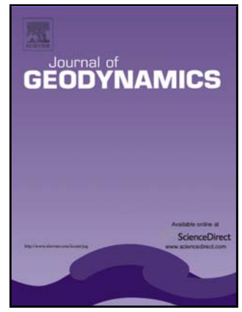
Common roots of modern seismology and of earth tide research. A historical overview

P. Varga

Accepted Manuscript



Title: Common roots of modern seismology and of earth tide research. A historical overview

Author: P. Varga

PII: S0264-3707(09)00099-4
DOI: doi:10.1016/j.jog.2009.09.032
Reference: GEOD 926

To appear in: *Journal of Geodynamics*

Please cite this article as: Varga, P., Common roots of modern seismology and of earth tide research. A historical overview, *Journal of Geodynamics* (2008), doi:10.1016/j.jog.2009.09.032

Common roots of modern seismology and of earth tide research. A historical overview

P. Varga*
Geodetic and Geophysical Research Institute, Seismological Observatory, Budapest, Meredek u. 18, H-1112

Abstract
The most important connection between earth tidal research and seismology is related to first attempts to measure the Earth's effective elasticity by using the tides. The main target of the present study is to describe some important developments in this common field of seismology and earth tide research until the middle of the XXth century.
Keywords: rigidity, horizontal pendulum, earthquake, seismograph, luni-solar effect, ISA

1. Introduction

The chief object of the following paper is to point out the parallelisms and common roots of the development of two important fields of geodynamic studies – earth tide research and seismology. The connection was based on the fact that for early seismology the effective rigidity observed by earth tidal observations was of prime order importance. The common interest in the study of rheological properties of the Earth still remains. In addition to this, seismology and earth tides have in common the same instruments observing directly accelerations due to gravitational forces or inertial accelerations due to ground deformations. In the same time an important difference should be mentioned: seismology deals with periods of second to minutes while earth tides mostly is related to periods longer than 12 hours

2. Theoretical works of W. Hopkins and W. Thomson (Lord Kelvin) and the activity of G. and H. Darwin.

Albeit the word geophysics** was first used in Germany (of course in form „Geophysik") by Julius Fröbel (1805-1893) in 1834, when he meant by this name theoretical geography (Buntebarth, 1981). Almost at the same time, in England W. Hopkins (1793-1866) has introduced the term "physical geology" with the same meaning, which was a term of a scientific endeavour to apply mathematical and physical principles that underlie the general description of certain geological processes. He tried to introduce in terms of new science geophysics (this is the real meaning of Hopkins's "physical geology") to transform geology into physical science (Kushner, 1993). Studies of Hopkins were primarily dealing with precession and nutation of the rotation axis of the Earth. At that time geologists thought the Earth is primarily liquid, being covered by a solid crust less than 100 km thick. Hopkins has shown with the use of mathematics that the minimum thickness of the solid uppermost layer is 1200-1600 km. In opposite case the calculated precessional constant would differ significantly from his observed value. It can be concluded that Hopkins imagined a largely solid but dynamic Earth. He also interpreted seismic events and volcanoes. Hopkins's student William Thomson is recognized first of all for his important work in mathematical theory of electricity and thermodynamics. He is less known for his extended interest in earth sciences. His study on the age of the Earth led to an intensive scientific debate with Charles Darwin (1809-1882) (Burchfield, 1974). At the same time, he was a follower of W. Hopkins and the second significant contributor to physical geology. In 1862 he presented to the Royal Society two important essays for further development of earth sciences. (Thomson, 1863a;b). It was shown by Thomson that the Earth's figure reacts to the distorting forces of the Moon and Sun as an elastic body with rigidity of steel. By the use of his theoretical results Thomson extended Hopkin's thickness of the crust from (1200 – 1600) km to at least 4000 km. It follows from contributions of Thomson (Thomson, 1863a;b) that he treated in his theory the Earth as a solid body. In spite of the discovery by R.D. Oldham of the earth core (Oldham, 1906) it was generally believed until 1926 that the entire Earth is solid (Brush,

---

*Phone:+36-1-248 2321, Fax:+36-1-248 2301, e-mail:varga@seismology.hu
**The word "geophysics" was not generally accepted till the end of XIXth century. Beside it, or instead of it, the phenomena of physical processes of the Earth were described in the frame entitled as "mathematical geography", "cosmography" or "physical geology". This terms were in use even during the first decades of XXth century.

1980; Brush, 1981). In this year appeared the paper of H. Jeffreys which presented evidence based on analysis of seismic waves that the core behaves as a liquid*(Jeffreys, 1926). The geologists around 1860-1870 thought that the Earth is liquid, and covered by a crust less than 100 km thick. The Earth being practically rigid as steel presents serious problems to scientists dealing with geological processes. To prove the validity of his theory and to determine experimentally the effective shear modulus of the Earth, Thomson proposed two possible ways**.

