C. R. Physique 18 (2017) 520–525

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

The *Comptes rendus de l'Académie des sciences* throughout history / Les *Comptes rendus de l'Académie des sciences* à travers l'histoire

Foucault and the rotation of the Earth

Foucault et la rotation de la Terre

Joël Sommeria

Laboratoire des écoulements géophysiques et industriels, Université Grenoble Alpes & CNRS, Grenoble, France

A R T I C L E I N F O

Article history:
Available online 21 November 2017

Keywords:
Coriolis
Pendulum
Gyroscope
History
Inertia

Mots-clés :
Coriolis
Pendule
Gyroscope
Histoire
Inertie

A B S T R A C T

In February 1851, Léon Foucault published in the *Comptes rendus* his famous pendulum experiment performed at the "Observatoire de Paris". This ended two centuries of quest for an experimental demonstration of Earth rotation. One month later, the experiment was reproduced at larger scale in the Panthéon and, as early as the summer of 1851, it was being repeated in many places across the world. The next year, Foucault invented the gyroscope to get a still more direct proof of Earth rotation. The theory relied on the masterpiece treatise of Laplace on celestial mechanics, published in 1805, which already contained the mathematical expression of the force that would be discovered by Gustave Coriolis 30 years later. The idea of a fictitious inertial force proposed by Coriolis prevailed by the end of 19th century, as it was conceptually simpler than Laplace's approach. The full theory of the Foucault pendulum, taking into account its unavoidable imperfections, was not obtained until three decades later by Kamerlingh Onnes, the future discoverer of liquid helium and superconductivity. Today, Foucault's exceptional creativity is still a source of inspiration for research and the promotion of science through experimental proofs widely available to the public.

R É S U M É

En février 1851, Léon Foucault publiait dans les *Comptes rendus* sa fameuse expérience du pendule réalisée à l'Observatoire de Paris. Cela mettait fin à deux siècles de quête d'une preuve expérimentale de la rotation de la Terre. Un mois plus tard, l'expérience fut reproduite à plus grande échelle au Panthéon et, dès l'été 1851, elle fut répétée dans de nombreux endroits du monde. L'année suivante, Foucault inventait le gyroscope pour obtenir une preuve encore plus directe de la rotation de la Terre. La théorie s'appuyait sur le traité de Laplace sur la mécanique céleste. Publié en 1805, celui-ci contenait déjà l'expression mathématique de la force qui sera découverte par Gustave Coriolis 30 ans plus tard. L'idée d'une force d'inertie fictive proposée par Coriolis a cependant prévalu à la fin du XIX^e siècle, car elle était conceptuellement plus simple que les calculs de Laplace. La théorie complète du pendule de Foucault, tenant compte ses inévitables imperfections, n'a été élaborée que 30 ans plus tard par Kamerlingh Onnes, le futur découvreur de l'hélium liquide et de la supraconductivité. De nos jours, la créativité exceptionnelle de Foucault est

E-mail address: joel.sommeria@univ-grenoble-alpes.fr.

https://doi.org/10.1016/j.crhy.2017.11.003

encore source d'inspiration pour la recherche et la promotion de la science par des preuves expérimentales largement accessibles au public.

1. The Foucault pendulum

In 1851 Léon Foucault first described his famous pendulum experiment in the *Comptes rendus* [1]. As he explains in his report, the principle is easy to understand at the pole: by inertia the plane of oscillation remains constant with respect to an inertial reference frame, so that in a sidereal day (23 h 56 min) it rotates or veers through a full 360° with respect to the Earth, in the opposite direction. Foucault checked that the rotation of the support has indeed negligible effect on the plane of rotation. He was inspired by the observation of a thin flexible rod on the axis of a lathe, which keeps oscillating in a constant plane in spite of the rotation of its support. The problem is more complicated at lower latitude, but Foucault rightly convinced himself that the angular speed of the veering of the swing plane should be proportional to the sine of the latitude. This point was, however, puzzling, and in his paper Foucault draws the attention of "*géomètres*" (as mathematicians were called at that time) to solve the problem in a more rigorous way.

