SEISMOMETRY

Suggested Literature:

Dewey, J. & Byerly, P. (1969). The Early History of Seismometry (to 1900). Bull.Seism.Soc.Am., Vol.59, 189-227.

Lay, T. & Wallace, T.C. (1995). Modern Global Seismology. Academic Press, Inc., 517 pages.

Mendecki, A.J. (1997). Seismic Monitoring in Mines. Chapman & Hall, 262 pages.

Scherbaum, F. (1996). Of Zeros and Poles. Fundamentals of Digital Seismology. In 'Modern Approaches in Geophysics', Kluwer Academic Publishers, 256 pages.

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OVERVIEW

SEISMOMETERS AND GRAVIMETERS

Early seismometers and gravimeters were pendulums[1]:

$$T \cong 2\pi\sqrt{\frac{L}{g}} \quad \text{or} \quad g \cong \frac{4\pi^2 L}{T^2}$$

$$g[m/s^2] = 9.78049(1 + 0.00528838\sin^2\Phi - 0.0000059\sin^2 2\Phi)$$

influence of height on gravity = 3.086 10^{-6} m/s²/m

with T... period, L... length of pendulum, g... gravity, Φ... latitude

Unit conversions:

1 gravity unit (g.u.) = 10^{-6} m/s² = 1 µm/s²
1 g ≈ 9.81 m/s² = 980 gal
1 mgal = 10^{-3} gal = 10 g.u. = 10^{-5} m/s²

Accuracies (±):

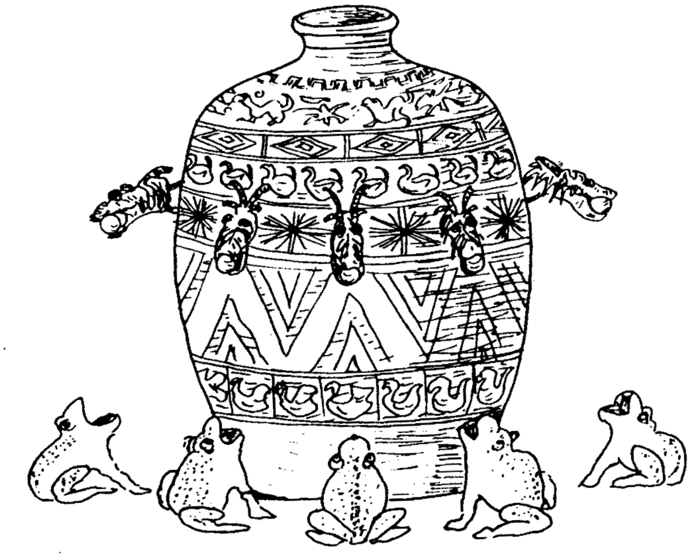
pendulum: 10 g.u. = 10^{-5} m/s²
needed in prospection: 0.1 - 0.2 g.u. = 1.10^{-7} m/s² - 2.10^{-7} m/s²
tidal gravimeters = 0.001 - 0.01 g.u. = 1.10^{-9} m/s² - 1.10^{-8} m/s²

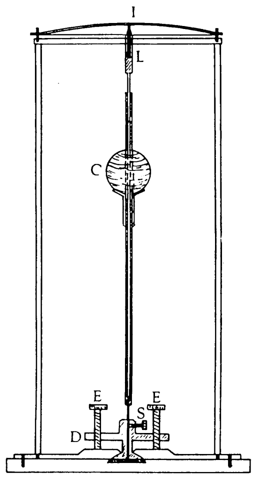
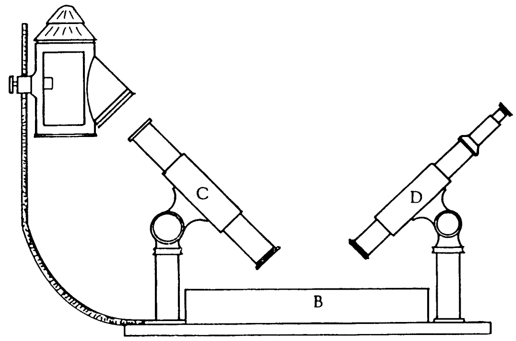
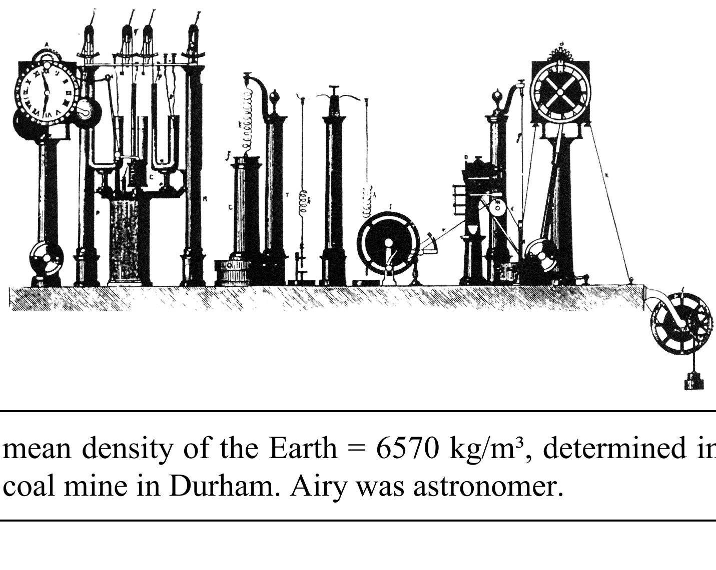
Categories of historical and modern instruments:

