The ‘nec plus ultra’ of precision measurement: Geodesy and the forgotten purpose of the Metre Convention

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Abstract

Geodesy—the determination of the size and shape of the earth—has often been the science operating at the frontier of precision in the measurement of length. Its contribution to the technologies and standards of length measurement has, however, been underestimated in the literature. That, instead, places emphasis on the on the creation and international acceptance of the metric system as a whole. By new research into the standards-in-use of the community of geodesists, I rediscover the original purpose of the Metre Convention of 1875, and show for the first time the significant influence of geodesy on the standardisation of length measurement thereafter. I emphasise the role of the coherence of the web of measurement in the context of change and improvement in standards.

1. Introduction

Our histories of standards of length are dominated by the metric system. This was based on a wholly new standard, represented by a metal bar called the archive metre—defined by the size of the earth and determined by an arc measurement in France during the 1790s. We have exhaustive historical analysis of the cultural, philosophical and technological issues surrounding this whole metrological project.¹ We also have an extensive literature on the international adoption of the metric system, generally argued to have accelerated from the 1850s. Within this historiography the Metre Convention of 1875, by which many countries formally adopted metric weights and measures, is considered a landmark event. The convention also founded an international standards laboratory, the Bureau International des Poids et Mesures (‘BIPM’), and mandated the creation of a new metal bar, known as the International Mètre, as a replacement for the archive metre. In this article I examine the purpose of the Metre Convention, and the subsequent use of the new International Mètre, in a manner which both challenges and supplements the existing historiography.

I make an important distinction between ‘standards’ as norms—regulatory or customary constructs, such as the Imperial or metric systems—and as the practical physical representations of those norms; there is no such ambiguity in the French language, where the words I shall use, norme and étalon, have the distinct meanings. In essence, the historiography deals with normes, a story of successful international standardisation in the face of long-lasting resistance from the Anglo-Saxon world. My story, based on étalons rather than normes, emphasises the needs of the users at the frontier of precision, the community of geodesists. During the 19th century they employed a wide variety of étalons for the measurement of length, largely representing non-metric units. It was they who by the 1860s required a new, more precise and shared étalon for the effective conduct of their science; this, I argue, was the now forgotten purpose of the Metre Convention. I also show how the new International Mètre was swiftly adopted by geodesists in both

¹ Historical themes include the role of the arc measurement in determining the figure of the earth, in the context of the competing natural philosophies of Newton and Descartes; the conceptual importance of universal measure drawn from nature; the revolutionary context of the change from local feudal to national metric measure; and France’s objectives in seeking to internationalise the system. Alder (2002) provides an introduction to the literature.
metric and Anglo-Saxon countries by the early years of the 20th century, in the latter countries under cover of their historic *normes* of feet and yards. The conflict of metric and Anglo-Saxon *normes* therefore conceals a very different story at the level of the *étalon*.

The analysis of standards of length set out in this article must be put into a wider context. We have an extensive literature addressing the role of standards in precision measurement, and the sociology of disputes about standards. This tends, however, to emphasise the establishment of new standards rather than address changes in standards, especially those changes over the *longue durée*. I argue here that the catalyst for change in 19th century standards of length was the search for coherence of a web of measurement, specifically the geodetic network of Europe. And whilst that network concerned only a single user group, I suggest that the maintenance of coherence of the wider web of measurement—both within and across user groups—is a powerful *explanans* for change and improvement in standards in general.

Geodesy was, after astronomy, the second precision science. During the 18th and 19th centuries its purpose was the determination of the size and shape of the world, known as the 'figure of the earth'. Initially that mattered as a proof of Newtonian over Cartesian mechanics, which predicted different shapes for the earth, but it also had much wider astronomical, cartographic and mathematical significance. The primary geodetic technique was arc measurement. Arc measurements made at different latitudes showed how the length of a degree of meridian arc varied from pole to equator, allowing deduction of the figure of the earth. Precise length measurement was a critical part of this process; the length of an arc being determined from a carefully measured base-line. Arcs were measured by French, German, British, Russian and other practitioners, all using their own *étalons* of length to calibrate their base-lines. It was here that the frontiers of precision in length measurement lay. As Charles-Édouard Guillaume (the most eminent metrologist of his generation) claimed in a history of the Metre Convention published in 1902, 'often, in the last two centuries, geodesy has preceded metrology proper, or at least dictated its progress'.

That certainly isn't apparent from the historiography of the metric system, with its emphasis on the internationalisation of metric *normes*. Here we read of a 'quarter-century of acceptance' between the 1851 Great Exhibition to the 1875 Metre Convention, in the context of frequent international exhibitions, new customs unions and free trade treaties, European national unifications and so on. During that period, the rhetoric in favour of standardisation was overwhelming. In 1867 alone we read of a *Comité des poids et mesures et de monnaies* at the Paris Exposition, the *Académie de Sciences* in St. Petersburg and a *Congrès internationale de Statistique* all expressing the strong opinion of the scientific and industrial worlds in favour of establishing metric uniformity. Within this historical construct, the importance of the Metre Convention is largely symbolic: it was the 'formal sanctioning' of the metric system as the international system of weights and measures and a step towards the 'century-old dream of the French for a metric world'. Then, after 1875, the historical focus shifts towards conflict between *normes*. The Metre Convention is interpreted as a landmark in the 'battle of the standards'—a subject which has been treated, as the *Bibliography of the History of Technology* observes, with 'ax[e]-grinding solemnity' by a huge number of authors. We now read of global metric dominance, constrained only by Anglo-Saxon recalcitrance. In the years before World War 1, industry, commerce, science and politics were all engaged in arguments about adopting the metric system, in both Britain and the United States, without any conclusions being reached. All this misses a fundamental point: the initial objective of the Metre Convention was simply to create a new metre bar. It was not to internationalise the *normes* of the metric system, nor to have anything to do with the standards of mass and volume that were part of that system. Its name makes the point quite clear: it was the *Convention du Mètre*, not the *Convention du Système Métrologique*.

In his description of the origins of the Convention, Guillaume starts by simply repeating the resolution of the *Association Géodésique internationale* in 1867: that, in order to define a common and precise measure for the countries of Europe, a new metre *étalon* should be constructed. The need for standardisation may be self-evident, but he offers no explanation of why the unit should be the metre (actually not, as I will show, the original preference) or more than brief comment on the need to replace the original archive metre. France certainly didn't seem to require a new metre bar, its network of hundreds of *bureaux de vérification* already being provided with metric standards sufficiently precise for domestic purposes. And the international dissemination of the metric system didn't seem to either: a dozen countries had already adopted it by the 1870s, on the basis of exchange of *étalons* with the *Conservatoire des Arts et Métiers*.

In this article, therefore, I explain for the first time why the geodesists of the mid 19th century needed not simply an internationally agreed standard of length, but a better standard of length. Geodetic and cartographic surveying continued apace, especially in Britain, many German states, Spain, France and the French colonies, and technologies of geodetic measurement improved continuously. Such improvement exposed a number of the weaknesses in the collection of *étalons* of length upon which European geodesy relied. These included imprecise duplication of an expanding collective, degradation of the primary *étalons* through decades of use, and unsuitability for new techniques of base-line measurement. The collective was therefore no longer able to provide a coherent metrological foundation for European geodetic measurement.