Foucault first tested a 2-m-long version of his pendulum in his cave, in January 1851. He then repeated the experiment more convincingly at the "Observatoire de Paris", with a pendulum 11 m in length, thanks to the support of François Arago, director of the Observatory. He presented his results to the "Académie des sciences" on 3 February 1851, an account of which [1] was published in the *Comptes rendus* issue dated the same day. The experiment, still visible at the "Musée des Arts et Métiers" (Fig. 1), was then repeated at the Panthéon in March 1851, using a 67-m-long pendulum with a hollow brass sphere, 17 cm in diameter, filled with lead to reach a mass of 28 kg. A heavy and compact mass indeed reduces air friction damping. A long pendulum has the advantage of reducing the influence of spurious perturbations, and it provides a stronger deviation at each period, reaching 2.3 mm in the Panthéon experiment. Thus it was strikingly visualized by marks left on sand piles by a stylus attached to the pendulum.

The experiments in the Panthéon had an immense popular impact. It ended several millennia of philosophical discussions about Earth motion with a definitive experiment, directly visible by the public. The experience was repeated in many cities in the world. It was performed in France at Rennes and in the cathedral of Rheims. It was repeated at least in 25 cities in the United States during the summer 1851 [2].

2. Two centuries of attempts at detecting Earth rotation

In retrospect, it may seem surprising that Foucault's pendulum was not invented earlier, since its concept is simple and relies on classical technology (however, it is very sensitive to imperfections, see below). Furthermore, although the existence

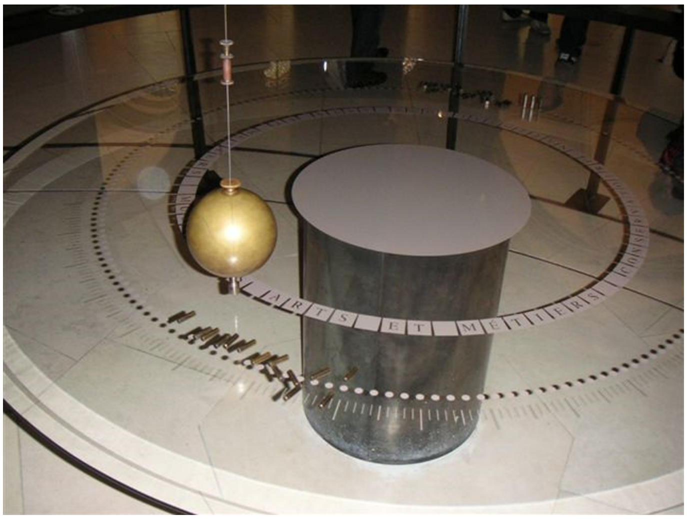

Fig. 1. The original Foucault pendulum exposed at the "Musée des Arts et Métiers" in Paris. Photo: Hervé Marchebois. Source: Wikimedia Commons. (This image is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license.)

of Earth rotation had been accepted long previously by scientists, there was a wish for a direct proof. Laplace had stated in his masterpiece treatise on celestial mechanics, 45 years earlier [3]:

> *quoique la rotation de la Terre soit maintenant établie avec toute la certitude que les sciences physiques comportent, une preuve directe de ce phénomène doit intéresser les géomètres et les astronomes.*

In fact, when hearing of the experiments of Foucault, Antinori, the director of the Museum for Physics and Natural History in Florence, relates in the *Comptes rendus* [4] that something similar has been reported by Vincenzo Viviani in old notes from members of the "Accademia del Cimento", an institution devoted to experimental physics in the 1660s. He mentions explicitly the veering of the pendulum, but does not make the connection with the Earth's rotation. This was a nuisance for their study of the pendulum, and they later fixed it with two ropes instead of one, in order to avoid this undesired veering.

It seems surprising that Vincenzo Viviani did not think about Earth rotation as the cause of the veering of the pendulum. He was a disciple of Galileo and collaborated with Giovanni Borelli, who made in the 1660s the first considerations of the problem of falling bodies on a rotating Earth. The existence of the Earth rotation was a topic of active debate at that time (much of the source material has been reproduced by Koyré [5]). In his theoretical analysis, Borelli found that a falling body should undergo a small eastward deflection. His result was only qualitatively correct. A precise calculation was only published by Denis Poisson (1837) in the *Comptes rendus* [6]. In fact, his result was already contained in Laplace's treatise [3].

