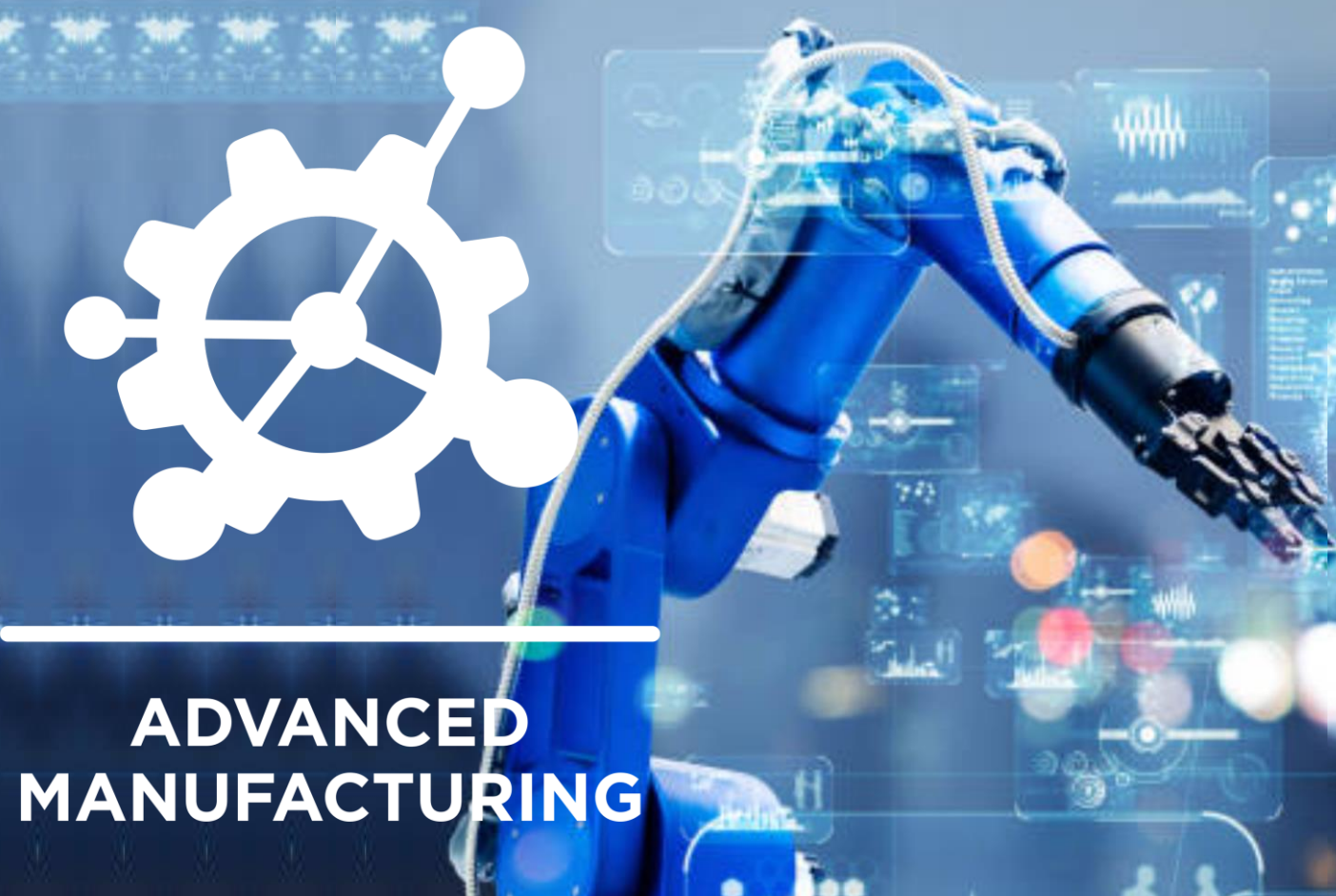




Advanced manufacturing and metrology – a historical liaison



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INTRODUCTION

Advances in manufacturing and progress in metrology have historically been strongly interlinked. Based on well-chosen historical examples we will demonstrate in this contribution how progress in manufacturing technologies have enabled progress in metrology, the science of measurements and its applications [1], and vice versa.

