The Reality of Precision in the 19th Century: Re-evaluating the Role of Geodesy

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SUMMARY

The creation of the metric system has been given a great deal of attention by historians. Its development and international dissemination, arguably rather more important, has received much less. The later history has, in any event, been treated in more rhetorical than scientific terms. In this paper, I review the historiography of the development of the metric system, and argue that the role of geodesy and the subject of precision have incorrectly gone missing from the 19th century. I describe one particular way in which geodesy was actually central to the history of the development of the metric system: it was the science for which the precision of existing physical standards of length first became inadequate and was therefore a catalyst for the *Convention du mètre* of 1875. And I argue that the attention given by historians to the subject of precision in the 19th century, directed very much towards industrial precision and the fundamental constants of energy physics, fails to acknowledge geodesy as *the* precision terrestrial science of the period. These observations are part of a research project aimed at putting geodesy back into the history of metrology.

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1. METROLOGY AND GEODESY

Geodesy and metrology have long been linked. The role of geodesy was clear to Charles-Édouard Guillaume (then deputy director of the *Bureau International des Poids et Mesures*) when he wrote the first paragraph of *La Convention du Mètre et le Bureau International des Poids et Mesures* in 1902: 'The classic geodetic measurements, undertaken at the initiative of the *Académie des Sciences*, made a powerful contribution to the progress of metrology'. But whilst historians link geodesy very closely to the creation of the metric system, they do so much less in relation to its development and international dissemination. I suggest that they have lost sight of Guillaume's important perspective.

In this paper, I review the historiography of the development of the metric system, and argue that historians of metrology have preferred discussion of the rhetoric of standardisation to the reality of precision. They have thus paid insufficient attention to the people and technologies that created that reality, and as a result the role of geodesy and the subject of precision have incorrectly 'gone missing'. In a new interpretation, I describe how progress in geodesy made it *the* precision terrestrial science of the 19th century. It was the science for which the precision of existing physical standards of length first became inadequate, thus being a catalyst for the signing of the *Convention du Mètre* in 1875 and the creation of new metric lengths standards.[1] This view of geodetic precision is necessarily a comparative one. I therefore review the historiography of the subject of precision in the 19th century, which is directed very much towards industrial precision and the fundamental constants of energy physics, to justify the argument. These observations are one important part of a research project aimed at putting geodesy back into the history of metrology.

1.1 The creation of the metric system

The definitive meter of French law, created in year VIII (1799), was characterised in two ways: as one ten-millionth part of the terrestrial meridian, measured from the North Pole to the Equator, and as the length of a particular bar of platinum, the *mètre des archives*. The first was a length based on nature, invariable and universal, yet incapable of direct

[1] This paper addresses the metric system. The history of the relationship between geodetic precision and British standards differs substantially. The imprecise national length standard of the 18th century was destroyed in the 1830s and not finally replaced, in technologically much improved form, until the 1850s. The major geodetic surveys of England and India, which were completed by the 1850s, therefore used specific Ordnance Survey standards.

measurement. The second was a usable artefact, capable of replication and comparison, yet not immutable. Histories of the creation of the metric system mirror, to a large extent, this contrast of the intangible and the tangible. We therefore see discussion, on the one hand, in philosophical and cultural terms and, on the other, in practical ones. Philosophically, historians have often addressed the correspondence between 'natural' metric measure and Enlightenment rationality, as well as the resolution of the competing natural philosophies of the 17th and 18th centuries. Examples include Favre's *Les Origines du Système Métrique* (1931), which explained how the philosophical importance of universal measure, and the practical importance of invariable measure, could only be achieved by trusting nature itself to provide the standard. The dispute between natural philosophies is summarised by Terrall in ‘Representing the Earth’s Shape: The Polemics surrounding Maupertuis’s Expedition to Lapland’ (1992). It was initiated by the different determinations of the flattening of the earth derived from Newton’s universal gravitation and Huygen’s plenum mechanics; and it was exacerbated by French attempts to explain by means of Cartesian vortices the prolate world that Cassini had (incorrectly) measured in the early 18th century. Cultural interpretations, arguing that systems of metrology are deeply embedded in society, started with Kula's *Measures and Men* (first published in Polish in 1970) and have been much followed by later authors. The issue of authority of metric standards has been addressed, too. Crosland's 'The Congress on Definitive Metric Standards, 1798-1799: The First International Scientific Conference?' (1969) explains how a number of foreign scientific representatives were assembled in Paris in 1798 to assist in the final definition of the meter. This, he argued, was a way in which France sought to enhance the validity and internationalise the acceptance of her new system.

