Seismic Instruments

- The seismometer as a forced oscillator
  - The seismometer equation
  - Transfer function, resonance
  - Broadband sensors, accelerometers
  - Dynamic range and generator constant
- Rotation sensors
- Strainmeters
- Tiltmeters
- Global Positioning System (GPS)
- Ocean Bottom Seismometers (OBS)

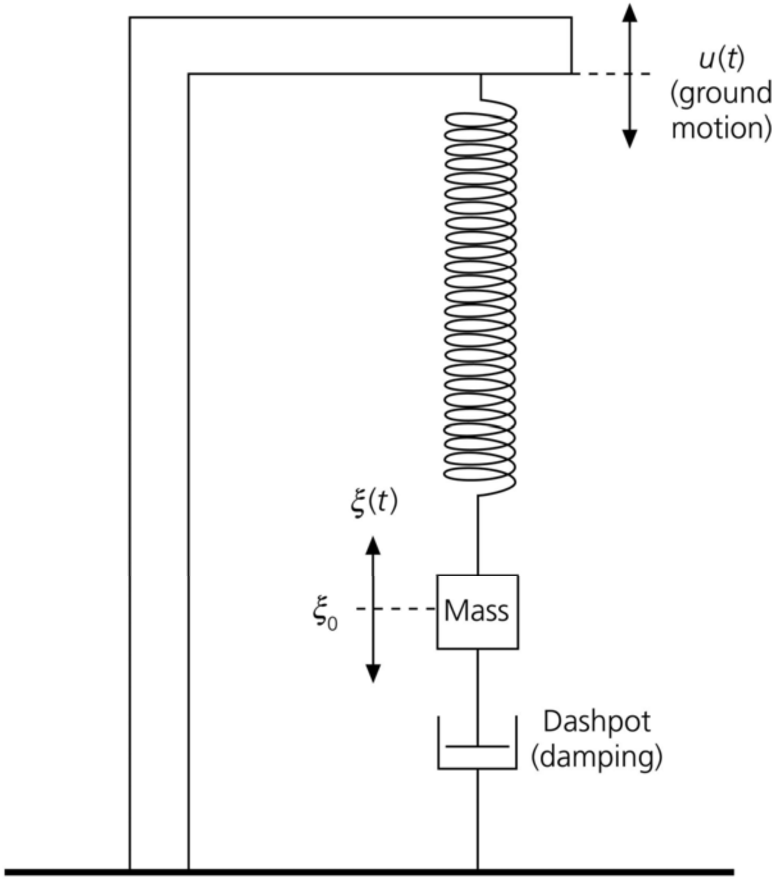
Data examples, measurement principles, interconnections, accuracy, domains of application

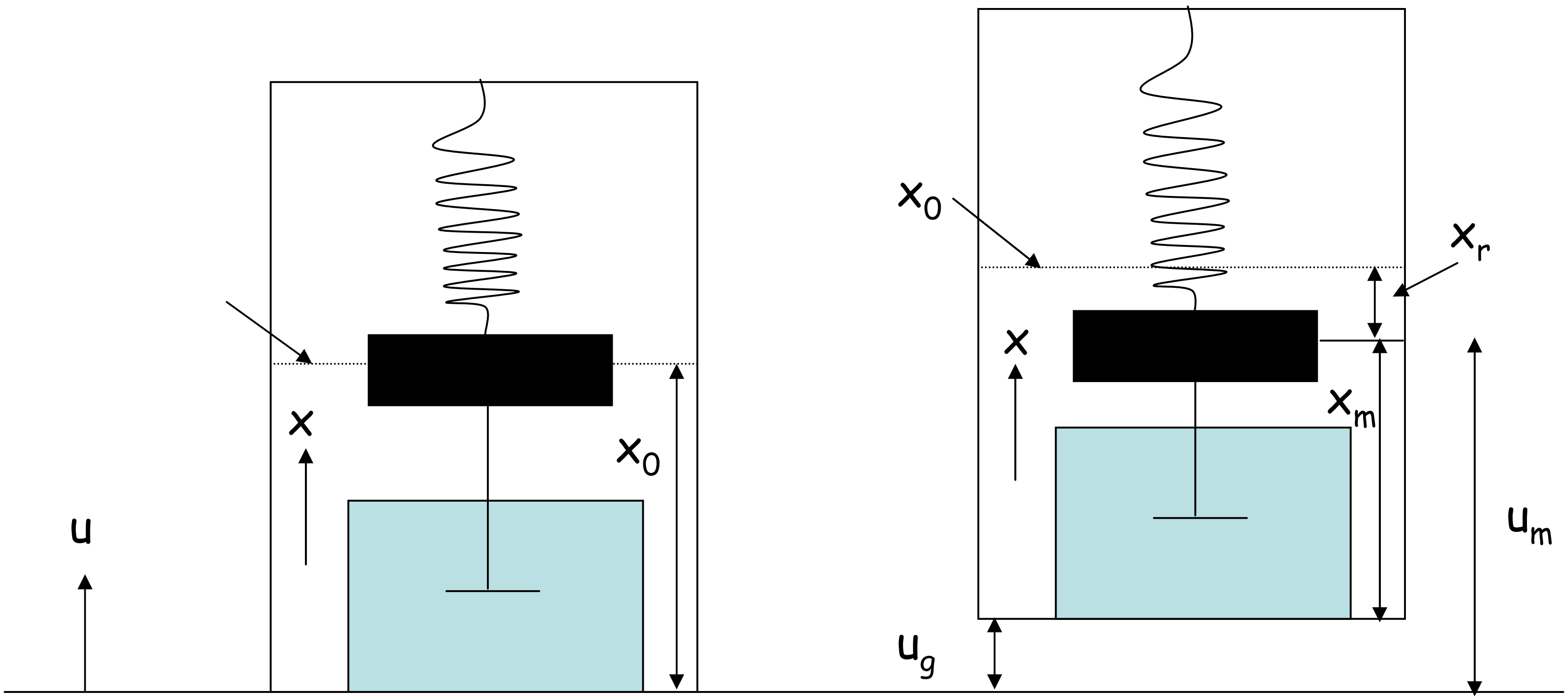
Spring-mass seismometer

vertical motion

Before we look more carefully at seismic instruments we ask ourselves what to expect for a typical spring based seismic inertial sensor. This will highlight several fundamental issues we have to deal with concerning seismic data analysis.

Figure 6.6-1: Diagram of a vertical seismograph.

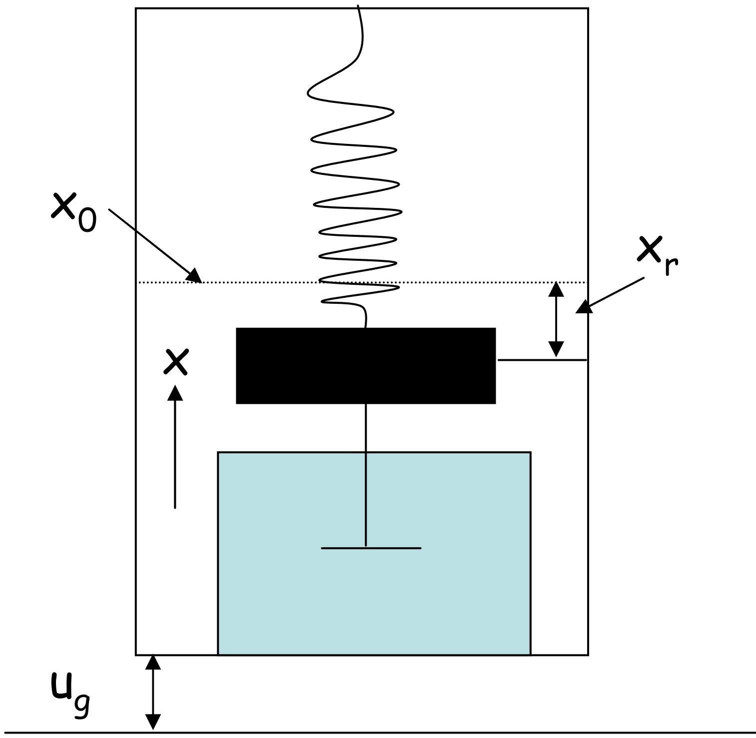




u	ground displacement
x_r	displacement of seismometer mass
x_0	mass equilibrium position

Seismometer – The basic principles

The motion of the seismometer mass as a function of the ground displacement is given through a differential equation resulting from the equilibrium of forces (in rest):



$F_{spring} + F_{friction} + F_{gravity} = 0$

for example

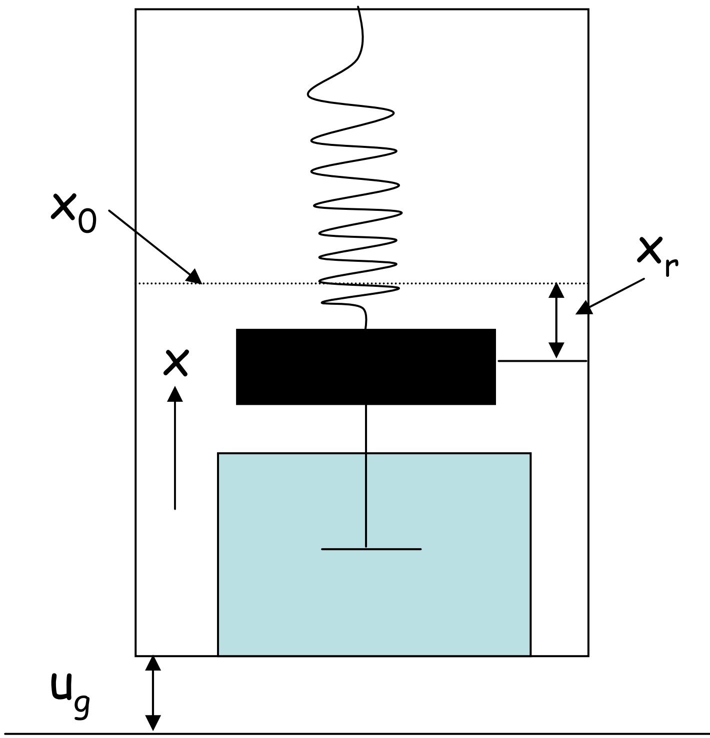
F_{sprin}=-k x, k spring constant

$F_{friction}$=-D $\dot{x}$, D friction coefficient

$F_{gravity}$=-m$\ddot{u}$, m seismometer mass using the notation introduced above the equation of motion for the mass is

$$\ddot{x}_r(t) + 2\varepsilon\dot{x}_r(t) + \varpi_0^2 x_r(t) = -\ddot{u}_g(t)$$

$$\varepsilon = \frac{D}{2m} = h\varpi_0, \qquad \varpi_0^2 = \frac{k}{m}$$



From this we learn that:

- for slow movements the acceleration and velocity becomes negligible, the seismometer records ground acceleration

- for fast movements the acceleration of the mass dominates and the seismometer records ground displacement

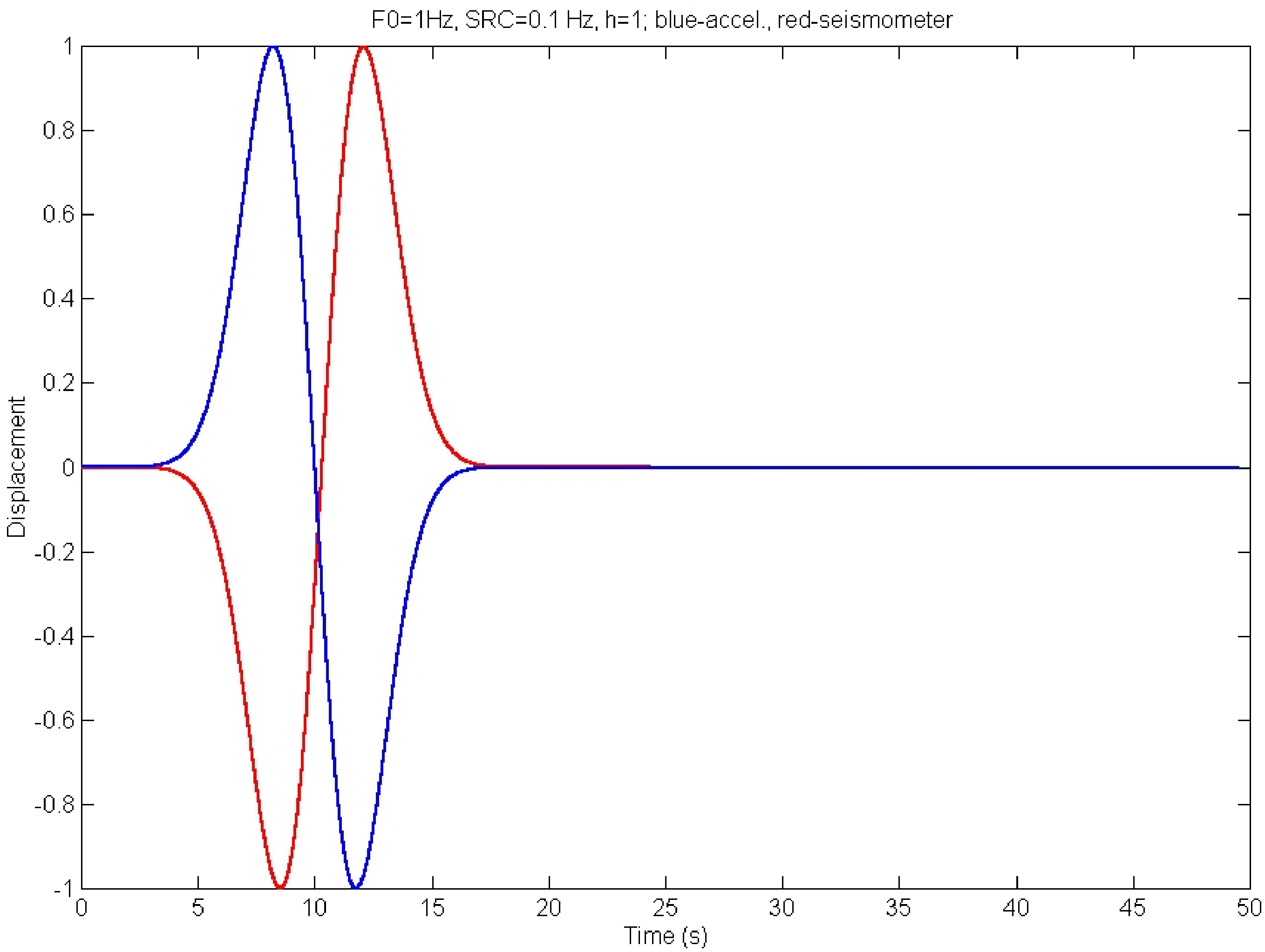
A simple finite-difference solution of the seismometer equation

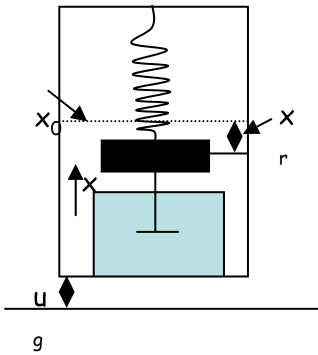
Editor - F:\Heiner\Matlab\Lectures\Prakt\Seismometer\seismometer.m

```matlab
src(1:length(u11))=u11;



x=(1:nt)*0;

% initial condition

eps=h*w;
x=0;
xnow=0;
xold=0;

for i=1:nt,
if i==1,xold=xnow;end

xnew=1./(1./dt^2+2*eps/(2*dt)) * (-src(i) -w^2*xnow + 2*eps/(2*dt) * xold - (xold-2*xnow)/dt^2 );
xold=xnow;
xnow=xnew;
x(i)=xnow;

plot((1:i)*dt,x(1:i)/max(abs(x(1:i))),'r-','LineWidth',1.5),hold on,
plot((1:i)*dt,src(1:i)/max(src(1:i)),'b-','LineWidth',1.5),hold off
title(sprintf('F0=1Hz, SRC=%g Hz, h=%g ',fu0,h));
axis([0 nt*dt -1 1]), pause(0.5),drawnow
xlabel('Time (s)')
ylabel('Displacement')

end
```

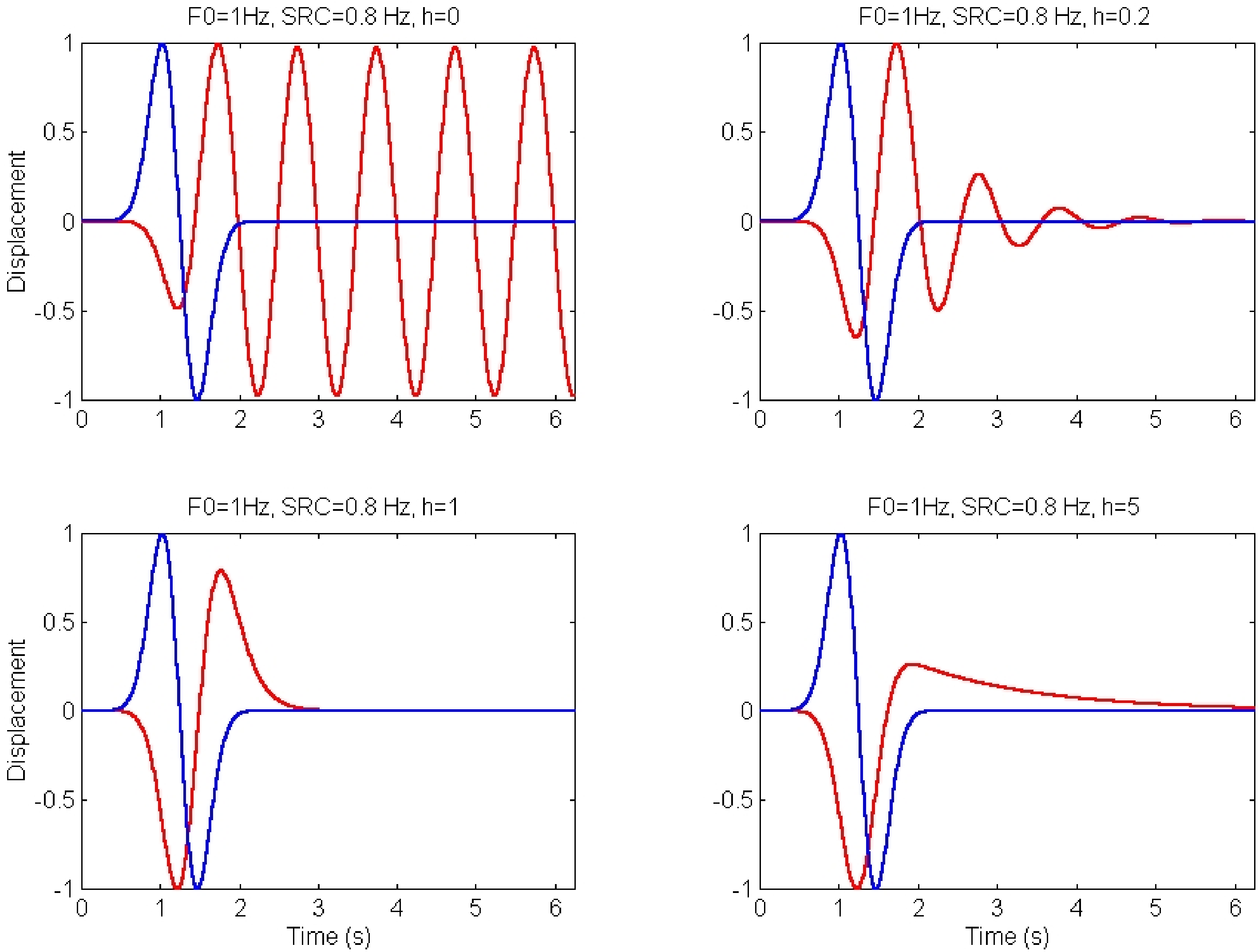
Quest_calculation_new.m | seismometer.m

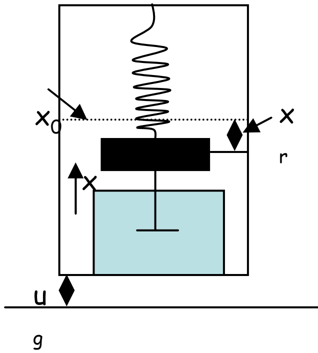
Seismometer – examples





Varying damping constant

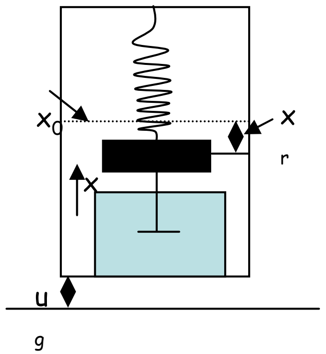




Seismometer – Calibration

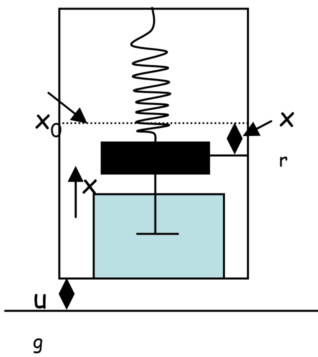
1. How can we determine the damping properties from the observed behaviour of the seismometer?