ANCIENT CULTURES

In ancient Egypt, for example, the construction of the pyramids would not have been possible without the high level of engineering and measurement knowledge required to establish a system of mass production of stone blocks, with high surface quality, each measured using stable references traceable back to the **Egyptian royal cubit**. Reliable length, angle and area measurements also were important to cope with the regular floodings of the river Nile to plan the harvesting of fertile plains to feed the people.



Fig. 1: Copy of an Egyptian royal cubit, 3000 BC.

The Egyptian royal cubit was made from stone and wooden copies used for manufacturing control were regularly compared to the master. By following this **traceability** process remarkable construction and manufacturing accuracy could be obtained: Square base: < 4 cm side uniformity over 230 m; < 1' squareness; Base orientation: < 2.8' north-south; < 2 cm from horizontal.



Fig 2: Cheops pyramid; 2500 BC

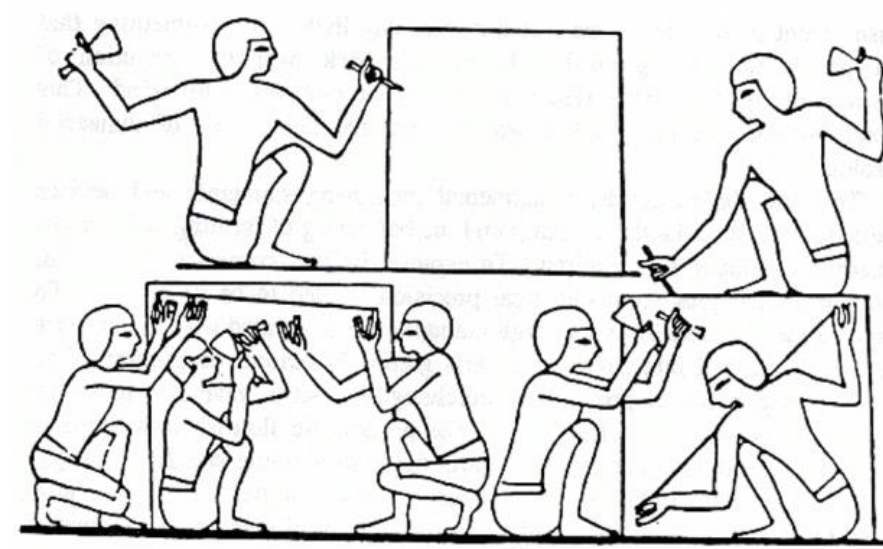


Fig. 3: One of the earliest records of geometrical measurement: Egyptian wall painting in the tomb of Rekh-mi-re' at Thebes built 1440 BC [2].

MEDIEVAL AND PRE-INDUSTRIALISATION TIMES

Up to the end of the 18th century, length standards were based on graduated scales, usually deduced from parts of human bodies (inch (FR: pouce, DE: Zoll, IT: pollice), cubit (aune, Elle, cubito), foot (pied, Fuß, piede), fathom (toise, Klafter) of leading persons of the political systems (emperor, king, sovereign). In the pre-industrialised era, the large variety of different national, regional or **local length standards** resulted in **barriers to trade** because producers and merchants had to show that they complied with the local length standards when selling their goods. Usually, the local standard or a copy of it was mounted close to the market place for direct reference, see Fig. 4.



Fig. 4: Local length standard (Braunschweiger Elle) to be used on the market place close to the Old Town Hall in the city of Braunschweig in Germany.

BEGINNING OF INDUSTRIALISATION AND SERIAL/MASS PRODUCTION

The concept of **interchangeability of parts** was developed first in France by Honoré Blanc (1785) and then adopted in the USA by Eli Whitney (1798) for mass production of muskets. Whitney had been ordered to manufacturing 10.000 muskets. The amount of rework was reduced by inspection by gauges and measuring instruments. Interchangeability was also a tactic advantage, as the muskets could be repaired locally. Driven by the needs emerging from early industrialisation and interchangeability of parts at the end of the 18th century, the need for a more precise and robust length standard was identified, to be widely adopted in the industrialised nations. Referring to the manufacturing process of the Ford Model T – a famous example of mass production – it was noted [3]: ‚The key in mass production was not – as many people then and now believe – the moving, or continuous, **assembly line**. Rather, it was the complete and consistent **interchangeability of parts** and the simplicity of attaching them to each other. These were the manufacturing innovations that made the assembly line possible.‘ To achieve interchangeability, Ford insisted that the **same gauging system** be used for every part all the way through the entire manufacturing process.