In terms of the practical creation of the meter there is also an extensive literature. A triangulation from North to South of France, undertaken between 1792 and 1798, was the basis of its definition. It was described by one of the participants, Delambre, in his three-volume *Base du Système Métrique Décimal* (1806-1810), a work which is an exceptionally comprehensive record of the chronology, locations, apparatus, techniques, measurements and mathematics of the project. Later accounts, both French and Anglo-Saxon, draw heavily on Delambre: Morin's 'Notice Historique sur le Système Métrique' (1870), Bigourdan's *Le Système Métrique des Poids et Mesures* (1901) and Hallock and Wade's *Outlines of the Evolution of Weights and Measures and the Metric System* (1906) all fall in to this category. They are accounts which are shorter and more readable than Delambre, bringing the story up to date, but are not additive in any material respect in relation to the creation of the system. And the recent bicentenary of the creation of the metric system has produced two more popular books: Guedj's *Le mètre du monde* (2000) and Alder's *The Measure of All Things* (2002) do not ignore the technical detail, but provide a more contextual view of the practical difficulties involved in a triangulation of France during the Revolution, the strained personal relations between the two surveyors, Méchain and Delambre, and the way in which the former struggled to cope with and explain inconsistencies in the results of his observations and computations.

1.2 The Rhetoric of Standardisation

Yet, when it comes to describing the later development of the metric system, it is the history of the intangible - the culture, rhetoric and politics of standardisation - which dominates. The subject of precision, the role of geodesy and even the *mètre des archives* itself largely fade from historical view for over 60 years. That view can be summarised as follows.

The metric system was initially largely a failure. On its legal imposition in France in 1793 (at this stage on the basis of a provisional meter) it was little adopted; from 1800 the old names of units were permitted to be used again, and a revised *système usuelle*, much more in harmony with the units of the *ancien regime*, endured from 1812 to 1840. Reasons that have been given for the initial failure include: politically, the instability in France in the early 19th century and Napoleon's lack of enthusiasm for metric measure; practically, a failure to construct and distribute enough secondary standards and conversion tables; and culturally, the attachment to familiar measures and divisions thereof and the consequent opposition to change. Whilst the subject is addressed in the more factual histories of the metric system noted above, there are more recent cultural interpretations. Alder's 'A Revolution to Measure: the Political Economy of the Metric System in France' (1995) concentrates on the contemporary perception of the metric system as being part of a state-imposed tyranny of uniformity, representing a return in a different form to feudal metrological subjugation and therefore to be rejected ; Heilbron's 'The Measure of Enlightenment' (1990) explores the ways in which both old and new measures co-existed in the first decades of the 19th century and how the acceptance of the metric system was related to the education of the population, inevitably slow, in decimal arithmetic.

It was the later 19th century that saw the most rapid international propagation of the metric system. Historians generally identify a renewal of interest in standardisation with the Great Exhibition of 1851, at which the inconvenience of widespread metrological diversity was juxtaposed with a possible solution, a set of metric standards exhibited by the *Conservatoire des Arts et Métiers.* Then the frequent international gatherings of the period - such as the International Statistical Congress of 1853 in Brussels, the *Exposition Universelle* of 1855 in Paris, the International Statistical Congress of 1860 in London, the International Exhibition of 1862 in London, the International Postal Congress of 1863 in Berlin, the International Statistical Congress in Florence, the *Exposition Universelle* in Paris and the International Geodetic Association meeting in Berlin (all in 1867) - produced a powerful rhetoric in favour of standardisation and metrication. That rhetoric repeatedly contrasted the inconvenience of metrological diversity with the political, social and commercial advantages of universal adoption of the metric system, and was reinforced by The International Association for Obtaining a Uniform Decimal System of Measures, Weights and Coins, a pro-metric lobby group which by 1859 had members from fifteen countries.

