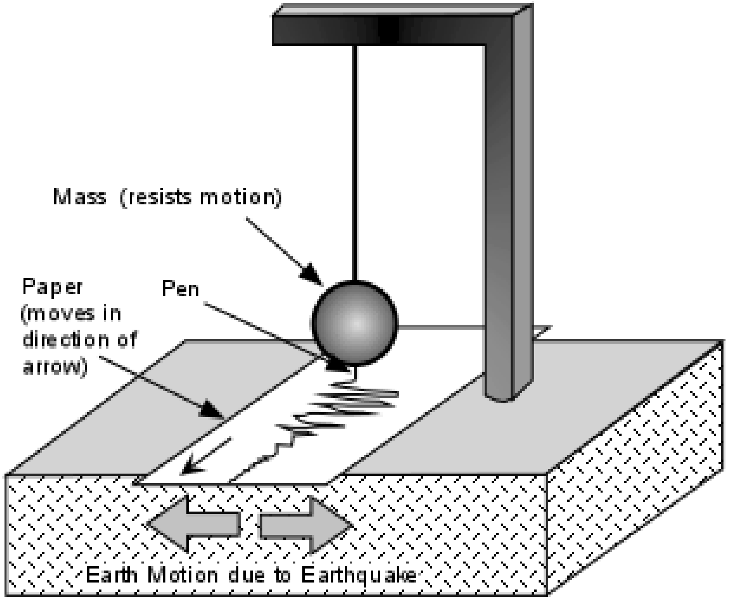
Overview of seismic instruments

Seismometer



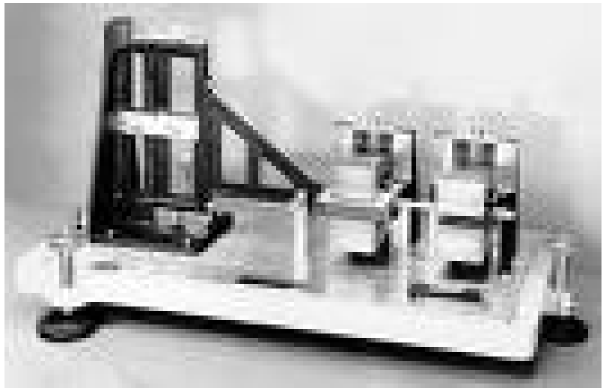
- A basic seismometer consists of a freely suspending mass from a frame attached to the ground.
- The relative motion of the frame with respect to the heavy mass is printed as a seismogram.

World’s First Seismograph

- The Chinese Ground Motion Meter, invented in 132 AD by the Chinese mathematician, Cheng Heng, was the world’s first seismograph.
- The eight wooden dragons each had a ball in its mouth. During an earthquake, a ball dropped from a dragon’s mouth into the frog’s mouth beneath it, indicating the direction of tremor.

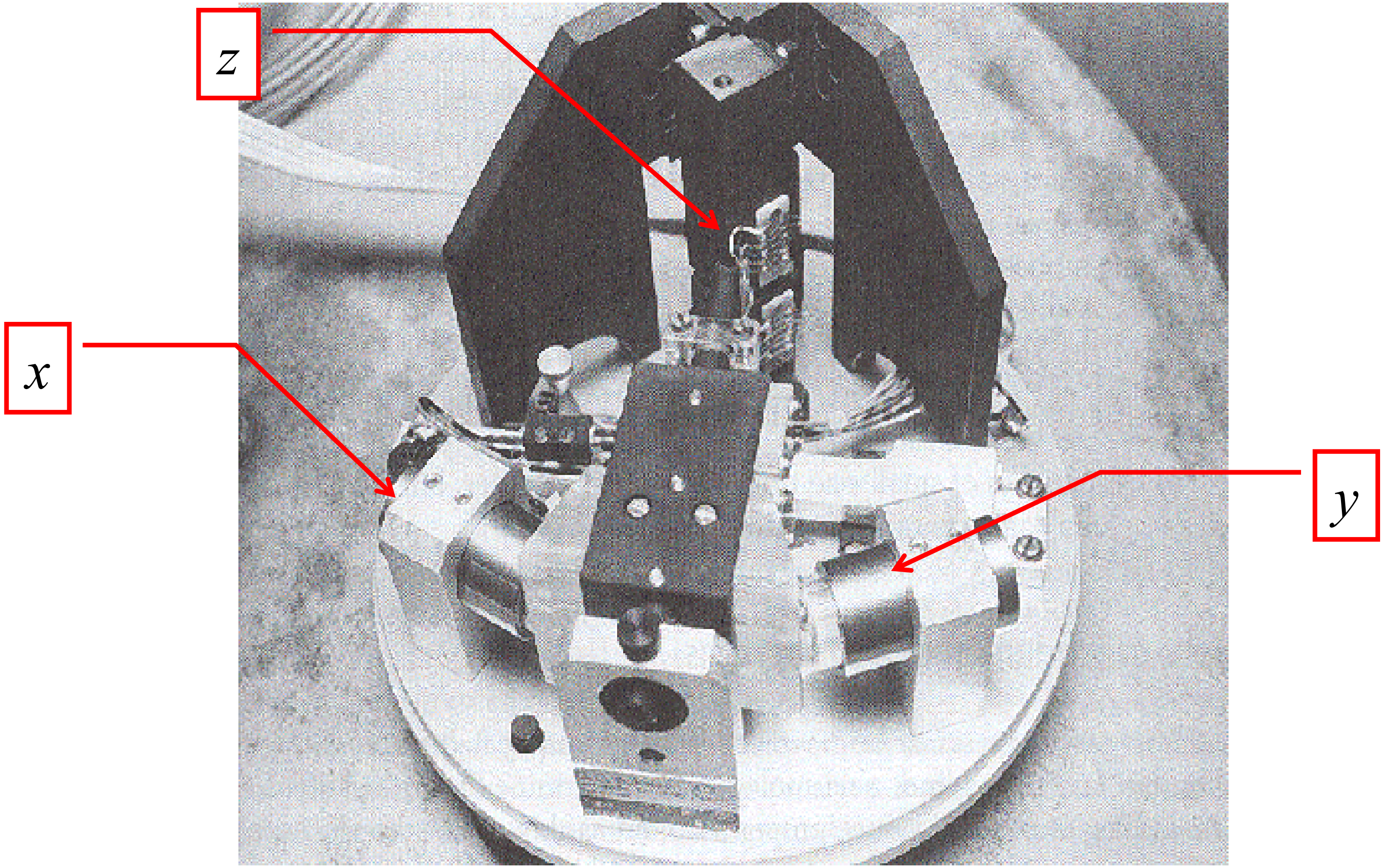
Components of motion

Vertical: Vertically suspended systems are sensitive to vertical ground motion.



Horizontal: Horizontally suspended systems are sensitive to horizontal component of ground motion perpendicular to pendulum axis

Modern (digital) seismometer

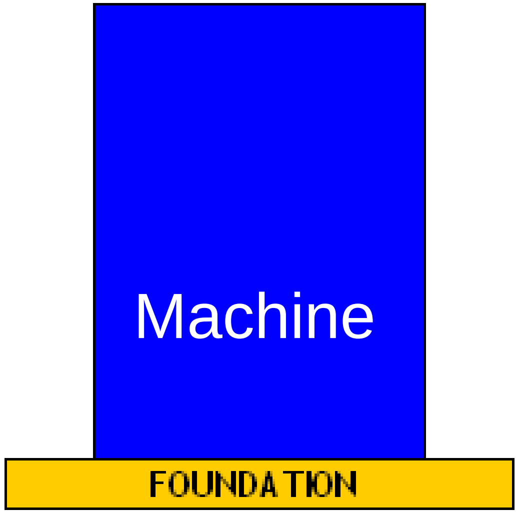


From Prof. B.A. Bolt, *Earthquakes*. W.H.Freeman, ISBN 071673396x

Vibration Components

- **Acceleration, Velocity and Displacement** Amplitudes are related by a function of frequency and time for sinusoidal excitations
- Acceleration is the most commonly measure component
- Acceleration is used to compute the Spectrum response due to a known force input

Theory of Vibration measuring instruments



The dynamic forces in a vibratory systems depend on the displacement, velocity and acceleration components of a system

Spring force $\propto$ displacement

Damping force $\propto$ velocity

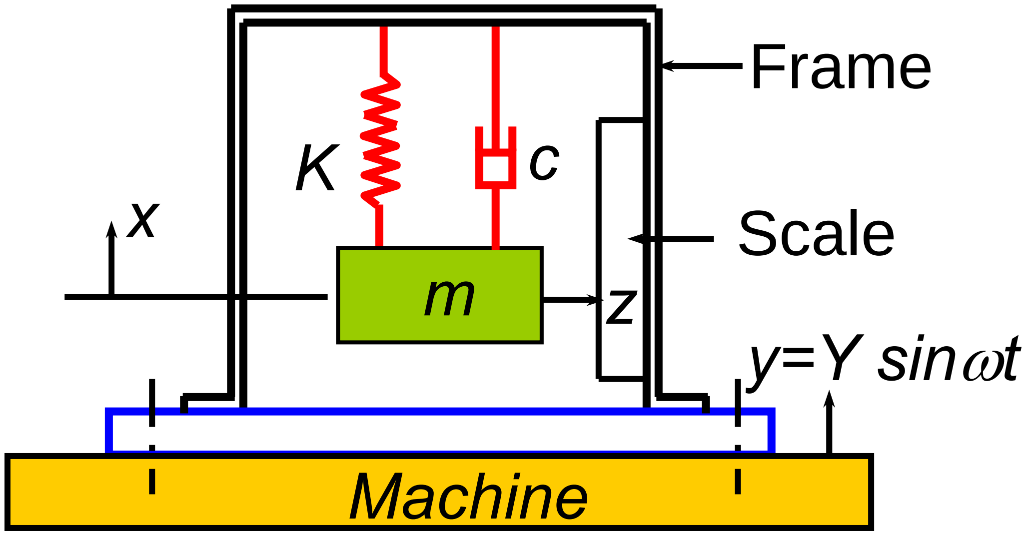
Inertia force $\propto$ acceleration

Therefore, In vibration analysis of a mechanical system, it is required to measure the displacement, velocity and acceleration components of a system

An instrument, which is used to measure these parameters, is referred as vibration measuring instrument or seismic instrument

The major requirement of a seismic instrument is to indicate an output, which represents an input such as the displacement amplitude, velocity or acceleration of a vibrating system as close as possible.

Model



m-seismic mass

c-damping coefficient of seismic unit

K-stiffness of spring used in seismic unit

x-absolute displacement of seismic mass

y-base excitation (assume SHM)

$z=(x-y)$ displacement of seismic mass relative to frame

Frequencies and Periods

- The frequency of vibration that stimulates the strongest response is called the natural frequency of the sensor (in terms of spring constant and mass):
- The natural frequency is the reciprocal of natural period of the instrument
- With a combination of damping and choice of mass and spring constant, the resonant period can be adjusted and the response made to be approximately constant over some range of frequencies.

$$\text{Natural Circular Frequency, } \omega_n = \sqrt{\frac{k}{m}};$$

$$\text{Natural Frequency, } f_n = \frac{\omega_n}{2\pi};$$

$$\text{Natural Period, } T_n = \frac{1}{f_n}$$

Mathematical Formulations For Single Degree of Freedom Dynamic System

Equation of motion of the seismic mass:

$$m\ddot{x} + c(\dot{x} - \dot{y}) + K(x - y) = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Let, relative displacement of seismic mass is *z*=(*x*-*y*)

$$m\ddot{z} + c\dot{z} + Kz = -m\ddot{y} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

consider base excitation to be Simple Harmonic Motion

$$y(t) = Y\, sin\ \omega t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

$$m\ddot{z} + c\dot{z} + Kz = m\omega^2 Y \sin \omega t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

The above equation represents a equation of motion of a forced vibration with $m\omega^2 Y = F$

The governing equation of motion of the system is:

$$m\ddot{z} + c\dot{z} + Kz = F\sin\omega t \quad \text{......................................}(4)$$

Solution of governing differential equation

$$z(t) = z_c(t) + z_p(t)$$

Transient solution Steady state solution

$$\text{...}(5)$$

Let, z(*t*), the steady state solution of equation of motion is:

$$z(t) = Z\sin(\omega t - \phi) \quad \text{...}(6)$$

Eqn.(6) has to satisfy Eqn.(4)

$$z(t) = Z\sin(\omega t - \phi)$$

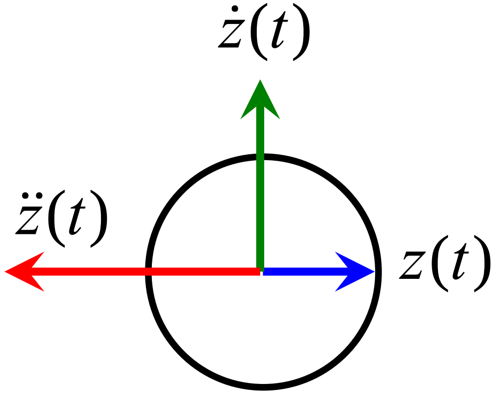
Displacement

Differentiating

$$\dot{z}(t) = \omega Z\cos(\omega t - \phi)$$

$$\dot{z}(t) = \omega Z\sin(\omega t - \phi + \frac{\pi}{2})$$

Velocity



$$\ddot{z}(t) = -\omega^2 Z\sin(\omega t - \phi)$$

$$\ddot{z}(t) = \omega^2 Z\sin(\omega t - \phi + \pi)$$

Acceleration

$$m\ddot{z} + c\dot{z} + Kz = F\sin\omega t$$

$$m\omega^2 Z\sin(\omega t-\phi+\pi)+c\omega Z\sin(\omega t-\phi+\frac{\pi}{2})$$

$$+KZ\sin(\omega t-\phi)=F\sin\omega t \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