I go on to describe how the community of geodesists influenced the creation of the International Metre—the characteristics of which were largely defined by their requirements, and the governing structure of which was based on geodetic precedent.
I then show how the length of the International Metre was rapidly and effectively distributed internationally. That involved developments in geodetic measurement technique, calibrated within an institutional framework centred on the BIPM, both led by Guillaume. By the early 20th century the International Metre was not just the metric geodetic standard, but also the defining étalon for the historic normes of feet and yards used by American and British geodesists. I therefore identify the International Metre as the first global étalon of length (one whose global role, as I have shown elsewhere, soon extended to industrial precision measurement). The history of the ‘battle of the standards’ tells us that there was a truce in the period between the two World Wars, and that battle was then re-engaged in the years after World War 2. In fact, for geodesists, it had by then been over for nearly half a century.

Finally, I offer an explanation of the inadequacies of the conventional history focussed on normes, which suffers from flaws that others have identified in the history of technology generally, resulting from a conflation of innovation and use. It is my new historical emphasis on standards-in-use that allows the rediscovery of the significance of now superseded étalons and techniques of measurement. And this approach also permits a re-assessment of the factors driving change and improvement in standards of length, with an emphasis on the search for coherence of the web of measurement.

2. The need for a new geodetic étalon

The measurement of the earth was one of the grands projets of 18th and 19th century science. The determination of the figure of the earth and the measurement of the geography of its surface probably generated more data than any contemporaneous activity other than astronomy—but, unlike astronomy, it required precision in standards of length. Following the first determination of the figure of the earth by modern techniques of arc measurement, undertaken near Paris in the 1660s, the project was given additional impetus by the need for experimental verification of the predictions of Newtonian or Cartesian natural philosophy. France continued to take the lead, with the Académie des Sciences mounting expeditions to make measurements near the Equator and the Arctic Circle from the 1730s. These expeditions were supplemented by more arc measurements during the 18th century, both in Europe and further afield, generally by French practitioners or with French collaboration.

The metrology for these arc measurements was based on an iron bar called the toise de Pérou, first used in the French expedition to the Equator, and a small number of closely managed copies—comprising what I have called elsewhere the ‘metrology of the Académie’. As a result, Pierre-Simon Laplace, the French mathematician and astronomer, could by 1789 take account of nine such

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14 See Kershaw (2009) on industrial precision measurement and standards of length.
16 See Kershaw (2011), Chapter 3, for a history of the establishment of the figure of the earth and the metrological issues involved.
17 I use the term because there were only a limited number of toise bars recognized as standards, and the Académie ensured their inter-comparison and calibration.
metrologically coherent arcs in a published derivation of a figure of the earth. A re-measurement of the arc through Paris soon followed with the objective of defining the length of the metre (using as étalon a platinum artefact known as the Borda module, deemed to have a length of exactly two toises). This arc measurement of the 1790s was, however, a high-water mark for French geodesy, which then entered a period of decline. During the following decades the emphasis was, instead, on military cartography, which fell short of the highest standards of geodetic precision. But many other countries entered the field of geodesy in the early 19th century, for reasons that combined scientific enquiry with military or imperial cartography. The British started the Principal Triangulation of Great Britain, certainly the most precise such national survey of the century, and the Trigonometrical Survey of de Pérou, which the metrology of the Académie had brought to 18th century geodetic practice was lost in the 19th century. This could be dealt with, to an extent, by inter-comparisons of national étalons. But there was an emerging problem in mainland Europe: although the toise was the widely shared standard of geodetic length, the many étalons in use were primary and secondary copies the toise de Pérou of inconsistent or unknown accuracy. As national triangulation networks across Europe were connected, they simply didn’t join up properly. That could only be attributed to the failings of the étalons that supported European geodesy.

The length of a geodetic arc, or the scale of a triangulation network, is defined by the étalon upon which it is based. But the operations used to measure geodetic length—the calibration of measuring rods with a particular étalon, the use of those rods to measure a base-line of some kilometres in length, followed by processes of triangulation over perhaps hundreds of kilometres—inevitably cause a degradation of precision. Using the techniques allowed gradually improving geodetic linkage across Europe, and constant refinement of the value of the figure of the earth—for which there were about 30 published determinations in the first half of the 19th century.

Geodesy was a science that relied upon the accumulation of long-lasting data within a coherent metrology, yet the coherence which the metrology of the Académie had brought to 18th century geodetic practice was lost in the 19th century.21

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18 The meridian arc through Paris, by definition 10 million metres in length, was thus measured in toises and the metre defined as a particular fraction of a toise before creation in physical form.
19 See Levallois (1988), p. 127, on the decline of French geodesy in the early 19th century. The main cartographical project of the time was the construction of the Carte de l’État Major, from 1816 to 1870. Its seven base-lines were measured with the Borda module; see Levallois (1988), Chapter VIII, for commentary on precision of the triangulations.
20 Butterfield (1906) details all the significant arc measurements. Gauss and Bessel’s involvement with Hanoverian and Prussian standards of length, as discussed in Olesko (1995), exemplifies the close inter-relationship with geodesy.
21 Derived from Strasser (1957), p. 86.
of the mid 18th century (an example of a baseline measurement being shown in Fig. 1) this was substantial, perhaps from the order of 20 parts per million for the étalon to hundreds of parts per million for the arc.\textsuperscript{22}

By the end of the 18th century, absolute precision had improved, but significant degradation from étalon to arc remained—perhaps from 1 part per million for the étalon, to a few parts per million for the baseline, to 25 parts per million for the arc. These estimates are based on the data from the arc of meridian through Paris that was measured to define the metre, explicitly an exhibition of precision geodetic measurement. The Borda rules that were enacted using a novel sighting instrument, known as the Borda repeating circle, degradation of precision remained.\textsuperscript{23}

The 19th century brought significant improvement in the techniques of end-contact base-line measurement. I give two examples, taken from important arcs. The first is from a base measurement in Prussia in the 1830s, by Bessel and General Johann Baeyer, which was part of an exercise to join the Prussian and Russian triangulation networks. Bessel fixed opposing knife edges at each end of his measuring bars. Their separation was then measured by inserting glass wedges of very narrow angle, themselves calibrated to a very high degree of precision, into the gap.\textsuperscript{24} The second is from the measurement of several base-lines by Struve, between 1827 and 1851, as part of the triangulation from the North of Norway to the Black Sea. Struve’s approach involved lever apparatus: a steel tip at the end of one rod pressed against a lever at the end of the next, which multiplied the relative motion of the two rods and produced a reading on an arc scale.\textsuperscript{25} These evolutions in the design of base-line measurement equipment were combined with mathematical revolution. Until the 19th century, discrepancies in observations were dealt with largely subjectively. A double-measurement of a base, for example, could do little more than give an impression of the trustworthiness of the result. The development of least-squares methodology transformed practice.\textsuperscript{26} Both Bessel and Struve produced extensive error analysis, with up to seven different error types being accounted for, including alignment, temperature measurement, calibration of the measuring rods and the

\textsuperscript{22} During the mid 18th century comparisons of the toise de Pérou with other toises could be carried out, using beam compasses, with a precision of the order of 20 parts per million. See Delambre (1912), p. 72. On errors in base lines, repeat measurements of the six base-lines described in Cassini (1744), showed precision of 50 to 100 parts per million.