2. How does the seismometer amplify the ground motion? Is this amplification frequency dependent?



We need to answer these question in order to determine what we really want to know:
The ground motion.

Seismometer – Release Test



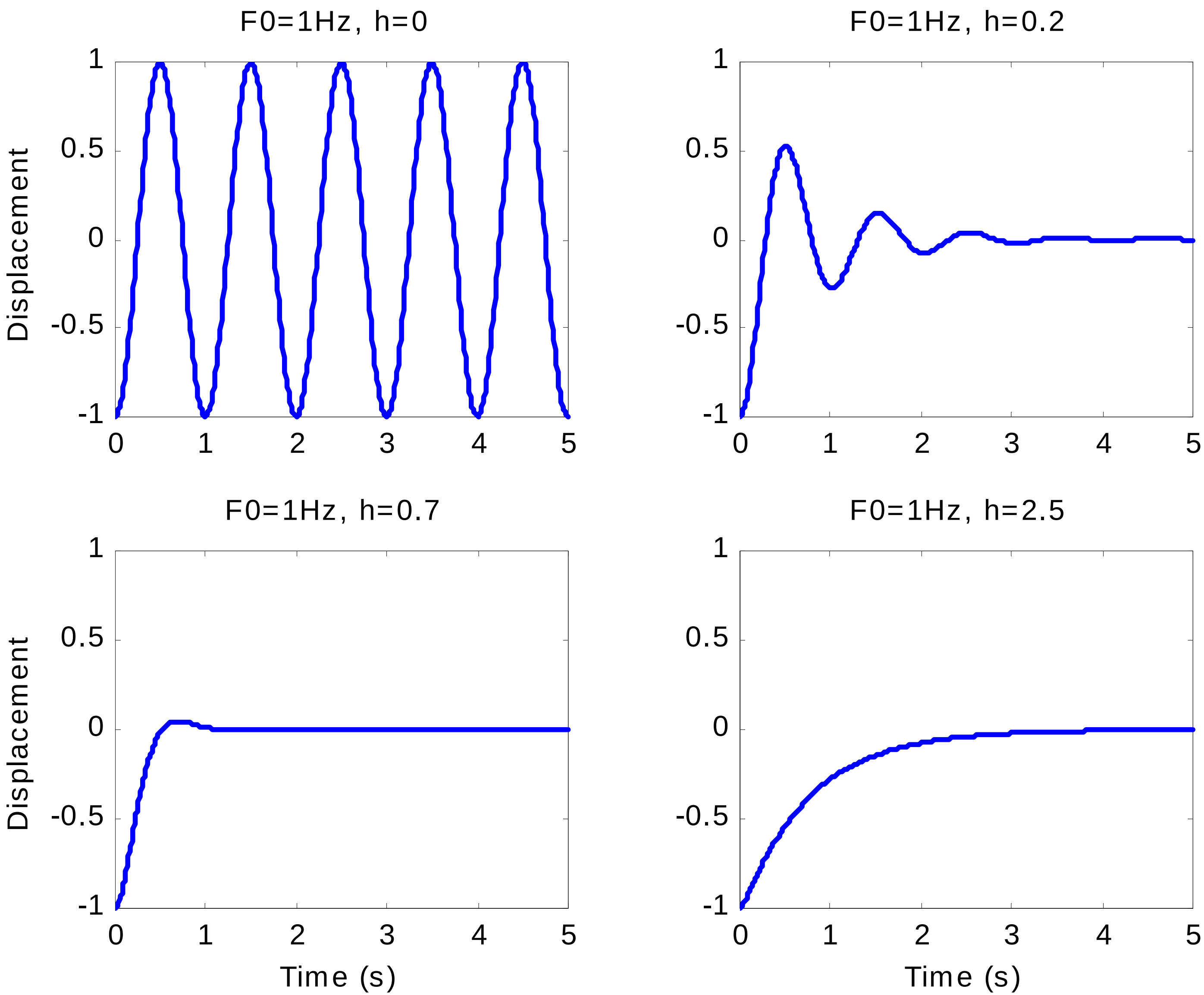
1. How can we determine the damping properties from the observed behaviour of the seismometer?

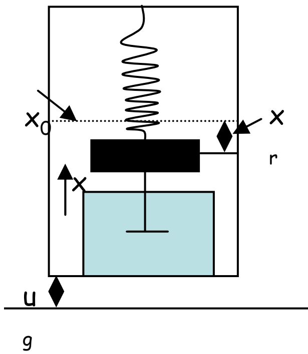
$$\ddot{x}_r(t) + h\varpi_0 \dot{x}_r(t) + \varpi_0^2 x_r(t) = 0$$

$$x_r(0) = x_0, \qquad \dot{x}_r(0) = 0$$

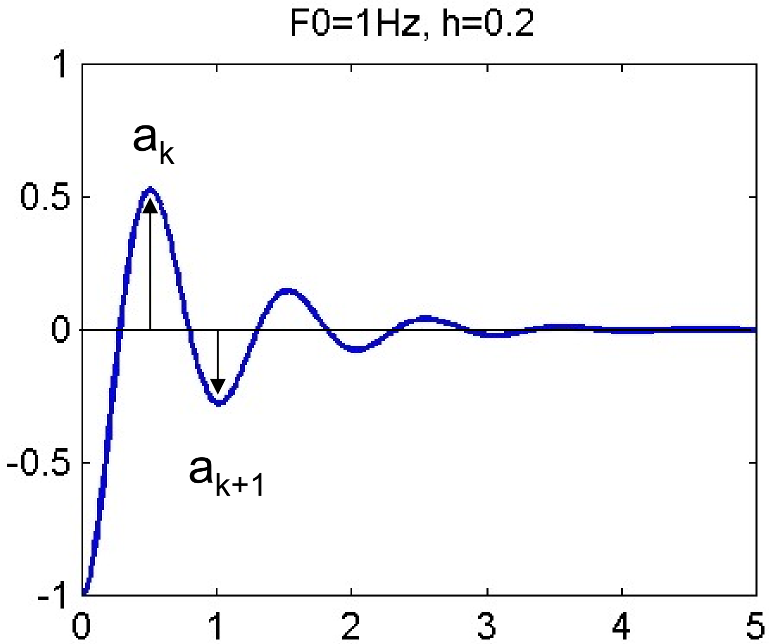
We release the seismometer mass from a given initial position and let it swing. The behaviour depends on the relation between the frequency of the spring and the damping parameter. If the seismometers oscillates, we can determine the damping coefficient h.

Seismometer – Release Test



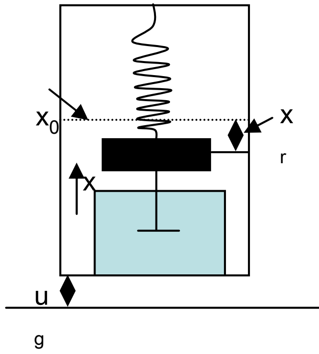


Seismometer – Release Test



The damping coefficients can be determined from the amplitudes of consecutive extrema a_k and a_{k+1}

We need the logarithmic decrement L

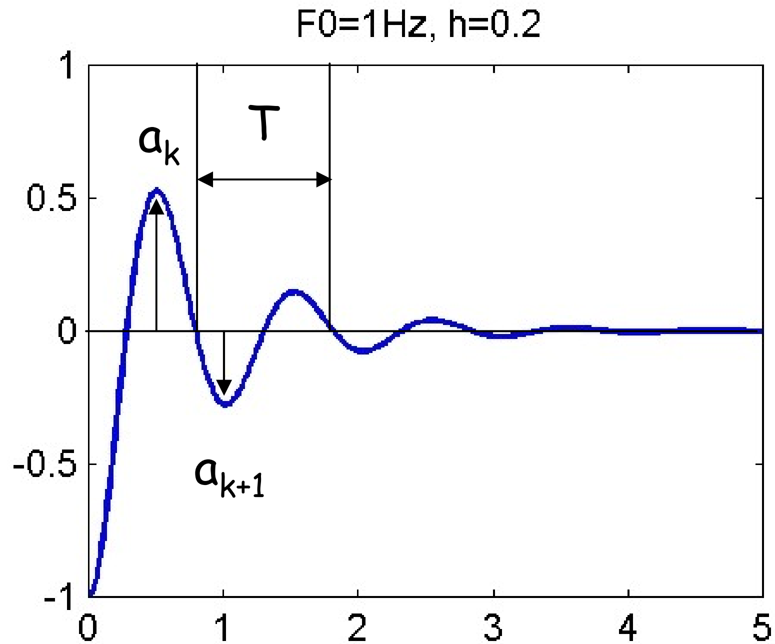


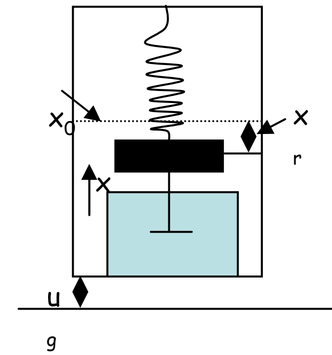
$$\Lambda = 2\ln\left(\frac{a_k}{a_{k+1}}\right)$$

The damping constant h can then be determined through:

$$h = \frac{\Lambda}{\sqrt{4\pi^2 + \Lambda^2}}$$

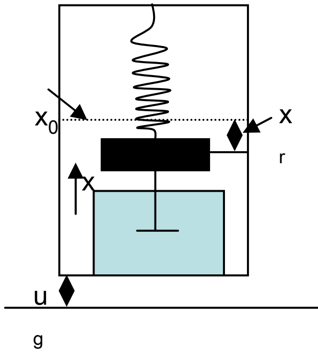
Seismometer – Frequency





The period T with which the seismometer mass oscillates depends on h and (for h<1) is always larger than the period of the spring T_0:

$$T = \frac{T_0}{\sqrt{1-h^2}}$$



2. How does the seismometer amplify the ground motion? Is this amplification frequency dependent?

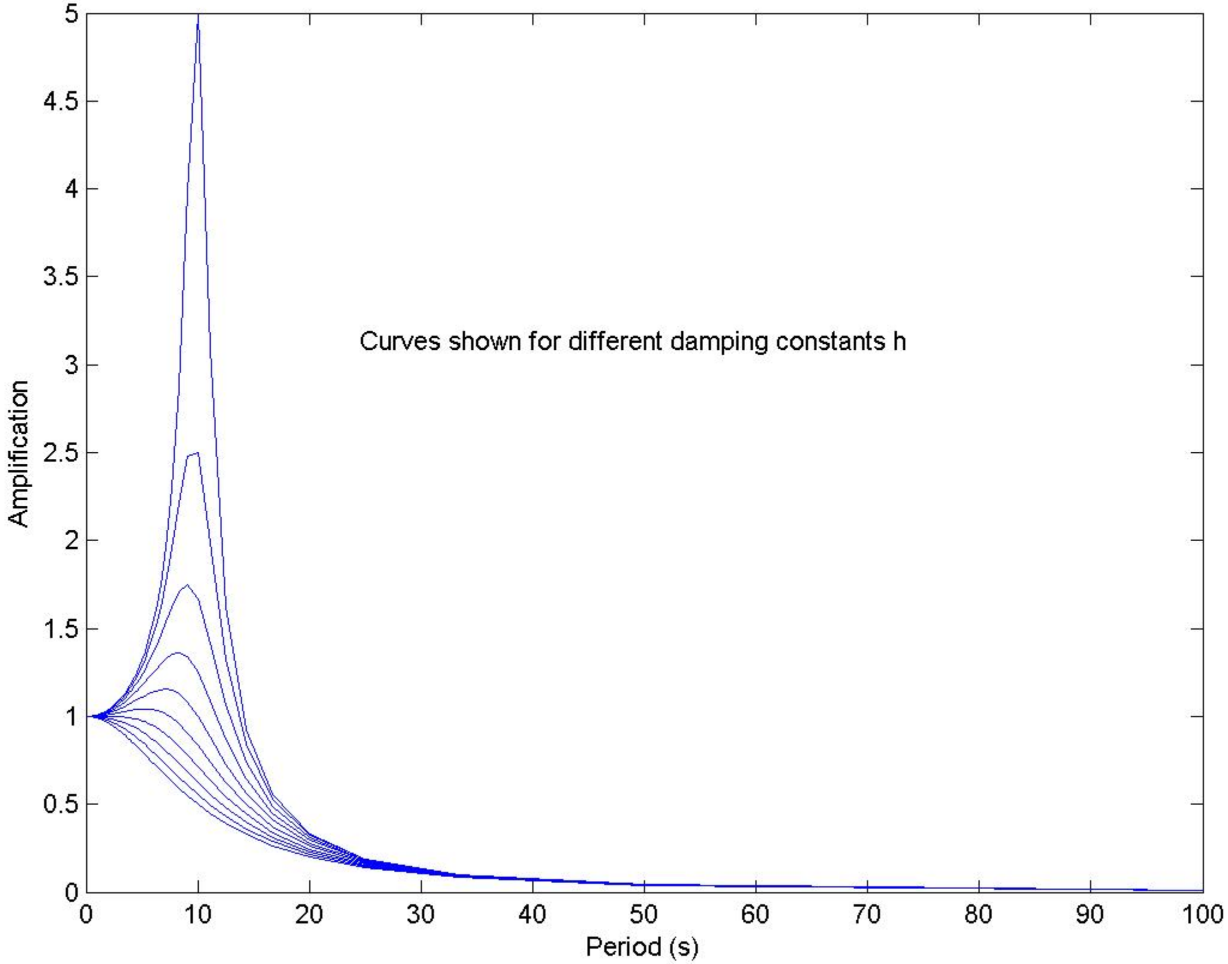
To answer this question we excite our seismometer with a monofrequent signal and record the response of the seismometer:

$$\ddot{x}_r(t) + h\varpi_0 \dot{x}_r(t) + \varpi_0^2 x_r(t) = \varpi^2 A_0 e^{i\varpi t}$$

the amplitude response A_r of the seismometer depends on the frequency of the seismometer w_0, the frequency of the excitation w and the damping constant h:

$$\left|\frac{A_r}{A_0}\right| = \frac{1}{\sqrt{\left(\frac{T^2}{T_0^2} - 1\right)^2 + 4h^2\frac{T^2}{T_0^2}}}$$

Amplitude Response Function - Resonance



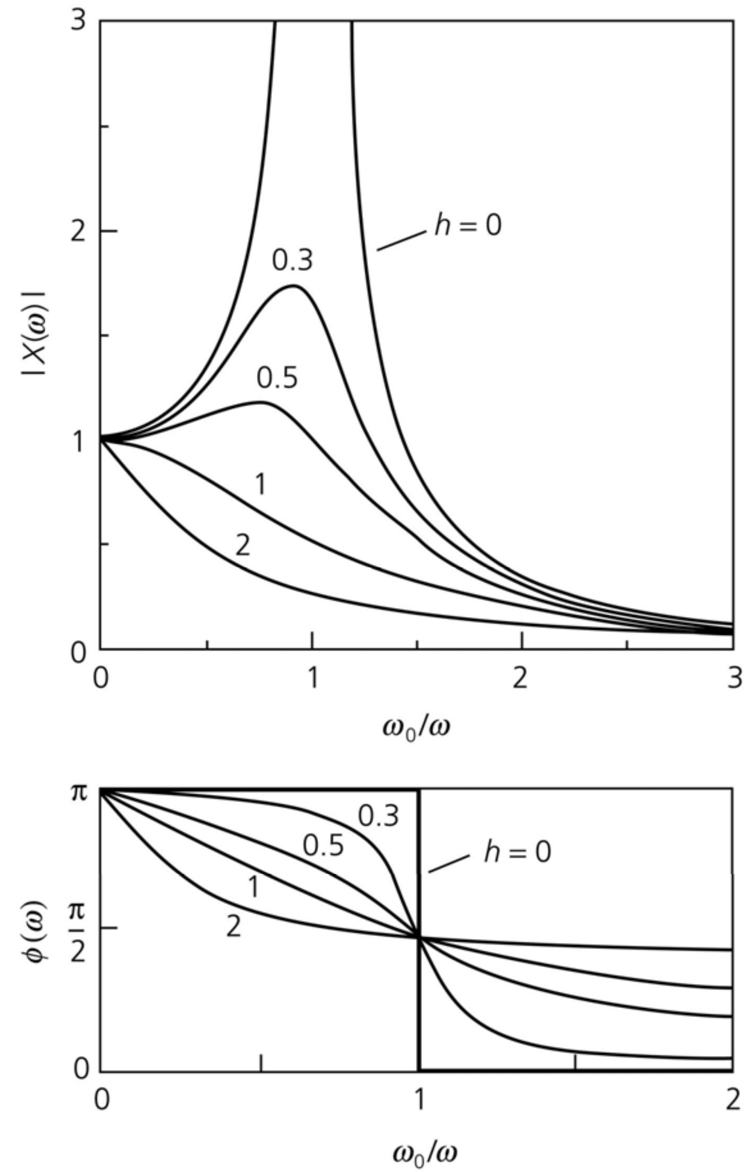
Phase Response

Clearly, the amplitude and phase response of the seismometer mass leads to a severe distortion of the original input signal (i.e., ground motion).