Rearrange with respect to phase angle

$$\mathrm{F}\sin\omega t-\mathrm{KZ}\sin(\omega t-\phi)-c\omega\mathrm{Z}\sin(\omega t-\phi+\frac{\pi}{2})-m\omega^2\mathrm{Z}\sin(\omega t-\phi+\pi)=0$$

Impressed force Spring force Damping force Inertia force

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

$$\left(KZ-m\omega^2 Z\right)^2+\left(c\omega Z\right)^2=F^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

$$Z^2\left[\left(K-m\omega^2\right)^2+(c\omega)^2\right]=F^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(10)$$

$$Z=\frac{m\omega^2 Y}{\sqrt{\left(K-m\omega^2\right)^2+\left(c\omega\right)^2}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(11)$$

divide the above Eqn. by *K*

$$Z=\frac{\dfrac{m\omega^2 Y}{K}}{\sqrt{\left(1-\dfrac{m\omega^2}{K}\right)^2+\left(\dfrac{c\omega}{K}\right)^2}} \quad \text{.............................(12)}$$

$$Z=\frac{r^2Y}{\sqrt{(1-r^2)^2+(2\xi r)^2}} \quad \text{....................................(13)}$$

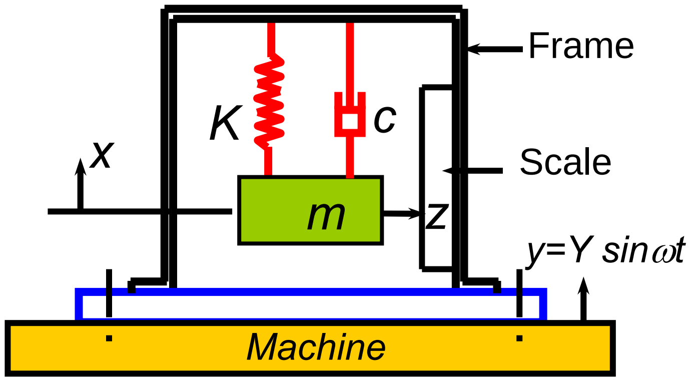
$$z(t)=\frac{r^2Y}{\sqrt{(1-r^2)^2+(2\xi r)^2}}\sin(\omega t-\phi) \quad \text{......................(14)}$$

the phase angle (from force diagram) is:

$$\phi=\tan^{-1}\left[\frac{c\omega}{K-m\omega^2}\right] \quad \text{OR} \quad \phi=\tan^{-1}\left(\frac{2\xi r}{1-r^2}\right) \quad \text{.......(15)}$$

$$\frac{Z}{Y}=\frac{r^2}{\sqrt{(1-r^2)^2+(2\xi r)^2}} \quad \text{...(16)}$$

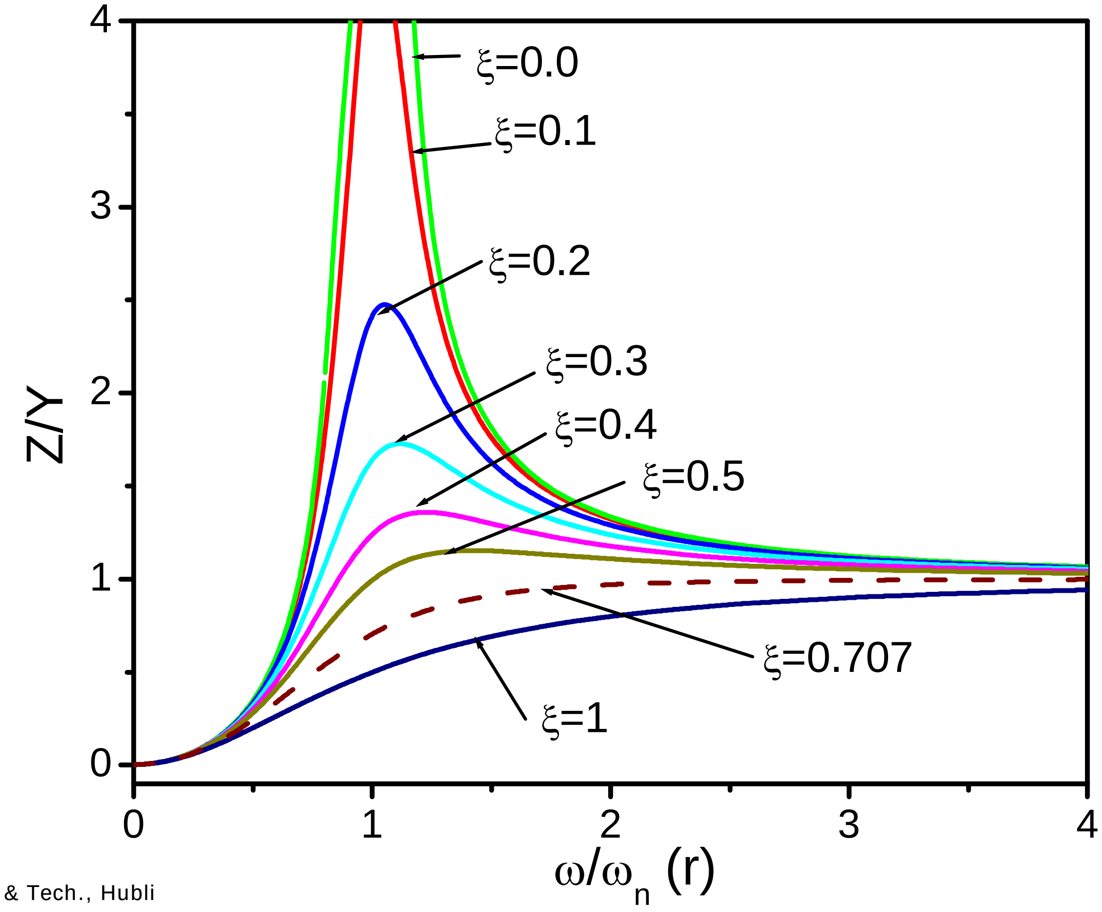
Dynamic Response Curves

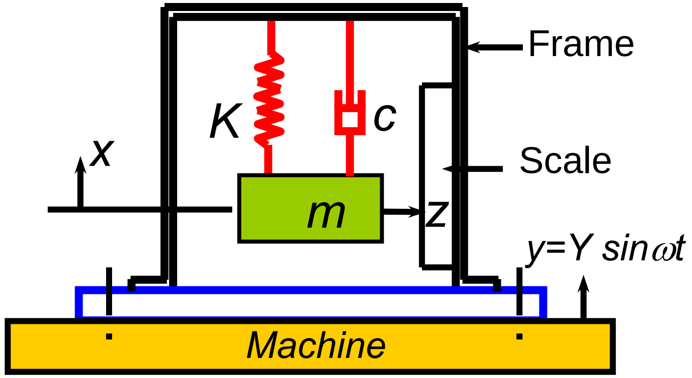


$$\frac{Z}{Y}=\frac{r^2}{\sqrt{(1-r^2)^2+(2\xi r)^2}}$$

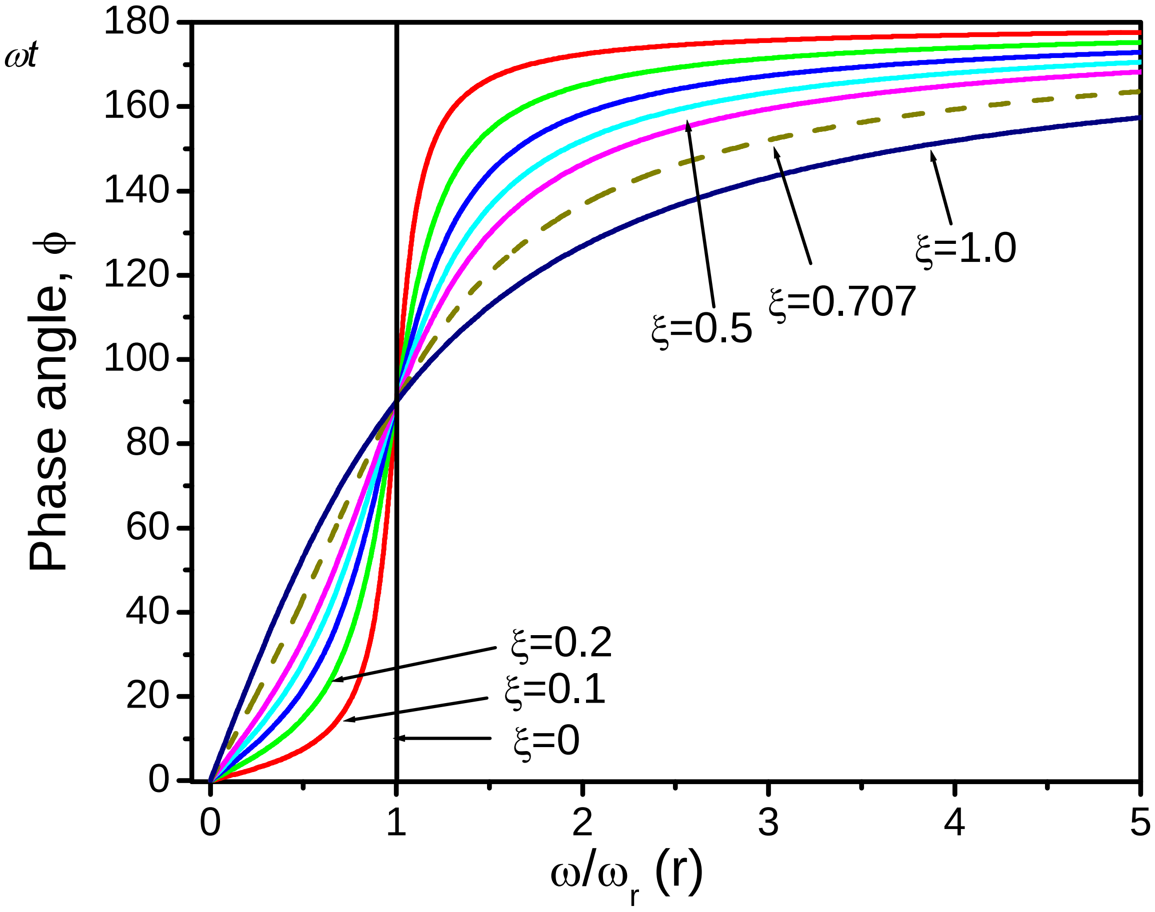
ξ is damping Ratio

r is frequency Ratio





$$\phi = \tan^{-1}\left(\frac{2\xi r}{1-r^{2}}\right)$$



Displacement measuring instrument (Vibrometer)

It is an instrument used to measure the displacement of a vibrating system

The seismic response is: $$z(t)=\frac{r^2Y}{\sqrt{(1-r^2)^2+(2\xi r)^2}}\sin(\omega t-\phi)$$

In above Equation, if $$\frac{r^2}{\sqrt{(1-r^2)^2+(2\xi r)^2}}\cong 1$$

Then $$z(t)=Y\sin(\omega t-\phi)$$

machine excitation is: $y(t) = Y\,sin\;\omega t$

Displacement measuring instrument (Vibrometer)

Condition for Vibrometer

$$\frac{r^2}{\sqrt{(1-r^2)^2+(2\xi r)^2}} \cong 1$$

To satisfy the above equation the frequency ratio, *r*, must be large, *i.e* natural frequency of vibrometer must be low compared to that of vibration to be measured.

i.e $\omega_n = (K/m)^{1/2}$ must be low, it can be achieved by higher mass and lower stiffness of the spring. This condition results in bulky instrument.