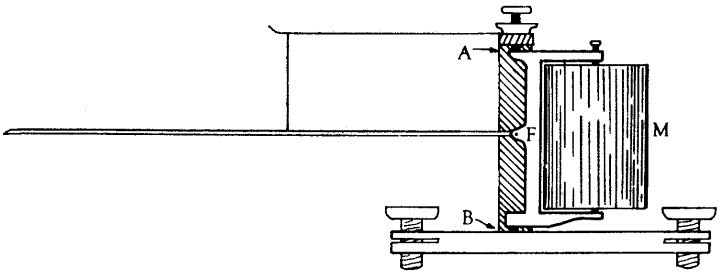
mechanical instruments	vertical
	horizontal
	torsion
	free-fall
electromagnetic	piezoelectric
	force-feedback
	super-conducting

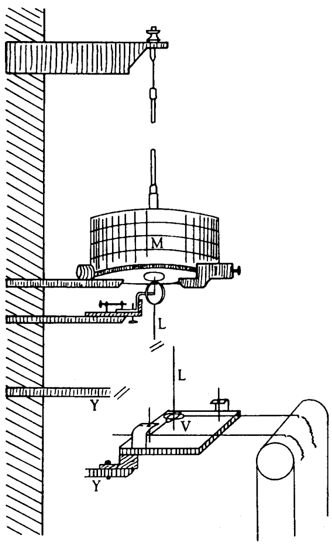
[1] Pendulums record displacements of ground shaking during an earthquake. In order to record high-frequency (low-period) signals, the pendulum's period has to be very high. With the begin of the 20th century, electrodynamic systems were introduced. Their output-voltage corresponds to ground-velocity instead of displacement. Later, during the early 1980s, force-balanced systems became available. They are much more robust and cover a high dynamic range.

HISTORY OF SEISMOMETRY

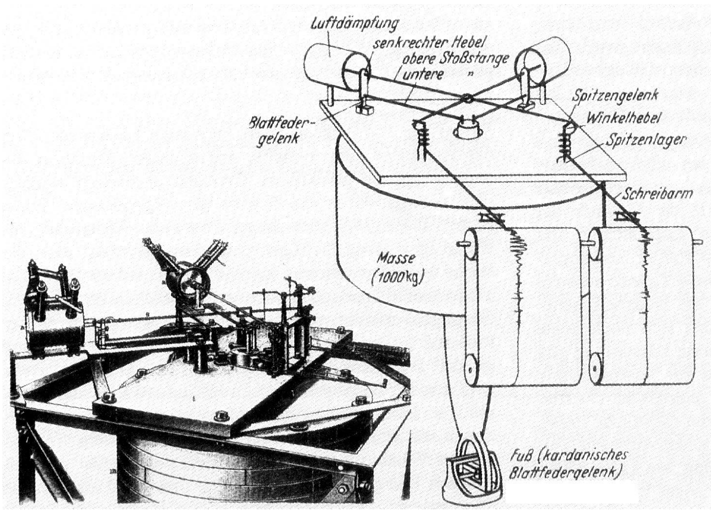
Year	Name	Remarks
132 A.D.	Chang Heng (China)	'earthquake weathercock', mechanism disputed 
1707	De la Haute Feuille (France)	spilling over of mercury bowl. The instrument was not realized. H.F. proposes to predict earthquakes based on foreshocks.
1731	Cirillo (Naples/Italy)	simple pendulum, observation of amplitude?
1751	Bina (Italy)	simple pendulum above tray of sand
1783	Salsano (Naples/Italy)	common pendulum
1784	Cavalli (Italy)	re-invented de la Haute Feuille's mercury-filled-bowl seismoscope
1792	Borda, de Thury (Paris/France)	wire pendulum for gravity observations
1796	Duca de la Torre (Italy)	common pendulum with timing device: first seismometer
1799	Laplace (France)	determines Earth flattening as 1:330
1811	Bohnenberger (Germany)	reversible pendulum
1828	Gauss (Göttingen, Germany)	suggests using the equipotential surface at sea level to describe the Earth's figure