1) It was suggested by him that the observation of oceanic tides at a point fixed to a continent will enable to record temporal variation of the vertical in case of the solid Earth. A ratio of observed data and the theoretical values (calculated on the basis of astronomical data) enables an estimation of the elastic effective shear of the Earth. With the use of a combination of Love numbers this ratio can be described as $\gamma=1+k-h$ (k is the Love number which is used to describe the variations of the gravity field due to earth tidal deformations). In 1881 G.Darwin analysed the oceanic tidal records of 14 station in Europe and India (Melchior, 1978). The total length of observations covered 33 years (Thomson & Tait, 1883). Later on, W. Schweydar investigated data of 43 worldwide mareographs (the total length of the investigated records was 194 years (Schweydar, 1916). The comparison of oceanic tides with theoretical ones is only possible in case of long-periodic zonal tides because their damping is low and they are –as was earlier supposed – close to static tides. These observations met however serious objections, because the zonal behaviour of oceanic tides deviates from static tides, since they can be realized only in case of an Earth completely covered by ocean. Effects, which are related to this incompleteness cannot be fully eliminated.

2) The second possibility suggested by W.Thomson to determine the effective shear modulus of the Earth, was to use a vertical bifilar pendulum to study the tilt of the surface of the Earth under the influence of the luni-solar effect. The pendulum was constructed and used by G. Darwin and his brother H. Darwin in the eighties of XIXth century (Darwin, 1881; 1907). The copper mass of the instrument (80kg) was suspended in two points and was connected to a small mirror hanged on a silk yarn, by which the system was fixed to the frame. The bifilar pendulum of a length 1.5m was installed in a brass case; water-alcohol damping was used. A light source to illuminate the mirror a gas lamp was used.The visual reading was realized with the use of a telescope. This was the first attempt to observe the earth tides by using an instrument directly. The instrument and the work carried out is described by G. Darwin in the eighties of XIXth century in his famous book "*The tides and kindered phenomena in the solar system, Boston and New York, 1898"*. This first experimental attempt to measure the earth tides was – in spite of high sensitivity of the pendulum – not successful because of very strong external disturbances affecting the instrument (temperature and air pressure variations, noise caused by the traffic in the town environment).

In 1898 G. Darwin wrote, that I doubt „if it would ever be possible to isolate the effects of tidal forces from the multitudinous disturbances" (Michelson, 1914; Gale, 1914).

3. Horizontal pendulum observations by E. von Rebeur-Paschwitz to observe earth tides and the birth of global seismology.

Almost at the same time, when the Darwin brothers were observing the movements of their bifilar pendulum in Cambridge (1880-1882) a young astronomer E. von Rebeur-Paschwitz started his activity at the astronomical observatories of Berlin and Karlsruhe. His duty as an assistant was to determine star positions and distances. Beside his main job he had a hobby to construct a device, a horizontal pendulum, which was able to record the deflection of vertical caused by the luni-solar effect (Vocilka, 2008). He became acquainted in 1884 with Zöllner's paper on horizontal pendulums (Zöllner, 1873). E. von Rebeur-Paschwitz started the construction of his own horizontal pendulum instrument in 1886, which was ready in 1888. In this year he had to leave his assistant position due to a serious illness. The instrument constructed by E. von Rebeur-Paschwitz was small in size, consisted of one horizontal pendulum, which had

---

*The state of the core was discussed after the publication of Jeffreys's contribution (1929). Many famous seismologists (Macelwane, Gutenberg, Lynch) refused to make a definite pronouncement on the nature of the core and leave it an open question till forties of XXth century (Lynch, 1940). The liquid nature of the core was definitively proven on the basis of theoretical works of Jeffreys, Vicente and Molodensky on the liquid core resonance with the use of earth tide records in fifties.- sixties of last century (Melchior, 1974).

** A third possibility was suggested in 1893 by Newcomb, who suggested to use for the determination of effective shear modulus a comparison of periods of Chandler (detected in 1891) and Euler (Torge, 2007).

two points of rotation and a moving mass of only 42 grams (Ehlert,1898). The new device had some disadvantageous features (lack of damping, low time resolution, long-term mechanical problems due to abrasion at the two points of rotation). At the same time it had very important innovations, because of the use of recording photographic paper, which allowed to achieve relatively large amplification at that time (Table 1) and the reduced size of the equipment.

