Astronomical Precision in the Laboratory: The Role of Observatory Techniques in the History of the Physical Sciences

by David Aubin, Paris

In the summer of 1829, Adolphe Quetelet who was planning to set up an observatory of his own in Brussels toured Germany to gather information from its main astronomers. Influenced by his mentors Alexander von Humboldt and François Arago, Quetelet had set out to measure the magnetic field of the earth in the several locations he visited. One day, he called on Carl Friedrich Gauss in his Göttingen observatory. The next day, they installed instruments in the garden of the observatory, far from any piece of iron to avoid perturbation on the delicate setup. The Göttingen astronomer was then sceptical of Humboldt's grand ambition of turning the study of geomagnetism into a global precision science. One year earlier he had had the opportunity to perform some experiments with Humboldt in Berlin and he had not been impressed by the quality of these measurements.

That summer day of 1829, both Gauss and Quetelet held a chronometer in their hand and timed the oscillations of a magnetic needle placed between them. At their utmost surprise, their respective measurements for the duration of a hundred oscillations differed by less than a tenth of a second. "But these observations," Gauss apparently exclaimed, "have the precision of astronomical observations."[1]

Astronomers have early on insisted on the precision of their measurements and computations. The transformation of industrial and scientific cultures in the nineteenth century has been traced in part to the rise of "the values of precision" and laboratories in universities and industries have traditionally been seen as central locations in this process. The observatory is arguably equally important, if only because a number of these values already pervaded observatory culture by the end of the eighteenth century.[2]

Viewed from today, the eclecticism of observatory scientists in the first part of the nineteenth century may seem puzzling. Famous for his social theory of the average man, Quetelet studied with just as much devotion and enthusiasm shooting stars, the influence of the moon on climate, probability theory, demography, or criminality. Similarly, one is often surprised to learn that Gauss, who was one of the greatest mathematicians of his time, spent several years to observe stars and comets, to triangulate the state of Hannover, or to perform delicate measurements of the earth magnetic field.[3]

At the heart of the observatory's material culture lay a family of scientific instruments, most of them, though by no means all, optical. The telescopes, polariscopes, spectroscopes, magnetometers, clocks, thermometers, hydrometers populating the observatory expressed the central concern of their users: to achieve the highest possible level of precision in the (mostly quantitative) measurement of celestial phenomena. Astronomy was the first precision science.[4]

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[1] Adolphe Quetelet, *Sciences mathématiques et physiques au commencement du XIX^e siècle* (Brussels: Mucquart, 1867), 646. See Gauss to Olbers, 12 October 1829, in C. F. Gauss and H. W. M. Olbers, *Briefwechsel*, 3 vols. (Hildesheim/New York: Georg Olms, 1976), 2:525. "Bei Beobachtung der Schwingungsdauer einer Nadel lässt sich eine Schärfe erreichen, die ich selbst früher für unglaublich gehalten haben würde" (ibid., 2:588).

[2] M. Norton Wise, ed., *The Values of Precision* (Princeton, NJ: Princeton Univ. Press, 1995). About observatory sciences, see David Aubin, "The Fading Star of the Paris Observatory in the Nineteenth Century: Astronomer's Urban Culture of Circulation and Observation," *Osiris* 18 (2003), 79-100; and David Aubin, Charlotte Bigg, and H. Otto Sibum, eds., *The Heavens on Earth: Observatory Techniques in the Nineteenth Century* (forthcoming).

[3] G. Waldo Dunnington, *Carl Friedrich Gauss: Titan of Science* (New York, Hofner, 1955); Tord Hall, *Carl Friedrich Gauss: A Biography*, trans. Albert Froderberg (Cambridge, Mass.: MIT Press, 1970).

[4] Historians of astronomy can be counted among those who have pioneered the exploration of nontheoretical issues in the history of science, in particular paying considerable attention to instruments of high precision and their makers. See for example Henry C. King, *The History of the Telescope* (Mineola, NY: Dover 2003 [1955]); Allan Chapman, *Dividing the Circle: The Development of Critical Angular Measurement in Astronomy, 1500-1850*, 2nd ed. (Chichester: John Wiley & Sons, 1995).