The above rhetoric, it is argued, was combined with commercial and political circumstances which created an environment favourable to metrological reform. These included the expansion of the German *Zollverein* (customs union) in the 1850s; a free-trade treaty between England and France in 1860, the unification of Italy in 1861, the end of the American Civil War in 1865, and German unification in 1871, which together created a great momentum behind the metric movement. Even the United Kingdom and the United States legalised the use of the metric system in the 1860s, albeit on a permissive basis. By the early 1870s, France, Switzerland, the Netherlands, Italy, Spain, Portugal and Germany, together with a number of other European and Latin American countries, had adopted the metric system. The signing of the *Convention du Mètre* by nineteen nations in 1875 (establishing the *Bureau International des Poids et Mesures* for the creation and maintenance of a new physical standard to replace the *mètre des archives*) is then portrayed as of as much symbolic as practical importance: a natural result of this momentum of metric progress and an event which then contributed to its continuation.

This international propagation of the metric system has received less attention from historians than its creation. Cox's 'The Metric System: A quarter century of acceptance 1851-1876' (1958) is the most complete exposition of the argument set out above. The earlier accounts by Morin, Bigourdan and Hallock and Wade follow the rhetorical approach that Cox then expanded, although he dismissed them as 'typically brief and pedestrian'.[2] He also correctly identified that these earlier accounts are mainly 'rehashes' of the remarks made by the British metric advocate Leoni Levi in his testimony before the Select Committee on Weights and Measures in 1862. Much of the argument can actually be seen earlier in the 'Narrative of the Origin and Formation of the International Association for Obtaining a Uniform Decimal System of Measures, Weights and Coins' (1856), by Yates. And this style of account is also reflected in more recent literature; Alder, for example, writes again of the importance of the international conferences and the 'Utopian dream' of international metrication.[3] A final example of the inadequacies of the literature is Guedj's *Le mètre du monde* (2000): notwithstanding its titular reference to the world, this is almost entirely a history of the meter and metric system in France up to 1806. The next two centuries and the international propagation of the system are dealt with in a brief and superficial epilogue.

1.3 The Missing Role of Geodesy and Precision

Whilst I believe that this history is inadequate in a number of ways, the one that I wish to address in this paper is the absence of any mention of precision. The *Convention du Mètre* was as much a technical as a diplomatic agreement. The technical and scientific issues debated, sometimes with acrimony, over the years from the mid 1860s to the mid 1870s were diverse in nature and importance. There was disagreement whether (as was the German preference) the meter should be re-determined by new measurement of the length of the meridian or whether (as the French insisted) the *mètre des archives* was to be taken precisely as it was; whether the new meter standard should be end-measure or line-measure, different nations having different practices and preferences; of what material the new standard should

[2] Cox (1958), p. 360.
[3] Alder (2002), p. 350.

be manufactured for best stability; what should be the profile of the standard bar, and how should it be supported; at what temperature the standard should be measured and how that temperature was to be determined; and which technologies of comparator were most appropriate.

The product - the new international prototype meter - was a line-standard of improved materials and profile, created with more precise comparator technology, with an institutional infrastructure to give it authority and ensure its effective replication and dissemination. The essentially arbitrary distance between two lines on this bar could be reproduced with a precision of the order of one part in 10 million.[4] It was a very important artefact. Aside from underpinning legal metrology in the signatory countries to the *Convention du mètre*, it was the metrological basis for scientific precision globally during the decades of scientific progress that followed. In addition, it was the basis for industrial precision everywhere outside the Anglo-Saxon world, which itself found it a more precise foundation than the yard from the early 20th century onwards.[5] And it was the need for geodetic precision that was a significant catalyst for its creation.

