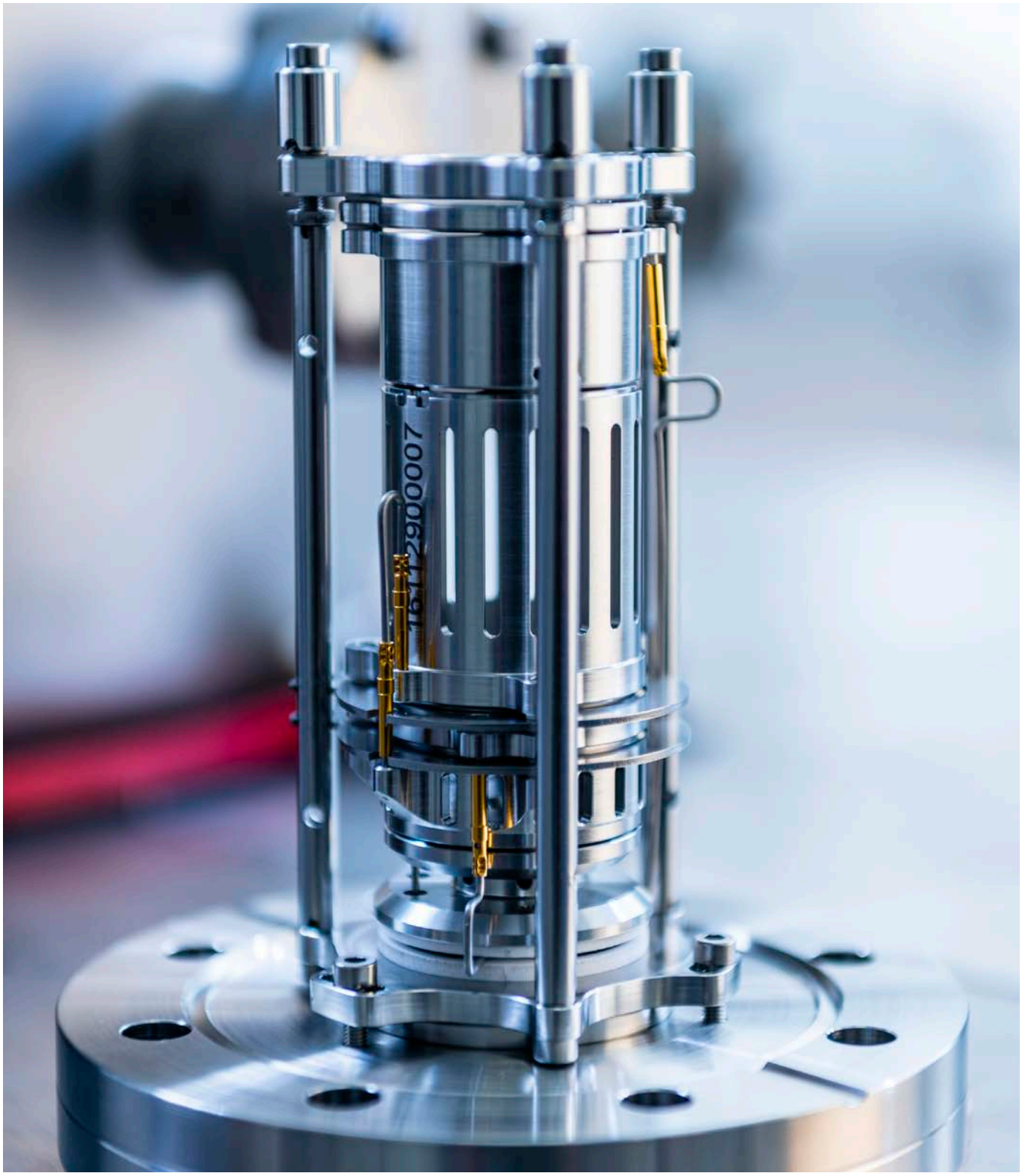


RESEARCH REPORT
2020

LABORATOIRE
NATIONAL
DE MÉTROLOGIE
ET D'ESSAIS

RESEARCH AT LNE IN 2020:

25%
of LNE's overall budget

120 research projects
including **54** JRPs *(Joint Research Projects)*

92
publications in peer-reviewed journals

18 PhD students

200 doctors et engineers

A portfolio of **17 patents**

RESEARCH CARRIED OUT BY THE RNMF IN 2020:

150 research projects
including **74** JRPs *(Joint Research Projects)*

183
publications in peer-reviewed journals

43 theses
including **5** defended in 2020
and **1** new **HDR**
(Qualification to supervise research)

COVER PHOTO:
ION GAUGE DESIGNED WITHIN THE FRAMEWORK OF THE EUROPEAN ION GAUGE PROJECT. THE 16NRM05 PROJECT RECEIVED FUNDING FROM EMPIR PROGRAMME, CO-FUNDED BY THE PARTICIPATING STATES, AND THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME.

EDITORIAL

Thomas Grenon,
Managing Director

Despite a complex year in 2020, LNE and the laboratories of the French National Metrology Network (RNMF) managed to continue their quest for excellence. Numerous European projects on major societal issues such as air quality measurement, hydrogen metrology and building insulation were completed.

This year more than ever, health was at the heart of everyone's concerns, and LNE demonstrated the importance of strong metrology research for society. Thanks to its expertise in aerosol metrology developed over many years, LNE was able to use its skills to assess the filtration performance of masks. In 2020, LNE's activity in the health field was also marked by work on cardiovascular diseases and extracellular vesicles. Two LNE researchers working to protect our fellow citizens through their work on Alzheimer's disease and air quality were recognised through the LNE Research Award 2020.

The work carried out this year by the LNE and RNMF teams also demonstrated the role of metrology in supporting innovation through research into future technologies such as hydrogen, artificial intelligence, 5G mobile electronics and their energy consumption, and atomic clocks, with a view to redefining the second.

I invite you to find out more about many of these achievements in the following pages. ■

SUMMARY

EXPERIMENTAL PLATFORM FOR THE ASSESSMENT OF THE PERFORMANCE OF AIR QUALITY MICROSENSORS.

ENVIRONMENT AND ENERGY: CONTRIBUTING TO A SUSTAINABLE WORLD

Pollution, climate change monitoring, future transport, building insulation, renewable energies, LNE and the French national metrology laboratories are essential partners in developing and implementing sustainable solutions.

ATMOSPHERIC CARBON SOOT: ITS CONCENTRATION TRACEABLE TO THE SI

Carbon soot is a major contributor to climate change and pollution. New standards will increase the accuracy of its measurement in ambient air.

Atmospheric monitoring has major climatic and health implications, particularly with regard to the contribution of particulate carbon soot. These aerosols, which are produced by industry, transport and, more generally, combustion processes, play a major role in the radiative forcing behind global warming and are also responsible for several hundred thousand premature deaths each year in Europe.

For several decades, optical techniques have been used to monitor atmospheric carbon soot concentrations. Nevertheless, measurements are marred by discrepancies of up to 30% depending on the instruments used and a lack of traceability to the SI with consequences for the comparability and interpretation of data.

The European BlackCarbon project, in which LNE participated alongside nine partners from six countries, and which ended in 2020, had the goal of putting things in order.

The major challenge was to develop equipment and methodologies enabling the calibration of the various types of equipment used to measure the mass concentration of soot in the atmosphere. "*In concrete terms, the partners had to develop several reference carbon soot aerosols representative of ambient air, characterise them in terms of stability, reproducibility and physical-chemical properties and test them in inter-laboratory comparisons involving each partner*", explains François Gaie-Levrel of LNE.

LNE's metrologists developed three candidate aerosol generators. The first and second enable the atomisation of aerosols based on colloidal graphite suspensions and black polystyrene latex beads. The third involves two graphite electrodes between which an electrical discharge is created to enable the desorption of carbon particles prior to their transport in a carrier gas. After optimising their instruments, scientists demonstrated that these generators can reproducibly produce soot analogue aerosols characterised by mean diameters of 179 nm ± 2 nm, 187.8 nm ± 0.2 nm and 38 nm ± 1 nm, with mass concentrations of 20 µg/m^3 ± 4 µg/m^3, 12 µg/m^3 ± 3 µg/m^3 and 68 µg/m^3 ± 3 µg/m^3 respectively.