Before analysing seismic signals this distortion has to be revered:

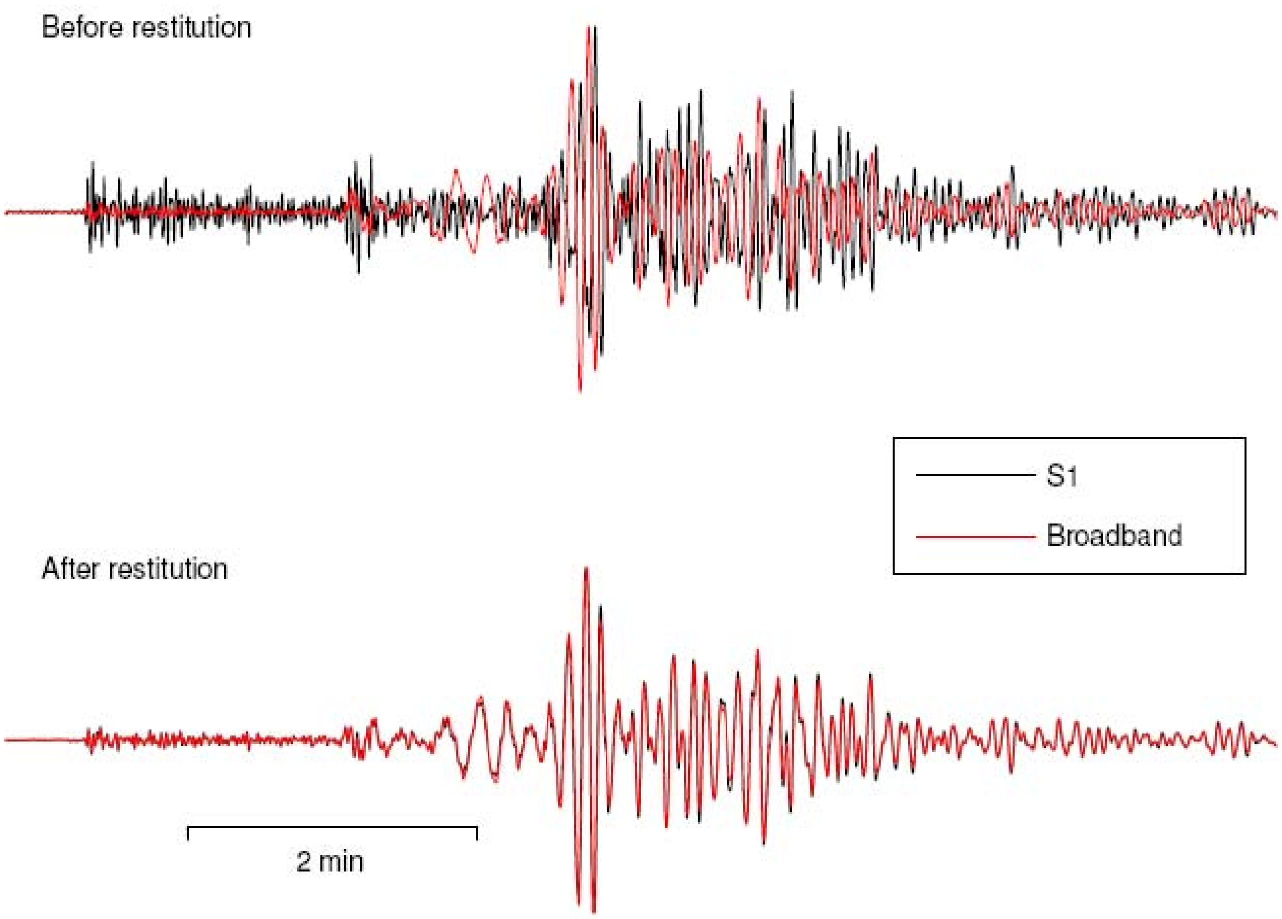
-> Instrument correction

Figure 6.6-2: Amplitude response and phase delay for a pendulum seismometer.



Seismometer as a Filter

Restitution -> Instrument correction



Electromagnetic Seismograph

Figure 6.6-6: Coupling of the transducer of an electromagnetic seismograph to a galvanometer.

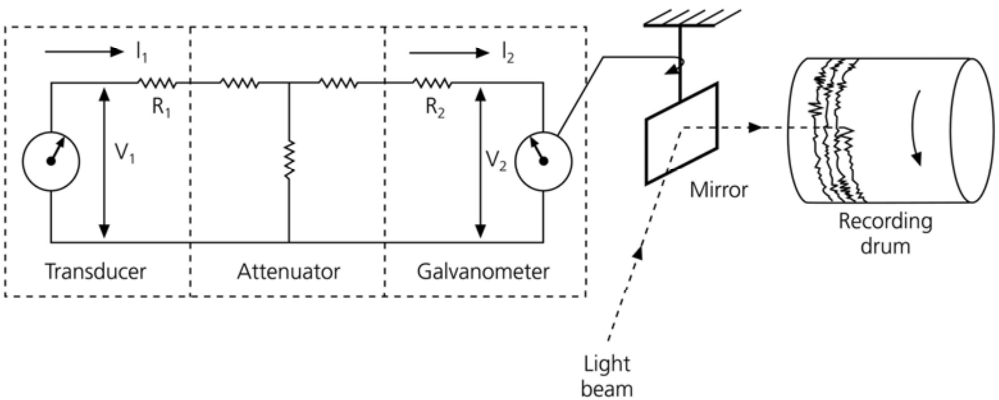
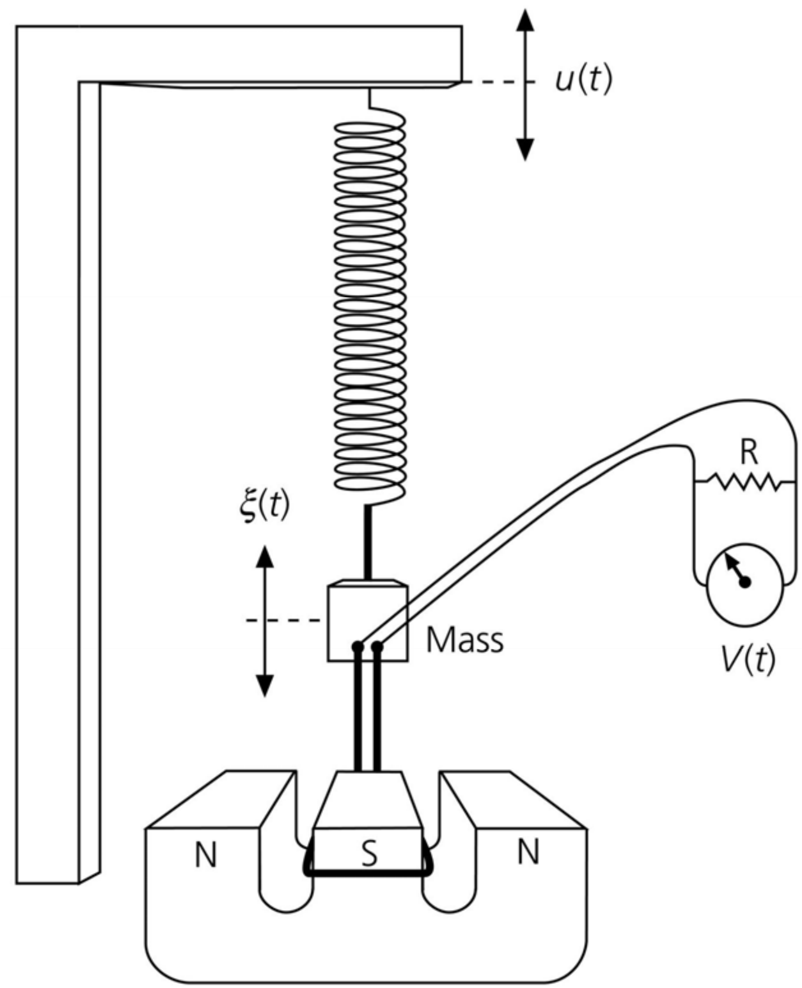


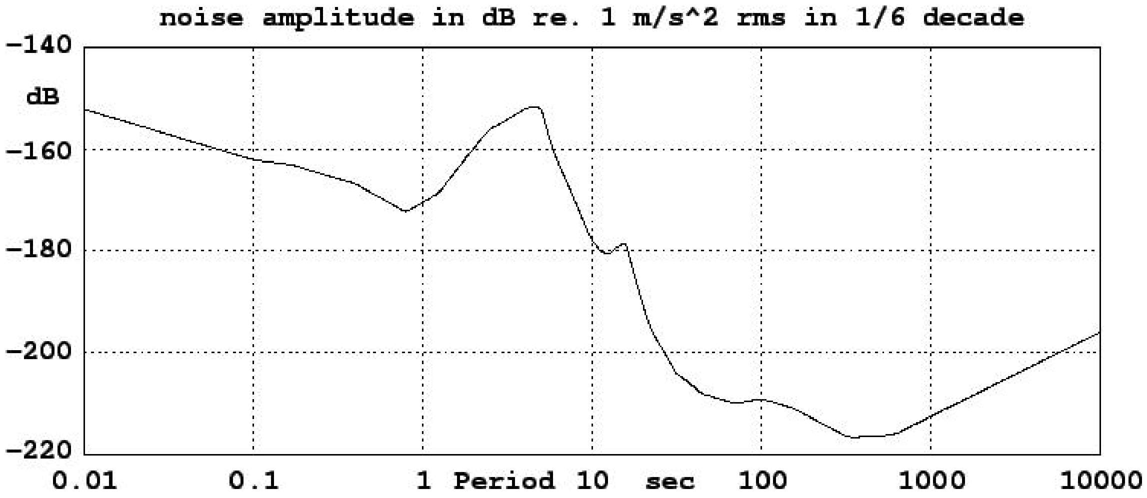
Figure 6.6-5: Illustration of an electromagnetic seismograph.



Electromagnetic seismographs measure ground velocity

Seismic signal and noise

The observation of seismic noise had a strong impact on the design of seismic instruments, the separation into short-period and long-period instruments and eventually to the development of broadband sensors.



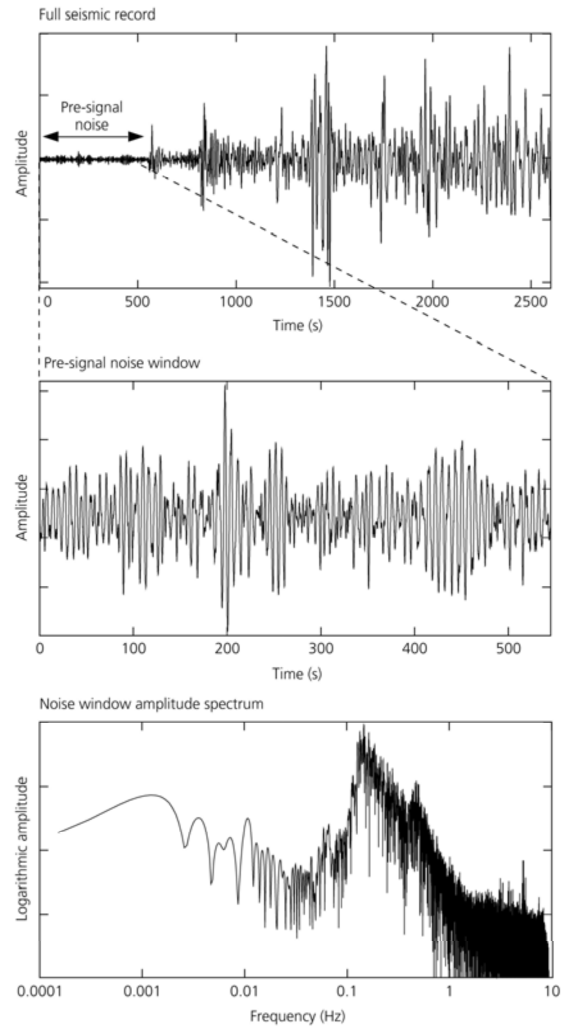
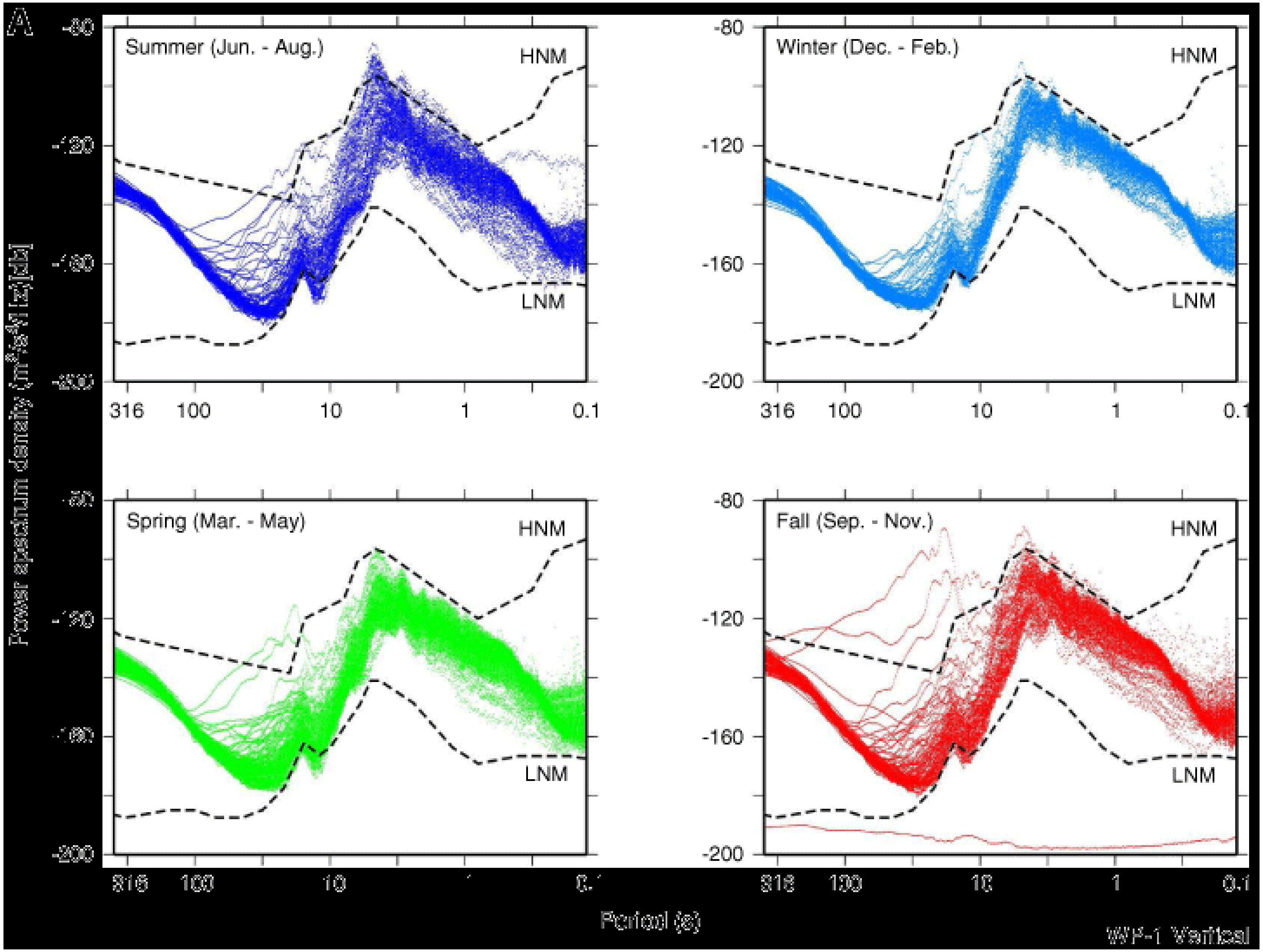


Figure 6.6-3: Demonstration of seismic noise on a broadband seismogram.

Seismic noise

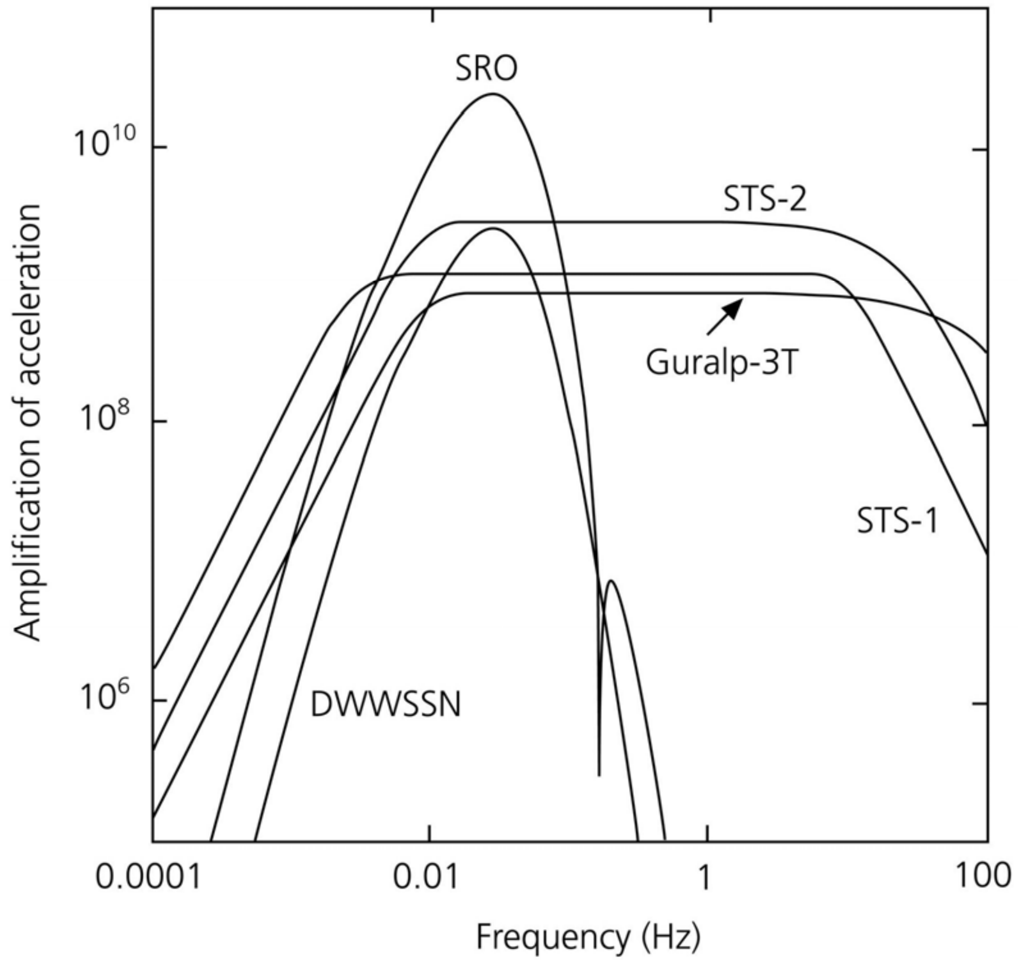


Seismometer Bandwidth

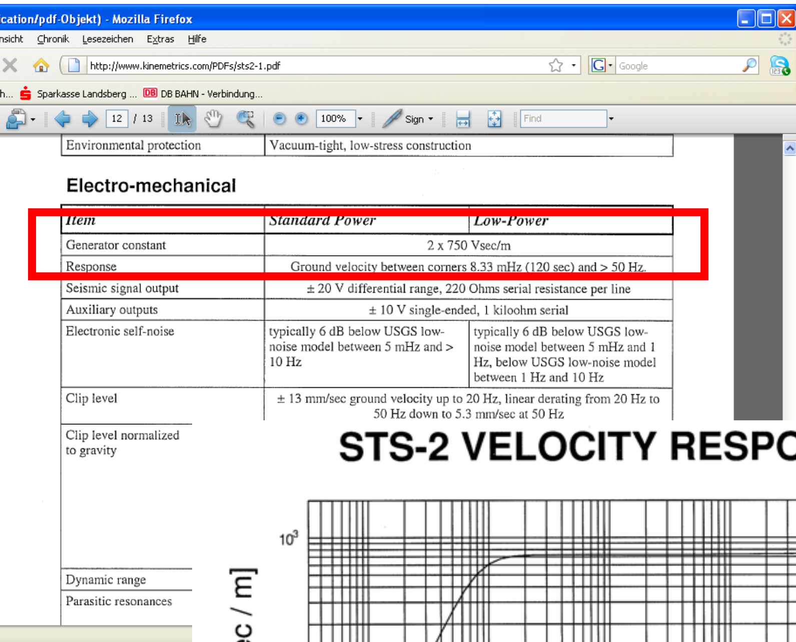
Today most of the sensors of permanent and temporary seismic networks are broadband instruments such as the STS1+2.

Short period instruments are used for local seismic events (e.g., the Bavarian seismic network).

Figure 6.6-8: Instrument responses for several types of seismometers.