Velocity measuring instrument (Velometer)

It is an instrument used to measure the velocity of a vibrating system

Displacement of the machine vibration is:

$$y(t) = Y\, sin\ \omega t \quad \text{.........}(19)$$

Velocity component of machine vibration is:

$$\dot{y}(t) = \omega Y \cos \omega t \quad \text{.......}(20)$$

Velocity measuring instrument (Velometer)

The seismic response is:

$$z(t) = \frac{r^2 Y}{\sqrt{(1-r^2)^2 + (2\xi r)^2}} \sin(\omega t - \phi)$$

velocity component of the seismic response is:

$$\dot{z}(t) = \frac{r^2 \omega Y}{\sqrt{(1-r^2)^2 + (2\xi r)^2}} \cos(\omega t - \phi) \quad \text{.................. ....}(21)$$

velocity component of the machine vibration is:

$$\dot{y}(t) = \omega Y \cos \omega t$$

Velocity measuring instrument (Velometer)

Condition for Velometer

$$\frac{r^2}{\sqrt{(1-r^2)^2+(2\xi r)^2}} \cong 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (22)$$

Then $\dot{z}(t) = \dot{y}(t)$ With some phase lag ϕ

$$\dot{z}(t) = \omega . z(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (23)$$

The seismic instrument can be calibrated so that the record directly gives value of velocity of base excitation

Acceleration measuring instrument (Accelerometer)

It is an instrument used to measure the acceleration of a vibrating system

Displacement of the machine vibration is:

$$y(t) = Y\,sin\ \omega t$$

Velocity component of machine vibration is:

$$\dot{y}(t) = \omega Y \cos \omega t$$

Acceleration component of machine vibration is:

$$\ddot{y}(t) = -\omega^2 Y \sin \omega t$$

Acceleration measuring instrument (Accelerometer)

The seismic response is: $z(t) = Z\sin(\omega t - \phi)$

where $$Z = \frac{r^2 Y}{\sqrt{(1-r^2)^2 + (2\xi r)^2}}$$

Acceleration component of the response is:

$$\ddot{z}(t) = -Z\omega^2 \sin(\omega t - \phi)$$

$$\ddot{z}(t) = -\omega^2 z(t)$$

Acceleration measuring instrument (Accelerometer)

$$-z(t)\omega^2=\frac{r^2}{\sqrt{(1-r^2)^2+(2\xi r)^2}}(-Y\omega^2\sin(\omega t-\phi)) \qquad \text{............}(24)$$

$$-z(t)\frac{\omega^2}{r^2}=\frac{1}{\sqrt{(1-r^2)^2+(2\xi r)^2}}(-Y\omega^2\sin(\omega t-\phi)) \qquad \text{............}(25)$$

$$-z(t)\omega_n^2=\frac{1}{\sqrt{(1-r^2)^2+(2\xi r)^2}}(-Y\omega^2\sin(\omega t-\phi)) \qquad \text{............}(26)$$

Acceleration measuring instrument (Accelerometer)

Condition for Accelerometer

If $$\frac{1}{\sqrt{(1-r^2)^2+(2\xi r)^2}} \cong 1 \qquad \text{..................................(27)}$$

Then, $$\ddot{z}(t) = -z(t)\omega_n^2 = -Y\omega^2 \sin(\omega t - \phi) \qquad \text{...............(28)}$$

Acceleration of the machine is:

$$\ddot{y}(t) = -Y\omega^2 \sin \omega t \qquad \text{..(29)}$$

$-z(t)\omega_n^2$ =acceleration of the base with phase lag ϕ

The seismic instrument can be calibrated so that the record directly gives value of acceleration of base excitation

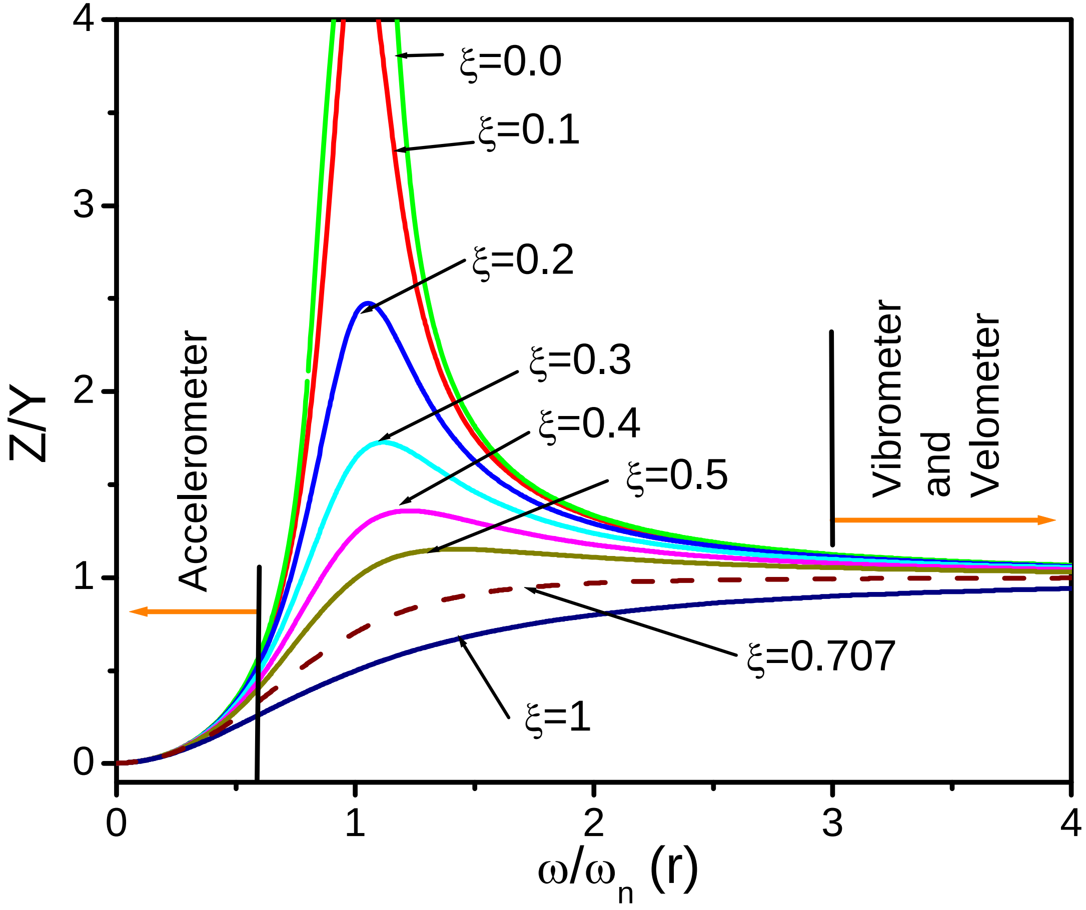
Acceleration measuring instrument (Accelerometer)

For accelerometer, the frequency ratio, *r*, must be very small between 0-0.6

Since, *r* is small for accelerometer, the natural frequency of vibration should be high compared to the frequency of vibration of base.

As $\omega_n = \sqrt{K/m}$, for condition to be satisfied seismic mass should be small and spring stiffness should be high. This indicates this instrument will be small in size

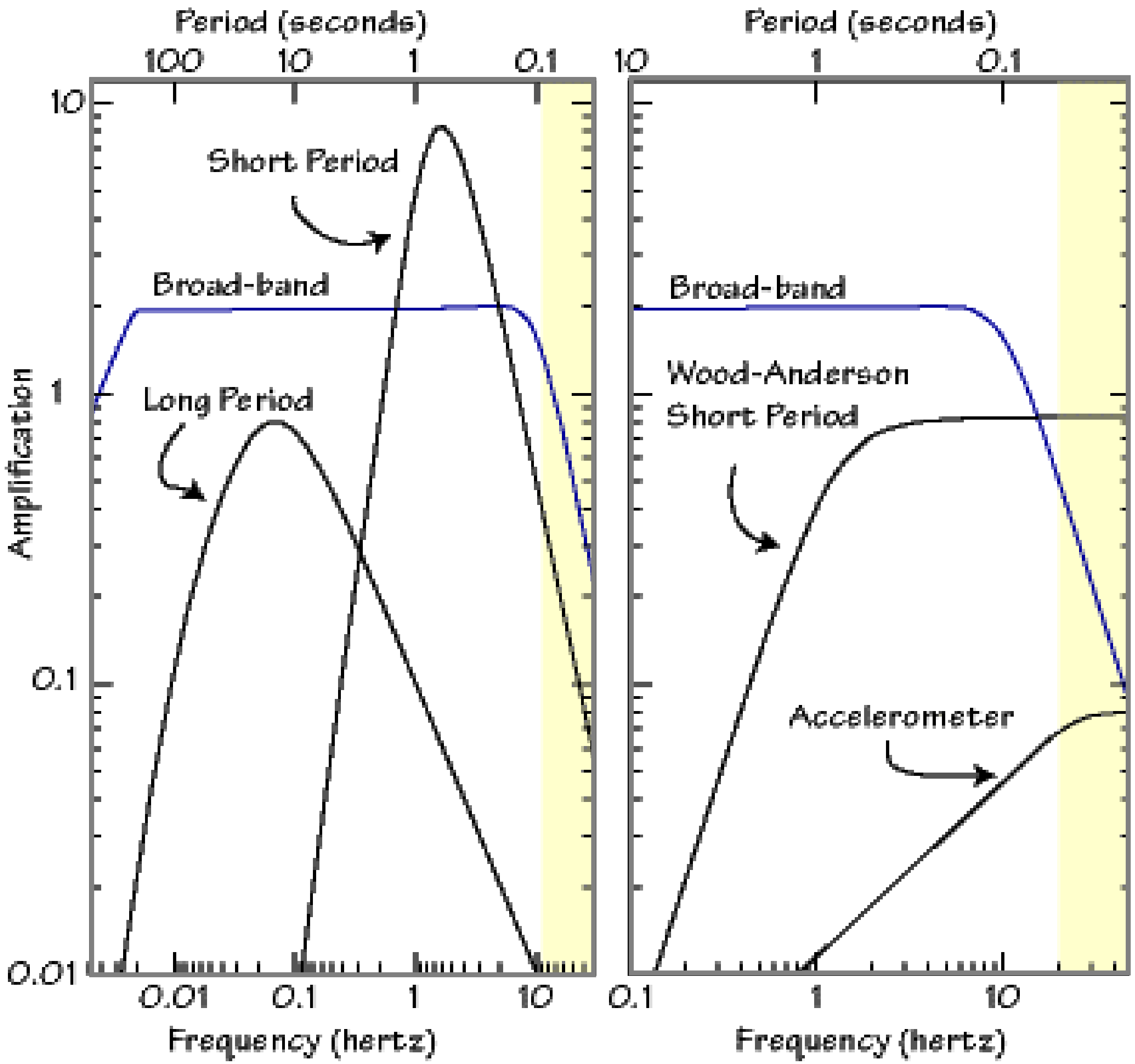
Seismic instrument



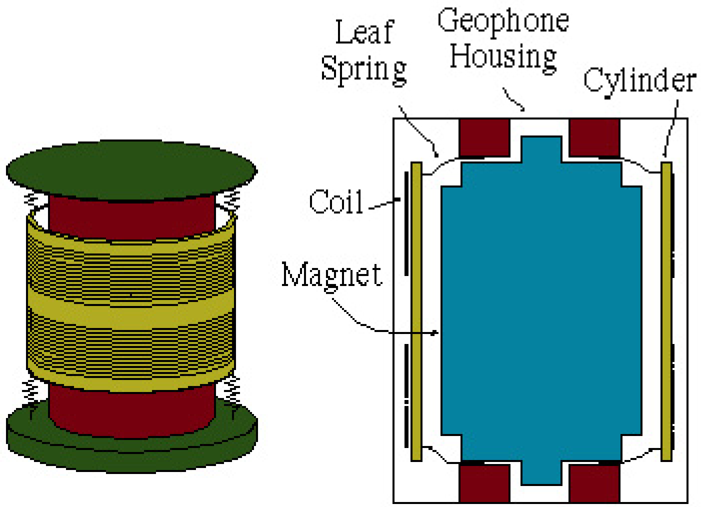
$$\xi = \frac{1}{\sqrt{2}} = 0.707$$

Is more suited for seismic instruments

Range of Sensitivity of Seismometers

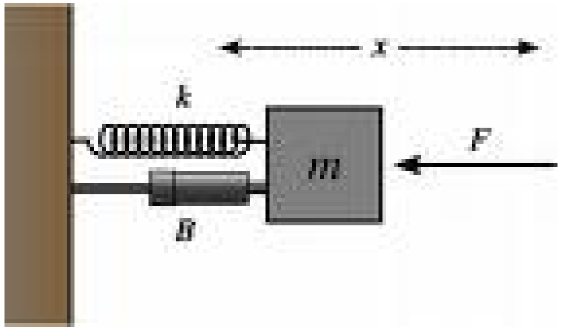


- Trend is to use more broad band sensors (BB), even when overkill, however BB sensors now have a similar price as 1 Hz sensors
- 1 Hz sensors will go out except when used with feedback technique
- FBA based sensors will probably dominate the market in the future

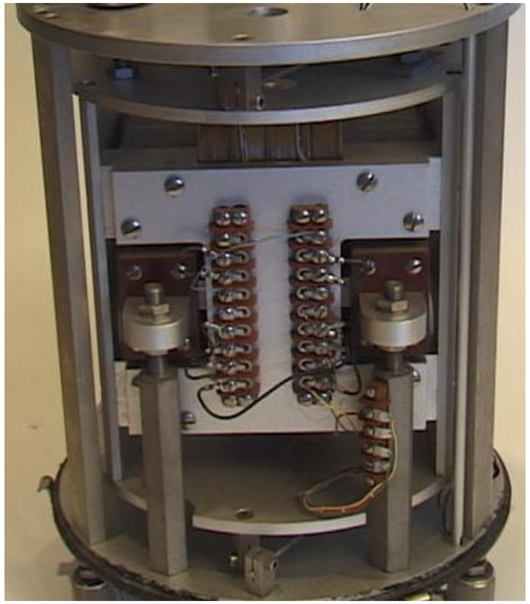


Typical geophone

Damping



Damping mechanism is typically displayed as a ‘dashpot’ in the mass-spring schematic. A dashpot is what is in the shock absorber on your car – piston with fluid pushed through a small hole.



- Resistive damping is used in most moving coil seismometers.
- A voltage is generated due to the motion of the main signal coil.
- This voltage induces a current in the resistors connected in parallel with it to dissipate the energy of the motion by heating the resistor and thus damp it.

Seismometer Sensitivity

- In the basic spring-mass system, the sensitivity of the instrument is greatest for a weak spring (giving a greater stretch for a given acceleration), but this means the instrument must be larger in dimension, because the mass is hanging in the gravity field, stretching the weak spring.
- How do we get around the design problem caused by this reliance on natural frequency?
- Modern seismometers use a ‘feedback’ system, applying electrical force to keep the mass centered, and keeping track of the required force. This allows for high sensitivity, constant response over a large frequency range, and large dynamic range (able to sense small and large shaking).