Fig. 5: Model 1795 Musket.

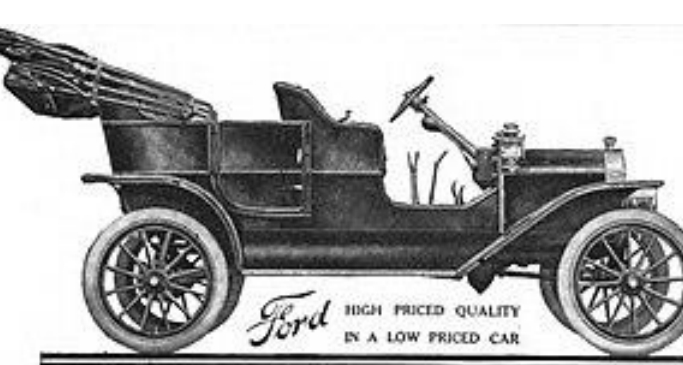


Fig. 6: Ford Model T, 1908; Advertisement.

MÈTRE DES ARCHIVES, 1799

In parallel to the development of industrial manufacturing, the metric system was starting to be developed in France with the **metre** being defined as 1/10,000,000 of the distance from the North Pole to the equator along the Paris meridian. Méchain and Delambre measured its portion between Dunkirk and Barcelona by **trilateration** in their measurement campaign 1792–1798 [4]. The introduction of the **Mètre des Archives**, a length bar made of solid platinum, as the length unit in France in 1799 was one of the important drivers of the establishment of the **Metre Convention in 1875**.