During a second phase, the laboratories involved in the project compared the various technical solutions proposed to generate these aerosols. The goal is to collectively define which ones to use as metrological references according to the range of particle sizes considered, as well as according to the "fresh" or "aged" state, i.e., whether or not altered by an organic phase of their synthetic soot. *"As 2021 begins, we are in the process of finalising this summary work,"* explains François Gaie-Levrel. After this, new references will be able to be disseminated Europe-wide for the harmonised monitoring of carbon soot in the atmosphere, with a target uncertainty of 10%. ■

THERE WILL SOON BE A EUROPEAN NETWORK FOR ENVIRONMENTAL MONITORING

Water, air, soil: pollution makes no distinction. Hence the need for the integrated monitoring of all compartments in our environment, in a multi-disciplinary, multi-pollutant approach harmonised at the European level. This is the aim of the POLMO project, coordinated by LNE and involving nine European national metrology institutes, which starts this year and which will run for three years. Its objective? To establish a European metrology network for environmental monitoring by mid-2022 at the latest. As Raphaël Maillard, project coordinator, explains,

"This network will aim to develop a strategic research agenda for and in close interaction with beneficiaries and end-users, in order to optimise the resources of the different institutes, and to better disseminate the results of their research work". This also provides end-users with a reference "one-stop shop", whatever their needs: reference materials or methods, best practice guides, etc., as close as possible to the requirements of the field. ■

PORTABLE GENERATOR FOR THE PRODUCTION OF CARBON SOOT MODEL AEROSOLS.

THERMAL RESISTANCE MEASUREMENTS OF BUILDINGS REACH METROLOGICAL PRECISION

The thermal renovation of a building requires the energy performance of its walls to be measured upstream. LNE and its partners developed a demonstrator adapted to this objective.

The thermal renovation of buildings is an essential component of the work to limit energy consumption and global warming. In order to apply the correct recommendations before the work, the thermal resistance of the walls to be insulated must be determined. Today, this can only be carried out at the building level, and then only indirectly from the overall energy consumption data. This results in very imprecise estimates. In order to do better, LNE researchers took part in the RESBATI project, funded by the ANR (National Agency for Research) and finalised at the beginning of this year, which aimed to develop a demonstrator for the direct measurement of the thermal resistance of a wall, adapted to users' needs.

On paper, the principle is simple: simply heat the insulated side of the wall and, once the thermal regime has stabilised, measure the heat flow supplied and the temperatures on both sides of the wall to determine the quantity sought, the insulating capacity of the wall. The result is an instrument consisting of a 60 cm square heating plate to be applied to the wall, and a programmable controller that records the data required to calculate the unknown thermal resistance.

In practice, however, it takes several days to reach a steady state, which is incompatible with the routine use of such an instrument. To overcome this difficulty, engineers developed a Bayesian identification method. This consists of adjusting the evolving experimental data according to complex mathematical instructions using randomness, thus reducing measurement time to only a few hours.

Once the prototype was produced, LNE researchers calibrated the measuring device. To do this, they qualified samples of different wall models using the laboratory's primary measuring equipment. They also carried out measurements on entire walls. Result: measurements obtained with an uncertainty of around 10% for walls with a thermal resistance of less than 4 $m^2 \cdot K \cdot W^{-1}$. *"This typically corresponds to the values observed for walls built up to the 1990s, i.e. typically in buildings that need to be renovated today,"* says Alain Koenen of LNE.

What's more, researchers also tested their demonstrator directly with individuals who wanted to carry out insulation work on their homes. This ensured that it did indeed meet requirements. *"We have shown that it is possible to obtain a relevant value after only a few hours of measurement,"* adds the metrologist.

At the end of the project, everything is therefore ready for the switch to the operational phase. For their part, LNE specialists are continuing their work to adapt their methodology to panels with greater thermal resistance. To do this, they plan to optimise the algorithm used to process measurement data. Measurement data must also be taken at several points instead of just one on each side of the wall. The energy renovation of buildings will then fully enter the era of metrological precision. ■

HEATING PLATE WITH FLOW SENSOR.

