
# MIKES Metrology

# TOPFIVE

SPRING 2014

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The cover image was taken in one of the length metrology laboratories where the most common industrial length measurements on devices ranging from micrometers to gauge blocks are performed.


Cover image and layout: Jenni Kuva
Espoo 2014

# SPIRIT OF THE GAME

Dear reader,

Uncertainty of the measurement result has to be known more accurately in industrial processes. Better, traceable measurements with better knowledge about uncertainty of measurement results are necessities in getting reductions in processing costs. These are among facts very well known to metrologists. However, when you read these on editorial page of a newspaper or from unknown student's thesis one is closer to the goal MIKES and the whole metrology community is aiming at. This change we are currently witnessing in Finland. It also is nice to deliver our research results to reporters in Finland and abroad when asked. Usually our research is highly valued and understood to be a necessity to support competitiveness in Finland and in Europe.

The importance of metrology is emerging in China. It is known that China has multiplied the investments for metrology infrastructure during the last years. New areas of metrology related to ICT, sensor networks and big data are emerging. These issues have been investigated in Finland in the CLEEN Ltd./MMEA research in energy and environment sectors. MIKES has an active role in this 50 M€ programme as the program manager, as a participant in its quality assurance task and as a developer for novel measurement technologies for water and air quality measurements. The quality aspects are at high priority and MMEA is even sometimes called as a very large metrology programme. One of the MMEA's pilot studies has been carried out at the Shenzhen University. In this pilot, a novel air quality monitoring system has been set up including data sources, such as on-line stations, crowdsourcing and big data. The quality assured value chain from sensors to services has successfully been implemented and tested. This pilot has been a good reference and it has created new business cases for MMEA partner companies in Asian market. Next the pilot concept will be set up in Beijing. Active discussions have been carried out with the Chinese National Institute of Metrology and CLEEN Ltd. See http://testbed.mmea.fi.

The favourable situation in metrology is not going to last long without targeted research. One big aid here is the actively proceeding EMRP-programme (European Metrology Research Programme) with its 400 M€ budget. At the moment, MIKES participates in 37 projects and coordinates four of them. Good results have been reached including world records. The big number of projects means that major part of our research originates from EMRP. Major part stands for roughly two thirds of the incoming research money. This active international cooperation also means increasing number of national research projects. Wishes are high about the possible, I believe probable, in 2014 starting EMPIR (The European Metrology Programme for Innovation and Research) with its 600 M€ budget. Opening of the new programme to universities and research institutes have already been widely noticed.

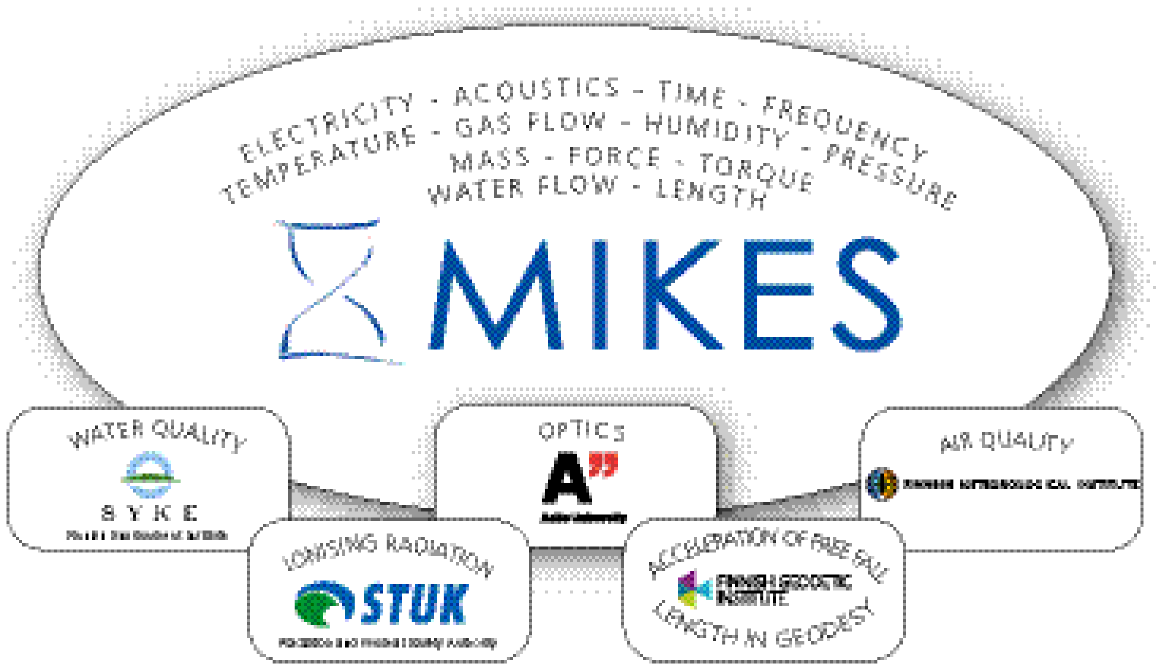
The invisible infrastructure of MIKES Metrology includes quality system. Here we continue the voluntary peer review program together with national metrology institutes from Czech Republic (CMI), Poland (GUM) and Slovakia (SMU). Several visits have been accomplished and new ones are planned. Activities of this project are coordinated by MIKES. In EURAMET it is Finland's turn to present our quality system to the other colleagues in EURAMET. Transparency is a valid value here.

In the year 2014, changes will be implemented in how research is organised in Finland and new decisions are expected. Restructuring is acceptable and even desirable, but the fear about cuts in budget is present. MIKES is involved in this intensification process too.

Otaniemi in January 2014

Heikki Isotalo

# MIKES METROLOGY IN BRIEF




*MIKES and Designated Institutes.*

MIKES is a specialised research institute for measurement science and technology. As the National Metrology Institute of Finland, MIKES is responsible for the implementation and development of the national measurement standards system and realisation of the SI units in Finland. MIKES designates other National Standards Laboratories in Finland. The number of designated institutes is 5. Staff number is 70 supported by MIKES administration and few outsourced positions. The MIKES building is situated in the city of Espoo and its branch office in Kajaani is the northernmost National Standards Laboratory in the world. The high-quality laboratories provide the most accurate measurements and calibrations – over 1600 certificates per year – in Finland. MIKES also performs high-level metrological research and develops measuring applications in partnership with industry. The activities of MIKES aim to improve industrial competitiveness, the national innovative environment, and public safety. MIKES is a signatory to CIPM MRA (International Committee for Weights and Measures, Mutual Recognition Arrangement) and a member of EURAMET e.V. (European Association of National Metrology Institutes). Through international collaboration, MIKES is linked to the international measurement system and to the European and international metrology research community. MIKES takes actively part in the European Metrology Research Programme (EMRP).

## INCREASING AT MIKES

- Impact of metrology
- Research money
- International collaboration
- Number of staff
- Peer review visits
- Reputation of MIKES
- Laboratory space
- World records

## DECREASING AT MIKES

- Uncertainty
- Direct state budget
- Derivative of increase in number of customers
- Number of CMCs (in Finland 341, total 24460 lines)

ARCTIC CIRCLE

Facts about Finland (12/2013)

- 5 449 657 inhabitants – and growing
- 338 430 km²
- Capital: Helsinki

KAJAANI

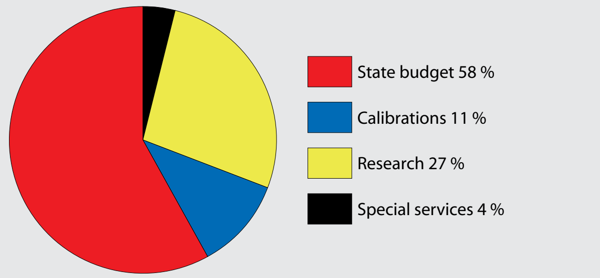
- Land border with: Norway, Sweden, Russia
- Official languages: Finnish and Swedish
- Currency: euro since 2002
- Gross domestic product: 194 • $10^9$ €
- Biggest trade partners (export): SE, RU, DE, USA, NL
- R&D investments: 4.0 % of the GDP
- Homeland of Angry Birds, Clash of Clans and Hay Day
- Standard & Poor's grade AAA
- Greediest ice cream eaters in Europe
- Public sector – biggest in the world
- Among the most uncorrupted countries in the world
- 188 000 lakes
- 2 000 000 saunas
- 203 700 reindeer (Ministry decision)
- Temperature variations: -38.2 °C … +32.4 °C
- National animal: bear

Source: Statistics Finland

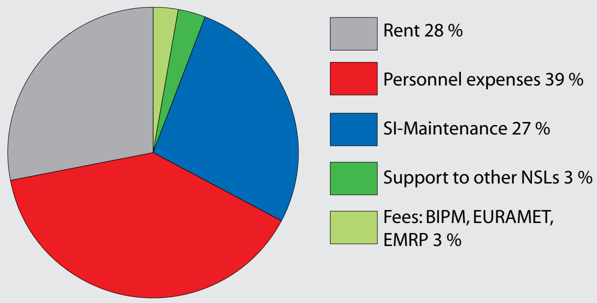
ESPOO HELSINKI

# YEAR 2013 IN NUMBERS

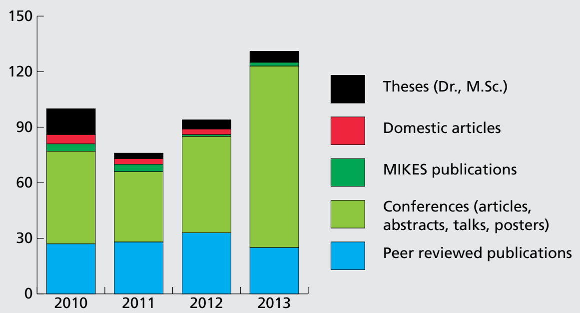
Total budget of MIKES was 12 M€ including MIKES Metrology, FINAS (Finnish Accreditation Service) and administration. FINAS is essentially self supporting and expenses of administration are divided to Metrology and FINAS as a ratio of personnel. Budget of MIKES Metrology alone was 7.8 M€ in 2013.




*Proceeds of MIKES Metrology.*




*Costs of MIKES Metrology.*




*Publications.*

# EMRP EUROPEAN METROLOGY

**EMRP is a metrology-focused European programme of coordinated R&D that facilitates closer integration of national research programmes. It enables European metrology institutes, industrial organisations and academia to collaborate on joint research projects within specified metrology fields.**

The EMRP has been established under FP7 and it is supported through Article 185 of the European Treaty. The EMRP is implemented by EURAMET e.V. (the European Association of National Metrology Institutes), organised by 23 National Metrology Institutes (NMIs), and supported by the European Union.

The EMRP is jointly funded by the European Commission and the participating countries with a total budget of 400 M€ over an approximately seven year period. It provides the opportunity for the user community and other stakeholders to directly suggest topics that the metrology community should address with its resources. Additionally, researcher grant schemes are available to bring external expertise into the research projects, and there will be the opportunities for organisations to participate in the research projects with their own resources where it is mutually beneficial to do so.

The last call of the current EMRP was in 2013. A preparation of a successor initiative of EMRP under Horizon 2020, called EMPIR, is underway. Tentative volume will be 600 M€ and it is planned to start in 2014.