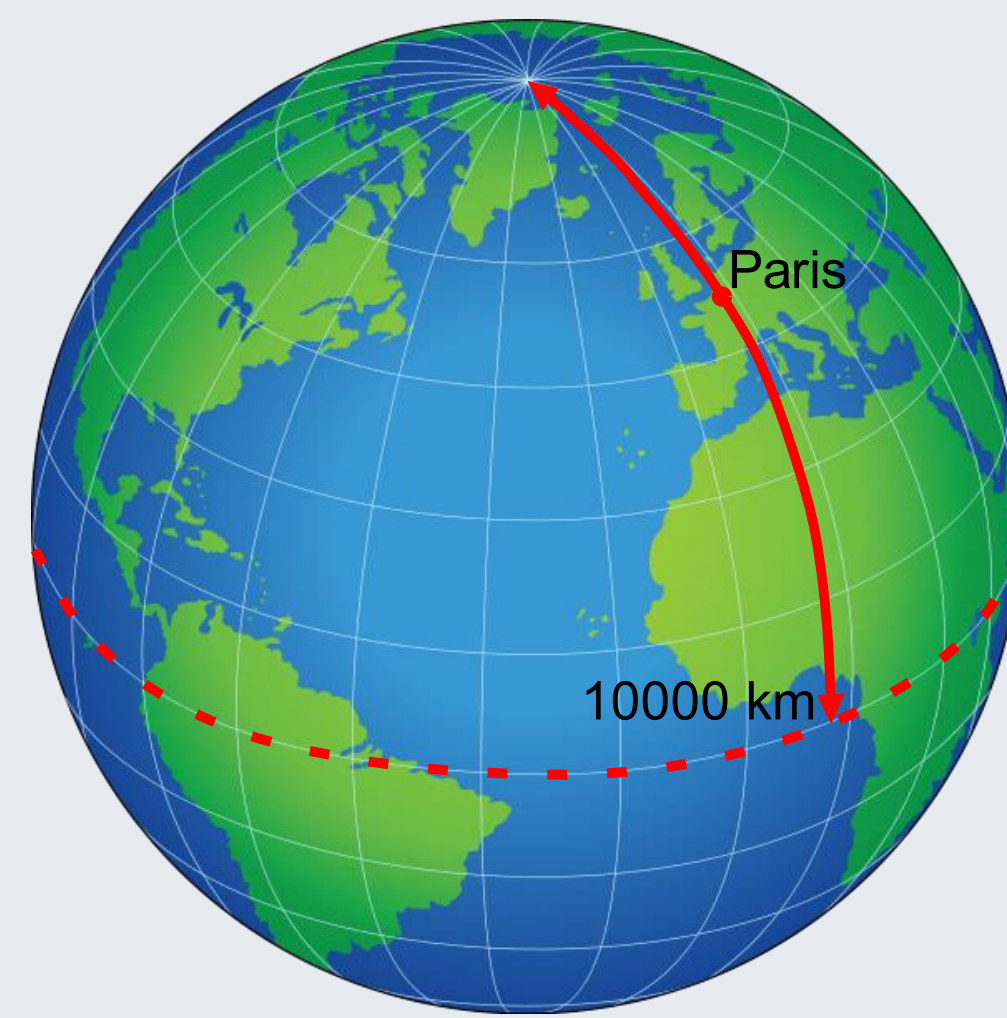


Fig. 7: Metre definition as one ten-millionth of the Earth quadrant, the distance from the North Pole to the Equator, measured along a meridian through Paris. [Wikipedia]

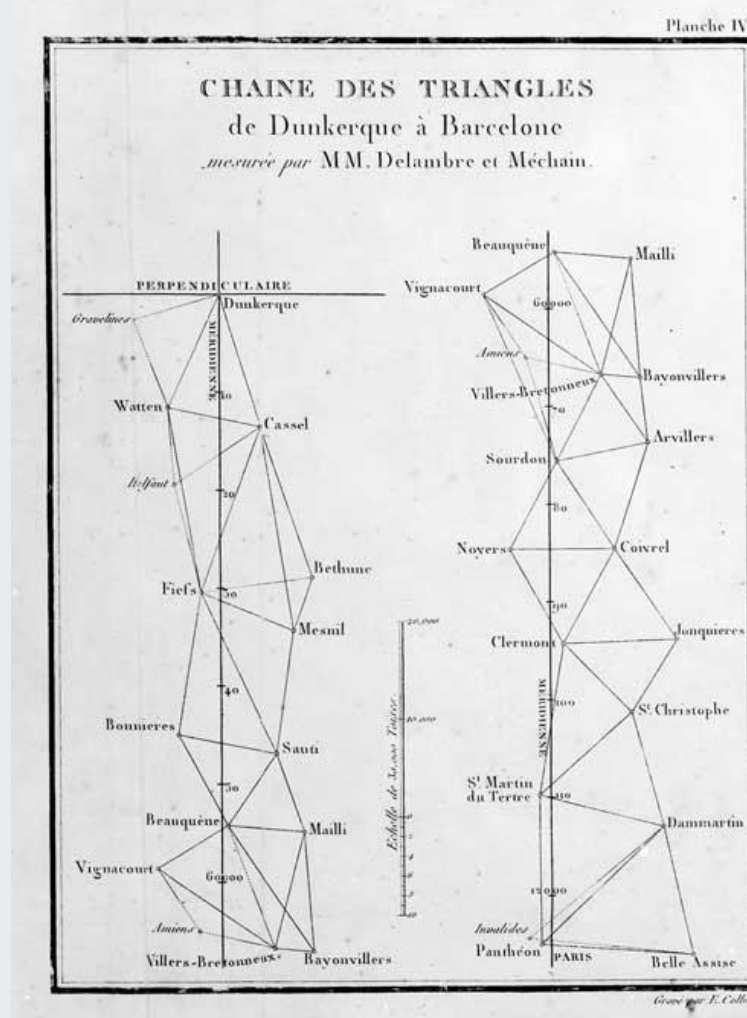


Fig. 8: Part of triangulation map between Dunkirk and Barcelona used for the definition of the Mètre des Archives [5].



Fig. 9: The Mètre des Archives [6].

