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THE COUDÉ EQUATORIALS

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Abstract: Between 1884 and 1892, no fewer than seven coudé equatorials were installed in France, Algeria and Austria. Invented by Maurice Lœwy, these equatorials allowed the observer to sit comfortably in a closed room, with all the controls and readings at hand. However they were expensive, they required two flat mirrors, which were a source of concern because of their thermal distortion, and their mechanics was complex and delicate, so that they did not succeed in replacing the conventional equatorials in spite of their advantages. Only two are preserved, in Lyons and in Algiers. We describe in detail these instruments, their history and their use.

Keywords: coudé equatorial, Lœwy, Paris Observatory, Algiers Observatory, Besançon Observatory, Lyons Observatory, Nice Observatory, Vienna Observatory, refraction, aberration.

1 INTRODUCTION

In 1824, Joseph von Fraunhofer (1787–1826) delivered to the Dorpat Observatory (now located at Tartu, in Estonia) a 23-cm aperture equatorial telescope which was considered as practically perfect.¹ It was taken as the model for most of the great equatorials built during the nineteenth century and the first half of the twentieth century (Lequeux, 2009b). Still, these instruments required large domes, and the observer had to stand or sit in the open air on clumsy movable stairs which could sometimes be dangerous. Several solutions were proposed in order to make observation more comfortable.

A first possibility was to build the equatorial mounting so that the head of the observer was located at the crossing of the right ascension and declination axes, so that he did not have to move when observing in different directions. This was realized in the *comet finder*, which was invented independently around 1859 by the Austrian-French instrument-maker Johann Josef Brunner (1804–1862) and the French astronomer and mathematician Antoine Yvon-Villarceau (1813–1883). This instrument is described by Yvon-Villarceau (1868). One was built for the Marseilles Observatory.² Another survives at the Strasbourg Observatory. A considerably larger instrument with the same properties was installed in 1896 in Berlin-Treptow by Steinheil und Söhne for the optics and Hoppe for the mechanics. With its 68-cm diameter and 21-m focal length, this was a real monster which remained unique.³

Siderostats and cœlostats offer another possibility. These instruments consist of one or two flat mirrors, driven by a clockwork or an electric motor, which reflect the light from the observed portion of the sky to a horizontal, fixed direction. This light feeds a fixed telescope so that the observer can be in a comfortable position in a heated room, and heavy instruments can be mounted at the focus. The best siderostats (with a single mirror) are due to Léon Foucault (1819–1868): see Tobin (1993: 266-267 and 274-276). A monster Foucault siderostat, 2-m in diameter, feeding a 58-m length, 125-cm diameter horizontal refractor, was built for the 1900 Universal Exhibition on Paris but was too impractical for real use (Launay, 2007; also see the image in Lequeux, 2009b: 10). Siderostats are unfortunately delicate and expensive, and their present use is essentially limited to solar telescopes.

The third solution is the coudé equatorial, which was invented by Maurice Lœwy (1833–1907) and is the subject of this paper. Previous papers on the coudé

equatorials are by Weimer (1982) and Lequeux (2010b).

2 LŒWY'S INVENTION

Moritz Löwy (or Maurice Lœwy; see Figure 1) was born in Vienna on 15 April 1833 (Anonymous, 1907; Dyson, 1908). He started an astronomical career at the Vienna University Observatory, observing comets and asteroids and calculating their orbits. However, being a Jew, he had no chance of obtaining a permanent position in anti-Semitic Austria. Urbain Le Verrier (1811–1877), the Director of the Paris Observatory, knew about his researches thanks to the recommendation of the Director of the Vienna Observatory, Karl Ludwig von Littrow (1811–1877), and invited him to come to France. He arrived on 15 August 1860. By this time he had already published about ten papers on cometary and planetary orbits in *Astronomische Nachrichten*. The following year, he was appointed *Astronome adjoint*. In 1869 he changed his name to Maurice Lœwy and obtained French citizenship. The remainder of his career was at the Paris Observatory, where he was appreciated for his professional and human qualities.



Figure 1: Maurice Lœwy (1833–1907), at the start of the twentieth century (© Bibliothèque de l'Observatoire de Paris).

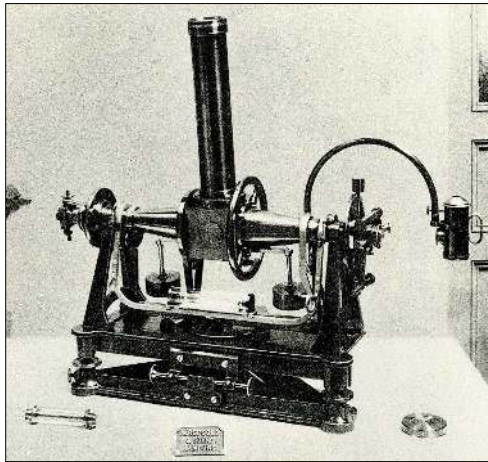


Figure 2: A coudé transit telescope by Repsold and Söhne, 1874 (after Repsold, 1914; © Bibliothèque de l'Observatoire de Paris).

He served as the Director from 1896 until his death on 15 October 1907, which occurred during a meeting of the *Conseil des Observatoires*.

Lœwy was very competent in astronomical instrumentation, especially for positional astronomy, and was a skilful observer. He was also familiar with surveying instruments, since geodesy was to some extent amongst the tasks of the observatories. Some meridian instruments and a large fraction of the theodolites built in Germany, in particular by Repsold in Hamburg, were of coudé type (see Figure 2): a 45° flat mirror or

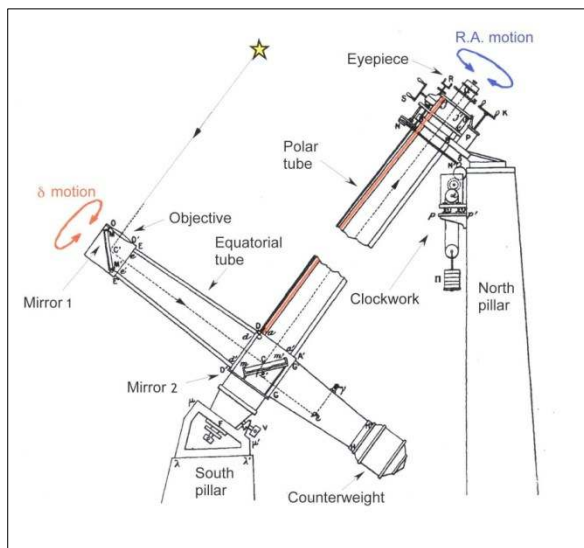


Figure 3: Principle of the coudé equatorials. The instrument schematized here is the 'Grand Coudé' of the Paris Observatory, adapted from Puisseux (1895: D.2). The other coudés are very similar. The crank K controls the fast motion in right ascension. The control of the slow motion is not represented. The tracking is driven by the clockwork which acts on the large toothed wheel NN'. The motion in declination is controlled by the cranks S (fast) and R (slow) which drive an axle (shown in red) located inside the polar tube. This axle drives the tube dd' ee' inside the equatorial tube by conical pinions. The cube which contains the objective and the 45° flat mirror #1 is attached to this tube dd' ee'. The axle drawn in red also controls the rotation of the tube aa' jj' concentric to the polar tube, which itself drives the graduated circle jj' on which declination is read. Initially, the Petit Coudé had its objective located behind mirror #1, but this was changed later to the disposition represented here in which the objective is in front of the mirror and closes the side of the cube.

total reflection prism at the crossing of the axes reflected light along the horizontal hollow arm for the convenience of the observer.⁴ This gave Lœwy the idea of his new instrument, and the report of the Paris Observatory for 1882 says (Mouchez, 1883: 7; all English translations are by the author):

M. Lœwy had the idea to apply to his instrument the system of the coudé refractor used by the Germans for the small meridian instruments, allowing the observer to be stationary in front of an eyepiece which never changes position.