EMRP
European Metrology Research Programme
▶ Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

## MIKES PARTICIPATION IN THE EMRP PROJECTS

### Environment and Metrology for Industry, 2011–2014:

**MacPoll** – Metrology for Chemical Pollutants in Air

**PartEmission** – Emerging Requirements for Measuring Pollutants from Automotive Exhaust Emissions

**MetEOC** – European Metrology for Earth Observation and Climate

**EUMETRISPEC** - Spectral Reference Data for Atmospheric Monitoring

**MeteoMet** – Metrology for Pressure, Temperature, Humidity and Airspeed in the Atmosphere

**MetroRWM** – Metrology for Radioactive Waste Management

**DYNAMIC** – Traceable Dynamic Measurement of Mechanical Quantities

**MADES** – Metrology to Assess the Durability and Function of Engineered Surfaces

**Frequency** – New Generation of Frequency Standards for Industry

**Ultrafast** – Metrology for ultrafast electronics and high-speed communications

**Scattero** – Metrology of Small Structures for Manufacturing of Electronic and Optical Devices

**SolarUV** – Traceability for Surface Spectral Solar Ultraviolet Radiation

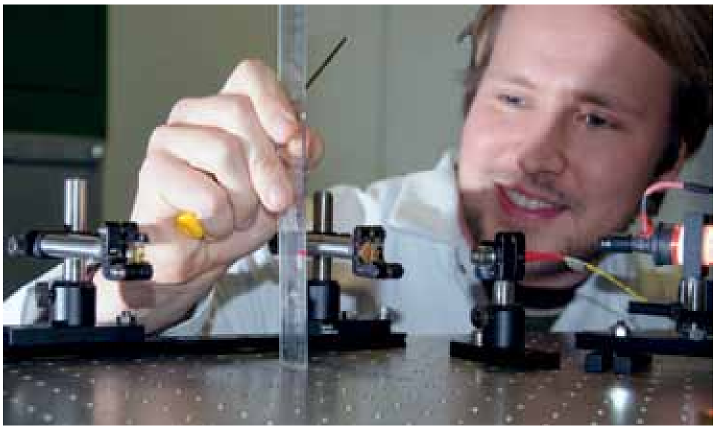
**MIQC** – Metrology for Industrial Quantum Communication Technologies

**Thin Films** – Metrology for the Manufacturing of Thin Films (Aalto University)

# MetAMC

## Metrology for Airborne Contamination in Manufacturing Environments

*Project coordinator Tuomas Hieta, MIKES*
*Partbers: CMI, INRIM, NPL, PTB, VSL, HC Photonics*
*REGs: Politecnico di Torino, University of Oxford, Aalto University*



Extreme purity in production is required in several industrial sectors where the aim is to operate at ever smaller scale, for instance in semiconductor, nanotechnology, photovoltaic and high-brightness and organic LED industries. New promising technologies for minimising the amount of contaminant particles in clean room environments have emerged in recent years. However, when aiming for smaller component sizes, the elimination of airborne contamination is becoming a true challenge in clean room microfabrication.

Airborne molecular contamination (AMC) is chemical contamination in the form of vapours and aerosols mainly formed by chemicals used in the manufacturing process. AMC has adverse effects on products, processes or instruments: e.g. corrosion of metal surfaces on the wafer and formation of contamination layers on surfaces like optics and wafers after reaction/condensation. The formation and behaviour of these contaminants in production environment is still largely unknown due to the lack of sensitive on-line on-site measurement methods. The detection of these molecules at trace levels introduces new challenges not only for the development of highly sensitive methods but for metrology as well.

The MetAMC project aims to measure airborne molecular contamination in clean room environments at low detection levels by developing highly sensitive and accurate methods of optical spectroscopy. Moreover the project aims to create reference materials at relevant concentration levels traceable to the SI-units.

In order to develop state-of-the art optical spectroscopic techniques for traceable AMC monitoring in clean room environ-

# RESEARCH PROGRAMME

## New Technologies and SI Broader Scope, 2012–2015:

**MechProNO** – Traceable measurement of mechanical properties of nano-objects

**MetNEMS** – Metrology with/for NEMS

**METCO** – Metrology of electro-thermal coupling for new functional materials technology

**InK** – Implementing the new Kelvin

**NEAT-FT** – Accurate time/frequency comparison and dissemination through optical telecommunication networks

**Ion Clock** – High-accuracy optical clocks with trapped ions

**NewKILO** – Developing a practical means of disseminating the new kilogram

**Qu-Ampere** – Quantum ampere: Realisation of the new SI ampere

**subnano** – Traceability of sub-nm length measurements

**NEWSTAR** – New primary standards & traceability for radiometry

**Angles** – Angle metrology

**Q-WAVE** – A quantum standard for sampled electrical measurements

**Surveying** – Metrology for long distance surveying

**CRYSTAL** – Crystalline and self-assembled structures as length standards

**Force** – Force traceability within the meganewton range

**METefnet**– Metrology for moisture in materials

## Metrology for Industry, Open Excellence and SI Broader Scope, 2013–2016:

**XD Reflect** – Multidimensional reflectometry for industry

**TIM** – Traceable in-process dimensional measurement

**MetAMC** – Metrology for airborne molecular contamination in manufacturing environments

**SIQUTE** – Single-photon sources for quantum technologies

**MICROPHOTON** – Measurement and control of single-photon microwave radiation on a chip

**GraphOhm** – Quantum resistance metrology based on grapheme

**AIM QuTE** – Automated impedance metrology extending the quantum toolbox for electricity

**ITOC** – International timescales with optical clocks

## Energy and Environment, 2014–2017:

**SolCell** – Metrology for III-V materials based high efficiency multi-junction solar cells

**SmartGrid II** – Measurement tools for Smart Grid stability and quality

**ThinErgy** – Traceable characterisation of thin-film materials for energy applications

**Biogas** – Metrology for biogas

**PhotoClass** – Towards an energy-based parameter for photovoltaic classification

**Drive Train** – Traceable measurement of drive train components for renewable energy systems

**FutureGrid** – Non-conventional voltage & current sensors for future power grids

**MESaIL**– Metrology for efficient and safe innovative lighting

**HIGHGAS** – Metrology for high-impact greenhouse gases

**MetEOC2** – Metrology for earth observation and climate

**MetroDecom** – Metrology for decommissioning nuclear facilities

**MetNH3** – Metrology for ammonia in ambient air

**MeteoMet 2** – Metrology for essential climate variables

**Atmoz** – Traceability for atmospheric total column ozone (Aalto University)

ment, the project has the following objectives:

- By laboratory tests, intercomparisons and field tests check the principal and practical usability of photo-acoustic spectroscopy (PAS), cavity ring-down spectroscopy (CRDS) and cavity-enhanced absorption spectroscopy (CEAS) for AMC online detection with a 5-min time resolution and 1 ppb sensitivity.
- Develop NICE-OHMS (Noise-immune cavity-enhanced optical-heterodyne molecular spectroscopy) for improved sensitivity of AMC and study options for extending the NICE-OHMS to more complex molecules. Investigate possibilities to develop alternative optical techniques such as femtosecond combs or FTIR for trace gas detection of multiple species.
- Improve the applicability of gas chromatography to AMC monitoring by using a technique based on a negative temperature gradient. The developed method will not only improve the separation of analytes, but also increase the sensitivity.
- Develop dynamic generation methods for trace level airborne molecular contaminants and a portable material generator as well as suitable sampling techniques for practical AMC monitoring.

During the first stages of the project MIKES has investigated suitable spectral windows for potential analytes using spectral databases. From the results of performed simulations, suitable spectral windows in the near-infrared were identified for ammonia, formaldehyde, hydrogen fluoride, hydrogen chloride and hydrogen bromide.

The main activity of MIKES is to develop a real-time photoacoustic spectroscopy analyser ready for field measurements. In cantilever-based photoacoustic spectroscopy, a conventional microphone used in PAS is replaced by a far more sensitive cantilever pressure sensor. The movement of the cantilever is precisely measured with a laser interferometer which is able to accurately measure displacement down to the picometre scale. MIKES will combine cantilever-based PAS with moderate cavity enhancement and/or optical amplification to achieve detection limits beyond the current state-of-the-art for analytes selected based on the spectral simulations. A PAS measuring device suitable for field testing will be constructed. By using a multi-pass configuration or optical amplifiers the effective light intensity is expected to enable detection down to the ppt level. Preliminary studies show that with 5 min averaging time detection sensitivities below ppb are achievable at least for ammonia using PAS with optical amplification.

Other activities of MIKES in the project include making a survey of commercial light sources for the potential analytes based on the spectral analysis, undertaking a comparison between the developed real-time photoacoustic spectroscopy analyser and existing commercial analysers in clean rooms, carrying out a comparison together with PTB and VSL between PAS, CRDS and CEAS for at least one analyte with the aim to reach detection limits of 100 ppt or better and together with PTB and VSL make recommendations on AMC monitoring in the form of a Good Practice Guide, among others.

# METefnet

## Metrology for Moisture in Materials

*Project coordinator: Martti Heinonen, MIKES*
*Partners: BRML, CETIAT, CMI, DTI, INRIM, NPL, TUBITAK, UL, University of Tartu*
*REGs: University of Cassino, University of Oulu*

Many solid materials are highly affected by moisture when processing into various products. Some 70 % of all producers industries use drying for removal of water or another solvent by evaporation of their products. Yet direct measurements of "dryness" are under-used, due to insufficient reliability and lack of traceability in moisture measurements. Errors and inconsistencies in moisture measurement and control in industrial processes lead to decreased process speed/throughput and increased wastage, shortened durability of materials, increased energy consumption in drying.

Reliable moisture measurements in solids are very challenging. More than 1300 documentary standards are in active use because available measurement methods, reference methods and even the current definitions for moisture as a measurand are material specific. Due to this method dependency, different measurements are not comparable and the actual uncertainty often unknown. Hence, there is a fundamental need to move away from method-based standardisation of procedures, towards outcome-based verification of measurement results through calibrations traceable to the SI.

The aim of this project is to enable improved dissemination of SI traceability to moisture measurements in industry by removing ambiguities and inconsistencies in moisture measurement and calibration techniques. This will be achieved through development of new more relevant and effective methods of realising and disseminating SI units of moisture and provision of metrology infrastructure for moisture measurements. The objectives of the project include:

- unambiguous realisation methods and new primary standards for water mass fraction
- effective general principles of SI traceability in the field of moisture measurements
- new certified reference materials with SI traceability & improved stability
- novel transfer standards to enable dissemination of SI traceability with optimal accuracy
- methods for quantifying and reducing the effect of sample transport and handling
- a novel calibration facility with SI traceability for surface moisture meters
- practical but metrologically sound methods for estimating uncertainty in selected industrial applications
- a coherent and developed moisture metrology infrastructure in Europe.

# MICROPHOTON

## Measurement and Control of Single-Photon Microwave Radiation on a Chip

*Project coordinator: Antti Manninen, MIKES*
*Partners: INRIM, NPL, PTB, Aalto University, Lancaster University, Royal Holloway University of London*

Our ability to build electronic devices at the nanoscale and operate them at millikelvin temperatures has opened up the possibility to design, operate and utilise devices based on quantum physics. One example is the possibility to implement interactions between microwave photons and electrons in superconducting circuits. This has promoted the progress of quantum information processing and communication in such a way that the information technology landscape may radically change over the next decade. Yet, electromagnetic metrology for microwave frequencies at very small signal levels, ultimately at the level of single photons, is still in its infancy.