In 1889, with the aim to observe luni-solar tilts, E. von Rebeur-Paschwitz installed two of his instruments in Potsdam and in Wilhelmshaven. He supposed, with isochronous parallel registration at two sites to be able distinguish local disturbances from global (astronomical) events. By chance, he read a report in Nature about an earthquake in Japan which occurred on April 18, 1889 just before his two instruments recorded unusual signals both in Potsdam and Wilhelmshaven. It was a very important recognition for the future development of seismology that E. von Rebeur-Paschwitz perceived: the signals are correlated with this seismic event and calculated the velocity of propagation of seismic signals from Japan to Germany. (Schweitzer J. 2002).

It was known already long time before 1889 that the effects caused by earthquakes can be observed at significant distances, so their signals arrive at different time at different locations. After the great earthquake of Lisbon in 1755, with the use of time difference of the arrivals of disturbances "the first seismologist" J. Michell estimated the propagation speed of the seismic effect (Michell J., 1759-1760). In 1847 J.J. Nöggerath and K.A.L. Schmidt calculated the propagation speed for the moderate Rhein earthquake (Nöggerath, 1847) and K.A. L. von Seebach did the same for the Central-German seismic event (Seebach, 1873). M. Nyrén, on May 10, 1877, observed a disturbance (duration 20s) in the level on the axis of the transit instrument at Pulkovo. Nyrén attributed this to an earthquake which had occurred 1h 14m earlier at Iquique (North-Chile), and calculated the rate at which the wave was transmitted across the Earth. Later on, M. Nyrén observed alterations in level at Pulkovo caused by further distant earthquakes (Milne, 1903). Already before 1889 seismographs also were used. The first seismograph was constructed in Italy by F. Cecchi in 1875, and the oldest known record with this device was obtained in 1887 (Dewey,Perry, 1969). The famous triad of British visiting scientists in Japan – J. Milne, J. Ewing and T. Gray– developed successful seismographs from 1879 (some of their devices were built with the use of horizontal pendulums), which were automatically recorded local seismic events since 1884 (Milne,1886, 1906).

What was really for the first time done by E. von Rebeur-Paschwitz, was the recording of a telemetric earthquake and the understanding the global character of seismological events. For this achievement he constructed an appropriate instrument much more sensitive than its precursors. That is why the birth of modern global seismology can be connected to his activity. E. von Rebeur-Paschwitz's merit is also the fact that he recognized that the study of seismic events is an excellent tool for the study of the Earth's interior, and that for this activity a global network of earthquake recording instruments is needed. Rebeur-Paschwitz confirmed J. Milne's forecast made in 1883:"…it is not unlikely that every large earthquake might be with proper appliances recorded at any point at the land-surface of the globe". Stimulated by E. von Rebeur-Paschwitz's observations, J. Milne also recorded distant earthquakes in Tokyo during 1893-1895 with his own seismograph and continued this activity till he returned to Great Britain (Davison, 1927).

At the same time E. von Rebeur-Paschwitz continued to work on his original determination to study earth tides. He published his results obtained in this field in 1892 (Rebeur-Paschwitz, 1892). As it was concluded by J. Milne (1896) "Von Rebeur found, after a careful analysis of his records, that …. at certain stations in Japan a slight superimposed lunar effect may be detected". From his own data at first glance the earth tides cannot be seen. The diurnal luni-solar variations are masked by daily temperature and barometric disturbations. The situation was somewhat more satisfactory in case of semi-diurnal tidal waves. In spite of these difficulties E. von Rebeur-Paschwitz was the first who detected the earth tides with the use of an instrument.

4. A note on the beginnings of international seismology, on the earth tidal activities in the frame of International Seismological Association (ISA), forerunner of the IASPEI.

The necessity of international cooperation in seismology was first recognized by E. von Rebeur-Paschwitz, when he understood the importance of earthquake research in the discovery of the internal structure of the Earth. He proposed to install a global network of seismological stations for the observation of seismic activity of the Earth (Rebeur-Paschwitz, 1895). The professor of geography in Strassburg between 1875-1910, G. Gerland, presented von Rebeur-Paschwitz's ideas at the 6th International Geographic Conference which took place in London in 1895. The participants of the Conference supported the proposal for international cooperation in seismology. Gerland prepared for the 7th International Geographic Conference in Berlin (1899) a proposal to establish an international seismological association which should promote worldwide macroseismic studies organize a global microseismic network and support publication of seismological contributions. The conference supported the suggestion and founded a Permanent Commission for Earthquake Research. In 1901 Gerland organized in Strasbourg the First International Conference on Seismology (1901) (Gerland, 1905) which proposed an International Association of States with a Permanent Commission, a General Assembly and a Central Bureau (Schweitzer, 2002). This structure was similar to the structure of the International Geodetic Association, founded in 1862. The Second International Conference on Seismology took also place in Strasbourg in 1903. During this meeting the statutes and the organization of the International Seismological Association (ISA) were elaborated in a draft also, which after finalization on a session in Frankfurt (October 1904) became a part of the statute signed during the Third International Conference on Seismology in Berlin (August 1905) by 22 representatives of 15 states and which should be valid till March 1916 (Agamennone, 1905). ISA organised five conferences in Rome (1906), The Hague (1907), Zermatt (1909), Manchester (1911) and Strasbourg (1922) which were important for the development both in seismology and earth tidal investigations (Kövesligethy 1906,1907,1909,1911,1922).