INTERNATIONAL METRE PROTOTYPE, 1889

At the first General Conference on Weights and Measures in 1889 the Metre Convention established the **International Metre Prototype** as the distance between two lines on an X-shaped cross section bar composed of an alloy of 90 % platinum and 10 % iridium, measured at the melting point of ice. The alloy and casting process were developed by Johnson Matthey in London in cooperation with the International Bureau of Weights and Measures (BIPM). **Thirty numbered copies** were produced and calibrated against the prototype for use as national standards.



Fig. 10: Copy #23 of international metre prototype [courtesy PTB].

THERMALLY STABLE REFERENCE MATERIALS

The development of **stable materials** with low thermal expansion properties has always been of interest for metrology as well as for high precision manufacturing. Examples are the invention of **Invar** (nickel–iron alloy FeNi36) by **Charles Édouard Guillaume** in 1895, and the development of ultra-low expansion glass ceramic materials, which are optimized and used in metrology and manufacturing devices still today. Guillaume was **Director of the BIPM** from 1915 to 1936 and **Nobel laureate in 1920**.



Fig. 11: Charles Édouard Guillaume [Wikipedia].

GAUGE BLOCKS (1911) AND THE INTERNATIONAL INCH (1959)

Gauge blocks were invented by Carl Edvard Johansson in Sweden in 1901 as a robust length standard to connect laboratories to manufacturing [7]. While doing, he effectively set two important conventional values still in use today: he decided in 1911 to manufacture gauge blocks in inches at the rate of 25.4 mm/inch (adopted as the **international inch in 1959**) and to do so at the **reference temperature of 20 ° C** (CIPM resolution, 1931; today ISO 1:2022).



Fig. 12: Metric gauge block set, 112 pieces [Wikipedia].

WAVELENGTH DEFINITION OF SI METRE, 1960

Shortly before the first CGPM, first **interferometric measurements** were performed by Michelson and Morley. It took, however, until 1960 until the scale-based definition of the length unit was replaced by a **wavelength-based definition** at the 11th CGPM: the orange line of the **krypton-86 isotope** ($\lambda \approx 606$ nm) was taken as the new vacuum-wavelength standard. The decision was made based on intensive investigations of stable gas discharge light sources with long coherence lengths and allowed improvements in interferometric accuracy [8].

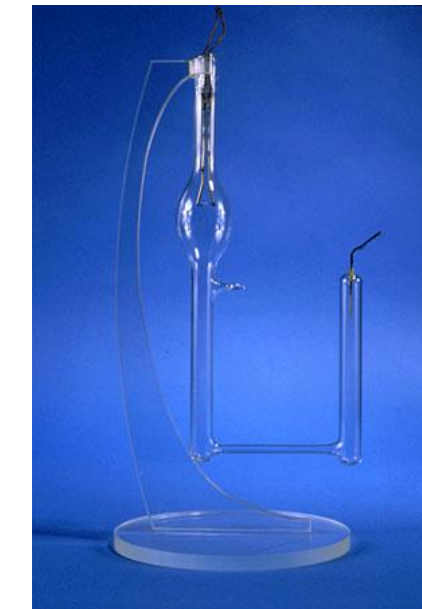


Fig. 13: A krypton-86 spectral lamp.

TIME OF FLIGHT DEFINITION OF SI METRE, 1983

Driven by the invention of the **HeNe laser in 1960**, and subsequent mass manufacture of lasers, interferometric length measurements were progressed up to the **redefinition of the metre in 1983**. The numerical value of the speed of light in vacuum was fixed, precursor of the 2019 redefinition of the entire SI. **The current metre definition is: The metre, symbol m, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum c to be 299 792 458 when expressed in the unit $m \cdot s^{-1}$, where the second is defined in terms of the caesium frequency $\Delta\nu_{Cs}$.**