MPEB: ENERGY PERFORMANCE METROLOGY FOR INDUSTRIALISTS

How can knowledge of building energy performance metrology be disseminated to industrialists and players in the materials market, in line with the realities in the field? This was the aim of the MPEB project, finalised this year, in which LNE participated under the aegis of the Fondation Bâtiment Énergie. In this context, metrologists prepared several summary documents reiterating the basics of metrology (concepts of measurement, uncertainty, etc.) and detailing all the methods that exist today to access the thermal properties of a building. Researchers also conducted a wide-ranging survey of the players concerned, in order to meet their expectations as best as possible. The results of their work were also the subject of several webinars and a major feedback conference in March 2020. ■

ANALYSIS BY GAS CHROMATOGRAPHY.

HEALTH: ENSURING THE SAFETY OF CITIZENS

Our societies are facing major health issues. LNE and the French national metrology laboratories contribute to the development of new treatments and new diagnosis techniques, not forgetting prevention.

CARDIOVASCULAR RISK ASSESSMENT: MOVING TOWARDS MORE EFFICIENT DIAGNOSIS METHODS

Cardiovascular diseases are responsible for 1.8 million deaths each year in Europe. To address this, reliable methods are needed to estimate the risks in patients. Currently, the risk of developing cardiovascular disease is assessed by dosing biomarkers in blood. Nevertheless, the traceability of these methods is not currently optimal. To improve this, LNE has been participating in the European CardioMet project with 12 partners since 2019.

Recently, work has shown the benefit of dosing not only the lipid part of lipoproteins (carriers of cholesterol in the blood) responsible for the occurrence of cardiovascular events, but also their protein part. Thus, one of the objectives of CardioMet is to develop higher order reference methods for the dosing of these so-called apolipoproteins and to assess their added value compared to conventional tests.

In this context, LNE's task is to prepare primary reference materials traceable to the International System of Units for the calibration of these methods. *"These will be samples containing peptides, i.e., the chemical building blocks of which proteins are composed, with a concentration guaranteed by reference spectroscopy,"* explains Vincent Delatour of LNE.

Thanks to these standards and reference methods, it will then be possible to connect the results provided by the dosing methods used in medical laboratories and hospitals to the SI, which will make it possible to assess and improve their comparability and reliability. ■

HIGH RESOLUTION MASS SPECTROMETRY FOR THE DEVELOPMENT OF REFERENCE METHODS FOR THE DOSING OF BIOMARKERS.

LNE RESEARCH AWARD 2020: VINCENT DELATOUR AND FRANÇOIS GAIE-LEVREL AWARDED FOR THEIR WORK IN THE SERVICE OF HEALTH

By awarding you this year, LNE is demonstrating the importance of its metrology research in the service of health, in a wide range of fields as illustrated by your respective specialities. Vincent Delatour and François Gaie-Levrel, could you start by introducing yourselves?

VINCENT DELATOUR

Vincent Delatour: I am an expert in biomarker analysis. The aim of my work is to improve the reliability and comparability of medical biology examinations. To this end, our team develops certified reference materials (CRMs) and reference methods for the dosing of biomarkers with the aim of improving patient diagnosis and rationalising healthcare expenditure.

FRANÇOIS GAIE-LEVREL

François Gaie-Levrel: As a specialist in aerosol metrology, my research work aims to provide robust, reliable and traceable methods for characterising aerosols for environmental, industrial and/or health issues. In this capacity, I play an expert role in several working groups and in particular within the Central Air Quality Monitoring Laboratory (LCSQA).

What are your specific researcher profiles?

Vincent Delatour: Since my secondary education, I have been interested in life sciences. I went to engineering school with an option in biotechnology, and then did a PhD at the interface between biophysics and biochemistry to study the mechanisms by which cancer metastases move. I was recruited at LNE in 2008 for my biology skills to act as a link between metrologists and doctors.

In my work, I enjoy being at the interface of three disciplines: medicine, bioanalysis and metrology. The first brings concrete questions as close as possible to the needs of patients, the second provides the means to meet them, and the third guarantees the quality of the dosing carried out to establish the diagnosis and follow-up of patients. It is this synergy that ultimately contributes to the usefulness of what we do.

François Gaie-Levrel: I have a university degree as a physical chemist with a specialisation in the atmospheric environment. During my thesis, I developed, characterised and validated an instrument dedicated to the real-time analysis of atmospheric organic aerosols. This doctoral specialisation in the field of atmospheric aerosols also enabled me to become aware of metrology, a dimension of my activity which took on its full meaning following my recruitment at LNE at the beginning of 2012.