2. GEODETIC PRECISION

Baseline measurement is at the core of geodetic precision. My estimate is that precision of geodetic baseline measurement increased by about two orders of magnitude between the mid 18th and mid 19th centuries. At the beginning of this period, the practice of baseline measurement was essentially that of counting wooden rods laid end-to-end on the ground. Errors in repeatability of a measurement were of the order of 100 parts per million. This was, for example, the sort of result achieved by Cassini de Thury in his measurement of a number of bases in France in the 1740s. A century later there had been a huge increase in the scale of resources devoted to geodetic activity, and technology and techniques had been transformed: metal rods, constructed by scientific instrument makers, were used instead of wood; alignment and levelling were carried out with the utmost care; temperature measurement in the field and calibration against reliable physical length standards was given great attention; and formal error analysis, using new techniques of probability calculus, allowed different types of possible error to be analysed and combined. By the mid 19th century, precision was of the order of 1 part per million. That increase in precision was enough to expose the inadequacies of the collection of length standards, and it was the geodesists who were the user group for whom existing standards first became inadequate.
A base measured at Madrilejos, near Madrid, in the 1850s demonstrated the state of the art. The reasons for this endeavour in precision geodesy were partly domestic, as the foundation of the first large scale topographical map of Spain. But they were also partly international, because France saw the opportunity to join the geodetic and cartographic work underway in

4 Benoit (1900), p. 65.
5 American units of length were, in principle, based on the meter from 1893. In practice, the inch came to be defined for industrial purposes in America and Britain on the basis of the meter during the early 20th century, and the relationship was formalised by standards associations from the 1930s.

Algeria to the French grid, and to combine the English, French and Spanish arcs to create a single long arc. The apparatus used in Spain was built by Brunner in Paris. The principle of its operation was somewhat different to most previous base apparatus in that it used a single four meter rod, moved forward sequentially, located at each end by a single micrometric microscope. It was, in effect, a complex collection of scientific instruments. The main rule was of platinum, forming a bi-metallic thermometer with one of copper, all supported by an iron bar. It was placed on two small wood tripods via metal supports which allowed adjustment by screw in three dimensions. At each end were placed larger wood tripods, which supported adjustable microscope stands, the latter also being used to hold the various telescopes and sights used for alignment and establishment of ground marks. The apparatus was slow and cumbersome. By fine adjustment of rod and microscope, the microscopes at each end of the rod had to be brought into coincidence with the engraved length marks, before the rod was moved forward to the next position along the base. A total of 4 microscope tripods were used, moved sequentially forward under cover of a large wooden shelter, each requiring precise positioning, alignment and levelling. Similar care was needed with the rod tripods and supports. Four officers and a troop of artillery were needed; twelve soldiers alone to move around the wooden shelter. Having decided on a long base of over 14km, divided into 5 sections, measurement took 78 days. The decision to create a triangulation network to cross-check the measurement of the individual sections added yet further time and complexity.[6]

The apparatus was not just slow in the field. It took two years to build, and a description of the equipment and the work required in the laboratory to calibrate it extends to about 300 pages.[7] Ibáñez gave credit not only to the makers, Brunner *père et fils*, but to a long list of distinguished scientific collaborators. The precautions taken were exceptional. For example, in order to ensure stability of the comparator apparatus used in Paris, foundations were excavated down to rock and stone pillars constructed thereupon; the mercury thermometers were marked not with divisions of equal length but with scales showing parts of equal capacity, to compensate for any minute deviation from true cylindrical form, and their calibration was carried out by Regnault, renowned for his experimental work in thermometry and calorimetry; experiments to establish dilation of the platinum and copper components of the rules were carried out in oil baths to ensure consistency of temperature and repeated 480 times in total. Finally, the Brunner bar was calibrated against a fundamental standard, the Borda module. This was the actual standard rod, named after its maker, used by Méchain and Delambre in the measure of the meridian that determined the meter. It was produced, with much formality and ceremony, and compared 120 times against the Brunner bar.