This instrument was officially proposed in October 1871 in a Note to the Académie des Sciences (Lœwy, 1871). It was a little later christened as the 'équatorial à deux miroirs', then as the 'équatorial coudé'. After discussing the inconvenience of the usual equatorials, of the comet finder and of the siderostat, Lœwy (ibid.) presents his new equatorial as follows:

The polar axle is supported at its two ends by two pillars and, as for a transit instrument, the telescope rotates between the two bearings of the axle. This telescope is folded at right angle and, with a prism or a mirror, it sends the light through one of the hollow pivots of the polar axle, where the micrometer is installed for observation. At this stage, the astronomer sees the equatorial stars pass in front of his eye. Let us add now, in front of the objective, a flat mirror inclined at 45 degrees, attached to the declination circle. When rotating around the axis of the refractor, this mirror brings to the focal plane the images of the stars located on a great circle perpendicular to this axis.

One can easily see that this set-up allows the observer to explore the whole sky without leaving his seat ...

The Director of the Observatory has been kind enough to agree to the construction of an equatorial according to this principle, with 3.55 m focal length and 9 pouces [24.4 cm] aperture.

Figure 3 shows the principle of the coudé equatorials, and Figure 4 shows the focal environment of one of the coudés.

It took eleven years before the first coudé equatorial was completed. Charles Delaunay (1816–1872), who headed the Observatory after the dismissal of Le Verrier in 1870, allocated 10,000 francs (equivalent to about 30,000 € or US\$42,000 today) for the project, but the war and the accidental death of Delaunay on 5 August 1872 stopped the work. Le Verrier was reinstalled the following year as Director. In the minutes of the meeting of the Observatory Council on 7 January 1874 one reads:

M. Bischoffsheim [sic. for Bischoffsheim] offers 20 000 francs for construction of the two-mirror refractor of M. Lœwy.

Raphaël Bischoffsheim (Figure 5), a prosperous banker, was enthusiastic about astronomy. He also financed a large observatory in Nice, which will be discussed later. The Paris Observatory Council must have been surprised by this generous offer, and we can presume that Lœwy visited Bischoffsheim privately and interested him in the project. At the next Council meeting, on 15 January 1874,

M. Lœwy presents to the Council and describes a model⁵ of his equatorial instrument with two mirrors, whose purpose is to lessen the observer's fatigue by allowing him to stay motionless.

Several members had objections to the principle of the instrument. In particular, the famous physician Hippolyte Fizeau (1819–1896) feared, not without reason, that the thermal deformations of the mirrors would degrade the images; but he said that he would nevertheless vote in favour of the project because it was difficult to resist such a generous offer! The instrument was presented as able to measure large angular distances, and there was a need for "... a special instrument which would allow one to study regions on both sides of the meridian ..." (Rapport ..., 1874: liasse AA) avoiding in this way the necessity to wait for meridian crossing to measure the coordinates of a celestial object. Thus the Council agreed that a coudé equatorial should be built, but with an aperture of 8 pouces (22 cm) instead of 9 pouces. The German telescope-maker, Friedrich Wilhelm Eichens (1818–1884), provided an estimate of 20,000 francs without the objective, which was probably expected to be taken from the Observatory's reserves (hence the change in diameter of the objective), plus 18,000 francs for the 'cabane' (rolling shelter) and for installation. The cost of the building was not estimated. In any case, this looked too expensive, and as the Council was not unanimously in favour of the project it was abandoned. Bischoffsheim's gift, now raised to 26,000 francs (happy times!), would finance a meridian circle instead. This instrument (see Figure 6) was indeed completed, in 1877.

After replacing Le Verrier as the Director of the Observatory, Admiral Ernest Mouchez (1821–1892) managed to convince Bischoffsheim to give 25,000 francs to complete the coudé equatorial (including a new objective which finally reached an aperture of 10 pouces = 27 cm, and a focal length of 4.22 m). The building and the cabane were paid for by the Observatory with a special grant of 140,000 francs from the Ministry. The instrument (Figure 7) was completed in 1882, and was later called the 'Petit Coudé' (the 'Little Coudé'), because a larger coudé equatorial was installed at the Observatory in 1891, as we will see later. The optics of all later coudé equatorials were built by the brothers Paul (1848–1905) and Prosper (1849–1903) Henry, excellent opticians attached to the Paris Observatory, while the mechanics were all due to Paul Gautier (1842–1909), Eichens' successor (Figure 8). This included, for tracking, a clockwork with a centrifugal fan governor built according to Foucault's principles, but which was improved on by Antoine Yvon-Villarceau.

The instrument, its advantages and the first successful tests were proudly presented by Lœwy during the 19 March 1883 meeting of the Académie des Sciences (Lœwy, 1883). The following year, Lœwy described the first results and discussed another advantage of the design: the possibility of a long focal ratio, which would be very expensive to reach with a conventional equatorial because an enormous dome would be needed. Lengthening the focal length would decrease the residual chromatic aberration (Lœwy, 1884a). Lœwy also cited enthusiastic reports by David Gill (1843–1914) and Sir Norman Lockyer (1836–1920), who both had the opportunity to observe with the equatorial. Lockyer (see Lœwy, 1884a: 775) even said that "... this is one of the instruments of the future." There are several popular accounts of the coudé equatorial (e.g. see Hément, 1883) and Gérigny, 1884: 220–225).