The earlier search for a direct evidence focused on the motion of falling bodies. Early experiments to test the idea of eastward deflection were inconclusive, for the effect is very small and easily dwarfed by other effects, such as wind (in open-air experiments, e.g., when dropping balls from a tower), or by a minute horizontal velocity accidentally imparted to the object at the start of its fall. In the 17th century, speculation on the fate of vertically launched objects elicited a lively debate, and attempts were made to settle the issue experimentally: balls were shot vertically upward by a cannon. Amazingly, many balls were never found again. This did not surprise Descartes, who thought that the balls were able to escape Earth attraction:

> [...] *on doit juger que la force du coup les portent fort haut, les éloigne si fort du centre de la Terre, que cela fait perdre leur pesanteur*" (letter cited by Benzenberg [7], p. 261).

At the beginning of the 19th century, serious attempts were made to minimize the perturbations. The most well-known experiments are those of Ferdinand Reich [8] in a mine pit 158 m in depth at Freiberg in Saxony. Over a total of 106 experiments, he found a mean eastward deviation of 2.8 cm, consistent with theory, but the dispersion around this value was larger than the mean, so the experiment was not fully convincing.

In fact there had been no real doubt about Earth rotation by the end of the 17th century, after the work of Newton on celestial mechanics. The astronomer Jean Richter discovered in 1672 that a pendulum has a lower frequency in French Guyana, near the equator, than in metropolitan France. This observation was later interpreted by Huygens as the effect of the centrifugal force which reduces the apparent gravity at the equator. Huygens was using the expression for the centrifugal force, which he had discovered in 1659. At about the same time, Newton was able to predict the oblateness of the Earth resulting from the combination of gravity and centrifugal force. This Earth oblateness was later measured by Maupertuis in 1738, which brought a clear confirmation of Newton's prediction, hence confirming the reality of Earth rotation. However the Foucault pendulum was the first direct experimental proof of Earth rotation.

3. The invention of the gyroscope

In spite of his great success, Foucault was not fully satisfied with his pendulum experiment, because of the dependency on the sine of latitude, which the public found difficult to understand. Following a suggestion of the mathematician Louis Poinsot, he later designed a purer and more compact device, which he named the gyroscope, from the Greek roots 'gyros' (rotation) and 'scope' (to observe). Although the technical realization was very challenging at that time, the principle is simple: a freely rotating torus keeps a constant axis of rotation in space, so it should slowly rotate with respect to an observer attached to the rotating Earth. In practice, the rotating torus is held by two gimbals with minimal friction, so its axis of rotation can freely reorientate with respect to the support stand (see Fig. 2).

The device was not quite new at the time of Foucault, and there was already a fierce competition to adapt it to the detection of Earth rotation. The challenge was mainly technical. The torus had indeed to be very well balanced to preserve a stable axis and the rotation had to persist long enough so that the deviation of the axis with respect to the Earth could be observed. Using a hand crank and four stages of gearing, the torus of Foucault's gyroscope was launched with an amazing initial speed of up to 200 rotations/second, allowing the rotation to persist for 10 minutes. This was sufficient to observe the deviation due to Earth rotation, using a microscope. This achievement was made possible by the legendary technical ability of Gustave Froment, the engineer who built many of Foucault's principal instruments, including the pendulum. Note that Froment, a former student at the "École polytechnique", had also an excellent scientific background. The experiment was performed in May 1852 and reported in the *Comptes rendus* [9], followed by two additional communications in the same journal [10,11].