\textsuperscript{23} See Delambre (1810), pp. 402-414, for a description of the Lenoir comparator.

\textsuperscript{24} Ibid., p. 418, shows an error of 7 parts per million on a partial re-measurement of a base-line (by my computation from the data).

\textsuperscript{25} Ibid. The northern and southern bases of the arc were linked by a chain of 53 triangles, by which the length of the southern base was computed from the northern. The difference between measure and calculation was roughly 30 centimetres over a base of 12 kilometres, using modern units, or 25 parts per million (by my computation from the data).

\textsuperscript{26} Bessel and Baeyer (1838).

\textsuperscript{27} Struve (1857), vol. 1, chapter VI.

\textsuperscript{28} See Stigler (1986), Chapter 1, on the history of the use of least-squares techniques in the combination of observations.
personal equation of observers. Bessel reported an overall probable error in his base-line of about 2 parts per million, and Struve of about 1 part per million.29

At the same time as traditional base-line measurement techniques were improving, a new method was developed. This involved the positioning of measuring bars by optical rather than contact means, with points or lines on the bar being aligned under microscopes. The first such apparatus was created in Britain in the 1820s by Troughton & Simms, at the request of the Ordnance Survey. It was then used for the measurement of a base at Lough Foyle in Northern Ireland, one of the two bases of the Principal Triangulation of Great Britain, and was employed successfully for decades both at home and across the Empire. Optical techniques were then adopted by the French in the middle years of the century on a base measurement in the colony of Algeria, for which new apparatus was procured from the Italian instrument maker Ignazio Porro. This used a single line-measure rod, moved forward sequentially under a series of stand-mounted micrometric microscopes, and was claimed to offer significant advantages in terms of both simplicity of use and precision.30 Optical base-line apparatus was therefore chosen for the next major project of French geodesy, the junction of the triangulation networks of France and Algeria. That required a triangulation of Spain.

The foundation of the Spanish triangulation was a base-line near Madrid, measured by General Ibáñez in the 1860s.31 He used a revised and improved version of the Porro apparatus, based on a 4-metre metal bar and constructed in Paris by the instrument maker Brunner.32 The equipment took two years to build, and the description of its construction and calibration fill a book of 300 pages. The principles of the apparatus, and its manner of use, are described in Fig. 2. The single rod was moved forward along a line of microscope tripods, each requiring precise positioning, alignment and levelling, and all kept under the cover of a long transportable wooden shelter as protection from sun, wind and dust. The base-line of 14 kilometres took over 10 weeks to measure, and required a complement of four officers and an entire troop of artillery. To give additional confidence, the base was divided into five sections, the lengths of which were cross-checked using a triangulation network. The conclusion was that this base measurement had a probable error of some 2.5 millimetres, or about one fifth of apart per million—even if that result was based on some rather doubtful mathematics.33 But no one quibbled at the time: the report received by the Académie des Sciences couldn’t have been more fulsome, suggesting that the Spanish officers had reached a level of precision which represented a ‘nec plus ultra that isn’t possible, that it wouldn’t even be useful, to go beyond’.34

The precision of base-line measurement had therefore come on a long way, improving by perhaps two orders of magnitude over the previous 100 years.

Such improvement was mirrored in the processes of triangulation. The most advanced sighting instruments of the late 18th century had been the cumbersome Ramsden Great Theodolite in Britain and the slow Borda repeating circle in France. German instrument makers created more compact theodolites, better suited to the taking of the multiple observations that became an integral part of the search for precision. Bessel and Struve, for example, used theodolites of between only 12 inches and 15 inches in diameter, from German manufacturers such as Ertel and Repsold, yet still accurate to within a few seconds of arc.35 The new techniques of least-squares error analysis could then be applied not only to individual triangles, but also to the construction of triangulation networks as a whole. It had long been common practice to measure a second base in a triangulation as a base of verification, but there was no objective way of dealing with the inevitable small difference between its calculated and measured value. Now, any number of bases could be placed in a triangulation, and—knowing the probable errors and probabilistic weights of measurements—a ‘best-fit’ triangulation could be computed. Instead of being a problem, additional bases now helped the precision of the triangulation as a whole. As the Académie des Sciences was told: ‘Isn’t it obvious that the bases don’t just serve for verification? Their simultaneous use has the effect … of considerably improving the precision of the results.’36

The clearest example of this came from the Principal Triangulation of Great Britain. This comprised a total of 289 triangulation stations and two bases, the one at Lough Foyle in Northern Ireland described above and one on Salisbury Plain, each of which had been measured with the Ordnance Survey’s new base-line apparatus. The data was then used to create a ‘best-fit’ triangulation for the network as a whole in an exercise of formidable computational complexity.37 The difference between measured and calculated values of the two bases was only a few parts per million. The resulting network was then considered sufficiently trustworthy to check the lengths of several other base-lines in Great Britain, ones that had been measured in years past using techniques now superseded. So we see that there had been a fundamental shift: rather than additional bases being used to verify the reliability of a triangulation, a triangulation network was being used to verify the length of older bases. It follows that by the mid 19th century the degradation in precision that took place in the extension from étalon via base-line to triangulation network had been very significantly reduced.

The focus therefore moved to the precision of the étalons themselves. As I have described, the étalons that supported continental European geodesy during the middle years of the 19th century were numerous. The parent étalon for all practitioners was the toise de Pérou, now no longer in use.38 In France, its direct descendant—the Bordé module of two toises—defined the French network. Elsewhere, the main international distribution mechanism for the metrology of the Académie had been copies of the toise de Pérou.

29 Bessel and Bayer (1838), pp. 52-58, Struve (1857), p. 54. Probable error was assessed against the particular étalon used for the base, so it was an assessment of precision, not accuracy in terms of any other standard. Oséko (1995) addresses German use of 1st-squared error analysis.

30 The description of the Porro apparatus given to the Académie in 1850 argues that, whilst it would be hard to improve on the precision achieved by Bessel and Struve, the new equipment would be simpler, quicker and cheaper. A later description places more emphasis on precision, with acknowledgment of the influence of British practice. See Lagrangeau. (1850), pp. 232-241, and Memorials du Dépôt Général de la Guerre (1871), pp. 1-7.

31 Soler (1997), gives a brief life of this military engineer-geodesist-metrologist. Ibáñez (1860) and (1863) describe the construction and use of the apparatus. These books were translated into French by Colonel Aimé Laussedat, an astronomer-geodesist and Académicien, who collaborated with Ibáñez. There were extensive refinements in the construction of the measuring rods, their support and calibration, temperature measurement and alignment which I have not described.

32 The transition from metre to toise as standard of length is not explained, but the metric system had finally been made legally compulsory in France in 1840.

33 Ibáñez (1863), p.117. He computed a probable error for the middle of the five sections that had been measured, and extended that to the whole base using a least-squares formulation. Such an approach is incorrect because a part of the error, that due to calibration against the étalon, is systematic and therefore simply additive. The total error was therefore underestimated.

34 Faye (1863b), p. 374.

35 The literature on surveying instruments is limited, but see Chapman (1990) on the technologies of angular division and Bennett (1987).