During these meetings, besides the seismological problems, the questions related to earth tides were also discussed. Let us see, for example some facts on the activity of O. Hecker in the ISA. He informed the Third Conference of the ISA Permanent Commission (Zermatt, 1909) on his two year long tidal records carried out in Potsdam (Klotz,1909). At the conference in Manchester (1911) a discussion took place on the possible reason of disparity of the results of earth tidal observations of O. Hecker in N-S and E-W directions. A. E. H. Love explained the phenomenon by the indirect effect of oceanic loading. In the frame of the ISA a special commission was organized for the study of earth tides under the leadership of O. Hecker, who was after the retirement of G. Gerland in 1910, the director of the Central Bureau of the ISA in Strasbourg.

5. Earth tidal observations carried out before 1914 with the use of horizontal pendulums.

After the early death of E. von Rebeur-Paschwitz in 1895 his work was continued by R. Ehlert in Strasbourg. The three Rebeur-Paschwitz type horizontal pendulums modified by him (with angles 120° between them) were installed on the same platform. The new instrument had increased in size and weight. The new Rebeur-Ehlert pendulums were built by the J. and A. Bosch company in Strasbourg and used later on in many seismological observatories. The first trustable observations of horizontal earth tidal variations were carried out by geodetist-seismologist O. Hecker in Potsdam (Telegraphenberg) in a gallery at the depth 26 m under the surface (Torge, 2007). For his observations he developed new horizontal pendulums of significantly larger size than earlier solutions. Hecker used the suspension suggested by Zöllner in 1873 (O. Hecker, 1896), what allowed him to solve the abrasion problem in the suspension, which reduced the stability of instruments of E. von Rebeur-Paschwitz and R. Ehlert. O. Hecker significantly damped the barometric effect acting on the instrument, and with the use of deep underground premises to install his horizontal pendulums he could effectively reduce the temperature effect which was deforming significantly the recorded tidal curves of his foregoers. These innovations led to the observation of the luni-solar tilt with accuracy of ≤ 0.01 arc second. O. Hecker progressively increased the length of his observations (Hecker, 1907; Hecker, 1911*)*. In this way the effective shear modulus was obtained for the Earth from direct instrumental observation of earth tides. O. Hecker was the first who detected the difference between the results of earth tidal observations (in Europe) in N-S and E-W directions, which he explained by the influence of ocean loading. Beside O.

Hecker in Potsdam W. Schweydar also carried out tiltmeter observations (Schweydar, 1912). It should be mentioned here that W.Schweydar was probably the first (in 1914), who carried out earth tidal observations using a gravimeter (Torge, 2007). In Russia I.E. Kortazzi, director of Naval Observatory in Mikolaiv, as early as in 1892, received a horizontal pendulum from E. von Rebeur-Paschwitz, fixed it in the basement premises of the observatory, and obtained interesting results in 1894. Before 1910 A.Ya. Orlov (University of Jurjev, today Tartu) started horizontal pendulum measurements also. The results of earth tide observations obtained before the 1st WW by the afore mentioned authors with the use of horizontal pendulums are summarized in Table 2.

It can be concluded that the horizontal pendulum observations before 1914 had amplitude ratios showing that the Earth's rigidity is of the order of that of the steel. At the same time, the majority of them is different from the γ- values recorded recently and from theoretically expectable ones.

6. Observations of the horizontal components of the earth tides carried out on large scale water levels. The Michelson-Gale experiment.

