The Reference.

Switzerland's metrology magazine

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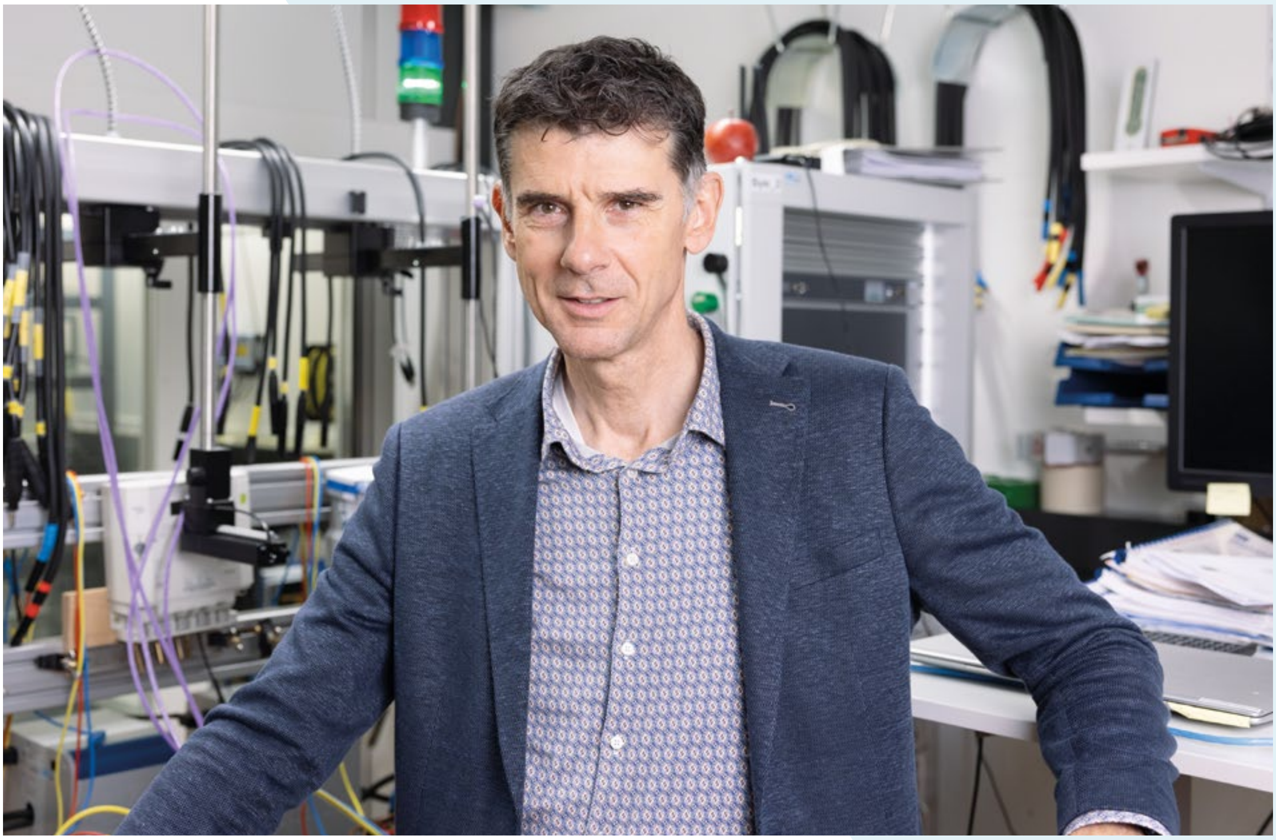
METAS



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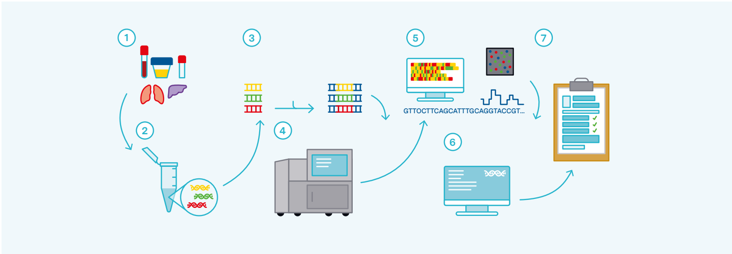
Tank-filling system for liquid helium.

Content



Editorial

Dear readers,

Last summer, I had the opportunity to attend the IMEKO World Congress (p. 24). While there, I was able to observe the advancements made in metrology on a global level and get an idea of the development of new measurement technologies that impact our daily work and in which we are actively involved.

The precision of our measurements not only rests upon the technological facilities and expertise of our colleagues, but on the environment in which measurements are taken as well. The stable measuring conditions in our labs are also made possible thanks to the work of the Technical Support Team. This team works actively in the background to provide metrologists at our Institute with optimal and safe working conditions (p. 12).

Metrologists' expertise and experience make it possible to carry out experiments at cryogenic temperatures in the field of electricity (p. 16/17). The Technical Support Team also ensures the continual electricity supply for numerous measuring instruments, e.g. for DNA sequencing in biological metrological experiments in aid of cancer research (p. 8).

I invite you to explore our work and take a look behind the scenes of our Technical Support Team.

Dr Fabiano Assi
Deputy Director and Head of
the Physics Department

Actuality

More accurate measurement results for ground-level ozone

Since 1993, the METAS gas analysis laboratory has applied a harmonised method to calibrate ozone-measuring instruments using a primary ozone photometer. This method will now be adapted to the latest findings as part of an internationally coordinated process, reducing measurement uncertainties.

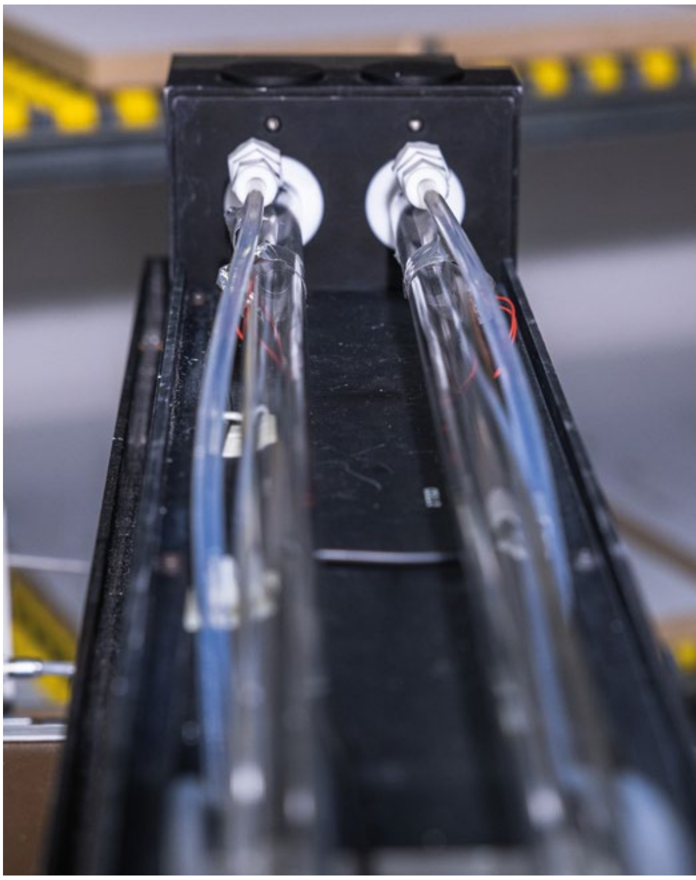
Bernhard Niederhauser

Measuring amount-of-substance fractions of ozone in the ground-level air has a long tradition in Switzerland. The measuring instruments used for air-quality monitoring and research are regularly calibrated following a standardised method. The process involves calculating the amount-of-substance fraction[1] of ozone in the air generated by a stable ozone generator through photometric measurement using a standard reference photometer (SRP). This ozone-air mixture is then simultaneously applied to a device under test to calibrate it accordingly.

$$x_{O3} = \frac{-1}{2 \cdot L_{opt} \cdot \sigma} \cdot \frac{R}{N_A} \cdot \frac{T_{mes}}{p_{mes}} \cdot \ln(D)$$

Formula for calculating the amount-of-substance fraction of ozone: x_{O3} is the amount-of-substance fraction of ozone; L_{opt} is the average optical length of the measuring cells; σ is the absorption cross section of an ozone molecule; R is the universal gas constant and N_A is the Avogadro constant. T_{mes} and p_{mes} are the measured temperature and pressure conditions and D is the product of the transmittances of both measuring cells.