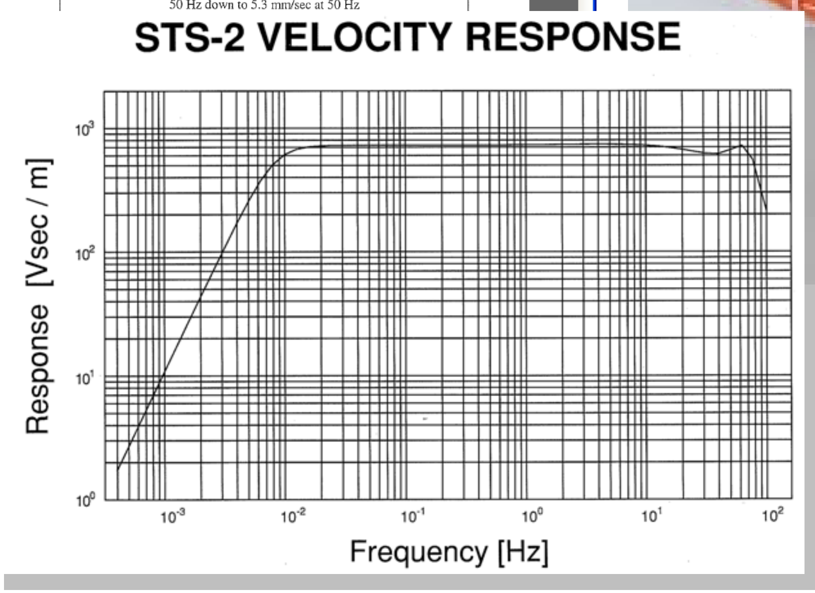
The STS-2 Seismometer



Environmental protection	Vacuum-tight, low-stress construction	

Electro-mechanical

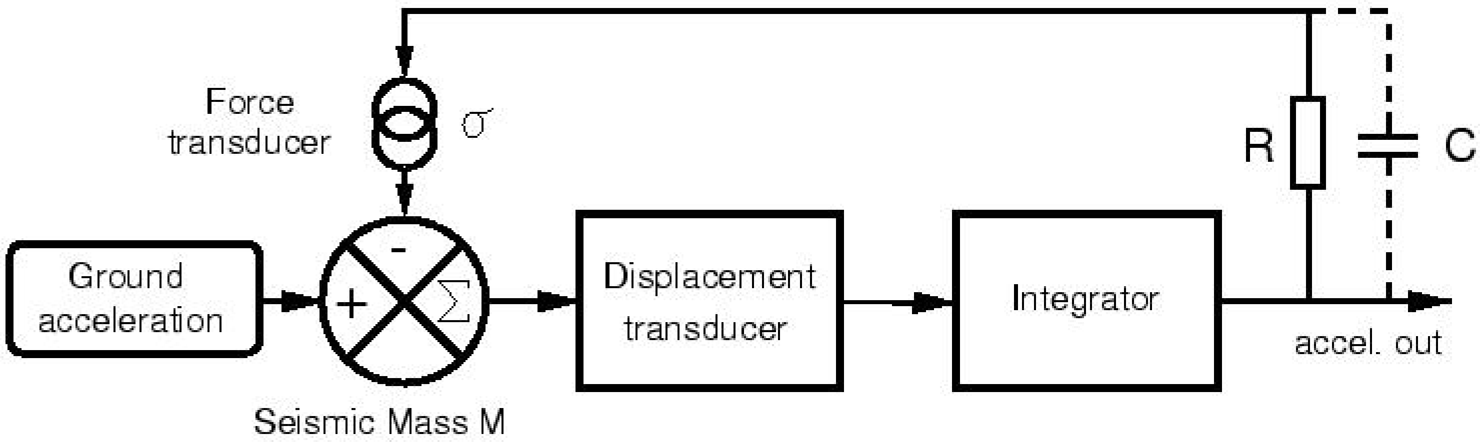
Item	Standard Power	Low-Power
Generator constant	2 x 750 Vsec/m	
Response	Ground velocity between corners 8.33 mHz (120 sec) and > 50 Hz.	
Seismic signal output	± 20 V differential range, 220 Ohms serial resistance per line	
Auxiliary outputs	± 10 V single-ended, 1 kiloohm serial	
Electronic self-noise	typically 6 dB below USGS low-noise model between 5 mHz and > 10 Hz	typically 6 dB below USGS low-noise model between 5 mHz and 1 Hz, below USGS low-noise model between 1 Hz and 10 Hz
Clip level	± 13 mm/sec ground velocity up to 20 Hz, linear derating from 20 Hz to 50 Hz down to 5.3 mm/sec at 50 Hz	
Clip level normalized to gravity		
Dynamic range		
Parasitic resonances		



www.kinemetrics.com

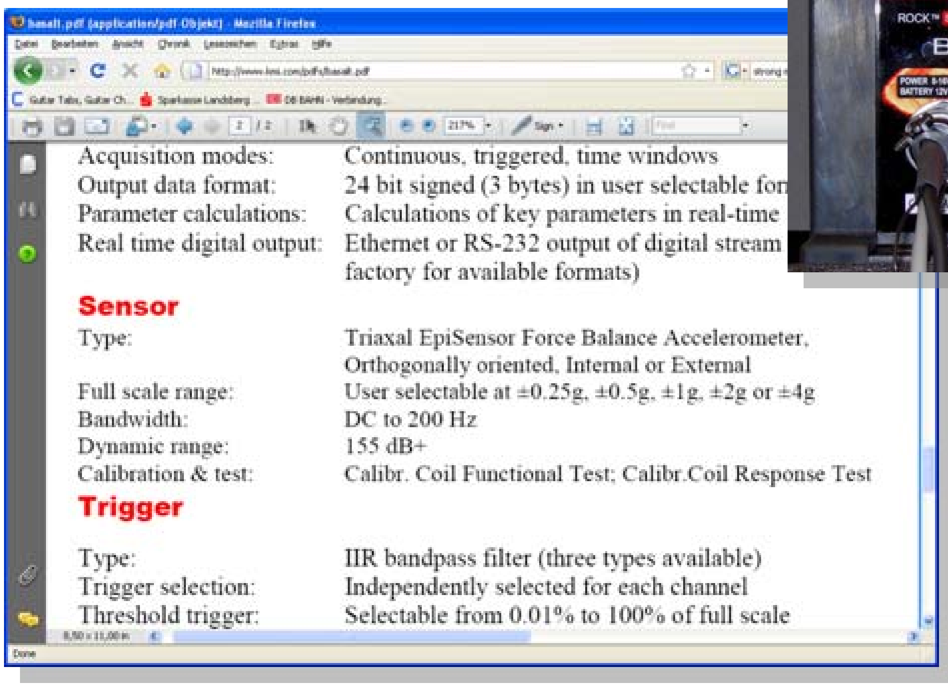
Accelerometer

force-balance principle



Feedback circuit of a force-balance accelerometer (FBA). The motion of the mass is controlled by the sum of two forces: the inertial force due to ground acceleration, and the negative feedback force. The electronic circuit adjusts the feedback force so that the two forces very nearly cancel. (Source Stuttgart University)

Accelerometer



Acquisition modes:	Continuous, triggered, time windows
Output data format:	24 bit signed (3 bytes) in user selectable for
Parameter calculations:	Calculations of key parameters in real-time
Real time digital output:	Ethernet or RS-232 output of digital stream factory for available formats)

Sensor

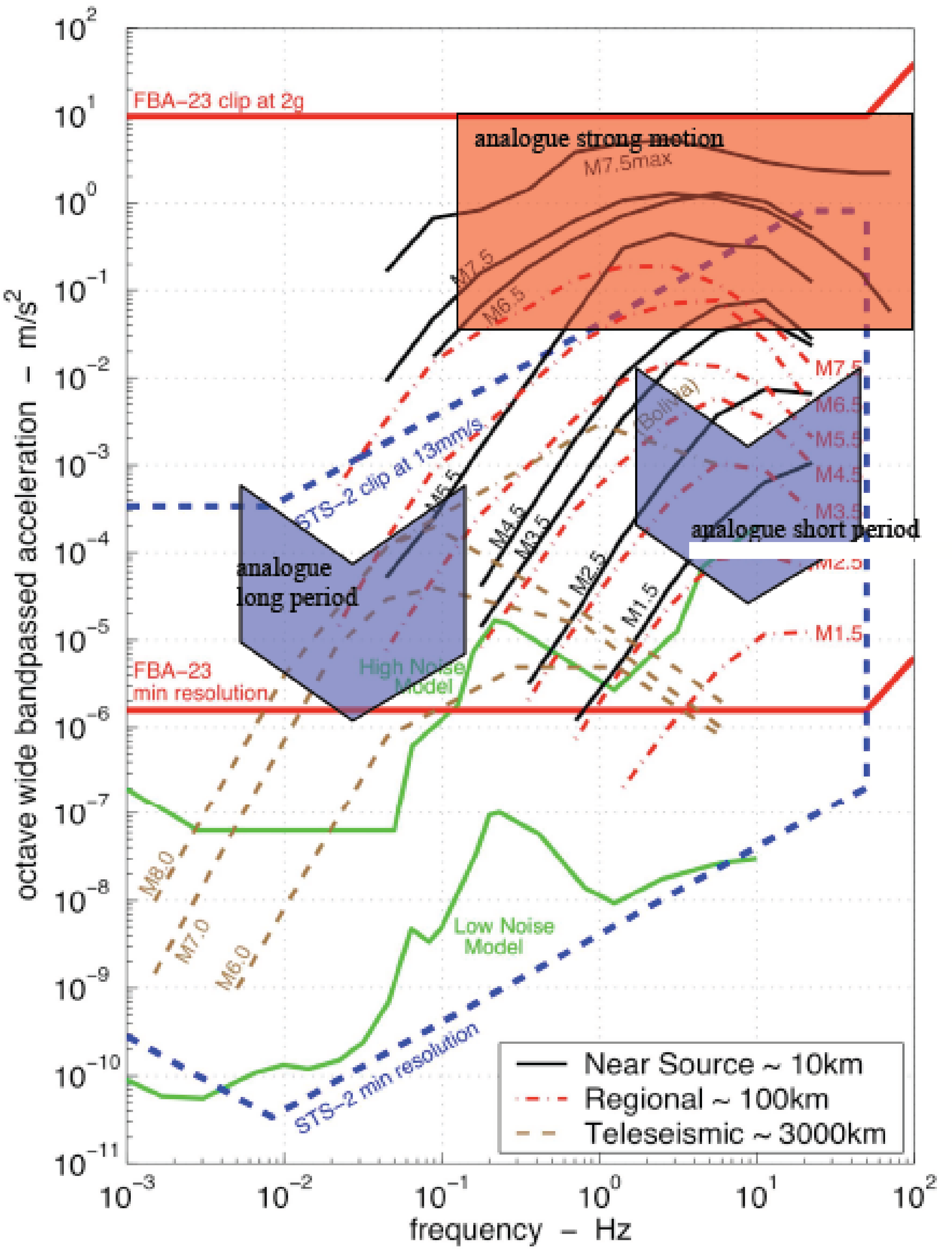
Type:	Triaxal EpiSensor Force Balance Accelerometer, Orthogonally oriented, Internal or External
Full scale range:	User selectable at ±0.25g, ±0.5g, ±1g, ±2g or ±4g
Bandwidth:	DC to 200 Hz
Dynamic range:	155 dB+
Calibration & test:	Calibr. Coil Functional Test; Calibr.Coil Response Test

Trigger

Type:	IIR bandpass filter (three types available)
Trigger selection:	Independently selected for each channel
Threshold trigger:	Selectable from 0.01% to 100% of full scale

www.kinemetrics.com

Observed amplitudes



(Relative) Dynamic range

Dynamic Range DR: the ratio between largest measurable amplitude A_{max} to the smallest measurable amplitude A_{min}.

$DR = V_{max}/V_{min}$

Units … what is 1 Bell?

… it is the Base 10 Logarithm of the ratio of two energies

$L= \log (P_1/P_2)$ B $= 10 \log (P_1/P_2)$ dB

Where B is a 10th of B, and in terms of amplitudes

$L = 10 \log (A_1/A_2)^2$ dB $= 20 \log (A_1/A_2)$

(Relative) Dynamic range

Nature:

The Earth has motions varying 10 orders of magnitude from the strongest motion to the lowest noise level

-> DR_{Earth}= 20 log (10^{10})dB = 200 dB !

Instruments: e.g., 10 bit digitizer

Dynamic range = $20 \log_{10}(A_{max}/A_{min})$ dB

Example: with 1024 units of amplitude (A_{min}=1, A_{max}=1024)

$$20 \log_{10}(1024/1) \quad \text{dB} \sim 60 \text{ dB}$$

Bits, counts, dynamic range

#bits	Dynamic Range *($2^{\#bits-1}$) counts*	DR$_{dB}$ *((#bits-1)x6)*	Orders of Magnitude *(DR$_{dB}$/20)*
8	256/2	42	~2
12	4,096/2	66	~3
16	65,536 /2	90	~4.5
20	1,048,576/2	114	~6
24	16,777,216/2	138	~7

Seismometer

Mechanical : 100*dB*

Force-balance : 140-150*dB*

Telemetry

analogue phone : 50*dB*

digital : α bandwidth (possibly ∞)

Recording

paper : 60*dB*

digital : $2^{\#bits-1}$ counts

(#bits-1)x6 *dB*

(up to 144*dB*)

Dynamic range of a seismometer
ADC (analog-digital-converter)

A n-bit digitzer will have 2^{n-1} intervals to describe an analog signal.

Example:

A 24-bit digitizer has 5V maximum output signal (full-scale-voltage)

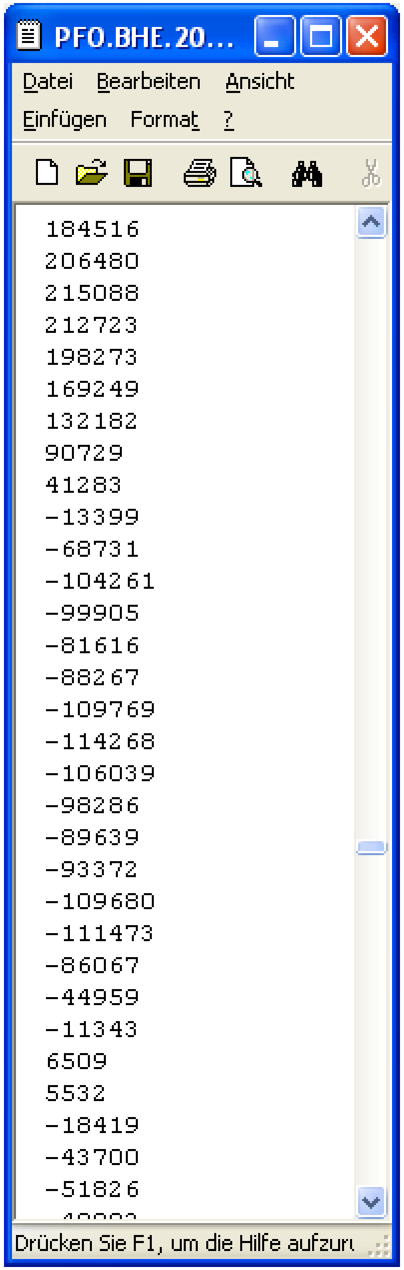
The least significant bit (lsb) is then

lsb = 5V / 2^{n-1} = 0.6 microV

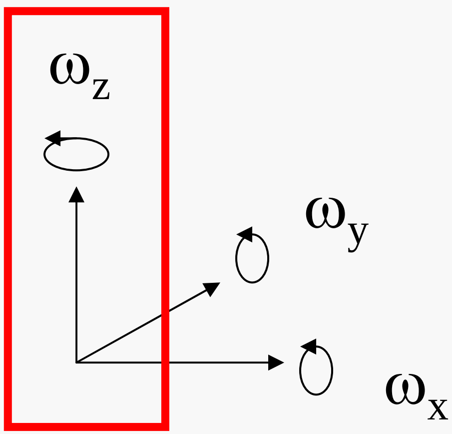
Generator constant STS-2: 750 Vs/m

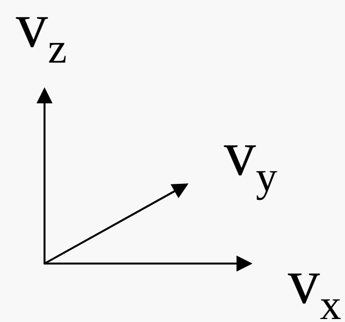
What does this imply for the peak ground velocity at 5V?

Seismogram data in counts



$$\begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = \frac{1}{2} \nabla \times \underline{\mathbf{v}} = \frac{1}{2} \begin{pmatrix} \partial_y v_z - \partial_z v_y \\ \partial_z v_x - \partial_x v_z \\ \partial_x v_y - \partial_y v_x \end{pmatrix}$$