Before:

-Seismographs were specially made

-Few standard components were used

- Very specialized software

Now:

-Stations and networks are mainly made with standard industrial components

-Digital technology used throughout

-More standardized software

-Sensors currently the most specialized element

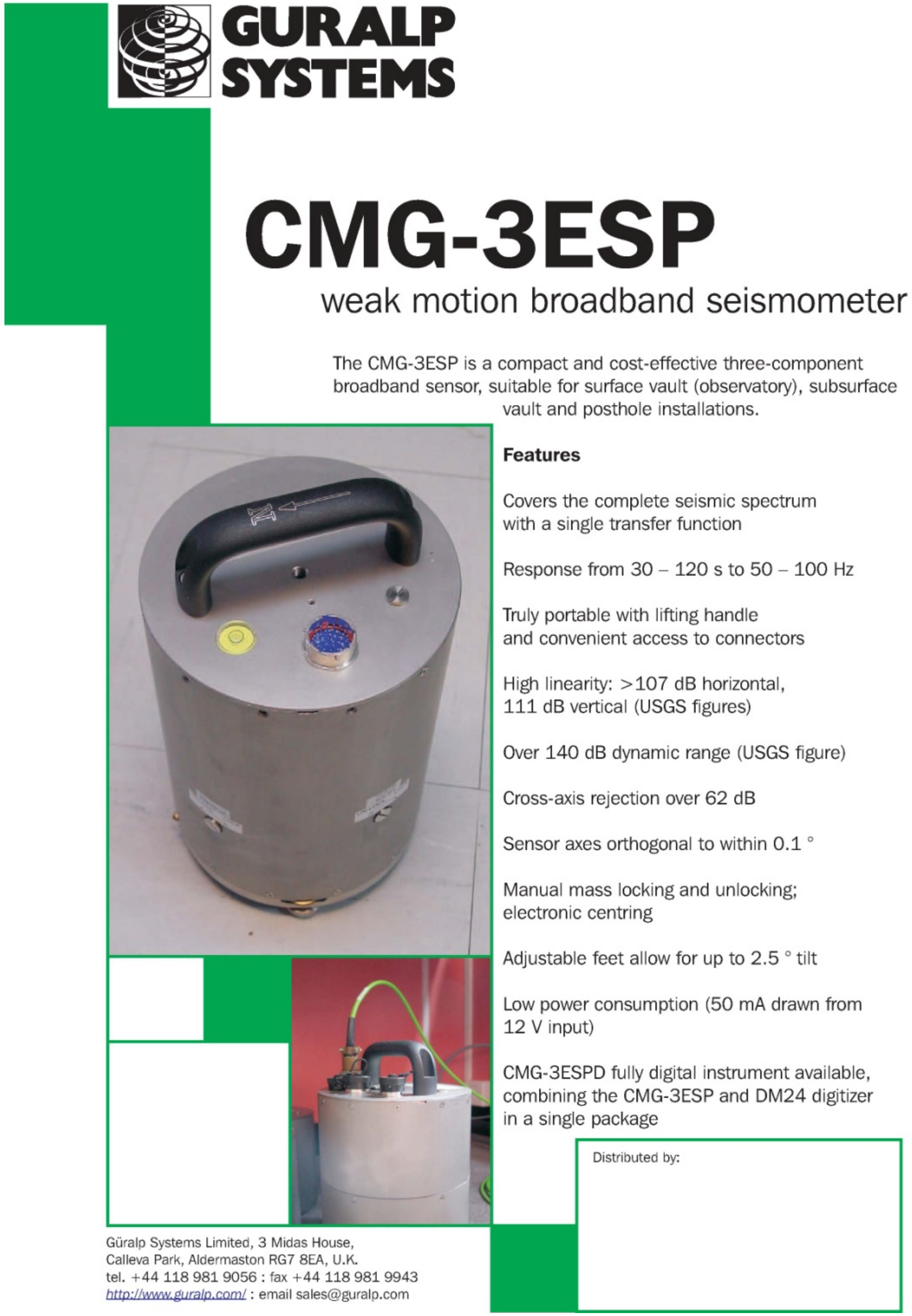
-Now possible to build a seismic station with mainly off the shelf products

Modern Equipment

Modern instruments are light-weight and portable.

Many are also set up in permanent arrays

This instrument is ‘broadband’. What does that mean? Why do we want instruments that can record ‘broadband’ data?



GURALP SYSTEMS

CMG-3ESP

weak motion broadband seismometer

The CMG-3ESP is a compact and cost-effective three-component broadband sensor, suitable for surface vault (observatory), subsurface vault and posthole installations.

Features

Covers the complete seismic spectrum with a single transfer function

Response from 30 – 120 s to 50 – 100 Hz

Truly portable with lifting handle and convenient access to connectors

High linearity: >107 dB horizontal, 111 dB vertical (USGS figures)

Over 140 dB dynamic range (USGS figure)

Cross-axis rejection over 62 dB

Sensor axes orthogonal to within 0.1 °

Manual mass locking and unlocking; electronic centring

Adjustable feet allow for up to 2.5 ° tilt

Low power consumption (50 mA drawn from 12 V input)

CMG-3ESPD fully digital instrument available, combining the CMG-3ESP and DM24 digitizer in a single package

Distributed by:

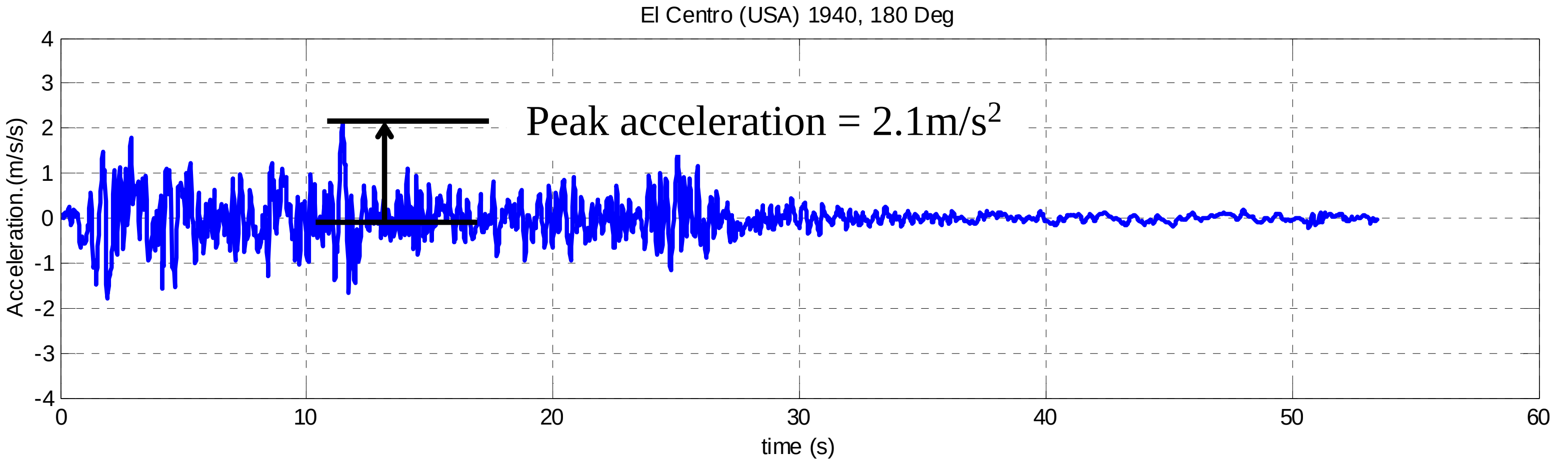
Güralp Systems Limited, 3 Midas House,
Calleva Park, Aldermaston RG7 8EA, U.K.
tel. +44 118 981 9056 : fax +44 118 981 9943
http://www.guralp.com/ : email sales@guralp.com

Strong-motion Seismometers (accelerometers)

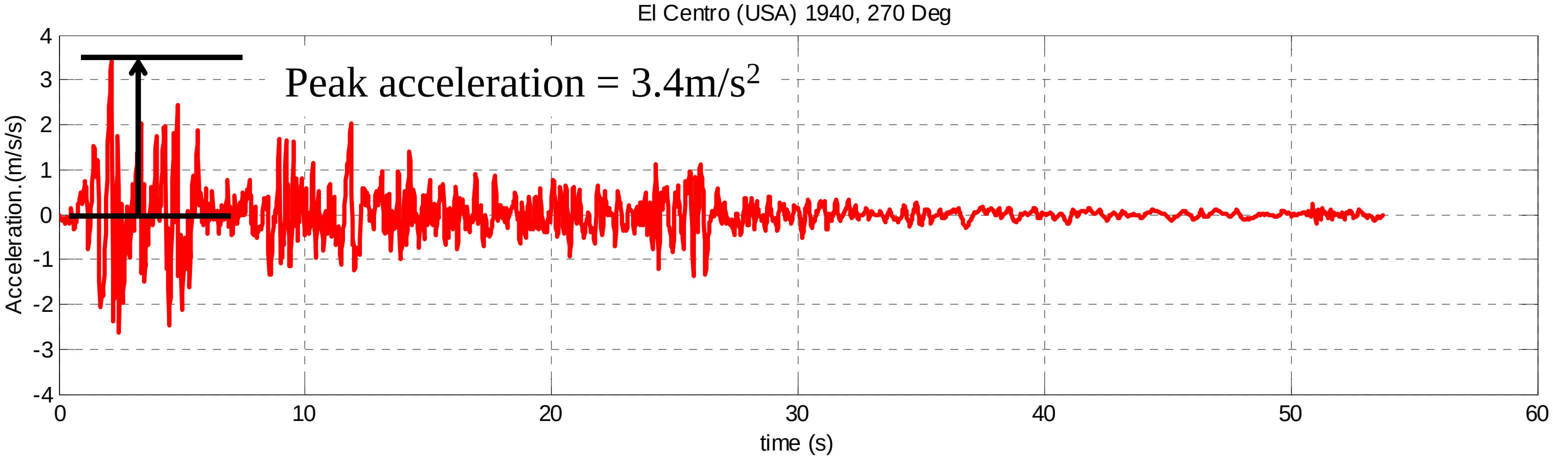
Strong-motion Seismometers (accelerometers)

- Developed for recording large amplitude vibrations that are common within a few tens of kilometres of large earthquakes
- typical frequency range 0-25Hz, sampled at 200Hz.
- Many instruments are actually analogue and hence they need careful processing (correction) of accelerations recorded.

El-Centro Accelerograms (horizontal)


El Centro (USA) 1940, 180 Deg

Peak acceleration = 2.1m/s^2

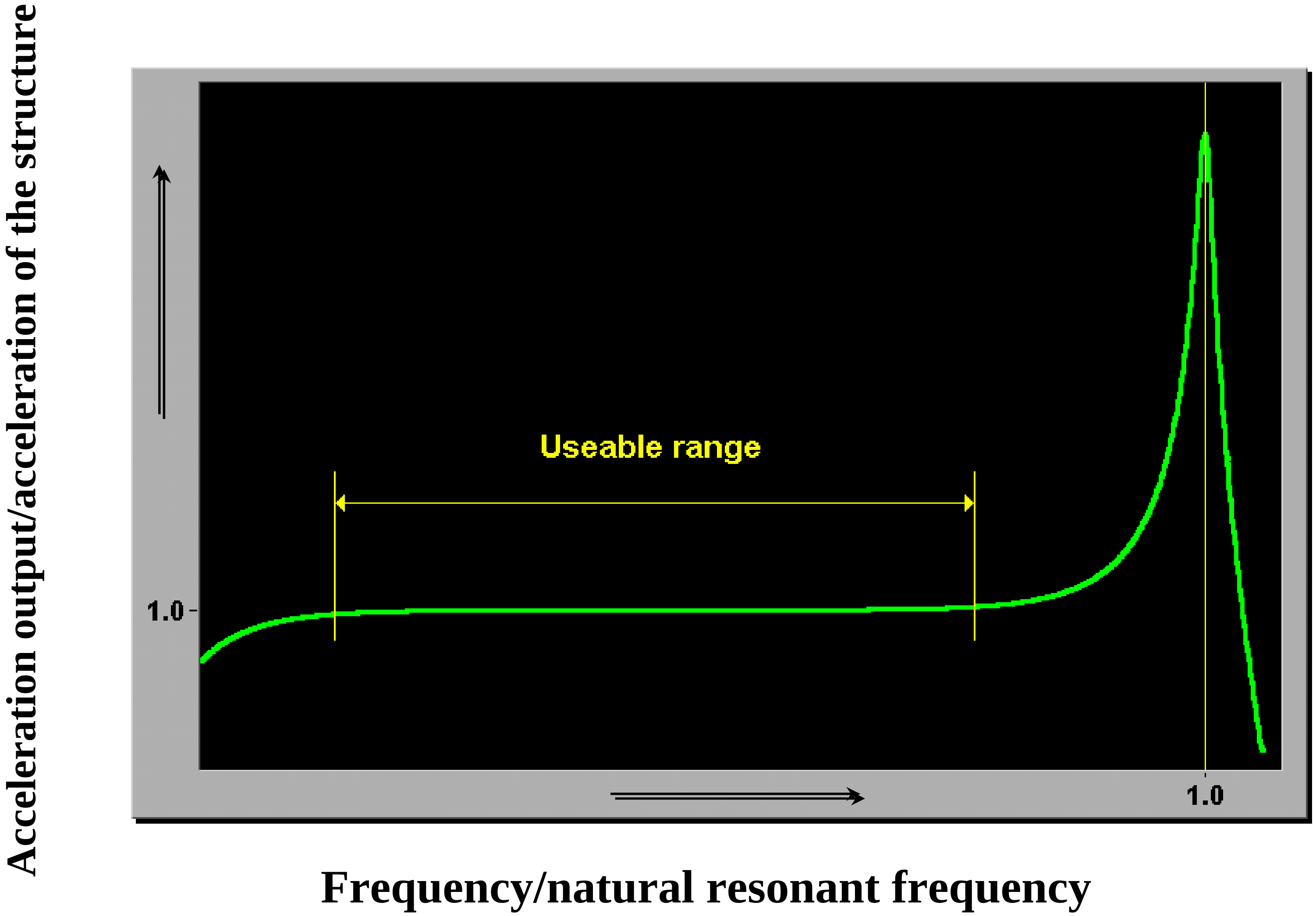

El Centro (USA) 1940, 270 Deg

Peak acceleration = 3.4m/s^2

Accelerometers

- Measure
  - Acceleration
  - Velocity and displacement (via integration versus time)
- Result is expressed in m/s^2 or g
  - 1g : acceleration at the surface of Earth
  - $1g = 9.81\ m/s^2$
- 1D or 3D (triaxial) accelerometers
- Calibration is performed with a vibration shaker