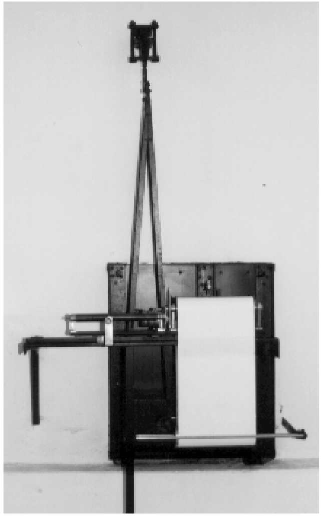
1844	Forbes (Comrie/Scotland)	inverted-pendulum seismometer, ground displacement records due to long period of pendulum 
1852	Mallet (England - Italy)	cross-hair seismoscope, observation of damage, estimate of wave-propagation velocities 
1856	Kreil (Vienna/Austria)	principle of seismometer with recording drum. Not realized.
1856	Palmieri (Vesuvius/Italy)	collection of seismoscopes for measuring different parameters (time, duration, amplitude in vertical and horizontal direction, size - measured in 'degrees', etc.), later to be used in Japan and California 
1856	Airy (Durham, U.K.)	mean density of the Earth = 6570 kg/m³, determined in coal mine in Durham. Airy was astronomer.

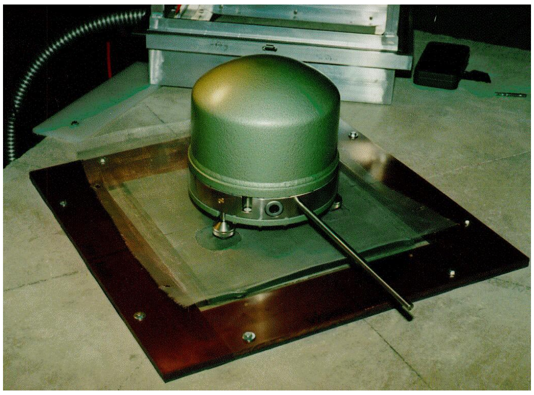
1858	Cavalleri (Italy)	used six short period pendulums to study frequency content of ground motions
1869	Zöllner (Leipzig/Germany)	first horizontal pendulum, constructed to detect gravitational changes. The principle of the 'Zöllner'-suspension was later used by Galitzin (1914), Wood-Anderson (1922) and Sprengnether (1940).
1873	Listing (U.K.)	names Gauss' equipotential surface ***geoid***
1875	Cecchi (Italy)	first 'true' seismograph which recorded the relative motion of the pendulum and the time. Recorded the 'Menton'-earthquake from February 23, 1887.
1877	Perry & Ayrton	theory of seismograph-response dealing with periodic ground motions and damping
1880	Milne, Ewing, Gray (U.K. - Japan)	visiting professors in Japan. Ewing designs 21 foot long pendulum
1881	Ewing	shake table test, disproves Mallet (who believed, that the earthquake pulse consists only of a longitudinal pulse): 1. seismic ground motions are irregular (= successive undulations differ in amplitude and period) 2. seismic ground motions contain a large number undulations 3. the maximum of ground motion occurs only after several undulations 
1882	Gray, Ewing	first vertical seismograph
1882	Milne	strain seismometer across 3 feet
1882	Ewing	studies effect of topography and geology on ground motions (microzonation!). This idea dates back to Dolomien (1784) who studied the Catalanian earthquake.