The development of earth sciences demands a more accurate determination of the elastic shear modulus of the Earth and, additionally, its viscosity. Two professors of Chicago University, T. C. Chamberlin (Professor of Geology) and F. R. Moulton (Professor of Astronomy), who developed earlier convincing arguments against Laplace nebular hypothesis and published a comprehensive 'planetesimal theory' of the origin of the solar system in 1905 (Brush, 1977), needed some definite data on elasticity and plasticity of the Earth. Through them, A.A. Michelson, Professor of the same University, became interested in the problem of observation of earth tides. The experimental works organized by Michelson had started in August 1913 ended in September by recording preliminary series in E-W direction and soon it became evident that the method was capable of yielding very accurate results. Therefore, in order to supplement the work, observations in N-S direction were realized in September-November of the same year. The preliminary series were observed till the end of November (Gale, 1914). A.A. Michelson's idea was to replace the pendulum by a long horizontal water level, and to use the measure the changes of water level at its ends. This instrument was the first water tube tiltmeter. The two half-filled water tubes were 150 meter long and had a diameter of 15cm. They were submerged at a depth 1.8 m at the grounds of Yerkes Observatory. The first series were carried out by measuring, with a microscope, the distance separating the point from its image obtained by total reflection in the liquid. The installation and the visual observations at both ends of the tubes (hourly or every two ours during night-time) were carried out by H.G. Gale while the calculations of the theoretical tidal curves for an absolutely rigid Earth with the use of Ephemeris were carried out under the direction of F.R. Moulton. The observations were interrupted by the World War I. The first results published before the World War gave an amplitude ratio $\gamma \approx 0.7$ as the mean of E-W and N-S components while for the mean phase shift 1.8 minute was obtained. Consequently, for the "mean" rigidity of the Earth $8.6 \cdot 10^{11}$ and for the viscosity $10.9 \cdot 10^{16}$ was obtained (in CGS units, of course). The results were published in the Journal of Geology and in the Astrophysical Journal for March 1914 (H.G. Gale, 1914*)*. The value obtained for N-S direction was recalculated in 1919 because of some calculation errors. The new value - $\gamma_{N\text{-}S}$=0.71- exactly equal to E-W ratio (Michelson, Gale, 1919a). The second series of observations was carried out from 20 November 1916 till 20 November 1917 using the interferential method of Michelson and the fringes were recorded on a film at a speed of 2cm/h. These observations led to $\gamma_{N\text{-}S}$=0.72; $\gamma_{E\text{-}W}$=0.66, while the corresponding phase delays were -0.4 hour and 1 hour (Michelson, Gale, 1919b). The recordings of Michelson and Gale were the first which gave results of the accuracy necessary for modern studies of the physics of the Earth.

7. The development of strainmeter by H. Benioff and of seismographs by L.J.B. LaCoste in the thirties of XXth century.

There were two significant steps forward during the thirties of XXth century, which were influencing the general development both in seismology and in study of earth tides.

The first is connected to the development of the strainmeter by H. Benioff . The idea of the relative movement of neighbouring points relative to each other was considered first by J. Milne in 1885. He constructed an instrument to measure the relative motion of two neighbouring points at ground of distances (1-3) m, i.e., a strain seismometer. Somewhat later, in 1900, E. Oddone also proposed instrument to measure deformation of the rocks between two points at a distance of few meters (Dewey, Beyerly, 1969*)*. The first strainmeter which was successfully used in recording seismic events and was able to record earth tides also was built by H. Benioff before 1930 and described in the Year Book of the Carnegie Institute of Washington No 29 (1929-30) and subsequent issues (Benioff, 1935). This device was the first instrument being not of pendulum type used in seismology. It improved significantly the earth tide observations. The strain seismometer measures the variation in the distance between two points, 25 m apart, caused by the passage of seismic waves. H. Benioff's recording was electromagnetic, the original galvanometer period being 40 sec, and was subsequently increased to 480 sec. His strain seismograph was the first to record earth motions with periods up to the order of hours, such as the longest mode of the free oscillations of the Earth after the Kamchatka earthquake in 1952. The bars used by Benioff originally were made from ceramics; during the fifties the fused quartz tubes were introduced with a capacitive tranducer for recording tidal and seismic strains (Benioff, 1959). With this type of Benioff-type horizontal strainmeter the first exploitable low-degree free oscillations of the Earth after the Chilean earthquake of 1960 (Benioff et al., 1961) were recorded. The quartz tube rod strainmeters are still in use in many countries worldwide. According to Bilham (1973) during the 1970'ies there were more than 100 strainmeter stations in use worldwide. In the United states in 1975 these instruments were in use at seven locations. At this time a significant number of strainmeters was used in the Soviet Union (Latinina L.A., Karmaleeva R.M., 1978). In the middle of eighties there were 25 strainmeter stations operated around the world (Varga, 1984).