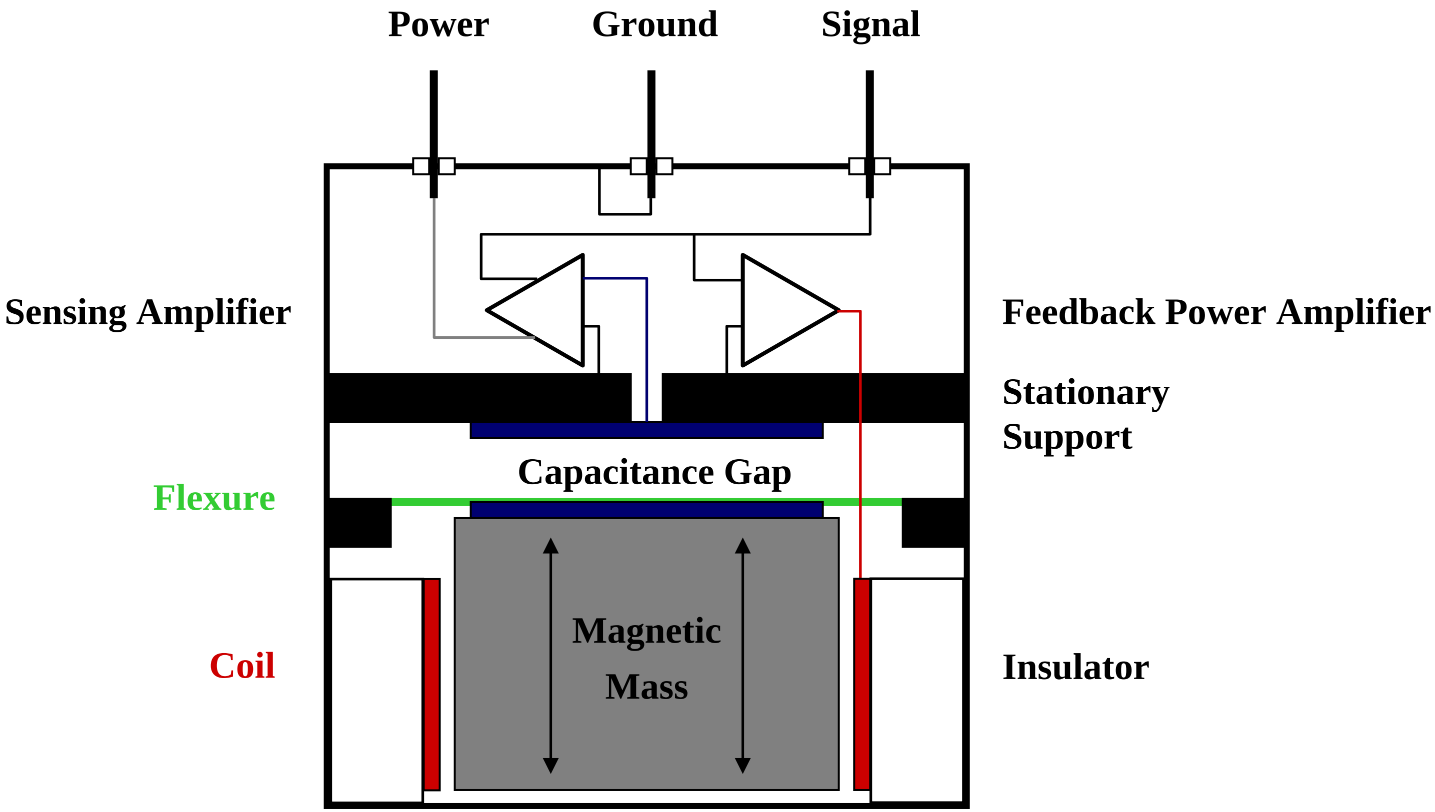
Typical Frequency Response



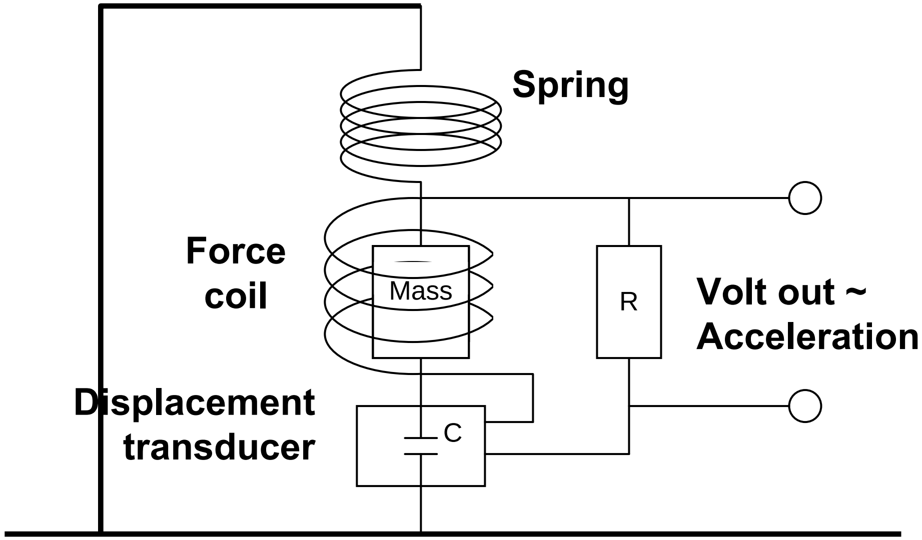
Common Accelerometer Types

- Servo or Force Balance
- Micro Electro Mechanical Systems (MEMS)
- Resistive
- Capacitive
- Fiber Optic
- Vibrating Quartz
- Piezoelectric

- Servo or Force Balance Operating Principle
  - Feedback force required to maintain uniform capacitance is proportional to acceleration



Principle of Force Balanced Accelerometer



The displacement transducer normally uses a capacitor *C*, whose capacitance varies with the displacement of the mass. A current, proportional to the displacement transducer output, will force the mass to remain stationary relative to the frame.

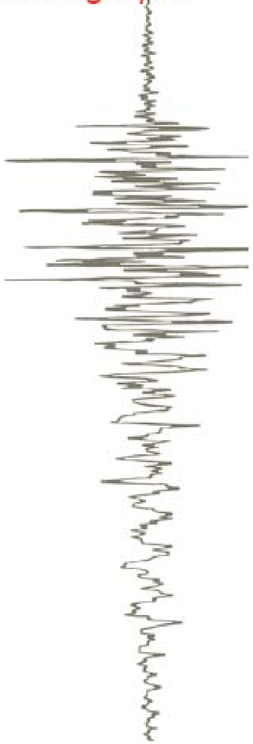
The FBA can have the digitizer integrated in feedback loop

- Force Balance / Vibrating Quartz
  - *Typical* Characteristics
    - Measure down to 0 Hz (DC response)
    - Wide dynamic range (>120 dB = 1,000,000:1)
    - Extremely stable over time and temperature (ppm)
    - Limited high frequency range (<1 kHz)
    - Poor overload survivability (<100 g’s)
    - Force balance may exhibit large magnetic sensitivity
    - Very expensive (~$1000 USD)

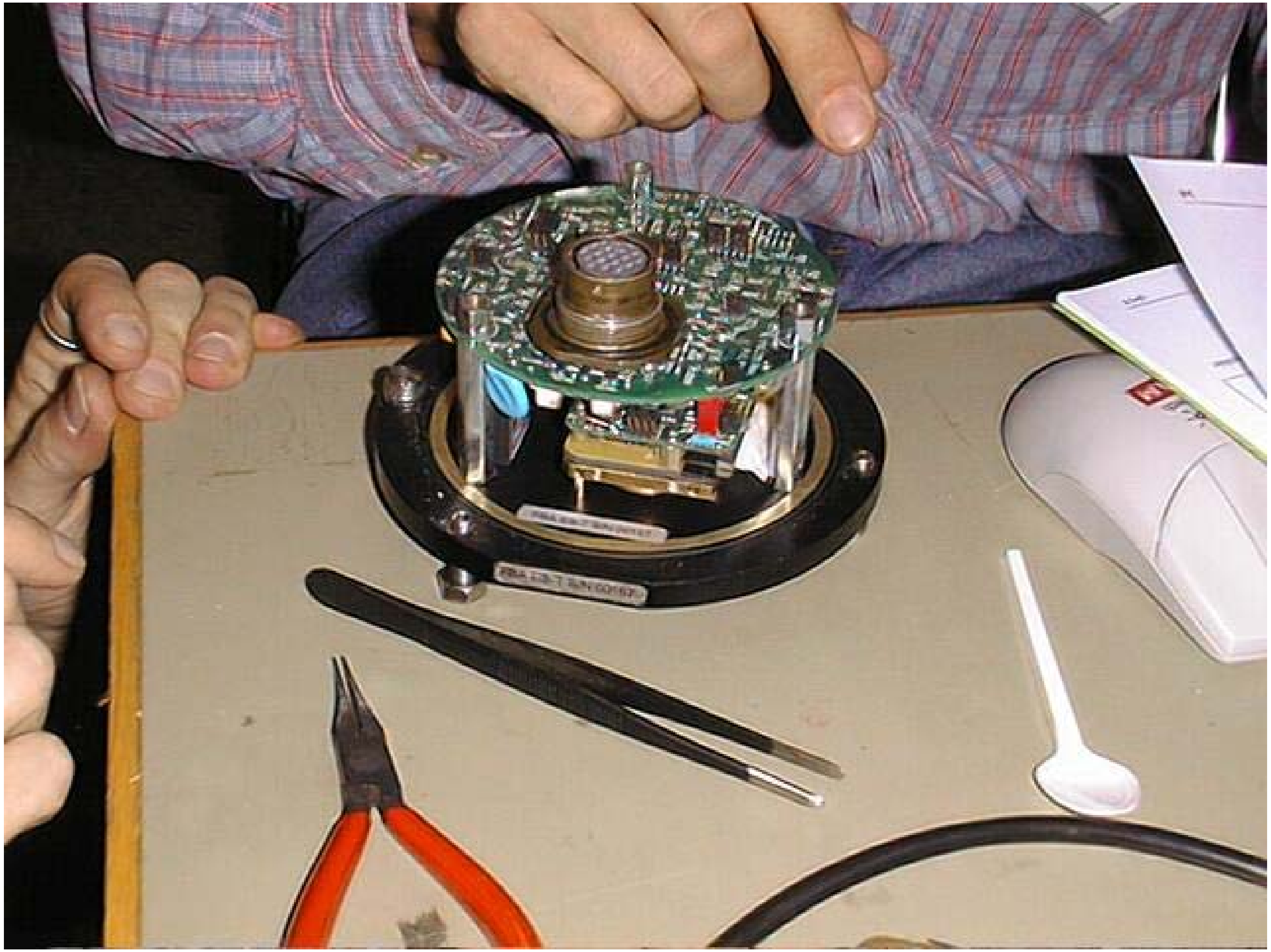
KINEMETRICS

Etna

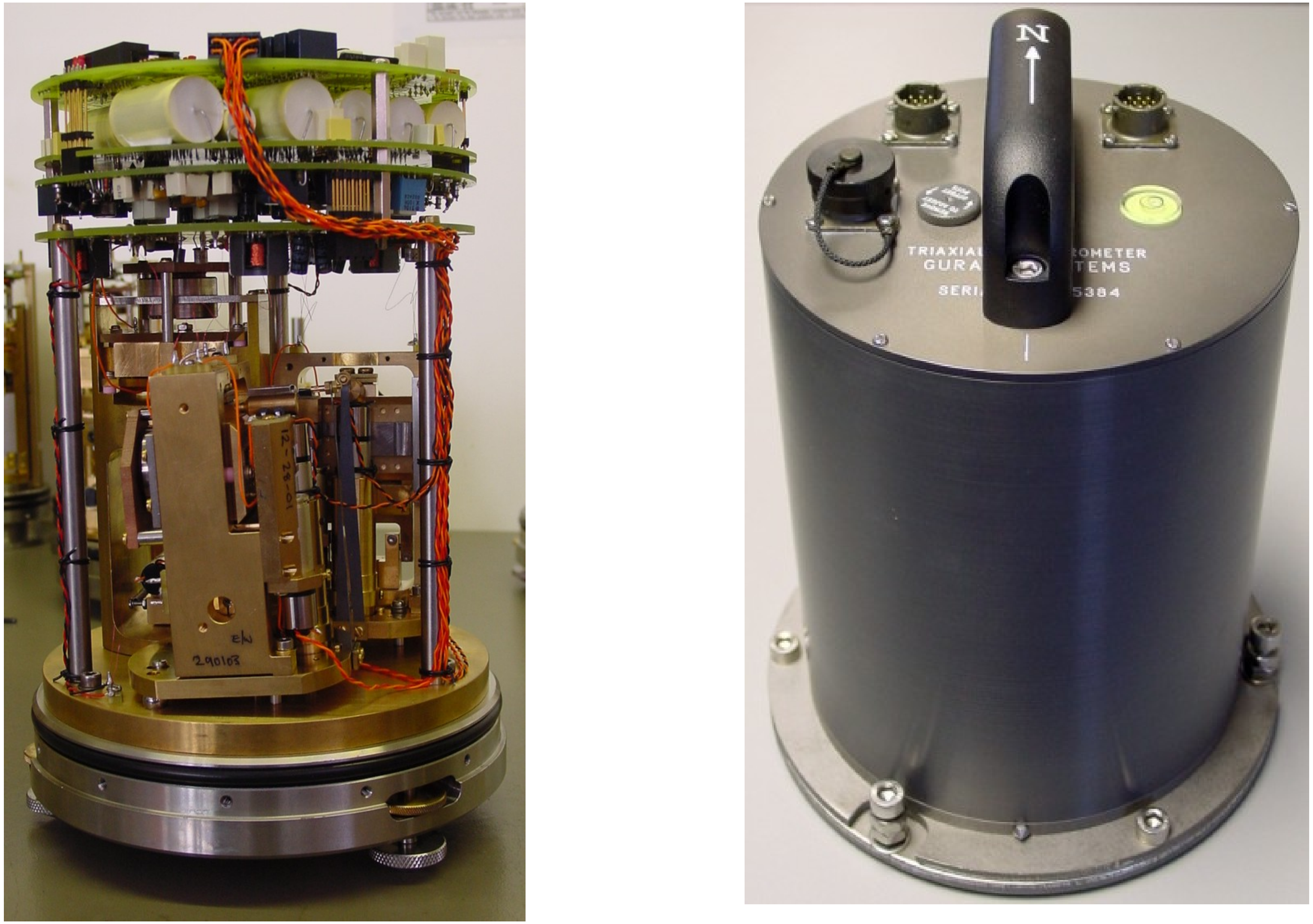
High Dynamic Range Strong Motion Accelerograph