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6 See Ibáñez (1863), Chapter II, for a description of the use of the apparatus. Hirsch (1880) describes in more detail the complex choreography of the process, which when used in Switzerland needed a chief, 8 operators, 10 helpers and 30 to 40 more men to deal with transport, marks and signals, helped by an *ajusteur-mécanicien* to deal with maintenance and small repairs

7 Ibáñez (1860).

2.1 The Foundations of Precision

Ibáñez concluded that his base measure had a probable error of 2.5mm in its 14 km, or about one fifth of a part per million. He was trained as a military engineer, not as a mathematician, and his analysis of error was not the most sophisticated. Indeed, in one respect I think it is quite wrong. [8] But no-one quibbled at the time. A report to the *Académie* couldn't have been more fulsome, suggesting that the precision now reached represented a '*nec plus ultra* that it isn't possible, that it wouldn't even be useful, to exceed'.[9] But it is essential to be clear about the foundation of the claim. Brunner had gone back as far as he could: the Borda module was the geodetic measure from which the meter had been created. It was *exactly* twice the length of the *toise de Pérou* (the artefact used in the French arc measurement of the 1730s) by definition, and that is how Brunner treated it. But he had to cope with two significant difficulties. The first was that the Borda module was used in end-measure, as had been the practice at the end of the 18th century; his comparator apparatus, in contrast, used microscopes and line measure. Accordingly small platinum end-pieces, their faces 'polished with the greatest care' and engraved with lines, were used to enable the comparisons and to bridge the gap between toise and meter standards. The probable errors arising from measurement of the end pieces could, in a fashion, be included in the computation of overall probable error. The second was that the ends of the Borda module were now imperfect. Ibáñez noted:

> '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...'[10]

All Ibáñez could do, however, was record. This problem was beyond quantification. Yet if the Borda module were imperfect, the metric system had two additional and competing foundations, both also causing difficulty. The first was the meter itself, which whilst defined as a particular fraction of a toise was also represented by the *mètre des archives*. [11] It had been America that had been the first major user of the meter for geodetic work. The US Coast Survey's length standard was its 'committee meter', an iron copy meter created in Paris around 1800. In 1867 the increasing precision of American geodesy demanded that it be re-calibrated and it was sent to Paris for comparison with the *mètre des archives*. At that time a thorough examination of the faces of the American standard showed that 'they both appear to have been slightly oxidised'.[12] Much worse were flaws in *mètre des archives* itself: although France always defended its integrity, the reality was that its condition was suspect. Clearly visible,

8 Ibáñez (1863), p. 117. He computed a probable error for the middle of the five sections measured, and extended that to the whole base using a least-squares formulation. That is incorrect because part of the error, that due to calibration against the standard rod, is systematic and therefore simply additive.

9 Faye (1863), p. 374.

10 Ibáñez (1860), p.139.

11 The meter was defined as 443.296 *lignes* of the *toise de Pérou* (itself comprising 864 *lignes*)

12 Barnard (1867), p. 134.

the repeated use of comparators had left depressions up to 1/100th of a millimeter deep in the ends, a potential error of 10 parts per million.[13]

The second competing foundation was the *toise de Pérou* itself. The toise was proving to have great longevity as a unit, being the standard for most European geodetic work until the later 19th century. It was, after all, on the basis of the *toise de Pérou* that the Borda module and the *mètre des archives* were defined. Yet the *toise de Pérou* itself was not being used for calibration any more – indeed, its history, state of preservation and even continued existence in the 19th century are the subject of much uncertainty.[14] It was actually represented by a series of copies of variable precision. A typical example was that used by Struve in the measurement of baselines for his Russian arc. He relied on a certificate of 1821 by Arago, the French instrument maker, that 'his' toise was exactly equal to the *toise de Pérou*. But the comparator that had been used could only detect differences of 1/200th of a millimetre, or about 2.5 parts per million.[15]

2.2 The Limits of Precision

The evidence is therefore clear that by the 1860s the increasing precision of the practice of baseline measurement was such that the claims to precision were undermined by the uncertainties in the underlying standards and their copies. The US Coast Survey was quite explicit:

> 'Whatever improvements may still be needed to be made in base measuring apparatus, this important point has been reached: that bases are measured at once with an accuracy ... of the same order with the comparisons between the actual standards and their copies used in measurements.'[16]

In other words, the foundations of the entire enterprise of precision geodesy were becoming inadequate. The potential problems were manifold: ambiguity through the existence of three underlying physical standards within or related to the metric system, the *toise de Pérou*, the Borda module and the *mètre des archives*; uncertainty, through damage to the ends of fundamental standards over the years and the possibility of change at the molecular level; variety, in an unstructured collection of subsidiary standards of various lengths and materials, and impracticality, because line-measure and end-measure standards co-existed and had to be compared. It was becoming nonsensical to claim precision in baseline measurement of fractions of a part per million, when the length standards in which they were quoted were uncertain to several parts per million. As a result, the geodesists were a catalyst for and

[13] Bigourdan (1901), p. 284.
[14] See Marquet (1988) for a discussion.
[15] Struve (1857), pp. 36 and 74.
[16] Hunt (1854), p. 108.

played a major role in the *Convention du Mètre* of 1875, which led to the creation of the new international prototype meter.[17]

3. 19TH CENTURY PRECISION IN OTHER FIELDS

In a wide body of literature, it is generally argued that the subject of industrial and scientific precision rose in importance in the 18th century. Industrially, the introduction of interchangeable parts in military and, later, civilian products together with the gradual increase in mechanisation of production were important. Scientifically, the energy physics of the 19th century, underpinned by precise experimental work in electricity and thermodynamics, required precision. A conventional assessment of the position for the second half of the 19th century, by Iwan Rhys Morus, is to emphasise manufacturing and modern physics:

> 'Factories depended on finely measured, identical and interchangeable components just as laboratory physics depended on reliable, robust and universal constants.'[18]

That statement is wrong in respect of both industry and laboratory. Morus does not use the words precision or accuracy, and paints an incomplete picture.

3.1 Industrial Precision

Morus uses the terms 'finely measured' and 'identical and interchangeable', but these are not necessarily the same thing. To the extent that parts were being made interchangeable, this was often a result of the use of gauges rather than direct reference to a national or international length standard. The distinction is not always clearly made in the literature.

In a wide historiography, authors usually identify the first use of interchangeable manufacture on an industrial scale with the production of armaments in pre-revolutionary France, initially with the manufacture of artillery and later with the production of firearms. It is here that the important features of interchangeable manufacture - mechanisation, division of labour and the need for dimensional precision - clearly emerge. In the early 19th century the French technologies found their way to America and were adopted by Eli Whitney in the manufacture of muskets. There has been debate as to what extent Whitney's factory production was interchangeable either in principle or in practice. More recent scholarship therefore puts much greater weight on the later contribution of the Federal armories at Springfield and Harpers Ferry, and of the private American armories, in developing 'armory practice' in the manufacture of small-arms. This involved the extensive use of pattern weapons together with sets of custom-made jigs and gauges in order to facilitate interchangeability, rather than reliance on dimensional accuracy. The way in which the techniques of armaments

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[17] The mechanisms through which this occurred, including that of the *Mitteleuropäische Gradmessung*, will be addressed in later research.

[18] Morus (2005), p. 227.

manufacture extended into non-military fields, such as sewing machine and bicycle manufacture, during the course of the 19th century, is covered by Hounshell in 'From the American System to Mass Production, 1800-1932'. But it is clear from this work that even proper interchangeability, let alone dimensional precision, was far from achieved in industry even by the later 19th century, when extensive hand-finishing continued to be common. The historiography of industrial precision in 19th century Britain is rather different, in that it tends to be told through the achievements of individuals. The emphasis is on the renowned British engineers, especially Maudslay, whose machine tools are said to have revolutionised mechanical engineering technique, and Whitworth, whose creation of true plane surfaces, manufacture of precise lead screws and promotion of standardisation and decimalisation are much repeated. The latter's mechanical achievements were exemplified by the 'Millionth Measuring Machine' shown at the Great Exhibition of 1851, which claimed to be able to detect a change in length of one millionth of an inch, but it was not very clear exactly what inch it was referring to. It was Whitworth's system of standard length gauges which underpinned his successes in standardization and precision, yet when these were first created in the 1830s, they were based on an improvised yard standard derived from the average of two commercial instrument makers' scales. Even thirty years later, there wasn't just one standard inch. The 1862 Report of the Select Committee on Weights and Measures gives some clues that variability in length standards was common. A Superintendent of the Royal Gun Factory at Woolwich, discussing precision in the manufacture of guns, explained how he obtained his standard:

> 'We have not gone to the fountain head for that. We consulted a good many of the gauges made by Mr. Whitworth. They are about the most correct of anything that has been attained in the country. I went also to one of the best houses in London for making measuring instruments, Messrs. Troughton and Simms; and having had from them some half dozen sets, took the average of all, and made an inch that way. After a great deal of trouble, I obtained what I thought was the inch. It is very difficult to say what a real inch is...'[19]

That British industry relied on gauges rather than dimensional precision for many more years was confirmed by Richard Glazebrook, in a discussion of 'Metrology in the Industries' in 1919. We read, for example, his explanation that inconsistency in length standards caused problems in arms manufacture during the Boer War, and again during the first World War. Addressing difficulties in the manufacture of munitions in 1915:

> '...the real standard was not the drawing or the figures - the dimensions - indicated in the drawing; in too many cases it was a set of gauges in some government department, and how near those gauges came to their nominal sizes was not known, with the result that the work first made was not interchangeable...'[20]

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19 Report from the Select Committee on Weights and Measures (1862), p. 46.
20 'Metrology in the Industries', p. 4.

The importance of an explicit linking of industrial precision to standards of length was first recognised in the United States in the late 1870s. From that time, increasing use was made of products defined by external standards, such as wires and sheet steel sold at standard gauges or screws made with standard threads. It was their growing use that stimulated real changes in metrological practice, including the development of measuring instruments of improved precision and suitable for factory use such as micrometers. These technologies of measurement could only be effective once they were explicitly linked to national physical standards of length. Pratt and Whitney were one company at the forefront of the work, and for them the challenge was described thus:

> 'Like Diogenes with his lamp, in search of an honest man, this company went to and fro in the land in search of a true inch, a true foot, or a true yard. They procured from different sources what they supposed were the most reliable standards of measurement, and found that none agreed. They had the same standards measured by what were considered the most reliable measuring machines and instruments in the country, and found that no two of these would measure the same standard alike.'[21]

Pratt and Whitney built a new comparator, which was calibrated by transfers from the copy standard yard in Washington and the *mètre des archives* in Paris, to provide an improved link between industrial measurement and the fundamental standards of length. But a more robust linkage required a new technology. This was provided by so-called Johansson gauges, a set of precision lapped gauges of a variety of thicknesses used additively to build up a required length, created in the early years of the 20th century. They did not come into wide use until during and after the first World War, promoted in particular by the manufacture of munitions and Johansson's employment at Ford's Dearborn plant. In summary, the evidence is that industrial precision in the mid and late 19th century had a somewhat tenuous linkage to fundamental length standards, quite unlike geodetic precision.

3.2 Laboratory Precision

The idea of the 'reliable, robust and universal constant' is an old one in the history of measurement, reflected both in the oft-proposed 'seconds pendulum' and in the determination of the meter by meridian measure. It took on new importance with the energy physics of the 19th century, through the basic electrostatic and electromagnetic constants and their ratio - the speed of light. In 1960 the *mètre des archives* was finally superseded and length finally came to be defined absolutely, first by the wavelength of a particular frequency of light and then via the speed of light. But indirect and direct determinations of the wavelength and speed of light were well underway a century before.