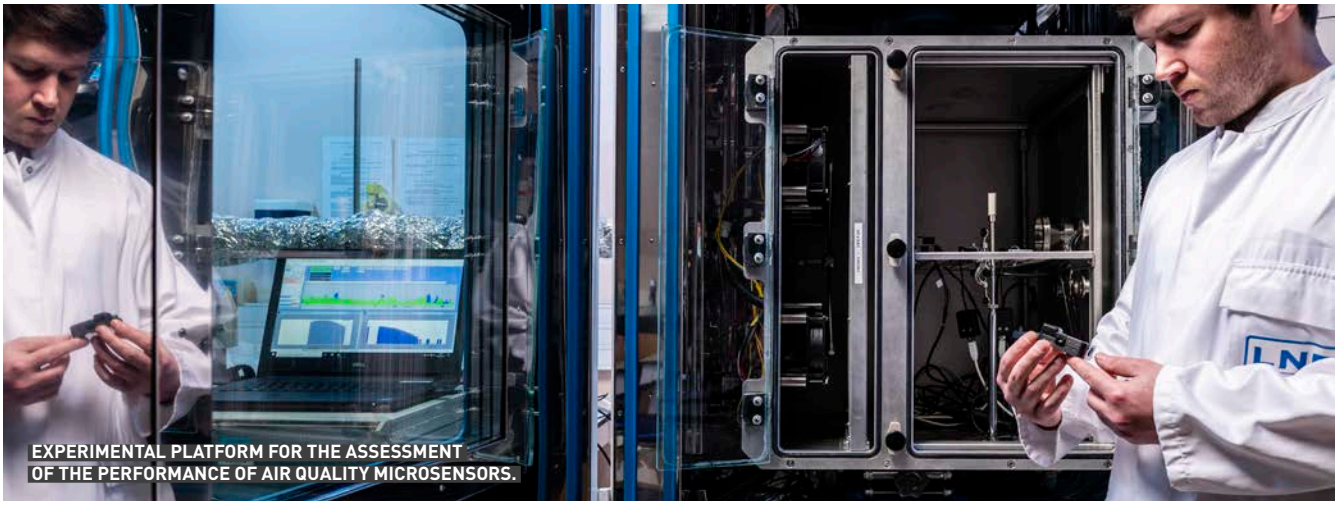
At LNE, I appreciate the very wide range of applications of my research, whether for studies associated with air pollution, combustion, industry, nano-bioparticles or worker health.

Can you describe a project that is particularly close to your heart and that illustrates your way of working?

Vincent Delatour: A recent project comes to mind, financed by the France Alzheimer association, on the Tau protein, a biomarker for Alzheimer's disease. It is interesting because it is both oriented as closely as possible to the needs of patients and at the same time very upstream, thereby making it possible to leverage all the facets of our activity.

In concrete terms, it was not only a question of working on making the measurements of already well-established biomar-

HIGH RESOLUTION MASS SPECTROMETRY FOR THE DEVELOPMENT OF REFERENCE METHODS FOR THE DOSING OF BIOMARKERS.



EXPERIMENTAL PLATFORM FOR THE ASSESSMENT OF THE PERFORMANCE OF AIR QUALITY MICROSENSORS.

kers more reliable, but also of identifying new ones, setting up methods for measuring them and finally making them reliable from a metrological point of view.
I would add that in the field of metrology for health, working on the "standardisation" of innovative biomarkers makes it easier to convince industrialists to use our metrological tools, rather than developing something that already exists routinely but needs to be improved. There is thus a greater chance of developing the value of research results from an industrial point of view or of achieving a technology transfer to meet an industrial need.
François Gaie-Levrel: As someone very interested in aerosols in general, it is very difficult to answer this question. However, perhaps our recent involvement in the fight against the Covid-19 pandemic could be mentioned. Thus, from the very start of the health crisis, we were mobilised to respond to this central problem of assessing the filtration performance of respiratory protection masks. To this end, relying on our expertise in aerosol metrology and our experience in numerous related research projects, we developed a test bench on which we have tested several hundred masks since the beginning of 2020. In particular, this project is a good example of how skills developed in a research setting can be mobilised to meet a concrete need.

