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ORIGINAL ARTICLE

Horizontal pendulum development and the legacy of Ernst von Rebeur-Paschwitz

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Abstract Horizontal pendulum development was paramount in the birth of modern instrumental seismology and solid-earth tide study. This paper presents a revised history starting in the first part of the nineteenth century and culminating with Rebeur-Paschwitz's masterpiece in its latter part. The first stage began with the invention of the horizontal pendulum by Lorenz Hengler in 1832. He was followed by several, mostly independent, inventors during the three decades from the 1850s to the 1870s, in particular Friedrich Zöllner in 1869–1872 who popularized this instrument. With the exception of an instrument designed by Alexander Gerard in 1851, all these preliminary pendulums were suspended with two wires. Slightly different forms of horizontal pendulums were invented in Japan by James Ewing and Thomas Gray in the early 1880s, based on bracket or conical suspensions. The merit of demonstrating the outstanding potential of high-sensitivity horizontal pendulums completely relies on the work of Ernst von Rebeur-Paschwitz between 1886 and 1895. He successively developed three models of pendulums, in collaboration with three different manufacturers: the Fecker pendulum in 1886, the Repsold pendulum in 1888, from which six copies were produced, and finally, the Stückrath two-component model in 1894, built in three copies. Based on the scrutiny of a large number of previously unexploited archives, the detailed chronology of Rebeur-Paschwitz's achievements is presented. Archive, and in situ explorations allowed us to discover five out of the six original copies of the first Rebeur-Paschwitz's Repsold pendulum previously unknown or thought to be lost.

Keywords Horizontal pendulum · Historical seismology · Rebeur-Paschwitz · Repsold · Stückrath

1 Introduction

Nowadays, the prominent role of pendulums in the development of modern science is often overlooked (Matthews et al. 2005). For three centuries beginning with Galileo's publication in 1638, pendulums were the basic tools for measuring two fundamental quantities, time and gravity. The first pendulum clocks were built by Huygens in 1656 and were then gradually perfected until the twentieth century, culminating in 1921 with Shortt's astronomical regulators accurate to about 3×10^{-8}. The length of the so-called seconds pendulum, whose period actually is 2 s, was considered in the seventeenth and eighteenth century for the definition of the meter. At the turn of the nineteenth

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century, it became the universal instrument of gravimetry. The simple pendulum was often used as an elementary seismoscope (Bina 1751; Ferrari 1992). However, it was not before the 1830s that the idea of tilting the pendulum emerged with the invention of the horizontal pendulum (Hengler 1832a). This allowed the reduction of apparent gravity, thus increasing its natural period, a similar approach to that of Galileo more than two centuries earlier when he used an inclined plane to study the motion of falling objects. A practical demonstration was later performed with Mach's pendulum (Mach 1883, p 158). The horizontal pendulum signaled a revolution in earth sciences giving birth to quantitative instrumental seismology (seismometry) and allowing the investigation of solid-earth tides. In this paper, we investigate the detailed history of the horizontal pendulum over a period of 65 years following its invention in 1831. New archive and field findings allow us to document its development in Germany and its spreading eastwards to Russia and Japan.

2 The horizontal pendulum invented

During the nineteenth century, various types of horizontal pendulums were developed independently in different regions of the world: France, Germany, Japan, UK, and USA (Dewey and Byerly 1969; Ferrari 1990; Agnew 2002). We will focus here on the discovery of the first horizontal pendulums (Table 1), followed by the pioneering contribution of Ernst von Rebeur-Paschwitz. The main lines of the early developments have already been presented in numerous articles and textbooks (e.g., Tams 1950; Melchior 1966; Dewey and Byerly 1969). They all refer to the names of Gruithuisen, Hengler, Perrot, and Zöllner and rely mostly on a series of papers published by Zöllner and colleagues between 1869 and 1873 and reprinted in 1873 in Poggendorff's Annals—*Annalen der Physik und Chemie* (Zöllner 1869, 1871, 1872; Safarik 1872; Zech 1873). We found and exploited several today unknown, uncited, or forgotten documents that enlighten the process of the discovery and consecutive vanishing of several of these instruments.

2.1 Gruithuisen's and Stark's elkysmometers

The first horizontal pendulum ever built was invented by Lorenz Hengler (1806–1858), a student of Franz Gruithuisen (1774–1852). Gruithuisen was a German astronomer and physician. The son of a Dutch falconer, he first received an education and worked as a barber (Zajaczkowski et al. 2003). In 1800, he was granted a fellowship by the Bavarian prince Karl Theodor and pursued university studies in Landshut until 1808. He then became a teacher with the Medical School of Munich and was eventually appointed Professor of Astronomy in the newly created Munich University in 1826, a position which he held until his death. Gruithuisen published a wealth of scientific papers and books, both in the medical and astronomical fields. He was a very imaginative scientist. This led him sometimes beyond common sense, particularly in his studies of the Selenites—the inhabitants of the moon. Nonetheless, a few of his discoveries and theories led to important breakthroughs. In 1812, he built several vertical pendulums, which he used to observe small deviations of the vertical (Gruithuisen 1812, 1817). This instrument was named the "elkysmometer" (from Greek elkysmos, meaning attraction). He observed the position of the 15-ft suspending wire by means of a wind rose drawn on a paper surrounding the wire. He found evidence of a 24-h period of oscillation, which, he believed, had its cause in the back-and-forth acceleration of a point at the rotating earth's surface. This was a misconception since the acceleration due to the rotation of the earth continuously points towards the earth's rotation axis, thus causing only a constant deviation of the vertical. It is well known nowadays that only extremely tight environmental isolation in an underground setting allows effective protection against the diurnal variations of temperature and humidity—not to mention pressure variations whose effects cannot be completely avoided. On some occasions, erratic movements of the pendulum occurred, which he associated with local or remote earthquakes (Gruithuisen 1813, 1817). He observed an earthquake on his pendulum that originated in Friuli (Italy) on 25 October 1812, at an epicentral distance of 250 km (I_o=VI–VIII MCS). His account of the record of an earthquake in Jamaica on 11 November 1812 (estimated magnitude, 6.75 Mw) is more than questionable: firstly because his observation was unclear, and secondly because from his report, the observation was made at about 10:15 GMT or earlier, whereas the earthquake origin time was 10:50 GMT (Shepherd and Lynch 1992). His claim that he could observe teleseismic events with his vertical pendulums is thus certainly erroneous.

Table 1 Summary of horizontal pendulums 1831–1896

Scientist	Date	Locations	Type	Observation method	Manufacturer
Hengler	1831	Munich	Wires	Microscope	
	1831	Munich	Wires, tabletop	Diopters	Weissenbach
Gerard	1851	Aberdeen	Conical	Direct	
Perrot	1862	Paris	Wires	Direct	
Zöllner	1869	Leipzig	Wires	Scale + Telescope	
	1870	Leipzig	Wires	Scale + telescope	
Close	1869	Dublin	Wires	Direct	
Rood	1875	New York	Wires, damping	Scale + telescope	
Ewing	1880	Tokyo	Bracket	Smoked glass plate	
Gray	1880	Tokyo	Bracket	Direct	
Gray	1881	Tokyo	Conical	Smoked plate/drum	
Ewing	1883	Dundee, etc.	Bracket	Smoked glass plate	Cambridge Sc. lnstr. Co.
Gray and Mime	1883	Tokyo, etc.	Conical	Smoked paper	James White
Rebeur-Paschwitz	1886	Karlsruhe	Points	Scale + telescope	Fecker
	1887			Photographic	
	1888	Potsdam, Wilhelmshaven	Points	Photographic	Repsold
	1890	Tenerife			
	1892	Kharkov, Nice, Nikolayev, Strasbourg			
	1895	Merseburg	Points, Biaxial	Photographic	Stückrath
	1896	Potsdam, Tartu			
Omori	1896	Tokyo	Points, Biaxial	Photographic	Repsold

Date=year of delivery or installation

Another elkysmometer was installed by Gruithuisen's acquaintance, Augustin Stark (1771–1839), an astronomer in the nearby town of Augsburg (Helms 2007) to record earthquakes. Stark's pendulum was 15 to 30 ft long and was carefully isolated from air disturbances by completely enclosing it in a 4-in.-wide rectangular wooden pipe and a similar glass pipe at its bottom end (Stark 1815). This instrument was used by Stark and his successors to observe and document regional earthquake occurrences in their meteorological yearbooks for at least the next 40 years (Stark 1814–1836; Plieninger 1852). Thus, Gruithuisen and Stark can be credited for building the first seismometer able to record regional-distance earthquakes.

In his *Analekten* (a title meaning "Reviews" or "Excerpts"), Gruithuisen (1828) suggested building a deep underground astronomical observatory. One of the instruments planned was a very long elkysmometer—several hundred feet long. He suggested observing the pendulum from a distance by means of a telescope and damping the oscillations by immersing the suspended weight in an oil bath. But Gruithuisen obviously never installed such an instrument. Indeed, shortly after he became Professor of Astronomy, one of his students named Hengler investigated the deviations of the vertical. Hengler dramatically improved the precision of the elkysmometer by inventing the horizontal pendulum in 1831.

2.2 Hengler

Lorenz Hengler was born in a modest farming family (Zech 1873; Boegehold 1937). During his youth, he managed to study in several religious schools. He eventually went to Munich where he spent one semester at the University studying mathematics and astronomy in the winter of 1830–1831. He was forced to give up his studies through lack of financial support and worked in an optical workshop in Stuttgart in 1831–1832. On 13 August 1831, Hengler presented a communication before the Bavarian Academy of

Science in which he described his invention: the horizontal pendulum (Anonymous 1833). In an accompanying paper, he developed the basic theory and presented his first observations (Hengler 1832a). Hengler named it the *Astronomische Pendelwage* (astronomical pendulum balance). Indeed, it can somehow be considered as a balance where the counterweight is replaced by a wire attached to a fixed point below. The pendulum consisted of a boom suspended in nearly horizontal equilibrium by two wires, one leading upward, the other downward to two fixed points (Fig. 1 in Online resource 1). This design is exactly what is known today as the Zöllner suspension (Dewey and Byerly 1969). However, a few details of Hengler's pendulum construction differ from Zöllner's. Firstly, it was much larger, being the size of the observation room. Secondly, Hengler observed the movements of the boom directly by means of a microscope and a scale placed at its end, while Zöllner used a telescope and a mirror attached to the boom to observe a remote scale (a technique first proposed by Poggendorff 1826). Hengler's pendulum was carefully isolated to avoid temperature and turbulence influences. The boom was made of brass and was suspended by means of two silk or metal threads. The whole instrument was isolated—probably using wooden tubes similar to Stark's implementation. He installed his 10-ft-long pendulum in a 16-ft-high room and adjusted the instrument such that its free period[1] was 10 min (a surprisingly high value even for today's standards). With the help of a ×100 magnifying microscope, the assumed resolution was around 10^{-5} arcsecond. During his 2-month long experiment beginning on 14 March 1831, Hengler observed a clear semi-diurnal period of oscillation in the east–west direction, which he assumed to be related to luni-solar attraction. He began his experiment at noon, at the new moon, on a day and at a time when the moon and the sun were nearly aligned at the Munich's zenith, and consequently, their effects cumulated.[2] The pendulum moved westwards from noon to 3 PM, then eastwards until 9 PM, then westwards again, returning towards its initial position shortly after midnight. Thus, his observations agree with the computed earth tide on this very day (Fig. 1), at least qualitatively, since Hengler did not give numerical values to his observed tilts. He also observed that the largest maximum of tilt occurred at the syzygies (new and full moon) and the smallest at the quadratures (first quarter and last quarter moon), as expected if the tilt is caused by the earth tides. However, his followers (Zöllner, Rebeur-Paschwitz) doubted strongly that Hengler could observe luni-solar attraction. The origin of the 12-h period observed by Hengler remains uncertain.

Hengler also designed a smaller tabletop horizontal pendulum—called the *Nivellirwage* (leveling balance)—which he had built by a mechanic called Weissenbach from Munich. This pendulum resembled Zöllner's design as it was built on top of a triangular base with two screws allowing adjustment of period and zeroing of the pendulum (Fig. 1 in Online resource 1). Since Hengler designed this pendulum as a leveling tool, it was also equipped with two sighting diopters. The instrument was exhibited at the Bavarian Academy of Science by Joseph von Baader, an engineer from Munich, during the same session as the horizontal pendulum on 13 August 1831. Hengler's work and article were praised by the Academy as highly valuable contributions. While engaged in a religious career, Hengler (1835) published a second article about the horizontal and vertical pendulums where he suggested damping the oscillations of the pendulum by means of a ball immersed in a container filled with water. From then on, Hengler's pendulum fell into oblivion until its rediscovery by Safarik (1872) following Zöllner's work.

It may seem surprising that Gruithuisen did not go on with horizontal pendulum observations. As a matter of fact, the link between Gruithuisen and Hengler is rather tenuous. Indeed, Hengler never referred to Gruithuisen in any of his known publications, and he did not publish in the *Analekten*, the periodical edited by Gruithuisen from 1828. Actually, Gruithuisen resorted to publishing this journal after the well-known *Astronomische Nachrichten* refused to publish his articles because of his flights of fancy about the Selenites (Herrmann 1968). The fact that Gruithuisen was so discredited by most German astronomers might explain why Hengler avoided appearing as his scientific disciple. Nonetheless, Hengler's achievements are obviously inspired by Gruithuisen's ideas about measuring gravity variations under luni-solar attraction and earth rotation with vertical pendulums. Gruithuisen (1832) clearly mentioned the invention of the horizontal

[1] Throughout this paper, we will use the word "period", rather than other confusing or ambiguous terms such as swing, oscillation, or beat, which were in use in several languages during the previous centuries, usually corresponding to half-periods.