The second important development during the thirties was made by L. J. B. LaCoste, who published a paper in 1935 on his zero-length-spring seismometer (LaCoste, 1934;L.J.B. LaCoste, 1935). L.J.B. LaCoste studied at the University of Texas (Austin) and obtained his doctorate in 1933. His professor A. Romberg gave each student a different technical problem to solve. L.J.B. LaCoste's was to design a long-period vertical seismometer. L.J.B. LaCoste made a suspension where the spring exerted a force proportional to its length. Using this idea he and A. Romberg built a seismometer superior to any instrument available. The majority of long-period vertical seismographs built during the next 50 years employed LaCoste's suspension. Since 1939 L.J.B. LaCoste and A. Romberg started to use this principle to built gravimeters. The first model weighted 40 kg and needed a two-man screw. In 1942 the LaCoste and Romberg Company produced a smaller, one man operated, model, in 1946– the underwater meter, in 1954– a submarine gravimeter, in 1960– a G meter (8.5 kg). In 1965– the S (submarine meter), in 1970– D meter, in 1970s– lunar gravity meter, in LCR ET earth tide recording meter before 1975, in 1978 – borehole gravimeter and in 1983–marine gravity sensor with fluid damping (Source: EOS, December 12, 1995, 516). The LaCoste-Romberg (LCR) gravimeters were used by different research teams during and since the Chilean earthquake (1960) for observation of free oscillations of the Earth. In the same time the LCR ET instruments produced the best records of gravity Earth tides before the advent of superconductive gravimeters. Many of these instruments are still used in different geodynamical observatories in many countries, and competiting with SGs in some cases (Zürn et al., 1991).

8.Closing remarks

The interference of seismology and tidal research was preserved during the XXth century, which allowed evolvement our knowledge on Earth interior. With the advent of very broad band seismology and superconducting gravimeters (SGs) in earth tide research new forms of interactions appeared. Data from SGs have shown great capabilities in long-period seismology. Investigation of SGs-records in the seismic band has demonstrated that they are particularly well suited for the studies of the long-period normal modes and thus are complementary to long-period seismometers (Rosat et al., 2004). At stations of the Global Seismographic Network (GSN) the earth tides will be observed (Davis, & Berger, 2007). The new very broad band seismographs, besides recording seismological signals are able to record tides of the solid earth reliably.

Acknowledgements

Erwin Groten is thanked for helping to develop the manuscript. This work received financial support from the Hungarian Science Found OTKA (Project No.: K 60394). The author acknowledges with thanks support obtained in the frame of the bilateral project of the Deutsche Forschungsgemeinschaft and of the Hungarian Academy of Sciences (436 UNG 113/133/0-1).

References

Agamennone, 1905, Le riunione di Francoforte s.M. nell ottobre 1904 é la III[a] conferenza sismologica internazionale tenta a Berlino nell' agosto 1905, Bolletino della Soc. Sism Ital., XI, 3-17

Benioff H., 1935. A linear strain seismograph, Bulletin of the Seismological Society of America, 25,4, 283-309

Benioff H, 1959. Fused-quartz extensometer for secular tidal and seismic strains, Bulletin of Geological Society of America, 70, 8, 1019-1032

Benioff H., Press F., Smith S., 1961.Excitation of the free oscillations of the Earth by earthquakes, Journal of Geophysical Research, 66, 605-619

Bilham R., 1973. The location of Earth strain instrumentation, Philosophical Transactions of the Royal Society, London, 274, 1239, 429-433

Brush S.G., 1977. The origin of the planetesimal theory, Origins of Life and Evolution of Biospheres, 8, 1, 3-6

Brush S.G, 1980. Discovery of the Earth's core, American Journal of Physics, 48, 705-724, Brush S.G, 1981. Earth's cores, Science, New Series, 213, 4511, 950

Buntebarth G., 1981. Eine kleine Historie zur Namengebung der Fachdisziplin Geophysik, Journal of Geophysics, 49, 247-248

Burchfield D., 1974. Darwin and dilemma of geological time, Isis, 65, 301-321

Darwin G.H., 1881. On an instrument for detecting and measuring small changes in the direction of the force of gravity, British Association Report 93-126

Darwin G.H., 1898. The tides and kindered phenomena in the solar system, Boston and New York

Darwin G.H.,1907.Scientific Papers, Cambridge University Press, Vol. I, 389-429

Davis P., Berger J., 2007. Calibration of the Global Seismographic Network Using Tides, Seismological Research Letters*,* 78, 4, 454-459; DOI: 10.1785/gssrl.78.4.454

Davison C., 1927. The founders of seismology, Cambridge, University Press, 240 p.