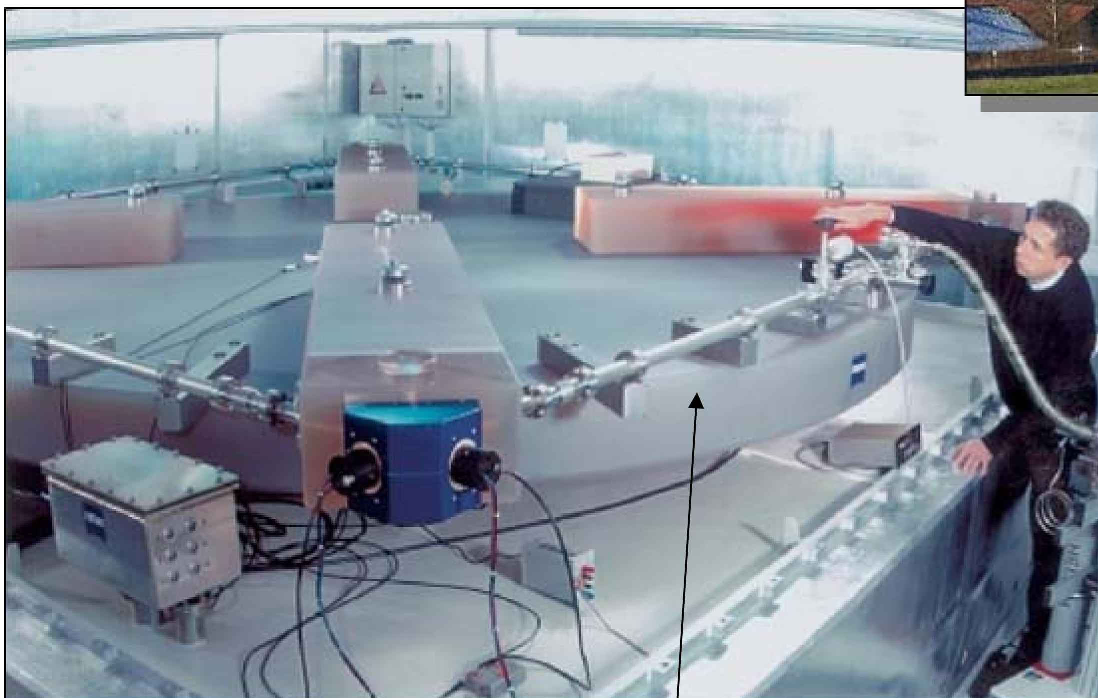
Rotation rate

Rotation sensor

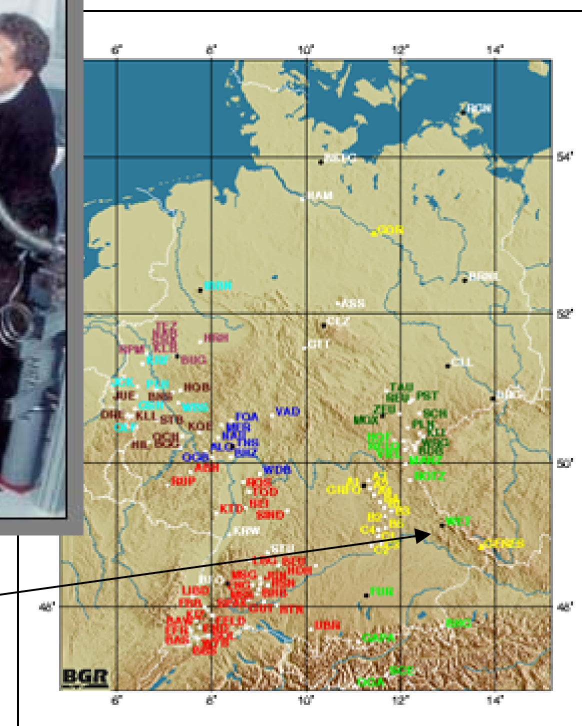
Ground velocity

Seismometer

The ring laser at Wettzell

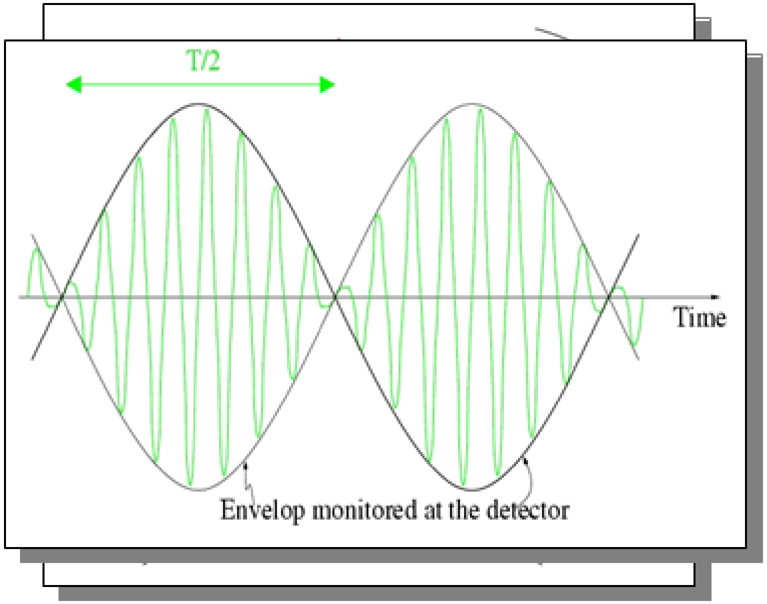


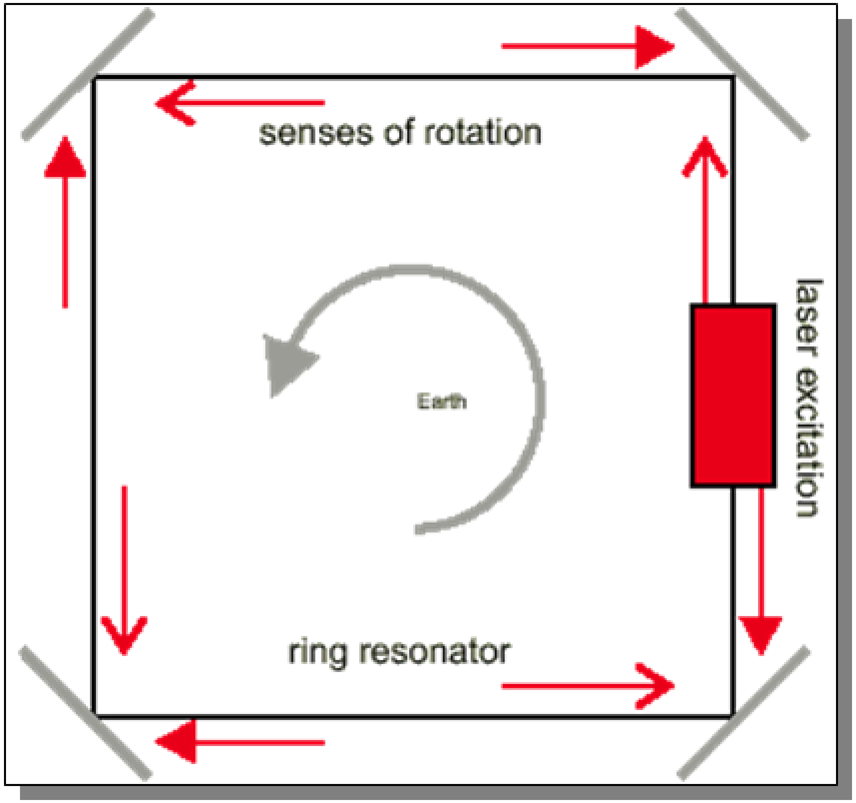
ring laser



Data accessible at www.rotational-seismology.org

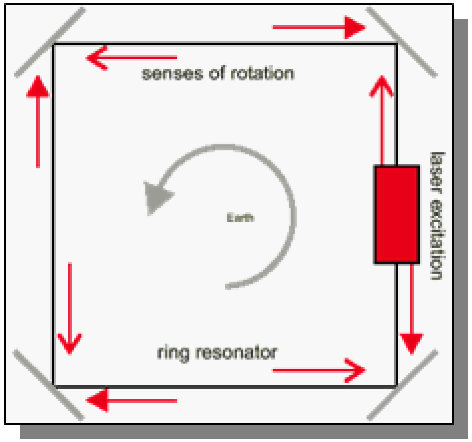
How can we observe rotations? -> ring laser





Ring laser technology developed by the groups at the Technical University Munich and the University of Christchurch, NZ

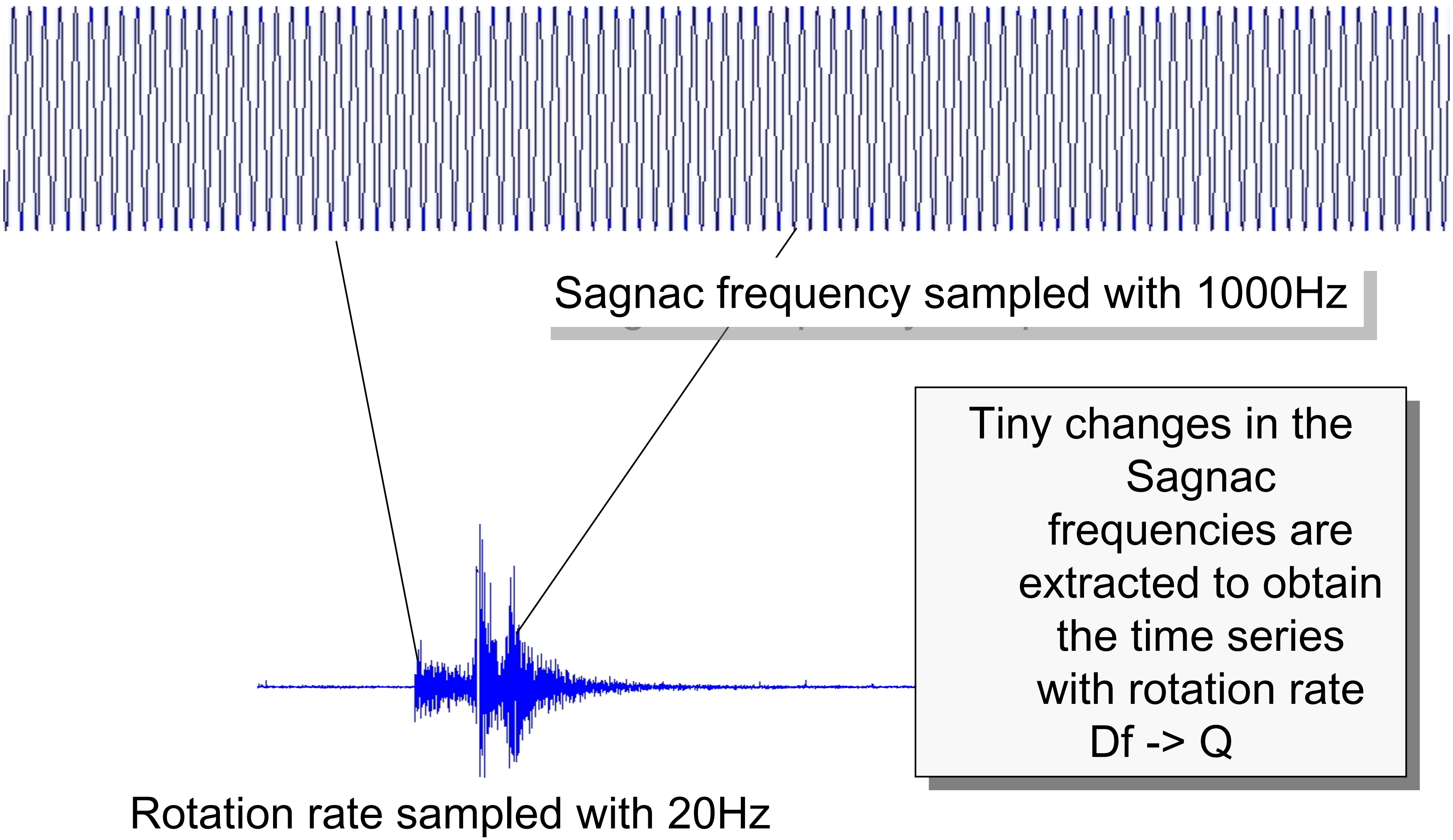
Ring laser – the principle



$$\Delta f_{Sagnac} = \frac{4\boldsymbol{\Omega} \cdot \mathbf{A}}{\lambda P}$$

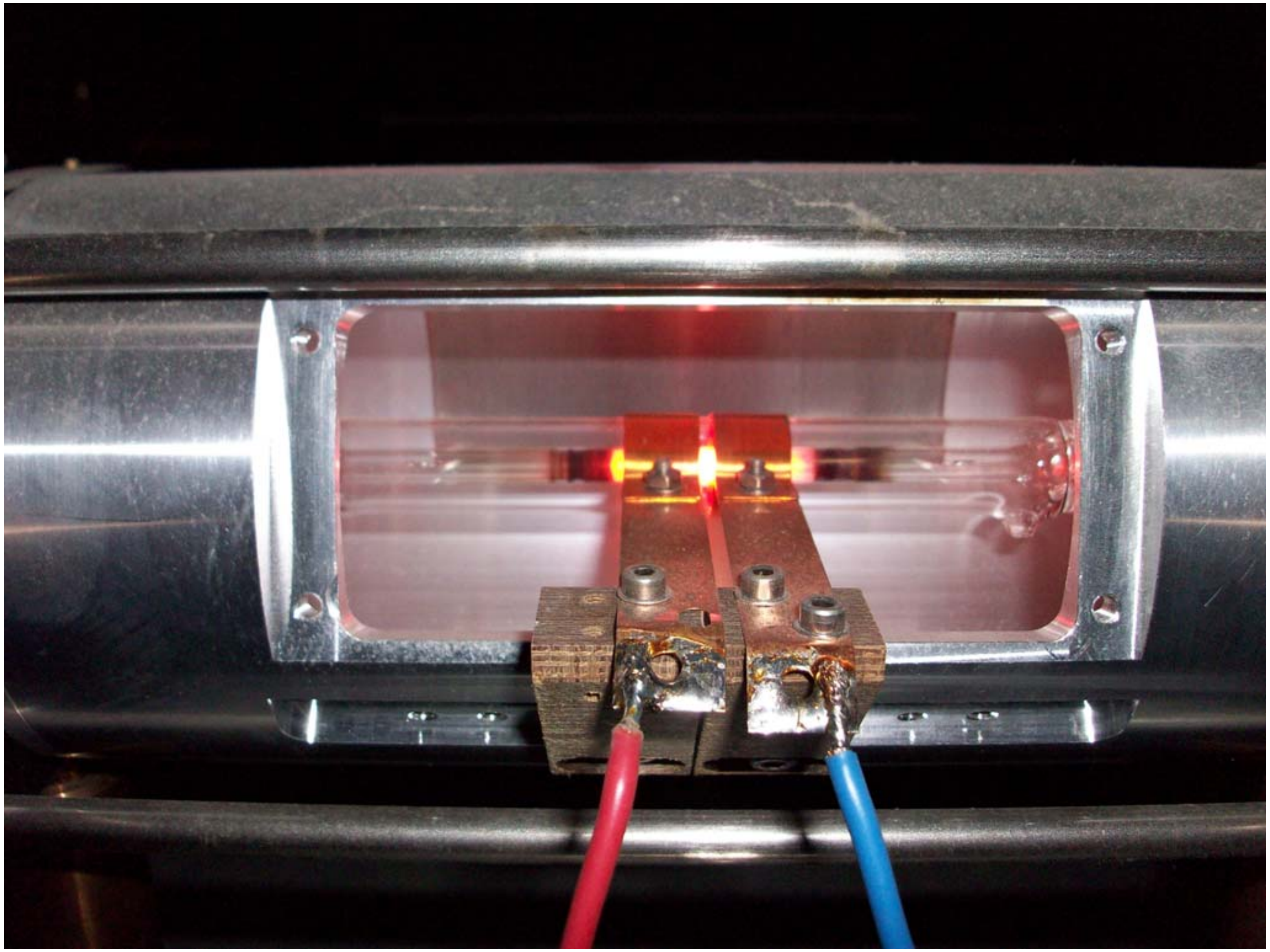
A	surface of the ring laser (vector)
Ω	imposed rotation rate (Earth's rotation + earthquake +...)
λ	laser wavelength (e.g. 633 nm)
P	perimeter (e.g. 4-16m)
Δf	Sagnac frequency (e.g. 348,6 Hz sampled at 1000Hz)

The Sagnac Frequency
(schematically)