The “Manifold” distributes the ozone-air mixture with the most stable amount-of-substance fraction to the reference and simultaneously to up to three test specimens.



The two 90 cm long measuring cells are alternately supplied with an ozone-containing mixture or zero air.

The absorption cross section has the biggest influence on this calculation and its uncertainty (see formula). The absorption cross section value currently used is from 1961[2] and is now being replaced internationally by a new, agreed value designated CCQM.O3.2019. From 2025, this value will allow for more accurate reference values and therefore more accurate measurement values.

A working group is coordinating the worldwide implementation

To ensure the change from the old to the new defined absorption cross section value proceeds as smoothly as possible and, above all, in a traceable manner, an international working group has been set up to coordinate the implementation and develop guidelines. The working group, which includes Swiss participants, has now published guidelines on the implementation and the harmonised use of metadata, as well as a series of reports on the facts and figures concerning the change.

Absorption characteristics

	Before the change	Conversion factor	After the change
Time period	Until Dec 2024		From Jan 2025
Name of reference	Hearn.1961		CCQM.O3.2019
Absorption cross section per molecule σ	$1.1476 \cdot 10^{-17}$ cm^2	1.01298	$1.1329 \cdot 10^{-17}$ cm^2 [4]
Rel. measurement uncertainty σ	1.06 %		0.31 %
Linear absorption coefficient α_x	308.32 cm^{-1}	1.01293	304.39 cm^{-1}
Rel. measurement uncertainty α_x	1.06 %		0.31 %

Table: The absorption values differ before and after the change. The value currently used is to be replaced by a new, somewhat lower value which is three times more accurate. Data not corrected according to CCQM.O3.2019 can be converted to the new reference using the conversion factor. Since the linear absorption coefficient is stored in the SRP, the line with the blue text is crucial for the conversion.

These and other insights are available on the International Bureau of Weights and Measures (BIPM)[3] information platform. Those interested can register to be notified of the latest updates. In addition, issues related to the adaptation of international, regional and national standards have been clarified and a timeline for implementation has been defined. Finally, a publication on the long-term effects of the change in different contexts is set to be prepared.

The procedure in Switzerland

In Switzerland, both calibration service providers, METAS and the Swiss Federal Laboratories for Materials Science and Technology (Empa) have agreed to only offer calibrations using the new absorption cross section from January 2025. Therefore, in the transition year 2025, all data based on a calibration certificate from 2024 or earlier can be converted to the new absorption cross section (see table).

Conversely, in 2025, all data from instruments that have been calibrated with reference to CCQM. O3.2019 can be corrected using the calibration function from the calibration certificate as usual. The procedure is expected to be completed by the end of 2025. After this point, it will only be possible to distinguish the new ozone measurement data sets by the detailed metadata.

Effects on the immission values

Because of the slight reduction in the absorption parameter by approx. 1.3 %, according to the Beer-Lambert Law (see formula) the measurement values will rise by the same amount. In rare cases, this may lead to additional instances where the immission limit values in accordance with the Air Pollution Control Ordinance are exceeded[5], as limit values are not adjusted accordingly and remain at the "round" numbers (e.g. 120 µg/m^3 for the one-hour average). Whether or not the change in absorption cross section causes other effects in other countries, or has a significant impact at all, will be laid out in future studies and publications on ozone time series.

1 For ideal gases, the amount-of-substance fraction is equivalent to the volume concentration.
2 Hearn, Proc. Phys. Soc., 78, 1961, DOI 10.1088/0370-1328/78/5/340; https://doi.org/10.1088/0370-1328/78/5/340
3 https://www.bipm.org/en/ozone
4 J T Hodges et al. 2019. Metrologia 56, 034001, https://doi.org/10.1088/1681-7575/ab0bdd
5 Ordinance on Air Pollution Control (OAPC, SR 814.318.142.1), https://www.fedlex.admin.ch/eli/cc/1986/208_208_208/en

Object

Magnetic suspension balance and permeator

METAS operates magnetic suspension balances to ensure the traceability of greenhouse gas and air-pollutant measurements. This enables the production of reference gas mixtures in amount-of-substance fractions that occur in ambient air. The centrepiece is a chamber where a permeator is suspended. The permeator is a small tube with an embedded membrane through which the contained substance, e.g. nitrogen dioxide, evaporates. By measuring the mass loss of the permeator through weighing and the gas flow through the chamber, the amount-of-substance fraction of nitrogen dioxide in the reference gas can be calculated. The crucial point here is that the permeator's mass loss must be determined at elevated temperatures, which cannot be done with a standard precision balance. The solution: the permeator in the heated chamber is connected to the precision balance at room temperature via a magnetic suspension coupling.

Research and development

Biological metrology supports personalised medicine

Although technological advancements like next generation sequencing have revolutionalised tumour diagnostics and today already enable personalised therapies, comparability and standardisation are still lacking. With the help of the GenomeMET project, METAS is developing metrological infrastructure to support genomic cancer profiles in precision medicine, with the aim of enabling a wider application of these new technologies.

Dr Sabrina Flütsch

According to the latest global cancer statistics (GLOBOCAN report), in 2022 there were around 4.5 million new cancer cases in Europe, and 2 million deaths linked to cancer were recorded. This corresponds to 22 % of global cases, even though Europe makes up less than 10 % of the world's population[1] (see Fig. 1). These figures mean that cancer is the second most common cause of death in Europe and could become the most common by 2035 without decisive action. Cancer is not only one of the biggest health challenges for Europe, it is also a financial challenge too, with estimated consequential costs amounting to over € 100 billion per year.[2]

The fight against cancer is a top priority in Europe and is being advanced thanks to early diagnosis and personalised therapies. These advancements are made possible by technologies like next generation sequencing (NGS), which can break down the genetic structure of a tumour in great detail. Creating genomic cancer profiles using NGS is based on an extremely complex procedure that consists of many substeps and enables the simultaneous detection of thousands of genetic variants (mutations). The information extracted about the mutations present can then be used as part of personalised therapy.

However, the individual steps in the NGS procedure are prone to considerable and little-understood uncertainties, which leads to great variability and a lack of comparability between measurements. This slows down or hinders the wider implementation of these new technologies in clinics. The development and establishment of metrological tools such as standards, reference materials, reference measurement procedures with low uncertainty to support quality assurance and guidelines for mitigating measurement uncertainty is urgently needed. These are set to be compiled through a joint European effort as part of the GenomeMET project.

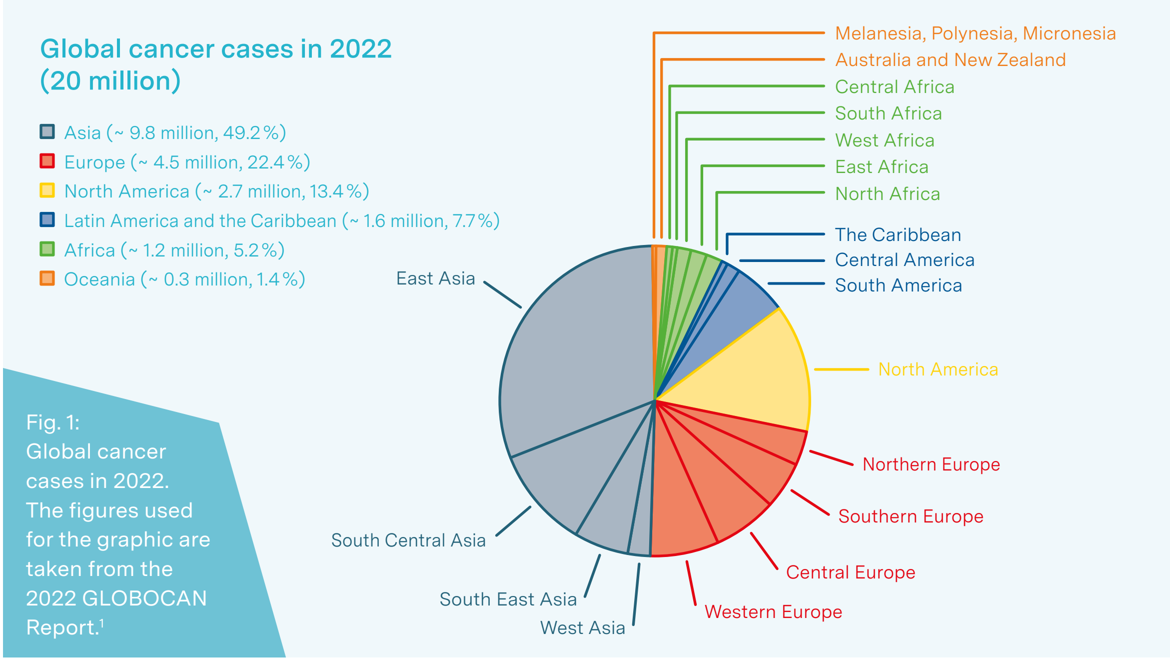


Fig. 1: Global cancer cases in 2022. The figures used for the graphic are taken from the 2022 GLOBOCAN Report.[1]