Dewey J., Byerly P., 1969. The Early History of Seismometry (to 1900), Bulletin of the Seismological Society of America, 59, 1, 183-227

Ehlert R., 1898. Zusammenstellung, Erläuterung und kritische Beurtheilung der wichtigsten Seismometer mit besonderer Berücksichtigung ihrer praktischen Verwendbarkeit. Beiträge zur Geophysik 3, 350-475

EOS, December 12, 1995, 516

Gale H.G., 1914. On an experimental determination of the Earth's elastic properties, Science,39, 1017, 927-933

Gerland G., 1905. Gründung, Organisation und Aufgaben der internationalen Seismologischen Assoziation, Beiträge zur Geophysik für physikalische Erdkunde, VII, 469-479

Hecker O., 1896.Das Horizontal Pendel, Zeitschrift für Instrumentenkunde, 16, 2-16

Hecker, O., 1907. Beobachtungen an Horizontalpendeln über die Deformation des Erdkörpers unter dem Einfluss von Sonne und Mond. Veröffentlichung des Königl. Preuszischen Geodätischen Institutes 32, Berlin

Hecker O., 1911. Beobachtungen an Horizontalpendeln über die Deformation des Erdkörpersunter dem finfluss von Sonne und Mond, Veröffentlichungen der Königliches Preuszischen Geodätischen Institutes 49

Jeffreys H., 1926. The rigidity of the Earth's central core, Monthly Notices of the Royal Astronomical Society, Geophysical Supplements, 1, 371-383

Klotz O., 1909.Report of the Permanent Commission of the International Seismological Association, Science, 32, 815, 199-200

Kövesligethy R. (Ed.), 1906. Comptes Rendus des séances de la première réunion de la Commission Permanente de l'Association Internationale de Sismologie, Réunion a Rome du 16 au 20 octobre 1906, Budapest, Hornyánszky, 1906

Kövesligethy, R. (Ed.), 1907. Comptes Rendus des séances de la de deuxième réunion de la Commission Permanente et de la première assemblée générale de l'Association Internationale de Sismologie, Réunion a La Haye du 21 au 25 septembre 1907, Budapest, Hornyánszky, 281 p.,1907

Kövesligethy, R. (Ed.),1909. Comptes Rendus des séances de la troisième réunion de la Commission Permanente de l'Association Internationale de Sismologie, Réunion a Zermatt, du 30 août au 2 septembre 1909, Budapest, Hornyánszky, 206 p.,1909

Kövesligethy, R. (Ed.), 1911. Comptes Rendus des séances de la quatrième conférence de la Commission Permanente et de la deuxième assemblée générale l'Association Internationale de Sismologie, Réunies a Manchester, du 18 au 21 juillet 1911, Budapest, Hornyánszky, 307 p.,1911

Kövesligethy, R. (Ed.), 1922. Comptes Rendus des séances de la cinquième conférence de la Commission Permanente et de la troisième et dernière assemblée générale, assemblée générale de dissolution de l'Association Internationale de Sismologie, Réunion a Strasbourg, les 24 et 25 avril1922, , Budapest, Hornyánszky, 81 p., 1922

Kushner D., 1993. Sir George Darwin and a British school of geophysics, Osiris, 8, 196-224

LaCoste L.J.B. , 1934. A New Type Long Period Vertical Seismograph,Journal of Applied Physics 5, 178