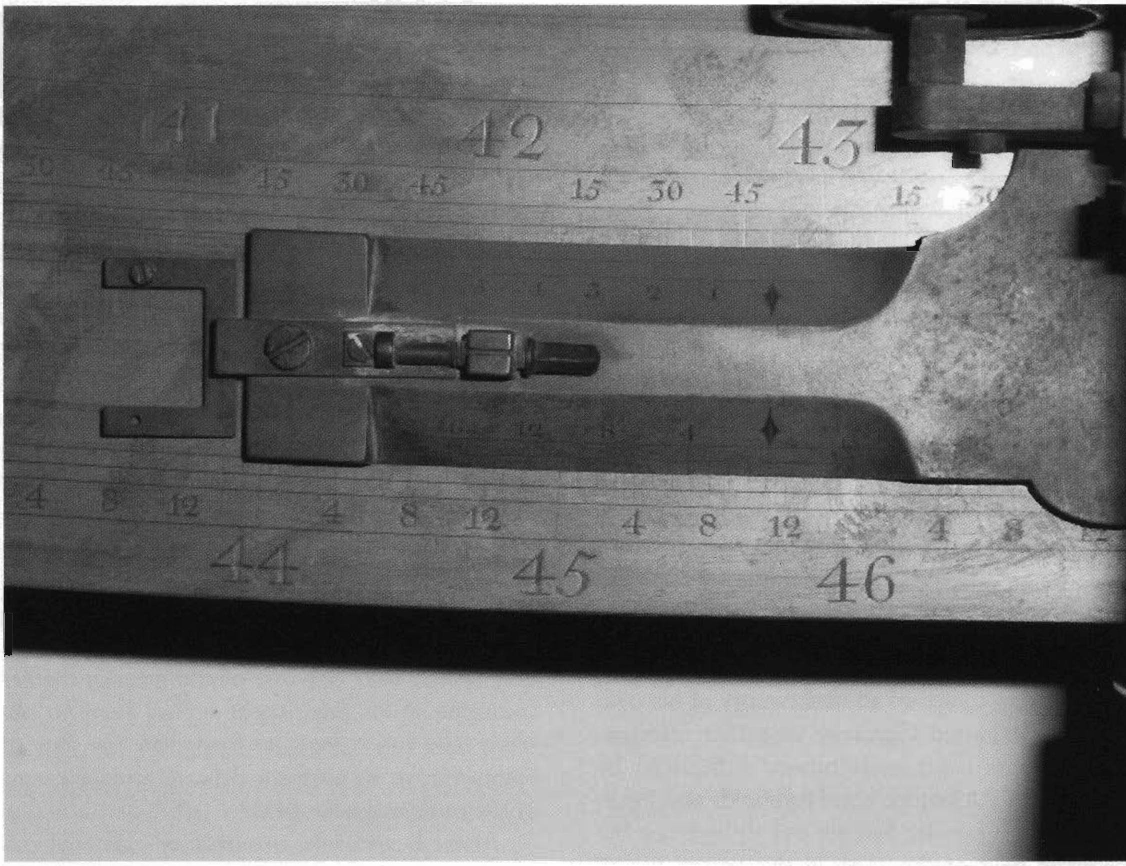

Abb. 9: Detail des Teilkreises mit Nonius auf dem Birdschen Mauerquadranten von 1756, der bis 1816 in der alten und danach in der neuen Sternwarte benutzt wurde (s. Abb. 25). Oben sind die Winkelgrade in Bogenminuten, unten in 16-tel Grad unterteilt. Der Nonius gestattete Messungen mit einer Genauigkeit von einigen Bogensekunden. Das Instrument ist heute nicht mehr voll funktionsfähig (Photo K. Reinsch, Universitäts-Sternwarte).