The Kinemetrics 3-component Episensor, an FBA accelerometer



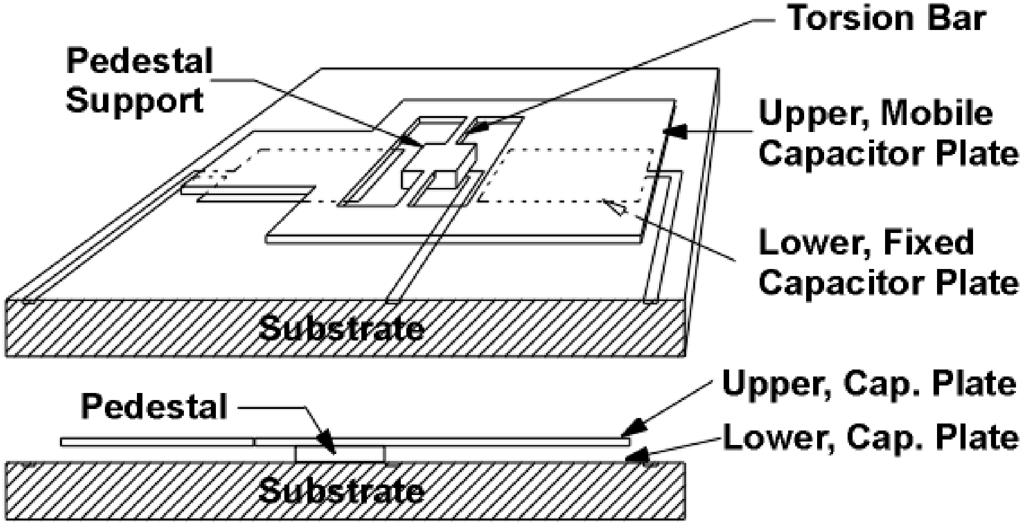
Kinemetrics Episensor internals



Left: The internals of the Güralp CMG-3T BB sensor. Right: Sensor with digitizer. Photo’s supplied by Nathan Pearce, Güralp.

Principal elements of MEMS

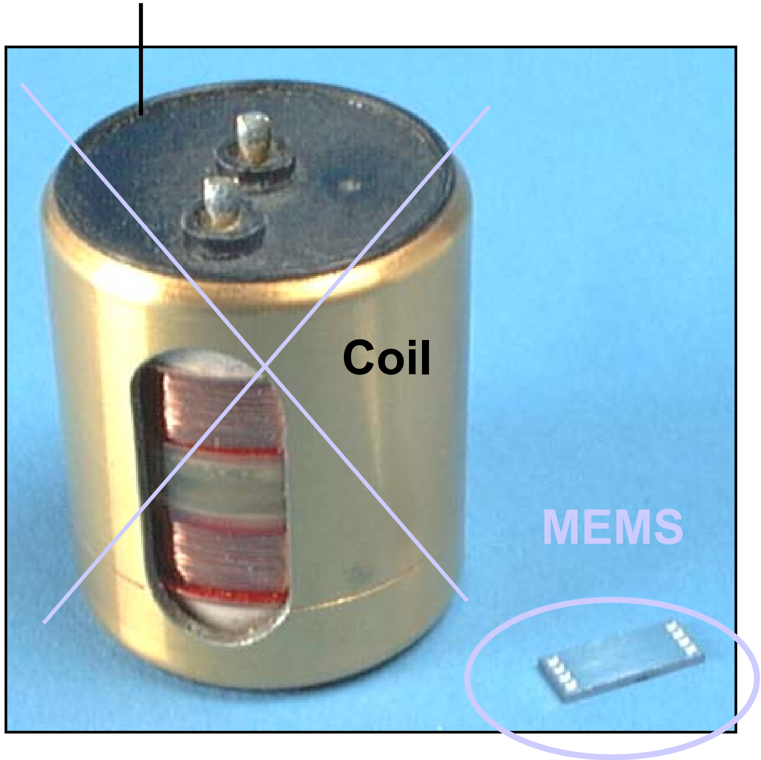
(Micro Electro Mechanical Systems)



Accelerometer with capacitive transducer. The mass is the upper mobile capacitor plate which can rotate around the torsion bars. The displacement, proportional to acceleration, is sensed with the variance in the capacitance. For high sensitive applications, a feedback circuit is added which controls a restoring electrostatic force, thus we have a FBA.

The size of the sensor above is about 2 mm. Figure from *www.silicondesigns.com/tech.html.*

Velocity Sensitive

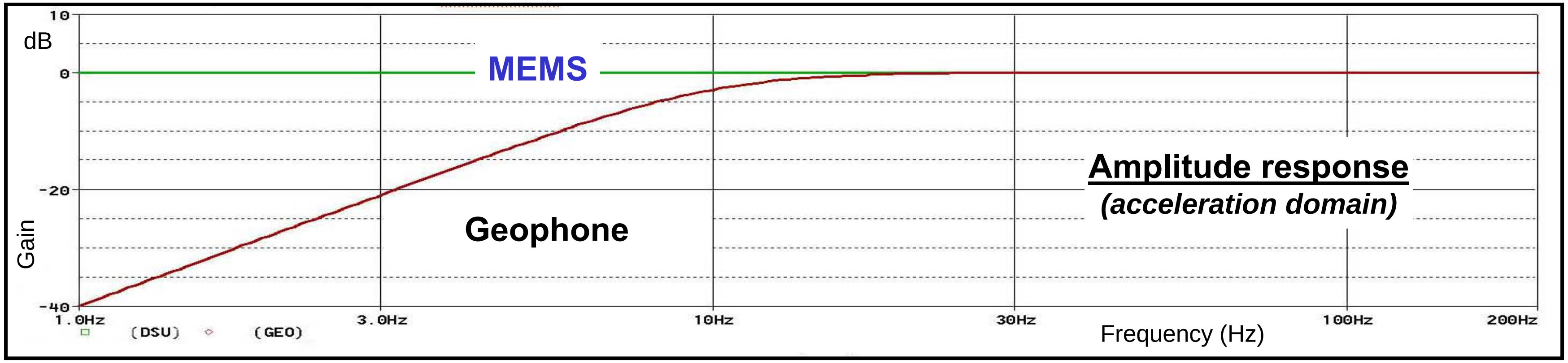


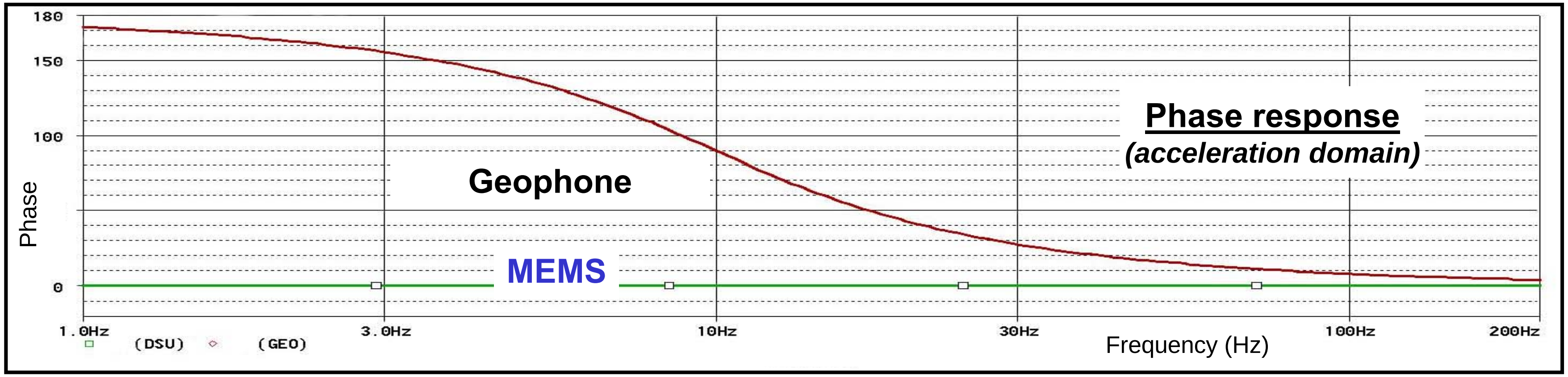
Acceleration sensitive

Micro Electronic Mechanical Systems (MEMS) accelerometers are a recently developed device Providing Broad-Band Sensing

How MEMS compares with geophones ?

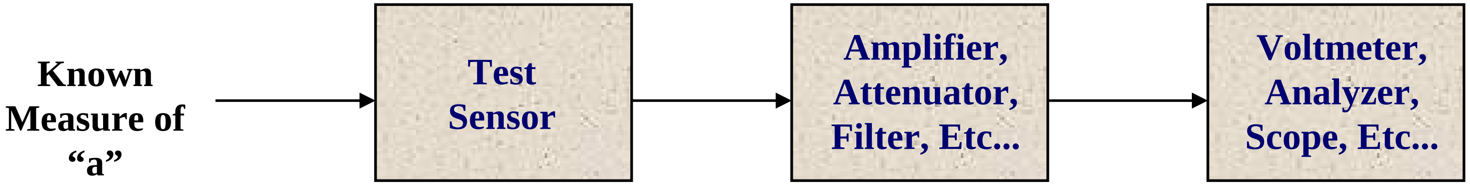
MEMS (0-800 Hz) **Geophone (10-250 Hz)**





Calibration Methods

- Absolute Method
  - – Single channel test where the sensor is subjected to a known, accurate and reliable measure of “a”
    - Drop Test
    - Gravity Inversion Test
    - Handheld Shaker

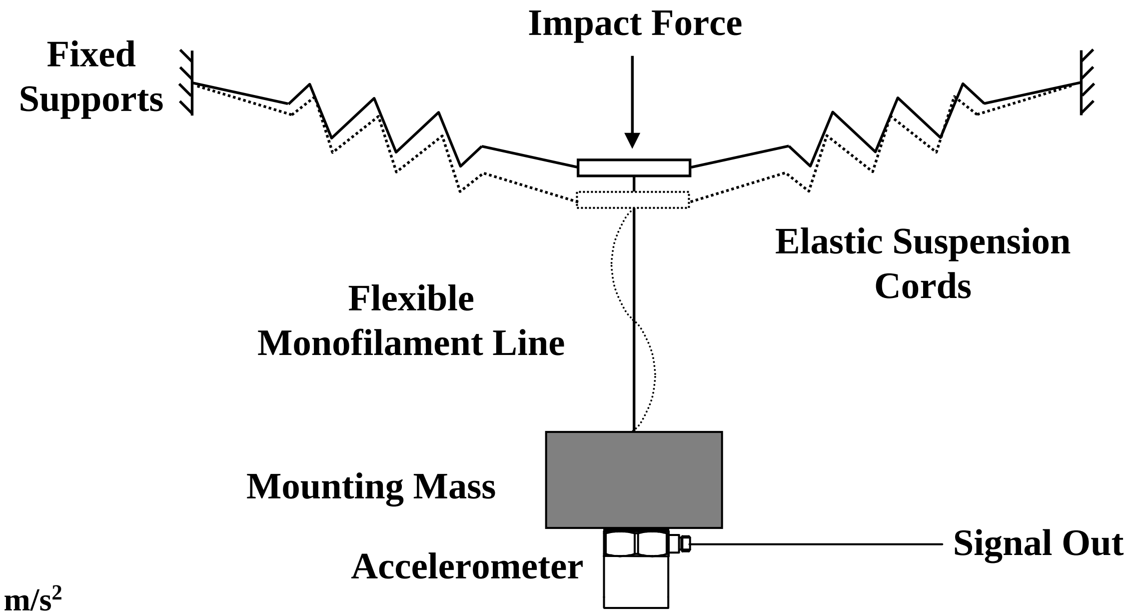

Known Measure of “a”

Test Sensor

Amplifier, Attenuator, Filter, Etc...

