitzen electro-magnetic instrument
  - Trace thickness = 1 mm
  - Minimum resolvable signal, A_0 = 0.1 mm
  - Maximum resolvable signal, A = 83 mm

    $A/A_0 = 830$ => 20 . log(830) = 58 dB

    Equivalent digital resolution **6 bits**!

Can adjusting the gain improve the dynamic range of this analog instrument?

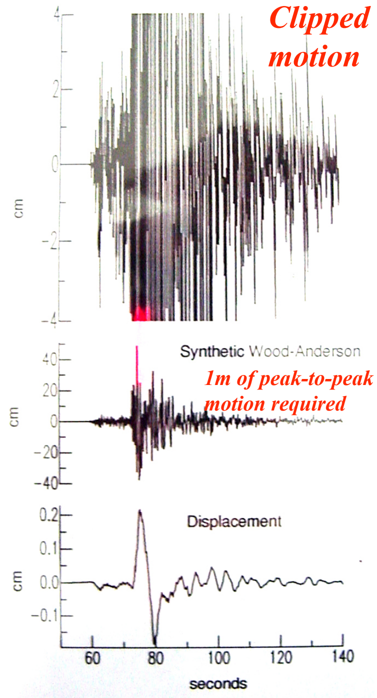
- Older strong motion instruments were 16-bit.

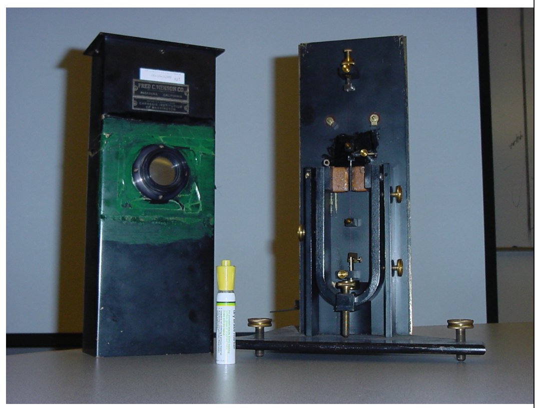
  16 bit -> 90 dB -> +/- 32,768 digital count
- Newer instruments are 24-bit

  24-bit -> 138 dB -> +/- 8,388,608 digital counts
- Total resolution is limited by:
  - 1) dynamic range of sensor: STS-1, STS-2, STS-3…
  - 2) internal digitizer noise
  - 3) external Earth noise
- Modern systems sport 24-bit data acquisition systems with colocated +/- 2g accelerometers, wide band velocity sensors giving a nominal 200 dB dynamic range

  200 dB => +/- 10^{10} range in recordable grand motions

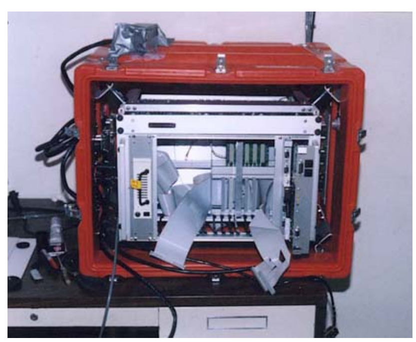
Clipped at 4cm of motion





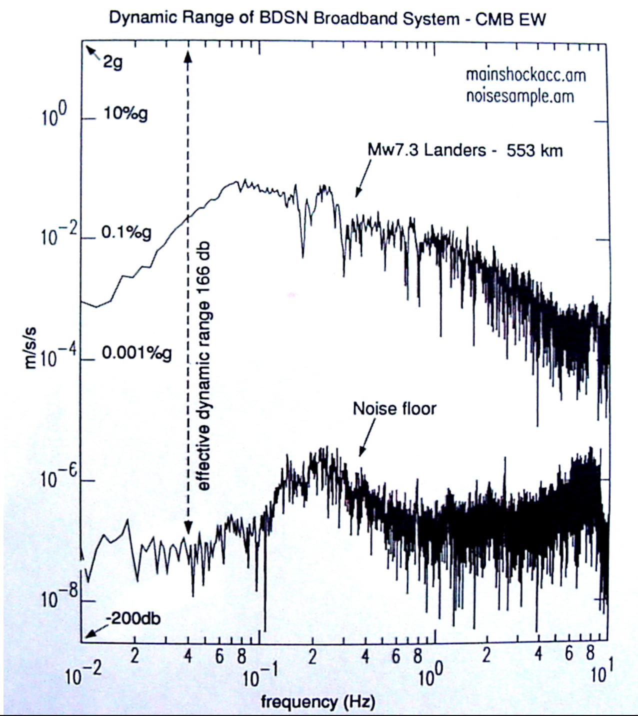
Kobe vid

Modern Instruments



Transducers sense mass offset – applied power to servos maintain mass position – mass moves with ground and instrument, but amount of power used is proportional to ground velocity (or acceleration)

→ ***Tremendous increase in linearity, recording bandwidth, and dynamic range***



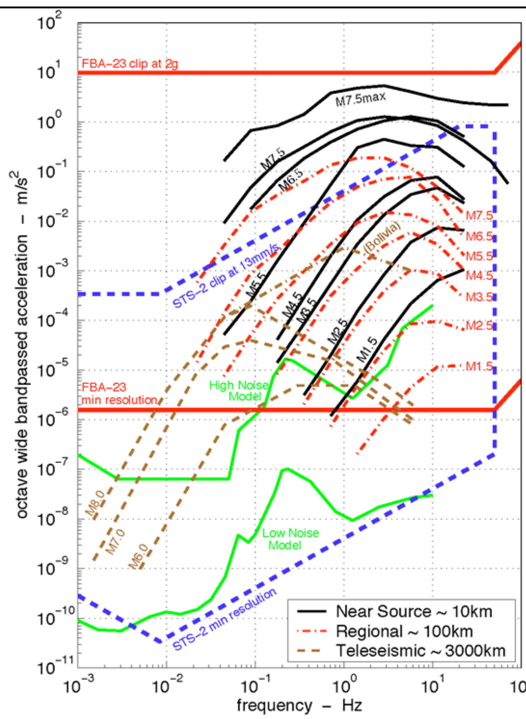


Figure from SCEC website – originally prepared by

Tom Heaton

Recap

- Seismic instruments make use of inertia to record ground motions in a moving reference frame
- Instruments have evolved over time
- Damping, dynamic range and spectral response are all important to obtain usable records
- Inertial instruments have limited dynamic range
- Force feedback instruments extend dynamic range and spectral response
- Digital recording and realtime telemetry lead to applications such as ShakeMap