1882	von Sterneck (Austria)	determines the Earth's density to be 5770 kg/m³, based on measurements at a mine near Pribram (today Czech Republic)
1883	Milne, Gray	propagation of elastic waves from artificial sources (dynamite explosions)
1885	Milne	interprets as one of the first ***surface waves*** (Rayleigh, 1885)
1887	Milne	'...***soft and hard ground*** influences ground motions...'
1888	Milne	'...***building types*** and different floors respond different to earthquakes...'
1889	Rebeur-Paschwitz (Potsdam/Germany)	observes distant earthquake with astronomic pendulum, which was similar to Ewing's pendulum (1880). For the mass amounted only to 46 grams, and the pendulum had a length of 10 cm only, R.-P. utilized photographic recording devices (used by Fouqué (1888) for recording magnetographs). Disadvantage: photographic records are not as sharp as smoked paper records, and rapid movements do not record. Expensive! Hence, slow paper advance (11mm per hour) was used to reduce paper-costs.
1889	Dutton (USA)	geologist coins the name ***isostasy***
1891	Milne	'...***faulting causes earthquakes***...' (Mino-Owari earthquake on October 28, 1891)
1893	Cancani (Italy)	7m-common pendulum seismograph (magnification = 10). Distinguished ***P- and S-waves***.
1895	Vicentini, Pacher (Italy)	1.5m-pendulum (mass = 100 kg), magnification = 80 

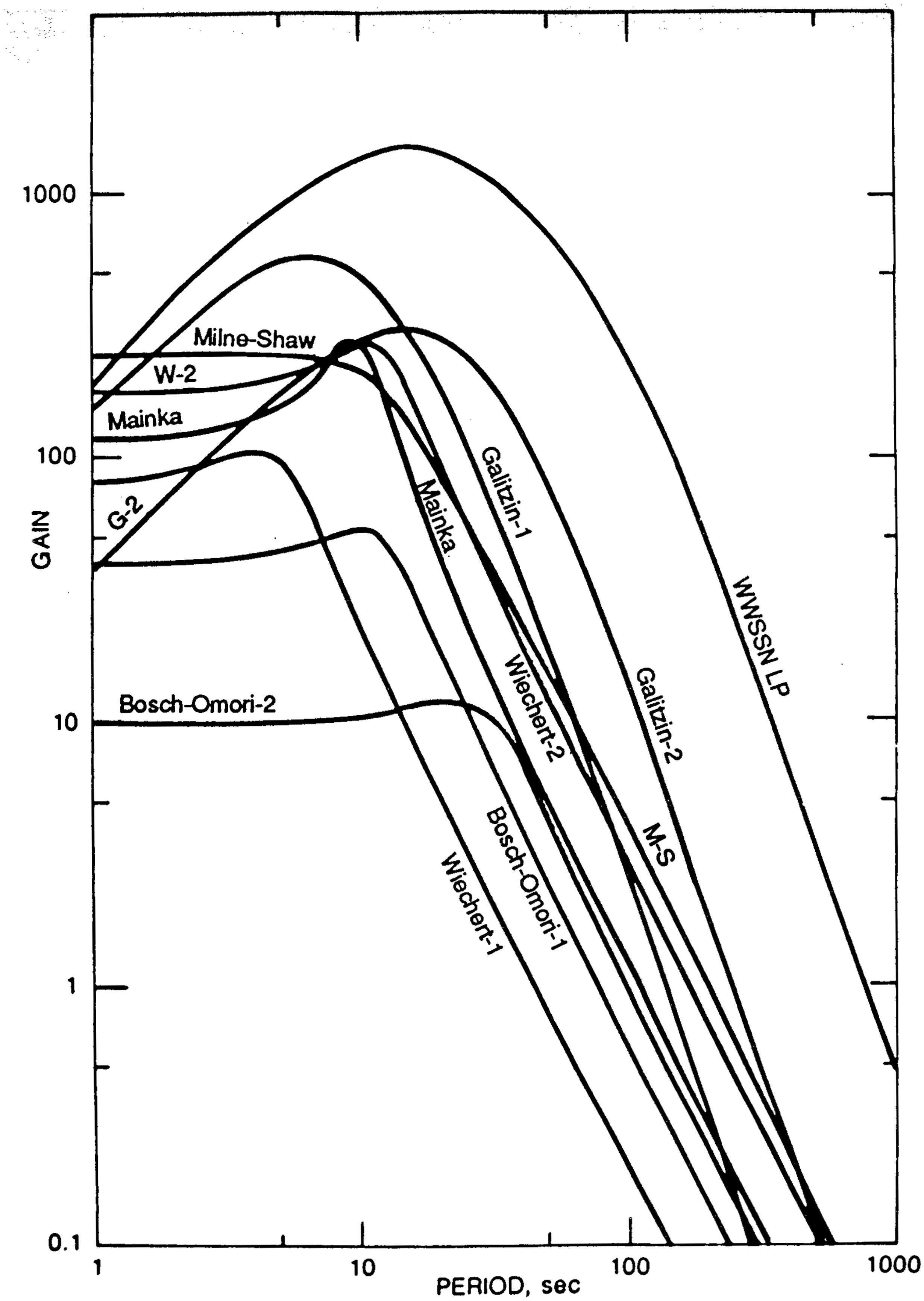
1895	Milne (U.K.)	leaves Japan after the 'Seismological Society of Japan' was already dissolved in 1892. Fusakichi Omori takes over.
1896, 1908	von Eötvös (today Hungary)	torsion balance gravimeter, used for determining the horizontal gravity gradient
1897	Milne	suggests world-wide network of seismographic stations with standard instrument (to be realized in the 1960's)
1898	Vicentini, Pacher	vertical seismometer, magnification = 130, period = 1.2 seconds, smoked paper
1898	Wiechert (Göttingen, Germany)	viscous-damping pendulum, photographic recording
1898	Milne	***first travel-time tables*** of surface waves
1899	Omori (Japan)	seismograph with magnification of 10, natural period 20 seconds (basis for Bosch-Omori seismograph build later in Strassburg/France)
1899	Milne	first travel-time tables of P-Waves
1900	Oldham	first travel-time tables of S-waves
1900	Wiechert	inverted pendulum (after Forbes - 1844), mechanic recording
1900	Schlüter (Göttingen, Germany)	***first long-period vertical seismograph***, magnification = 160, period = 16 seconds, photographic record
1901	Helmert (Vienna/Austria)	Earth flattening 1:298.3
1903	Galitzin (Russia)	electromagnetic seismograph, based on ideas on seismoscopes and galvanometers expressed by Gray (1879) and Milne (1882)