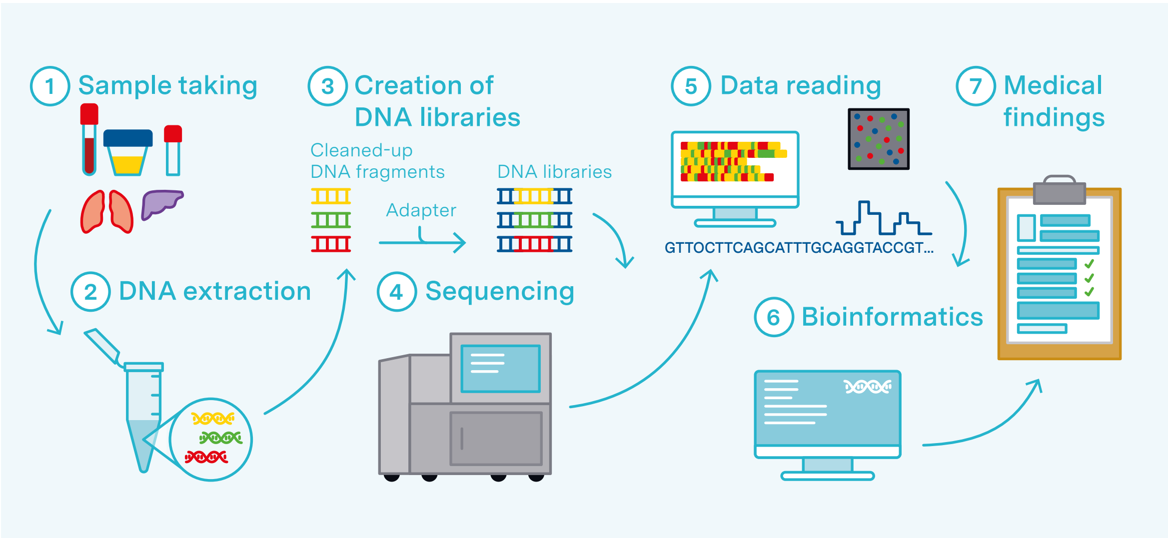


Fig. 2: Next generation sequencing process. For the first step, samples are taken from the tumour and healthy tissue/blood, DNA is extracted from these samples and this DNA is then made sequenceable as DNA libraries. After this comes the actual sequencing of the DNA and the bioinformatic analysis of the sequencing data, which consists of combinations of the four bases of DNA (A, T, G, C). The results of the sequencing can eventually be used in precision medicine.

Cancer: a disease of the genome

Cancer is a disease of the genetic material (genome). During the course of our lives, our genes may suffer damage that can no longer be repaired. This damage, known as genetic mutations, can be hereditary (germline mutations), but is more commonly random, caused by mechanisms such as copying errors during DNA replication or defective DNA repair mechanisms. The occurrence of so-called somatic mutations (acquired mutations) can be exacerbated by various genetically harmful factors such as UV radiation, smoking, alcohol and viruses.

Nevertheless, not all cancers are the same. There are currently around 300 different known cancers that are distinguished by both their genetic characteristics and their treatment options. For example, skin cancer involves up to 100,000 somatic mutations, while bowel cancer involves an average of just 100 to 200 genetic changes.[3] The same type of cancer can involve different mutations in patient X than in patient Y, and within one patient whose cancer has spread (metastasis), there may be different mutational signatures.

Project partners

National measurement institutes

Genomics institutes

Pathology institutes

Cancer institutes

EQA providers

Technology provider

Fig. 3: GenomeMET project consortium.

Each cancerous disease, then, is unique and is characterised by its specific combination of mutations. Genomic tests using NGS can help to decode a tumour's individual DNA changes and identify so-called driver mutations that are responsible for a tumour's growth. Advancements in molecular tumour profiling enable the development of targeted, personalised therapies that cause fewer side effects and are more cost-effective than traditional, widely used therapies.

Molecular tumour diagnostics

To create a molecular tumour profile, a sample from the tumour and a comparison sample from healthy tissue or blood are taken and the DNA is extracted (see Fig. 2, steps 1 and 2). DNA libraries are then created from the genomic DNA by fragmenting the DNA and providing it with universal sequencing adapters and specific barcodes (indices). This process is what makes the DNA sequenceable. The indices are unique sequences that facilitate the simultaneous analysis of multiple samples, as they can later be used bioinformatically to trace the sample origin. The sequencing adapters are needed to bind the DNA libraries for analysis to the flow cell, where substantial amplification of the source DNA and the actual sequencing take place (see Fig. 2, steps 3 and 4). The sequencing is followed by the bioinformatic analysis of the resulting sequences, the so-called reads. In the process, the individual reads are compared with a suitable reference genome, DNA base by DNA base, to identify deviations in the sequenced DNA compared with the reference (Fig. 2, steps 5 and 6). After this, the sequence changes are assessed for their clinical relevance and the results are summarised in a medical report (Fig. 2, step 7).

The GenomeMET project

The analytical complexity of genome sequencing brings with it considerable uncertainties, which influence the accuracy and reliability of tumour profiles. Metrology, the science of measuring, can play a decisive role in negotiating these challenges and establishing trust in the data in order to enable the necessary access to genetic tests in cancer dianostics and treatment. This is why the METAS Laboratory for Biological Analysis and References (BAR) is participating in the European project GenomeMET, which is aiming to tackle these challenges.

The three-year GenomeMET project was launched in September 2023 as part of the European Metrology Programme for Innovation and Research (EMPIR), which is led by the European Association of National Metrology Institutes (EURAMET). The project consortium includes 17 members, of which seven are national metrology institutes (NMIs) or designated institutes (DIs), five are research institutes, three are reference institutions for external quality assurance, one is an industry partner and one is a producer of reference materials (Fig. 3). The EU has provided a total of € 1.75 million for the project.

The focus of the project is on developing a robust and reliable metrological infrastructure to help improve the quality of genomic tumour profiles. To this end, different metrological resources are being developed in four experimental work packages:

1. Traceable methods for assessing the critical quality characteristics of the individual NGS steps (e.g. DNA extraction, sequencing, bioinformatics).
2. Reference measurement procedures with low measurement uncertainty to guarantee reproducible measurements.
3. Standards and reference materials to support measuring processes.
4. Statistical procedures to mitigate measurement uncertainty.

METAS is responsible for managing and executing work package 4 and is also involved in the other three work packages. The main goals of work package 4 are:

- conducting a detailed analysis of the bioinformatic evaluation of NGS data to identify possible relevant sources of uncertainty,
- devising statistical approaches to mitigating measurement uncertainty for genomic tumour profiles,
- developing innovative reference data sets for detecting somatic mutations,
- preparing guidelines for mitigating measurement uncertainty for genomic data sets.

Insight into a METAS biology laboratory.

The GenomeMET project is intended to serve as the prelude to a series of similar projects that are geared towards improving the use of NGS protocols in clinical diagnostics. The aim is to increase the accuracy and reliability of these processes and, with this, to realise the enormous potential of this technology in full.

By integrating metrology into genome profiling, this project is enabling earlier and more precise cancer diagnoses as well as individually adapted treatment strategies. This marks a significant step forward towards a future in which cancer treatment is not just a standard procedure, but a personalised journey to recovery.

Genome MET

You can find more information on the GenomeMET project on the GenomeMET website.