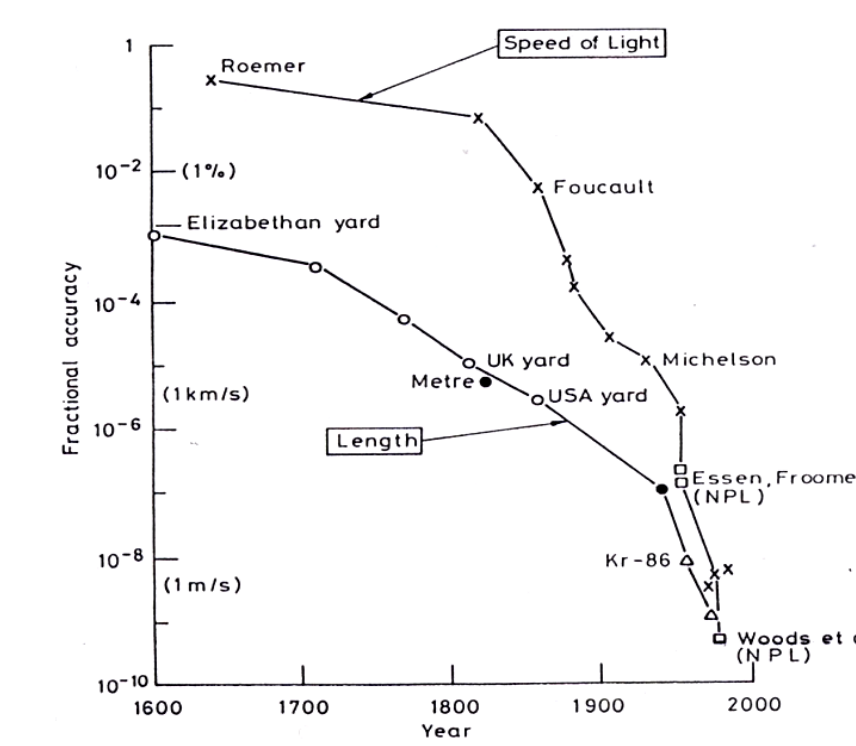


Fig. 14: Improvements in the accuracy of realisation of the unit of length and measurement of the speed of light [9].

PRECISION MANUFACTURING AND THE SI REDEFINITION, 2019

The 2019 SI redefinition challenged the metrology community with several **precision experiments**. Some had very high demands on **manufactured components** and **their alignment** in complex instruments, which needed experience in precision engineering [10]. Examples are: (1) the manufacturing chain for isotopically enriched monocrystalline Si²⁸ spheres and measurement of their volume for determining the Avogadro constant N_A using the **XRCD** method; (2) the realisation of electromagnetic **Kibble balances** for determining the Planck's constant h . After the 2019 redefinition, both experiments have been used as primary methods for realising of the unit of mass, the kilogram.



Fig. 17: Units and defining constants of the revised SI [10].

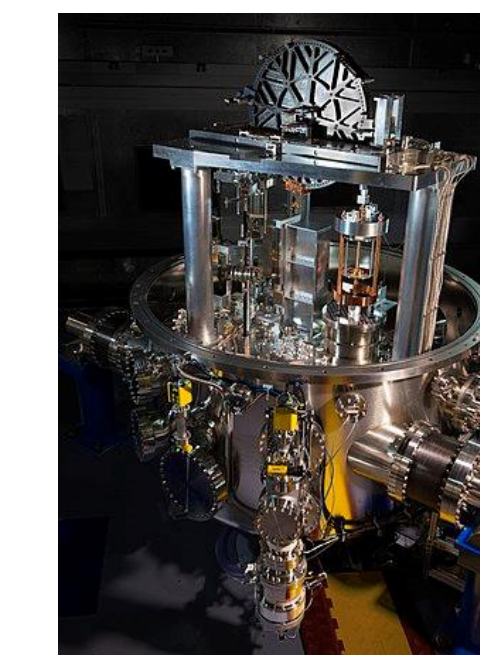


Fig. 18: NIST 4 Kibble balance [10].