Precision relied on an array of techniques that were rooted in the culture of the observatory. Around 1800, there were few places as entirely devoted to the pursuit of research in the physical sciences as the observatory. In Paris, Greenwich, and elsewhere, maritime nations maintained large buildings, expensive instruments, and qualified staff for the advancement of knowledge, the improvement of maps, the computation and publication of tables and almanacs, and the development of navigational methods.[5] During the French revolution, observatory scientists were entrusted with the determination of the new metric units.[6] Nineteenth-century observatory scientists were at the forefront of scientific networking. In 1800, an international group of astronomers led by Franz Xaver von Zach had set up the Vereinigte Astronomische Gesellschaft to look for what they thought was a missing planet between Mars and Jupiter. They established an early international vehicle for communication by publishing regular observations in Zach's *Monatliche Correspondenz* (1800-1814), and later in Schumacher's *Astronomische Nachrichten* (from 1821).[7]

[5] The search for a reliable method for longitude determination at sea looms large in the early history of observatories. Cf., in particular, Derek Howse, *Greenwich Time and the Discovery of the Longitude* (Oxford: Oxford Univ. Press, 1980); William J. H. Andrewes, ed., *The Quest for Longitude* (Cambridge, Mass.: Harvard Univ. Press, 1996); Guy Boistel, *L'Astronomie nautique au XVIII^e siècle en France: tables de la Lune et longitudes en mer*, Ph.D. thesis (Université de Nantes, 2001) ; and Vincent Jullien, ed., *Le Calcul des longitudes. Un enjeu pour les mathématiques, l'astronomie, la mesure du temps et la navigation* (Rennes: Presses univ. de Rennes, 2002).

[6] Ken Alder, *The Measure of All Things: The Seven-Year Odyssey that Transformed the World* (London: Little, Brown, 2002).

[7] The history of astronomy's early professionalization is well documented. For Germany, see Jürgen Hamel, "H. C. Schumacher: Zentrum der internationalen Kommunikation in der Astronomie und Mittler zwischen Dänemark und Deutschland" and Gudrun Wolfschmidt, "Internationalität von der VAG (1800) bis zur Astronomischen Gesellschaft," W. D. Dick and J. Hamel, eds., *Astronomie von Olbers bis Schwarzschild, Nationale Entwicklungen und internationale Beziehungen im 19. Jahrhundert/ Acta Historia Astronomiae,* 14, 89–120 and 182–203; Dieter B. Herrmann, "Das Astronomentreffen im Jahre 1798 auf dem Seeberg bei Gotha," *Archive for the History of Exact Sciences* 6 (1969/1970), 326–44. About

By 1800, the observatory, therefore, had given rise to an epistemological space defined by a coherent set of techniques in precision, standardization and networking: the design and manipulation of delicate instruments, the material and mathematical treatment of numbers extracted from observation, and the social management of qualified personnel working together towards common aims, either inside one particular observatory or in collaboration across national boundaries. Borheck's manuscript is a striking testimony to the fact that little was left to improvisation when it came to ensure that an observatory yielded only the most precise data. Borheck divided his memoir into three parts concerned with, respectively, the location of the observatory, its instruments, and its building. In all cases, his utmost concern to which all others were subservient was that the best possible, most precise observational data could be produced in the observatory. Equally important was the willingness of European states, and especially German ones, to allocate the required funds to this enterprise. As Friedrich Bessel wrote Gauss when the Prussian government agreed to set up an observatory in Königsberg:

Dennoch kostet das Gebäude nahe an 20000 Thaler; der Grund 6000 Thaler; die Instrumente etwa 4000 Thaler. Es kann sonderbar scheinen, das in den jetzigen Zeiten so viel an eine Sternwarte verwandt wird; allein die Zeiten, wo das Militair alles wegnahm, sind vorbei, und so wird denn das lebhaftere Interesse an wissenschaftlichen Sachen erklärlicher.[8]

Precision attracted Gauss's attention to astronomy.[9] Few of his contemporaries excelled as he did in the several sides of astronomical work, from the most theoretical studies to routine observation. Having studied astronomy in Göttingen in 1795–98, assisted Lieutenant K. L. E. von Lecoq in his geodetic survey of Westphalia, and visited Zach at the Seeberg Observatory (Gotha), Gauss was struck by the announcement in Zach's journal for September 1801 of the discovery of a new planet (Ceres) by Giuseppe Piazzi. Before disappearing behind the Sun, the planetoid had been observed for 41 days only. This short duration made it difficult to compute the size and shape of its orbit and thus to predict where and when the faint light deflected by Ceres would be visible again. Gauss saw a golden opportunity to demonstrate his mathematical skills to the astronomical community when he calculated the orbit of Ceres on the basis of three observations only. On 1 January 1802, Gauss's approach was vindicated when, relying on his computations, Zach sighted the planet again.