1 F. Bray et al. Global cancer statistics 2022: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. CA Cancer J Clin 74, 229–263 (2024).
2 EU, E. C. Communication from the Commission to the European Parliament and the Council – Europe's Beating Cancer Plan. COM(2021) 44 final (2021).
3 https://www.wissensschau.de/krebs_tumor/tumor_genmutation_umwelt_vererbung.php

About METAS

Technical Support Team: the invisible foundation of precision work

In the ultra-modern laboratories of the Federal Institute of Metrology (METAS), measurements that are some of the most precise in the world are carried out daily. Behind the scenes, a team works on creating and maintaining the optimal conditions for this challenging work: the Technical Support Team of the Infrastructure and Logistics Department.

Dmitry Beer

The challenge of precision

The requirements on the buildings and technical facilities at METAS are extraordinarily high. In some of the labs, the temperature has to be consistently kept at one hundredth of a Kelvin exactly. Often, the humidity may only fluctuate by a few percentage points. And when it comes to shocks, even tiny vibrations that are imperceptible to humans can influence our highly sensitive measuring instruments.

For example, in the lab for length measurements, length standards are calibrated and serve as a reference for the whole of Swiss industry. A deviation in room temperature of just 0.1 K could cause measuring errors that would already be unacceptable for a high-tech company specialising in precision parts manufacturing. The Technical Support Team ensures, for example, that the temperature in this lab is kept at ±0.01 K exactly – day and night, summer through winter.

The Technical Support Team consists of four members:
Heinz Strässler, Rolf Zwahlen, Roland Rüfenacht and Dmitry Beer.

The team behind the technology

The Technical Support Team is no maintenance team. Rather, it is a highly specialised, interdisciplinary team of specialists who, together, cover an impressive spectrum of expertise:

- Electrical engineers specialising in building technology ensure a reliable power supply and the complex electrical installation of the labs.
- Specialists in climate, heating and sanitary engineering maintain the precise environmental conditions that are essential for measurements.
- Experts in security systems and access control guarantee that the sensitive areas are optimally protected.

This variety of expertise means the Federal Institute's complex technical systems can be monitored and maintained independently – often at a level that few external service providers can achieve.

Guarantors of the conditions for daily, precise measurements

The day begins with an inspection of the heating, ventilation and air conditioning systems. In the clean room lab, where particles in the air can influence scientists' measurements, the air filter system is subjected to a thorough inspection. At the same time, another member of the team inspects the building management system, which manages and monitors all building services centrally.

In the course of the morning, the system reports small deviations in the temperature in a precision lab. Roland Rüfenacht immediately sets off to find and rectify the cause. It transpires that a sensor was moved slightly – a problem that, thanks to the team's quick response, was rectified before it could have any effect on ongoing measurements.

Shortly afterwards, Roland Rüfenacht, who knows METAS like the back of his hand with his 30 years of experience, carries out a monthly service of the emergency power diesel generator. This generator is crucial to guaranteeing the uninterrupted supply of power to our critical systems in the event of an outage. The interruption-free supply of power is also regularly inspected to ensure that even power outages lasting milliseconds do not negatively impact the sensitive measurement instruments in all labs.

Clean water for experiments and the environment

In the afternoon, it's time to inspect the water processing unit. For many of the experiments, the metrologists need water of the highest purity. The regular maintenance of this unit is decisive in guaranteeing this purity at all times.

At the same time, another team member, Rolf Zwahlen, takes care of the wastewater system. In the chemistry lab, wastewater accumulates regularly and needs to be neutralised before it is fed into the public sewage system. The monitoring and maintenance of this neutralisation system is an important task that is not only hugely significant for METAS operations, but also for environmental protection.

Guaranteeing the safety of the infrastructure and workforce

Safety is a top priority for all the Technical Support Team's activities. The gas detection systems in the labs are inspected during the course of the day. These systems are critical, as some experiments involve potentially dangerous gases.

Alongside this, Heinz Strässler leads a training session on operating our access control system for new employees. This system makes sure that only authorised staff can access sensitive areas. It is complex and must be updated and expanded regularly to keep up with the latest security standards.

Production of liquid helium

A particular highlight of the day is the production of liquid helium using the Institute's in-house helium liquefaction system. This system is essential for quantum experiments in electricity. It liquefies helium at −269 °C, just a few degrees above absolute zero. The maintenance and operation of this system, including processing the returned helium gas, demands the highest precision and the expertise of Roland Rüfenacht. Like other members of the team, he has spent years acquiring the specialist knowledge required to operate this system to the optimal standard.

The technical and environmental improvement of this system has only recently been implemented. Without the extensive input of the specialists in the Technical Support Team, an external service provider would have taken weeks to get to grips with the specific needs at play.

Innovation and energy efficiency

In the age of climate change and rising energy costs, energy efficiency is playing an ever-greater role. The innovative strength of the Technical Support Team is particularly evident here. Through the use of state-of-the-art "smart building" technologies, the team can continually optimise energy consumption without compromising on accuracy.

Roland Rüfenacht fills a tank with 450 litres of liquid helium.


The liquid helium is carefully brought to the lab for direct current and low frequency experiments.

By installing an intelligent shading system, which automatically adapts to daylight conditions, energy costs have been reduced by 15 %. At the same time, the system ensures optimal lighting conditions in our labs, which increases the quality and safety of our work.

Overcoming challenges 24/7

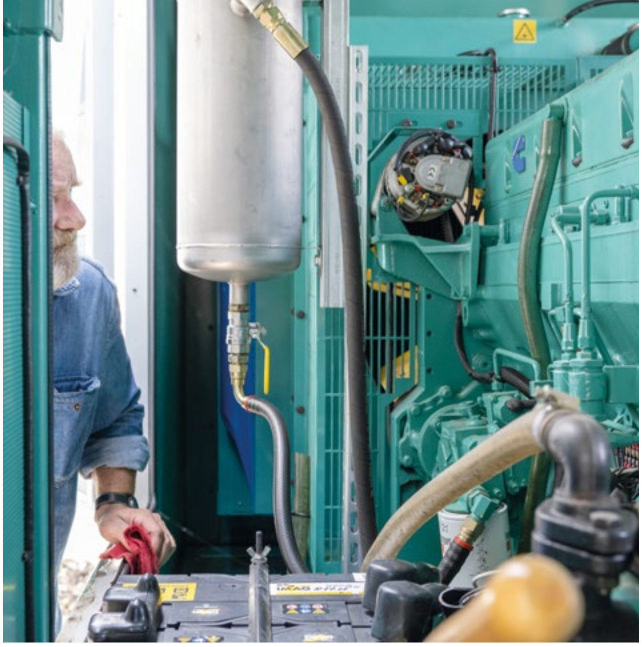
One of the biggest challenges for Roland Rüfenacht, Heinz Strässler, Rolf Zwahlen and the leader of the Technical Support Team, Dmitry Beer, is the need to be ready to act around the clock. The technical infrastructure on-call service ensures that an expert is always available to respond to unforeseen events, even outside regular working hours.

This readiness is decisive, as many measurements and experiments span long periods of time and are extremely sensitive to disruptions. In the lab for time measurement technology, atomic clocks run which are so precise that, in a million years, they would only deviate by one second. A brief outage of the air conditioning or a fluctuation in the energy supply could negatively impact the precision of these clocks and undo weeks or even months of work!

As a result, staff in the Technical Support Team must not only have sound technical knowledge, but must also be capable of working calmly and effectively under pressure. Regular training courses and exercises ensure that the team is equipped to deal with any eventuality.

Planning for the future

The expertise of the Technical Support Team goes beyond mere inspections and maintenance. The team's specialists offer their expertise in case of new builds and conversions to ensure that METAS laboratories remain among the most modern and accurate in the world.


The functioning of the diesel-powered emergency power system is tested monthly.

A current example is the planning of a new quantum metrology lab. Here, the Technical Support Team is working closely with scientists to create an environment that fulfils the extremely high requirements of this technology of the future. In the process, aspects such as the absence of vibration and temperature stability are considered at a level that was still deemed impossible a few years ago.

As contact partner for the building owner, the Federal Office for Buildings and Logistics (FOBL), the Technical Support Team plays a key role in the long-term planning and development of METAS infrastructure. The detailed energy accounting carried out for the FOBL is an important tool for the sustainable management of the Institute's energy consumption. It helps to identify potential ways to save energy and to quantify the success of efficiency measures introduced.

Furthermore, the Technical Support Team and the head of the Infrastructure and Logistics Department are supporting the FOBL, architects and various specialist engineers in the tailored and sophisticated planning of a required extension building for the laboratories. In order to implement the federal laboratory strategy and to meet the requirements of METAS's growth over recent decades, this extension will be necessary in a few years, as will other projects that are directly and indirectly linked to this major project.