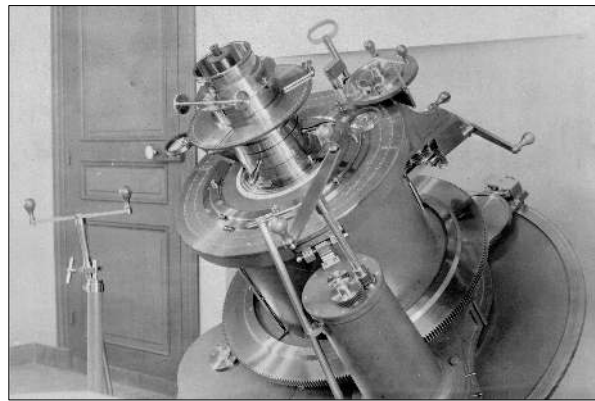


Figure 4: The focal environment of the Grand Equatorial Coudé. All the coudés are very similar in this respect. All the controls and readings are concentrated here. The crank in front drives the fast motion in right ascension and the long rod to its left drives the slow motion. The separate crank at the extreme left lifts the weight of the clockwork which insures the tracking. The cranks for driving the declination are at the back, at the top right of the image. Right ascension and declination are read on the two concentric large graduations. The smaller circular graduation on the top gives the orientation of the micrometer. For more details, see Puiseux, 1895 (© Bibliothèque de l'Observatoire de Paris).

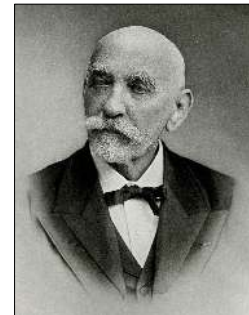


Figure 5 (right): Raphaël Louis Bischoffsheim (1823–1906), at the beginning of the twentieth century (© Bibliothèque de l'Observatoire de Paris).

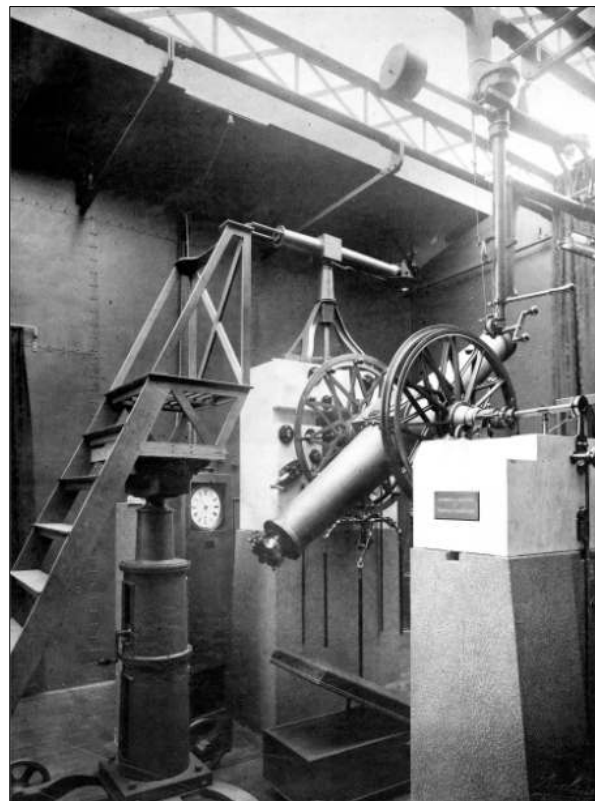


Figure 6: The Bischoffsheim meridian circle of the Paris Observatory (1877), contemporary photograph. The instrument has been in use for a century and can still be seen at the Observatory, but in a new shelter (© Bibliothèque de l'Observatoire de Paris).

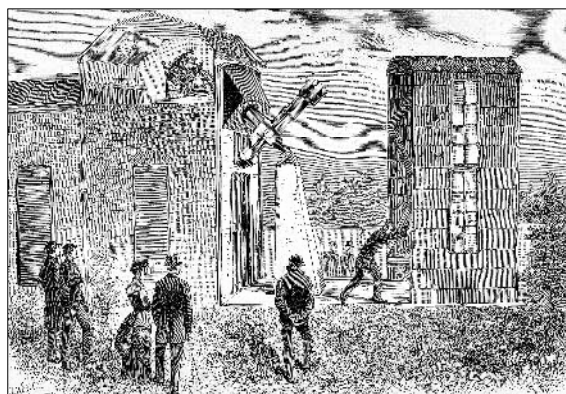


Figure 7: A somewhat schematic and inaccurate representation of the Petit Coudé at the Paris Observatory. A beautiful, accurate engraving can be seen in Lequeux (2010a: Figure 6), and on the cover of the November 2010 issue of this journal (© Bibliothèque de l'Observatoire de Paris).

In 1899, the Henry brothers installed a new objective with the focal length increased from 4.22 m to 5.25 m. As for all later coudés, the objective was now placed in front of the first 45° mirror, on one side of the rotating cube, and closed the tube of the instrument. Thermal insulation was applied to the tube. The cabane had been insulated the preceding year.

Given the success of his coudé refractor, Lœwy proposed two possible designs for a coudé reflecting telescope, of which he gave a complete theory (see Lœwy, 1884b). They are shown in Figure 9. However no instrument was constructed according to these principles.

3 SCIENCE WITH THE PETIT EQUATORIAL COUDE IN PARIS

The first observations made with the Petit Coudé were of minor planets (Lœwy, 1884a). These were position measurements with respect to nearby standard stars, made with a micrometer. Contrary to initial promises, the coudé equatorial was never used for measuring absolute positions as transit instruments do. Probably the flexions and the backlashes in the gears were judged too large for this. More differential observations were performed on minor planets, comets and nebulae. For the latter, one wanted to detect possible proper motions in order to obtain an estimate of their distance which

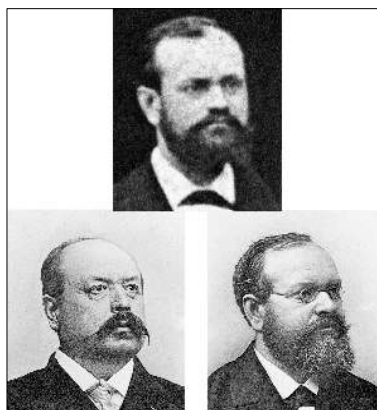


Figure 8: The builders of the seven coudé equatorials: Paul Henry (bottom left), Prosper Henry (bottom right), and Paul Gautier (top) (© Bibliothèque de l'Observatoire de Paris).

was then completely unknown. The main observers were Pierre Puiseux (1855–1928) and Charles Le Morvan (1865–1933), from 1882 to 1886 (Anonymous, 1894) and from 1891 to 1893 (Anonymous, 1910; Anonymous, 1911). There were also a few observations of occultations of stars by the Moon, of the libration of the Moon, of eclipses of Jupiter's satellites, and of photometry of these satellites with a photometer using polarizers built by Alfred Cornu (1841–1902).

The apparent gap in the observations from 1886 to 1891 corresponds to another, original use of the Petit Coudé: an attempt to measure atmospheric refraction and a new determination of the constant of aberration. The latter determination is the realisation of Le Verrier's wish to check a new estimate of the parallax of the Sun he obtained in 1858 as a by-product of his theory of the motions of the planets of the Solar system (see Tobin, 1993: 278). Le Verrier found $8''.95$ whilst the best previous determination made in 1824 by Johann Franz Encke (1791–1865) from observations of the 1761 and 1769 transits of Venus gave $8''.57$. For his check, Le Verrier proposed to use the aberration constant, which, when expressed in radians, is the ratio of the mean orbital velocity of the Earth to the velocity of light: from an accurate measurement of both the velocity of light and the constant of aberration, one would obtain the orbital velocity of the Earth, hence the length of its orbit and its semi-major axis (this semi-major axis is inversely proportional to the solar parallax).