36 Faye (1863b), p. 376.

37 Seymour (1980), p.142 summarises the technique of ‘adjustment by condition equations’.

38 The history, state of preservation and even the clear identification of the toise de Pérou during the 19th century are the subject of some uncertainty. See Marquet (1988) for a discussion of the evidence.
made in the 1820s. These were used to generate further copies and it was from such copies that Bessel, Struve and others calibrated the base-lines which formed the foundation of their arc measurements. This diverse mechanical collective had three weaknesses, clearly identified by the geodesists of the 1860s, which I discuss below.

2.1. Imprecise copies

The collective of European toise étalons had grown over decades. Inevitably differences in length amongst them now existed. That was most evident in the incoherence that was becoming apparent between French and non-French geodetic measurement. The important junction between the French and German triangulations showed a discrepancy in length of about 15 parts per million, which was suspected as being the result of a difference in length of their respective toises. The triangulation of Great Britain had met that of France very satisfactorily when they were linked across the channel in the early 1860s. Yet when the British triangulation was extended into Belgium, an error several times greater was revealed, because the French and Belgian triangulations were not coherent. Again, this was suggested to be at least in part due to uncertainty over the length of the standard toise of Belgium.

These issues of incoherence between national networks could, in principle, be dealt with by physical inter-comparisons between national étalons. That was, for example, how British and continental measurements had always been brought together for computations of the figure of the earth and for cross-channel triangulations. In this context an extensive and painstaking series of inter-comparisons was carried out by the British Ordnance Survey in the 1860s, bringing together étalons from Britain and its Empire, Prussia, Russia and Belgium. But this had left loose ends. The most important related to the difficulty of calibrating modern toise étalons in terms of the toise de Pérou, which was itself no longer serviceable. Reliance had to be placed on copies, especially Struve’s toise and Bessel’s toise, themselves deduced from copies calibrated decades before using technology long superseded. Ideally, comparison would have been made with the Borda module. It was this—rather than the toise de Pérou itself or the archive metre—that was regarded in France as the ‘true’ standard of length. But Le Verrier, the director of the Paris Observatory, resolutely refused to let it leave Paris, recording his ‘extrême répugnance’ at the prospect. This problem of metrological incoherence was widely acknowledged: evidence to one of the preparatory committees of the Metre Convention was that ‘many scientists’ believed the differences between geodetic measurements in different countries to be caused by ‘incompletely defined’ relationships between the units of length employed.

2.2. Deterioration of the primary étalons

The most precise geodetic measurements of the later 19th century were based on the Brunner apparatus first used in Spain. The Brunner bar was calibrated against the Borda module itself, but that artefact had been created in previous century and had been extensively used in the field. The calibration of the Brunner bar had been a matter of critical importance, requiring over 100 sets of observations to be made over a period of two months. But precision was thrown into doubt by the poor state of preservation of the Borda module, the ends of which were visibly imperfect. Ibáñez couldn’t even quantify the problem, and just noted that:

to observe in what state were the extremities, they were examined with strong magnifying lenses; pictures were recorded photographically, and sketches also made by hand, at a scale four times greater than life, of the inequalities and the small burrs that were noticeable…

This could barely be reconciled with the claimed precision of a fraction of a part per million in the calibration of the Brunner bar. An alternative primary étalon to the Borda Module was the archive metre itself, their lengths being defined in fixed proportion. But a variety of doubts existed about the archive metre too, which were summarised in another preparatory committee for the Metre Convention:

From the first séance we could tell how much doubt there was in foreign countries as to the good conservation of the archive metre: metres deduced from it, distributed outside France, showed highly uncertain comparability, which put in doubt the qualities of the original. We were struck by the depressions left on the ends by the use of comparators, some as deep as 1/100th of a millimetre [10 parts per million]. Finally, there were questions as to whether molecular changes hadn’t resulted in a change to its length.

There was, in principle, a third option. The toise de Pérou was the parent of both the Borda module and the archive metre. But, according to one contemporary source, it was so far damaged by the 1850s that comparisons with it were worthless. The metrology of European geodesy was therefore now admitted to be without a firm foundation.

2.3. The wrong kind of étalon

There is a need, for reasons of convenience and precision, to conform the particular techniques of geodetic measurement operations and their standards of length. When the British introduced their new base-line apparatus employing optically positioned measuring bars in the 1820s, they created new étalons at the same time. These were 10-foot line-measure étalons, capable of use in the same optical comparator apparatus as the 10-foot measuring bars. The need for conformity was plainly articulated by George Biddel Airy, the Astronomer Royal, who had been deeply involved in the construction of new British standards of length. He wrote that ‘the whole of the British geodetic bases have been measured by bars constructed on the line-principle; and a standard which is intended to apply advantageously to them must be constructed on the same principle’. When the British adopted these new Ordnance Survey standards, however, they were just starting the Principal
Triangulation of Great Britain the first such exercise. The Ordnance foot could be defined *de novo*, with comparatively little care for coherence with older geodetic measurements.

European geodesy, until the mid 19th century, had been based on end-contact base-line measurement techniques. The calibration of the measuring rods therefore employed mechanical comparators with compatible end-contact *étalons* of length. The change in measurement operations in French geodesy, from end-contact to optical positioning, therefore left the Borda module as the wrong kind of geometric *étalon*. The new *étalon*, the 4-metre line-measure Brunner bar, could not however be defined *de novo*. The web of European geodetic measurement was now extensive, coherence between historic and future measurements was essential, and the precise calibration of new against old standard was a necessity. The techniques to achieve this were complicated—optical comparator apparatus was used, with the end-contact Borda module being made observable by the addition of small, highly polished, scribed platinum end-pieces—and risked imprecision. As far as I can ascertain, the exercise was never repeated, and all future Brunner apparatus (which came to be widely used in Europe) was calibrated indirectly from Madrilejos bar.49 This difficulty of comparison be-tain, the exercise was never repeated, and all future Brunner appa-ratus (which came to be widely used in Europe) was calibrated indirectly from Madrilejos bar.49 This difficulty of comparison be-tain, the exercise was never repeated, and all future Brunner appa-ratus (which came to be widely used in Europe) was calibrated indirectly from Madrilejos bar.49 This difficulty of comparison be-tain, the exercise was never repeated, and all future Brunner appa-ratus (which came to be widely used in Europe) was calibrated indirectly from Madrilejos bar.49 This difficulty of comparison be-tain, the exercise was never repeated, and all future Brunner appa-ratus (which came to be widely used in Europe) was calibrated indirectly from Madrilejos bar.49 This difficulty of comparison be-tain, the exercise was never repeated, and all future Brunner appa-ratus (which came to be widely used in Europe) was calibrated indirectly from Madrilejos bar.49 This difficulty of comparison be-tain, the exercise was never repeated, and all future Brunner appa-ratus (which came to be widely used in Europe) was calibrated indirectly from Madrilejos bar.49 This difficulty of comparison be-tain, the exercise was never repeated, and all future Brunner appa-ratus (which came to be widely used in Europe) was calibrated indirectly from Madrilejos bar.49 This difficulty of comparison be-tain, the exercise was never repeated, and all future Brunner appa-ratus (which came to be widely used in Europe) was calibrated indirectly from Madrilejos bar.49

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To summarise, by the mid 19th century, the technologies of tri-anulation and base-line measurement were sufficiently well developed that a particular triangulation network could be relied upon to have been robustly constructed and calibrated against its own *étalon* of length. But the collection of *étalons* on which European geodesy relied was no longer able to provide a sound metrological foundation.