Early 19th-century German astronomers, von Zach, Olbers and Gauss, among others, were drawn to emphasize the need of furthering the precision of astronomical observation. Variations in brightness, misrecordings and misprints, and errors in the reduction of data marred extent star catalogues and made them acutely aware of the need to rework older catalogues introducing more precise corrections for astronomical refraction, stellar aberration, and the precession of equinoxes. Olbers made a chance discovery of a second minor planet (Pallas), and in September 1804, Göttingen astronomer Karl Ludwig Harding spotted a third one (Juno). As new data on minor planets gathered, Gauss set out to compute the perturbations due to the gravitational attraction exerted by Jupiter on them. From this work, he developed the least-square method which enabled him to make use of all—not merely three—observed positions of a planet.[10]

From early on, Gauss felt that observations were as useful to his theoretical undertaking as his theory in assisting observation.[11] After having been unsuccessful in his bid for an observatory in Brunswick, Gauss was attracted to Göttingen by the promise of directing a state-of-the-art observatory: „*Sie wissen, dass in Göttingen ein Observatorium erbaut wird, wenigstens der Absicht nach so gut, wie irgend eines in der Welt ist.*"[12] When he moved to Göttingen Gauss began to observe minor planets regularly in the old observatory of Tobias Mayer.

the solidarity of German astronomers, see Gauss to Bessel, 5 March 1820, in Carl Friedrich Gauss and Friedrich Wilhelm Bessel, *Briefwechsel*, 2 vols. (Hildesheim/New York: Georg Olms, 1976), 1:324.

8 Bessel to Gauss, 10 März 1811, in *Briefwechsel*, 1:144

9 M. Brendel, "Über die astronomischen Arbeiten von Gauss," *Carl Friedrich Gauss Werke*, 11, 2, Abh. 3 (1929), 1–258. Otto Volk, "Astronomie und Geodäsie bei C. F. Gauss," *C. F. Gauss: Leben und Werke*, ed. Hans Reichardt (Berlin: Haude & Spenersche, 1960), 207–16; Eric G. Forbes, "The Astronomical Work of Carl Friedrich Gauss (1777–1855)," *Historia Mathematica* 5 (1978), 167–81; also in *Sterne und Weltraum* 16 (1977), 158–66.

10 See Oscar B. Sheyhin, "C. F. Gauss and the Theory of Errors," *Isis* 20 (1979), 21–72.

11 About theoretical vs. practical astronomy, see Bessel to Gauss, 10 July 1820, in *Briefwechsel*, 1:358; and Gauss's reply, 362.

12 Olbers to Gauss, 12 November 1802, in *Briefwechsel* 1:107.

He used Mayer's 6-foot mural quadrant, a pendulum clock made by John Stelton and an achromatic refracting telescope from the John & Peter Dollond firm equipped with micrometers to measure small angular distances from neighboring stars with great precision. Although he made good use of them, Gauss knew that these instruments were no substitute to a meridian transit circle which he ordered from Johann Georg Repsold in Hamburg. Custom-made for Gauss and delivered in 1818, this instrument yielded *absolute* measurement with respect to celestial coordinates whereas the Dollond telescope could only give *relative* positions with respect to neighboring stars. From his arrival at Göttingen, Gauss constantly endeavored to equip his observatory with the latest instrumental technology. He obtained from the Munich workshop of Reichenbach a new meridian circle to replace Repsold's, a Liebherr clock to replace Stelton's, a repeating circle and a theodolite.