The development of microwave photon detectors and sources at the single-photon level is essential in many quantum applications, e.g., in quantum computing, in quantum metrology, and in ultrasensitive spectrum analysis of cryogenic environments. However, currently no detector can reliably resolve single microwave photon events, because the energy of a microwave photon is much lower than of an optical photon. Also, the blackbody radiation spectrum has occupancy of microwave photon states down to below 100 mK. Hence, the detection of microwave photons at the quantum level must depend on extremely sensitive detectors, operating in highly shielded environments at low temperatures.

The project develops microwave detectors and sources on single-photon level and improves performance of cryoelectronic quantum devices by minimising effects from background microwave radiation. The objectives of the project include:

- Development of single-microwave-photon detectors which give spectral information of radiation and cover a frequency range from below 10 GHz up to 300 GHz. The methods will be based on superconductor and semiconductor nanodevice technologies.
- Development of cryogenic sources of microwave photons to cover frequencies between 4 GHz and 300 GHz and their use in characterisation of the developed photon detectors.
- Characterisation and minimisation of background microwave radiation in cryogenic measurements of nanoelectronic devices.
- Demonstrations of improved performance of cryoelectronic quantum nanodevices by close-to-perfect elimination of background microwave radiation from the environment.

The project will have a great scientific impact realising for the first time practical single-microwave-photon detectors and sources. This will lead to electromagnetic metrology for microwave frequencies at very small signal levels, ultimately at the level of single photons.

MIKES has two main technical activities in the project. One of them is to develop and optimise single-photon microwave detec-

The work focuses on the following material groups: pharmaceuticals, polymer/plastic, foodstuffs, feed, biomass, wood based material. However, many of the outcomes will be suitable for extension to wider classes of materials and applications.

The main activities of MIKES include development of a primary standard for water mass fraction of solid samples up to 400 g and investigation of the effect of sample handling on the uncertainty of moisture determinations in laboratories.

The primary standard will comprise the oven-drying method and measurement of vaporised water during drying by a capacitive humidity sensor and a steam trap. In this way we can determine the fraction of total mass loss that is actually due to water in the sample. Also, continuous exhaust humidity monitoring enables the determination of the binding level of water removed from the sample during drying. These are the key features when looking for unambiguity and true SI traceability in moisture measurements.

Sample handling is often a major error source in moisture determinations. The moisture content of a sample is affected by variations in ambient conditions when packing, transporting, unpacking, crusching and grinding. MIKES will develop methods for including this in the measurement uncertainty analysis.

In this project, MIKES will focus in moisture in biomass and wood-based materials.

During the first stages of the project MIKES has designed and set up a prototype of the primary standard and performed preliminary tests for it.

tors based on single-electron transistors (SETs). Especially SINIS (Superconductor - Insulator - Normal metal – Insulator - Superconductor) structures will be investigated due to their unique potential to detect even single microwave photons and give spectral information.

In a SINIS-SET detector, a microwave photon excites an electron from a normal-metal island to a superconducting electrode and a nearby SET observes the transition. The detector can be used to measure the spectrum of the incoming radiation by tuning the energy threshold with a nearby gate electrode voltage. Different versions of SINIS-detectors (SINIS trap, double SINIS-SET) will be studied in environments with different background microwave radiation. Special focus will be on understanding the coupling of microwaves to the detector through the leads and from the free space.

Another major task of MIKES is investigation on the effects of background microwave radiation on quantum nanodevices in cryogenic environment and implementation of an ultraquiet microwave environment for quantum nanodevices: quiet beyond anything known in the universe. Improvement of performance beyond the present state of the art is expected in at least two categories: reduction of dark counts, i.e. noise induced photon counts, in SINIS-SET based devices, and reduction of the average number of noise-generated quasiparticles in a superconducting circuit to well below 1.

During the first stages of the project MIKES has concentrated on nanofabrication issues of the SINIS devices in order to minimise dark counts caused by nonidealities of the components. Design and realisation of measurement setup and software are in progress. The first experiments on NISIN-SET samples with a superconducting island in the middle have been performed to investigate the effect of microwave background on superconducting elements.

# ENVIRONMENTAL RESEARCH

Text: Markku Vainio, Alexandre Satrapinski, Martti Heinonen
Photos: MIKES archives

**Accurate measurements of atmospheric composition reveal essential information on the state of our environment and on climate change and provide experimental basis for the development of climate models. For the measurement of trace gases MIKES has investigated and developed:**

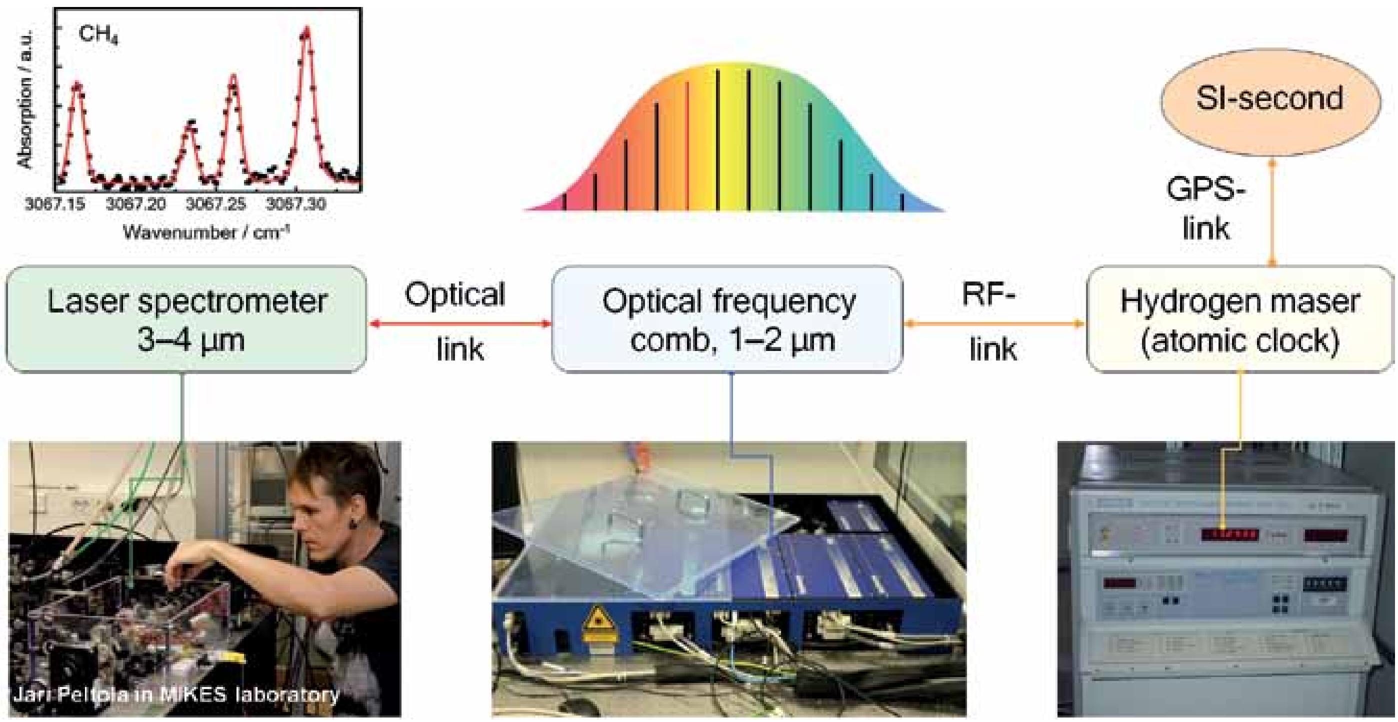
- **a device for spectral measurements of atmospheric gases at mid-IR**
- **graphene-based ultrasensitive gas detectors**
- **metrology for meteorology.**

## ACCURATE SPECTRAL ATLAS FOR ATMOSPHERIC MOLECULES

In practice, accurate measurements of atmospheric composition are based on spectroscopy, i.e., on how different molecules in the atmosphere absorb electromagnetic radiation at different wavelengths. The measured absorption spectra are compared with spectral databases, which contain detailed information on molecular absorption lines. The most extensive databases contain important line parameters determined experimentally for several million absorption lines. By using the listed parameters it is possible to simulate absorption spectra of molecules in various gas compositions and environmental conditions and thus to find the optimal spectral windows for the detection of each molecule and to analyse experimental results by fitting simulated spectra to measured ones. Metrological traceability via an optical frequency comb to an atomic clock gives a hundredfold improvement in accuracy of the absorption line central frequency.

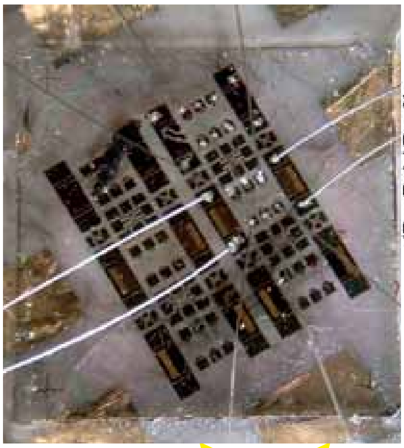
In the EMRP-project EUMETRISPEC, a European high-resolution spectroscopy infrastructure for traceable measurements of spectral line data will be accomplished and the quality of the spectral databases improved by developing measurements traceable to the SI units for determining molecular absorption parameters. The project has concentrated on molecules that are most important in climate sciences and models, e.g. on $CH_4$, $N_2O$ and $CO_2$. MIKES duties include absolute frequency measurements of molecular absorption line central frequencies and pressure shifts in the mid-infrared spectral region that is the most important region for climate sciences.

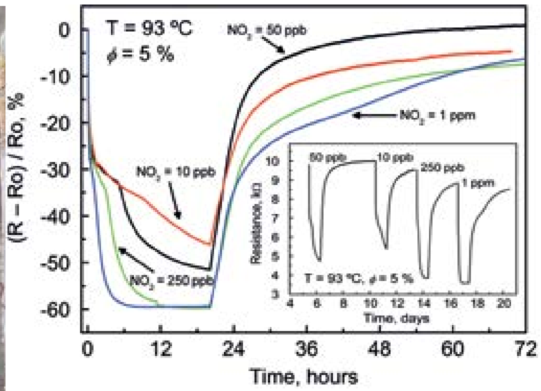
MIKES has in collaboration with University of Helsinki developed a spectrometer that enables traceable frequency measurements at the wavelength region 3–4 µm, in which many important molecules have strong absorption lines. The spectrometer is based on a wavelength tuneable continuous-wave optical parametric oscillator (OPO). The frequency of the OPO beam that is used in the measurements is linked to an optical frequency comb, which in turn is locked to MIKES atomic clocks. This setup guarantees improved measurement accuracy. The first traceable high-resolution spectral measurements were performed using methane. The sensitivity and accuracy of the developed equipment and method allow, in addition to spectral measurements atmospheric gases, measurements of other molecules at trace levels, e.g., molecules present at expiration.



# ULTRASENSITIVE GAS DETECTION USING GRAPHENE

The extreme sensitivity of graphene as a gas detector was realised soon after the discovery of the material, and even individual molecules have already been detected by graphene sheets. However, development of graphene sensors sensitive enough to detect e.g. nitrogen dioxide with concentration below one part per million (ppm) is still an international challenge. MIKES and Aalto University have recently observed a 45 % resistance drop in a graphene film exposed to gas that contained only 10 ppb (parts per billion) of $NO_2$ (see figure, right). Only very few groups have demonstrated as good sensitivity before. Later we observed a clear resistive response even for $NO_2$ concentration below 0.1 ppb. In a recent MSc Thesis work at MIKES, Mr Joni Hämäläinen showed that sensitivity and linearity of $NO_2$ detection can be improved considerably by heating the graphene detector to a temperature above 100 °C. The thesis also includes the first ever results of detecting ozone at 10 ppb concentration by a graphene sensor. This work is a part of the EMRP project Metrology for Chemical Pollutants in Air (MACPoll).