The indispensable cog in the METAS wheel

The requirements of the Technical Support Team will increase further in the future. Advancing digitalisation, the trend towards even more precise measurements, the growing significance of energy efficiency and sustainability and the pending expansion of METAS present the Technical Support Team with new challenges.

Facts and figures

To illustrate the significance and scope of the Technical Support Team's work, here are some impressive figures:

- Footprint: 35,485 m^2
- Developed area: 15,400 m^2 of which 4,900 m^2 is lab space
- 1,000 maintenance and repair orders per year
- 15 % less energy consumption in the last 5 years
- 50 on-call assignments per year outside regular working hours

Through their work in the background, the silent heroes of the Technical Support Team like Roland Rüfenacht, Rolf Zwahlen and Heinz Strässler enable the scientists and engineers to concentrate fully on their demanding measuring tasks and carry out world-class measurements – safe in the knowledge that the technical infrastructure reliably offers the best possible conditions. In a world where precision and reliability are of immense significance, the METAS Technical Support Team is the guarantor METAS needs to fulfil these demands and maintain our position as one of the world's leading metrology institutes.

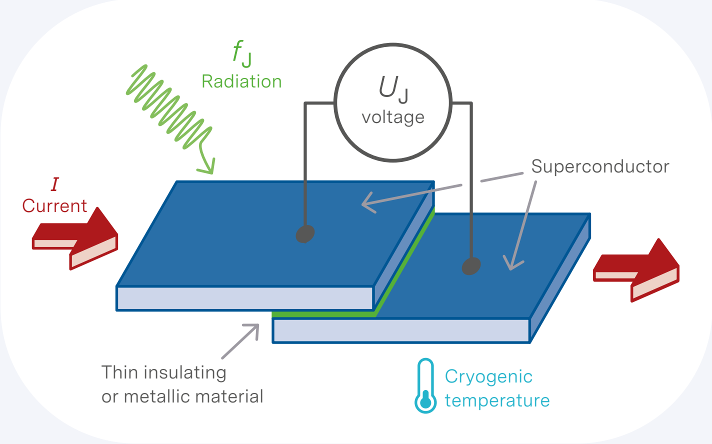
Principle

The Josephson effect is a physical phenomenon that occurs at low temperature when two superconductors are placed in proximity with some barrier or restriction between them, thus forming a Josephson junction.

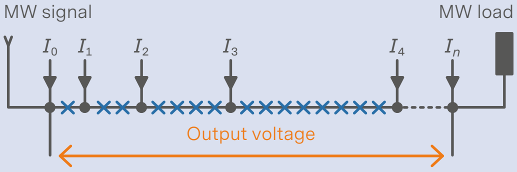
In the Josephson AC effect, microwave radiation can induce quantised DC voltages across a current-carrying Josephson junction. This means a Josephson junction behaves like a perfect frequency-voltage converter, resulting in a Josephson voltage standard. This voltage depends only on the frequency of the radiation and on two natural constants, the Planck constant and the elementary charge.

Electricity

Realisation of the volt



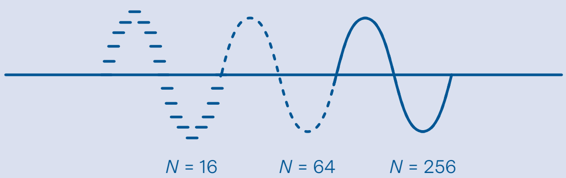
Josephson arrays: voltage standards and programmable arrays



Schematic view of a Josephson array divided into a binary sequence with independent current sources (I_x).

A Josephson junction exposed to microwave radiation at a frequency of 70 GHz generates a first voltage level (n = 1) of 145 µV. Several tens of thousands of contacts must therefore be arranged in series in order to obtain Josephson arrays that can be used to calibrate between 1 V and 10 V.

A programmable Josephson voltage standard (PJVS) is used when junctions are grouped in powers of 2 in a binary sequence with each segment individually controlled.



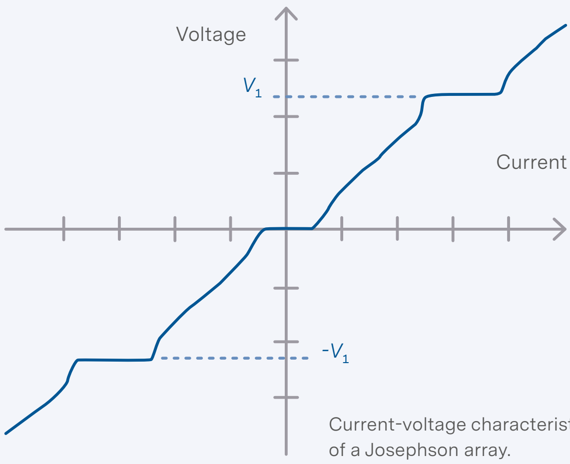
Sinusoidal waveforms generated by binary sequences of arrays with N junctions.

Variable voltages can also be generated using pulse patterns with variable repetition frequency, also known as Josephson arbitrary waveform synthesizers (JAWS).

Josephson voltage

$$U_J = \frac{h}{2e} n \times f_J = \frac{n}{K_J} \times f_J$$

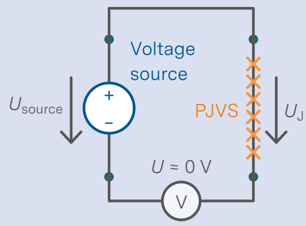
- Josephson voltage: U_J
- h = 6.62607015 × 10^{-34} J s — Planck constant
- Step number (integer number): n
- Frequency of the microwave radiation: f_J
- Elementary charge e = 1.602176634 × 10^{-19} C
- K_J = 483,597.848416984 GHz/V



Current-voltage characteristic of a Josephson array.

Calibration scheme

Calibration of a voltage source is carried out by comparison with a standard of the same voltage level, e.g. a Josephson array. The voltage difference measured is as close to 0 V as possible.



1911 Discovery of the superconductivity phenomenon by Heike K. Onnes.

1913 Nobel Prize in physics to Heike K. Onnes.

1962 Theoretical discovery of the Josephson effect by Brian D. Josephson.

1973 Nobel Prize in physics to Brian D. Josephson.

2019 Fixing the Planck constant h and the elementary charge e. New definition of the ampere.

Principle

The quantum Hall effect occurs in certain types of thin films whose electron dynamics correspond to a two-dimensional gas, i.e. the electron gas is free to move in two dimensions but is strongly confined in the third. Such arrangements are found in semiconductors, especially in insulated-gate field-effect transistors (MOSFETs), where the Hall resistance transverse to the current direction is quantised and exhibits plateaus.

The quantum Hall effect occurs at very low temperatures and strong magnetic fields. It only depends on two natural constants, the Planck constant and the elementary charge.

Hall resistance

h = 6.62607015 × 10⁻³⁴ J s — Planck constant

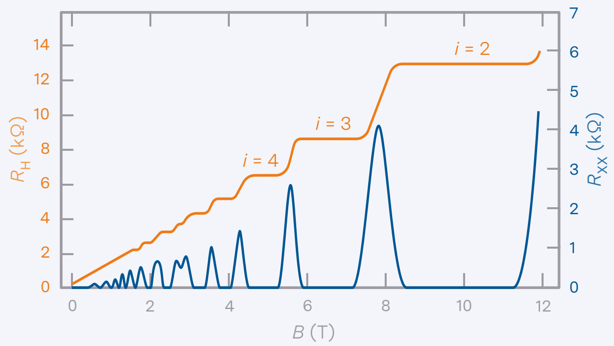
R_K = 25,812.870459 ohm

$$R_H = \frac{1}{i} \times \frac{h}{e^2} = \frac{R_K}{i} = \frac{V_H}{I}$$

Hall resistance (R_H)

Step number (integer number) (i)

Elementary charge e = 1.602176634 × 10⁻¹⁹ C

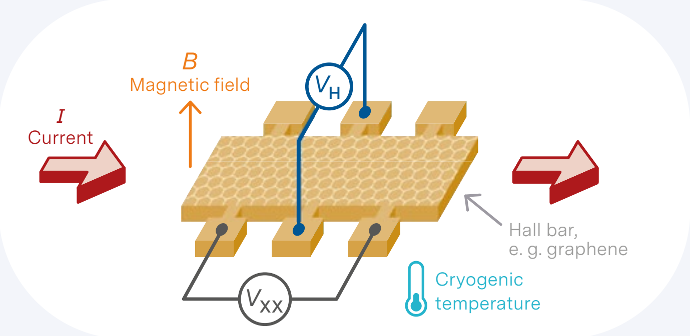


Quantum Hall effect in graphene

Graphene is a two-dimensional crystalline material made of carbon. Its theoretical structure is the basic structural element of carbon arrangements such as graphite, carbon nanotubes and fullerenes.