The observatory's culture of precision had a wide-ranging influence on scientific practice. The crusade undertaken by Humboldt to survey the magnetic field of the Earth provides an example of how observatory techniques were adopted for electromagnetic research. In 1828, Humboldt built a small magnetic observatory in Berlin and initiated a program of coordinated observation at various locations at prearranged times. This required a precise knowledge of time and of the geographical location determined by astronomical means. Gauss took a major part in Humboldt's survey. Mathematical equations had previously been used to account for electromagnetic phenomena, but Gauss was arguably the first to quantify them.[13]

By the late 18th century, it had been recognized that the period of oscillation of a suspended needle was inversely proportional to the square root of the magnetic field.[14] But such measurements were relative since the intensity of the field could not be separated from the magnetic moment. In his great contribution, "Intensitas vis magneticae terrestris ad mensuram absolutam revocata," read at the Royal Society of Göttingen on 15 December 1832, Gauss explained that a second experiment could be performed that gave out an absolute measurement of the field.[15] This was the first non-mechanical quantity to be expressed in terms of mass, length and time. Gauss explained to Olbers:

Ich beschäftige mich jetzt mit dem Erdmagnetismus, namentlich mit einer absoluten Bestimmung von dessen Intensität. (…) So wie man z. B. von Geschwindigkeit nur durch Ansetzung einer Zeit und eines Raums einen klaren Begriff geben kann, so, finde ich, muss zur vollständigen Bestimmung der Intensität des Erdmagnetismus angegeben werden 1) ein Gewicht = p, 2) eine Linie = r, und dann man kann den Erdmagnetismus durch $\sqrt{p/r}$ *ausdrücken.*[16]

But more than the pleasure of finding out new facts about the earth magnetic field, what truly attracted Gauss's interest to geomagnetism was the prospect of modelling this area of science more thoroughly on astronomy. After the mechanics of moving bodies and optics, electrodynamics would be the next area of physics to be expressed in the form of analytical laws submitted to the test of high-precision measurement:

Fast noch wichtiger aber, als der glänzende Zuwachs unerwarteter Thatsachen, die in diesen Gebieten entdeckt sind [the work of Oersted, Ampère, Arago and Faraday], ist der Umstand, dass auch hier die Versuche einer frühere weit überflügelnden Schärfe, und ihre einfachen Grundgesetze einer wahrhaft mathematischen Präcision fähig werden, so dass die Scheidewand zwischen eigentlich sogenannter Physik und angewandter Mathematik auch hier (wie längst in der Bewegungslehre und Optik) zu sinken, und die tiefer eingreifende Bearbeitung dem Mathematiker anheim zu fallen anfängt.[17]

Characteristically for an astronomer, Gauss gave thorough descriptions of the instruments he had taken from the observatory panoply and adapted to geomagnetic surveys. His addition of a telescope to Gambey's dip magnetometer allowed the scientist to observe the needle at a distance and avoid its disturbance though air currents and

[13] Olivier Darrigol, *Electrodynamics from Ampère to Einstein* (Oxford: Oxford Univ. Press, 2000) and Christa Jungnickel and Russel McCormmach, *Intellectual Mastery of Nature: Theoretical Physics from Ohm to Einstein*, 2 vols. (Chicago: Chicago Univ. Press, 1986).

[14] Hans Falkenstein, "Die wesentlichsten Beiträge von C. F. Gauss aus der Physik," *C. F. Gauss: Leben und Werke*, ed. Hans Reichardt (Berlin: Haude & Spener, 1960), 232–51; G. D. Garland, "The Contributions of Carl Friedrich Gauss to Geomagnetism," *Historia Mathematica* 6 (1979), 5–29.

[15] Werke V, 79ff., *Annalen der Physik* (1833). *Ostwalds Klassiker der exakten Wissenschaften* 53 (Leipzig: Akademische Verlagsgesellschaft, 1894).

[16] Gauss to Olbers, 18 Februar 1832, 2:584-585.