*Relative change in resistance of a graphene gas sensor (left) under exposure to different concentrations of nitrogen dioxide; temperature is 93 °C, relative humidity 5 %. The $NO_2$ exposure starts at time 0 and stops after 20 hours. During that time, $NO_2$ concentration of only 10 ppb causes a resistance drop of 45 %. The inset shows the response of the sample to exposed gas in the real time.*

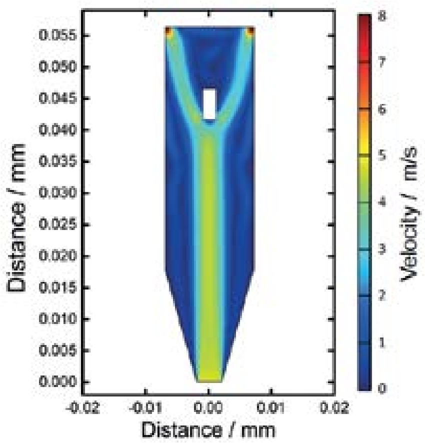
# METROLOGY FOR METEOROLOGY

The assessment of climate change crucially depends on the robustness of climate data and on the uncertainties associated with measurements. New stable and traceable measurement standards, protocols, sensors,calibration procedures and uncertainty-evaluation methods are needed to enhance data reliability and reduce uncertainties in climate models.

In the EMRP project MeteoMet, MIKES is developing a new calibration system for reference radiosondes in terms of air humidity, temperature and pressure. In particular, accurate measurements in a reasonable time is challenging at low temperatures (down to -80 °C) and low pressures (down to 10 hPa abs.). Numerical simulations and experiments were carried out to find an optimal design for a measurement chamber. Applying these results, a first prototype operating in the full humidity and temperature range was recently set up. First calibrations of radiosondes are expected in summer 2014.

In the EMRP MeteoMet2 project starting in autumn 2014, the MIKES radiosonde calibration system will be developed further, with the goal of extending the operating absolute pressure range down to 10 hPa.

*Measurement chamber with an entrance chamber of the first prototype for a calibration system for radiosondes designed at MIKES.*




*Simulated air velocity distribution in a measurement chamber at -70 °C. Stationary solutions was used for studying air velocity and temperature profiles with different inlet flow rates. Effects of water vapour diffusion were simulated time dependently.*


Compact 10

Text: Jari Hällström
Photos: Tatu Nieminen, Serkan Dedeoğlu, Tapio Lehtonen

# THE MOST ACCURATE MILLION-VOLT MEASUREMENT

**Researchers have developed a mobile million-volt DC voltage divider, coordinated by MIKES.**

High-voltage direct current (HVDC) connections are the only technique for transmitting power over the long distances between wind farms far out in the sea to the continent through submarine cable lines, or between countries when interconnection of AC networks is not possible. There are two HVDC cable connections between Finland and Sweden, and one between Finland and Estonia. A second cable connection to Estonia is under construction.

An increasing number of new HVDC lines are being built globally. To measure the power of the current point-to-point HVDC networks, a conventional AC voltage measurement is being used. A precondition for this is that line users reach a mutual agreement on sharing the costs of power losses. For the radial HVDC networks of the future, quantifying losses between various substations and line sections – and sharing the costs fairly between various stakeholders— will not be possible without HVDC metering. For this purpose, calibration techniques need to be developed to assess the uncertainties of HVDC power metering.

The million-volt DC voltage divider enables accurate calibration of voltage sensors used for high voltage direct current transmissions in the manufacturers' laboratories before their delivery on-site. The mobile divider consists of five 200 kV modules, usually located in Finland, Sweden, Germany, Holland and Turkey. To measure voltages in excess of 200 kV, the required number of modules is taken to the calibration site. The highest possible voltage at the moment is one million volts.

Each 200 kV module consists of 204 precision resistors connected in series, providing a total resistance of 2.04 GΩ for one module. When five modules are connected in series for 1000 kV measurement, the total resistance is 10.2 GΩ. A stable 102 kΩ resistor is connected between ground and the low end of the module chain. The scale factor of divider depends on the number of modules connected in series – e.g. 20000:1 for one module and 100000:1 for a system with five modules. The output voltage of the divider is always from 0 to 10 V; this output voltage can be measured by a precision voltmeter.

*Ahmet Merev from TUBITAK checking the precision resistors.*

*Precision resistor sub-modules.*

*Five 200 kV modules of PTB, TUBITAK, VSL, MIKES & SP.*

Inside each module the precision divider is surrounded by another divider for shielding the resistors against interference. The shielding divider takes care of linearisation of the electric field along the divider column, and it also provides a path to lead the corona induced charges to ground.

The uncertainty of the measurement of 1000 kV measurement is less than 0.01 % ($k$=2). The divider is typically used for calibration of DC voltage measuring systems in high voltage testing laboratories; during calibration the reading of the measuring system under calibration is compared with the reading of the reference system.

**NEW WORLD RECORD!**

The testing and calibration of the divider took place in early June 2013 in Aalto University's High Voltage Laboratory. This is the only facility in Finland where voltages of up to one million volts can be tested and calibrated. Five European national standards laboratories took part in the design and construction of the DC voltage divider. Cooperation in this subproject was coordinated by MIKES.

The measurement was part of a project on metrology techniques for HVDC connections under the EMRP.

# THE NEW SI

Text: Ossi Hahtela, Kari Riski, Antti Kemppinen, Alexandre Satrapinski
Photos: Ossi Hahtela, MIKES archives

**In the coming years, the SI system of units is likely to undergo the most comprehensive revision since its introduction 50 years ago. Four base units out of seven, kilogram, mole, kelvin, and ampere, will be redefined in terms of fixed values of fundamental constants: Planck constant $h$, Avogadro constant $N_A$, Boltzmann constant $k_B$, and elementary charge $e$, respectively. Moreover, some of the derived units will be redefined and new recommendations for the practical realisation of the units will be given. MIKES has an important role in this ambitious plan in developing:**

- **primary thermometry methods for the new kelvin definition**
- **a practical means of linking the new kilogram definition to the current mass scale**
- **a quantum standard for current**
- **a quantum resistance standard based on graphene.**

## PRIMARY THERMOMETRY METHODS FOR THE NEW KELVIN

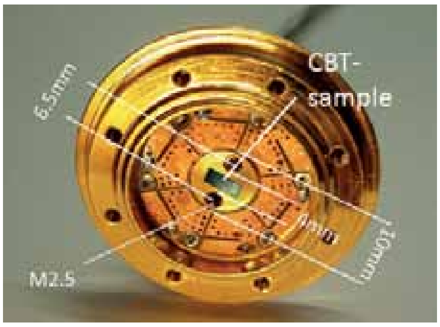
Currently, temperature is defined as thermodynamic temperature and its SI unit is kelvin. The kelvin temperature scale is defined using absolute zero (0 K) and the triple point of water (273.16 K); the point at which the three phases of water – ice, liquid water and water vapour – all exist in equilibrium. In real life, temperatures are often expressed in Celsius: one Celsius degree (°C) equals one kelvin.

Since thermodynamic temperature is difficult to measure, international practical temperature scales based on fixed points have been developed. A fixed point is composed of a pure metal, which has a melting or freezing temperature with good reproducibility. Temperatures between these points are measured using calibrated platinum resistance thermometers. A new definition for kelvin is necessary, as the temperature scale based on separate fixed points has become unpractical and too inaccurate, especially at temperatures far away from the fixed points, e.g. at very high or low temperatures.

A new definition that fixes kelvin to the Boltzmann constant has been proposed. The Boltzmann constant links thermal energy and temperature and its value can be verified with various experimental methods. Thus, problems related to the definition based on the triple point of water can be overcome: e.g. the isotope distribution of water affects the obtained temperature. The new definition enables more accurate temperature measurements in a larger temperature range: from millikelvins to over 3000 kelvins.

MIKES studies potential schemes for the realisation and dissemination of thermodynamic temperature above 1000 °C using absolute radiometers and develops Coulomb blockade thermometers (CBT) for primary and practical thermometry at temperatures below 1 K. So far MIKES has modified its cryostat for CBT measurements, designed and built better performing CBT devices and measurement set-ups. The first measurements have just started.

*Above: Hannu Räsänen aligning the high temperature measurement setup. Below: CBT-sample and its holder for cryostat.*



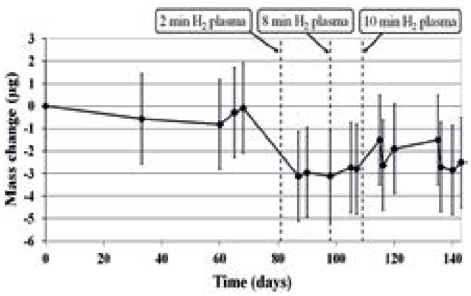

## LINKING THE NEW KILOGRAM TO THE CURRENT MASS SCALE

The unit for mass, the kilogram, is the last of the seven SI base units that is still defined in terms of a material artefact: the International Prototype of the Kilogram (IPK) stored in an environmentally safe vault at the International Bureau of Weights and Measures. Redefining the kilogram in terms of the Planck constant has been proposed.

In order to redefine the mass unit, a practical means of traceability between the current mass scale and the new definition has to be developed. This is necessary for two reasons. First, the watt balance and Avogadro experiments proposed for the realisation of a new definition realise the kilogram in vacuum. On the other hand, the current definition is realised in air. In order to fix the initial value of the Planck constant with relation to the current mass scale, a means to link the IPK in air with a mass in vacuum must be realised. Secondly, once the kilogram is redefined, its realisation in vacuum has to be disseminated to mass standards kept in air.

MIKES investigates changes in surface properties of weight samples due to vacuum exposure and cleaning. The results are compared with mass changes. Also the surface roughness of the samples is determined. Most samples are investigated with an atomic force microscope and some also with a scanning electron microscope. An automatic system for air–vacuum cycling of samples was developed to determine mass or surface changes in weights due to repeated vacuum exposure. Previous measurements with a single exposure have not revealed any measurable mass or surface change.

Several cleaning methods were investigated: Low pressure hydrogen plasma cleaning and UV activated ozone cleaning. Ultrasonic cleaning in ethanol is under way. At present the plasma cleaning seems to be most effective. It is important that the cleaning is effective, reproducible and does not remove base material.




*Measured mass change of a weight after $H_2$ plasma cleaning.*

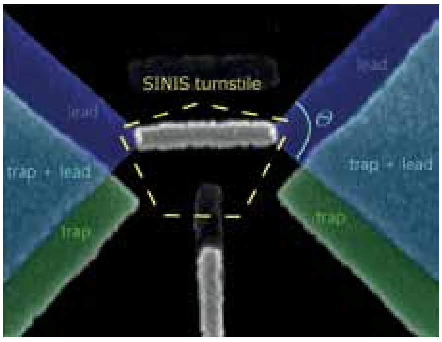
# QUANTUM STANDARD FOR CURRENT

Quantum standards for the volt and ohm have been available for decades but so far a quantum ampere standard that is accurate enough and produces sufficiently high current still does not exist. The recent advancements in single electronics have raised hopes of increasing the current to a level acceptable for a quantum ampere standard. Hence, in the proposed new SI system, the unit of electric current, the ampere, will remain the base unit for electrical quantities and it will be defined by fixing the value for the elementary charge e. The most direct way to realise the ampere in practice would then be pumping a known number ($N$) of electrons one by one with a frequency $f$, thus producing the current $I = Nef$. This requires a device that is able to generate electric current by allowing single electrons to flow in a controllable manner.