This is the reason why Le Verrier asked Foucault to make his famous accurate measurement of the velocity of light in 1862: using a rotating mirror, Foucault obtained 298,000 km/s. Combining this velocity with the value of $20''.445$ given in 1843 for the aberration constant by Wilhelm Struve (1793–1864), a value which was then considered as the best available, one obtained $8''.86$ for the solar parallax, a value closer to Le Verrier's than Encke's one, which pleased Le Verrier very much. Later, Alfred Cornu, who had no confidence in Foucault's method, measured again the velocity of light, this time with a toothed wheel, and obtained 300,400 km/s, which was in agreement with Foucault's determination (Tobin, 1993: 280–282). It remained to measure the constant of aberration. This should have been the task of Yvon-Villarceau, but he was reluctant to undertake it (Lequeux, 2009a: 372). Lœwy was the one who performed this work, but quite a bit later.

Lœwy had the clever idea to put in front of the coudé objective two mirrors making an angle of 45° , in order to be able to see simultaneously two fields 90° apart (Figures 10 and 11). These mirrors were silvered faces of a glass prism, making their angle very stable. Lœwy first attempted to apply this principle to a measurement of atmospheric refraction, by following for several hours a couple of stars chosen such that they were initially at the same elevation, until one of them came close to the horizon. The variation of their angular distance projected on a vertical would give a measurement of refraction (Lœwy, 1886). It seems that these measurements were not made systematically, as I have not been able to find any published result. Lœwy was still considering the problem in 1905 (Lœwy, 1905), probably with the intention of making new measurements, but his death in 1907 definitively ended the project.

Aberration produces an apparent annual motion of a star such that it describes an ellipse with its major axis parallel to the ecliptic. Its semi major-axis is equal to the constant of aberration; the length of the minor axis is proportional to $\sin \lambda$, where λ is the ecliptic latitude. Consequently, the angular distance between two stars varies in general during the year. In order to measure the constant of aberration, a couple of stars at 90° from each other with ecliptic latitudes as different as possible must be observed during a large fraction of the year, at times when they are at the same elevation in order to get rid of refraction. As the angle of the prism may vary with temperature, another couple of stars taken such that their angular distance is unaffected by aberration must be observed at about the same times in order to provide the corresponding correction. One can also chose the second pair of stars so that their angular distance varies with aberration (see Lœwy, 1887a, for a complete discussion). Lœwy went to great pains to find suitable pairs of stars. He even had a 1-metre diameter celestial sphere built by Gautier, where all the stars brighter than the 6th magnitude were accurately plotted: with a curved ruler, angular distances could be measured to within 2 arc minutes (Mouchez, 1888: 11-12). The observations were made by Lœwy and Puiseux in 1890 and 1891 using four pairs of stars (Lœwy and Puiseux, 1891). In order to avoid obstruction they had to lower the roof of the building and to lengthen the tube of the instrument by 50 cm by inserting a diverging lens in the optical path. This set-up was probably not very satisfactory, hence the construction of a new objective with a larger focal length in 1899.

The value found for the constant of aberration was $20''.447 \pm 0''.047$, in excellent agreement with Struve's value. Combined with Foucault's velocity of light, it yielded an unchanged value of $8''.86$ for the solar parallax. If we combine it instead with Cornu's speed of light, 300,400 km/s, we obtain $8''.80$.

Lœwy's method for measuring large angles on the celestial sphere was novel and promising: it probably inspired Pierre Lacroute (1906–1993) when in 1968 he proposed the HIPPARCOS astrometry satellite, which measured stellar angular distances close to 58° by using two mirrors at 29° angle cut in a single solid block (see Kovalevsky, 1986: 584-585). However, the result of Lœwy and Puiseux remained relatively unnoticed, because one was soon to obtain a supposedly more precise value for the solar parallax through a campaign of measurements involving the asteroid 433 Eros.

Discovered in 1898, Eros came as close as 18 million kilometres from the Earth in 1901. Lœwy himself was very involved in the organisation of this international campaign, and apart from being busy with many other tasks this is why he could not continue his observations with the Petit Coudé. Observations of Eros produced a parallax of about $8''.81$, independent of the velocity of light and aberration constant. The modern values of the constant of aberration and of the solar parallax are respectively $20''.4955$ and $8''.79414$, with very small errors, while the velocity of light is fixed by international convention at 299,792.458 km/s.

After the parallax measurements, the Petit Coudé equatorial was again used during a few years for mea-

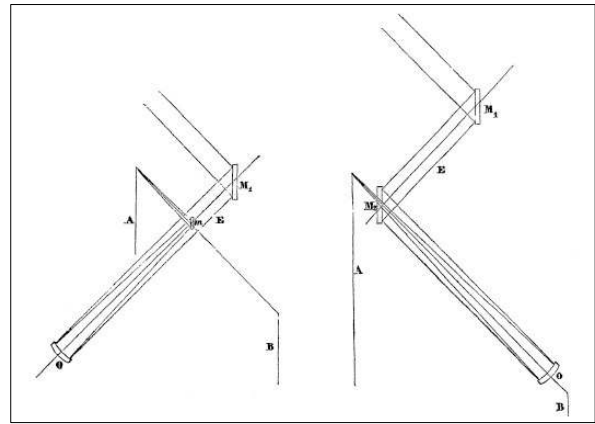


Figure 9: Two possible designs for a coudé reflecting telescope, according to Lœwy (1884b). The polar axis is AB and the observer sits in A. In the design at the right, the flat mirror M2 is pierced (© Bibliothèque de l'Observatoire de Paris).

suring positions of comets and asteroids and for double star studies. In 1897, Maurice Hamy (1861–1936) undertook measurements of the diameters of Jupiter's satellites with an interferometric method invented by Fizeau in 1867 and applied for the first time by Édouard Stephan (1837–1923) using the 80-cm Foucault reflector in Marseilles (Stephan, 1873); observing the object with two slits placed on the objective, interference fringes modulate the image. When the separation of these slits is sufficiently increased, these fringes disappear; then the angular diameter of the object is close to the ratio of the wavelength to this separation. This is the very method used by Albert A. Michelson (1852–1931) and Francis G. Pease (1881–1938) in their famous 1920 observation of the diameter of Betelgeuse with the Mount Wilson 2.5-m telescope, although in their case the two light beams came from small mirrors located at some distance from the reflector. With the 80-cm telescope, Stephan could not see the disappearance of the fringes because the diameters of the stars were too small. But this was pos-

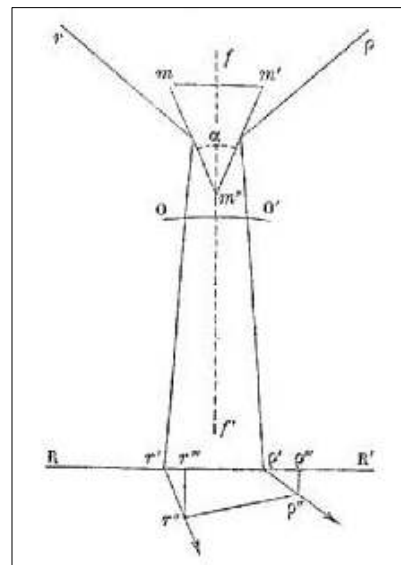


Figure 10: Principle of the measurement of the variations of the angular distance of two stars 90° apart. The faces of the prism with angle $\alpha \approx 45^\circ$ reflect into the objective OO' of the telescope the light from two fields 90° apart. The images of two stars r and ρ separated by $90^\circ + \epsilon$ are distant by the small angle $90^\circ + \alpha - 2\epsilon$ when seen in the eyepiece (after Lœwy 1886: 77; © Bibliothèque de l'Observatoire de Paris).