This shared interest in research work in the service of health has recently led you to work on a joint project. What does it concern?
Vincent Delatour: This is a project on cardiovascular risk measurement. This is mainly determined on the basis of various risk factors (age, sex, high blood pressure, smoking, etc.), one of which is excess cholesterol. The dosing of these cholesterol carriers in the blood can be indirectly estimated by measuring the cholesterol contained in high and low density lipoproteins (incorrectly called good and bad cholesterol). Studies have shown that the size and concentration of lipoproteins are better estimators of cardiovascular risk than cholesterol as such. This is the theme around which François and I have been working.

Why exactly?
François Gaie-Levrel: Lipoproteins are biological nanoparticles. The identification of work carried out by an American team, on their characterisation in terms of number concentration and size of lipoproteins using an SMPS (scanning mobility particle sizer) coupled to an electro-spray generator, proved to be the starting point for our collaboration with Vincent, as we were already using these techniques at LNE in the context of our own work. Vincent therefore suggested that we work together to assess this technique as a possible reference method for the dosing of lipoproteins as a cardiovascular risk biomarker.

And so?
Vincent Delatour: The SMPS distinguishes objects of different sizes, without any specific chemical identification associated with them. Since blood serum is an extremely complex medium, we had to develop biochemical tools to enable the isolation of lipoproteins upstream of their characterisation.
François Gaie-Levrel: It was also necessary to implement a major instrumental development enabling the counting of lipoproteins through SMPS from samples atomised during the aerosol phase. Added to this was all the metrological development making it possible to trace a particle concentration in human serum for a lipoprotein size class, namely LDL, based on an aerosol phase count.

Was the result conclusive?
François Gaie-Levrel: We demonstrated a very high level of feasibility of the method, although we also highlighted its very time-consuming nature in terms of the need for daily calibration.
Vincent Delatour: In a very positive way, we demonstrated that a technique that was not designed to address a biomarker dosing problem can nevertheless be used to do so. Nevertheless, we came to the conclusion that SMPS coupled with an electro-spray generator is not the most suitable technique to become the "ultimate" reference method for absolute lipoprotein counting.

Isn't that a bit disappointing?
Vincent Delatour: No, I wouldn't say that. We carried out this work as part of a European project, which led us to organise an inter-comparison with the aim of defining which technique would have the best potential to become a reference method for lipoprotein counting. Ultimately, it turns out that this is mass spectroscopy, which is now the subject of a new European project for which we will produce reference materials. Thus, through our work, we were the instigators of something that will eventually provide a concrete response to a major health issue.
François Gaie-Levrel: In addition, in very concrete terms, we have just developed a similar test bench in the context of an industrial need for the characterisation of nanoparticles in a colloidal suspension. This is the very essence of applied research work: transferring the skills developed to a concrete need that is not always known in advance! ■

RADON AND THORON: REFERENCES FOR LOW ACTIVITIES

LNE-LNHB and its partners developed new radon and thoron standards to cover the full range of commercial instruments.