MIKES is developing a hybrid turnstile based on both superconducting and normal-metal elements for a quantum standard for electric current. The ultimate goal is a quantum current standard that can be used in the closure of the quantum metrology triangle. In such an experiment the quantized Josephson voltage is applied over a resistor calibrated against the quantum Hall resistance standard and the resulting current is compared against the hybrid turnstile.

In theory, the current of about 100 pA with relative uncertainty below 0.1 parts per million should be feasible by applying 10 hybrid turnstiles in parallel. The theory has been verified and refined by comparing it to experiments in about 20 scientific papers. However, before 2013, the electron beam lithography (EBL) facilities did not permit fabrication of samples that simultaneously fulfil all the criteria, set by the theory, to reach the expected performance. Presently, there is a major ongoing effort to develop fabrication processes that utilise a new state-of-the-art EBL system, and to fabricate samples that could be used as current standards. Hence, 2014 is expected to be a crucial year for the hybrid turnstile development.

The biggest open issues are suppression of electron transport errors due to quasiparticles in the superconducting elements of the turnstile and error counting. The latter is required in the quantum triangle experiment for independent detection of $N$ to separate the potential electron transport errors from the more unexpected deviation of the theoretical output values of any of the three quantum standards.



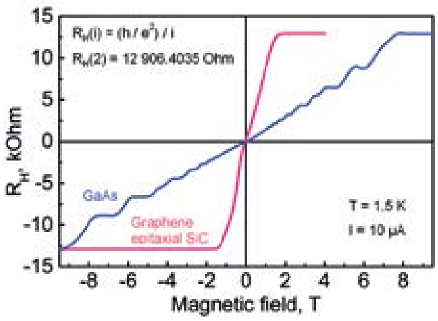

*Hybrid turnstile with fast widening superconducting leads to improve quasiparticle diffusion away from the vicinity of tunnel junctions. Normal-metal traps also reduce the density of quasiparticles.*

# QUANTUM RESISTANCE STANDARD BASED ON GRAPHENE

Graphene, the two-dimensional sheet of carbon atoms with thickness of one or few atomic layers, is the new wonder material for future technology. MIKES has investigated graphene for several years due to its unique properties that make it very promising for metrology. We have concentrated on developing graphene for resistance metrology based on the quantum Hall effect (QHE). Recently MIKES has achieved important breakthroughs in research: quantum Hall resistance plateau with sub-ppm (parts per million) accuracy has been observed in a magnetic field of only 3 tesla.

Since the early 1990's, traceability of resistance has been based on quantum Hall effect which allows very accurate realisation of ohm in terms of two fundamental constants of nature: elementary charge $e$ and Planck constant $h$. Quantum Hall effect can be observed in a two-dimensional electron gas at low temperature and high magnetic field. The most commonly used material system is the phase boundary of a GaAs/AlGaAs heterostructure in which metrologically accurate QHE requires a magnetic field of about 10 T and temperatures below 1.5 K.

Ever since the discovery of graphene about 10 years ago, metrologists have been excited about the possibility of a graphene-based quantum Hall resistance standard, which is expected to be operational at lower magnetic fields and/or higher temperatures than the GaAs-based devices. The groups at NPL, PTB and LNE have previously demonstrated sub-ppm accuracy (even sub-ppb by NPL) for resistance quantisation in graphene in magnetic fields of about 10 T or more. MIKES has now for the first time demonstrated quantum Hall effect at sub-ppm accuracy in a much lower magnetic field, 3 T (see figure on right). This remarkable result was obtained in a large-area sample (0.8 mm x 0.2 mm) of graphene that was grown epitaxially on silicon carbide (SiC). The graphene film was fabricated by Graphensic AB (Linköping, Sweden), and the contacts and patterning were made by Aalto University. Accurate quantisation of Hall resistance was possible due to reduction of carrier concentration with the use of photochemical gating.




*Hall resistance $R_H$ as a function of magnetic field in graphene (red curve) and in GaAs/AlGaAs (blue curve) measured at MIKES. In the photochemically gated SiC graphene sample, the metrologically useful quantised plateau at $R_H \approx 12.9$ kΩ is reached already at magnetic fields below 2 T.*

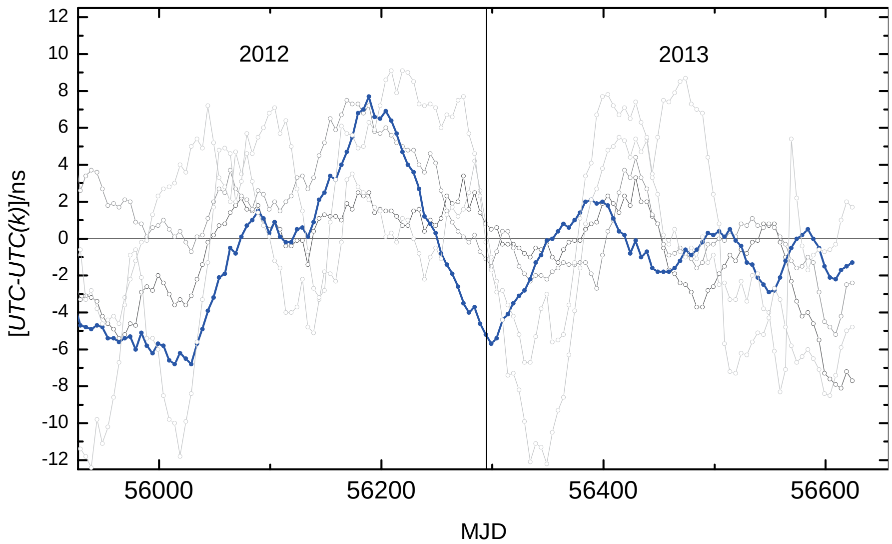
# TIME AT MIKES

Text: Mikko Merimaa, Thomas Lindvall, Thomas Fordell, Anders Wallin, Teemu Tomberg
Photos: Anders Wallin, MIKES archives

**Coordinated Universal Time (UTC) synchronises the world and provides the unit of time, the SI-second. This global atomic time scale is calculated by the International Bureau of Weights and Measures (BIPM) using data from national time laboratories. MIKES is one of the seventy four national laboratories contributing to the world-wide timekeeping and provides the Finnish realisation of the Coordinated Universal Time, the UTC(MIKE).**

Keeping of the national timescale UTC(MIKE) is based on a clock ensemble composed of two complementary types of commercial atomic clocks, caesium beam standards and hydrogen masers, the latter being the primary source of UTC(MIKE). An international network of time links that continuously compares the differences between national time scales, is organised by the BIPM. MIKES participates through navigation satellite observations, continuously sent to BIPM. The results of this key comparison are published monthly through BIPM Circular T (http://www.bipm.org/jsp/en/kcdb_data.jsp) that is also used to disseminate the UTC for synchronisation of the national time laboratories.

Over the years MIKES researchers have accumulated considerable expertise in clock prediction, yielding a hydrogen maser steering algorithm that makes UTC(MIKE) an optimal estimate of UTC. Although our only link to primary frequency standards is through Circular T, accurate maser steering combined with the exceptionally well-controlled MIKES building environment for the clocks has allowed us to keep UTC(MIKE) within 10 ns of UTC for the past few years.



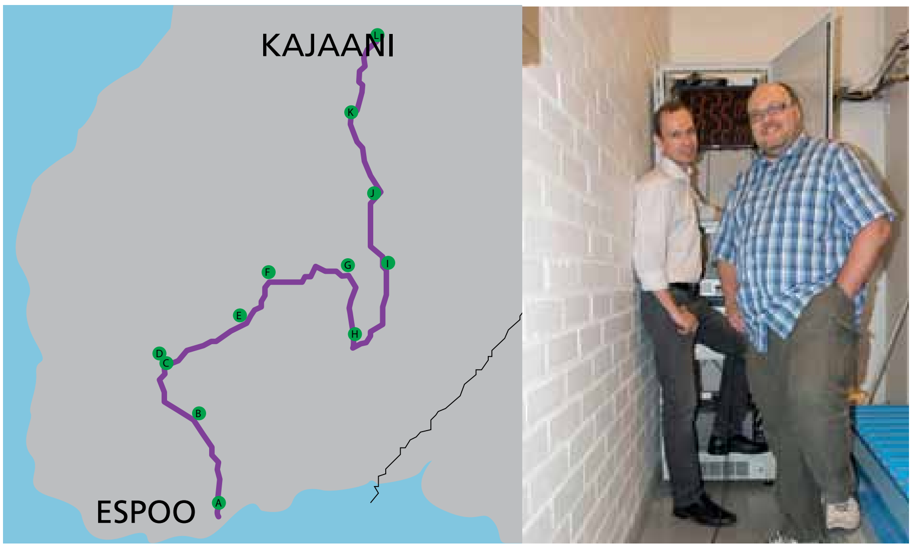

*The five most stable national time scales of the world. UTC(MIKE) in blue. MJD = Modified Julian Date.*

In addition to the realisation and dissemination of the national time-scale, we do scientific research in time and frequency metrology. For instance, we develop a single-ion atomic clock and study the use of optical telecommunication networks in comparisons of distant clocks and in dissemination of highly accurate time.

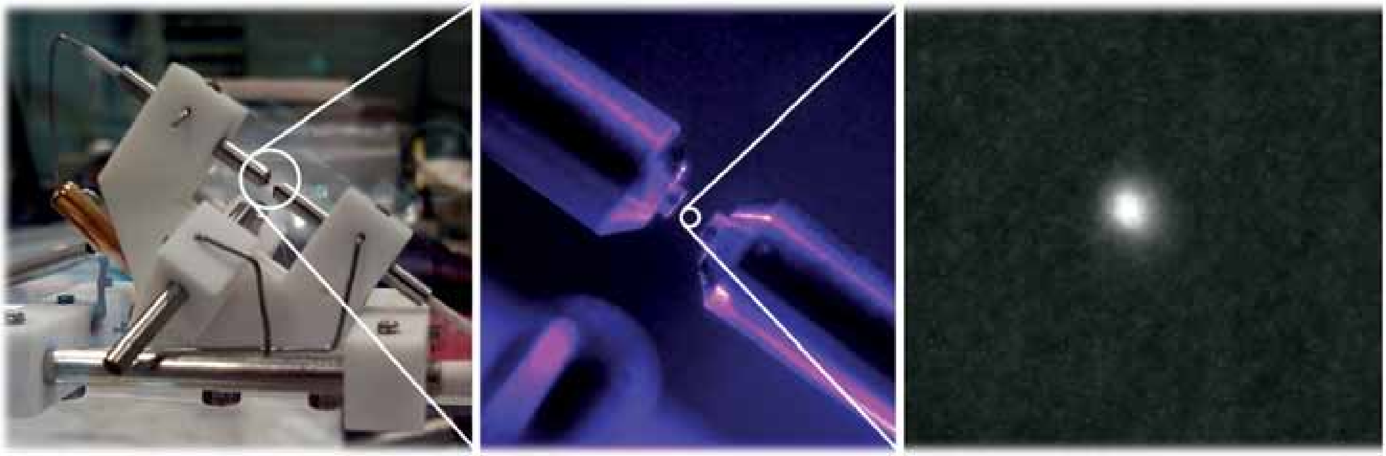
## DISTRIBUTED TIMEKEEPING OVER THE WORLD'S LONGEST WHITE RABBIT LINK

The White Rabbit (WR) technology was originally developed at CERN for control and data collection with sub-nanosecond accuracy at the Large Hadron Collider, but it is now used wherever precise synchronisation is required,e.g., in time and frequency distribution, radio astronomy and "big-physics" experiments (accelerators, synchrotrons). All hardware and software are available under an open license (see http://www.ohwr.org), allowing anyone to modify the software or manufacture the hardware.