[2] The new moon occurred precisely on 14 March 1831 at 05 h59 UTC, i.e. 06 h45 Munich Mean Time.

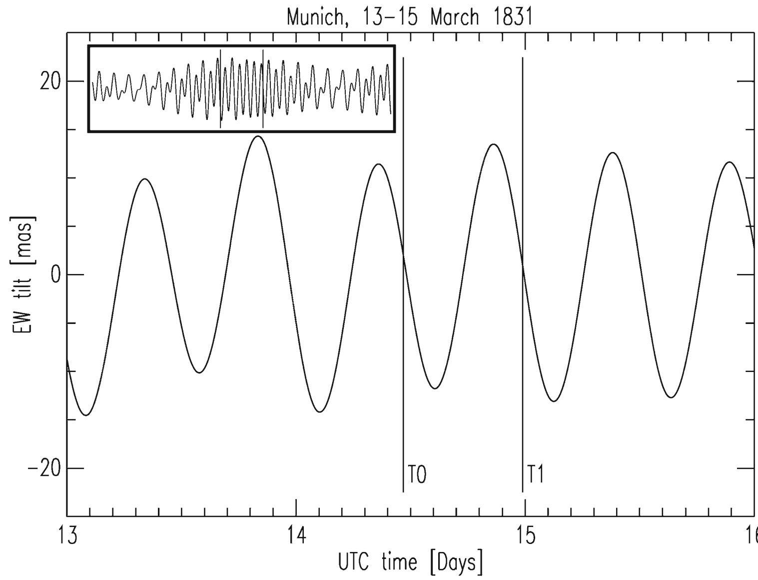


Fig. 1 Computed east–west ground tilt in Munich, Germany, from 13 to 15 March 1831, using the Ertid software (Agnew 1996). *Horizontal scale* is days; zero is 13 March 00 h00 UTC. *Vertical scale* is milliarcseconds, tilt to the east is positive. T_0 is the time when Hengler started his observations, on 14 March 12 h00 noon Munich Mean Solar Time (11 h14 UTC), until time T1, 12.5 h later. The *inset* shows the tilt variations between 4 March and 24 March

pendulum by his "student Hengeller" (sic). One could think that the mistyping of Hengler's name suggests that Gruithuisen did not know him very well and that he did not read his article. Similarly, he misnamed the instrument *Schwungwage* whereas the name given by Hengler was *Pendelwage*. However, Gruithuisen mentioned several details that are not revealed in Hengler's paper, e.g., that a cannonball placed close to the pendulum bob was able to deflect the boom through direct gravitational attraction.

From 1832 on, Hengler studied at the Faculty of Catholic Theology in Tübingen, until he became a priest in 1835. During the rest of his religious career, he continued to work in the field of optics and astronomy, building and selling refracting and reflecting telescopes with the help of his brother Matthäus. Besides his interest in astronomy and optics, Hengler is also known as an aeronaut. Already as a teenager, he began building small balloons during his school holidays. While in Munich, he prepared a large balloon that unfortunately burst into flames just after taking off (by chance the balloon was unmanned). A short time later, he invented a parachute, which he successfully tested by jumping from a balloon (Hengler 1832b).

2.3 Gerard-Perrot

Alexander Gerard (1811–1880) was a Professor of Mathematics at Robert Gordon's Hospital (now Robert Gordon University) in Aberdeen, Scotland (Smith 1913). He built several scientific instruments (e.g., a gyroscope, a portable transit instrument, a Foucault pendulum). In 1851, he contrived a horizontal pendulum with a new type of suspension, the conical pendulum (Gerard 1853). The wooden boom of his pendulum was held horizontally on one end by an oblique copper wire attached to the wall and on the other end by a sharp point resting against the wall (Fig. 2 in Online resource 1). The free period was about 30 s. Gerard observed a diurnal displacement of the bob reaching 5 mm, which he explained by unequal thermal expansion of the building, or by a hypothetical change in gravity through solar radiation. He abandoned his observations after some weeks.

The horizontal pendulum was reinvented by Perrot (1862a, b) more than 30 years after Hengler, apparently independently. Adolphe Perrot (1833–1887) was a Swiss physicist (not French as often stated). He studied in Paris between 1852 and 1862, and then returned to Geneva, Switzerland, where he worked in industry, manufacturing gas ovens (Wartmann 1887, 1888). Perrot introduced two instruments devoted to the accurate measurement of gravity. One was a gravimeter; the other was a horizontal pendulum with the same design as Hengler's. Perrot had a prototype built measuring 40 cm high. He submitted it to the French Science Academy and Meteorological Society in March–April 1862 and declared that its sensitivity was very satisfying. He added that he had been thinking about this problem since his teenage years. Unfortunately, it seems that Perrot deserted the horizontal pendulum a short time later when he returned to Geneva, where he got married in October 1863 and became a businessman.

2.4 Zöllner-Close-Rood

For the fourth time, the horizontal pendulum was reinvented in 1869. Zöllner (1834–1882) was a skilled German physicist and astronomer from Leipzig, where he had been Professor of Astrophysics since 1866 (Koerber 1899; Herrmann 1982). Zöllner invented several instruments, the most prominent being his astro-photometer in 1858 (Staubermann 2007) and the horizontal pendulum—a name he introduced. His travels to England in 1875 marked a turn in his career, since he devoted himself to the link between physics and spiritualism, which, together with his polemics against colleagues, ruined his relations with the scientific community.

Zöllner successively devised two slightly different horizontal pendulums. His first pendulum (Zöllner 1869) comprised a glass boom suspended by two steel wires attached to a brass tripod with adjusting screws. He measured the deflections of the boom by means of a mirror fixed to the boom, and a telescope and a scale placed at a distance of 2.5 m (Poggendorff's method, 1826). This instrument was installed in a 12-ft-deep cellar in the University building. Adjusting the free period at 104 s, the theoretical tilt resolution was 3.5 10^{-4} arcsecond, given a reading accuracy of 0.1 mm. Zöllner measured the tilt related to the filling and ensuing emptying of an amphitheater three stories above. The deflection reached 20 mm on his scale. Zöllner briefly mentioned that his pendulum could be used as a seismometer, given its great sensitivity, but he did not make any observation in this regard. The second pendulum (Zöllner 1871) was about twice as large as the first one, reaching a height of more than 60 cm (Fig. 2). The main difference was that Zöllner replaced the two suspension steel wires with two flat steel watch-springs. It was first installed in a small room he had discovered 15 ft below the previous cellar and later in the garden of the observatory. There, Zöllner had a pillar built, protected inside a double-walled cage, next to a small cupola that served as an observation room. He performed several series of measurements in 1870–1871. Based on the mirror-

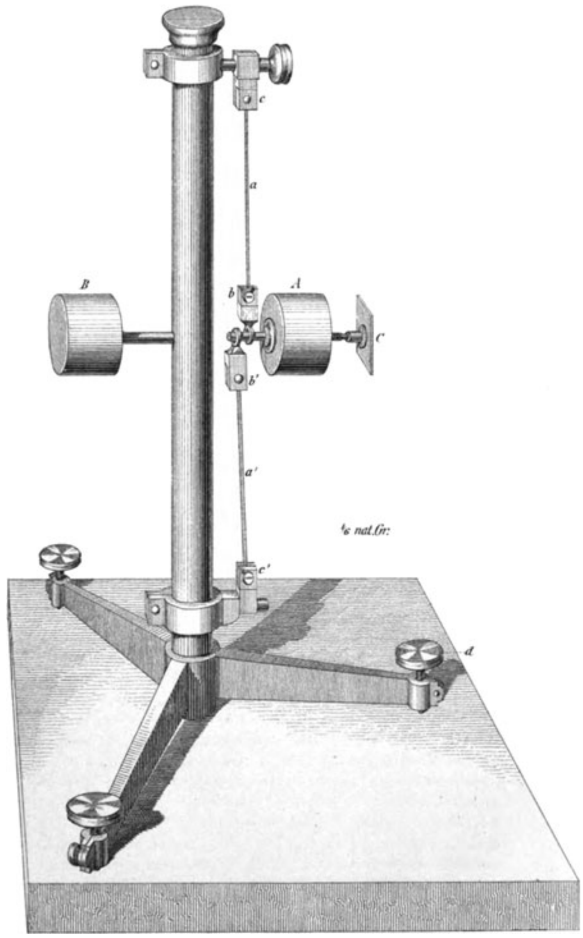


Fig. 2 Second Zöllner's horizontal pendulum (Zöllner 1871)

scale distance of 3.2 m and a free period of 28.9 s, the tilt resolution evaluates as 10^{-3} arcsecond. Zöllner observed scale deflections that were too large when compared with the expected luni-solar tilt variations (which do not exceed 0.05 arcsecond). He concluded that the observations needed to be carried out in a mine shaft in order to reduce the background noise. For some reason, he did not pursue this project and did not publish further about the horizontal pendulum. Rebeur-Paschwitz (1888c) mentions that he could not find evidence of later trials in Zöllner's handwritten *Nachlass* (scientific estate). He also relates that after Zöllner's death on 25 April 1882, his second pendulum was acquired by the Astrophysical Observatory in Potsdam and that a new series of observations was attempted there in 1886 by Paul Baltin (Rebeur-Paschwitz 1892b).

Much later, an Irish geologist in Dublin, Maxwell H. Close (1822–1903), claimed he had invented a horizontal pendulum in early 1869, a few months before Zöllner (Barrett and Brown 1892; Kennedy 1894). Close is known for his work on glaciations (Cole 1903, 1912). He was also interested in astronomy and, for example, published a note about the viscosity of the earth (Close 1870). But, as far as we know, Close did not write about his pendulum before 1894, and then he did it under a pseudonym (Claudius Kennedy) in the aforementioned book. He writes (p 96) that he installed his instrument "In the early part of the year 1869", while Zöllner set up his pendulum "In the same year 1869, and, to judge from his own words, in the middle part of the year." We could not find these words in Zöllner's papers. Zöllner introduced his pendulum on 11 November 1869 before the Saxon Society of Sciences, but says nothing about the date he installed his pendulum, which could well have occurred in 1868. Cole's pendulum differed slightly from the Hengler-Zöllner design in that the lower suspension wire was replaced by an upwardly directed wire connected beyond the center of gravity of the boom (Fig. 3 in Online resource 1). Close-Kennedy did not describe any observation performed with his pendulum; however, Barrett and Brown (1892) mention that Close installed it in the basement of a house and that the instrument was so sensitive that it went off-scale in strong winds.

The American physicist Ogden N. Rood did not claim his work was independent from Zöllner's when he devised his horizontal pendulum (Rood 1875), quite the contrary. A Professor of Physics at Columbia University, Rood had spent several years in Germany and was acquainted with German scientific literature (Anonymous 1903). He contrived a well-designed apparatus in which, for the first time, he introduced a damping mechanism through a small wire immersed in oil, as suggested by Gruithuisen and Hengler. The stand was made of brass, and the pendulum itself was suspended with two copper foils (Fig. 4 in Online resource 1). Rood made observations by means of scale and telescope like Zöllner. He used his pendulum as a laboratory physics instrument to measure small distances accurately rather than as a geophysical instrument.

2.5 Darwin

In 1880–1881, following a suggestion by William Thomson, or Lord Kelvin, the brothers George H. Darwin (1845–1912) and Horace Darwin (1851–1928), two sons of Charles Darwin, set up a very sensitive device for measuring tilt (Darwin and Darwin 1882). The instrument design had been devised by W. Thomson: It was a vertical pendulum, equipped with a mirror suspended through a bifilar suspension both to the bob and a fixed stand. The pendulum and the mirror were completely immersed in water in order to damp unwanted oscillations. Despite several series of observations and careful experimental procedures, the Darwins could not find evidence of the lunar disturbance of gravity (Darwin 1883). The only evidence of solid-earth tides, though indirect and not strongly grounded, was found a short time later by George Darwin from the analysis of ocean-tide measurements with tide gauges in Indian ports (Darwin 1882).

2.6 Ewing-Gray-Milne

The instruments described above were chiefly devoted to the observation of minute tilts of the earth's surface related to luni-solar attraction. Simultaneously, a large number of devices were developed worldwide to detect or record strong ground motion during earthquakes (e.g., Ehlert 1898b; Dewey and Byerly 1969; Ferrari 1990, 1992). Beside the simplest seismoscopes, based on falling bodies or moving liquids, most recording instruments were common-pendulum seismometers. Some other instruments relied on inverted pendulums or springs. The history of pendulums swings to Japan, where seismographic studies were given impetus by several foreign scientists invited there soon after the beginning of the Meiji era in 1868. They came from Germany (Knipping, Wagener), The Netherlands (Verbeck), the USA (Chaplin), and above all, Great Britain (Alexander, Ewing, Gray, Knott, Milne). Among the numerous seismographs, they devised in the period 1875–1895, several relied on horizontal pendulums. We briefly sketch here the early development of seismographs using horizontal pendulums, based on the so-called bracket and conical suspensions.[3] In 1878, the American civil engineer Winfield S. Chaplin (1847–1918) designed the first Japanese horizontal pendulum

[3] We avoid using the name garden-gate suspension which is used by several authors as a synonym for bracket suspension (e.g. Wielandt 2002), while others use it for conical pendulums (e.g. Aki and Richards 1980).