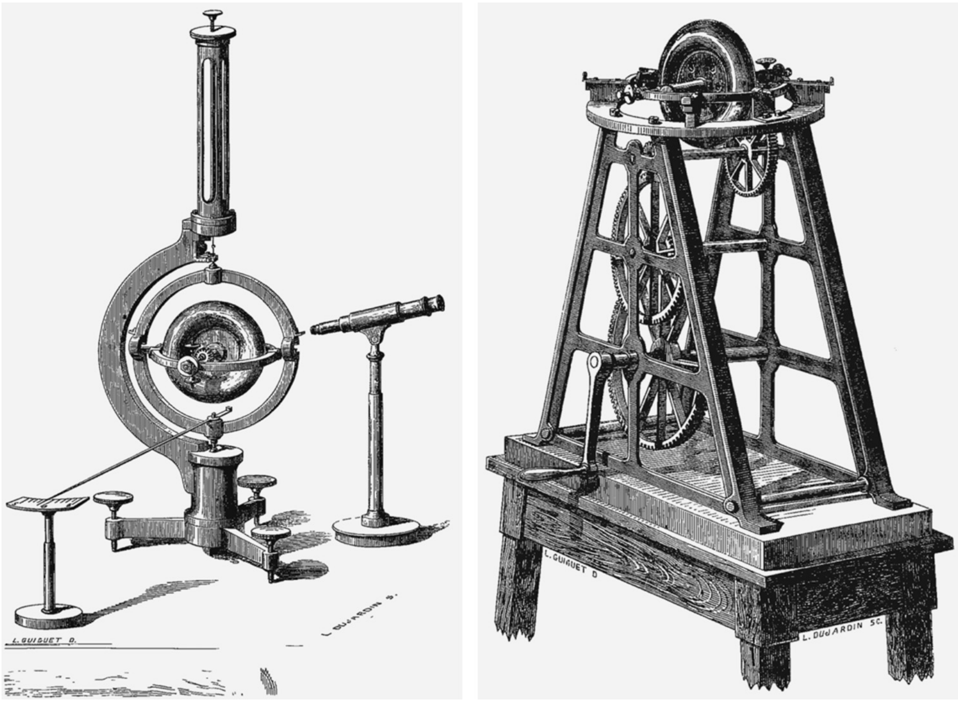

Fig. 2. Drawing of Foucault's gyroscope (left), and of its launching device (right). Taken from the *Astronomie populaire* by Camille Flammarion.

4. Theoretical interpretations and further developments

The first theoretical discussion of the effect of Earth rotation on a pendulum was made by Poisson in 1837 [5], before Foucault's experiment. However, Poisson concluded hastily that it was too weak to produce a significant effect. After the experiments, Binet (1851) [12,13] revisited the theory and was able to prove the dependency of the veering frequency on the sine of the latitude intuited by Foucault.

It is noteworthy that none of these authors mention the work of Gaspard-Gustave Coriolis [14] on the "*force centrifuge composée*", now known as the Coriolis force, published in 1835. Gustave Coriolis was a member of the French "Académie des sciences", but he died in 1843, eight years before Foucault's experiment. He was interested in rotating machinery, and no connection was drawn with astronomy and meteorology at that time. These early studies of Earth rotation effects refer instead to Laplace, who already published the mathematical expression of the Coriolis force in the fourth volume of his treatise of 1805 [3], dealing with the theory of tides. The American meteorologist William Ferrel also refers to Laplace in his discussions on the effects of Earth rotation on the atmospheric and ocean currents published in the 1850s, first in a journal of medicine! [15] A good overview of these historical aspects can be found in [16].

The work of Coriolis brought real novelty in terms of physical interpretation, introducing fictitious forces that were easier to handle than the earlier derivations by Laplace. The connection with Laplace's theory was debated at the French Academy of Sciences in 1859. The Foucault pendulum was discussed in these reports, as well as an observation by Perrot [17] of a vortex attributed to Earth rotation in a sink from a "small hole at the centre of a circular tank of large size".

This experiment was however poorly described, and convincing evidence of this "bath tub effect" was only provided in 1908 by the Austrian physicist Ottokar Tumlirz [18], and later nicely illustrated by the classical educational movie of Shapiro (1962). This requires very quiet initial conditions in a meter-size tank, not available in usual home facilities. Observations of effects of Earth rotation in river and ocean currents were reported by Babinet [19] in the same issue of the *Comptes rendus* as that in which Perrot's work has been published. The advantage of introducing fictitious forces in a rotating reference frame was advocated by Delaunay, but highly debated. As stated by Bertrand, "these fictitious forces lead to an exact result; but precisely because they are fictitious, they are not able to lead to a good understanding of the real causes of the phenomena involved." The use of the "Coriolis force" became standard only by the end of the 19th century. Nowadays, it still retains a mysterious flavour, and coming back to an inertial (non-rotating) reference frame can be useful for grasping the "real causes of the phenomena" invoked by Bertrand.