While WR is originally designed for links up to 10 km in length, MIKES has pushed the boundaries to connect our Espoo and Kajaani sites, separated by ~1000 km of optical fibre – in effect setting a world record for a WR link length! The fibre-link is provided by CSC (http://www.csc.fi) who maintains the Finnish University Network. Preliminary results indicate excellent performance of the fibre time link. This opens up opportunities for a national WR timing network, linking government and commercial timekeepers to industrial and academic users.




*Left: Fiber-link connecting Espoo and Kajaani. Optical amplifiers are spaced up to 150 km apart over the total 1000 km link length. Right: Atomic timekeeping at MIKES Kajaani. A time-interval counter is used to monitor a local Cesium clock against the White Rabbit timebase, while a GPS receiver allows comparison against UTC.*



# THE OPTICAL ATOMIC CLOCK PROJECT

**A major milestone was reached at MIKES in the development of an optical frequency standard based on a single cooled and trapped strontium ion.**

A major milestone towards the MIKES strontium ion clock was recently achieved when the first strontium ions were trapped. This involved resistively heating a small metal tube containing strontium (leftmost in the picture above). A small part of the released atoms fly in between the trap electrodes where two blue laser beams (405 nm and 461 nm) excite and ionise the atoms. Once a positively charged ion is formed, it is immediately trapped between the electrodes by a radiofrequency electric field. A third blue laser beam (422 nm) is used to Doppler cool the ion. It is tuned slightly to the red side of a strong transition in the ion, which causes the absorption of photons from the laser beam to be velocity selective. Thus the ion is slowed down. As the cooling transition is not a closed transition, an additional infrared 'repumper' beam is required to keep the cooling process running. The continuous photon absorption and emission not only cools the ion – it is also used for fluorescence imaging of the ion (rightmost picture).

The ion clock will require two additional light sources. An ultra-stable red laser at 674 nm forms the 'pendulum' of the clock. Once the ion is cooled to a few mK above absolute zero, this 'clock'-laser is locked to the very narrow transition at 674 nm. This 'clock' transition in strontium is, among several similar ultra-narrow cold atom or ion clock transitions, accepted as a secondary representation of the SI second. Finally, a commercial frequency comb is used to make a coherent leap from the optical domain to the radiofrequency domain for comparison with the hydrogen masers that maintain the Finnish realisation of UTC, UTC(MIKE).

MIKES is participating in two European Metrology Research Programme (EMRP) projects related to the ion clock. Within the project High-accuracy optical clocks with trapped ions (IonClock), MIKES is experimentally exploring the frequency shifts in ion clocks together with PTB in Germany, NPL in the UK, and CMI in the Czech Republic. Within another, recently started EMRP project, International timescales with optical clocks (ITOC), MIKES will perform an absolute frequency measurement of the strontium ion clock against a primary cesium standard at PTB over a satellite link. Later the MIKES clock will be transported to NPL and compared against their strontium ion clock.

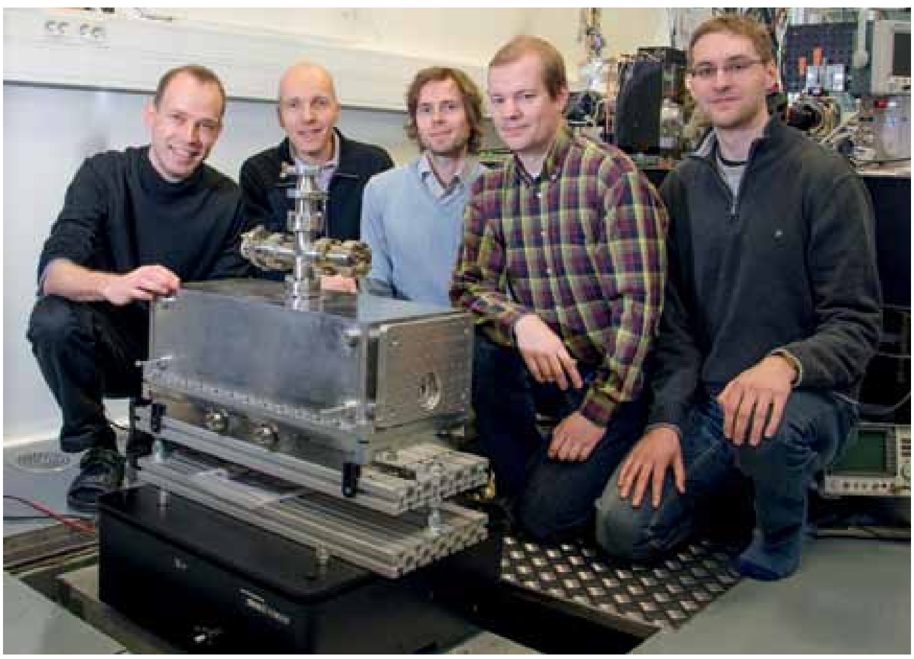
"Come what come may, time and the hour runs through the roughest day."
— Shakespeare, Macbeth

"Time is money." — Benjamin Franklin

"I hate time. It never does what you want it to." — Nick Hornby, Slam

"Time is what keeps everything from happening at once."— Ray Cummings, The Girl in the Golden Atom

"Time is the most valuable thing that a man can spend." — Diogenes Laertius



*The MIKES Time team.*

# NEW EXTREMES

Text: Antti Lassila, Hannu Sairanen, Ilkka Iisakka
Photos: MIKES archives

**MIKES performs measurements that cover many orders of magnitude for several quantities. Here we present our length, flow and resistance measurements and calibration services.**

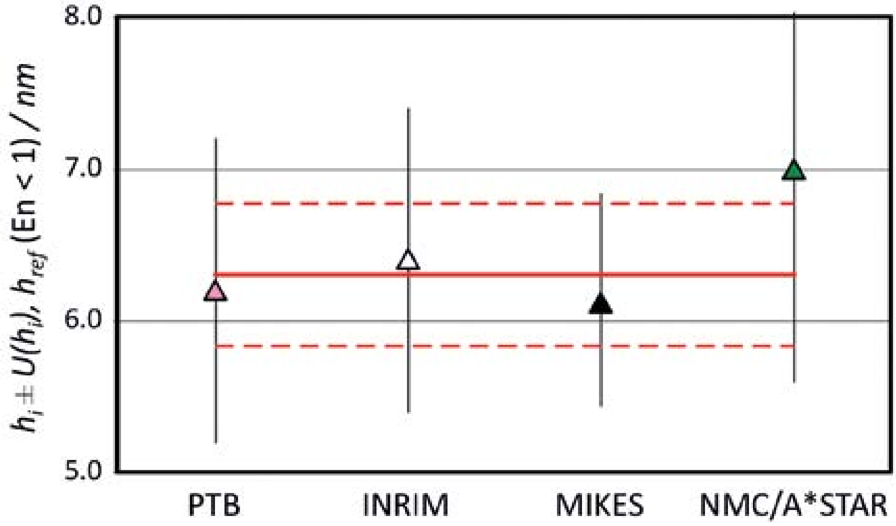
## DIMENSIONS FROM PICOMETERS TO A KILOMETER

How many orders of magnitude is there between one tenth of an atom and the geodetic baseline? The answer is 14 orders of magnitude.

One tenth of an atom, i.e., ten picometers, is the accuracy level of MIKES's symmetric differential heterodyne laser interferometer SDHLI developed in the iMERA Nanotrace project, and of the laser diffractometer developed for calibration of grating pitches. Both instruments get their traceability from the vacuum wavelength of the lasers that are calibrated against the MIKES frequency comb.

The DNA nano-origamis under development in the Crystal EMRP project have feature sizes of a few nanometres, and they are suitable measurement targets for, e.g., the MIKES interferometrically traceable metrology atomic force microscope (IT-MAFM). More traditional but still important transfer standards of length, gauge blocks and line scales, usually have maximum lengths of 1 m, but they can still be calibrated with an accuracy of a few tens of nanometres. Gauge blocks are often used for calibration of the length scales of co-ordinate measuring machines (CMM). MIKES's Legex CMM is the most accurate CMM in northern Europe in the 0.5 m$^3$ measurement volume class and has a probing uncertainty of 0.35 µm.

MIKES 30-m interferometric bench is a versatile instrument for calibrations of, e.g., optical co-ordinate measuring instruments such as total stations or laser trackers with uncertainty down to 3 µm over the total length. The interferometer for long gauge blocks is also used, e.g., for calibration of quartz meters of the Finnish Geodetic Institute that are used in the measurement of the Nummela Base line (864 m) with the Väisälä interferometer.




*Results of EURAMET 925 comparison for 7 nm step height standard.. MIKES data is measured with the IT-MAFM.*

*A laser tracker is calibrated against the MIKES 30-m interferometric bench.*

# LIQUID FLOW – FROM NANO- TO KILOLITRES PER SECOND

Kilolitres per second liquid flow measurements require huge apparatus: pipes with 50 cm diameters, 100 kW pumps and a big water tank located 20 meters above the ground level. These have been recently taken into use in our Kajaani site. The other extreme, low liquid flows, need a carrier gas and a water vapour generator. Humid air in other words. The extremities of these flow rates can differ by 12 orders of magnitude.

In MIKES, a new measurement method for the determination of very low stream flow rates has been developed. The method was validated in the range 2–200 nl/s. This extremely low flow rate can be illustrated by comparing it to the evaporation rate of liquid water from a table, which is roughly 200 nl/s at room temperature.

In the new method, liquid is pumped in to a gas flow that has known humidity, pressure and flow rate. When the humidity of the gas is known before and after the addition of water, the volume flow of water can be determined by humidity measurements. Uniform evaporation plays an important role in the developed equipment. This was achieved by developing the so-called porous cloth method, in which the gas-liquid mixing point is stocked with a piece of a cloth to force the water to spread evenly over the whole gas area and thus preventing unstable evaporation. The motivation for the development came from the need to produce traceable low stream flows. The work was part of the EMRP-project "Characterization of Energy Gases".

Traceability of high water flow measurements (0.2–750 l/s) is based on reference meters, comparisons, and a gravimetric reference standard based on water weighing. Our gravimetric measurement system consists of two diverter-weighing systems with an 800 kg and 6000 kg balance. Measurements carried out using this calibration rig are traceable to the national standards of mass and time. This gravimetric primary standard serves as the national standard for flow and is used to calibrate all types of flow meters sizing DN10, DN50, DN100 and DN200. The targeted measurement uncertainty is 0.03 %.

Our customers for low flow rates are research institutes and the health-care and medical industry. High flow rates are needed in, e.g., power production and waterworks.