3. The creation of the International Metre

The catalyst for unification of European standards of length was a proposal by General Baeyer, Bessel’s collaborator on the earlier arc measurement in East Prussia, made in 1861. His suggestion was that the numerous astronomical observatories of Central Europe should be connected by triangulation, using a combination of some improved existing networks and some new ones. The resulting geodetic and gravitational data would, he argued, allow determination of local variations of the earth’s shape and provide results of ‘great interest and importance’.50 The idea was not completely new. The forward to Bessel and Baeyer’s *Gradmessung in Ostpreussen*, which had linked the Prussian and Russian triangulation, had explained the potential benefits of further linkages between the triangulations of the German states and to other arcs such as that being measured by Struve. The proposal was taken up by the King of Prussia, and fifteen countries and states accepted the invitation to take part. In 1864 the *Mitteleuropäischen Gradmessung* met for the first time.51 A formal institutional structure was put in place, with a General Conference meeting every three years supported by subsidiary bodies that included a Permanent Commission. The establishment of consistent standards of length was fundamental to the project, and was an immediate concern. The scientific recommenda-tions of the first conference therefore included the following:52

- Bessel’s toise shall be used as the unit in geodetic calculations.
- All the standards used in triangulations that are part of interna-tional geodetic enterprise must be compared to Bessel’s toise by the Permanent Commission.
- The Permanent Commission will nominate a special commis-sion which will determine in a scientific fashion the relationship between the metre and the standards of measurement used in other countries, and submit the results of its work to the gov-ernments of those countries in order to facilitate the introduc-tion of a general and international standard.
- Once the relationship between the metre and Bessel’s toise has been determined, all results contained in publications concern-ing the Central European arc measurement will be expressed in metres as well as toises.

We see here a programme which is still metrologically local, not conceding primacy to the metric system. It proposes that Bessel’s toise be the standard of length, both *norme* and *étalon*, for the group of members; that members’ existing *étalons* are mutually grounded to provide coherence within the group; and that a link to metric geodesy be made—just as the British had done—by com-parison of *étalon* to *étalon*. It was not at that stage a proposal for unification of European standards of length. This was to emerge some three years later, as a somewhat reluctant product of metro-logical failure. When the General Conference of the (now slightly enlarged and more realistically named) *Europäischen Gradmessung* met on its second time in 1867, it heard the disappointing conclu-sions of the last three years work of the special commission on standards. In their comparison of the Bessel toise with the Italian standard toise, troubling results had been obtained. The difference in length between the two was so great that a change in the length of the Italian toise, or in its coefficient of expansion, had to be sus-pected. The alarming possibility was even admitted that the Bessel toise might not be of invariable length.53 In these circumstances, a new *étalon* was the only solution, and it was implausible to create one *ab initio* outside the metric system. It was therefore agreed that the adoption of a common European standard was desirable in the interests of science in general, and in the interests of geodesy in par-ticular. So the resolutions proposed at this second conference included:54

As it has the greatest probability of gaining widespread accep-tance, the Conference supports the choice of the metric system. . . . the Conference considers the creation of a new European metre *étalon* desirable. The length of this European metre should differ as little as possible from the original archive metre . . . In the construction of the new metre *étalon*, special account should be taken of easy realisability of future comparisons.

Two areas of potential disagreement were concealed in the above formulation. The first was over the length of the metre. The term ‘differ as little as possible’ was ambiguous. It was by now known that the archive metre was slightly too short in terms of its definition as one ten-millionth part of the meridian. The words could therefore be read to imply that the length of the metre

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49 See Hirsch and Dumur (1888), chapter 3, for a history of later calibrations of the Brunner apparatus.
50 Levallois (1980) gives an English translation of Baeyer’s original memorandum.
51 As well as German states, members included Denmark, the Netherlands, Austria, Switzerland, Russia (for Poland), Sweden, Norway and Belgium. The early involvement of France was limited. See Faye (1863a) for a diplomatic description of the French reservations about the project: there was ‘perhaps, something too distinctively German’ in the techniques, calculations and apparatus proposed together with regret that preference had been given to the toise rather than the metre.
52 Levallois (1980) contains English and French translations of the original resolutions.
53 Bericht über die Verhandlungen . . . (1868), pp. 124-125.
54 Ibid., p. 126.
should be adjusted to make it ‘right’, rather than conserving the length of its conventional representation, the archive metre.\textsuperscript{55} The second potential disagreement was over the form of construction of the new metre étalon, obscured by the reference to ‘easy realisability’ of future comparisons. The special commission on standards of the Europäischen Gradmessung was composed of members used to end-contact standards, but fully aware of the progress being made in line measure standards. Their researches into techniques of length comparison in the three years up to 1867 had been inconclusive, so they had no choice but to leave matters open.\textsuperscript{56} These issues, articulated by geodesists, were critical to the creation of the new metre étalon.

The first resolutions of the Europäischen Gradmessung pre-date a flurry of reports on the benefits of an international standard of length by the Académie des Sciences in St. Petersburg and Paris, the Bureau des Longitudes, the Ministre du Commerce and others. A very brief summary of the chronology of the lengthy birth of the new metre would then include the diplomatic communication in 1869 from the Emperor of France to foreign governments inviting their participation in a commission charged with its creation; a first meeting of the Commission Internationale du Mètre in 1870 (lacking German representation, because of the Franco-Prussian war); the establishment of a committee of preparatory research to deal with a number of technical matters; a second meeting of a now quorate Commission Internationale in 1872, establishing 11 sub-committees to address various issues, now including standards of mass, as well as those of length, and matters of governance and administration; and then the Metre Convention of 1875. The actual creation of the International Metre and its copies for distribution then suffered significant delay as a result of metallurgical difficulties, and was not eventually completed until the end of the 1880s. The chronology is well documented.\textsuperscript{57} I do not propose to repeat such detail here; rather, I will look at the resolution of three of the most important issues that required debate, and the role of geodesists in deciding their outcome: the length of the International Metre, its physical form and its governing structure.

3.1. The length of the International Metre

There was one school of thought that the opportunity should be taken to change the length of the metre—albeit very slightly—to conform to it in its theoretical definition. One Académicien articulated the point of view as follows:

\begin{quote}
\ldots the metre must be \ldots the ten-millionth part of the terrestrial meridian, so that if by a new cataclysm all our étalons were lost, we could easily recreate them by simple geodetic measurements on the surface of the earth; it is this truly philosophical idea which ruled at the creation of this great system. \ldots\textsuperscript{58}
\end{quote}

For others, the preference was to admit that the universal nature of the metre had been a convenient ‘fiction’, and that the length of its conventional representation, the archive metre, was to be taken as the basis for the International Metre.\textsuperscript{59} The argument against the theoretical definition was expressed thus:

The value of the metre would therefore change with countries and time, if it were not accepted as the fixed value attributed to it by the first measurement of the meridian. The changes, it is true, would be absolutely undetectable in practical use; they would, nevertheless, cause trouble in scientific work.\textsuperscript{60}

I would characterise the debate, therefore, as being about the coherence of the web of geodetic measurement. The Europäischen Gradmessung was clearly in favour of preserving the length of the archive metre, and any suggestion otherwise was soon clarified as being due to ‘certain misunderstandings’; they actively supported the establishment of an international commission to take this forward, and intended to represent their ‘scientific interests at the heart of the commission’.\textsuperscript{61}

A decision as to whether to take the archive metre as the basis for the International Metre was the first item on the agenda of the first meeting of the Commission Internationale du Mètre in 1870. The main contribution to the debate on this fundamental point was by Adolph Hirsch—who had been the Swiss representative to the meeting of the Europäischen Gradmessung in 1867.\textsuperscript{62} He repeated the argument that never-ending progress in geodesy would lead to continuous change in the length of the theoretical metre; but also noted that there was an element of circularity in the process of using a pre-existing étalon, and a series of complicated measuring operations, to define a new one. The archive metre, he argued, was actually defined rather more by the toise de Pérou than the length of the meridian itself. By the end of the meeting, the geodetic view had prevailed: it had been said without contradiction that ‘no serious scientist’ could consider anything other than the archive metre as basis for definition of the length of new metre étalon. The subject was effectively closed, with due respect for the web of geodetic measurement.