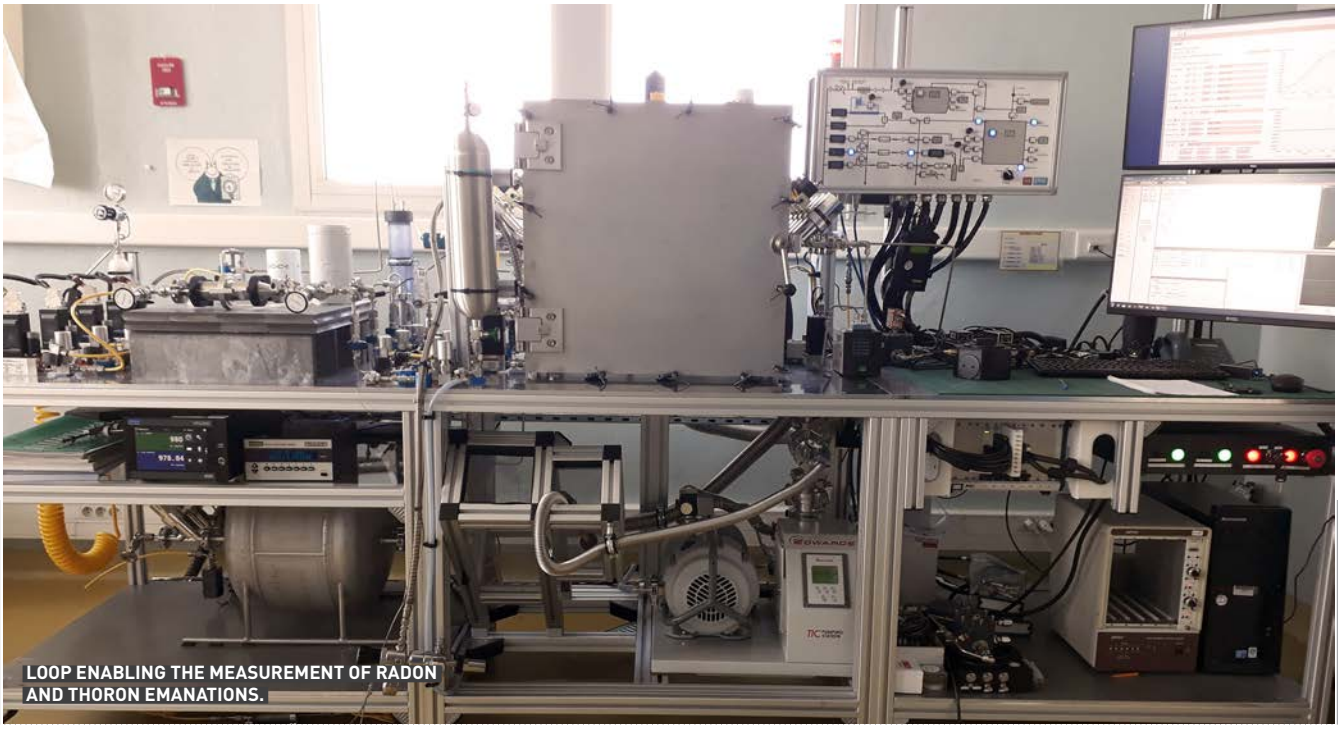
Radon and thoron, two gaseous isotopes descended from uranium-238 and thorium-232 respectively and present in the earth's crust, are the two main sources of natural radioactivity. Their presence above the thresholds recommended by the WHO in homes or workplaces requires specific monitoring. To this end, fifteen partners, including LNE-LNHB, from twelve European countries, carried out the MetroRADON project. Between 2017 and 2020, it aimed to increase the traceability of typical low activity measurements in the environment.

More specifically, French metrologists have been working to develop standards with activity between 100 Bq/m^3 and 300 Bq/m^3, which were previously lacking. These low activity levels are incompatible with the use of gas standards, given the short lifetimes of the elements considered. In practice, their activity would decline too quickly to be of any practical use. LNE-LNHB researchers therefore developed a new type of standard known as "by emanation". These take the form of a tube containing radium-226 (or thorium-228) powder, sandwiched between two membranes and calibrated to emit radon (or thoron) continuously, with the desired activity. More specifically, their activity decreases over time, but slowly enough for these references to be used in laboratories in charge of the calibration of routinely-used measuring devices.