LaCoste L.J.B., 1935. A simplification in the conditions for the zero-length-spring seismograph, Bulletin of the Seismological Society of America, 25, 1, 176-179
Latinina L.A., Karmaleeva R.M., 1978. Deformation measurements, Nauka, Moscow, 154 p. (in Russian)
Love A. E. H., 1909. The Yielding of the Earth to Disturbing Forces*,* Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*,* Vol. 82, No. 551, 73-88
Lynch J., SJ., 1940. What is the state of the Earth's core? Bulletin of the Seismological Society of America, 30, 1, 337-341
Melchior P., 1978.The tides of the planet Earth, Pergamon press, 609 p.
Michell J., 1759-1760:Conjectures concerning the Cause, and Observations upon the Phaenomena of Earthquakes; Particularly of That Great Earthquake of the First of November,1755, Which Proved So Fatal to the City of Lisbon, and Whose Effects Were FeltAs Far As Africa, and More or Less throughout Almost All Europe, Philosophical Transactions, 51, 566-634
Michelson A. A., 1914. Preliminary results of measurements of the rigidity of the Earth, The Astrophysical Journal, XXXIX, 2, 105-138
Michelson A.A., Gale H.G., 1919a. The rigidity of the Eart, Science, 50, 1292, 327-328
Michelson A.A., Gale H.G., 1919b. The rigidity of the Earth, The Astrophysical Journal, L, 330-345
Milne, J., 1886. Earthquakes and other earth movements, London, Kegan Paul, Trench & Co., 1886
Milne J., 1896. Movements of the Earth's Crust, The Geographical Journal, 7, 3, 229-247
Milne J.,1903. Seismological observations and the Earth physics, The Geographical Journal, 21, 1, 1-22
Milne J., 1906. Recent advances in seismology, Proceedings of the Royal Society of London, Series A, containing Papers of a Mathematical and Physical Character, 77, 518, 365-376
Nöggerath J.J.,1847. Das Erdbeben vom 29 Juli 1846 im Rheingebiet und denbenachbarten Ländern, Bonn, 60 p
Oldham R. D., 1906. The constitution of the interior of the Earth, as revealed by earthquakes. Quarterly Journal of the Geological Society of London, 62, 456-473
Rebeur-Paschwitz E.von, 1892.Das Horizontalpendel und seine Anwendung zur Beobachtung der absoluten und relativen Richtungs-Aenderungen der Lothlinie, Nova Acta der Ksl. Leop.-Carol. Deutschen Akademie der Naturforscher**,** LX, 1, Halle, 216 p.
Rebeur-Paschwitz, 1895. Vorschläge zur Errichtung eines internationalen Systems von Erdbeben-Stationen, Beiträge zur Geophysik für physikalische Erdkunde, II, 773-782
Rosat S., Hinderer J., Crossley D., J.P. Boy J.P., 2004. Performance of superconducting gravimeters from long-period seismology to tides, Journal of Geodynamics, 38, 3-5, 461-476
Schweitzer J., 2002. Early German contributions to modern seismology, In: International handbook of earthquake and engineering seismology, Chapter 79.24, Part A, 36 p.
Schweydar W., 1912.Untersuchungen über die Gezeiten der Festen Erde, Potsdam, 1912, Leipzig, B.G. Teubner
Schweydar W., 1916:Theorie der Deformation der Erde durch Flutkräfte, Veröffentlichung des Königlich Preuszischen Geodätischen Institutes, neuc Folge, No. 66
Seebach K.A.L. von, 1873. Das mitteldeutsche Erdbeben vom 6 Märtz 7 1872, 192 p.
Thomson W., 1863a. On the rigidity of the Earth, Philosophical Transactions, 153, 573-582
Thomson W., 1863b. Dynamical problems regarding elastic spheroidal shells and spheroids of incompressible liquid, Philosophical Transactions, 153, 583-616
Thomson W. , TaitP.G, 1883. Treatise on Natural Philosophy, 2nd edition, Oxford
Torge W., 2007. Geschichte der Geodäsie in Deutschland, Walter de Gruyter380 p.
Varga P., 1984. Long-term variations recorded by extensometers. Journal of Geophysics, 55, 68-70
Vocilka W., 2008.Ernst von Rebeur-Paschwitz oderDie Karlsruher Sternwarte im Erbprinzengarten, Die Stadtmitte, 29, 2, 5-8
Zürn W.,. Wenzel H.-G., Laske G., 1991. High quality data from LaCoste-Romberg gravimeters with electrostatic feedback: A challenge for superconducting gravimeters. Bull. d'Informations Marees Terrestres, 110, 7940-7952
Zöllner F., 1873.Beschreibung und Anwendung des Horizontalpendels, Annalen der Physik und Chemie, CL, 134-140

Table legends

Table 1. Amplification of some historical seismographs (1879-1947).

Table 2. Results obtained before World War I with the use of horizontal pendulums (Schweydar, 1912). The results are based possibly on wave M_2, though this mentioned by the author. In the table γ=1+k-h is the observed amplitude ratio, while κ is the phase shift.

Instruments of XIXth century

INSTRUMENT TYPE	Year	Amplification
Ewing, simple pendulum	1879	6
Ewing, horizontal pendulum	1883	4-6
Gray Ewing vertical	1882	6
Rebeur-Paschwitz, horizontal	**1889**	**100**
Agamennone horizontal	1893	10
Cancani horizontal	1894	10
Vicentini horizontal	1897	80
Vicentini vertical	1898	130
Milne horizontal	1894	6
Grablovitz horizontal	1896	8
Omori-Bosch horizontal	1899	10

Instruments of 1900-1947

INSTRUMENT TYPE	Year	Amplification
Wiechert 1000 kg, horizontal	1904	200
Mainka 135 kg	1908	60
Mainka 450kg	1908	250
Galitzin horizontal	1911	1000
Galitzin vertical	1910	1000
Milne horizontal	1915	150-250
Quervain-Piccard 3comp., 21 t	1924	1500
Quervain-Piccard ransportable	1913	180
Anderson-Wood	1925	2800
Kirnos horizontal	1945	1000-2000
Kirnos vertical	1947	1000-2000

Table 1

Author		γ	κ
Rebeur-Paschwitz		0.362	7°30’
Kortazzi		0.608	0°
Ehlert		0.448	12.1°
Schweydar		0.338	-8°31’
Hecker	N-S	0.643	-11,9°
	E-W	0.259	-7.0°
Orlov	N-S	0.412	0.8°
	E-W	0.326	3.2°

Table 2