The electron gas in graphene is two-dimensional and develops a quantum Hall effect at higher temperatures, lower magnetic fields and higher currents than in semiconductor materials.

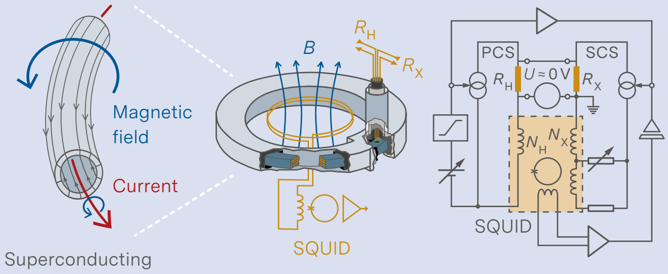
Realisation of the ohm



Cryogenic current comparator

The cryogenic current comparator (CCC) is used to calibrate a resistor against a QHR (Quantum Hall Resistance) standard. At equilibrium, the two currents flowing through the two resistors being compared are exactly in the inverse ratio of these resistors: $I_H \times R_H = I_X \times R_X$. The number of turns of two windings in series is chosen so that the additional condition $I_H \times N_H = I_X \times N_X$ is met.

To achieve this, the windings are housed in a superconducting toroid, around the periphery of which flows a current that is the opposite of the net residual current flowing in the windings (Meissner effect). The field induced by this current can be detected by a highly sensitive sensor (SQUID) and cancelled by a current source controlled by the SQUID signal (SCS). The equilibrium condition can be achieved with an accuracy of the order of 10^{-9}.



Superconducting toroid comparator — Cryogenic current — Comparator scheme

History

Electrical units are realised using ohms and volts. Ohm's law directly links the electrical quantities of voltage (volts), resistance (ohms) and current (amperes). Since the 1990s, the units of resistance and voltage have been realised using the quantum Hall and Josephson effects.

1980 — Discovery of the quantum Hall effect by Klaus von Klitzing.

1985 — Nobel Prize in physics to Klaus von Klitzing.

2005 — Discovery of the quantum Hall effect in graphene by Andre Geim and Konstantin Novoselov.

2010 — Nobel Prize in physics to Andre Geim and Konstantin Novoselov.

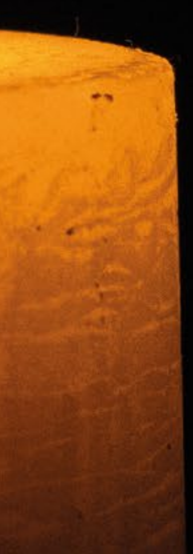
2019 — Fixing the Planck constant h and the elementary charge e.

New definition of the ampere.

Commentary

The candela or the human side the International of Units

# of System



Dr Hugo Lehmann

All units are man-made. Nature doesn't need seconds, metres or kilograms. Ultimately, the way units are defined is arbitrary. While the majority of Europeans – which even includes the Swiss for once – measure distance covered in metres, across the countries that made up the former British Empire – hence "imperial" – and in the United Kingdom's former North American colonies, people still give lengths in inches, yards or feet. Even the distance to Mars is sometimes expressed in feet, which can cause some confusion.[1] Would metres or maybe even the number of wing beats of the imperial eagle have been more appropriate here? Regardless of whether you measure in metres or feet, covering long distances makes you thirsty. If you want to quench your thirst on the other side of the English Channel, then you don't order a litre of a drink like at Oktoberfest, but a pint. Whether that means that Bavarians are more likely to have one too many than the Brits is anyone's guess. Regardless, you get the impression that the Brits and Americans forget about the SI system on occasion, or even pass it off as fake news.

Having said that, these old imperial units have a somewhat profoundly human quality. They are literally guardians of the anthropocentric world view. Is a foot not a unit that simply illustrates human dimensions? And is a pint, or even maybe two, the exact right amount of beer needed to quench the average person's thirst? It's highly likely that a Swiss motorist wouldn't fall under the legal blood alcohol limit of 0.5 during a police breath test after two pints. They would have to finish their journey on foot, but, as we all know, the journey is the destination …

Every Cartesian academic would say it's a good thing that the SI unit system has bid farewell to such intersubjective definitions and, since 2019[2], is now defined using more rigorous and objective natural constants.

Away with this subjective sentimentalism that refers to people and their smelly feet. No more of the British lords living the high life on vast acres or the Egyptian pharaoh's cubit length! Units ultimately have a political dimension. Ever since the Enlightenment and the French Revolution, the metre has emancipated itself from the absolute monarchical hegemony and democratised the unit of length. In this way, modern metrology is also a child of the post-revolutionary world order!

In our technocratic society, the human dimension is pushed further and further into the background. The micro and the virtual dominate our lives thanks to the complex depths of our smartphones; the fast pace at which we spend our time is no longer measured in hours or minutes, but, ever since 2022[3], in rontoseconds[4], while the mass of AI-generated data is given in Quettabytes[4].

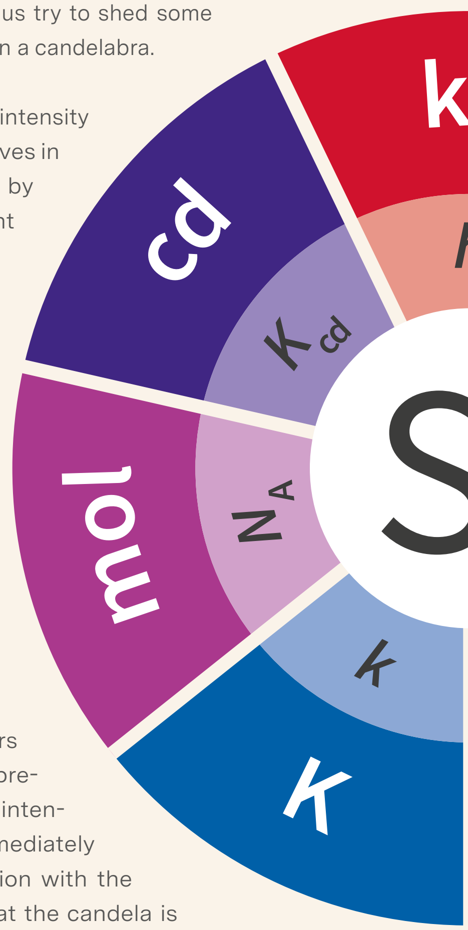
But as critical children of the Enlightenment, we want to put the SI unit system under the microscope for an even closer look. Have the human components really completely disappeared from this logically sterile system? Or is there still a last bastion of humanism? I'm not sure which option is most worth striving for from a philosophical point of view. But I do know that I know nothing …

The second is based on an atomic shift, the metre on the speed of light – neither have anything to do with human dimensions. Now to the kilogram, which, metrologically speaking, has been associated with Planck's constant h since 2018. Aha! So Mr Planck played his small part in defining the kilogram. How? Was Mr Planck's mass used to set the scale, or maybe even tip it over a bit? Far from it; Mr Planck simply lends his name to this natural constant, which describes the proportionality between the frequency of a vibration and the associated quantum energy. After all, he theorised about these trendy quanta. With the ampere (here, too, Monsieur Ampère is just the eponym) and the mole, you simply count the electrons or particles. What's more objective than counting? One, two, three, four …

Now back to our search; just the base units Kelvin and candela are left. In the case of the Kelvin, the unit of temperature, two eminent physicists who dealt with the subject were drafted in: Lord Kelvin gives the unit (which we use to count) its name, while Ludwig Boltzmann named the defining natural constant. But, even though Boltzmann had frail health, the Boltzmann constant has nothing to do with a fever spike suffered by poor Ludwig, but describes the universal relationship between temperature and thermal energy. Even when dealing with high temperatures, there are no warm, human elements to speak of. The SI unit system still positions itself at absolute zero, Cartesian cold.