3.2. The format of the International Metre

A choice had to be made as to whether the International Metre was to be a line-measure or end-measure étalon. I have shown that one of the problems faced by French geodesy was that, following the adoption of optical techniques in the 1850s, the end-measure Borda module was the wrong kind of étalon. The French preference for the new metre to be a line-measure étalon was first formally articulated by a Commission of 1868, constituted to advise the French government on the creation and distribution of a new metre and its copies.\textsuperscript{63} The invitations to foreign countries to join a metric commission even made clear that a line-measure copy of

\textsuperscript{55} This ambiguity was compounded by a proposal from a recent international statistical conference. Here, the suggestion was that a commission might correct the ‘minor scientific defects’ in the metric system, which was thought by some to mean change its length. See Bigourdan (1901), p. 260.

\textsuperscript{56} New comparators, capable of dealing with line measure and end measure standards were required to take the researches forward. See Bericht über die Verhandlungen... (1868), p. 123.

\textsuperscript{57} Bigourdan (1902), chapters XXIV and XXV also reproduces in full a number of the significant reports leading up to the Convention du Mètre. See also Quinn (2012), Chapters 2 to 5, which provide additional detail based on the archives of the BIPM.

\textsuperscript{58} de Pontécoulant (1869), p. 720.


\textsuperscript{60} Report of a French commission on the prototype of the metric system, reproduced in Bigourdan (1901), p. 261.

\textsuperscript{61} Bigourdan (1901), p.264. My reading of the original resolution of the Europäischen Gradmessung is that their meaning was quite clear: ‘Die Länge dieser Europäischen Meters sollte sich von der des ursprünglichen Französischen metres des archives so wenig als möglich unterschieden, und muss mit demselben auf den Genauesten verglichen werden.’ See Bericht über die Verhandlungen... (1868), p. 126. My surmise is that confusion was caused by the suggestion that a French base be re-measured to verify the length of the archive metre; this, it was later clarified, was intended to be done a posteriori, to ensure coherence between new and old measurements. See Commission International du Mètre (1872), p.3.


\textsuperscript{63} The report is referred to in Bigourdan (1901), p. 270. It was, as far as I can ascertain, never published, so the rationale for the choice of line-standard is not made explicit. The stated need for techniques of comparison with ‘all the precision entailed or required by modern science’ is, however, a clear reference to the optical techniques recently developed for geodetic étalons.
pressed a need. This is all evidence of the influence of geodesy on would be calibrated from it and distributed to any countries who ex-
end-measure one. A committee for preparatory research was set
that the new metre would be a line-measure standard and then gave
ments and standards of length I have mentioned, simply 'anticipated'
whose views on the need for conformity between geodetic opera-
the only ones recorded, and were addressed by the kind of compro-
was nonetheless clear. Hirsch expressed the straightforward view
that line-measure standards were to be preferred for reasons of
precision and permanence. He did also give news of technical pro-
gress by the Europäischen Gradmessung, conceding that improve-
ments in end-measure comparators were promised. But Airy,
whose views on the need for conformity between geodetic opera-
tions and standards of length I have mentioned, simply 'anticipated'
that the new metre would be a line-measure standard and then gave
instructions on how best to deduce a line-measure standard from an
different length. A committee for preparatory research was set
up to consider this and other issues. To its several French members
were added foreign representatives, including Airy, Hirsch, and IIbáñez, together with Wilhelm Foerster of the Europäischen Grads-
zung. When the committee eventually met, the decision to create a
line-measure étalon was a fait accompli. Discussion centred on how,
rather than whether, to construct one. Foerster’s reservations were
the only ones recorded, and were addressed by the kind of compro-
mise so usual in this type of forum: the new International Metre
would be a line-measure étalon, but some end-measure étalons
would be calibrated from it and distributed to any countries who ex-
pressed a need. This is all evidence of the influence of geodesy on
the format of the International Metre: by that, I am not suggesting
that there was a single geodetic view that prevailed; rather, that
the arguments reflected the views of geodetic practitioners and the
decision suited the majority.

3.3. The governing structure of the International Metre

Historians of international standards have given little attention
to the institutional structures that create and maintain them. The
first exercise in international standardisation of length of the 19th
century, the creation of the Imperial Yard, actually managed
without any. Some 40 copies of the new yard were created and dis-
tributed internationally, not just to Empire but to America and
many European countries. But there was no mechanism for later
inter-comparison or verification. This was an exercise in the creation
of metrological coherence, not its maintenance. The Europäischen
Gradmessung, in strong contrast, had a structure with clearly defined
roles and responsibilities and with continuity at its core. It operated
at three levels. First, there was a conference of all member states,
meeting annually and responsible for 'directing all the
consistency in existing European geodetic data, and to pro-
provide a firm basis for future geodetic measurements. These objec-
tives, I will show in this section, were achieved with great
success—even if the developments in measurement technology
that assisted the achievement of the second objective were not foreseeable in the 1870s. I will describe, too, one unanticipated
consequence—the replacement of the étalons for the British and

64 Commission International du Mètre (1871), p. 28.
65 Ibid., p. 12. Airy, being unable to attend, wrote to the Commission in French and used the verb prévoir in this context.
66 See Guillaume (1927), pp. 19-20 for a brief biography of Foerster. He was a member of the Central Bureau of the Europäischen Gradmessung, later played a part in the
establishment of the Physikalisch-Technische Reichsanstalt, and became second president of the Comité Internationale des Poids et Mesures in 1891.
68 Airy (1857) sets out the recipients.
70 The similarities to the Europäischen Gradmessung are even stronger when it is noted that the Comité Internationale des Poids et Mesures was, when originally proposed, to be
called the Comité Permanent. See Commission International du Mètre (1871), p.63. Bigourdian (1901), pp. 328-337 reproduces the Metre Convention, where this whole structure is
defined, in full.
71 See Bigourdian (1902), p. 325.
72 Commission International du Mètre (1871), pp. 64-65.
73 See Quinn (2012) p. 38 for a more detailed analysis of geodetic membership of the Metre Commission, and Chapter 6 on the negotiations that resulted in the eventual
structure of the BIPM.
American norms of measurement by the International Metre. The International Metre therefore became the universal standard for geodetic precision measurement.