[17] Gauss, [Magnetismus und Galvanismus : Amtlicher Bericht], (Gauss an Königliches Universitäts-Curatorium, 29. Januar 1833), *Werke* 11:55–8.

bodily heat. With his bifilar magnetometer, Gauss claimed that "the horizontal part of the earth's magnetic field can now be observed as precisely as the stars in the sky."[18] In 1838, Gauss published the "Allgemeine Theorie des Erdmagnetismus," in which he expressed the potential of the field in terms of a sum of spherical harmonic functions.[19] He then went on to compare the results of his theoretical investigations with observations taken all over the earth.

As soon as he became interested in magnetism and after Wilhelm Weber was hired as physics professor by the University in Göttingen, Gauss geared his effort at setting up a new laboratory, a "magnetic observatory," where such studies could be performed. *"Vielleicht wird unser Gouvernement, wenn die Geldklemme nicht zu gross ist, demnächst nicht abgeneigt sein, ein eigenes magnetisches Häuschen, worin gar kein Eisen ist, zu errichten."*[20] In his petition to the Curatorium, Gauss insisted that astronomical precision required thorough mathematical studies, expensive instruments, skilled experimenters, and a specific space devoted to their manipulations:

Von jeher schien mir, dass die Apparate, deren man sich für die magnetischen Bestimmungen bedient, sehr unvollkommen, und in einem schreienden Missverhältnisse gegen die Schärfe unserer astronomischen und geodätischen Messungen sind. Ich habe seit etwa 5 Monaten angelegen sein lassen, diesem Uebelstande abzuhelfen, wobei ich gleich Anfangs von einigen schon seit vielen Jahren gehabten Ideen ausging, aber freilich fast jede Woche noch etwas Neues gekommen bin. Gegenwärtig habe ich zwei Apparate fertig (...), womit absolute Dekl. und ihre Aenderungen, Schwingungsdauer etc. mit einer Schärfe gemessen werden können, die gar nichts zu wünschen übrig lässt. Ausgenommen für mich ein angemesseneres Lokal, wo kein Eisen in der Nähe ist und jeder Luftzug abgehalten ist.[21]

Recognizing the need for a specially-designed environment for his experiments, Gauss had an iron-free building set up on the grounds of the astronomical observatory. This was one of the first modern physics laboratories. In Germany, his collaborator Wilhelm Weber wrote to Edward Sabine, *"until now there existed only collections of physical instruments without permanent facilities for their use; there were no physical laboratories or observatories."*[22] The physical laboratory borrowed heavily from the observatory. Before large physical laboratories were established in the 1860s and 1870s, it was common to speak of "physical observatories" and the laboratory building of the Physikalisch-Technische Reichsanstalt was named the *Observatorium*.[23]

Two years before Quetelet, Jean-Jacques Ampère had also visited Göttingen and its observatory. On April 22, 1827, he wrote to his father Adrien-Marie Ampère that his work on the theory of electromagnetism was greatly appreciated in Germany and that he should send copies of his latest work to the Göttingen library. "I think it is as important for the Germans to learn what concerns the sciences from us as it is useful to us to study there literary criticism and history."[24] A mere decade later, German observatory scientists had much to teach French physicists, not only about the theoretical development of electromagnetism, but also and more importantly about the way in which observatory techniques could be successfully transferred into the physical laboratory.

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18 Gauss to Olbers, 2 September 1837, in *Briefwechsel*, 2:649.

19 *Werke* V.

20 Gauss to Olbers, in *Briefwechsel*, 2:590.

21 Gauss to Olbers, 2 August 1832, in *Briefwechsel*, 2:587.

22 Weber to Sabine, 20 Feb. 1845; quoted in Jungnickel and McCormmach, *Intellectual Mastery*, 1:77. My emphasis.

23 David Aubin, "Orchestrating Observatory, Laboratory, and Field: Jules Janssen, the Spectroscope, and Travel," *Nuncius* 17 (2003), 143–62.

24 "Tu devrais réserver une certaine quantité d'exemplaires de ton oeuvre dernière pour Bonn, Goettingue, Weimar et l'Allemagne en général. Je crois aussi important pour les Allemands d'apprendre de nous ce qui concerne les sciences, qu'il nous est utile d'étudier chez eux la critique et l'histoire des différentes littératures." Jean-Jacques Ampère, *Correspondance* (Paris: Hetzel, 1875), 441–2.