*Nanoliter flow originates from a pipette.*

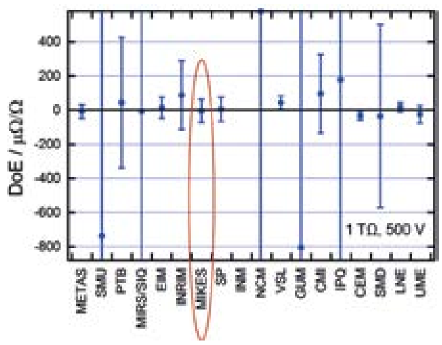
*Water flow facility at MIKES-Kajaani, DN500 tube.*

# MILLIOHM TO TERAOHMS

What does an audiophile's short, high fidelity speaker cables and a piece of insulator have in common? Both are called resistors at MIKES, and both can be calibrated although their resistance values may differ by as much as 18 orders of magnitude; from parts of milliohms to teraohms.

Resistance and direct voltage are the most important quantity in electrical measurements. In addition to resistance calibrations, resistance standards are needed for providing traceability to other electrical quantities. The traceability of resistance standards at MIKES is based on MIKES's own quantum Hall standard, which connects the unit of resistance to the values of physical constants with a relative uncertainty of $10^{-8}$. The dissemination to secondary and working standards is performed using a cryogenic current comparator (CCC) or a direct current comparator resistance bridge (DCC). By storing the standards in oil or air baths, millidegrees short-term temperature stability is achieved. The traceability of resistance standards with values above 1 GΩ is realised by using a modified Wheatstone bridge.

Our customers include foreign national metrology laboratories, national research groups, calibration laboratories and companies, whose field of operation changes from exhaust gas measurements to military technology and from aviation to metal industry.




*The accuracy of MIKES's resistance standard calibrations is at a high international level, confirmed by good results in international resistance comparisons, the latest example being the EURAMET comparison of 1 TΩ (in Figure) and 100 TΩ resistances.*

*Ilkka Iisakka holding a resistance standard.*

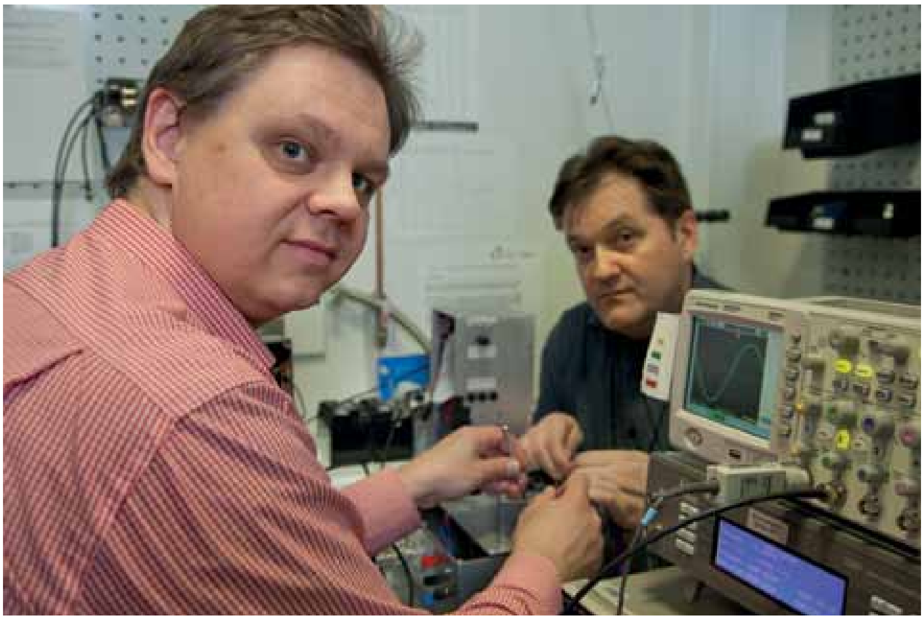
# METROLOGY SHOP

Text: Jaani Nissilä, Farshid Manoocheri, Risto Rajala
Photos: Marko Rättö, MIKES archives

**MIKES offers targeted services to meet the special needs of research and industry and develops tools based on solid metrology for both industry and its own use.**

## NEW NMI-LEVEL FUNCTION GENERATOR FROM MIKES

For decades the most accurate measurements of AC voltage and current have been based on thermal converters and calibrated external resistors. A thermal converter is a device that converts electrical power into heat. Heat (temperature) is measured by precise thermocouples. The effective value of AC voltage is obtained by comparing the heat to that produced by an accurately measurable DC voltage. The disadvantage of thermal converters is that they tell nothing about the spectral content of the measured signal. Measurements are also time-consuming. To improve the measurement and calibration infrastructure for new advanced devices (e.g. high-resolution analog-to-digital converters (ADC)), the electrical metrology community is developing new faster and more direct ways of measuring AC quantities with better accuracy and spectral information.

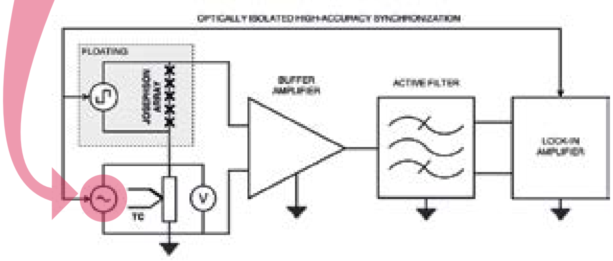


*Jaani Nissilä and Kari Ojasalo testing the function generator.*

The direct traceability of AC voltage will be based on Josephson voltage standards, which have been used in the DC voltage realisation since the 1970s. National metrology institutes (NMI) around the world are developing different concepts for that including MIKES. One general basis is to have an extremely stable voltage source to produce the utility sine wave and compare this with a calculable Josephson waveform which closely resembles it. At MIKES a calculable square wave voltage is used as a reference. The difference of the two waveforms is then measured accurately resulting in traceable voltage information about the utility signal (sine wave). In the future, traceable methods for including higher harmonic components besides the fundamental tone will be developed.

*The NMI-level function generator commercialised by Aivon Ltd.*

*Application of the new extremely stable voltage source in AC Josephson voltage standard for calibration of thermal converters (TC).*




MIKES has designed and built a two-channel arbitrary waveform generator for audio frequencies. The stability and resolution of the instrument are in many ways exceeding those of best commercial devices. For example, the amplitude stability is such that the relative uncertainty in one minute averaging is better than 0.1 μV/V. Some key properties of the source are as follows: voltage range 0.1– 5 V in frequency band 1 Hz – 20 kHz, two independent channels (high resolution amplitude & phase adjustment), voltage long term stability 1 ppm, short term stability 0.1 ppm at 1 kHz, stability of amplitude ratio between outputs better than 0.1 ppm at 1 kHz, inputs: reference voltage (zener, for example), optical 10 MHz timing (atomic clock), optical trigger in and out, and GPIB.

The applications in sight include use of the developed device for more accurate calibrations of commercial calibrators in AC and DC and in calibration of state-of-the-art ADCs. In general, any precision measurements in which AC quantities are involved, like impedance measurements, may benefit from these new sources.

The device is commercialised through Aivon Ltd, www.aivon.fi

## RELIABILITY WITH GOLD-PLATED CONNECTORS

In low frequency electrical measurements, connectors coupled to measurement devices play an essential role in guaranteeing the reliability of results. Optimal connectors should provide a good and repeatable coupling, minimise error sources, be durable and tolerate environmental effects. Moreover, their contact resistance should be small, the current-carrying capacity sufficient and they should be mechanically compatible with the devices to which they are coupled. In low frequency measuring instruments, 4-mm banana plugs are most commonly used. They are available in different forms but the connection is typically based on spring tension.

As we at MIKES could not find commercial 4-mm connectors that fulfilled the requirements of our special tasks, we had to develop such a connector ourselves. Also a multipurpose offset gauge needed in direct voltage and resistance measurements was designed.

As a result of several years' empirical research, we designed and created for our own use gold-plated connectors and short-circuit pieces. The optimal form and material for the connectors were finally found to be precision machine tooled conical 4-mm connectors made of special copper plated with hard gold. The equipment wire is coupled to the connector mechanically with a crimp. The short-circuit piece is a massive gold-plated copper block having holes optimised for the MIKES connector. The compatibility of the connectors with a diverse equipment base has found to be successful. The utilisation area of the connectors is wide: from low frequency precision measurements of electrical quantities to calibration of temperature and high-voltage. By using these connectors, the repeatability and reliability of measurements have clearly been improved.

The connectors are implemented in collaboration between MIKES and Millog Oy.

*Risto Rajala verifying the operation of the connectors.*

*MIKES gold-plated connectors and a short circuit piece.*

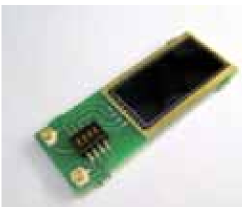
## ALL PHOTONS COLLECTED WITH PQED

A European metrology research project developed specially designed silicon photodiodes (see lower figure) which open new possibilities for accurate optical power measurements. By minimising the optical and electrical losses MIKES and Aalto University produced a photodetector whose quantum efficiency is close to unity and whose spectral responsivity is determined almost completely by the fundamental constants. This novel photodetector – predictable quantum efficient detector (PQED) – has been compared with the most accurate optical detector presently available, i.e., the cryogenic electrical substitution radiometer. In test experiments the PQED performed equally well as the cryogenic radiometer having similar low uncertainties (of the order of 0.01%) in the determination of optical power.

The advantage of the PQED as compared with the cryogenic radiometer is its compact design and simple operation. For example, the PQED works at room temperature, whereas the cryogenic radiometer requires low temperatures in the 10 K range (-263 °C). Such benefits of the PQED reduce both the initial and running costs of a photodetector but still maintain the high accuracy of optical power measurements. The PQED does not require calibration against any other radiometric standard, and it may thus become a new primary standard of optical power at visible wavelengths.

The compact room temperature PQED (upper figure) is commercialised through a Finnish company Fitecom Oy, www.fitecom.com. The detector enables optical power measurements between 400 nm and 800 nm with a very low relative standard uncertainty of 0.008 %. The PQED has an adjustable Brewster window for normal operation with collimated p-polarised light and gas valves for flow of particle-free scientific grade nitrogen through the instrument when operated without the window. The nitrogen flow prevents dust and moisture contamination of the photodiodes, now offering a primary standard with similar ease of use as present transfer detector standards.

*The room temperature PQED showing (from left to right) the Brewster window, adjustment screws, flexible bellows and the photodiode chamber. The total length of the detector is 215 mm.*



*Bonded PQED photodiode of 11 mm × 22 mm on a printed circuit board with a switch and connectors for wiring.*

# THE MIKES BUILDING
## THE HOME OF HIGH-PRECISION METROLOGY

### 1 Building maintenance technology with a focus on airconditioning

About 30 % of the total building area is devoted to building maintenance technology, mainly ventilation equipment, required for creating laboratory conditions. Potential sources of electromagnetic interference, such as compressors and the emergency power generator, are located as far away from the laboratories as possible. There are 36 laboratories that are divided in 20 sections, each of which has its own dedicated ventilation system used for the fine tuning of temperature.

### 2 Expansion joints and double walls

The propagation of internal vibrations caused by building maintenance technology and the movement of people has been inhibited by dividing the building into several separate sections using expansion joints. In the surface laboratories, the basic idea is an onion-like structure, in which the laboratories at the core are protected from external temperature variations by a corridor, an office room and outer protective shutters. To optimise vibration performance, the walls, floor and ceiling of each laboratory are joined together by steel rods and poured concrete in such a way that each laboratory behaves as a rigid body.

### 3 Isolation of heat sources

Because of the strict room temperature requirements, the air heated by, for example laboratory light fixtures and hot furnaces, is drawn directly away from the laboratory and returned into circulation. The temperature, humidity and pressure of the air in laboratory facilities, as well as the mechanical vibrations between floors are constantly monitored.