But what about the candela? Just the name appears somewhat special, with likely etymological origins in the word candle and reminiscent of Christmas, religion or even a potential blackout on the horizon … Now, be that as it may, the candela is defined as follows:
"The candela, unit symbol cd, is the SI unit of luminous intensity in a specific direction. It is defined by setting the numerical value 683 for the photometric radiation equivalent K_{cd} *of monochromatic radiation with a frequency of* $540 \cdot 10^{12}$ *Hz …"*[5]

So apart from the complicated formulation, there doesn't appear to be any human characteristic here either. The candela is defined using the fixed value of the constant K_{cd}. But what is hidden behind this somewhat suspicious phrase "photometric radiation equivalent"? Which fundamental physical constant? "Equivalent" doesn't exactly inspire confidence when it comes to universality. So let us try to shed some light on this like we're candles on a candelabra.



In actual fact, to determine the intensity of light (or electromagnetic waves in general), the power measured by a unit area would be sufficient as a unit and we would not need a base unit at all. But the candela goes a little further: it is the intensity of the light of a given frequency and in a specific direction. Why? Luminous intensity relates to the human observer through the constant K_{cd} and reveals how efficiently the radiation flux of a given frequency affects the human eye. For the sake of historical compatibility, the unit also refers to candlelight, which was previously used to measure light intensity. A Latin speaker would immediately be able to make the connection with the name candela. This means that the candela is not least defined by a typical human eye through the constant K_{cd}. With that, we've found the last bastion of man in the SI unit system. What constitutes a typical human eye, though, is not defined.

Phew! Thanks to the candela, even the fact-based and nit-picking metrologists have allowed a little humanity into their SI system. On the one hand, the humanist in me is quite happy, whereas the Cartesian scientist in me is a little sad. Two souls, alas, dwell in my breast[6], as Goethe's Faust said.

But why the eye is given this honour and not the ear, where perceived sound intensity is also dependent on the frequency of the sound, the direction and therefore the ear is a mystery to me as a music lover. Could it be because us humans live in a world shaped by the visual? Or maybe the brains of the SI units in Paris didn't want to oppose divine power. After all, in Genesis, it says:

"In the beginning God created the heaven and the earth. And the earth was without form, and void; and darkness was upon the face of the deep. And the spirit of God moved upon the face of the waters. And God said, Let there be light: and there was light. And God saw the light, that it was good."[7]

Ditto: despite all Cartesian tendencies, man has still managed to smuggle himself into the objective definition of the SI system of units.

The seven base units and, in the inner circle, the associated, defining natural constants.

Perhaps that's also the reason why we like to light a Christmas candle when the nights draw in. The soft light gives us warmth and comfort. Is this feeling not worthy of defining an SI base unit for luminous intensity that is based on a human "natural constant"?

Johann Sebastian Bach anticipated this in a wonderful aria in his St John Passion, putting the following text to beautiful, heavenly music:

"I will follow you likewise with joyful steps,
And will not let you go, my life, my light."

Dear readers are recommended to listen to Bach's masterpiece for themselves[8], because seeing alone isn't everything …

Etymology of the word candela

Borrowed from the Latin, in English "candela" means candle or light.
The name of the unit points to the beginning of light measurement technology: to determine luminous intensity, people relied on candles as reference light sources with which a light source that needed to be measured could be compared.

A luminous intensity of 1 candela corresponds to a radiant intensity of 1/683 watt per steradian at a frequency of 540×10^{12} Hz.

1 https://science.nasa.gov/mission/mars-climate-orbiter/
2 https://www.bipm.org/en/measurement-units
3 https://www.bipm.org/en/cgpm-2022/resolution-3
4 ronto (lower case since we're dealing with very, very small, puny even, amounts) represents 10^{-27} and Quetta (upper case to signify super, super, super, super, super BIG) represents 10^{30}.
5 https://www.ptb.de/cms/fileadmin/internet/forschung_entwicklung/countdown_new_si/Lesezeichen_zum_neuen_SI.pdf
6 Johann Wolfgang von Goethe, Faust: A Tragedy, Part One.
7 Genesis, 1.1–1.5.
8 https://youtu.be/nhqlOI-WSxU?si=TeX8FAYyu2WVZ8tn

METAS article on climate and ocean observations

Over the last five years, **Céline Pascale,** Domain Manager at METAS, has been actively involved in the development of the European Metrology Network (EMN) for Climate and Ocean Observation as Vice-Chair. The EMN promotes partnerships between measuring specialists and communities that carry out climate and ocean observations. In this way, metrology provides the expertise needed to accurately and reliably monitor essential climate and ocean variables. METAS benefits from this directly, particularly in its reference work with gases and particles.

Dr Cédric Blaser receives the IEC 1906 Award

The Head of the METAS Laboratory Electrical Energy and Power, **Dr Cédric Blaser,** has received the IEC 1906 Award for his work on standardising electricity meters. In recent years, he has been actively involved in creating and revising more than ten standards at the European and international level. He is a member of the Technical Committee "Electrical energy measurement and control" (IEC TC 13).

Of the 228 IEC 1906 Awards bestowed in 2024, five went to Swiss experts.

New Head of Metrology in Physics

Ulrich Schlapbach is to take over as Head of Metrology in Physics 2 from the beginning of January 2025. Schlapbach studied electronics at ETH Zurich and had a long career with ABB, where he worked in various positions and departments. During this time, he led multiple large development and innovation groups, as well as major projects.

Did you know that METAS, the Federal Institute of Metrology, has more than 6,400 measuring instruments?

These instruments and the extensive specialist expertise of our employees enable accurate and traceable measurements for a wide range of applications. Through maintenance, renewal, further development and the advancement of new methods, METAS remains at the forefront of international metrology, guaranteeing first-class services.

Film recommendation

The Last Artifact – (Re)Defining the Universe

The film is in English and is available to watch on PBS.

In 2018, the kilogram was redefined: the metal cylinder, which had been the international weight standard since the French Revolution, was decommissioned. This was, and is, an important milestone in the history of metrology. The film "The Last Artifact – (Re)Defining the Universe" documents the historical significance of the cylinder and its impact on everyday life.

BA student at METAS awarded the Max Lüthi Prize

The Max Lüthi Prize recognises young researchers for their excellent Bachelor's dissertation in chemistry at a Swiss university of applied sciences. **Céline Spack,** the winner of this year's prize, completed her Bachelor's thesis in cooperation with the School of Engineering and Architecture of Fribourg (HEIA-FR) at METAS. As part of her thesis, Céline Spack worked on a peat detection method using long-chain alkanes. In METAS labs, she tested whether these biomarkers could be used as suitable indicators of peat in plant soil.

METAS Prize for physics awarded to Simon Scheidegger

At the annual conference of the Swiss Physical Society held at ETH Zurich in September, **Simon Scheidegger** was awarded the 2024 METAS Prize for physics. Simon used the METAS frequency distribution network, which is traceable to the International System of Units, to determine the frequency of electron transitions between states with high quantum numbers. With the results of his excellent doctoral thesis, he was able to determine a more precise value for the Rydberg constant and the size of the proton.

Dr Andrea Rösch wins the METAS Award

With this prize, METAS recognises young researchers for outstanding contributions in the field of metrology in chemistry and/or biology. **Dr Andrea Rösch** has received this year's METAS Award for her outstanding work at Agroscope on the development of a comprehensive method for measuring around 150 pesticides in soils. The method is based on quantification using 95 isotope-labelled internal standards, which compensate for the matrix effects of the soil samples. This new measuring method enables precise monitoring of traces of pesticides in agricultural soils.

A. Rösch et al., A multi-residue method for trace analysis of pesticides in soils with special emphasis on rigorous quality control, Analytical and Bioanalytical Chemistry, Volume 415, p. 6009–6025, 2023, https://doi.org/10.1007/s00216-023-04872-8

International

The International Measurement Confederation IMEKO

At the end of August 2024, the World Congress of the International Measurement Confederation (IMEKO) took place in Hamburg. METAS was also represented at this Congress through various contributions. But who is familiar with this organisation and what is IMEKO's purpose? Reason enough to introduce this institution in a little more detail.