1904	Wiechert	improved version of 1900, mass = 1000 kg, magnification = 200, period = 12 seconds 
1909	Bosch-Omori	large horizontal pendulum for observation of distant earthquakes (mass = 25 kg, period 15 – 20 seconds) 

1910	Conrad (Austria)	small horizontal pendulum for observation of local earthquakes 
1914	Galitzin	moving-coil transducer to convert pendulum movement into electric current which corresponds to the mass velocity, photographic records.
1918	Schweydar (Germany)	torsion balance gravimeter used to detect salt domes in Northern Germany
1922	Wood-Anderson (USA)	torsion seismograph (not electromagnetic!), period = 0.8 seconds, magnification = 2800, and period = 6 seconds, magnification = 800. The ***Richter-magnitude*** scale (1935) is based on Wood-Anderson records.
1926	Quervain, Piccard (Zurich, Switzerland)	***first force-feedback system*** which compensates mass-movement, 21-ton seismograph
1934	LaCoste	long-period vertical seismometer
1938	Schleusener (Germany)	gravimetric profile across Iceland
~1940	Benioff	short-period instrument, based on Galitzin, period = 1 second for pendulum, 0.7 seconds for galvanometer
~1940	Sprengnether	long-period instrument, based on Galitzin, period = 15 or 30 seconds for pendulum, 100 seconds for galvanometer
1948	Worden (USA)	quartz spring gravimeter
1950	Woollard (USA)	gravimeter with thermostazied metal spring (0.1 - 0.5 mm/s²)
1957	Graf	***first sea gravimeters***

1969-1971	HGLP	'High Gain Long Period' digital instruments distributed by Columbia University in Alaska, Australia, Israel, Spain and Thailand. First stations to resolve Earth's noise in the 20 - 100 second period range
~1973	force-feed back for broad-band sensors	from now on all broad-band sensors incorporate the force-feedback principle
1977-1987	LaCoste-Romberg	force-feedback gravimeters are used for recording free oscillations of the Earth
1982	Wielandt, Streckeisen	STS-1® sensors are deployed under the GEOSCOPE project
1984	Wielandt, Steim	high-dynamic-range (>140 dB) seismic sensor, very-broad-band seismograph, 'Quanterra®'
1990	Wielandt, Steim, Streckeisen	Q680-family (Quanterra's® low power, 6-channel 24-bit with 80 Hz sampling an remote data access) with STS-2® wide-bandwidth sensors by Streckeisen. 