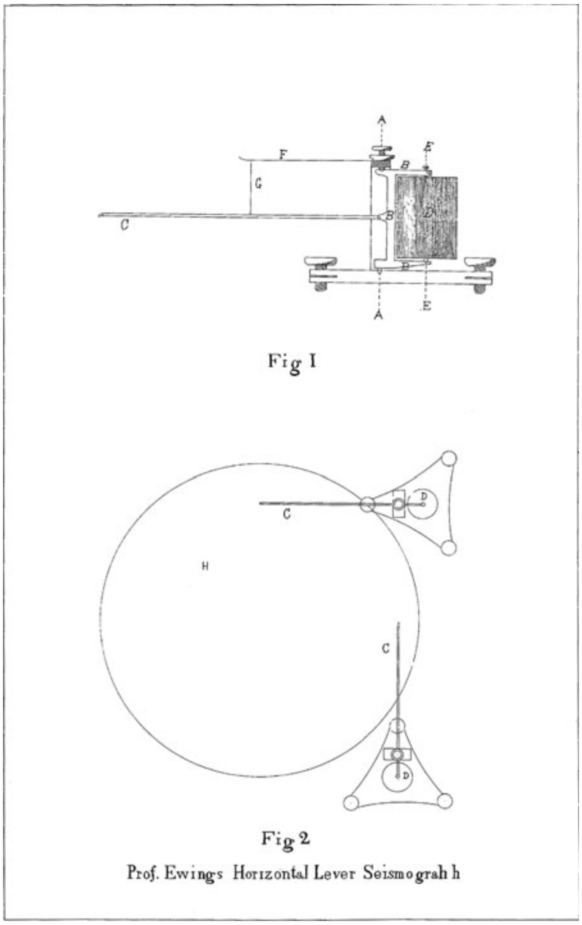


Fig. 3 Horizontal pendulum designed by Ewing (1880), with *bracket* suspension (Ewing 1880)

(Ewing 1883, 1886b), while he was a Professor at the Imperial College of Tokyo (1877–1882). Unfortunately, Chaplin did not publish his experiments; hence, his seismograph is poorly known, its sole description is found in Ewing (1883). It was a T-shape model, based on a horizontal wooden boom pivoting about a vertical axis; recording was performed by direct inscription on a plate below, but Chaplin did not succeed in recording any earthquake. According to Gray (1881a), Chaplin's contrivance was inspired by Zöllner's pendulum. The Britton James A. Ewing (1855–1935), Professor of Physics and Mechanical Engineering at the Imperial College from 1878 to 1883, improved Chaplin's pendulum in 1880 (Ewing 1880). His instrument, which he named the astatic horizontal lever seismograph, was based on a light boom pivoting about a hinge terminated by two steel points (Fig. 3). It had a small amplification and recorded local earthquakes on a rotating smoked glass plate. Strictly speaking, this seismometer was not a pendulum because the friction prevented it from oscillating. In his paper, Ewing regarded the bob as a steady-point and assumed that the lever recorded the true ground displacement. With this instrument, he succeeded in obtaining the first seismogram ever recorded, i.e., the first complete record of horizontal displacement versus time during an earthquake. He developed several other seismographs, including one after his return to Dundee, Scotland, in 1883 (Ewing 1886a), which he had built by the Cambridge Scientific Instrument Company founded in 1881 by Horace Darwin and Albert Dew-Smith (Williams 1994). This instrument was acquired by several observatories, including Lick Observatory at Mt. Hamilton, California, where, in 1906, it provided the only usable strong-motion record of the San Francisco earthquake (Boore 1977).

In a parallel and independent development, Thomas L. Gray (1850–1908) designed bracket-pendulum seismographs as early as January 1880 (Gray 1881a). Gray spent 2 years in Tokyo, as a Professor of Electrical Engineering at the Imperial College from 1879 to 1881. His first paper on horizontal pendulums (Gray 1881c) appeared only one and a half months after Ewing's. There, he described a new horizontal pendulum based on a double articulated boom. He also suggested another type of horizontal pendulum that he called a conical pendulum, which consisted in a bob suspended to a post by a wire and connected to the same post by a horizontal boom resting on it through a knife-edge. Only later, in 1881, did he contrive this pendulum, in the shape of a complete seismograph, with two perpendicular pendulums recording on a smoked plate or drum (Fig. 4). Gray worked in close collaboration with John Milne (1850–1913). The conical pendulum soon became a successful instrument; it was, for example, part of the three-component Gray-Milne seismograph (Gray 1883) manufactured by the James White Company in Glasgow (a company founded in 1849, supported by William Thomson—or Lord Kelvin) and of many other instruments in the ensuing decades.

A controversy arose in 1881 (Gray 1881b, c; Ewing 1881) and lasted for several years between Gray and Milne on one side, and Ewing supported by Chaplin on the other. It centered on several issues regarding their instruments and in particular, precedence in the devising of horizontal pendulums (*Nature*: vol 35, 1886–1887, p 36, 75–76, 126, 172–173, 559–560,

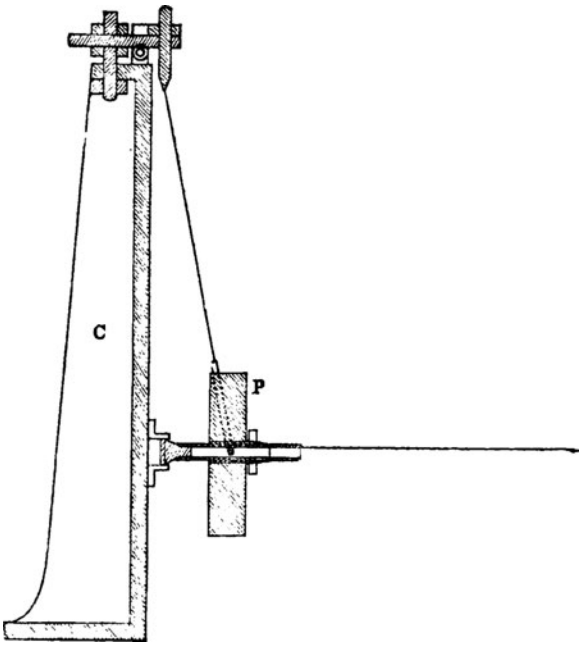


Fig. 4 Gray's conical pendulum (1881) (Gray 1883)

606; vol 37, 1888, p 570–571; vol 38, 1888, p 30). Everyone acknowledged that the first horizontal pendulum in Japan was the work of Chaplin. Gray claimed that he contrived horizontal pendulums before Ewing, but Ewing was clearly the first to publish on this subject, and moreover, he obtained the first complete seismograms at the same time. The detailed chronology and reciprocal influence of the above four cited scholars regarding the development of horizontal pendulums will however probably never be completely elucidated.

3 Rebeur-Paschwitz pendulums

3.1 Karlsruhe

In 1880, the Grand Duchy of Baden, in southwest Germany, decided to transfer the old, inconveniently situated observatory from Mannheim to its capital city Karlsruhe, under the direction of the astronomer Wilhelm Valentiner (1845–1931). The project was to erect a large modern observatory. Meanwhile, Valentiner settled in a temporary shed in the garden of the state library—today known as the Nymphengarten (Vocilka 2008). The project eventually resulted in the creation of the Baden Observatory in Heidelberg instead of Karlsruhe in 1897. In June 1882, Valentiner succeeded in recruiting an assistant. He first hired Herrmann Büttner, replaced in July 1884 by Ernst von Rebeur-Paschwitz (1861–1895), a young astronomer from Berlin specialized in the study of comets. During his three-and-a-half-year term in Karlsruhe, Rebeur-Paschwitz devised a horizontal pendulum that led to major developments in world seismology and constitutes the main subject of this paper. On 26 November 1886 and on 29 April 1887, he presented two papers about horizontal pendulums before the Karlsruhe Association for Natural Sciences—*Naturwissenschaftlicher Verein* (Rebeur-Paschwitz 1888a; b). Along with a historical reminder on Zöllner experiments with horizontal pendulums, he presented theoretical considerations on the measurement of lunar and solar attraction by means of horizontal pendulums. He asked for, and was granted, an endowment of 300 Marks to perform observations with a Zöllner-type horizontal pendulum. This was the starting point of a successful instrument development that would be paramount in seismology and geodesy for the recording of earthquakes and earth tides. It is not known exactly how Rebeur-Paschwitz became interested in the development of horizontal pendulums. He began working on the subject in 1885 (Rebeur-Paschwitz 1888c), his first readings being Zöllner's and the Darwin brothers' papers described in the previous sections. He was also aware that the Astrophysical Observatory in Potsdam inherited Zöllner's scientific papers and pendulum after his death on 25 April 1882. Rebeur-Paschwitz may have heard of Zöllner's pendulum while he was working in the nearby Berlin Observatory in 1883–1884 just before moving to Karlsruhe. Another particular circumstance may have influenced Rebeur. Astronomers had long observed that local conditions may generate small changes of the vertical (e.g., Milne 1898). The provisional observatory in Karlsruhe was probably the poorest place imaginable to execute professional astronomical observations. For instance, the meridian circle was installed in a small wooden hut built on soft ground without foundations right in the middle of the city (Valentiner 1884). As soon as he arrived in Karlsruhe, Rebeur assisted Valentiner for the meridian circle observations. The noisy conditions may have encouraged him to investigate the deviations of the vertical by means of levels or pendulums.

Ernst von Rebeur-Paschwitz was born on 9 August 1861, at Frankfurt an der Oder, in a Protestant family (Eschenhagen 1895; Gerland 1895; 1896a; b; Valentiner 1895; Ranneberg 2010). He was the eldest son of a civil servant with the tax department of the Prussian State and his mother was English. This led him to live in England and Ireland for several months in the fall of 1879. He read English periodicals, like *Nature* or the reports of the British Association for the Advancement of Science, on a regular basis. He studied mathematics and astronomy at the universities of Leipzig (May–August 1879), Berlin (November 1879–March 1880), Geneva (April–June 1880), and Berlin again (October 1880–July 1883), with a 12-month interruption to perform his military service (October 1880–September 1881). He defended his PhD thesis in Berlin in July 1883 entitled "On the movement of comets in a resisting medium" (Rebeur-Paschwitz 1883). Many interesting biographical details and documents can be found in his personal file at the Halle University archive, including his handwritten curriculum vitae in Latin.

Rebeur-Paschwitz had a small horizontal pendulum built in 1886 by the firm Fecker & Comp., in Wetzlar, a small workshop owned by Gottfried L. Fecker, which produced telescopes and optical devices (Fig. 5). His first observations were made in August 1886 (Rebeur-Paschwitz 1888c) in the provisional Karlsruhe observatory. His pendulum was more or less similar to Zöllner's, but he replaced the bifilar suspension with a bracket steel-points suspension. The pendulum was a T-shape model, where the moving element was in the shape of a "T" with its long arm being the horizontal boom and its short vertical arm the suspended axis of rotation. The boom was a wooden rod bearing a light adjustable mass with a reading mirror at its free end and was fixed to a vertical steel bracket at the other end. The bracket had two agate cups at its upper and lower ends resting on two corresponding steel points fixed on the stand. The stand was a standard tripod with three leveling screws, a design similar to Zöllner's. The observation conditions in the Nymphengarten observatory were very poor. With the grant from the *Naturwissenschaftlicher Verein*, Rebeur-Paschwitz prepared an isolated pillar in a vaulted cellar of the university, the *Technische Hochschule.* During a first observing run in March 1887, the horizontal pendulum had a free period of 40.9 s, decreased to 32.2 s in a second run in April. The readings were made with a telescope and a scale set 4 m apart from the pendulum, allowing a tilt resolution

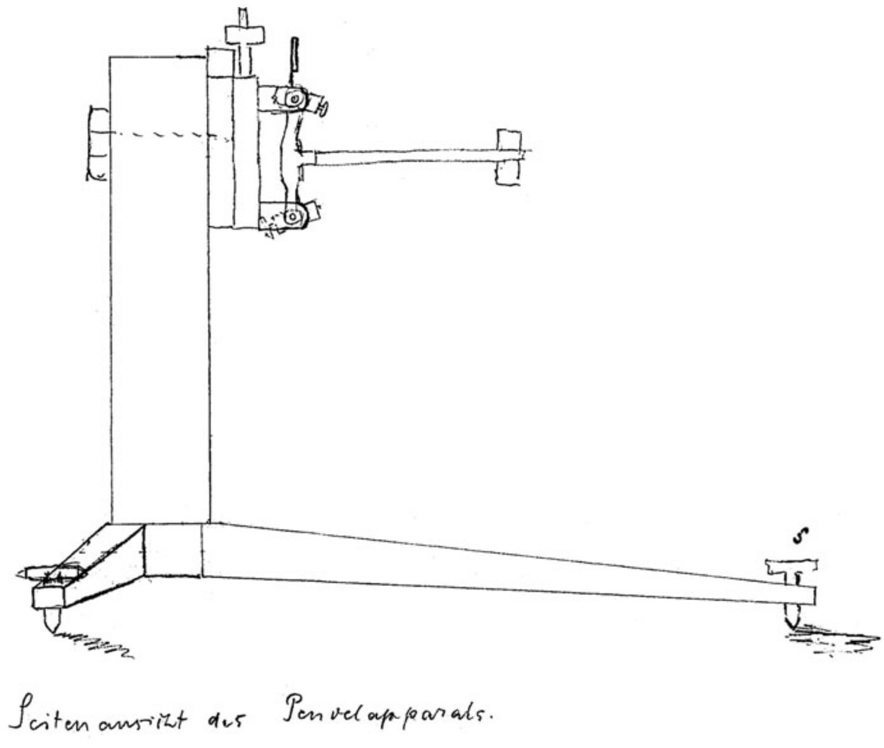


Fig. 5 First Rebeur-Paschwitz's pendulum in Karlsruhe (1886) (sketch excerpt from the letter of Rebeur to Repsold of 4 June 1888). In the sketched instrument, the mirror had been displaced from the boom's tip to a near-rotation-axis position for the photographic recording implemented in 1887 (Credit Staatsarchiv Hamburg)

of 2.5 10^{-3} to 4.0 10^{-3} arcsecond, given the reading accuracy of 0.2 mm. The pendulum was carefully isolated by a double-walled casing: a wooden inner one and a metal outer one. Rebeur-Paschwitz presented evidence of a clear diurnal period with a peak-to-peak amplitude of 24.5 mm on his scale, which corresponded to a tilt amplitude of 0.501 arcsecond. This value is approximately ten times the maximum expected luni-solar tilt amplitude.