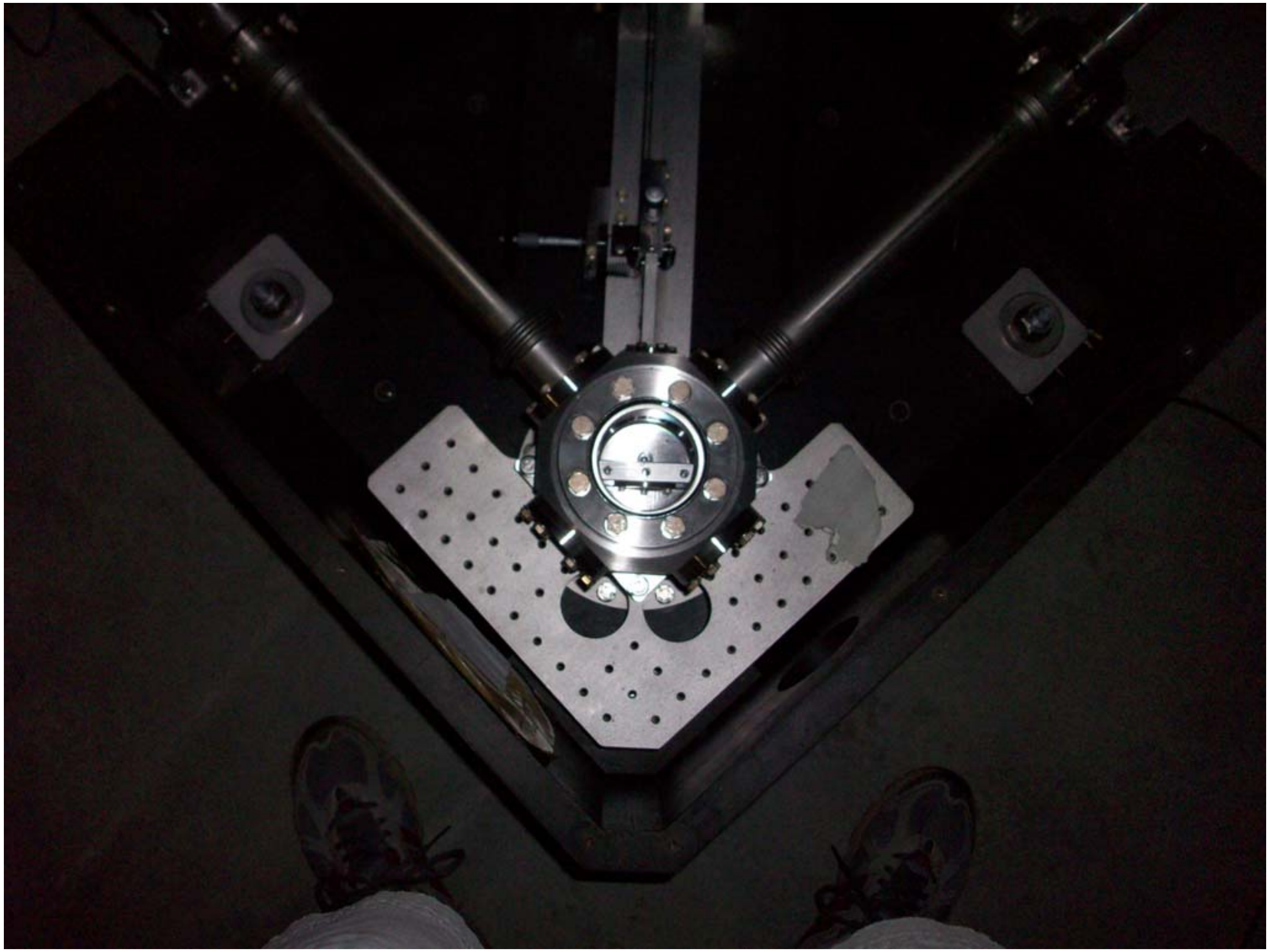


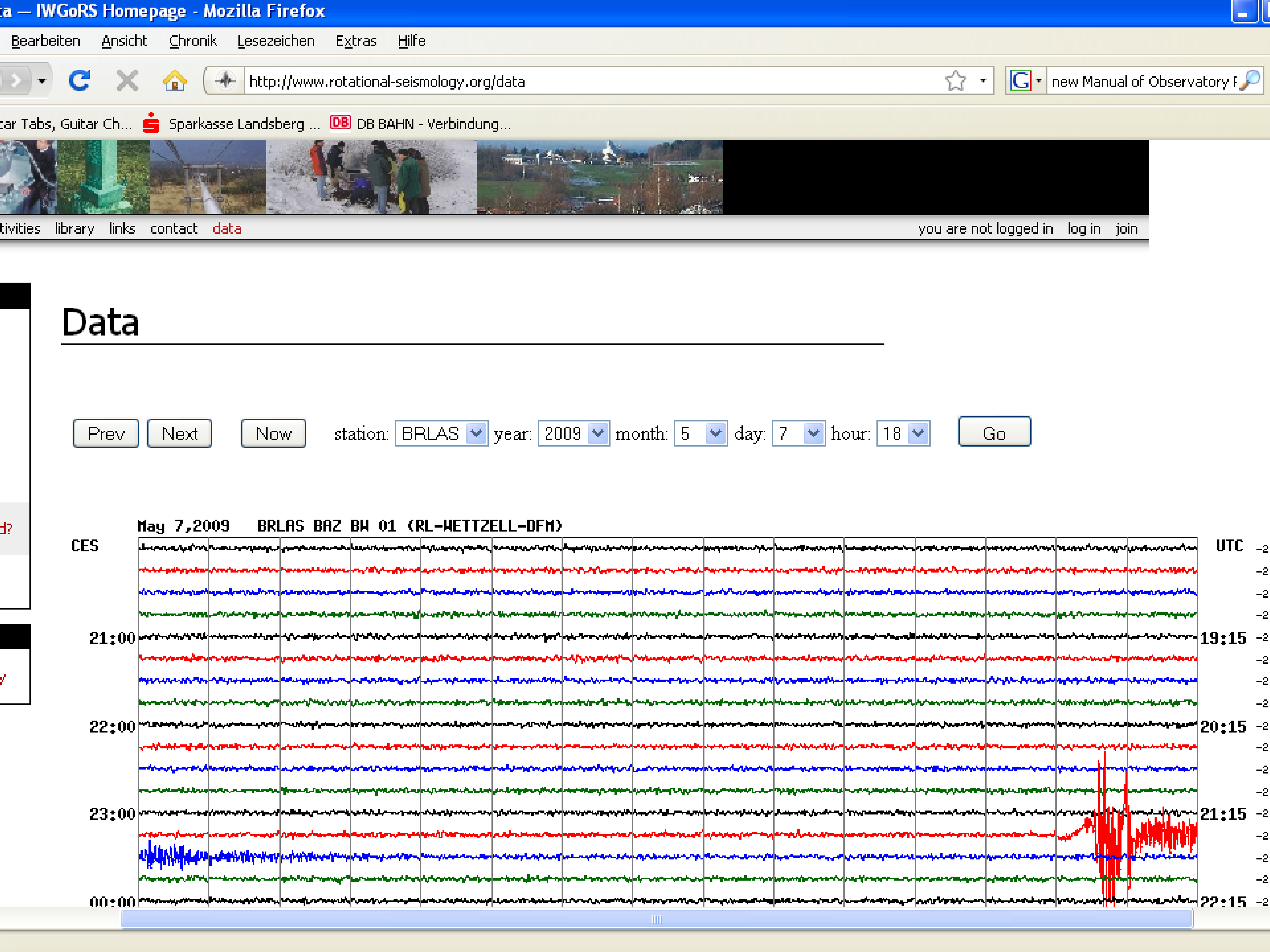
The Pinon Flat Observatory sensor

PFO



PFO

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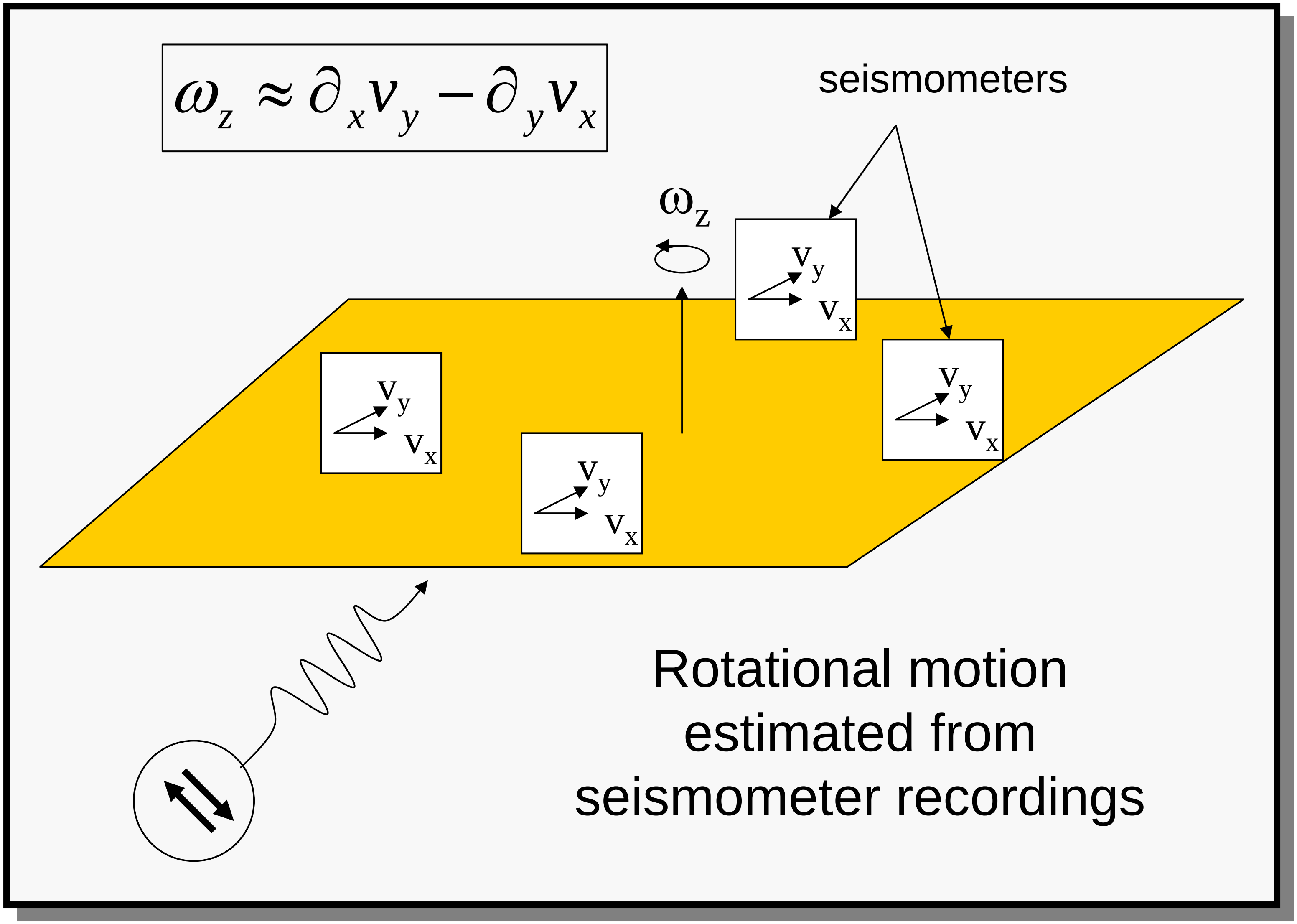
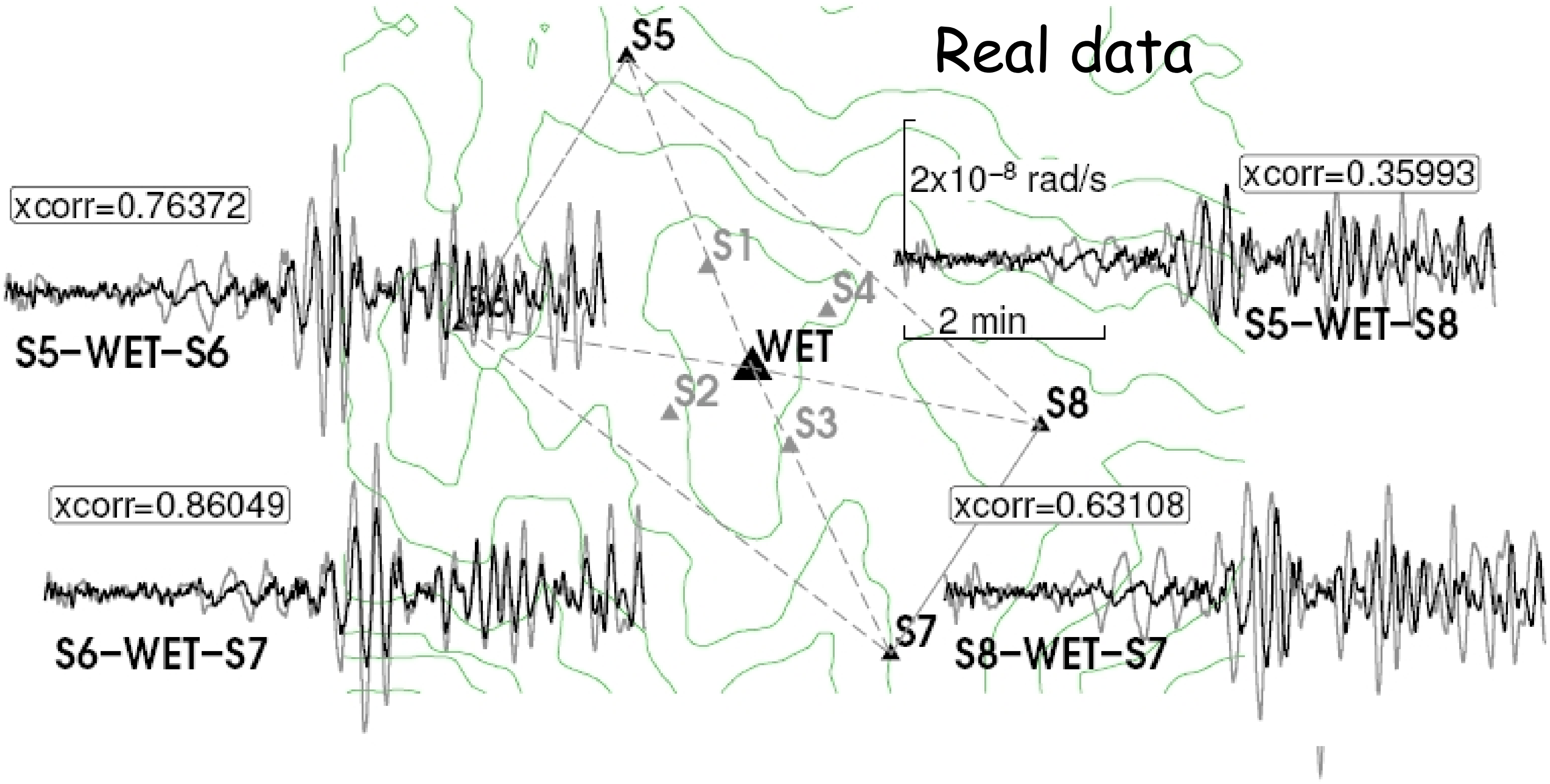
Rotation from seismic arrays?

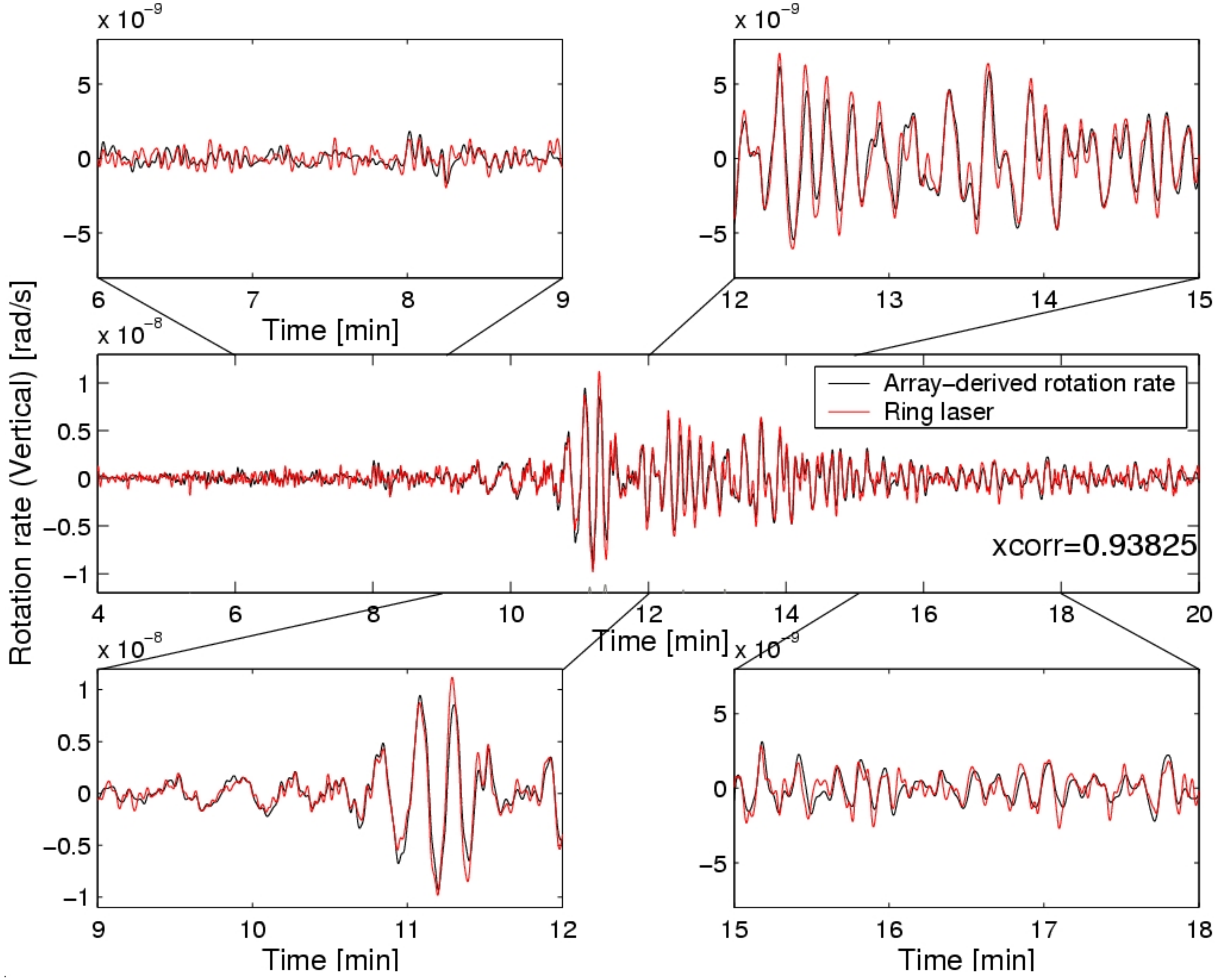
... by finite differencing ...



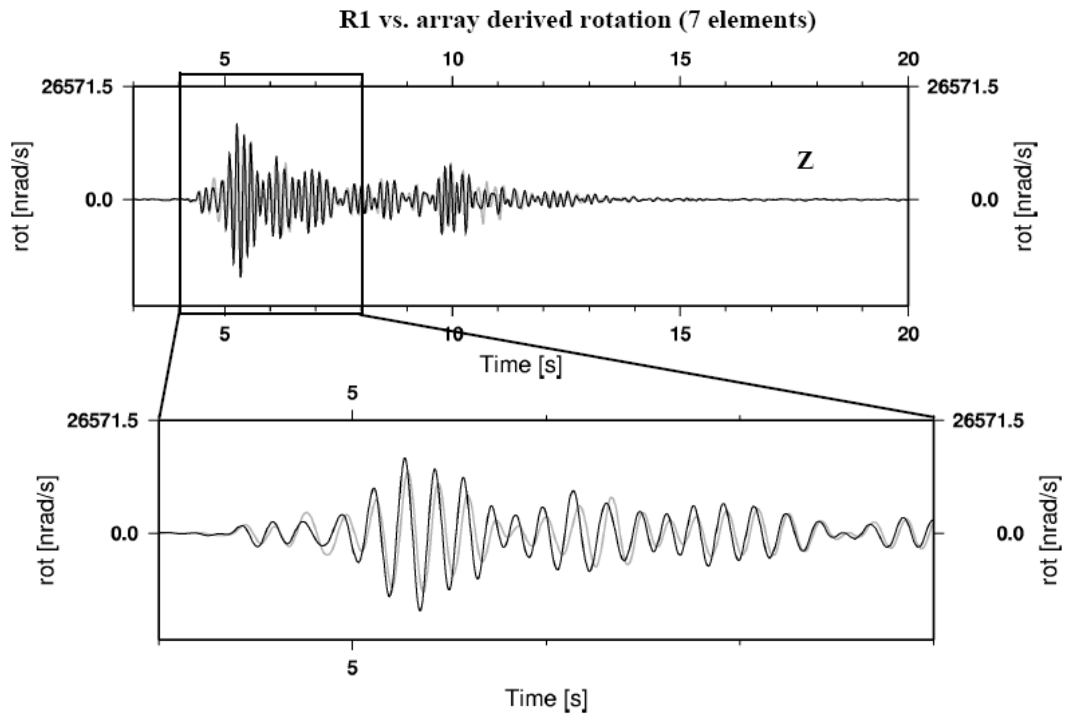
Uniformity of rotation rate across array