HISTORIC SEISMOMETERS



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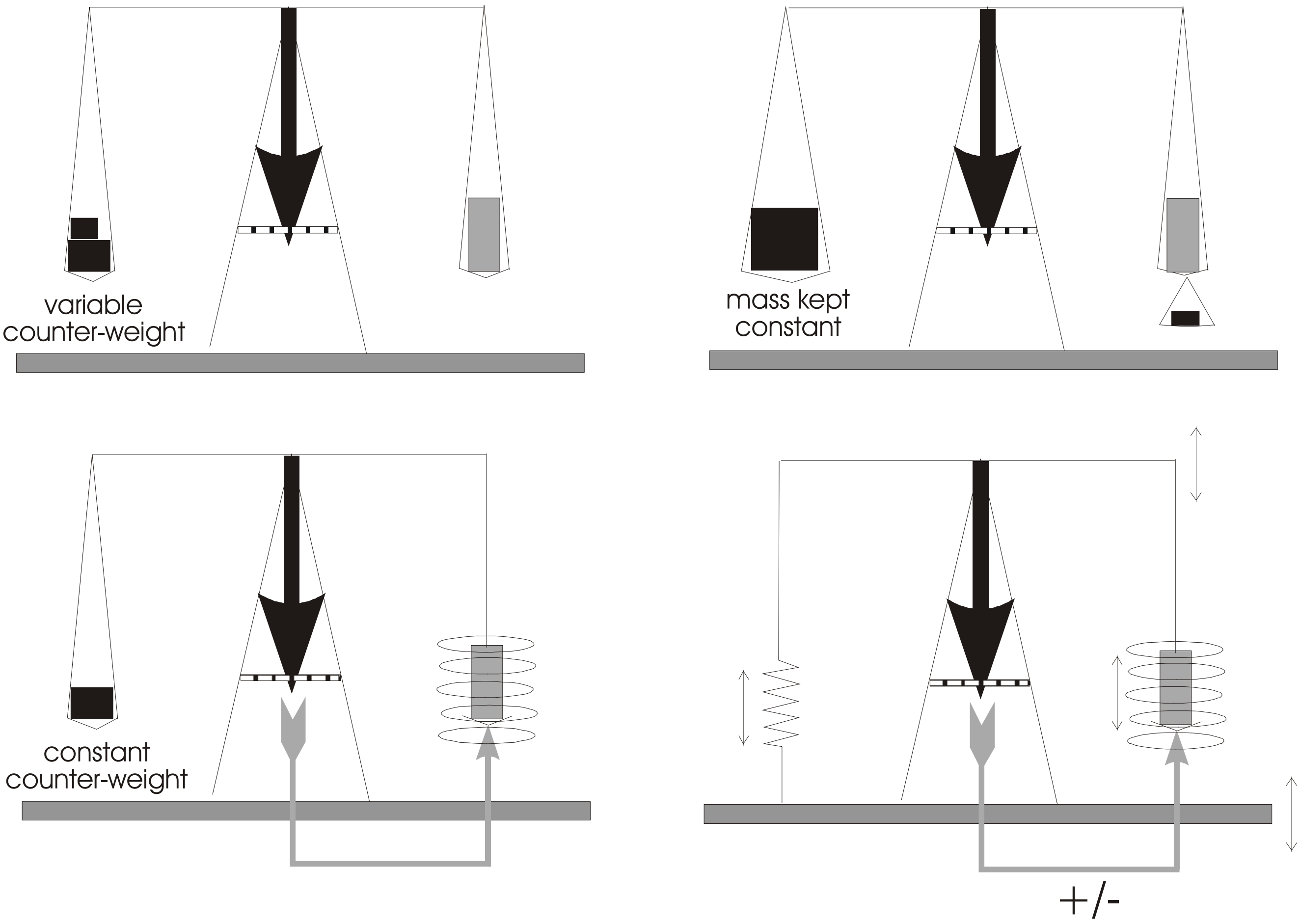
(see Lay, T. & Wallace, T.C. 1995)

MODERN SEISMOMETERS

DEVELOPMENT

The development of force-balance systems can be visualized with a balance:



- Principle of balance (top left): A counter-weight is increased as long as the balance indicates, that the mass to be determined, is heavier than the counter-weight.