Earthquakes are not infrequent in Baden and its neighboring regions, mostly related to the Upper Rhine Graben seismic activity. The protracted Gross Gerau earthquake swarm that occurred in 1869–1871 awoke interest in the seismic phenomenon. In the aftermath of this event, the geologist Georg R. Lepsius (1851–1915) developed a mercury seismoscope that was eventually installed in 50 different locations in the Hesse region, just north of Baden by 1882 (Lepsius 1884). On 24 January 1880, a moderate earthquake (I_0=VI MSK) occurred in Kandel, a few kilometers to the northwest of Karlsruhe. It induced the creation of the first German seismological commission on 6 February 1880 by the *Naturwissenschaftlicher Verein* in Karlsruhe, 1 month before the creation of the Seismological Society of Japan. With this background, and his own knowledge, Rebeur-Paschwitz foresaw as early as 1886 that he would record earthquakes with his pendulum. In Rebeur-Paschwitz (1888c), he wrote that the horizontal pendulum "is very appropriate to record remote earthquakes" (*sehr geeignet ist…entfernte Erdbeben…anzuzeigen*). On 27 April 1887, at 21:37 local time (i.e., 28 April 09:03 GMT), he observed an oscillation that he believed was caused by a small earthquake. This however remains hypothetical, since we could not find any corresponding earthquake in the many regional and global catalogues, we searched through.

Rebeur-Paschwitz decided to implement continuous recording on his pendulum in order to record all transient signals (in particular earthquakes) and obtain a better sampling rate for low-frequency ground-movement analysis. Mechanical recording was impracticable. Rebeur turned himself to photographic recording, which had been in use since the 1840s in magnetic observatories for the same reason (Schröder and Wiederkehr 2000). He installed and tested a photographic recording system in the summer of 1887 (Rebeur-Paschwitz 1888d; 1889a). Two parallel mirrors were used, one fixed, attached to the stand, and one mobile, attached to the pendulum, and a glass lens placed in front of them. A lamp and a drum carrying the photographic paper were placed at a distance of 4 m from the pendulum (Fig. 6). A clockwork rotated the drum in 48 h, allowing a recording speed of 1.1 cm/h. It also marked the time by screening the spot reflected from the fixed mirror every hour for a few minutes. The 12-day observing run in August was successful. Once again, he observed a transient signal he assumed to be an earthquake.

By September 1887, Rebeur-Paschwitz had developed all the necessary theoretical and instrumental baggage necessary to record and analyze earth tides and teleseismic events. He knew that his pendulum was sensitive enough to record them and that his photographic recording system would allow powerful data processing. He foresaw installing two-component horizontal pendulums in many remote stations. But this project came to a premature—fortunately only provisory—end when he became sick with tuberculosis in the summer of 1887. He resigned his Karlsruhe assistant position in September and spent a year trying to cure the disease, first at his parents' home in Oppeln (today Opole, Poland) and later (January–May 1888) in the then famous sanatorium of Görbersdorf (today Sokolowsko, Poland). Apparently, his health had sufficiently improved by June 1888 for him to begin to work on his new project to build and operate a pair of high quality horizontal pendulums in two separated observatories.

3.2 Repsold

Gottfried Fecker, who built Rebeur-Paschwitz's prototype in 1886, emigrated to the USA in July 1887 (Rosenbauer 2003). To build his two new horizontal pendulums, Rebeur turned to Repsold, a renowned workshop making astronomical and geodetic instruments in Hamburg. He probably chose Repsold because they had produced reversible pendulums for decades. The A. Repsold & Söhne firm was owned and managed by the brothers Johann Adolf (1838–1919) and Oscar Repsold (1842–1919). During the nineteenth century, Repsold provided astronomical observatories worldwide with telescopes and many other instruments (Repsold 1914). When the company folded in 1919 with the death of the two brothers, its records were fortunately saved and are now stored in the Hamburg State Archives. The records hold a large

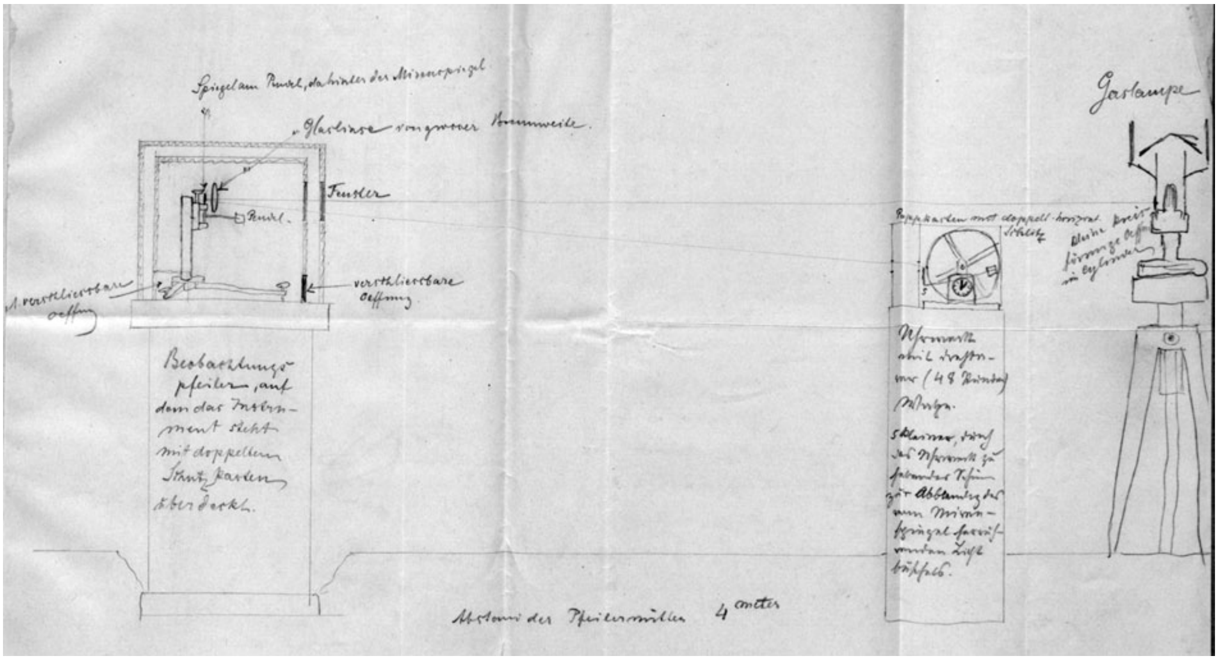
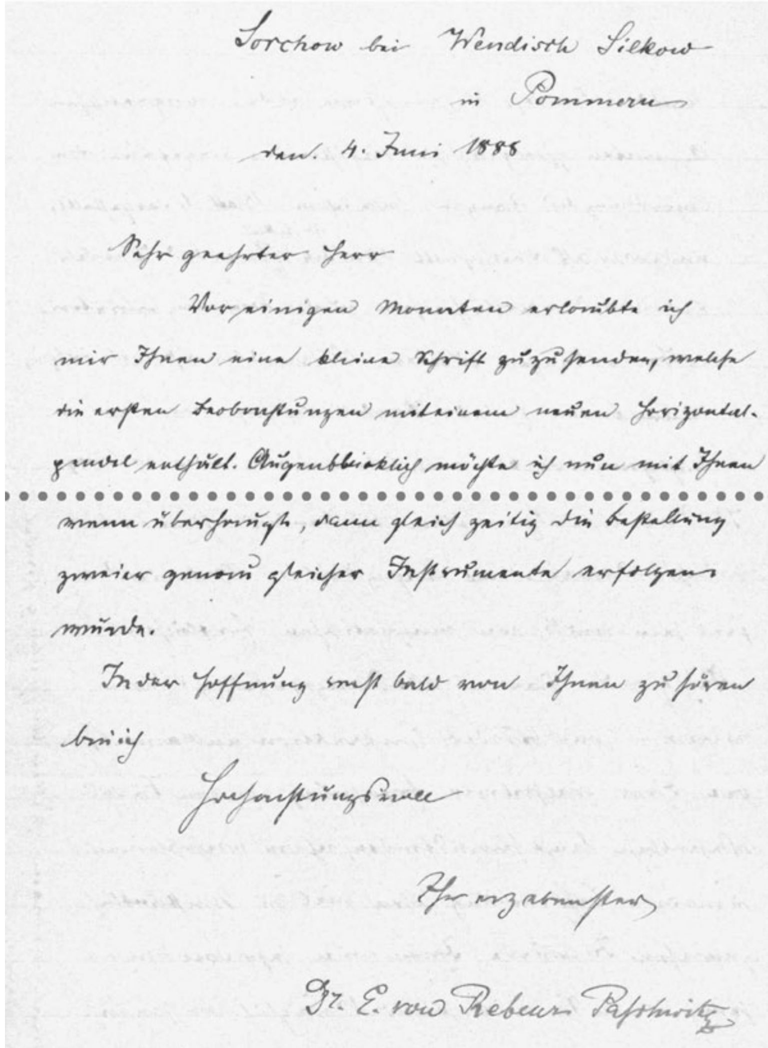


Fig. 6 Photographic continuous recording implemented by Rebeur-Paschwitz in Karlsruhe (1887). *Left*: pendulum installed on the pillar; *right*: recording system, including a gas lamp and a drum with photographic paper at a distance of 4 m from the pendulum (sketch excerpt from the letter of Rebeur to Repsold of 4 June 1888) (Credit Staatsarchiv Hamburg)

number of documents related to horizontal pendulums for the period 1888–1903. The correspondence includes 49 incoming and 41 outgoing letters or postcards between Repsold and Rebeur-Paschwitz.

On 4 June 1888, Rebeur-Paschwitz wrote a long letter to Repsold (Fig. 7), from his small convalescence village Sorchow in Pomerania (today Zoruchowo, Poland). The letter included many figures and a copy of his Karlsruhe article (Rebeur-Paschwitz 1888c) was enclosed. He discussed many parts of the instruments he wanted to have built and requested Repsold to provide him with an estimate of price and delivery time for the production of two pendulums and two recorders. In response to Rebeur's request, Repsold initially declined, arguing they could not compete with Fecker's price of 80 Marks. On Rebeur's insistence, they replied on 20 June that they could produce the two instruments for a total price of 800 Marks. The ensuing correspondence comprises an exchange of no less than 42 letters or postcards continuing until the end of 1888. Several technical issues were discussed. The main point was the type of suspension. Repsold preferred a pivot rotation (*Zapfendrehung*) while Rebeur defended his previously used points suspension (*Spitzenaufhängung*). On 24 July, Rebeur, after being granted financial support amounting to 1,500 Marks from the Prussian Academy of Sciences (Bois-Reymond 1888), confirmed his order with Repsold. He also obtained the consent of the Naval Observatory in Wilhelmshaven and the Astrophysical Observatory in Potsdam to host and operate his pendulums in dedicated rooms. In August, the old Fecker pendulum was sent from Karlsruhe to Hamburg, where the Repsolds equipped it with their proposed pivot suspension and sent it back to Karlsruhe for testing. Rebeur-Paschwitz traveled to Karlsruhe in October to perform the test. On 5 October, he informed Repsold that the new pendulum's sensitivity was much too low due to high friction and returned the pendulum, recommending that the points suspension should be adopted instead. One week later, he traveled to Hamburg to meet the Repsold brothers and settle the final construction details. Among several improvements, Rebeur suggested a device to damp the pendulum oscillations, but unfortunately, this was not realized. While the pendulums were being constructed, Rebeur spent the end of October in Wilhelmshaven, and the months of November and December in Potsdam to prepare the necessary observation conditions. The two pendulums



Sorchow bei Wendisch Silkow
in Pommern
den 4. Juni 1888

Sehr geehrter Herr
Vor einigen Monaten erlaubte ich mir Ihnen eine kleine Schrift zuzusenden, welche die ersten Beobachtungen mit einem neuen Horizontalpendel enthielt. Augenblicklich möchte ich nur mit Ihnen

wenn überhaupt, dann gleichzeitig die Bestellung zweier genau gleicher Instrumente erfolgen würde.
In der Hoffnung recht bald von Ihnen zu hören bin ich
Hochachtungsvoll
Ihr ergebenster
Dr. E. von Rebeur Paschwitz

Fig. 7 First letter from Rebeur-Paschwitz to Repsold on 4 June 1888 (excerpts). "Sorchow bei Wendisch Silkow, Pomerania, 4 June 1888. Dear Sir, a few months ago I sent you a short article containing the first observations with a new horizontal pendulum. (…) an order of two identical instruments would be placed. Hoping to hear from you soon, I remain, respectfully, yours most faithfully, Dr. E. von Rebeur Paschwitz" (Credit Staatsarchiv Hamburg)

were finally delivered to Rebeur-Paschwitz on 18 December 1888, less than 5 months after the order was placed. On 7 January 1889, Rebeur confirmed that the two pendulums were running in Potsdam in a very satisfactory manner in a test configuration. In the following month, he performed several tests, including the implementation of damping through a small piece of brass immersed in glycerine (Rebeur-Paschwitz 1892b). As expected, the damping reduced the continuous oscillations of the pendulum. However, the damping was abandoned at the end of March because it seemed to induce a large unwanted drift, and from then on, all Rebeur's observations were made without damping.