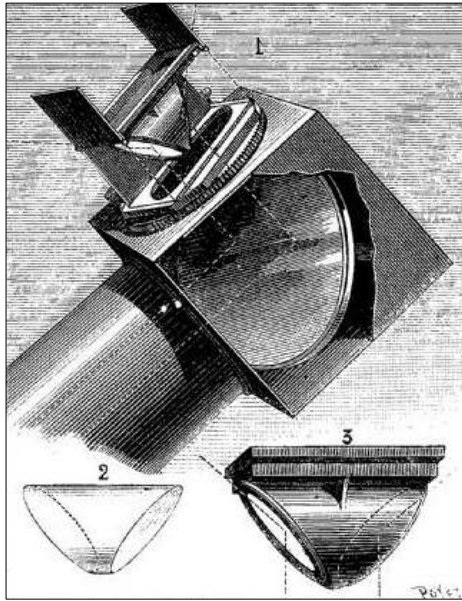


Figure 11: The device to measure the variations of the angular distance of two stars 90° apart (see scheme on Figure 10). The angle of the prism as drawn here is too large: the real angle is 45° . The device could rotate around the optical axis as a function of position of the target stars (after Lœwy, 1887b: 16; © Bibliothèque de l'Observatoire de Paris).

sible with Jupiter's satellites, whose angular sizes were measured in 1891 by Michelson with this method (Michelson, 1891). Tests were performed by Hamy with the Petit Coudé, but he decided afterwards to use the 38-cm refractor and the Grand Coudé—which will be described in the next section (Hamy, 1899). Neither Michelson nor Hamy supplied errors with their results, but Table 1 gives an indication of these errors. As can be seen from the discussion in Michelson (1891: 277), they are no better than those obtained using micrometers.

In 1901, it was decided that the Petit Coudé would be used for solar spectroscopy, and the following year a grating was ordered for a spectrograph which was installed in 1906. I could not find any published result from this set-up. Then Charles Nordmann (1881–1940) and collaborators used the Petit Coudé for multicolour photometry of stars, from 1908 on; for details, see Lequeux (2011). In 1939, the objective of the telescope was taken down owing to the threatening war. The coudé was reinstalled after WWII, and was used after 1951 for tests of the electronic camera of André Lallemand (1904–1978). It was finally dismantled in 1973. Nothing remains of this instrument, with the possible exception of the two objectives, which might exist among the large collection of old objectives in the reserves of the Paris Observatory.

4 THE GRAND EQUATORIAL COUDE

4.1 The 75-cm Equatorial: An Aborted Project

While the Petit Coudé was under construction, Admiral Mouchez was trying to revive an old project for which Le Verrier had obtained financing as early as 1865: that of a large equatorial with an objective 75 cm in diameter. The crown and flint disks for this objective were purchased from Chance Brothers even earlier, in 1856. Foucault worked for some time on testing these disks, but did not have time to make an

objective from them because of his illness and death in 1868. Then the turmoil in the Observatory was such that nothing happened for several years. Work on the mechanics resumed in 1874, and by 1877, when Le Verrier died, Eichens had built a large part of the mount. Gustave Eiffel (1832–1923), the famous engineer who built the Eiffel Tower in 1889, was to be in charge of the dome. But when soundings were made at the place where the dome was to be built, in the garden of the Observatory, the numerous underground cavities they revealed prevented the erection of this instrument.

In 1883 Mouchez tried to create a subsidiary of the Observatory in the neighbourhood of Paris, where the refractor would be placed, but he did not succeed. Moreover, while the available money (187,257 francs) was sufficient for the equatorial itself, the dome would have cost between 500,000 and 600,000 francs, an enormous sum, which was simply not available. Algeria, then a colony of France, could have housed the telescope at the Bouzareah Observatory near Algiers, but the Parisian astronomers wanted it in Paris and did not accept the offer. Eventually the project was abandoned, and the parts that had already been built were given to Jules Janssen (1824–1907) for his Observatoire d'Astronomie Physique at Meudon. Some components are included in the mechanics of the large Meudon double equatorial of 1896, and it may be that one or two of the five 75-cm glass disks cast for the refractor served to build the photographic objective of the Meudon equatorial, which is 62-cm in diameter. A 75-cm crown disk still exists at the Paris Observatory.

4.2 The Grand Équatorial Coudé Replaces the Aborted Equatorial

Mouchez was so impressed by the Petit Coudé that he was able to convince the Minister of Public Education to devote what remained of the money intended for the 75-cm refractor to the construction of a 'Grand Équatorial Coudé'. He must have obtained more, as the total cost of the instrument, including the building and accessories, was around 400,000 francs, equivalent to some 1.2 million Euros today (Fraissinet, 1891). The coudé had two interchangeable objectives, each 60 cm in diameter, one for photography and the other for visual observations. Figure 3 shows a schematic cut-away section of the instrument; Figure 4 shows its focal environment, and Figure 12 is a complete image (for another photograph see de la Noë and Soubiran, 2011: 448). The photographic objective had a remarkably large field of $1^\circ 30'$. The focal length was 18 m, and the 45° flat mirrors had respective diameters of 86 cm and 73 cm. As for all coudés, the Henry brothers built the objectives and Gautier the mechanics. It was completed in 1891. The design was similar to that of the 'Petit Coudé', except that the objective was now placed in front of the first 45° mirror, closing the tube in this way and avoiding fast degradation of the silver layer on the mirrors. A 4-horsepower Otto gas machine driving a dynamo was placed in the basement, in order to charge the 39 accumulators which provided lighting to the coudé buildings with filament bulbs (the rest of the Observatory being lit with coal-gas). For short descriptions, see Fraissinet (1891) and Lœwy (1894), while Puiseux (1895) gives a detailed description, with drawings of the very complex mechanics of the equatorial.

Table 1: Diameters of Jovian satellites and of Vesta, as measured by Michelson and by Hamy.