The use of the wavelength of light to measure length was practical by the 1860s, when Fizeau had used interference phenomena to determine expansion coefficients, but such techniques were not practical for the meter standard as a whole. Real progress was not made until

[21] Bond (1887), p. 67.

the1890s, based on the then well established American capabilities in precision engineering and Michelson's development of the interferometer. He 'measured' the *mètre des archives* in terms of the wavelength of cadmium light. The process, involving repetition with small intermediate standards, was exceptionally difficult and took a year to complete.[22] This was, however, experimental rather than definitional metrology. Much further work was needed over decades to develop improved interferometers and to choose the optimum isotope for light emission. If the nature of the successor technology to the physical length standard was clear, that succession was something for the 20th rather than 19th century. As Benoit wrote in 1900, ‘I am persuaded that our descendants will do better than us, but in all probability they will do it differently’.[23]

It is the speed of light which is currently used as the basis of our definition of the meter. But again, notwithstanding the fact the first successful terrestrial measure was made in 1849, precision in the 19th century was limited to orders of magnitude less than that of geodetic length measurement. The primacy of the latter well in to the 20th century is evidenced by Michelson's 'Measurement of the Velocity of Light between Mount Wilson and Mount San Antonio' (1927). In what was intended as the most accurate determination yet of the speed of light, a 35km distance between two peaks was measured by the US Coast and Geodetic Survey using traditional baseline and triangulation methods. They claimed that 'the length of this line has been determined with greater accuracy than that of any other line of triangulation in this or any other country', with a probable error of less than 2 parts per million.[24] Michelson's elaborate experimental procedure, which used pneumatically powered rotating mirrors and stroboscopic timing, showed differences between the highest and lowest determinations of the speed of light of a hundred times that.[25]

The indirect determination of the speed of light by the related electromagnetic constants is more multi-faceted. The major part of the history is reflected in the extensive literature on standardisation of electrical units, which is summarised in my 'The International Electrical Units – A failure in standardisation?' (2007). This type of precision in the 19th century was also orders of magnitude worse than in geodetic length measurement: the original BA resistance unit of the 1850s was 2 per cent adrift from absolute measure, the difference being in effect an error in the speed of light. A flavour of the nature of experimental precision of the 1860s is given by this description of the measurement of the length of the wire in a spinning coil apparatus used to determine absolute measures of resistance:

> ' At the conclusion of the experiments, the wire to be measured was uncoiled in the Museum at King's College and lay in awkward bends on the planked floor ... a joint between the planks was found where the opening was just sufficient to hold the wire

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22 Michelson (1903), p.104.
23 Benoit (1900), p.77, my translation.
24 Bowie (1927), p. 16.
25 Michelson (1927), p. 12.

> when pushed in this little groove. Held in this way, the wire when measured was quite straight...'[26]

This rough and ready approach is in stark contrast to the attention to detail demonstrated by Ibáñez at about the same time: he took four years of preparation and measurement to determine a baseline with a probable error of less than one part in one million. Even decades later, the international electrical units (which lasted from 1893 to1948) were adrift from absolute measure by a few hundred parts per million. I think it is quite clear that the constants of physics were not, even in the early 20th century, reliable, robust, or universal. Their values were still in a comparatively early stage of exploration, and the precision with which they could be determined was very materially less than the standards of length through which they were quantified.

4. CONCLUSION

To summarise, I believe that the existing historiography of the development of the metric system places undue emphasis on rhetoric and politics. The reality was that there was an important user group, the geodesists, at the forefront of improvements in precision measurement. It was only for geodesists that precision of the order of one part per million or better was important by the mid 19th century. It was thus for them, and not industrialists or physicists, for whom the inadequacies of existing length standards first became apparent. The requirements of geodesy were therefore an important catalyst for the signature of the *Convention du mètre* and the creation of the new international prototype meter, an artefact of considerable metrological importance. That conclusion is one important aspect of my work of putting geodesy back into the history of 19th century metrology. It will be expanded in further research, which will address the influence of geodesy on standardisation of units of length, and the institutional mechanisms through which geodesy informed metrology.

[26] BAAS Reports of the Electrical Standards Committee (1913), p. 73.

BIOGRAPHICAL NOTES

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