The pendulum designed by Repsold comprises the following parts (Fig. 8):

– A main stand in cast iron, in the shape of a hollow cylinder 30 cm in diameter and 8 cm high inserted in a triangular base. The stand is heavy (16 kg) to ensure high stability. Three foot-screws below the stand allow accurate leveling and adjustment of the free oscillation period and the equilibrium position of the pendulum (see Rebeur-Paschwitz 1892b and 1894 for details). The cylinder includes a rectangular window, closed by a glass lens, providing optical access to the pendulum mirrors from the outside.

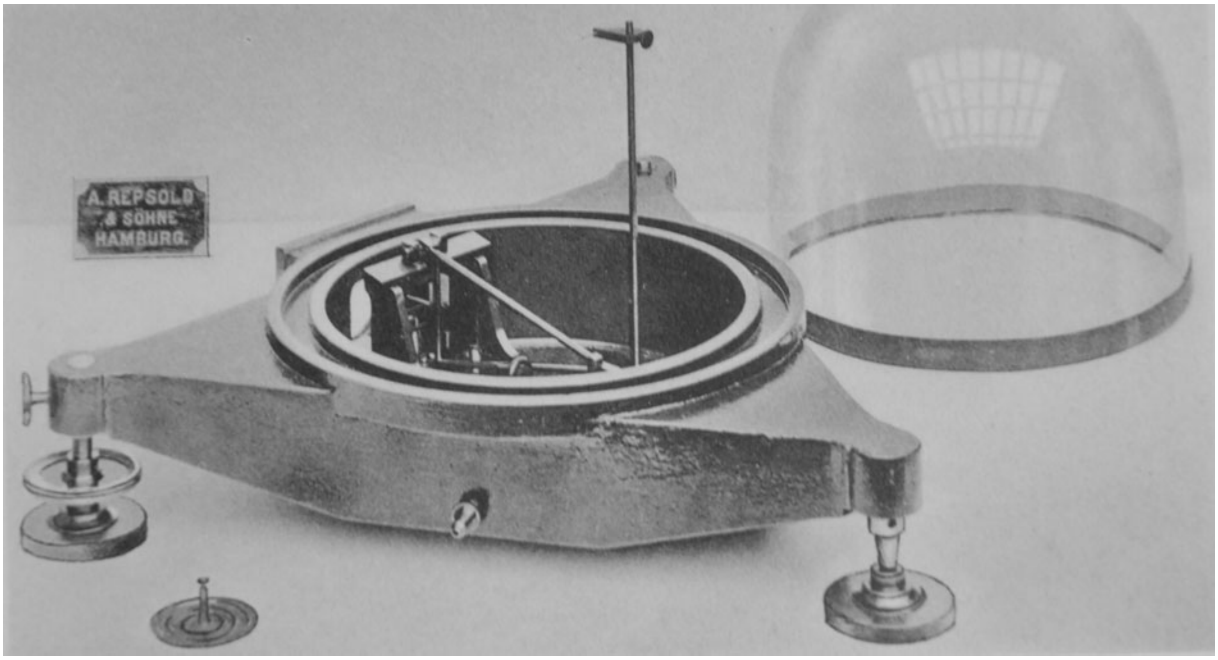


Fig. 8 First horizontal pendulum designed by Repsold. Six copies were produced between 1888 and 1892 (Repsold 1914)

- A glass bell covering the base cylinder eliminates draughts and provides some thermal insulation, while ensuring visual access to the pendulum parts.
- The support for the moving pendulum itself. It is a rectangular frame in brass, screwed to the bottom plate. It bears two small horizontal adjustable shafts, placed one above the other at a distance of 6.8 cm. Each shaft carries a small steel point on which the pendulum rests via two agate cups.
- The moving element, in the shape of a triangle 16.5 cm long made of light brass tubes. Its total weight is 42 g. The mobile mirror is attached to the vertical segment and can be adjusted by pivoting it around a vertical axis.
- A small brass support for the fixed mirror, located just below the mobile mirror. It includes two levers for the adjustment of the mirror from the outside.
- Finally, two vertical rods on both sides of the moving element serve as mechanical stops to limit pendulum excursions. One of them, a long vertical tube almost the height of the glass bell, was also used to hang the pendulum in the vertical position and measure its free period in this position; the second one is connected through a hole on the side of the base cylinder to an external rubber pipe and a blowing pear used to allow the pendulum to oscillate.

The original Repsold blueprint is part of the Repsold archive. It exhibits a surprising evolution of the pendulum during its development (Fig. 9). Initially, the moving part was placed above the cylindrical stand and was supported laterally, probably for easy access. Rebeur-Paschwitz was highly unsatisfied with this design, which was adversely influenced by temperature variations. In a letter dated 16 November 1888, he computes the influence of small temperature variations and urges Repsold to modify the shape of the pendulum support in order to make it symmetrical. In the final version, the moving element and its support were placed in-line on the bottom of the base stand. The recorder and the petroleum lamp were purchased from the Julius Wanschaff workshop in Berlin, a world renowned manufacturer of instruments for astronomy and geophysics.

3.3 Potsdam and Wilhelmshaven pendulums

In February 1889, Rebeur left Potsdam and spent 4 months in Montreux, Switzerland, for a rest cure.

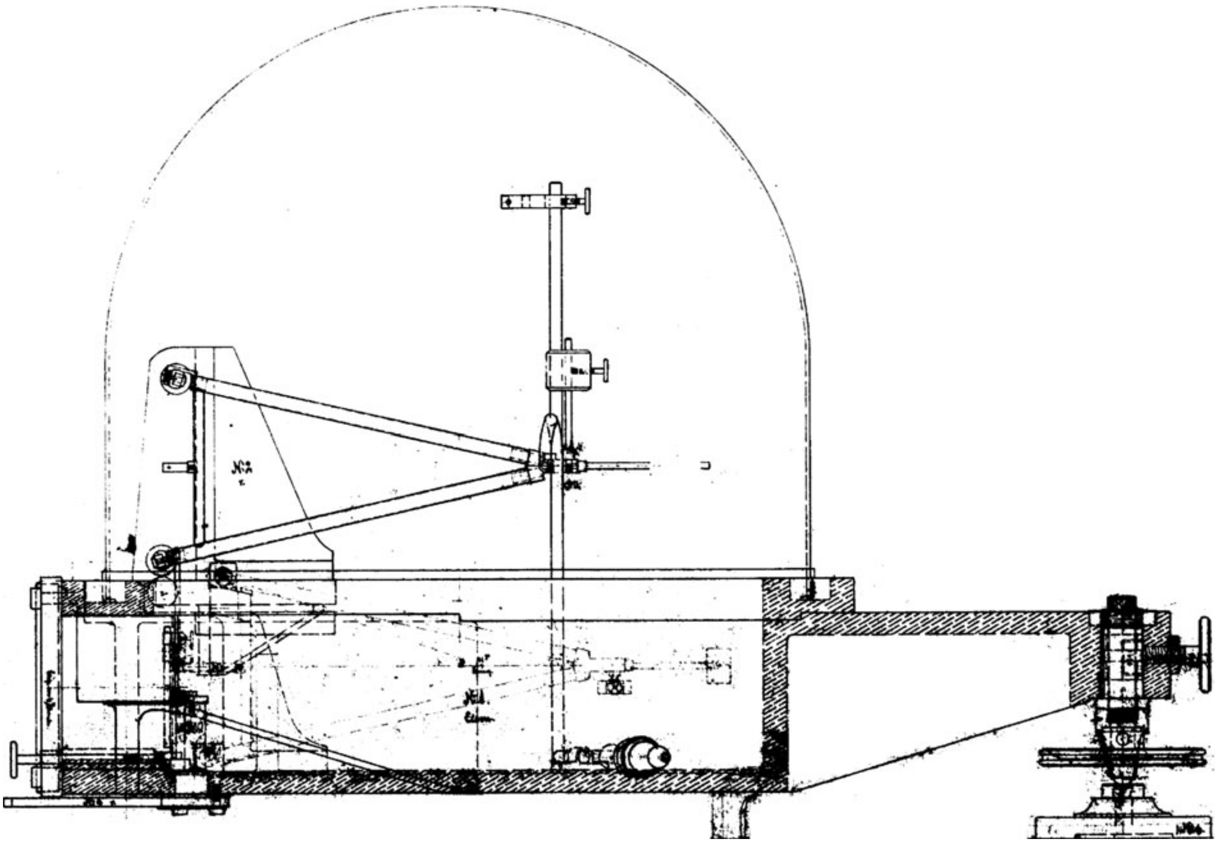


Fig. 9 Repsold's original blueprint of their 1888 horizontal pendulum ordered by Rebeur-Paschwitz. In the initial design, not realized, the boom and its stand were placed above the cylindrical base. In the final version, they were moved to the bottom of the base (Credit Staatsarchiv Hamburg)

Meanwhile, the two pendulums started simultaneous operation in March. Both instruments were placed on isolated piers in underground rooms, covered by tin-sheeted wooden casings. The lamp and the recorder were installed in an adjacent room. The Wilhelmshaven pendulum was installed and operated by Carl Börgen (1843–1909), the Director of the Naval Observatory, and his assistant Max Eschenhagen (1858–1901). The Potsdam instrument was installed by Rebeur-Paschwitz personally and then operated by Hermann Vogel (1841–1907), the Director of the Astrophysical Observatory, and his assistant Johannes Wilsing (1856–1943). The recordings continued until the end of September.

When Rebeur-Paschwitz returned to Potsdam at the beginning of June, he rapidly analyzed the first recordings obtained in Potsdam and Wilhelmshaven. He quickly found out that some transient disturbances occurred simultaneously at both stations, as he expected, and associated them with remote earthquakes. In a well-known paper to *Nature* (Rebeur-Paschwitz 1889b), he investigated a Japanese earthquake on 17 April 1889 that was recorded on his two pendulums. This event is often quoted as the first teleseismic event ever recorded on a seismogram, though some doubt persists as to the actual earthquake recorded (e.g., Schweitzer 2003, 2007). An unpublished note by Utsu (Utsu 2000, personal communication by W. H. K. Lee) discusses the epicentral origin of this event.[4] Utsu concludes that Rebeur's event was indeed a large teleseismic event, most probably a low-frequency earthquake in the vicinity of Japan. In his 1889 paper, Rebeur identified ten other disturbances in April and May that he supposed to be caused by earthquakes. In the following years, Rebeur performed a complete analysis of these

[4] This note is not included in the International Handbook of Earthquake and Engineering Seismology (W. H. K. Lee et al., eds.).

recordings (Rebeur-Paschwitz 1891; 1892a). His main conclusions, still valid today, boosted the development of geophysics and seismology in the next decades. He observed four main characteristic signals in his seismograms:

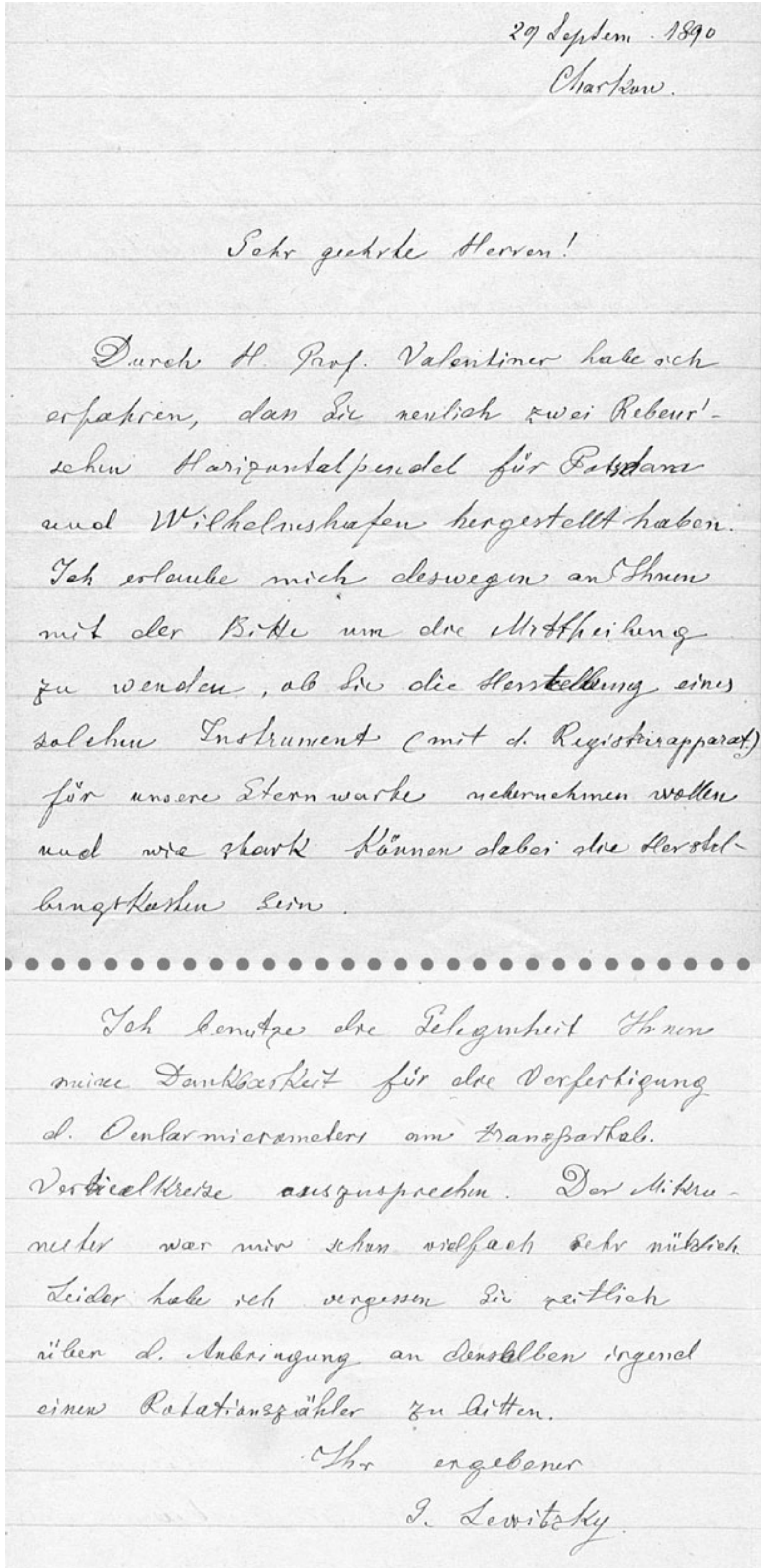
– long-term drift (which he named *Nullpunktbewegung*, i.e., zero-line variations) caused by local tilting of the ground through weather and geotechnical conditions;
– diurnal periodic wave primarily related to environmental changes;
– semi-diurnal oscillation related to moon and sun attraction, i.e., earth tides;
– transient disturbances mostly caused by remote earthquakes.

3.4 Repsold pendulum diffusion (Tenerife, Strasbourg, Nikolayev, Kharkov, Nice)

While he was in Switzerland in the spring of 1889, Rebeur-Paschwitz applied for Habilitation at the University of Halle, in Saxony, with a work on comets (Rebeur-Paschwitz 1889c). He was awarded the title of *Privatdozent* in astronomy after his thesis defense on 1 July, which entitled him to teach at this university. Unfortunately, he fell ill again in September 1889 and never recovered enough to fulfill his teaching task. Following medical advice, he decided to move for some time to Tenerife, Canary Islands. The recordings in Potsdam and Wilhelmshaven were stopped at the end of September. Rebeur left Germany next November and stayed in the Canaries until May 1891. He planned to set up simultaneous observations in Wilhelmshaven and Tenerife and had the Potsdam pendulum sent to him in June 1890. He recorded with this pendulum in Puerto Orotava, Tenerife, between 26 December 1890 and the end of April 1891. However, the Wilhelmshaven pendulum was not put back in service. Rebeur asked Ernst Becker (1843–1912), the Director of the Strasbourg Observatory (Strasbourg was then German and became French in 1919), to host and operate the Wilhelmshaven instrument. The pendulum was revised and the mirror modified by Repsold in October–November 1891 and thereafter sent to Strasbourg. Becker, assisted by the technician Carl Sabel, installed the pendulum on the pillar of the Cauchoix meridian telescope and recorded the ground movement from February 1892 to September 1893 (Rebeur-Paschwitz 1895b). The sandstone console built to support the pendulum on the pillar side is still visible today. Simultaneously, recordings started at the Russian Naval Observatory in Nikolayev (today in Ukraine) by its Director Ivan E. Kortazzi (1837–1903). Rebeur had been looking for a remote station to install his pendulum (previously in Potsdam and Tenerife). Following a recommendation by G. Levitski, it had been sent from Tenerife and delivered to Nikolayev on 5 November 1891 (letter from Kortazzi to Rebeur-Paschwitz dated 8 November 1891, Nikolayev Observatory archive). Kortazzi installed the pendulum on a dedicated pillar in one of the observatory's underground rooms and the recording started in February 1892. Kortazzi (1894, 1895) describes the installation and the results obtained during the first years. He confirmed all the results obtained by Rebeur-Paschwitz and recorded many earthquakes simultaneously with the Strasbourg pendulum.

The installation of Rebeur's pendulum in Russia may seem surprising at first glance. But, it results from the growing Russian interest in seismic recording in the 1890s and the influence of German science in this country, particularly German astronomy. After the devastating earthquake of Verniy (today Alma-Ata, Kazakhstan) in 1887, the Russian Geographical Society (RGO in Russian) created the Seismological Commission under the direction of Ivan V. Mushketov (1850–1902). In 1890, the Commission decided to implement seismic stations equipped with seismoscopes and seismographs. Arcady V. Voznesensky (1864–1936) developed the so-called RGO seismoscope, while Grigory V. Levitski (1852–1917), the founder and Director of the Kharkov Observatory, was entrusted with the implementation of seismographs. Levitski was apprised of Rebeur-Paschwitz's work by the military topographer Illiodor I. Pomerantsev (1847–1921) (Levitski 1902). He wrote to Valentiner in Karlsruhe, who recommended that he should contact Repsold directly. On 29 September 1890, Levitski wrote to Repsold requesting a quote for a Rebeur-Paschwitz type pendulum with its recorder (Fig. 10). This initiated a two-decade-long collaboration between Repsold and the Russian seismologists. The correspondence between Levitski and Repsold includes 22 letters between 1890 and 1893. Repsold quoted the price for one pendulum as 700 Marks and explained that he did not build recorders. He also rejected Levitski's request to build two

Fig. 10 Letter from Levitski to Repsold on 29 September 1890 requesting a quote for a Rebeur-Paschwitz type pendulum (excerpts). "29 September 1890 Charkow. Dear Sirs, I learned from Prof. Valentiner that you produced two Rebeur horizontal pendulums for Potsdam and Wilhelmshaven. I ask you the favor of informing me if you could produce such an instrument and its recorder for our observatory, and how much it would cost. (…) Yours faithfully G. Lewitzky" (Credit Staatsarchiv Hamburg)



29 Septem. 1890
Charkow.

Sehr geehrte Herren!

Durch H. Prof. Valentiner habe ich erfahren, dass Sie neulich zwei Rebeur'schen Horizontalpendel für Potsdam und Wilhelmshafen hergestellt haben. Ich erlaube mich deswegen an Ihnen mit der Bitte um die Mittheilung zu wenden, ob Sie die Herstellung eines solchen Instrument (mit d. Registrirapparat) für unsere Sternwarte unternehmen wollen und wie stark können dabei die Herstellungskosten sein.

Ich benutze die Gelegenheit Ihnen meine Dankbarkeit für die Verfertigung d. Ocularmicrometers am Transportabl. Verticalkreise auszusprechen. Der Mikrometer war mir schon vielfach sehr nützlich. Leider habe ich vergessen Sie zeitlich über d. Anbringung an denselben irgend einen Rotationszähler zu bitten.

Ihr ergebener
G. Lewitzky

perpendicular pendulums in a single stand[5] as suggested by Rebeur-Paschwitz (1891). Levitski ordered the two pendulums on 20 October 1890 and separately ordered a recorder from Wanschaff. The pendulums were delivered in Kharkov on 2 December 1891 and the recorder only sometime later. This, and Levitski's illness in 1892, delayed the operating of the two Kharkov components until August 1893, about the same time as Becker's recording came to an end in Strasbourg. He encountered several difficulties with his pendulums, related in part to the wearing of points, which resulted in too short a period of swing. Repsold provided a new set of points in September 1893. In a last letter from Kharkov on 20 October, Levitski reported that his problems were largely solved by the new points and some other circumstances. He reported his observations in the Kharkov University publications (Levitski 1894, 1896). In November 1894, Levitski had to move to Yuryev (previously Dorpat, today Tartu, Estonia) to take the directorship of the Observatory. This was a consequence of the policy of Russification in the Baltic provinces. Levitski was replaced in Kharkov by the "German" Ludwig O. Struve (1858–1920). Levitski became one of the leaders of Russian seismology until he left Tartu in 1908.

A third and last pair of horizontal pendulums was produced by Repsold, for the Nice Observatory in France. The Observatory was founded in 1881 and funded by the banker Raphaël Bischoffsheim. Its first Director, Henri Perrotin (1845–1904), equipped the observatory with modern instruments. He purchased an Angot seismograph in August 1886, which was delivered in May 1887 and recorded at least one, and probably a few, regional earthquakes during the next decade. After reading Rebeur-Paschwitz's (1891) paper, he wrote to Repsold on 18 June 1891 and ordered a pair of pendulums on 7 July. The two pendulums were delivered on 12 February 1892. It is likely that they were never installed or used since we could not find any mention of observations with this instrument. In two letters to Perrotin (29 November 1893 and 1 April 1895), Bischoffsheim complained about not receiving any news about the pendulums. From the proceedings of the Observatory's Steering Committee in 1903, it seems that Perrotin did never purchase a photographic recorder for his Repsold pendulums.

[5] This was based more on commercial than on technical ground, since Repsold manufactured later in 1896 a two-component pendulum for Omori in Japan.

3.5 Repsold two-component pendulum

After he returned from Tenerife in May 1891, Rebeur-Paschwitz, still ill, settled at his parents' home in Merseburg. His father had been posted to this small town a few kilometers south of Halle in January 1890. During the next 4 years, Rebeur spent most of his time working in this house, when his health allowed. He maintained an intense scientific correspondence with scientists worldwide. He achieved an outstanding analysis of his observations published in several papers. Morphine helped him often to withstand the pain and may also have enhanced his outstanding intellectual performance.

Rebeur's strong desire was to develop a new two-component horizontal pendulum in order to perform a 2-D analysis of earth tides. He also wanted to purchase an enhanced drum-recorder with faster rotation speed, in order to improve the time precision on earthquake waves. His correspondence with Repsold contains 20 letters on this topic between 23 May 1892 and 25 April 1894. Rebeur had tough requirements: He wanted a compact, lightweight instrument to facilitate implementation at a low cost. Several technical issues were discussed in detail, such as the size and strength of the supporting steel points, the effect of differential dilatation of screws, the adjustment of the mirrors by external remote controls, the use of one or several lenses, etc. Rebeur feared he would not be able to find financial backing to pay the—in his opinion—high price requested by Repsold for the pendulum and by Wanschaff for the recorder. Hence, he asked Repsold to develop a mobile mirror device that could allow the simultaneous recording of the two previous one-component pendulums. Some of Rebeur's ideas were published by Davison's (1894) with the description of Rebeur's own design of a two-component pendulum. On 14 January 1894, Repsold sent a sketch of their proposed instrument–including two pendulums set at right angles one above the other, a much more compact design than Rebeur's, proposed at a price of 1,200 Marks (as compared with the 700 Marks for the one-component model). But Rebeur disagreed with many characteristics of the proposal, including the price. The long-lasting disagreements between Rebeur and Repsold quickly degenerated into personal attacks, and, on 18 April 1894, Rebeur wrote a letter to Repsold announcing the end of the negotiation and effectively putting an end to their collaboration.