A fuller treatment of Foucault's pendulum was given only decades later in the doctoral thesis (1879) of Kamerlingh Onnes, the future discoverer of liquid helium and superconductivity. An extensive historical overview on the subject can be found in a three-volume book [20] (written in French), with a booklet by J. Stein offering a clear summary of the thesis by Onnes. It is also summarised and discussed with a more recent perspective by reference [21]. Advised by his former teacher Gustav Kirchhoff, Onnes first repeated Foucault's experiment with a rigid pendulum body supported by a double knife-edge suspension. He then analysed the deviations from the ideal behaviour observed by himself and by many other investigators attempting to repeat Foucault's experiment. While the pendulum is initially excited to a motion whose horizontal projection is a straight line, it initially changes direction as expected, but after typically one hour the motion "deteriorates" into one with an elliptical projection. Onnes made a novel perturbation analysis taking into account a slight difference of the pendulum natural frequencies along the two horizontal directions. This was found to result in a beating between the two horizontal modes of oscillation. The asymmetry can be due to a geometrical imperfection or to the elasticity of the pendulum support. Using his analysis, Onnes was able to improve the device by correcting the slight asymmetries.

Building Foucault's pendulums with increasing precision is still a topic of interest as a technical challenge and an educational tool. Recent designs maintain a permanent oscillation by equipping the pendulum with a magnet. It receives impulses from a coil excited by a feedback electronic circuit. Furthermore, the growth of the elliptical motion is damped by a mechanical device. The veering speed then fits with the Earth rotation period with a precision of the order of 1% [22]. Modern gyroscopes, however, provide a much better precision.

Finally, these experiments on Earth rotation have been a source of reflection about the meaning of absolute motion, which was at the root of Einstein's theory of general relativity. In this context, a gyroscope does not remain exactly fixed with respect to the distant stars, but is slightly entrained by Earth rotation at a rate of 0.2 arc seconds per year. The existence of this so-called Lense–Thirring effect was checked in 2005 by the satellite Gravity Probe B.

5. Foucault's legacy

Besides the pendulum and the gyroscope, Foucault is known for many discoveries and technical developments, most of them published in *Compte rendus*. Foucault first studied medicine, which he progressively abandoned in favour of physics. He started physics as an amateur, with no theoretical training beyond the *baccalauréat* level. His initial professional activity was as a journalist, reporting results from the "Académie des sciences" in the *Journal des débats*, a Parisian newspaper. This activity probably contributed to his wide scientific culture and favoured his exceptional creativity.

Foucault first directed his attention to the improvement of Daguerre's photographic processes and he carried out different investigations in optics with his friend Hippolyte Fizeau. In 1850, they were able to show that light travels more slowly through water than through air, in accordance with wave theory. In 1855, he discovered that the force required for the rotation of a copper disc becomes greater when its rim lies between the poles of a magnet, the disc at the same time becoming heated by the eddy currents or "Foucault currents" induced in the metal. In 1857, Foucault invented the polarizer that bears his name, and in the succeeding year devised a method of testing the mirror of a reflecting telescope to determine its shape. An excellent description of his many scientific contributions and inventions can be found in reference [2].

In spite of these important inventions and discoveries, the pendulum remains the most well-known contribution of Foucault because of its immense impact on the public. Foucault pendulums are still being installed in a variety of exhibition halls all over the world. One was reinstalled in the Panthéon in 2015 as part of a wider restoration project. It symbolically represents the triumph of the human mind over old dogmas: truth does not come from religion, or political or social authorities, but it can be directly assessed by experiments accessible to everybody. Modern science becomes more and more specialized and complex, moving away from this ideal of the 19th century. But Foucault's work can still be a source of inspiration to promote science through widely accessible experimental proofs and demonstrations.

Acknowledgements

The author thanks Achim Wirth and Louis Gostiaux for the many discussions that contributed to the writing of this paper.