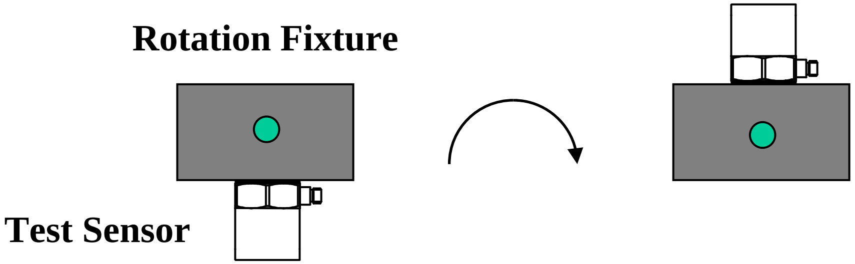
Voltmeter, Analyzer, Scope, Etc...

- Drop Test
  - Accelerometer is allowed to free-fall in Earth’s gravity which varies by less than +/-0.5% around the globe

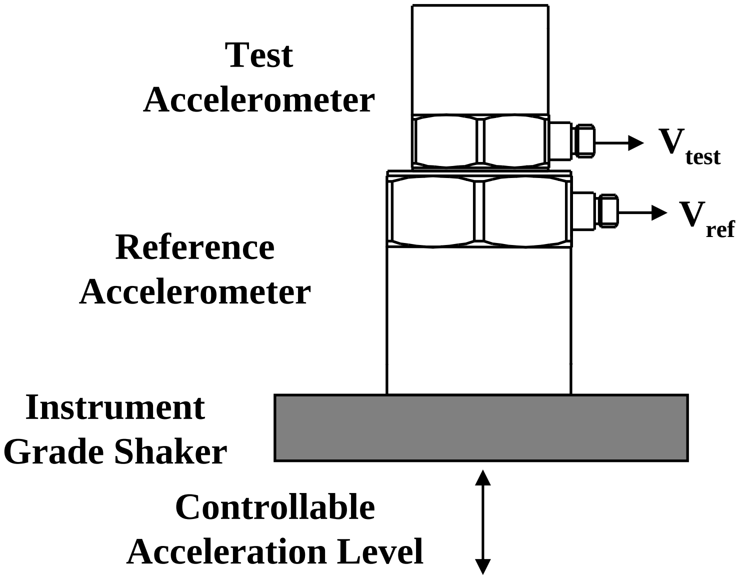


Earth’s Gravity
0 Deg Latitude: 9.78 m/s^2
90 Deg Latitude: 9.32 m/s^2
Altitude Correction: -3 mm/s^2 per 1000 m above sea level

- Gravity Inversion Test
  - Sensor is rotated 180 Degrees in the Earth’s gravity so that it experiences a 2g (-1 g to +1 g) step function
    - Requires long DTC or DC response for accurate results
    - Signal Conditioning and readout device must be DC coupled



- Relative Method
  - Dual channel test where the test sensor and *calibrated reference* are subjected to the *identical input acceleration.* The ratio of the output signals provides the calibration factor.

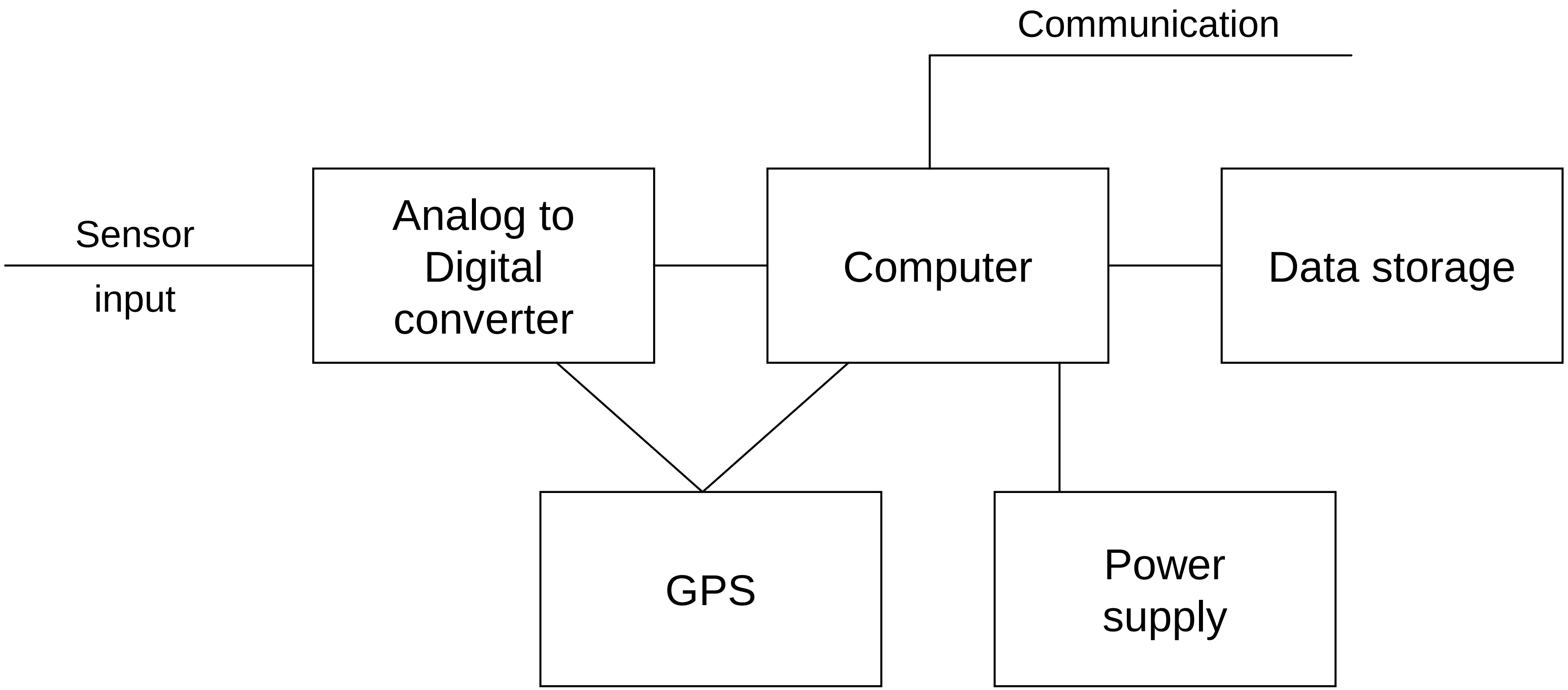


Data Acquisition System Fundamentals

Data Acquisition System Introduction

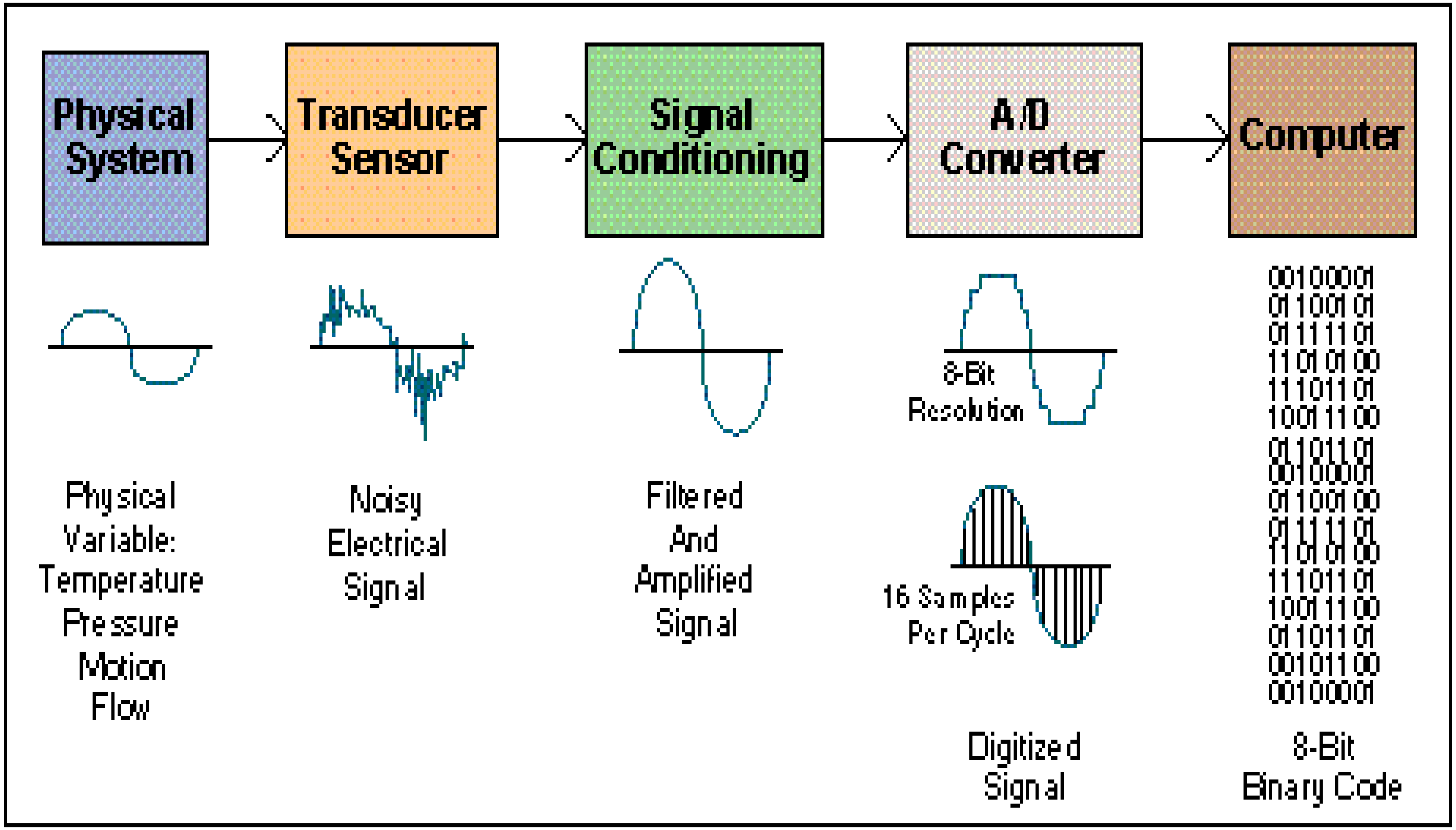
A data acquisition system consists of many components that are integrated to:

- Sense physical variables (use of transducers)
- Condition the electrical signal to make it readable by an A/D board
- Convert the signal into a digital format acceptable by a computer
- Process, analyze, store, and display the acquired data with the help of software



Main units of a seismic recorder. There are no flow arrows between the units since all can have 2 way communication. The GPS can be connected to the digitizer or the recorder. The power supply may be common for all elements or each may have its own regulator, but usually the power source is unique (e.g. a battery).

Data Acquisition System Block Diagram



Signal Conditioning

- Signal conditioning circuits improve the quality of signals generated by transducers before they are converted into digital signals by the PC's data-acquisition hardware.
- Examples of signal conditioning are signal scaling, amplification, linearization, cold-junction compensation, filtering, attenuation, excitation, common-mode rejection, and so on.

Signal Conditioning

- One of the most common signal conditioning functions is amplification.
- For maximum resolution, the voltage range of the input signals should be approximately equal to the maximum input range of the A/D converter. Amplification expands the range of the transducer signals so that they match the input range of the A/D converter. For example, a x10 amplifier maps transducer signals which range from 0 to 1 V into the range 0 to 10 V before they go into the A/D converter.

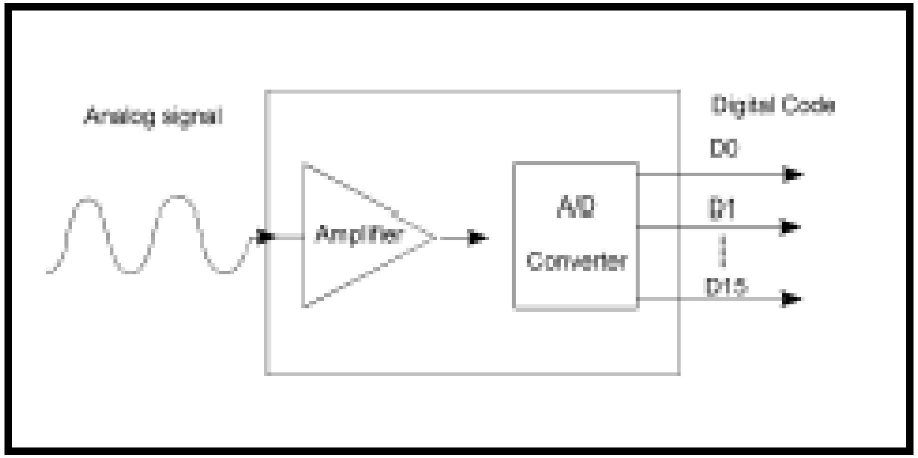
Signal Conditioning

Electrical signals are conditioned so they can be used by an analog input board. The following features may be available:

- Amplification
- Isolation
- Filtering
- Linearization

Analog Inputs (A/D)

- Analog to digital (A/D) conversion changes analog voltage or current levels into digital information. The conversion is necessary to enable the computer to process or store the signals.