After the breaking-off with Rebeur, the Repsolds found an unexpected market for their double pendulum in Japan. The Japanese Earthquake Investigation Committee (EIC) was established in June 1892 in the aftermath of the disastrous Nobi–or Mino-Owari–earthquake of 1891 (Clancey 2006). The EIC decided to acquire geophysical apparatuses. One of its founding members was Fusakichi Omori (1868–1923), Milne and Seikei Sekiya's former student. He wrote to Repsold in May 1893 to purchase a pair of Rebeur-Paschwitz horizontal pendulums. Soon after, he asked another member of the Committee, the physicist Hantaro Nagaoka (1865–1950), to negotiate with Repsold since, at that time, Nagaoka was studying at Berlin University. Nagaoka had already been corresponding with Repsold since May 1893 to prepare the order of a reversible pendulum for the measurement of gravity. Within a year, 27 letters were exchanged between Nagaoka and Repsold. The reversible pendulum was delivered in May 1894. However, the horizontal pendulums could not be purchased due to administrative and political difficulties in Japan. Negotiations were started up again by Omori in January 1896, when he arrived in Germany for a 2-year term in Berlin and Potsdam. The correspondence includes 16 letters up to the end of 1896. Omori was not aware of the breakdown in relations between Rebeur and Repsold, and he planned to order two single pendulums of the 1888 type. Repsold suggested replacing the points suspension by a Hengler-Zöllner suspension with wires. Omori preferred to keep the points suspension. Repsold succeeded in convincing him to buy the new double component turned down by Rebeur. The T-shaped mobile booms crossed one another, allowing for the compactness originally required by Rebeur-Paschwitz (Fig. 11). Each boom was equipped with a mirror and could be adjusted by means of 3-m-long external keys. A mechanism allowed the pendulums to be slowly laid down on the fixed points. The pendulum

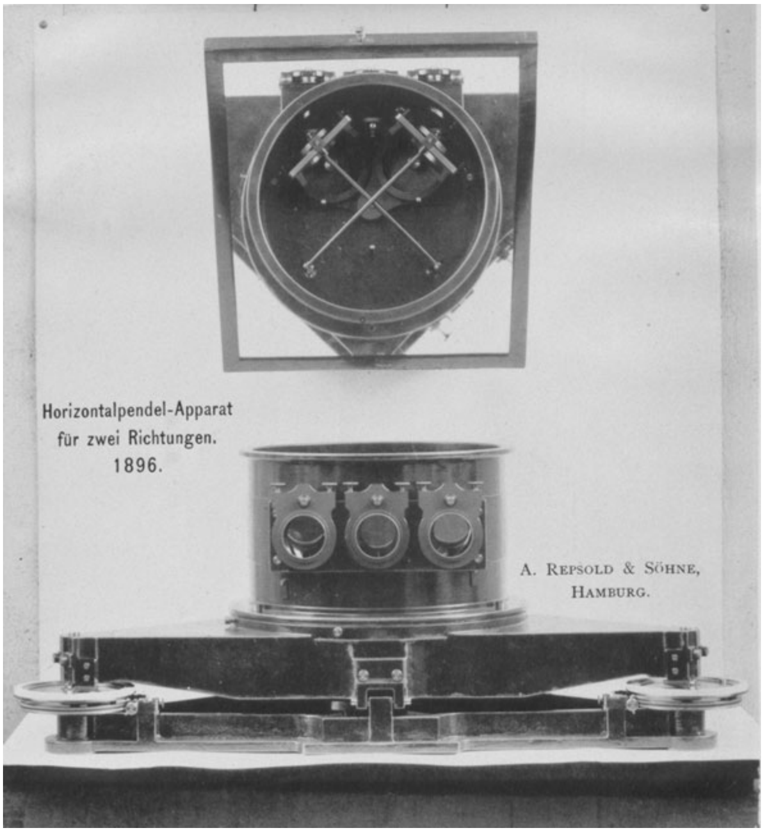


Fig. 11 Two-component horizontal pendulum produced by Repsold for F. Omori in Tokyo in 1896 (Credit Staatsarchiv Hamburg)

was ordered in July and delivered to Omori in Potsdam on 12 December 1896. In the first tests in Potsdam, Omori easily achieved free periods of 45 s.

3.6 Stückrath

Some of the behind-the-scene details about Rebeur's motivations and plans are found in his correspondence with Georg Gerland (1833–1919), in particular regarding his development of a new pendulum by another manufacturer, Stückrath. Gerland was Professor of Geography at Strasbourg University. He had a strong "geographical" interest in earthquakes that led him to create a regional Seismological Service in Alsace (*Landes Erdbebendienst Elsaß-Lothringen*) in 1892 and a small seismological station in Strasbourg in 1894 (Gerland 1894). By chance, the correspondence between Gerland and Rebeur-Paschwitz has been preserved, with some gaps though, and is now divided between the archives of the universities in Jena (22 letters in 1894[6]) and Freiberg (20 letters in 1894 and 1895). Gerland had found out that Becker's observations with Rebeur's pendulum in the nearby astronomical observatory were stopped in September 1893. He wrote to Rebeur-Paschwitz on 8 January 1894 with a proposal to purchase the instrument, in agreement with Becker. Rebeur had received a similar proposition by Kortazzi about his instrument in Nikolayev. After some negotiations, both transactions went through, leaving Rebeur with the necessary funds to develop and purchase his two-component pendulum.

In 1893, Rebeur had already been in touch with Paul Stückrath (1844–1916), a manufacturer of precision balances in Berlin (Felgentraeger 1916). Stückrath had developed a balance suspended on points in 1879. After abandoning Repsold's proposal in April 1894, Rebeur contacted Stückrath again. Their relationship was much easier than with Repsold, and Rebeur gave him carte blanche. Stückrath came to Merseburg in person at the beginning of 1895 to deliver the new pendulum, but details escape us since the correspondence is missing from February to July of that year. In a letter to Gerland dated 4 September 1895, Rebeur mentions he had received the help of a local clockmaker to operate the pendulum in a cellar of Merseburg's castle. This was probably the last letter written by Rebeur-Paschwitz. He was hospitalized on the next day in Halle for a knee operation (a common manifestation of tuberculosis). He suffered from a dangerous hemorrhage a few days later and was transported back home to Merseburg in the last week of September. He died there on 1 October 1895 as a result of heart failure.

The pendulum developed by Stückrath was a two-component horizontal pendulum with lightweight aluminum moving elements (Hecker 1896). It benefited from many of the ideas discussed with Repsold. It differed, however, in several points from Repsold's one- and two-component instruments. Stückrath's two components did not cross one another, a design less space-saving than Repsold's. The points were part of the moving element and were made out of steel or agate, as ordered. They rested on plane agate plates fixed to the two stands. The two pendulums were enclosed in a container comprised of a cast-iron base, a copper cylinder, and a plane glass cover (Fig. 12). As with Repsold's 1896 model, a very minute device allowed the points to be carefully laid down on their plates. Each pendulum carried a plane mirror and was seen through an adjustable prism.

A second copy of Stückrath's pendulum was produced for Levitski in Estonia following a personal recommendation by Rebeur in 1895. In his 1897 correspondence with Repsold, Levitski mentions that he was unsatisfied with this pendulum, without elaborating on his arguments. He preferred the Repsold single-component instruments.

4 Rebeur-Paschwitz's observations

Rebeur-Paschwitz performed three different types of observations: secular ground tilt, periodic deviation of the vertical (including solid-earth tides), and earthquakes. In order to quantify his observations, he developed mathematical analyses and obtained the necessary equations. As early as 1888, he computed an expression giving the static displacement of the spot for a given deviation of the vertical, based on spherical trigonometry (Rebeur-Paschwitz 1888c). In Rebeur-Paschwitz (1891), he derived a simpler expression, assuming a small deviation of the vertical θ in a direction perpendicular to the pendulum boom:

$$\alpha = \theta / \sin i \quad (1)$$

where α is the angular deflection of the boom and i the inclination angle between the vertical and the

[6] Some Jena letters are analysed in Cremer (2001).

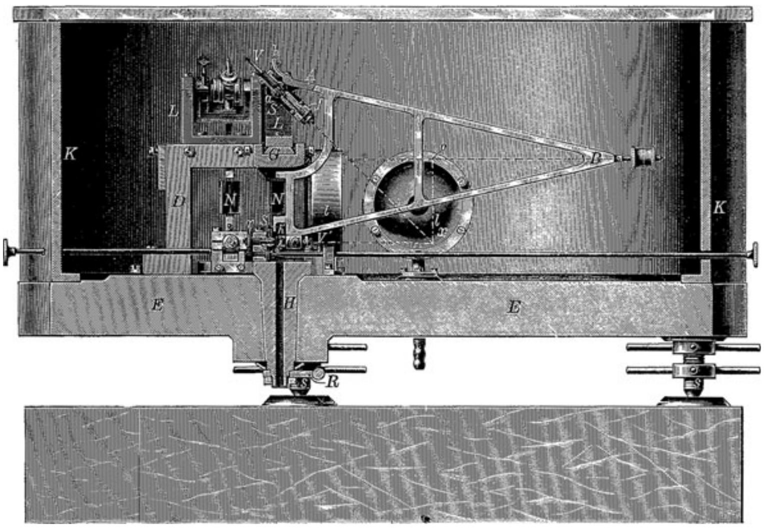


Fig. 12 Vertical cross-section of Stückrath's two-component horizontal pendulum built for Rebeur-Paschwitz in 1895 (Hecker 1896)

pendulum's axis of rotation. This expression assumes that α and θ are small with respect to i. The value of sin i is obtained from the relation:

$$\sin i = (T_{\mathrm{v}}/T_0)^2 \tag{2}$$

where T_0 is the measured free period of the pendulum and T_{v} its free period when suspended vertically. The displacement y of the spot is obtained as:

$$y = 2a\ \alpha \tag{3}$$

where a is the distance between the mirror and the scale or the recording device. From Eqs. 1, 2, and 3 follows:

$$r \equiv y/\theta = 2a(T_0/T_{\mathrm{v}})^2 \tag{4}$$

Equation 4 gives the tilt sensitivity r of horizontal pendulums. It strongly depends on the value of the free period, which changed with time and often needed to be calibrated, as a consequence of points wearing or small offsets caused by high-frequency earthquake waves. It was used by Rebeur-Paschwitz and his continuators to compute the deviations of the vertical versus time for the measurement of earth tides (Amalvict et al. 1992; Varga 2009). Table 2 compares the sensitivity achieved by Rebeur and by some of the horizontal pendulums investigated in this paper.

The recording of earthquakes with horizontal pendulums relies on the inertia of the bob. It aims at the measurement of the lateral displacement of the stand, rather than its deviation with respect to the vertical. The transfer function that relates the spot displacement to the ground displacement is well known (e.g., Aki and Richards 1980; Wielandt 2002):

$$H(\omega) = G\,\omega^2/\left(-\omega^2 + j\,\omega\,2\,h\,\omega_0 + \omega_0^2\right) \tag{5}$$

where ω is the angular frequency, h is the damping ratio, ω_0 is the natural angular frequency, and G is the system gain or magnification factor. The knowledge of G, of the free period T_0=$2\pi/\omega_0$, and of the damping h is sufficient to determine the movement of the pendulum in response to a given seismic wave.

The gain G results from the amplification of the relative bob displacement by the optical lever. It is very stable, contrarily to the free period T_0 and the damping h, which vary with time. G almost solely depends on the geometrical features of the instrument:

$$G = 2a/s \tag{6}$$

where s is the distance between the bob's gyration center and its rotation axis, given by:

$$s = g/\omega_{\mathrm{v}}^2 \tag{7}$$

(ω_{v}=$2\pi/T_{\mathrm{v}}$ is the free angular frequency in vertical position, g is the acceleration of gravity).

From Eqs. 6 and 7, we get:

$$G = 2a\,\omega_{\mathrm{v}}^2/g \tag{8}$$

The resulting values of G are reported in Table 2. The effective gain G_E measured by Abe (1994) represents the gain at periods around 20 s, whereas the

Table 2 Main characteristics of the first horizontal pendulums

Pendulum	Author	Location	Dates	T_v (s)	T_0 (s)	a (m)	r (mm/as)	G
Hengler	Hengler	Munich	1831	3.60[a]	600.0	3.25	867.4	2.0
Zöllner	Zöllner	Leipzig	1869	0.96[a]	104.0	2.50	285.7	21.9
			1870.09.18	0.50	28.9	3.19	103.1	102.6
Fecker	Rebeur	Karlsruhe	1887.03.21	0.91	40.9	4.00	78.7	39.0
			1887.04.18	0.91	32.2	4.00	48.9	39.0
Repsold	Rebeur	Potsdam	1889.04.01–1889.09.30	0.81	18.7–23.6	4.52	23.2–36.9	55.0
		Wilhelmshaven	1889.03.07–1889.09.30	0.81	16.0–16.5	4.46	16.6–17.8	54.2
		Tenerife	1890.12.22–1891.04.28	0.81	22.6	4.58	34.1	55.7
		Strasbourg	1892.04.06–1893.09.06	0.81	24.1–36.6	1.84	15.8–36.6	22.6
	Kortazzi	Nikolayev	1892.02–1900	0.80	16.0–37.6	4.70	18.2–100.7	59.1
	Levitski	Kharkov	1893.08.04–1894.10.11	0.83	13.3–34.5	4.23	10.5–71.1	49.9

T_v=free period of pendulum in vertical position; T_0=free period of pendulum in horizontal position; a=distance between mirror and recording device; r=tilt sensitivity; G=magnification of spot displacement with respect to ground displacement

[a] Hengler pendulum: T_v is estimated, a=distance between bob and rotation axis; Zöllner pendulum: T_v is computed from r as given by Zöllner. A more complete and detailed Table is available in the Online resource 2

system gain G is defined at high frequency. Since the Rebeur-Paschwitz pendulums were strongly underdamped, their effective gain G_E as reported by Abe[7] is larger than G, by a factor of 4 to 7.