- Principle of compensation (top right): The counter-weight is kept constant, and additional mass is added to the mass to be determined. Hence, the counter-weight must be larger than the mass to be measured.

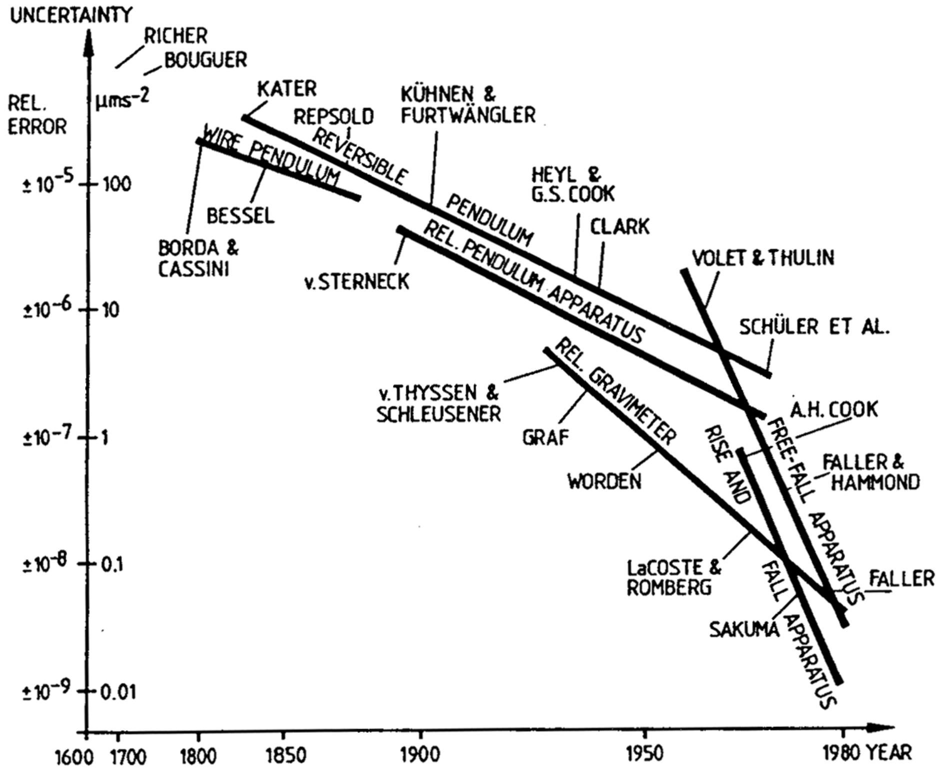
- Electro-dynamic principle (bottom left): A current is applied to a coil which compensates the mass-difference between the counter-weight and the mass to be determined. Note: No change in ground movements nor in gravity can be observed.

- Force-balance principle (bottom right): A spring replaces the counter-weight enabling the system to respond to ground movements due to the flexibility of the spring. The coil compensates continuously the displacement of the reference-mass, thus trying to keep the reference-mass at rest.

COMPARISON

GEOPHONES	ACCELEROMETERS
$T << T_0$ $h \approx 0.7$ $f_0 = 0.5$ Hz - 100 Hz	$T >> T_0$ $h = 0.01 - 0.7$ $f_0 = 2$ kHz - 70 kHz
Superior sensitivity over narrow band of corner frequencies above the natural frequency.	Less sensitive (relative motion of the mass is small), but ground motion is recorded over a wide frequency band almost right down to DC.
The peak-amplitude in the near-field corresponds to the displacement at the source.	The peak-amplitude in the near-field corresponds to the stress drop at the source.
Principle:	Principle:
Coil and magnet are used to detect the motion of the inertial mass, which is proportional to the ground velocity. Early instruments (pendulums, that is without velocity transducer) recorded displacement.	Mass and case move almost identical. The extension of the spring serves as measure of the force to accelerate the mass. Therefore, these systems are used to record strong ground motions. In force-balanced accelerometers the spring is replaced by an electronic feedback-circuit. In piezo-electric accelerometers, the mechanical strain is measured.
Problem:	Problem:
It is difficult to design a geophone with a low natural resonant frequency. This requires a soft axial response, and a stiff radial response.	Low sensitivity. Piezo-type sensors experience electrical leakage (they do not measure down to DC).
Types:	Types:
Miniature geophones (4.5 - 100 Hz) are used in exploration and in mines	Piezo-electric sensors with amplifier
Low frequency geophones (0.5 - 2 Hz) are used for monitoring earthquakes	Force-balanced accelerometer (electronic feedback instead of spring)