In terms of the historic data, progress was swift. At the BIPM, work was undertaken to compare many of the important European étalons against the International Metre. These included the Bessel toise, the double-toises of Russia and Austria, and the Imperial Yard. In addition, comparisons were made with the foundations of the metric system, the toise de Pérou and the Borda module. This was, in effect, a continuation of the work of mutual grounding carried out in years past. Results from the new comparisons were now highly satisfactory. The flawed junction between the geodetic grids of France and Germany had shown a difference of 15 parts per million in the length of the sides of some common triangles; once corrected for recalibration of standards of length, the discrepancy was reduced to a few parts per million, a level quite consistent with the limits of geodetic precision. Other inconsistencies were tidied up. And the actual relationship between the lengths of the Borda module and International Metre were found to be within one part per million of the numerically defined value. One might well raise an eyebrow at this result, and even Guillaume, director of the BIPM, had to admit that he was ‘forced, given all the intermediaries through which it has been necessary to pass, to attribute part of such a remarkable agreement to chance’. Fortuitous or not, the first objective of improving the coherence of existing European geodetic data was successfully achieved.

The distribution of the length of the International Metre as the basis for new geodetic measurements in countries already accustomed to the metric system was rapid. The BIPM was calibrating new 4-metre geodetic étalons for use in Europe, Japan, Russia, South America and Africa in the very early years of the 20th century. But the speed of distribution of the new standard was increased by the first ever fundamental change in the techniques of base-line measurement. This was the replacement of rigid measuring bars with metal wire or tape. The idea, first proposed by the Swedish geodesist Edvard Jäderin in 1879, was simple. Steel tapes of a length of some tens of metres, stretched over two pulleys and kept under known tension, would allow base-line measurements that were not only more rapid than those with cumbersome rods but also less troubled by irregular terrain. The difficulty of determining the precise temperature of the metal was an initial problem, but that was solved with the invention in 1896 of invar, a particular alloy of nickel and steel which has an extremely small coefficient of expansion (and for which Guillaume received the Nobel Prize for Physics in 1920). Invar tape apparatus came into wide use in early years of the 20th century, and Guillaume records its application in such diverse locations as Uganda, Portuguese West Africa, Argentina, Mexico, Rumania and Canada. Indeed he jointly wrote the standard text on the subject, La Mesure Rapide des Bases Géodesiques in 1906, a book that was in its fifth edition within little more than a decade. Adoption of invar tape apparatus was swift in the United States and Britain too. The Coast and Geodetic Survey thought it ‘decidedly more accurate’ and ‘very much more economical’ than traditional methods. Its use is illustrated in Fig. 4.

There was an imperialist context to this surveying activity, as the British and French, followed by Germans, Americans and others, staked out their growing empires. The survey of Uganda for which tapes were calibrated was just one part of a huge endeavour to map the British African colonies. The French were active through a number of their Services Geographiques in Indo-China and Africa. The survey of Portuguese West Africa was one component of the surveys of Portugal’s colonies by their Comissão de Cartografia. The annexation of the Philippines by the United States at the turn of the century was swiftly followed by a topographical survey, and there are many more examples. Other survey work was based on the needs of nation states: topographical and geodetic measurement of such vast areas as Asiatic Russia, many countries in South America and the Dominion of Canada were still working-in-progress. Even Peru was revisited by a French scientific mission in the early years of the 20th century, to re-measure the arc that they had first measured over 150 years before.

These measurements were grounded on the new metre. In 1901 the BIPM had set up a standard base-line in an underground corridor, specifically to allow calibration of invar wire apparatus in terms of the International Metre. It was quite remarkably busy: in the first decade, over 650 wires and tapes were calibrated, this being by far the largest part of the standardising activity of the entire BIPM. In 1920, the BIPM’s work of calibrating wires and tapes was still being described as ‘very abundant’, and another decade later, demand remained ‘exceptional’. Thus there was a clear primary channel for the widespread distribution of the length of the International Metre. In addition, secondary distribution channels were swiftly developed: institutions such as the National Physical Laboratory in England, the National Bureau of Standards in Washington and others in Europe, Russia and Japan established their own bases for calibrating invar tapes, which were calibrated using either their national copies of the International Metre or geodetic rules calibrated at the BIPM. There was also a double-check of precision, achieved by mutual grounding between standards laboratories. As early as 1913, the lengths of the base of the BIPM and that of the National Physical Laboratory were being compared by exchange of invar tapes, and the extension of this practice to other laboratories followed after World War I. This was all exactly what the BIPM was designed to do: create and maintain metrological coherence.

The length of the International Metre was distributed, too, outside the metric world. An unanticipated result of its creation was that various incarnations of the foot as a geodetic unit—English, South African, and American—soon came to rely on it as their étalon. In the late 19th century geodetic length measurement in Britain and its Empire was still based on the series of 10 foot Ordnance Survey bars. These pre-dated the construction in the 1850s of the Imperial Yard, the stability of which was in any event becoming a matter of concern. The need to re-rule particular Ordnance Survey bars led to them being calibrated instead against the Interna-

74 Guillaume (1927), pp. 128-132. No mention is made of the uncertainty as to the identity of the toise de Pérou discussed by Marquet (1988) or the damage mentioned in Clarke and James (1867).
75 Guillaume (1927), p.129.
76 Ibid., pp. 132-135.
77 Jäderin (1895) is an English translation of the original article.
78 Guillaume (1927), pp. 145-146.
80 These examples are taken from Encyclopedia Britannica 1911 on topographic surveys.
82 Derived from the table in Comité Internationale des Poids et Mesures (1913) p. 47. To put this number in context, it was reported at the Geodetic Conference held at Washington, D.C. in 1894 that only 157 geodetic base-lines had been measured globally up to that time.
84 The National Bureau of Standards tape tunnel is illustrated in Briggs (1913) is very similar to the one at the BIPM illustrated in Guillaume (1927).
tional Metre. This was first done in preparation for a triangulation that was to extend from the Cape to Egypt, known as the Arc of the 30th Meridian. The Cape 10 foot standards were considered insufficiently well defined for new work of the highest precision, so they were returned to be newly scribed by Troughton & Simms in London. They were then calibrated against a provisional International Metre by the BIPM in 1886.86

Further change was brought by the adoption of invar tape base measurement technology. A proposal was made in 1908 to test the accuracy of the Principal Triangulation of Great Britain, by that time over half a century old.87 For this exercise a new base-line was to be measured in Scotland with invar tapes, calibrated on the Ordnance Survey's 100 foot geodetic base. That base in turn relied upon the 10 foot Ordnance Survey bar standards, but the new techniques of measurement required the standards to be re-rulled on their flanges. It is clear from the Ordnance Survey's own account that they had neither the ruling apparatus nor the comparator technology to undertake this effectively. The work was again carried out at the BIPM in Paris, who created what was in effect a new Ordnance Survey 10 foot standard based the International Metre.88 Meanwhile in British colonies at much the same time, metric invar tapes calibrated on the BIPM came into use. The Ugandan survey mentioned above, for example, was in part to resolve a colonial border dispute with Belgium. The only étalon trusted by both countries would, therefore, have been the International metre.