	I: Io	II: Europe	III: Ganymede	IV: Callisto	Vesta
Michelson, 1891	3850 km	3550 km	5170 km	4940 km	-
Hamy, 1899	3550 km	3150 km	4640 km	5100 km	392 km
Modern value	3630 km	3138 km	5268 km	4800 km	576 km (aspherical)

Many difficulties were encountered during the period of tests with the visual objective, which lasted for two years. In particular, deformations of the flat mirrors were present, as foreseen by Fizeau, requiring replacement of supports and thermal insulation of the cabane and of the tube. When the photographic objective replaced the visual one in 1893, new difficulties arose, in particular with the motion of the 12 tons of the instrument. Small movements were almost impossible, so that the fine pointing and corrections of the tracking were done with the eyepiece holder rather than by moving the whole telescope.

4.3 The Photographic Atlas of the Moon

During the tests, it was noticed that the instrument gave impressive images of the Moon, and Lœwy decided to use it to make a photographic atlas of our satellite. The program started in 1894 and lasted until 1900, with a few supplementary observations until 1909. In order to track the Moon accurately, the plate was moved slowly at the focus during the exposure according to calculations of the Moon's motion. About 6,000 photographs were taken during some 500 nights. The beautiful photographs of the Moon during its different phases, 18 cm in diameter (Figure 13), were enlarged for heliographic publication in the Atlas: the size of each plate is 50 × 60 cm. The Belgian astronomical society also published a reduced-scale atlas with 20 × 24 cm plates, with the photographs reproduced at the original scale (Lœwy and Puiseux, 1898a; 1899). For exhibitions, the lunar images were enlarged to a diameter of 80 cm, on special plates supplied for free by the Lumière brothers. The atlas (Lœwy and Puiseux, 1896-1910) was still found to be useful when choosing the landing sites for the Apollo project.

In a lengthy series of papers (Puiseux, 1896; Lœwy and Puiseux, 1897, 1898b, 1902a, 1902b, 1906), Lœwy and Puiseux attempted to use their photographs to understand the origin of the lunar features and the evolution of the Moon. They acknowledged that the maria were not liquid, but solid, formed by ground collapse according to them. They believed that the craters were of volcanic origin. In general, they tried to understand the Moon by comparison with the Earth, assuming that the primitive Moon had properties similar to those of the Earth. The Moon was supposed to have cooled from a fluid state (hence its volcanism), and to have later possessed some water, a windy atmosphere, etc. Not much remains of their conclusions, which were already received with some scepticism by their contemporaries: in Lœwy's obituary one reads:

I do not think that one should subscribe to all their conclusions, and many of them certainly will have to be modified; but they were certainly allowed to be adventurous, like the first geologists who, albeit closer to the objects of their studies, sometimes proposed hazardous hypotheses which were not necessarily useless to their successors. (Anonymous, 1907: 393).

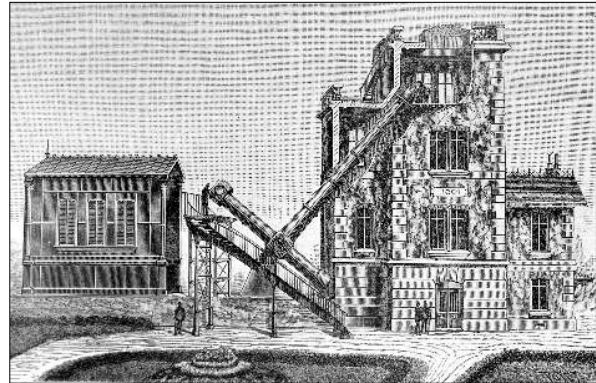


Figure 12: The Grand Équatorial Coudé of the Paris Observatory. North is to the right of the picture. The building and 'cabane' (rolling shelter on the left) are still visible in the garden of the Observatory, but are now in very poor condition (© Bibliothèque de l'Observatoire de Paris).

4.4 Stellar Spectroscopy with the Grand Coudé

Apart from photographing the Moon, the Grand Coudé was used occasionally for various observations of the positions of minor planets and comets; for lunar eclipses; for photography of planets, stars and clusters; and for the measurements of the diameters of Jupiter's satellites, as mentioned in the preceding section. When the program of lunar photographs neared completion, in 1906, Hamy installed a relatively high-resolution prism spectrograph at the focus. This was built by Gauthier and mounted on a rotating support so that it could be substituted for the photographic equipment (see Figure 14). This instrument is described by Hamy (1925). It was used to obtain radial velocities of bright stars, but this resulted in few publications. Pierre Salet and Gaston Millochau also used it in an attempt to detect the displacement of some iron lines due to the Stark Effect in the solar chromosphere (Salet and Millochau, 1914), then for a study of line displacement in stellar spectra (Salet, 1921). Later Salet (1934) used this



Figure 13: Photograph of the Moon obtained with the Grand Coudé (© Bibliothèque de l'Observatoire de Paris).

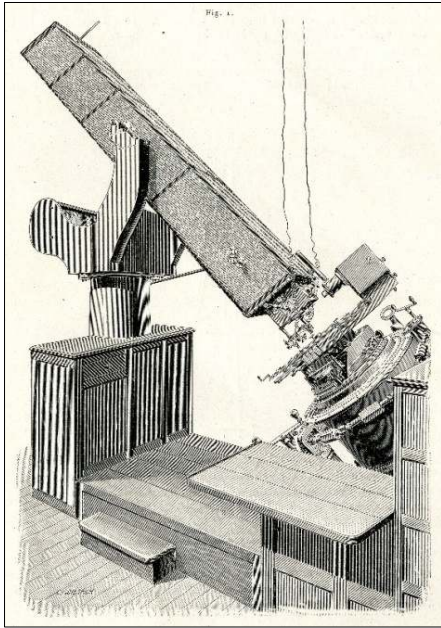


Figure 14: The stellar spectrograph of the Grand Équatorial Coudé (© Bibliothèque de l'Observatoire de Paris).

spectrograph to measure the velocity of light coming from various stars close to the ecliptic, by observing the Doppler shifts of their lines at two epochs, when the Earth approached or receded from them. He found that the velocity of light seemed to vary with spectral type, but he certainly underestimated the errors. Surprisingly, this result raised no comment from him. Clearly, Special Relativity was not yet universally accepted at that time.

The spectrograph and the Grand Coudé were partly dismantled during WWI. When it was a question of re-installing the Coudé, in 1920, the Director of the



Figure 15: The equatorial coudé of the Besançon Observatory, before 1934 (© Jérôme Mongreville, Région Franche-Comté, Inventaire du patrimoine ADAGP).