Analog Inputs (A/D)

- The most significant criteria when selecting A/D hardware are:
  - 1. Number of input channels
  - 2. Single-ended or differential input signals
  - 3. Sampling rate (in samples per second)
  - 4. Resolution (usually measured in bits of resolution)
  - 5. Input range (specified in full-scale volts)
  - 6. Noise and nonlinearity

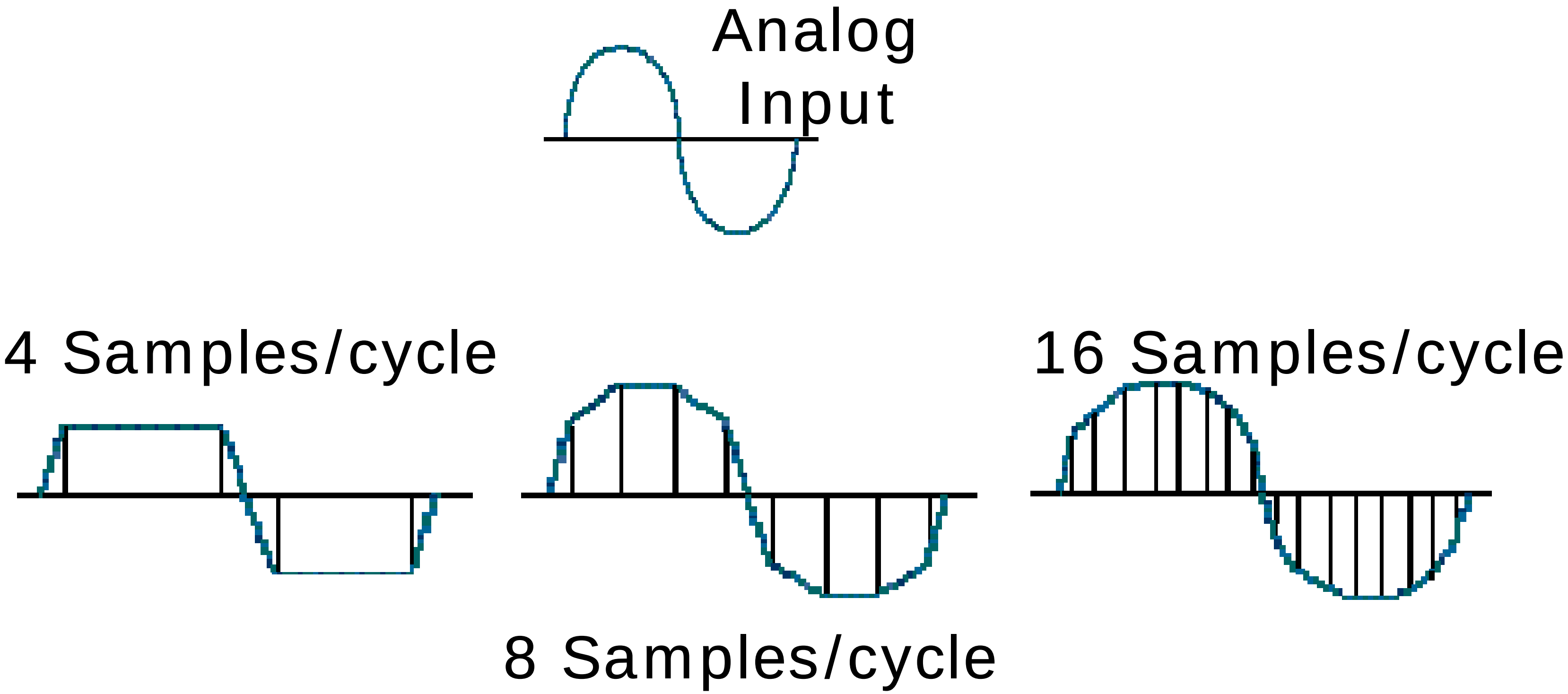
Analog to Digital (A/D) Converter

- Input signal
- Sampling rate
- Throughput

- Resolution
- Range
- Gain

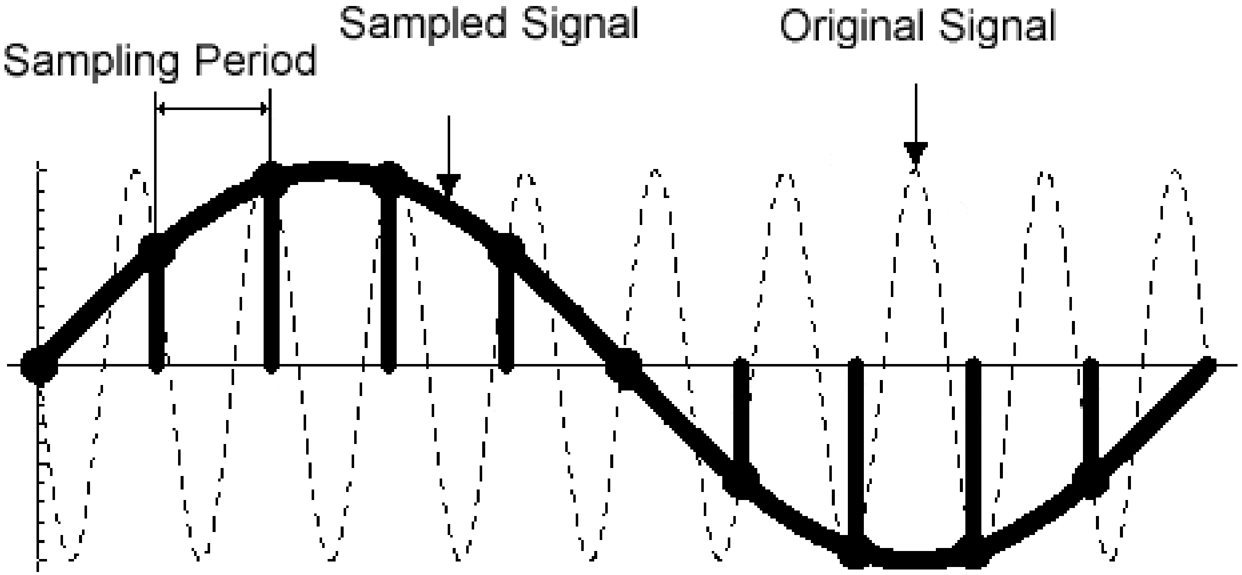
A/D Converter: Sampling Rate

- Determines how often conversions take place.
- The higher the sampling rate, the better.



A/D Converter: Sampling Rate

- Aliasing.
  - ✓Acquired signal gets distorted if sampling rate is too small.



A/D Converter:

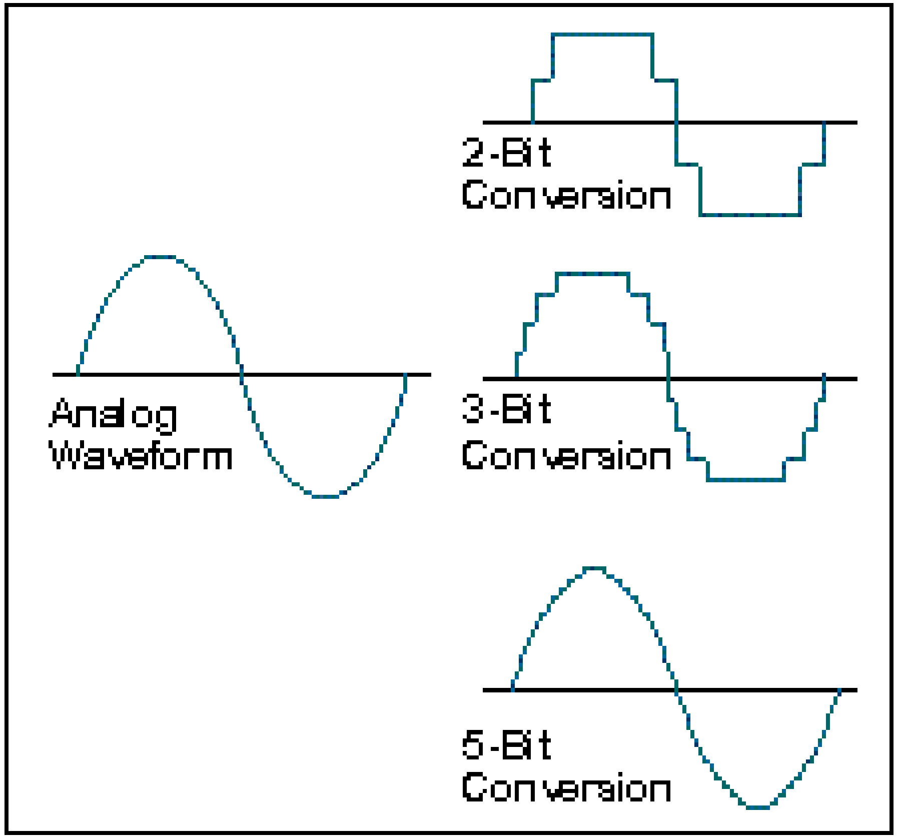
Input Signal

- Analog
  - ✓Signal is continuous

    Example: strain gage. Most of transducers produce analog signals
- Digital
  - ✓Signal is either ON or OFF

    Example: light switch.

A/D Converter:
Resolution



The Definition of Dynamic Range

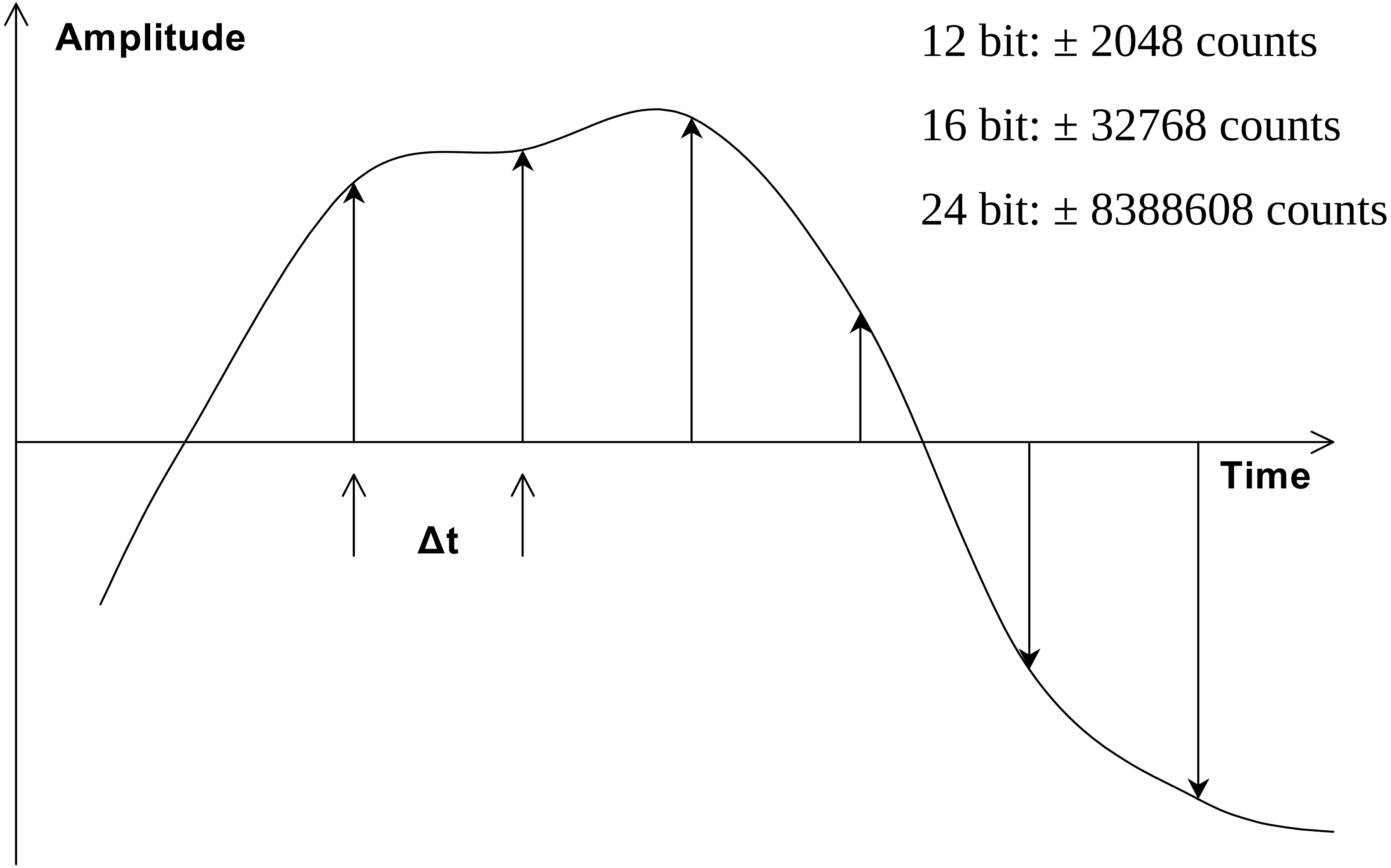
- Following Heaton (2003), the dynamic range, *DR*, of an instrument is defined as the ratio of the largest on-scale/linear measurement, *Mmax* divided by the smallest measurement resolvable by the instrument, *Mmin*:

$$DR = \frac{M_{max}}{M_{min}}$$

Dynamic Range

- Traditionally, dynamic range is given in the units of decibels (*dB*), 1/10 th of a Bel. A Bel is defined as a base 10 logarithmic measure of energy per unit time, or power. Since the power of a signal is proportional to the square of the signal amplitude:

$$
\begin{aligned}
DR_{dB} &= 10log_{10}\left[\frac{M_{max}}{M_{min}}\right]^2 dB \\
&= 20log_{10}\left[\frac{M_{max}}{M_{min}}\right] dB
\end{aligned}
$$



12 bit: ± 2048 counts

16 bit: ± 32768 counts

24 bit: ± 8388608 counts

The analog to digital conversion process. The arrows show the location and values (amplitudes) of the samples and the signal is thus approximated with a sequence of numbers available at time intervals *Δt*.