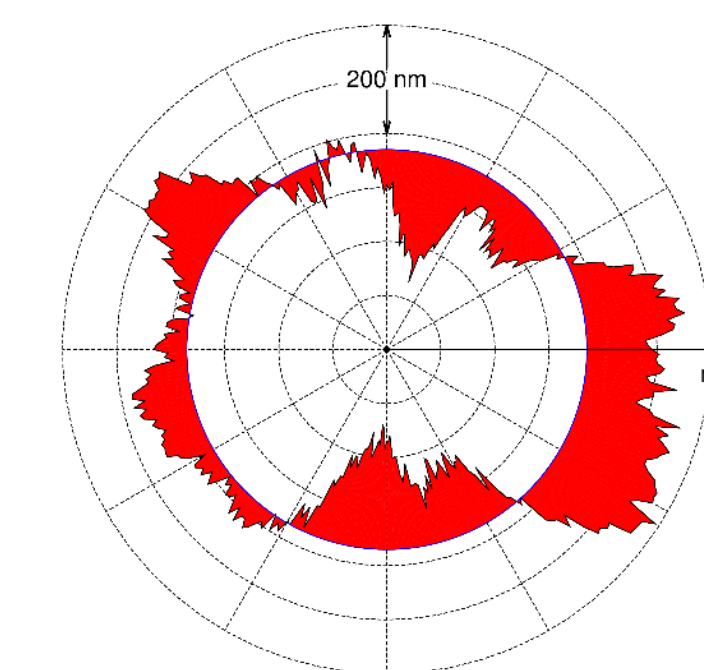


Fig. 16: Spherical-etalon interferometer developed at PTB [10].

Fig. 19: Coordinate measurements of the NIST-4 balance wheel. The wheel has a nominal radius of 300 mm [10].

OUTLOOK

This contribution shows examples of the progress of metrology and precision manufacturing and their mutual interaction. Progress in manufacturing will enable progress in metrology also in future, and vice versa. An example is the secondary realisation of the definition of the metre by means of the **Si atomic lattice spacing in nanometrology** [11].

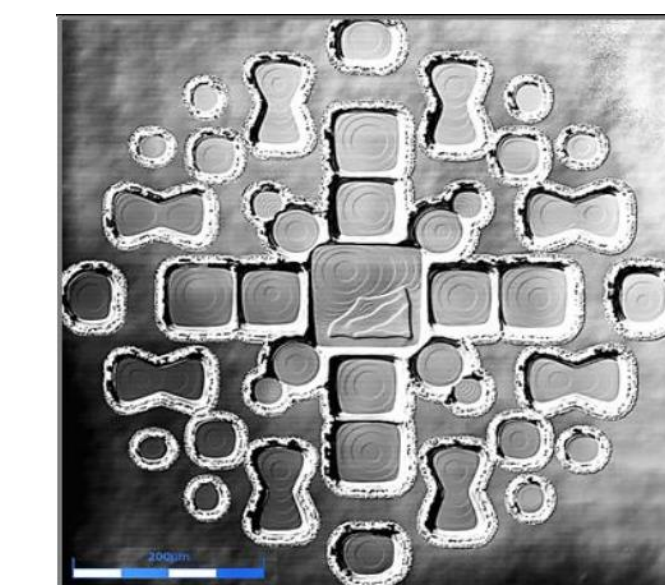


Fig. 20: Silicon surfaces showing monoatomic steps [CCL-GD-MeP-3].

REFERENCES

- [1] International Vocabulary of Metrology (VIM)
- [2] de Garis Davies N (1943), The Tomb of Rekh-mi-Ré' at Thebes
- [3] Womack J.P. et al. (1990), The Machine That Changed the World
- [4] Alder K (2002), The Measure of all Things—The Seven-Year- Odyssey that ...
- [5] Delambre JP (1806), Base du système métrique décimal/Méchain, Delambre, Paris
- [6] Kind D (2000), Für alle Zeiten, für alle Menschen. Phys. Blätter 56 Nr. 6: 63-66
- [7] Ålström, G. (2001), "The Edison of Sweden" C.E. Johansson and the 'Standards ...
- [8] Barrell H (1962), The Metre, J. of Contemporary Physics 3, (1962), 415-434
- [9] Petley BW (1987), Physical Constants and the SI, NPL News Jan. 1987.
- [10] Bosse H et al. (2017), Contributions of precision engineering to the revision of the SI
- [11] SI Brochure (2019) – App. 2 Mise en pratique for the definition of the metre in the SI

ACKNOWLEDGEMENTS

We would like to thank Dr. Karl-Dietrich Imkamp, ZEISS Industrial Quality Solutions Germany and the EMN Stakeholder Council members for giving strategic advice and support to the EMN for Advanced Manufacturing.



The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