Paris Observatory, Benjamin Baillaud (1848–1934), proposed to send it to the Pic du Midi Observatory. But there was no money for this, and the instrument was re-installed in Paris in 1922, now with the spectrograph in a fixed position. Stellar spectroscopy was then resumed. In 1927, Henri Deslandres (1853–1948), who succeeded Baillaud in 1926, wanted to dismantle the instrument in order to use some elements for a fixed refractor in Meudon which would serve to observe the displacements of the Pole using photography. But nothing happened. The Grand Coudé was used from time to time until WWII, first for radial velocities, then for photography of star clusters. The objective was taken down in 1939, and it is presently in storage at the Paris Observatory. As to the visual objective, which was used very little, in 1943 it was sent to the Pic du Midi Observatory, where Bernard Lyot (1897–1952) used it to take very high-quality photographs of the Moon and planets on orthochromatic plates through a yellow filter. In 1981 the mounting was dismantled and transferred to the new Museum of Arts and Techniques at La Villette. It should have been installed in the park, but this was not done, and the tubes are presently rusting on the Observatory grounds in Meudon. As to the building and cabane, they are slowly decaying at the Paris Observatory—a sad end for a prestigious instrument which deserves better preservation.

5 THE OTHER FRENCH COUDÉS

On 11 March 1878, new public astronomical observatories in Besançon, Bordeaux and Lyons were created by decree. They added to the existing ones in Paris, Algiers (then a part of France), Toulouse and Marseilles (for details, see de la Noë and Soubiran, 2011). The new observatories had to be equipped, and the older ones required some new instrumentation. Given the success of the coudé equatorial in Paris, Besançon and Lyons received similar instruments. Algiers succeeded in obtaining a coudé as well for its observatory in Bouzareah (now the Centre de Recherches en Astronomie, Astrophysique et Géophysique—CRAAG). The three new coudés were all built by Gautier, with optics by the Henry brothers. They are slightly different from each other, with larger focal lengths than the Parisian Petit Coudé (Table 2). While the Lyons coudé had a rolling cabane similar to that in Paris, the coudés in Besançon (Figure 15; for other pictures see de la Noë and Soubiran, 2011: 176 and 190) and in Algiers (see an old photograph as Figure 16 in Lequeux 2010b) had very similar buildings and a different moving shelter in which a slit parallel to the celestial equator opened for observations. This saved room, but apparently the observers in Algiers found this device unsatisfactory

Table 2: Characteristics of the seven coudé equatorials.

Observatory	Diameter	Focal length	Operational	End of operations	Status
Paris (Petit Coudé)	27 cm	4.22, then 5.25 m	1884	1952	destroyed
Algiers	32 cm	6.78 m	1888	1934	good
Lyons	35 cm	7.80 m	1888	1949	good
Besançon	33 cm	6.40 m	1890	1934	dismantled
Vienna	38 cm	9.25 m	1890	1925	destroyed
Paris (Grand Coudé)	60 cm	18 m	1891	1939	dismantled
Nice	40 cm	10 m	1892	(1935)	renovated

Consequently, the Algiers coudé is presently housed in a rolling cabane (Figure 16; for other photographs see de la Noë and Soubiran, 2011: 248 and 249).

In 1879, Raphaël Bischoffsheim financed entirely a new observatory in Nice, which he later bequeathed to the University of Paris. As Bischoffsheim had already paid for the Parisian coudé, it is not surprising that he included a coudé equatorial amongst the instruments at the Nice Observatory, along with a large 76-cm diameter equatorial, a smaller 38-cm equatorial and meridian instruments, all built by Gautier and the Henry brothers. The Nice coudé (Figure 17; for another photograph see de la Noë and Soubiran, 2011: 273) is housed in a beautiful building and cabane built by Charles Garnier (1825–1898), the architect of the Paris Opera house, who designed all the Observatory buildings, together with Gustave Eiffel, who built the metallic structures.

Three of these instruments are still extant: those at Algiers, Lyons and Nice. The Algiers coudé has been restored recently. The Lyons coudé, located in the observatory at Saint-Genis-Laval near the great city, is preserved in its original state (Figures 18 and 19; for other photographs see de la Noë and Soubiran, 2011: 207 and 436) and is used for public demonstrations. The Nice coudé was modified in 1971–1972 for solar observations (Aime et al. 1974): in particular, the two flat mirrors—weak parts of the instrument—were replaced by low thermal expansion ceramic (Cervit) ones in order to minimize thermal deformations. This coudé served until 1975 or so—when the Nice astronomers gained access to the better facilities at Sacramento Peak—and it is presently used by amateur astronomers.

The four non-Parisian equatorials in their original form were used rather intensively, but in less imaginative ways than their Parisian brothers. The vast majority of the measurements were of positions of comets and asteroids, and there was no spectroscopy at all. Presumably the provincial observatories were supposed to do the ‘grunt work’ of astronomy while the Parisian ones had more freedom. Figure 20 displays the cumulative number of publications of each of the four provincial observatories as a function of year.

Figure 20 needs some comments. Until 1917, the results were published in the *Comptes Rendus hebdomadaires de l'Académie des Sciences*, in the Parisian *Bulletin Astronomique*, in observatory publications (for Nice) and in *Astronomische Nachrichten*. The last-named journal offered a fast and convenient way of disseminating information on positions of comets and newly-discovered asteroids. It is remarkable that papers and telegrams were still sent to this German publication at times when the relations between France and Germany were very bad. The last papers with coudé observations were published in the October 1914 issue of *Astronomische Nachrichten*, after war was declared between the two countries. In 1917, a new journal, the *Journal des Observateurs*, was created by the Marseilles Observatory in order to publish observations made in France, and most of the coudé results went to this journal; however, the Besançon observer, Chofardet, published thirteen papers in the *Astronomical Journal* between 1918 and 1929, and only started publishing in the *Journal des Observateurs* in 1922.

Figure 16: The equatorial coudé at the Bouzareah Observatory near Algiers, photographed in the 1990s (courtesy: <http://www.sao.ac.za/~wgssa/as2/sadat.html>).



Figure 17: The current state of the Nice Observatory equatorial coudé (© Région Provence-Alpes-Côte d'Azur, Inventaire Général - Marc Heller (1996)).



Figure 18: The equatorial coudé of the Lyons Observatory (© Jean-Marie Refflé, DRAC Rhône-Alpes, 2004).



Figure 19: The focal environment of the Lyons coudé. Compare with Figure 9 (© Jean-Marie Refflé, DRAC Rhône-Alpes, 2004).

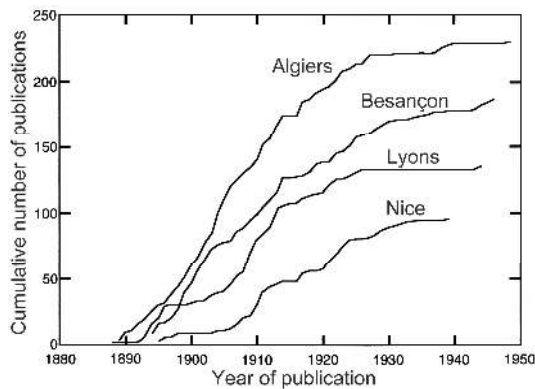


Figure 20: Cumulative number of publications of the Besançon, Lyons, Algiers and Nice Observatories based on observations with their coudé equatorials as a function of publication year.