IMPROVEMENT OF GRAVIMETERS



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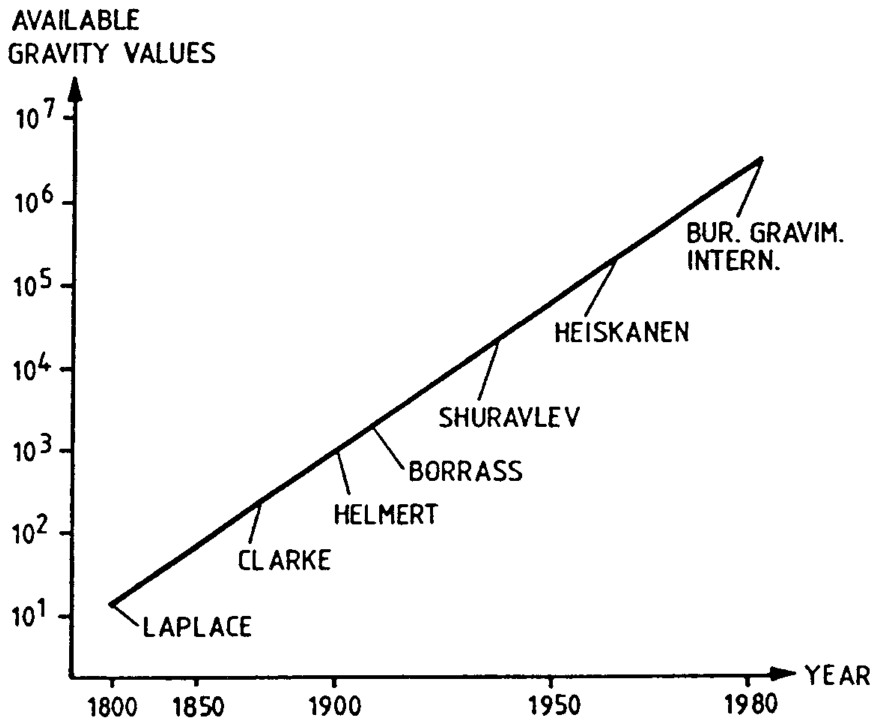

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From Torge, W. (1989). Gravimetry. Walter de Gruyter, Berlin - New York.

TRIGGERING AND ASSOCIATION

Trigger

short term average (STA) to long term average (LTA):

STA/LTA > k

or

signal to noise ratio ‘SNR’:

SNR > k

As ‘k’ depends on the noise, the ‘SNR’ detection may vary during the day. A common value for ‘SNR’ is 2.5.

Signal envelope

$$E = \sqrt{(S^2 + S_H^2)}$$

with

$$|S| = \sqrt{x^2 + y^2 + z^2}$$

and

S_H = output of Hilbert transformer

Association

$$|T_i - T_j| \leq \Delta t_{ij} = \frac{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}}{V}$$

NETWORK COMPARISON

	regional	local	micro
M_{min}	0 to 1	-1 to 0	-4 to -3
M_{max}	4 to 5	4	3
average volume (km)	30 x 30 x 5	3 x 3 x 3	0.3 x 0.3 x 0.3
events/day	100	1000	10000
sensors	1 Hz ; 4.5 Hz geo.	4.5 Hz ; 28 Hz geo.	10 kHz accel.
minimum density (km)	5 stations > 2	5 stations < 1	5 stations < 0.3
useful frequency band (Hz)	0.5 to 300	2 to 1000	3 to 10000
communications (kbps)	1.2	9.6	115
storage (GB)	0.2	2	20

see Mendecki (1997), Tab.2.2