Dr Hugo Lehmann

International Measurement Confederation IMEKO

Technological advancements and globalisation are unthinkable without the standardisation of units of measurements and the accompanying measuring methods. This is what makes international norms and standards and the global compatibility of technology possible in the first place. This is where IMEKO comes in; its goal is to support the international exchange of knowledge on measuring technology. Today, over 40 countries are represented in IMEKO, including Switzerland. The Swiss Society of Automatic Control (SSAC) (Schweizerische Gesellschaft fur Automatik [SGA]) acts as the Swiss member organisation, while METAS, as the national metrology institute, provides the national delegate on behalf of the SSAC.[1]

IMEKO has been domiciled in Hungary as an association since its foundation in 1958. This is astonishing when you consider that, just two years prior, the Hungarian revolution was quashed by the Soviet Union. Establishing an international organisation in support of East-West dialogue in this historical context demonstrated the IMEKO founders' courage, conviction and world view.[2]

Technical Committee

IMEKO's scientific and technical work takes place within the framework of 25 Technical Committees (TCs).[3] These are broadly autonomous and organise thematic conferences, symposiums and workshops to promote scientific exchange. Over the course of the years, this has involved consistently addressing new topics. For example, the "Quantum Measurement and Quantum Information" TC was only formed in 2021. Switzerland is represented in more than half of the TCs. In terms of METAS, its active involvement in TC9 "Flow Measurement" is particularly worth highlighting.

World Congress 2024 in Hamburg

The IMEKO World Congress takes place every three years, with all TCs taking part. At the end of August 2024, the Congress[4] took place in the Hanseatic city of Hamburg. Under the motto "Moin", the local dialect word for hello, the IMEKO President Prof. Frank Härtig – who is also Vice President of the Physikalisch-Technische Bundesanstalt (PTB), the National Metrology Institute of Germany – welcomed the IMEKO community to Germany. Over 1,100 participants came together from 25th to 29th August in the

IMEKO 2024 conference participants in the plenary hall of the Hamburg Congress Centre.

renovated Congress Center in Hamburg. There, the participants were greeted with excellent conditions for a week full of numerous presentations, posters and, above all, plenty of opportunities for discussion. The Congress was rounded off with the opportunity to visit various companies in the Hamburg area and the PTB in Braunschweig. Those who missed the wonderful congress in Hamburg can already note the details of the next IMEKO World Congress in 2027[5] in Rimini on the Adriatic Sea.

IMEKO publication bodies

As well as organising congresses and technical meetings, IMEKO also has its own publication bodies. On the one hand, the open-access online magazine "Acta IMEKO"[6] enables direct access to publications from the IMEKO TCs. On the other hand, the IMEKO magazine "Measurement"[7] is a reference for publications in the field of measuring technology.

Last but not least

A Swiss article about IMEKO wouldn't be complete without mentioning Karl Ruhm. Karl has represented Switzerland as a delegate in IMEKO for 25 years, alongside his work at ETH Zurich.[8] He deserves a big thank you for his tireless work for IMEKO, but also for measurement technology in general.

Global dialogue across political boundaries was not just important in the founding years of IMEKO, it has also retained its relevance in today's geopolitical environment. Institutions like IMEKO offer a necessary platform for such dialogue. We are therefore committed to preserving such opportunities. We wish IMEKO every continued success!

1 https://www.sga-asspa.ch/verein/fachdelegierte
2 https://sztaki.hun-ren.hu/en/current/news/2018/nobel-prize-holders-aircraft-turbines-and-new-hungarian-members-success-imeko
3 https://www.imeko.org/index.php/technical-committees
4 https://www.imeko2024.org/home
5 https://imeko2027.org/
6 https://acta.imeko.org/
7 https://www.sciencedirect.com/journal/measurement
8 https://www.imeko.org/images/imeko/Newsletternovember2022.pdf

Courses

Knowledge transfer for all

The Federal Act on the Federal Institute of Metrology stipulates that the Swiss Confederation must provide the necessary metrological infrastructure and expertise for the Swiss economy, research and administration. METAS fulfils the duties assigned to it by offering numerous training courses on metrology that are accessible to all.

Is it really possible to guarantee an accuracy approaching one hundredth of a billionth of a second for a GPS-type navigation system to display a resolution of 1 m?

How can a coffee capsule manufacturer guarantee the stability of the range of flavours on offer?

Can we be confident that a speeding ticket is not the result of an arbitrary decision?

The difference in average global surface temperature rose by 0.7 °C during the 20th century. How can such small variations be measured on such a large scale?

In recent years, annual sales of smartphones have exceeded 1.3 billion units. How do manufacturers manage to ensure the quality of models that have sold over 100 million units?

To achieve such performance, you need to be able to measure it accurately, fairly, repeatedly and reproducibly. In a word: you have to measure!

> “They meet the expectations and needs of participants very effectively.”
>
> Helena L., Switzerland

From ancient measurements to metrology

Even in the earliest cultures, measurements had to be made (weight, lengths), for example for bartering with third parties or for taxes. To avoid disputes between the parties involved, “reference measurements”, today called “standards”, quickly emerged.

> “Without a doubt the best course I’ve ever taken. VNA Tools is very effective and well designed.”
>
> Thecla C., USA

Yet every country and every province had established their own units of measurement over thousands of years. Only during the course of the Enlightenment and the French Revolution did French scientists develop a reference system based on natural reference quantities that had the same value for everyone. Metrology, the science of measuring, was born and has been developing further ever since.

Training for businesses and flexible approach

METAS courses can also be held for businesses and abroad. Our programme includes one- or three-day course modules, comprised of the basic courses, with more in-depth focus on specific subject areas that you can tailor to your needs.
On request, METAS can also develop new courses or share insights that relate to very specific topics.

The experimental determination of the gravitational constant and its uncertainty is part of the course on the Principles of Measurement Uncertainty.

The quality infrastructure

Today, the quality infrastructure of a modern state like Switzerland is a system that includes public and private organisations. These organisations define the guidelines, the relevant legal and regulatory frameworks and the procedures required to support and fortify the quality, safety and environmental compatibility of goods, services and processes. There is general consensus that this quality infrastructure is based on three main pillars, namely metrology, standardisation and accreditation.

Having an understanding of the fundamental and essential principles of metrology is therefore greatly significant. Article 2 of the Federal Act on the Federal Institute of Metrology (Bundesgesetz über das Eidgenössische Institut für Metrologie, EIMG) stipulates that the Confederation pursue a series of objectives through the Institute, including the provision and organisation of the metrological infrastructure necessary for the Swiss economy, research and administration. Alongside the commercial and research services that METAS provides, the Institute also shares basic metrological knowledge through its wide range of courses. These courses are aimed at all stakeholders mentioned in the law: technical professionals, scientific staff and management staff.

Overview of METAS courses.

The basic knowledge

Two basic courses teach the essentials of metrology. They form the backbone of METAS's range of courses:

- The **Basics of Metrology** course is designed for anyone who wants to invest a day in getting an overview of all essential aspects: from the history of the International System of Units to traceability, and from public and private regulations to conformity assessments, to name but a few.
- The **Principles of Measurement Uncertainty** course is designed for those interested in gaining a deeper understanding of the estimation and assessment of uncertainty, a parameter that is inherently tied to any measurement. The theoretical part of the course is interspersed with subjects such as the experimental determination of the value and the uncertainty of the gravitational constant.

Targeted in-depth study

METAS offers a range of special courses for certain sectors or on highly specialised, technical subject areas. These courses take place at regular intervals or when there is enough demand, and cover topics such as

- **Measurement uncertainty and conformity assessments:** reliable assessment of the conformity of a product or measurement, in particular by estimating the conformity probability, determining acceptance ranges and carrying out risk analyses.
- **VNA Tools course:** introduction to an internationally used free software from METAS for the analysis and metrological quantification of high-frequency signals using a vector network analyser. The free METAS library UncLib, a calculation tool for general measurement uncertainty for all specialist areas, is also introduced.
- **Distance-time analysis using video recordings:** determining the speed of vehicles using videos and distance measurements.
- **Nanoparticle measuring instrument course:** overview of the legal aspects and challenges of measuring nanoparticles in diesel engines.

Training

Designers, engineers and technicians working creatively to develop and fine-tune a GPS system, a manufacturing process for smartphones or coffee capsules, or scientists studying the health of the Earth's climate, all need to be able to make decisions based on reliable data. The courses offered by METAS are one response to the need for continuing education in a rigorous approach to the discipline of measurement.

METAS
Your reference.

WORLD METROLOGY DAY

20 MAY 2025

150 years of the Metre Convention

Measurements for all times, for all people

BIPM CELEBRATING 150 1875 - 2025

70 OIML celebrating 70 years 1955 - 2025

In support of the World Metrology Day 2025
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2024 • 2033 International Decade of Sciences for Sustainable Development

worldmetrologyday.org