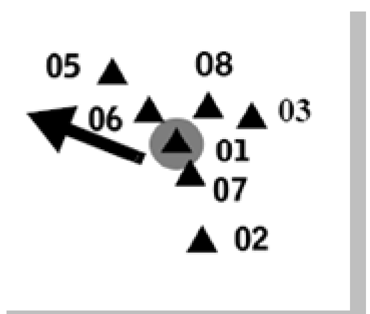


Direct vs. array-derived rotation



Array vs. direct measurements

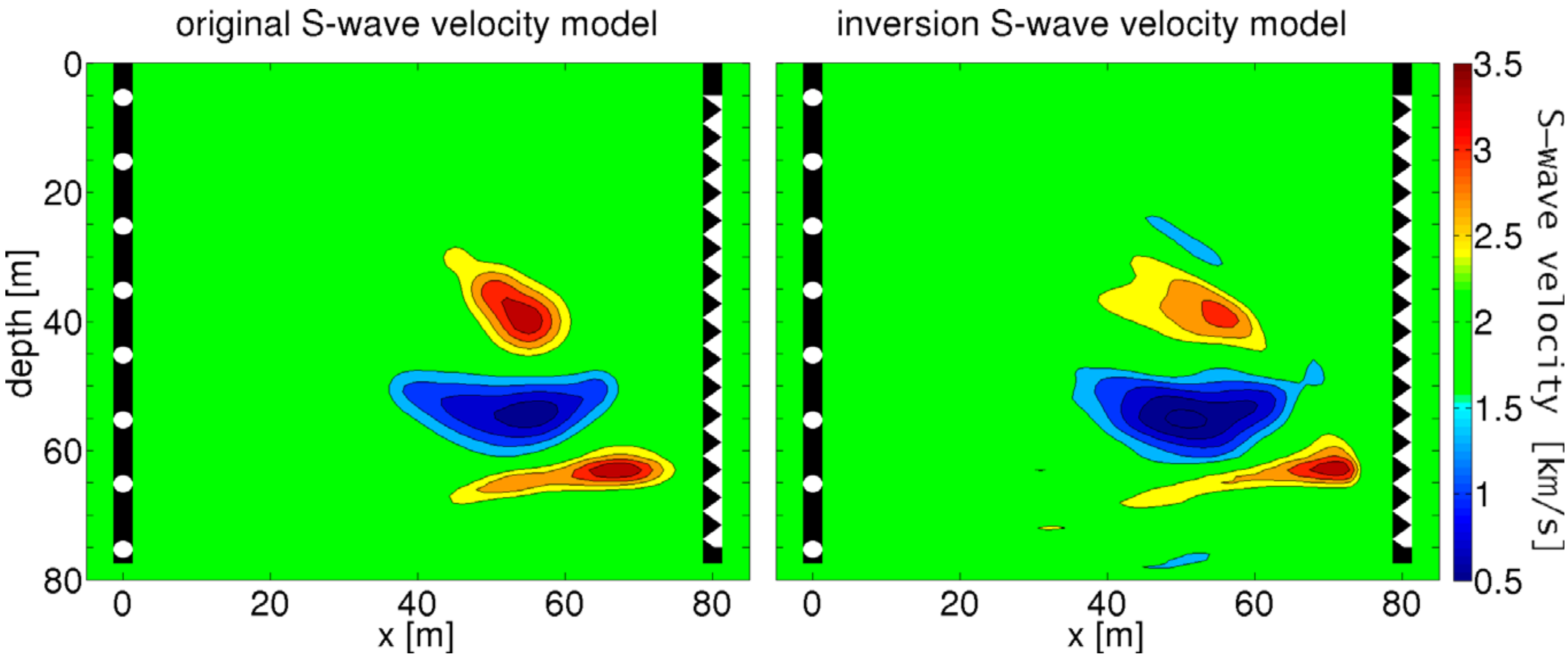




Wassermann et al., 2009, BSSA

A look to the future

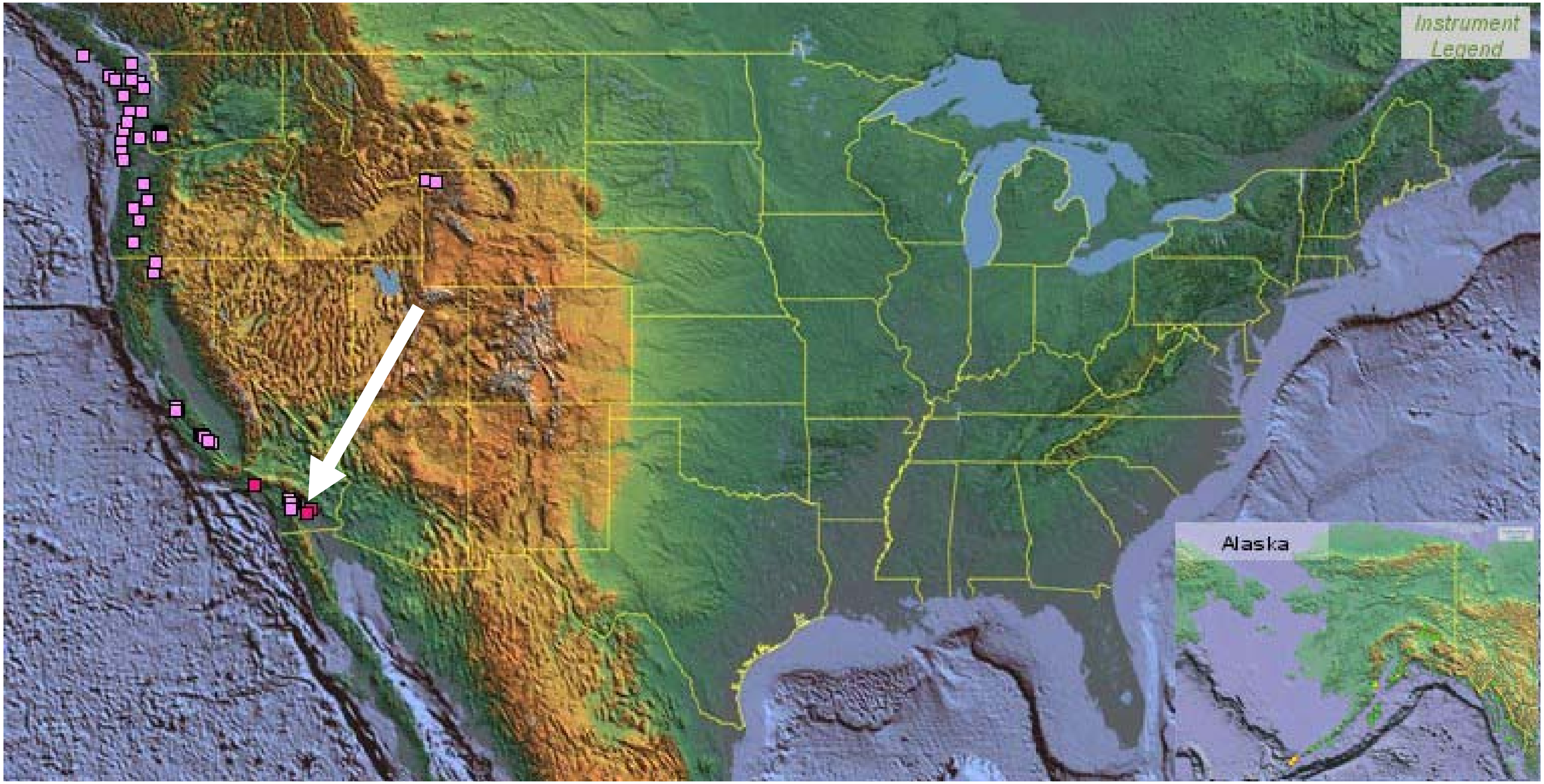
seismic tomography with rotations



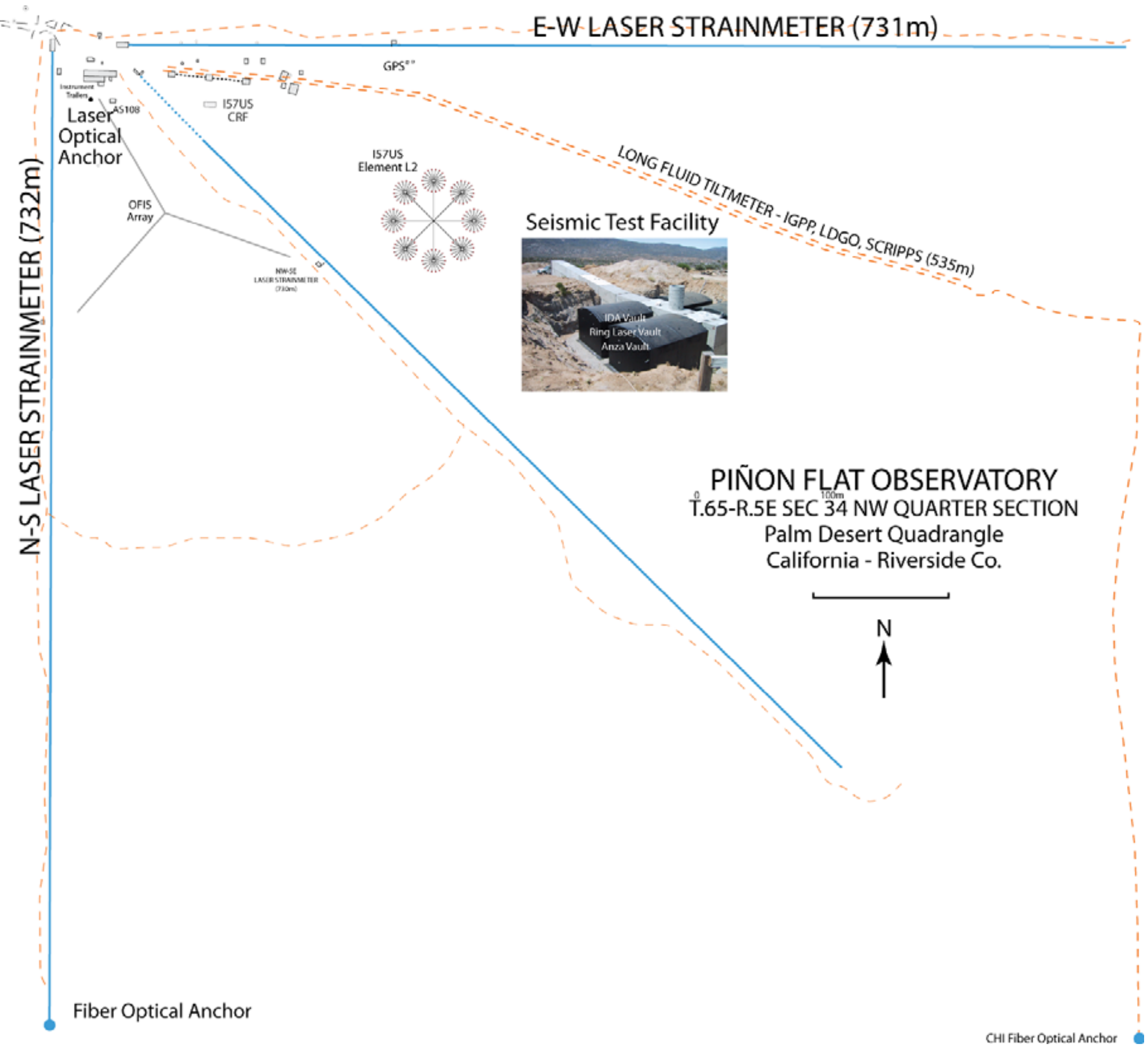
From Bernauer et al., Geophysics, 2009

Strain sensors

Network in EarthScope



Pinon Flat Observatory, CA



Strain meter principle

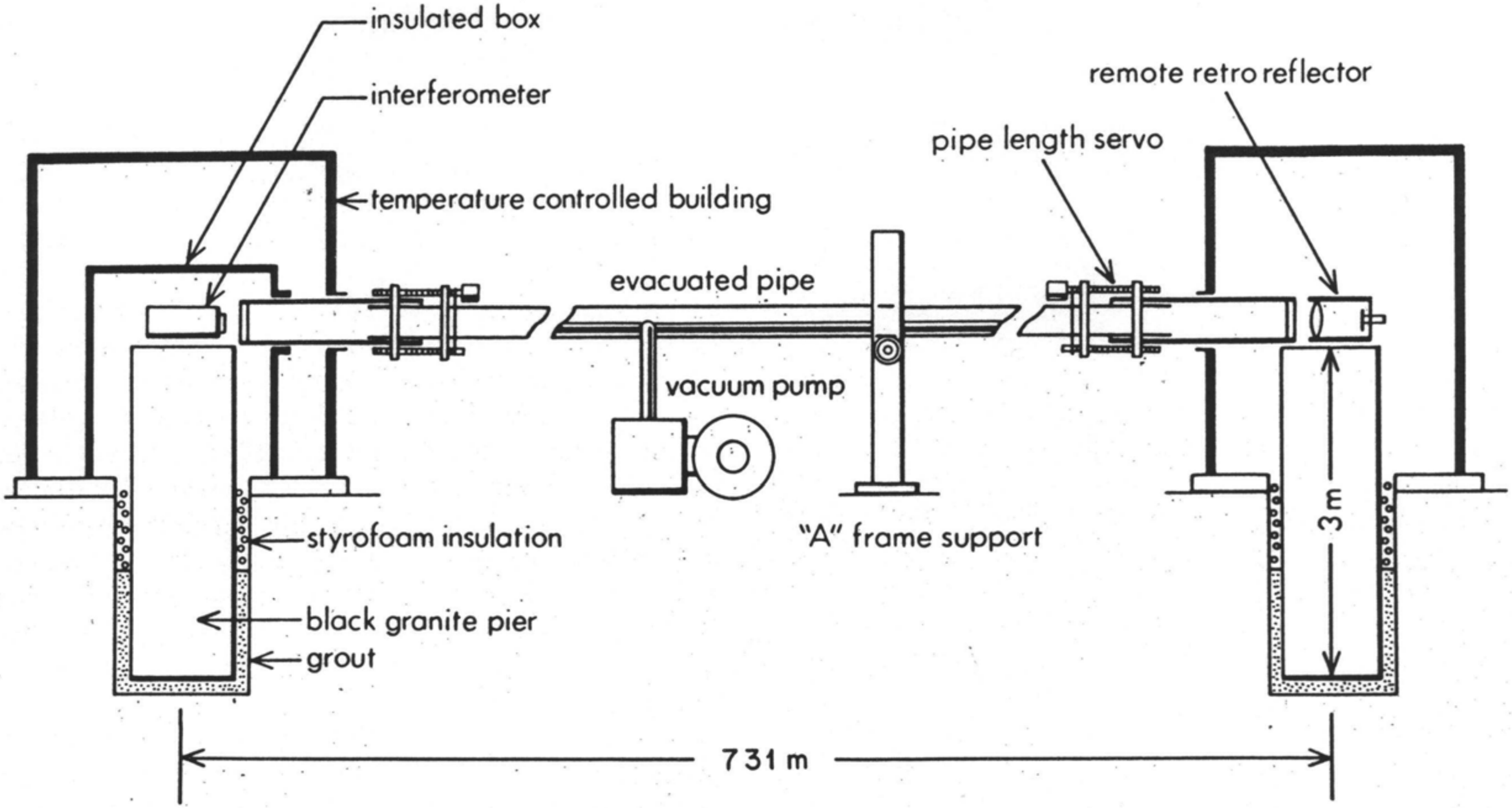
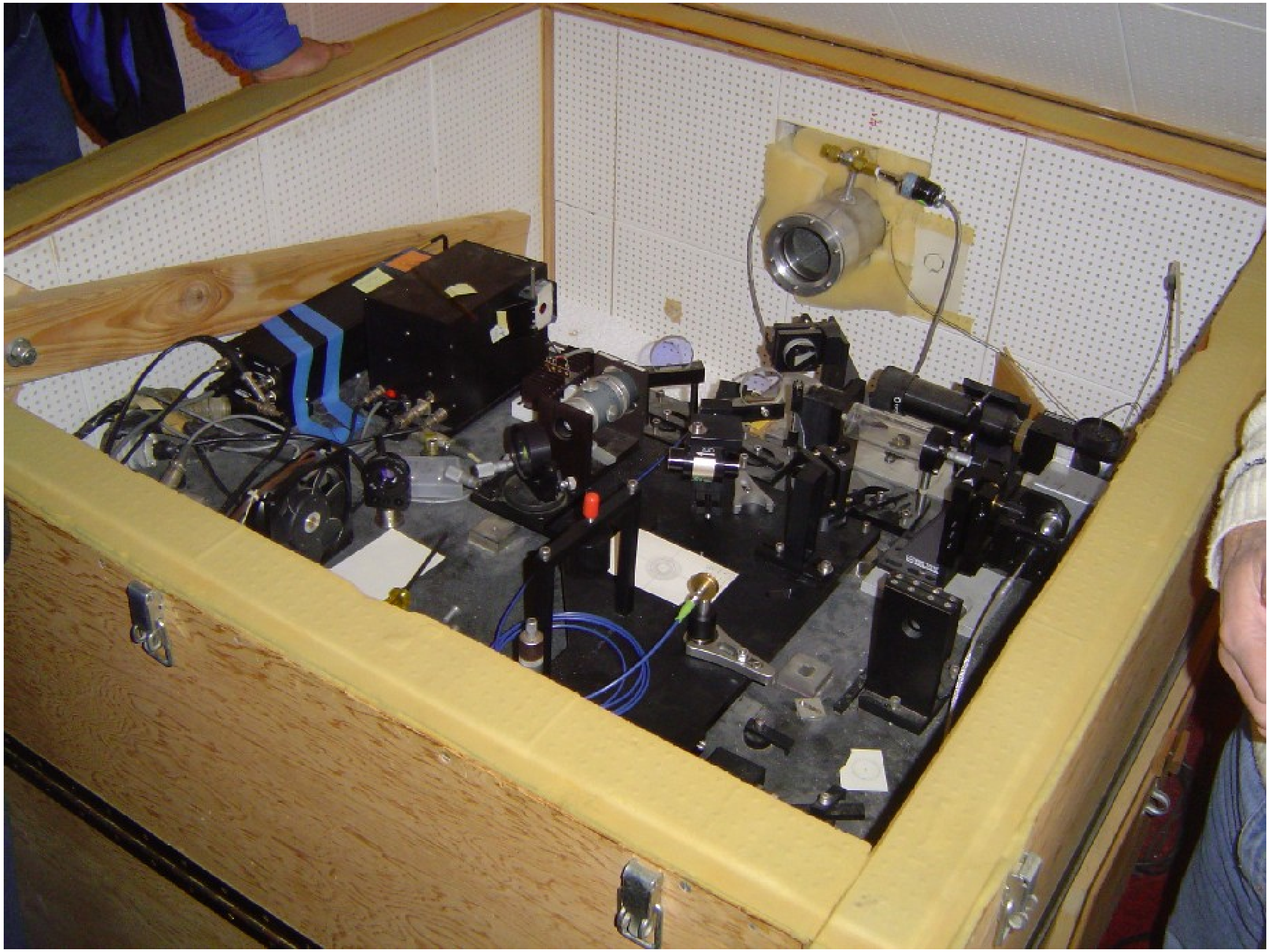
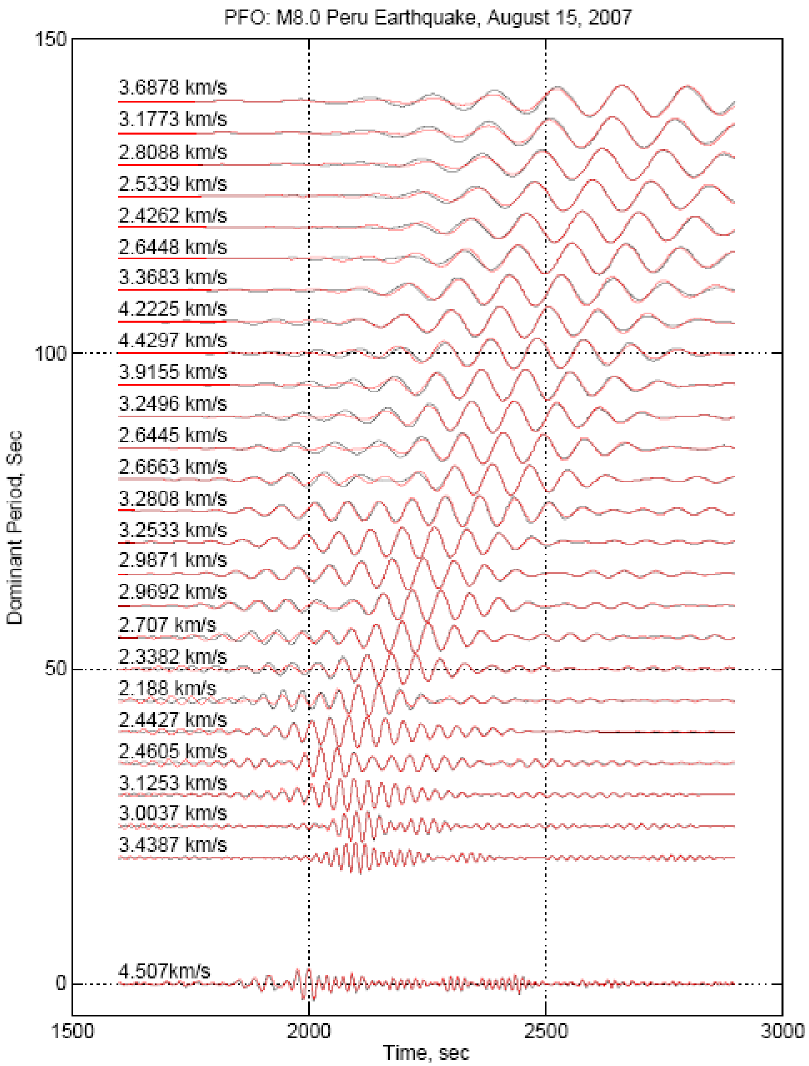


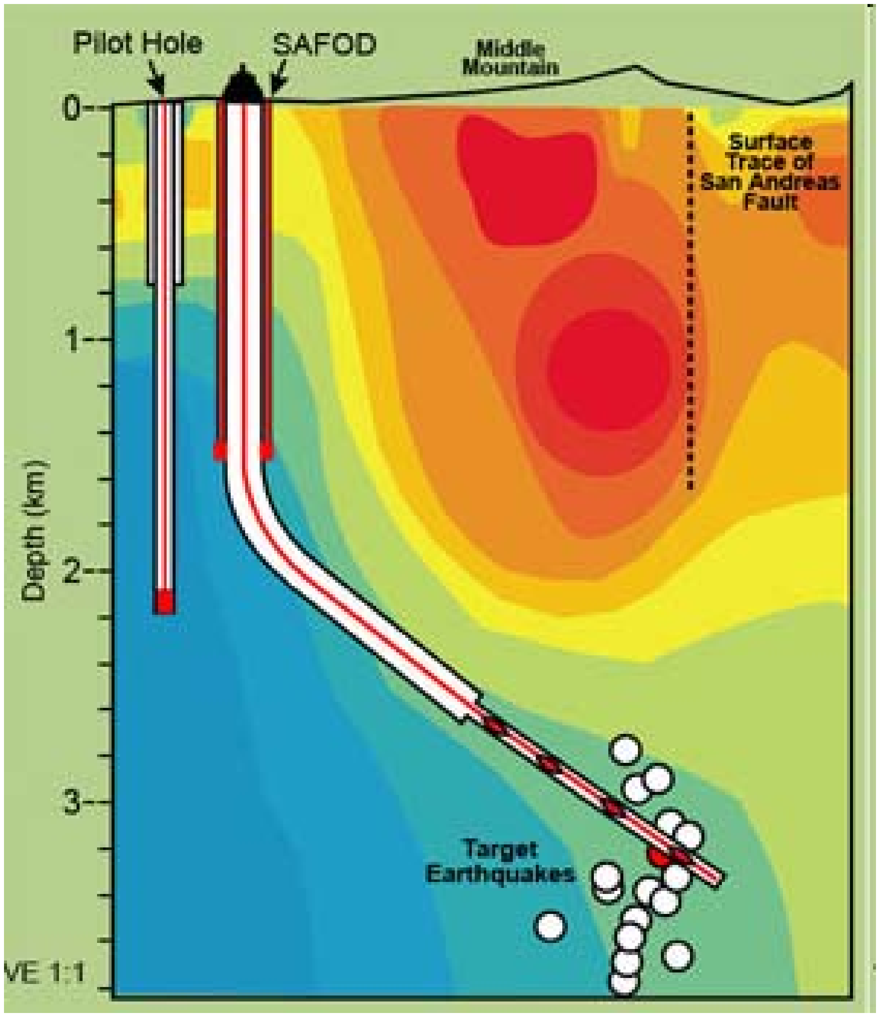
Fig. 21. Mechanical design of the UCSD laser strainmeter. The two endpoints are tall piers of dimension stone sunk in the ground. These, and the optics they carry, are inside temperature-controlled enclosures in air-conditioned buildings. The measurement path is inside a vacuum pipe except at the very ends; telescopic joints keep the length of the air paths constant.