Surveys using these tapes and bars calibrated against the International Metre were still reported by the British in feet, converted using ratios based on historic inter-comparison of yard and metre. Inevitably confusion followed. The length of the Cape bar was converted using a yard-metre ratio determined in the 1860s, before the International Metre had been created. That was different from the ratio used for the British Ordnance Survey bars, determined in the 1890s from new comparisons between the Imperial yard and the International Metre itself. So the South African geodetic foot was different by a few parts per million from the English geodetic foot. To add to the difficulty, there was evidence—disputed by some—that the Imperial Yard had shortened by several parts per million since its creation.89 By the time that a re-triangulation of Great Britain was underway in the 1930s, the existence of a multiplicity of units—Clarke feet, Ordnance Survey feet, Cape geodetic feet, American feet and British feet were various names mentioned—was said to be such as to lead to ‘hopeless confusion and the vitiation of good field measures’.90 There was no single cause of the difficulty: imperfect definition, imperfect understanding of perfect definition, tautological definition by statute and by measurement, inconstancy of the older bar standards and insufficient continuity on the adoption of new standards could all be all blamed. But as Brigadier Hotine, who directed the re-triangulation, wrote: ‘...the ‘foot’ dog has so many bad names... that it cannot escape hanging, as far as future surveys are concerned. It is a question of expediency, not justice’.91 The re-triangulation of the 1930s adopted the metric norme and the metrication of British geodesy was complete, a half-century after it first adopted the metric étalon.

In America, whilst standards of measurement generally followed British practice, geodetic measurement had always been based on a metric étalon. This was an iron bar known as the Committee Metre. The bar was one of the twelve first copies of the archive metre, and had found its way to America in the hands of Ferdinand Hassler, the Swiss surveyor who became the first director of the US Coast Survey in the early 1800s.92 When survey distances were reported in feet and yards, metric measurements were converted using a fixed and long-established ratio.93 American surveying tended to place a greater emphasis on speed and economy than was customary in Europe, but their practices of calibration against their primary standards were just as rigorous.94 It followed that the International Metre was immediately welcomed as an improvement of the old Committee Metre. As soon as the copy allocated to the United States was available in 1890, it was received by the American ambassador in Paris, transported with great care to Washington and opened with much ceremony in the presence of the President.95 It was quickly put into use. The first base to be calibrated using it was measured only two years after its receipt, using cumbrous new apparatus of hitherto unseen accuracy.96 The American foot used by surveyors was, therefore, always based on a metric étalon and derived from the metre in fixed ratio, although that ratio and the length of the American foot was different from any one ever used in Britain and its Empire.97 But what matters in the context of metrological standardisation is not this multiplicity of norms; it is that by the early 20th century, geodetic measurement globally was supported by a single étalon, the International Metre.

To summarise, I have shown that the mechanisms for the distribution of the length of the International Metre, centred on the BIPM, were highly effective. The technological characteristics of the International Metre were consistent with the operations of geodetic measurement and cartographic surveying, allowing a clear continuum from étalon, via secondary geodetic bar and then invar tape, to base-line. In addition, the governing structure of the International Metre, based on geodetic precedent, brought effective maintenance of global metrological coherence. Thus the International Metre became the sole étalon of length supporting immense surveying activity around the world—not only in countries accustomed to the metric system, but also Britain and America—and therefore became the first global étalon of length. It was a textbook example of a successful exercise in standardisation from creation to use.

5. Conclusion

The origins of International Metre were made quite clear by Guillaume in his history of the BIPM, a body which he had joined
not very many years after the signing of the Metre Convention. In describing the first meeting of the Commission Internationale du Mètre in 1870, he wrote:

From the very first moment there became apparent, amongst many of the delegates, the intention to widen considerably the original programme, which comprised only the establishment of an international line-measure metre and of copies of that metre.98

The programme did indeed widen, to encompass the creation and maintenance of the metric system as a whole. Yet the historiography of the Metre Convention, based on a rhetoric of the benefits of international standardisation, has since lost sight of its very straightforward origins. I have shown that the need for a new international étalon of length in the 19th century resulted from a series of innovations that significantly improved geodetic precision and thus exposed weaknesses in the collective of étalons upon which European geodesy relied. These included the imprecision of various copies of toise standards, the degradation of the primary étalons and the technological unsuitability of those primary étalons for the new non-contact techniques of base-line measurement. It was for the community of geodesists for whom these problems first came to matter and who took action to seek improvement—with a structure designed to create and maintain international coherence in geodetic measurement, which became the model for the BIPM. The inadequacies of this historiography are, I believe, explicable. They are in part, as I have described in the introduction to this article, caused by a failure to distinguish between two very different types of standards, the norme and the étalon. That matters because, as I have shown, the Metre Convention is treated by historians as being about metric normes. That has allowed its original purpose, the creation a new metric étalon, and therefore its origins in geodesy, to be obscure.

There is, in addition, a wider historiographical explanation. As David Edgerton has argued, histories of technology, in conflating innovation and technology-in-use, distort both histories of innovation and histories of technology-in-use.99 They pay greater attention to the study of radical or discontinuous change rather than to the role of incremental improvement. They tend to be systematically biased towards study of innovations that succeed, at the expense of those which fail or have slipped from current view. They therefore give a misleading impression of the significance of some innovations, whilst others that were of equal or greater significance do not appear at all. And they present an incorrect chronology. Much this is apparent in the historiography of standards of length, made clear when proper attention is given to standards-in-use.

The conventional story has been distorted by success-bias. When historians write of the Metre Convention, the context is the unarguable success of the product of its programme as eventually widened, the now-dominant metric system. The International Metre, created by that convention, has long been superseded and therefore gets ignored. The conventional story is also innovation-centric. Its focus is the single event of the Metre Convention and the creation of the new metre, while little attention has been paid to the standard-in-use thereafter. Study of the latter emphasises the institutional significance of the BIPM as the body responsible for maintenance and distribution of the new standard, an effective guarantor of global metrological coherence. It shows the technique of invar tape base-line measurement, largely missing from the conventional history of standards of length, to have been crucial to the distribution of the length of the International Metre (an omission all the more surprising given its invention by Guillaume, the director of the BIPM). And attention to standards-in-use also offers a new perspective on the chronology of international standardisation, in that the International Metre became the global étalon of geodesy many years before any other global standardisation of measures of length, and decades before the ‘battle of the standards’ came any closer to resolution. The place of the International Metre as the first global étalon is lost, therefore, never before been properly identified.

Yet changes in the techniques of users at the frontier of precision continually disrupt what Norton Wise has called the ‘potentially infinite chain of trusted calibrations’.100 The metrological coherence that the International Metre brought was thus only temporary. Various groups of users—spectroscopists, industrialists and geodesists—soon adopted innovative electromagnetic techniques for length measurement that disrupted the web of measurement. So new standards of length were required during the 20th century to restore coherence, and the International Metre was in due course consigned to history.101 To give an example in another field, the much-studied new electrical standards of the late 19th century created metrological coherence for the community of telegraphic and electrical engineers. Yet as electrical techniques were applied to the precision measurement of a whole new range of physical quantities, incoherence with the wider web of measurement was revealed and, again, new electrical standards followed.102 Many more such episodes in the history of standards of measurement will, I am confident, be well explained by taking proper account of this search for coherence of the web of measurement.

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References


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100 See Silsbee (1949), pp.18-19. The electrical standards of the early 20th century were artefactual approximations to ‘absolute’ standards based on fundamental units. Discrepancies first became apparent in the field of thermochemistry during the 1920s.