The most active users of the provincial coudés were the ones in Algiers, partly due to a better climate and partly because there were several very motivated observers there. Besançon comes next, with essentially a single observer.

In Lyons, there was more variety in the observations than in the three other observatories: there was some specialization on the satellites of Jupiter and their mutual phenomena; after 1907, most observations in Lyons were of visual photometry of variable stars, performed by a specialized observer, Michel Luizet (1866–1918). But observations stopped in 1926, earlier than in the other observatories, although three papers were still published in 1944 in the *Journal des Observateurs*, reporting double star observations made in 1941–1942.

In Nice, the observations were centred on asteroids—a speciality of this observatory. Figure 16 gives a biased impression of the activity of the Nice coudé, because some of the relevant articles contain more observations than the papers from the other coudés.

6 THE VIENNA COUDÉ EQUATORIAL

In their famous book, *Lunettes et Télescopes*, André Danjon and André Couder (1979) mention a 43-cm

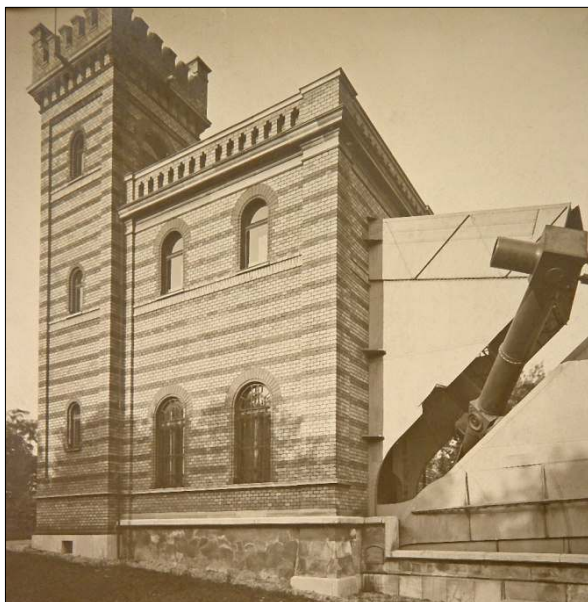


Figure 21: The coudé equatorial of the Vienna Observatory (© Archive of the Institute for Astronomy, University of Vienna).

coudé equatorial at the La Plata Observatory in Argentina. As noted by Weimer (1982: 117) this instrument never existed, and was confused with a classical Gautier equatorial of this diameter installed in 1894. Still, this mention deceived many historians, including myself (see Lequeux, 2009b).

However, there was a real coudé equatorial outside France, at the Vienna Observatory. This instrument (Weimer 1982: 117; Schnell, 2009) resulted from a gift of 10,000 Gulden made by Baron Albert von Rothschild (1844–1911), banker and amateur astronomer, as a tribute to his compatriot Lœwy. Like the other coudés, it was built by Gautier, with optics by the Henry brothers (Figure 21). The shelter had an oblique slit aperture like the coudés in Besançon and Algiers. Anneliese Schnell (2009) writes that the idea of the shelter came from Johann Palisa (1848–1925), an Austrian astronomer who was a friend of Rothschild. The Vienna building was completed in 1885, while that of Besançon dates from 1884 (but the instrument was only installed in 1888), and that of Algiers was finished in 1886: it is thus possible that the Vienna instrument inspired those of Besançon and Algiers. In Vienna, observations of asteroids and comets started in 1890, until the most valuable metallic elements of the instrument were stolen in 1903. Renovation was decided upon in 1909, and Adolf Hnatek (1876–1960) was put in full charge of the equatorial. He carefully tested the objective and the attached Askania spectrograph, and studied the effects of temperature on image quality (Hnatek, 1911; 1913). The coudé was used for measurements of the radial velocities of stars, resulting in four publications in *Astronomische Nachrichten*. In 1920, a photometer was added and used for visual photometry of the Pleiades (Hnatek, 1922). But one of the pillars started to collapse, and observations ceased in 1925. Five years later, the instrument was considered completely unusable and was decommissioned. The only remaining part is the objective, which was reworked by Zeiss in 1952 and installed in one of the solar towers of the Kanzelhöhe Observatory of the University of Graz.

7 CONCLUDING REMARKS

There are two reasons for the decommissioning of all the seven coudé equatorials near the middle of the last century. One is the growing disinterest of astronomers in their main use, the measurement of the positions of comets and asteroids. The other reason is that these instruments were sensitive to temperature, complicated, difficult to point and in general less handy than the ordinary equatorials. Failures were numerous, and maintenance was costly. One reads in the report for 1909 of the Lyons Observatory:

The instrument is somewhat old and, every year, shows some new weakness. Mounting peculiarities have been accumulated by the builder as for the fun of the thing, probably in order to require his costly intervention.

Surprisingly, this bad impression was not confirmed by Maurice Duruy (1894–1984), the astronomer who used the Lyons coudé during WWII and declared:

The comfort of the observer is very remarkable. It allows one to use completely the data from the instrument whatever its direction. (Duruy, 1944: 1).

Nevertheless he said that the image quality was better with the 27.5-cm conventional Lyons equatorial! It

seems indeed that, in spite of the lack of comfort of the classical domes, the astronomers preferred to use ordinary equatorials or reflecting telescopes when they had the choice. This appears to have been foreseen by the planners of the new observatories, as one or several conventional equatorials were always installed in parallel to the coudés. In spite of their initial enthusiasm, which perhaps was only on the surface, foreign astronomers did not adopt the system, mainly because they would have been forced to have the coudé equatorials built in France by Gautier, who was the only experienced constructor. The Vienna coudé is an exception because it was offered to the Observatory.

However, the principle is interesting, and during the second half of the twentieth century Zeiss built two small coudés. One was for the Radebeul Popular Observatory near Dresden and the other one, with the same optical dimensions, was for the Ankara Observatory in Turkey (Figure 22). Another 25-cm coudé equatorial built by Nikon is at the Kastushika City Museum in Tokyo.



Figure 22: The coudé equatorial of the Ankara Observatory. This instrument has a 15 cm aperture and 2.25 m focal length. It is used for observations of the Sun. The observer stands in a fixed position at the bottom of the polar tube, not as the top as for the Gautier equatorials. The light from the objective is sent to the polar tube by two flat 45° mirrors located on each side of the very short equatorial tube (© Ankara University Observatory).

8 NOTES

1. Recently restored, the Fraunhofer equatorial can still be seen in Tartu.
2. The Marseilles instrument has disappeared, but see a photograph in Lequeux (2009a: 102).
3. See images in Lequeux, 2009b: 55, and in http://en.wikipedia.org/wiki/Archenhold_Observatory
4. Many such instruments are depicted in Repsold (1914).
5. There is in the collections of the Musée des Arts et Métiers/CNAM in Paris a beautiful model of the coudé equatorial built by J. Digeon (inv. 10848-0000), but it is said to date from 1882 to 1886 and was probably intended for presentation in an exhibition. The model presented to the Council by Lœwy in 1874 was certainly simpler.

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