### Technical specifications

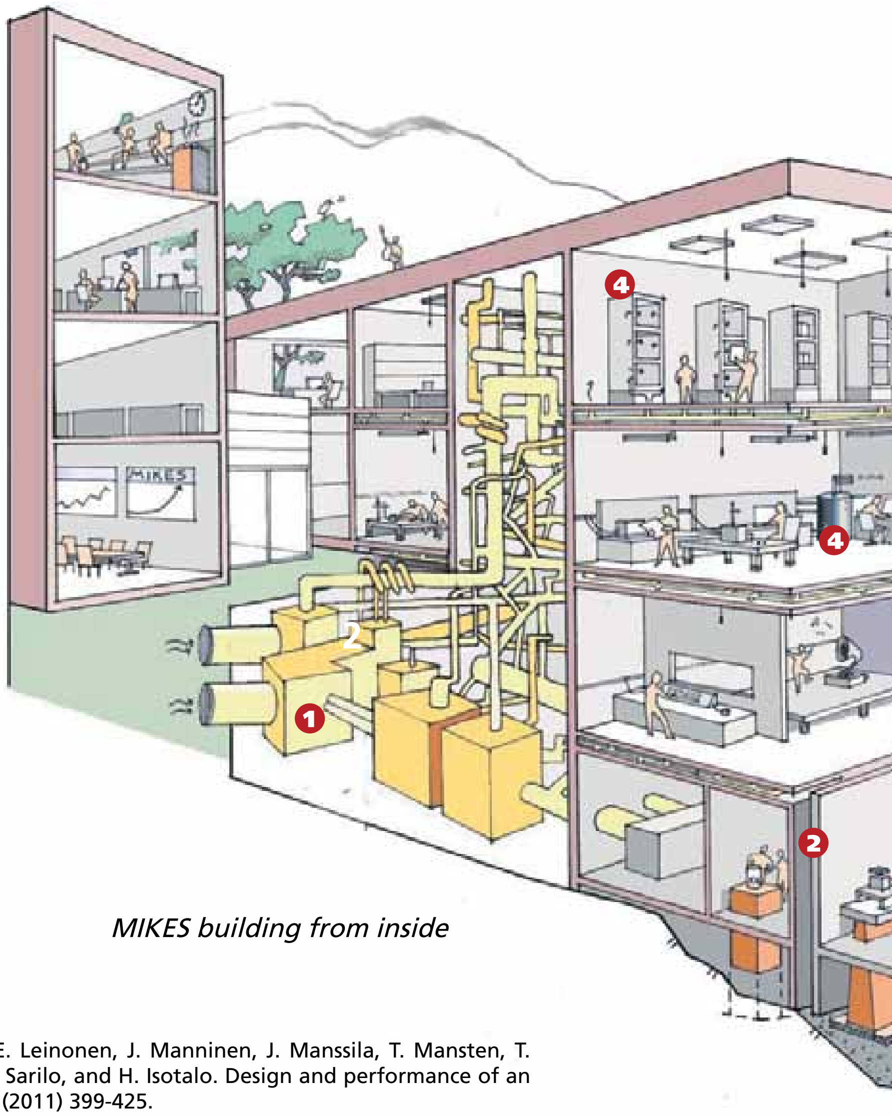
- Building volume: 51 000 m$^3$
- Total building area: 9 100 m$^2$
- Net floor area 6 500 m$^2$
- Number of employees: 80
- Number of offices: 60
- Number of laboratories: 36
- Total laboratory floor area: 1 700 m$^2$, out of which 670 m$^2$ is underground

### 4 Stable temperature

Instruments requiring high temperature stability are mounted in enclosed equipment cabinets supplied with air whose temperature is regulated to an accuracy of ±0.01 degrees, or liquid baths that can achieve accuracies of a few millidegrees. For vibration-sensitive equipment, the laboratories use granite tables with natural rubber isolators.

### 5 Vibration isolation

Extremely vibration-sensitive length and mass metrology equipment is mounted on either air-spring supported 80–120 ton concrete slabs of gravel/insulation carpeting/solid slab structures. These provide attenuation of bedrock vibrations at 1 Hz and higher frequencies. The building is founded on a competent bedrock.




*MIKES building from inside*

**See publication**

A. Lassila, M. Kari, H. Koivula, U. Koivula, J. Kortström, E. Leinonen, J. Manninen, J. Manssila, T. Mansten, T. Meriläinen, J. Muttilainen, J. Nissilä, R. Nyblom, K. Riski, J. Sarilo, and H. Isotalo. Design and performance of an advanced metrology building for MIKES. Measurement 44 (2011) 399-425.

## 6 Electrical interference and electromagnetically shielded laboratories

Steel reinforcements within the concrete frame of the building are welded together at 1.2 m intervals to provide a continous mesh. This type of a "Faraday Cage" protects the laboratories from external electrical interference up to the radio frequency range ($f_{cut-off}$~200 MHz). The thick concrete walls and the underground placement of the laboratories also reduce interference. For extremely sensitive electrical measurements, the building has 12 electromagnetically shielded "rooms". For external fields, their minimum shielding attenuation is 100 dB (10 kHz to 20 GHz). In order to minimise power supply interference, these rooms are equipped with optical fibre lighting and symmetrical filtered power supplies (2 x 115 V). See Figure 1.

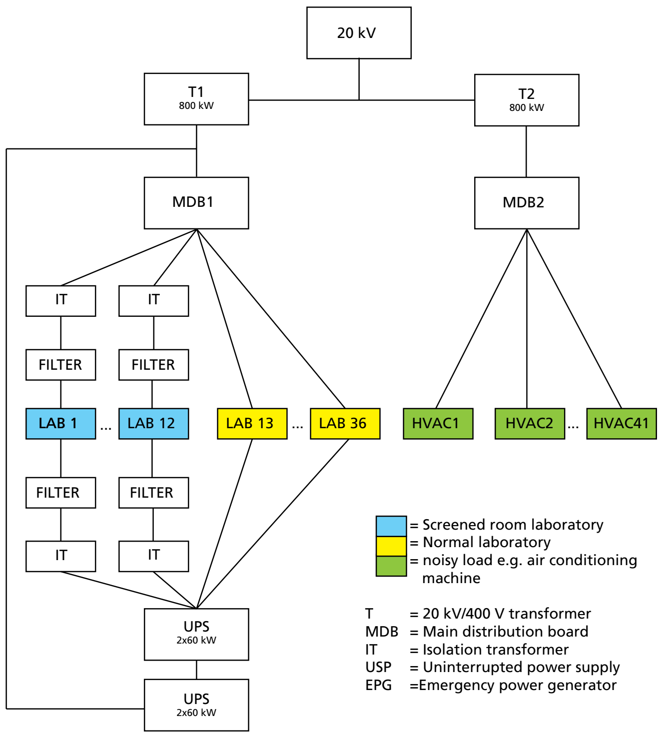
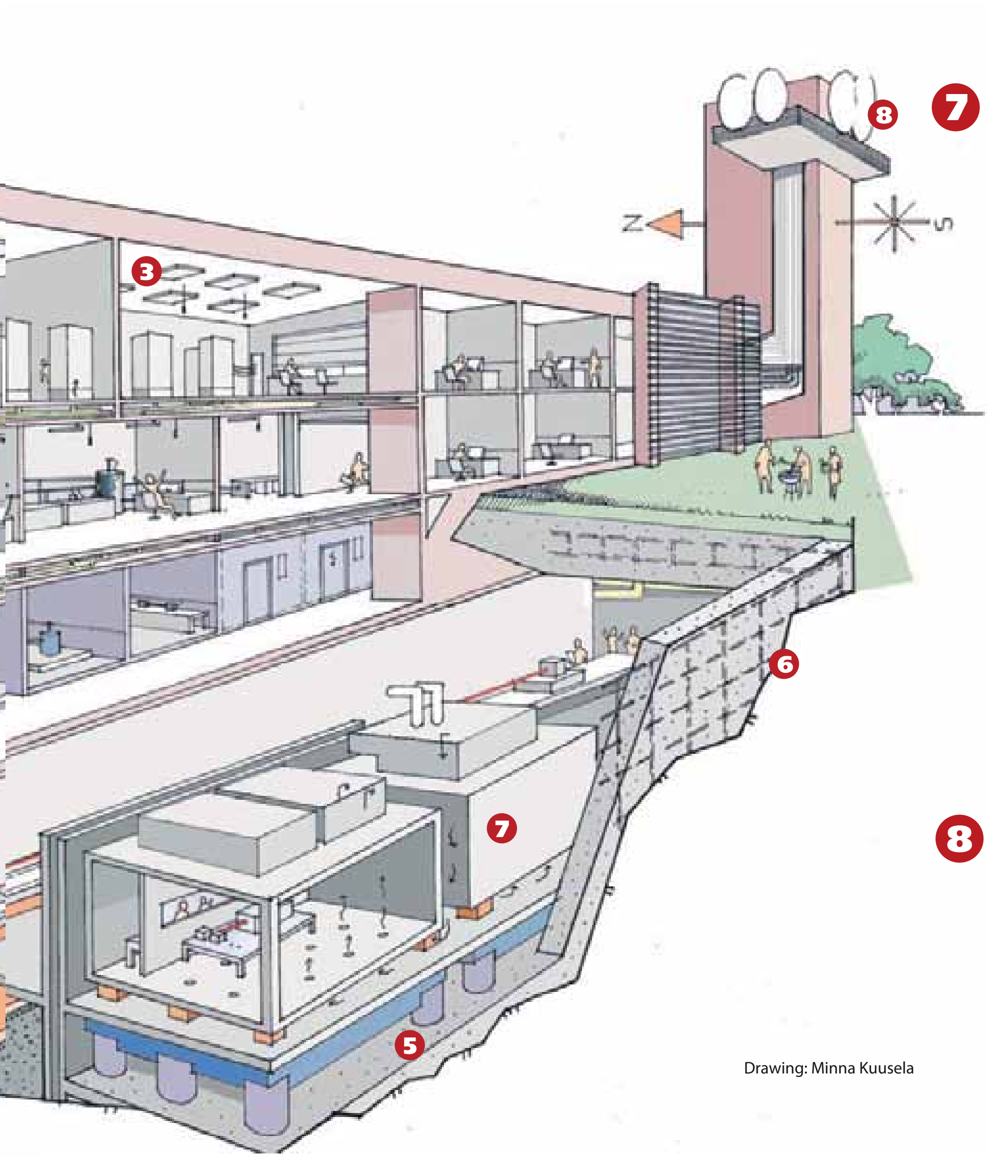



*Figure 1. The principle of electrical power distribution.*




Drawing: Minna Kuusela

## 7 Ventilation and diffusion technology

The laboratories with the strictest temperature stability requirements have been constructed in naturally constant temperature underground floors based on the "room within a room" principle. The actual measurement room is placed within a slightly larger room so that the air drawn from the measurement space air washes the intermediate space as it is returned into circulation. This solution enables the maintenance of a set temperature of 20 °C to an accuracy of 0.01 degrees. Most of the laboratories are constructed using the floor diffusion principle, with the exeption of mass metrology laboratories, which require cleaner conditions, where ceiling diffusion is used, and the humidity laboratory, where wall diffusion is used. A room where the temperature can be set at (20±5) °C makes studies of the temperature dependence of devices and meters possible.

## 8 Atomic clocks

The atomic clocks are continuously compared against UTC using a GPS satellite receiver. An antenna tower provides optimum satellite visibility in the southern sky.

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