References

[1] L. Foucault, Démonstration physique du mouvement de rotation de la terre au moyen du pendule, C. r. hebd. séances Acad. sci. Paris 32 (1851) 135–138.
[2] W. Tobin, The Man Who Proved the World Turned Round, Cambridge University Press, 2002;
French translation: W. Tobin, Léon Foucault, EDP Sciences, Paris, 2002.
[3] P.S. Laplace, Traité de Mécanique Céleste, t. IV, Courcier, Paris, 1805 (an XIII).
[4] V. Antinori, Anciennes observations faites par les Membres de l'Académie del Cimento sur la marche du pendule, C. r. hebd. séances Acad. sci. Paris 32 (1851) 635–636.
[5] A. Koyré, A documentary history of the problem of fall from Kepler to Newton (De motu gravium naturaliter cadentium in hypothesi Terrae motae), Trans. Am. Philos. Soc. 45 (4) (1955) 329–395;
French version: A. Koyré, Chute des corps et mouvement de la terre – de Kepler à Newton, J. Vrin, Paris, 1973.
[6] S.D. Poisson, Extrait de la première partie d'un Mémoire sur le Mouvement des projectiles dans l'air, en ayant égard à leur rotation et à l'influence du mouvement diurne de la Terre, C. r. hebd. séances Acad. sci. Paris 5 (1837) 660–667.
[7] J.F. Benzenberg, Versuche über das Gesetz des Falls, über den Widerstand der Luft und über die Umdrehung der Erde nebst der Geschichte aller früheren Versuche von Galiläi bis auf Guglielmini, Mallinckbodt, Dortmund, 1804.
[8] F. Reich, Fallversuche über die Umdrehung der Erde, Engelhardt, Freiberg, 1832.
[9] L. Foucault, Sur une nouvelle démonstration expérimentale du mouvement de la Terre, fondée sur la fixité du plan de rotation, C. r. hebd. séances Acad. sci. Paris 35 (1852) 421–427.

[10] L. Foucault, Démonstration expérimentale du mouvement de la Terre, addition dans les communications faites dans les précédentes séances, C. r. hebd. séances Acad. sci. Paris 35 (1852) 469–470.
[11] L. Foucault, Sur la tendance des rotations au parallélisme, C. r. hebd. séances Acad. sci. Paris 35 (1852) 602–603.
[12] J. Binet, Note sur le mouvement du pendule simple en ayant égard à l'influence de la rotation diurne de la terre, C. r. hebd. séances Acad. sci. Paris 32 (1851) 157–160.
[13] J. Binet, Suite de la note sur le mouvement du pendule simple en ayant égard à la révolution diurne de la terre, C. r. hebd. séances Acad. sci. Paris 32 (1851) 197–205.
[14] G. Coriolis, Sur les équations du mouvement relatif des systèmes de corps, J. Éc. Polytech. XXIV^{e} Cahier XV (1835) 142–154.
[15] W. Ferrel, An essay on the winds and the currents of the Oceans, Nashville J. Med. Surg. 11 (4) (1856).
[16] T. Gerkema, L. Gostiaux, A brief history of the Coriolis force, Europhys. News 43 (2) (2012) 14–17, https://doi.org/10.1051/refdp/2009026, French version: Reflets de la Physique 17 (2009) 18–21.
[17] M. Perrot, Nouvelle expérience pour rendre manifeste le mouvement de rotation de la Terre, C. r. hebd. séances Acad. sci. Paris 49 (1859) 637–638.
[18] O. Tumlirz, Ein neuer physikalischer Beweis der Achsendrehung der Erde, Sitz.ber. Wiener Akad. Wiss. Abt. IIa 117 (1908) 819–841.
[19] M. Babinet, Influence des mouvements de rotation de la Terre sur le cours des rivières, C. r. hebd. séances Acad. sci. Paris 49 (1859) 638–641.
[20] J.G. Hagen, La rotation de la Terre, ses preuves mécaniques anciennes et nouvelles, Tipografia Poliglotta Vaticana, Rome, 1911, with an Appendix by J. Stein, Les preuves de M. Kamerlingh Onnes.
[21] E.O. Schulz-DuBois, Foucault pendulum experiment by Kamerlingh Onnes and degenerate perturbation theory, Am. J. Phys. 38 (1970) 173–179.
[22] H.R. Salva, R.E. Benavides, J.C. Perez, D.J. Cuscueta, Rev. Sci. Instrum. 81 (2010) 115102.