Interferometer



Strain - Observations





Strain vs. translations

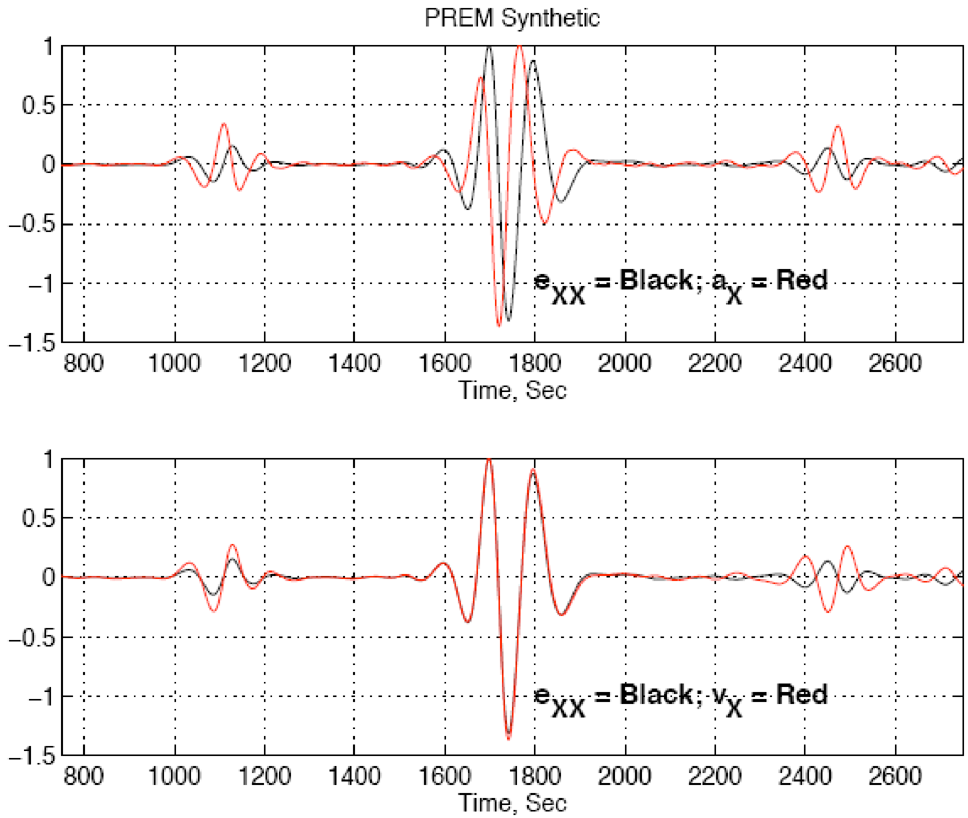
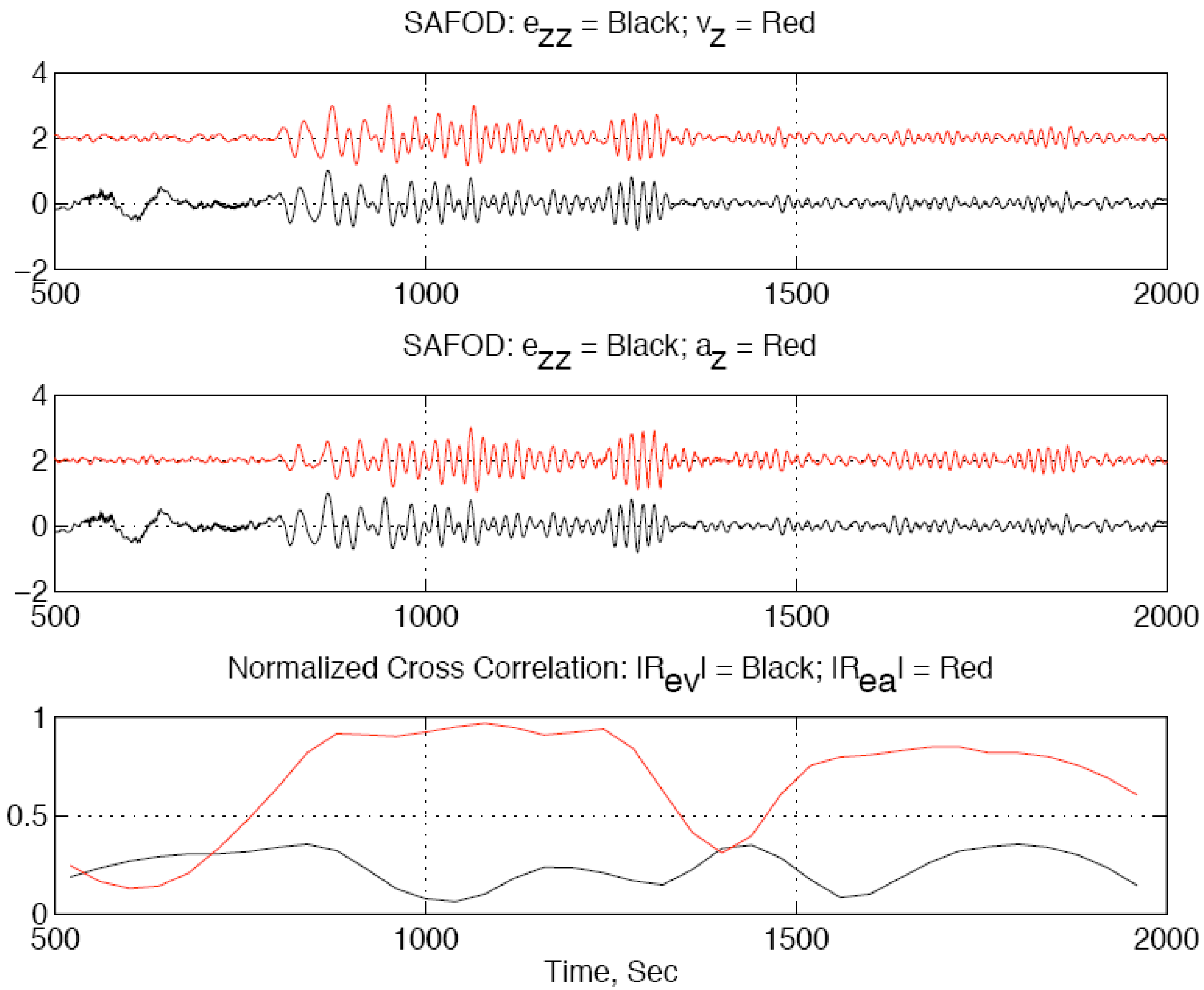


Figure 1: 2D synthetic seismic wave modeling using the PREM velocity model. The receiver is at an epicentral distance of 60°. **Top**: Normalized superposition of horizontal strain, e_{xx} or e_{rr} (black) in cylindrical coordinates, with horizontal velocity v_x, or $\frac{\partial u_r}{\partial t}$(red). **Bottom**: Normalized superposition of e_{xx} (black) with a_x (red).

Strain vs. translations
(velocity v, acceleration a)



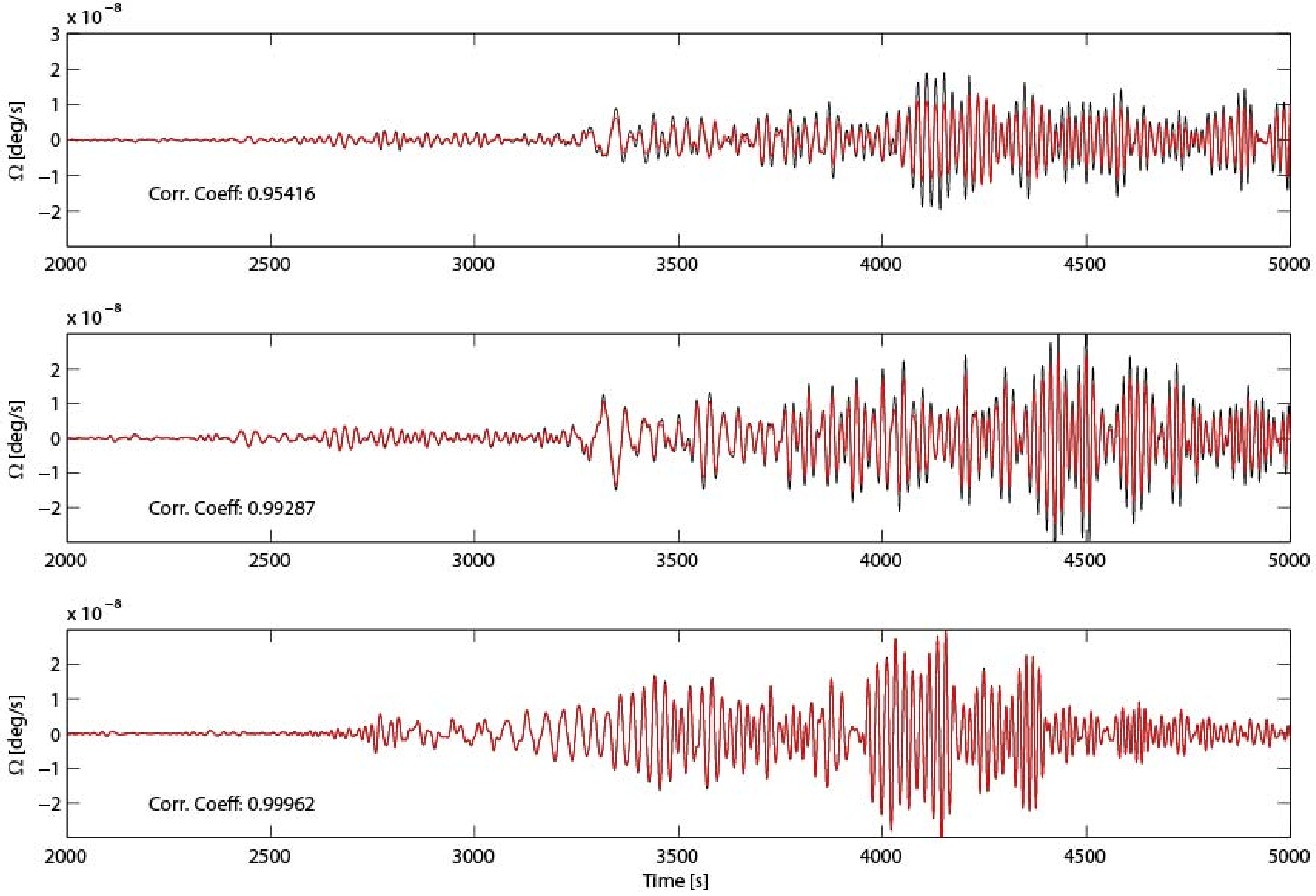
Tiltmeters

- Tiltmeters are designed to measure changes in the angle of the surface normal
- These changes are particularly important near volcanoes, or in structural engineering
- In the seismic frequency band tiltmeters are sensitive to transverse acceleration

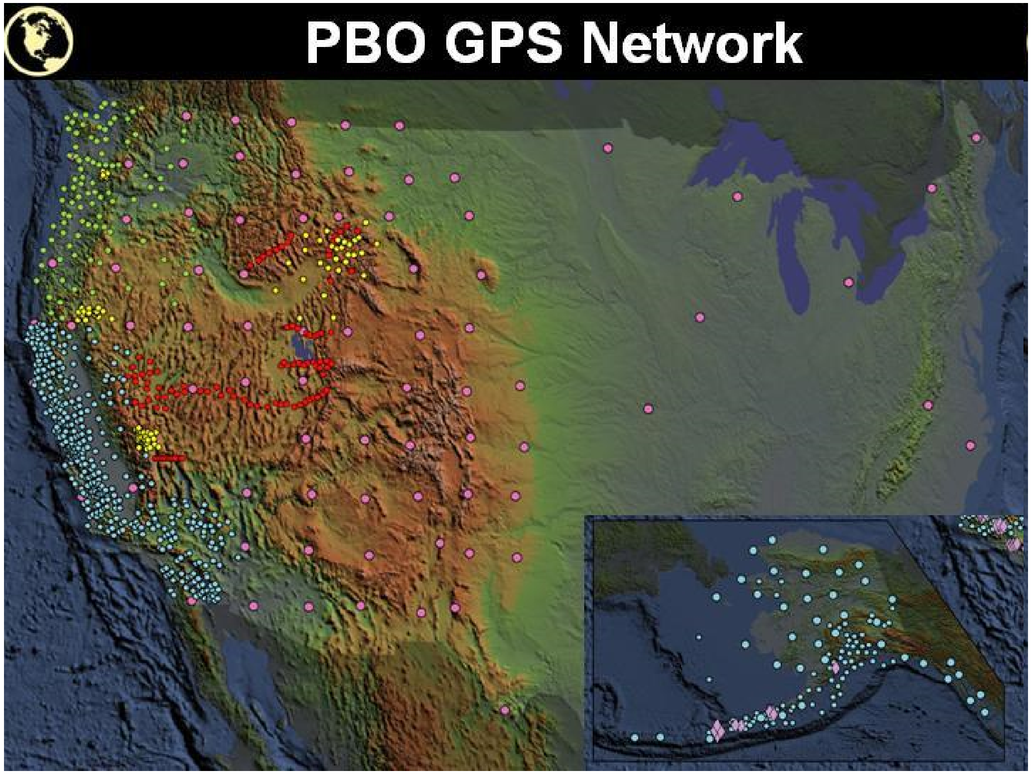
Source: USGS

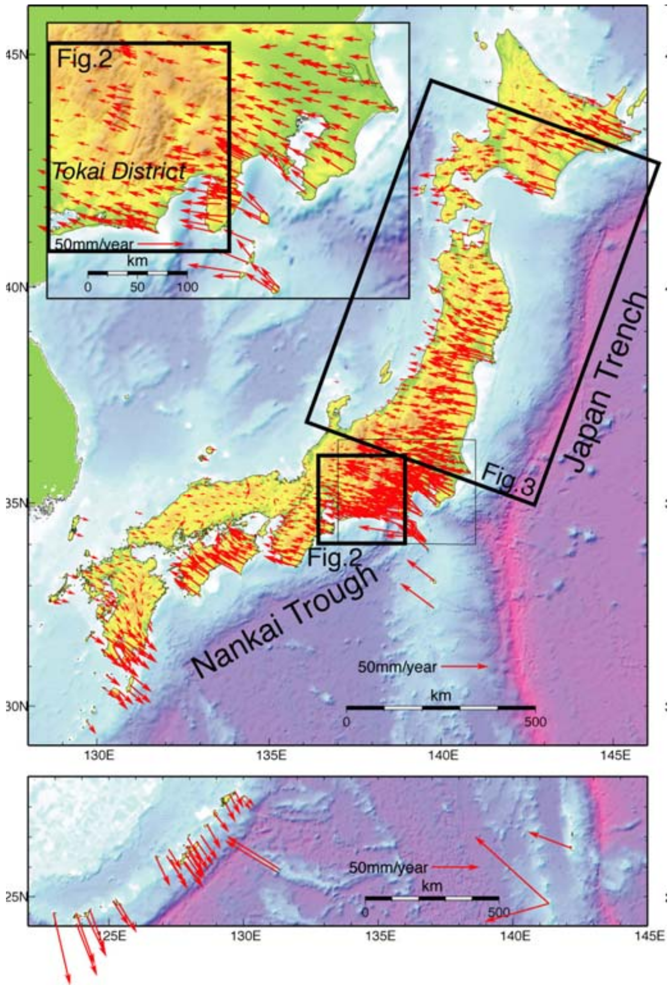
Tilt vs. horizontal **acceleration**

Earthquake recorded at Wettzell, Germany

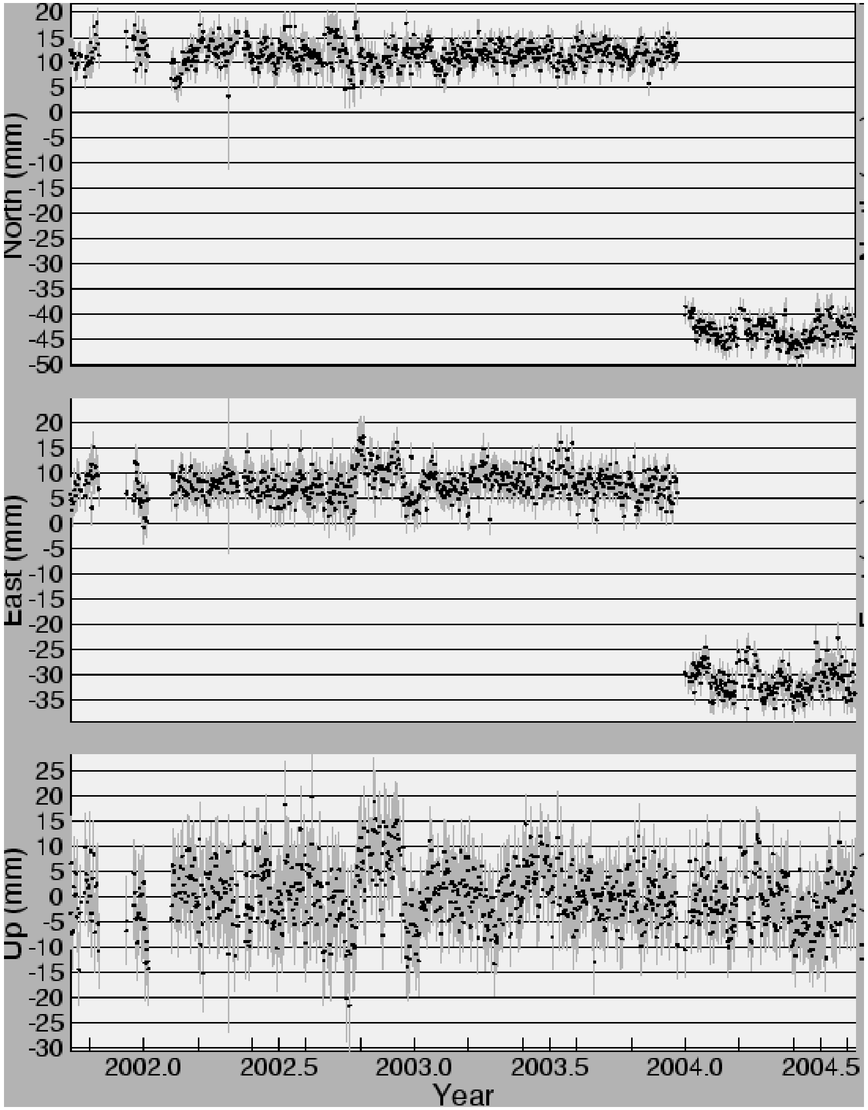


GPS Sensor Networks



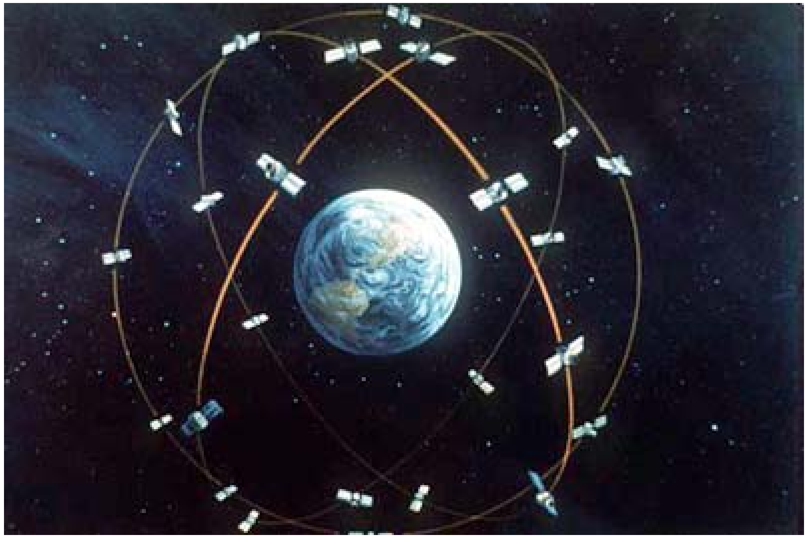


San Francisco GPS Network



Co-seismic displacement measured in California during an earthquake.

(Source: UC Berkeley



Ocean Bottom Seismometers

The OB Unit is equipped with a broadband *Güralp* seismometer and a Differential Pressure Gauge (from *Scripps Institution of Oceanography*). Additionally, it measures the absolute pressure with a *Paroscientific Intelligent Depth* sensor, manufactured by *DIGIQUARZ*.

Source: GFZ Potsdam

Source: USGS

Other sensors and curiosities

- Gravimeters
- Ground water level
- Electromagnetic measurements (ionosphere)
- Infrasound measurements

Summary

- Seismometers are forced oscillators, recorded seismograms have to be corrected for the instrument response
- Strains and rotations are usually measured with optical interferometry, the accuracy is lower than for standard seismometers
- The goal in seismology is to measure with one instrument a broad frequency and amplitude range (broadband instruments)
- Cross-axis sensitivity is an important current issue (translation – rotation – tilt)