It is not uninteresting here to mention another parameter, the resolution. The resolution is equal to the smallest amplitude change that can be measured divided by the sensitivity. It is given above for the older optical instruments of Hengler, Zöllner, and Rebeur-Paschwitz. For later instruments using photographic paper, the resolution varies with the size and sharpness of the spot and can only be roughly estimated. For his 1889 observations, Rebeur-Paschwitz (1892a) evaluates the precision on amplitudes as 0.5 mm (Rebeur-Paschwitz 1892b, p 61). From Table 2, the sensitivity was 23.2 mm/arcsecond in Potsdam and 16.6 mm/arcsecond in Wilhelmshaven during the first run of observations. This implies a resolution of 2.2 10^{-2} and 3.0 10^{-2} arcsecond, respectively, a lower performance as compared with his prototype in Karlsruhe.

We mentioned previously that damping was suggested by Gruithuisen and Hengler and was later introduced by Hood and Darwin and by Rebeur-Paschwitz in February and March 1889. With the exception of this short period, all the recordings performed with Rebeur-Paschwitz pendulums were performed without any damping device. The residual natural damping was low, thanks to the optical recording method. This low damping led to long-lasting natural oscillations during earthquakes, which hampered detection of seismic waves and accurate reading of arrival times. On the other hand, these oscillations allowed the precise free-period determination that was required for the tilt measurements. For calibration purposes, Repsold's pendulums were fitted out with a rubber pipe and a blowing pear allowing for the excitation of minute oscillations. In Strasbourg in 1892, Becker measured the exponential decay of amplitude extrema with time during free oscillations (Rebeur-Paschwitz 1895b). The values he obtained allow us to compute the damping ratio h from:

$$A_k/A_{k+n} = \exp\left(n\,\pi\,h/\sqrt{\left(1-h^2\right)}\right) \tag{9}$$

where A_k and A_{k+n} are the amplitude extrema of the k^{th} and $(k+n)^{\text{th}}$ oscillations. From Eq. 9, we obtain:

$$h = L/\sqrt{\left(L^2+n^2\pi^2\right)} \tag{10}$$

where $L=\ln(A_k/A_{k+n})$. Another quantity often used to evaluate damping is the quality factor Q. It is related to h by the relation $Q=1/2h$.

From the first series of measurements made on 17 November 1892, we obtain a mean damping ratio h=0.0134. This is a very small value, as expected, since

[7] Note that the system gain 230 computed by Abe (1994) p 419 for Nikolayev is erroneous because Abe used the half-period instead of the period (see Kortazzi 1895, p 28).

the damping only stems from air resistance and friction between the steel points and the agate cups. The corresponding value of the quality factor is Q=37. A second series of measurements by Becker on the same day (Fig. 13) leads to a very similar mean damping ratio h=0.0138. This damping ratio however exhibits significant variation during the calibration experiment. It indeed decreases monotonously from 0.04 at the beginning to 0.01 at the end, possibly revealing some dependence of h on the amplitude or non-viscous damping. The identification of seismic-phase arrivals was rendered difficult with such low damping. Combined with the very slow recording speed (1.1 cm/h), the overall timing accuracy of seismic phases was estimated by Rebeur-Paschwitz (1895b) to between 1 and 3 min.

Rebeur-Paschwitz (1895b) lists 301 events recorded between 1889 and 1893 that he identified as probable earthquakes. Out of these 301 events, he could identify the probable seismic source for 60, based on his search of catalogues, newspapers, and through letters exchanged with many correspondents worldwide. However, the number of earthquakes for which seismograms are available (reproduced in Rebeur's papers) amounts to only 31.

5 Surviving Rebeur-Paschwitz pendulums

Our research led us to the following question: What did the instruments developed by Rebeur-Paschwitz become after he passed away? Surprisingly enough, we found that at least five out of the six Repsold instruments have survived to the present day, though nobody was aware of their existence. The two instruments in Nice are still present in the Observatory, but some parts are missing, principally their moving elements (Fig. 14). They had been labeled as theodolites in a provisional inventory when we identified them in 2008. The two instruments of the Kharkov Observatory were in service at least until 1909 (Struve 1898, 1904; Kudrevich 1911) under the supervision of Struve and later Boris I. Kudrevich (1885–1970). When we found them in Kharkov, they were thought to be some sort of level, which is not wrong. The instrument we could see is in a similar condition to those in Nice (Fig. 14 and Online resource 1). Kortazzi's pendulum in Nikolayev is the only missing instrument. It was operated by Kortazzi until his death in 1903 and afterward until approximately 1908 by his successor P. A. Brovtsin. In 1909, the Nikolayev Observatory was transferred from the Navy to the Pulkovo Observatory. Most instruments were removed by the Navy, which may explain the disappearance of the pendulum. Oral memory in the Observatory says that it may have been stored in the basement of the prison in Samara, Russia. Figure 15 sketches the transfer and fate of all the instruments produced under Rebeur-Paschwitz directions.

After Gerland purchased the Strasbourg pendulum from Rebeur in the spring of 1894, he also needed a photographic recorder. The original Wanschaff recorder was not part of the deal and had to be forwarded to Rebeur in Merseburg. Instead, Gerland obtained another recorder, the personal property of Rebeur, from a mathematician in Freiburg im Breisgau, Jakob Lüroth (1844–1910). The pendulum was put under the responsibility of Gerland's student Reinhold Ehlert (1871–1899). Ehlert operated the instrument between January 1895 and March 1896, at the very place where Becker installed it in 1892 (Ehlert 1898a, 1900). The instrument was then replaced by the new triple

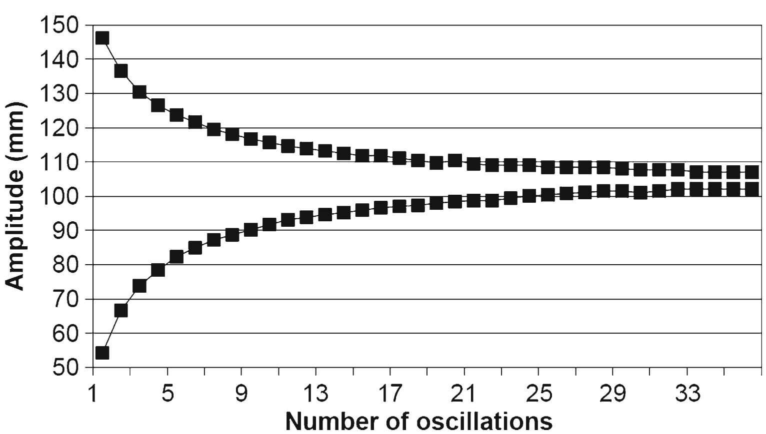


Fig. 13 Amplitude extrema measured during natural damped oscillations measured by Rebeur-Paschwitz in Strasbourg in November 1892

Fig. 14 Surviving Repsold horizontal pendulums. *Top*: Strasbourg (inner brass support and glass bell are present-day replicas); *bottom left*: Kharkov; *bottom right*: Nice

horizontal pendulum developed by Ehlert. It was moved to the new seismological station inaugurated in 1899. We discovered it there in 2007 (Fig. 14), stored upside down in a cupboard, unfortunately missing all its internal parts (pendulum, mirrors, etc.).

Omori's pendulum, the Repsold two-component instrument, was not much in use in Tokyo after its purchase in 1896. It was moved in July 1909 to the newly opened Kamigamo Geophysical Observatory in Kyoto where Toshi Shida (1876–1936) planned to perform earth-tide measurements (Shida 1912). The recordings started in 1910. The pendulum was taken to the Aso volcano for several years in the 1930s before returning to Kyoto (Takemoto et al. 2010). The last reported

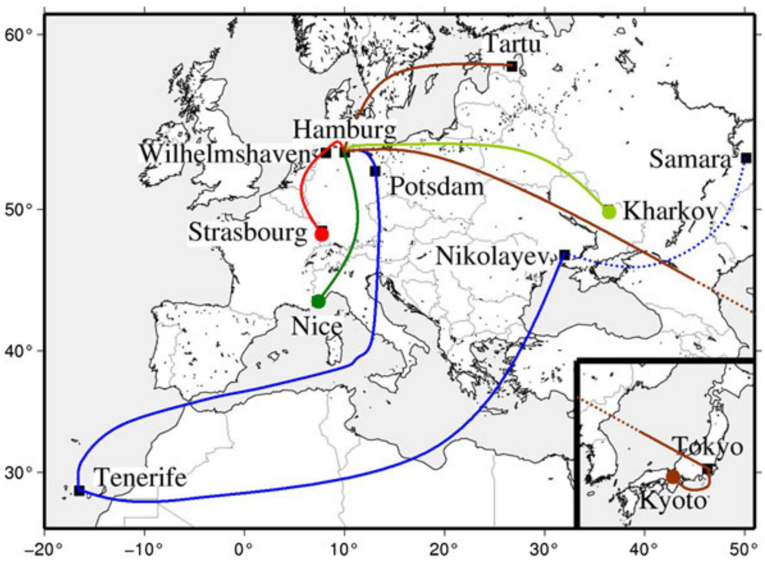


Fig. 15 Transfers and fate of the Rebeur-Paschwitz horizontal pendulums and the Omori produced by Repsold from 1888 to 1896

observation dates back to 1938 by Eiichi Nishimura. One of us (L. R.) visited the Kamigamo Observatory in June 2009 with Jim Mori. From a previous visit, we knew that the pendulum was not to be found in the Observatory. However, in the nearby ruins of an old hut, L. Rivera was lucky enough to find the pendulum buried in the rubble, after being missing for 70 years (Mori et al. 2009; Takemoto et al. 2010).

The Rebeur's Stückrath pendulum in Merseburg was acquired by Valentiner and sent to Karlsruhe in 1895. In 1898, the provisional Karlsruhe Observatory was relocated to Heidelberg in a new building. Valentiner installed the pendulum in a cellar of his new Astrometrical Institute in Heidelberg. Recordings were performed until 1905 in turn by Leopold Courvoisier, August Caspar, Wilhelm Schweydar, and Martin Knapp (Valentiner 1900–1906; Schweydar 1905). In 2004, the instrument could not be found in the observatory (Holger Mandel, personal communication). The second Stückrath instrument, in Tartu, is also missing, as are all other pendulums there (Olga Heinloo, personal communication).

Our search for surviving original seismograms from the above-described Repsold and Stückrath pendulums has been unsuccessful to date.

6 Conclusions

From the very beginning with Hengler's instrument in 1831, the horizontal pendulum was used as a highly sensitive device to detect minute movements of the ground. It was clear that its purpose was to record both ground tilt due to luni-solar attraction, i.e., earth tides, and ground displacement during the passage of seismic waves. During the nineteenth century, astronomers often observed vibrations of telescopes, levels, or magnetic needles and associated them with regional earthquakes (e.g., Fouqué 1888; Baratta 1897). Since regional moderate earthquakes produce signals significantly larger than ordinary background noise, very simple instruments, such as vertical pendulums, provided relatively early a wealth of information on the seismic process in active regions like Italy or Japan. Observing solid-earth tides, on the contrary, remained a challenge until the first results were published by Rebeur-Paschwitz (1891; 1892b). Indeed, the earth tide tightly competes with strong long-period noise and requires extremely well-installed and isolated instruments.

Inertial devices are both sensitive to tilt and horizontal acceleration, which are thus, in principle, indistinguishable. However, in practice, the former predominates at long period and the latter at high frequency. As a result, the horizontal pendulum is mainly affected by the deviation of the direction of gravity and the tilt of the ground surface in the case of earth tides, whereas it mostly responds to horizontal acceleration of the ground in the case of earthquakes. The discovery of the horizontal pendulum was not sufficient in itself to unravel the laws of earth dynamics. In addition, it needed low-friction continuous recording, high amplification, constant-temperature, and low-noise environmental conditions. All these requirements were met by Rebeur-Paschwitz with his pair of Repsold pendulums. During his first series of observations in Potsdam and Wilhelmshaven and his second series in Strasbourg and Nikolayev, he recorded a large number of teleseismic events with sources all over the globe (Rebeur-Paschwitz 1892b; 1895b). Moreover, he succeeded in observing the luni-solar tide for the first time, by recording and measuring its effect on the apparent ground tilt. The method he used to obtain this result was based on a detailed quantitative analysis of the photographic seismograms, which probably only an experienced astronomer was able to perform. He measured the amplitude every hour on the hundreds of seismograms he had gathered (in other words he digitized the amplitude) and applied corrections for the long-term drift. Finally, he applied a technique suggested to him by Börgen, the Director of the Wilhelmshaven Observatory, the interpolation of the data, to obtain amplitudes at lunar instead of solar hours and taking means over long periods. This was quite an achievement. Similar methods were used and improved by his successors Hecker, Schweydar, Shida, etc.

The contribution of Ernst von Rebeur-Paschwitz was seminal for seismology. But, much remained to be done, to say the least. It was known since Wertheim (1849) that earthquakes may generate P- and S-waves. But, the slow drum speed of Rebeur's recorders (1.1 cm/h) and the absence of damping did not allow him to observe or measure unambiguously different wave types in the seismograms. However, he foresaw that the successive phases he observed traveled through the earth at velocities increasing with depth (Rebeur-Paschwitz 1895a), as suggested by Schmidt (1888). It was left to others like Oldham in Calcutta or the Wiechert's group in Göttingen to identify the arrival of body- and surface-waves and to produce the first models of seismic-wave velocity inside the globe (e.g., Schweitzer 2007). Rebeur-Paschwitz (1895c) also initiated the move that resulted in the creation of the International Seismological Association in 1904 with its Central Bureau in Strasbourg (Rothé 1981; Cremer 2001; Schweitzer 2003).

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