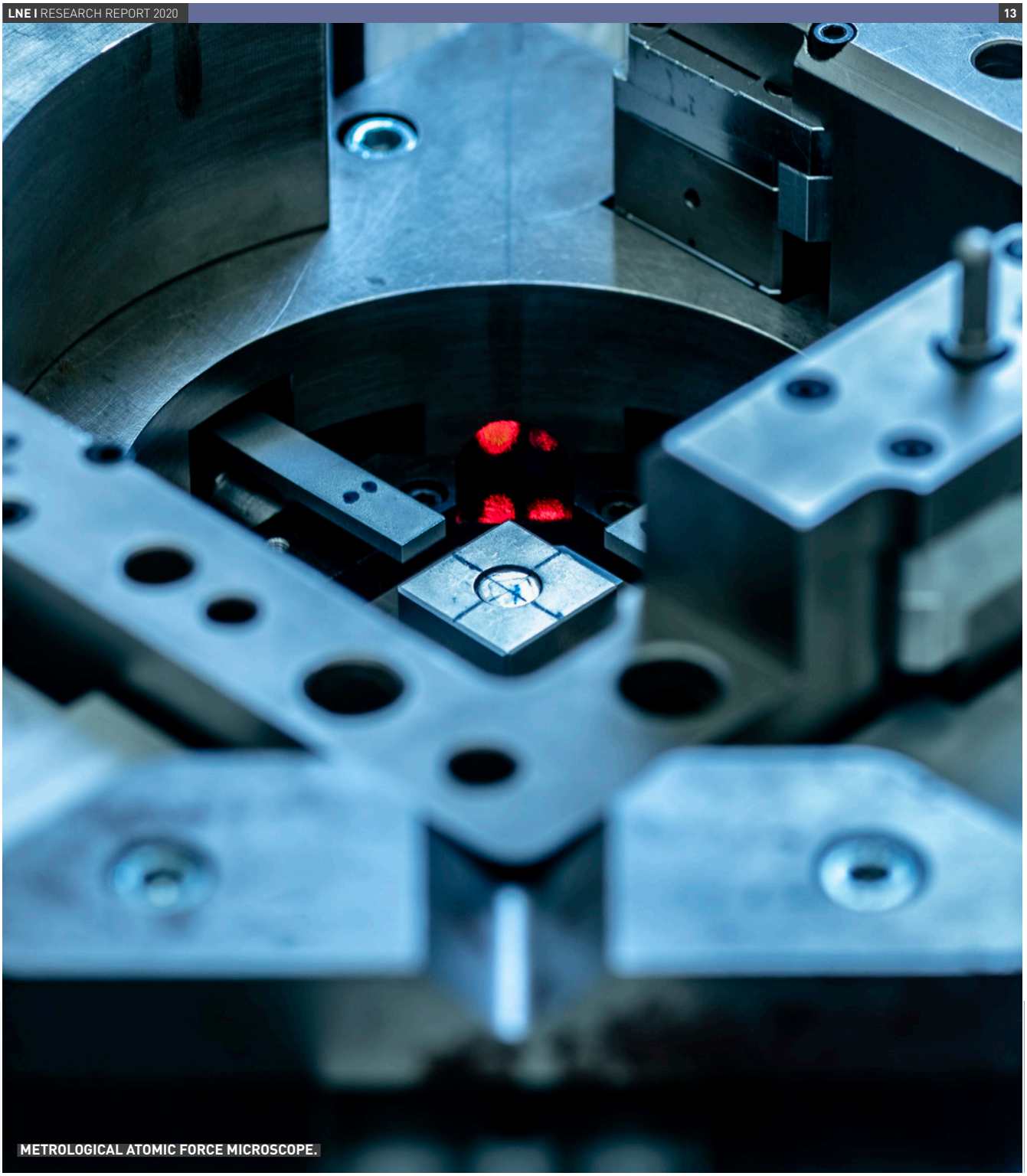
As Sylvie Pierre, from LNE-LNHB, explains, *"The development of these new standards required a great deal of work on chemical synthesis to obtain a solid deposit from liquid elements."* As a result, metrologists improved the device developed since 2015 in their laboratory to determine the activity concentration of the standard according to measurements traceable to the International System of Units.

In parallel, physicists developed an experimental device to characterise selective membranes that are impermeable to thoron but that allow radon to be filtered. In fact, many commercially available radon measurement devices are also sensitive to thoron activity, resulting in biased and temperature-dependent measurement results. This study was also used to validate the physical model of radon diffusion in a membrane as a function of the temperature, from which the correction factors to be applied depending on the temperature for any device with a selective membrane can be determined.

Finally, together with eight partners in the project, LNE-LNHB organised an inter-comparison to check the compatibility of the measurements carried out in the various European national metrology laboratories. To do this, French specialists prepared a large-volume gaseous standard of radon which they then divided into eight equal parts and verified through gamma spectrometry (a non-destructive technique) that they all had exactly the same initial activity. Final result: consistency of all measurements within the limit of relative uncertainties of between 1% and 4% depending on the laboratory. This will ensure the traceability of low activity thoron and radon measurements on a European scale. ■



LOOP ENABLING THE MEASUREMENT OF RADON AND THORON EMANATIONS.



METROLOGICAL ATOMIC FORCE MICROSCOPE.

INDUSTRY: SUPPORTING INNOVATION

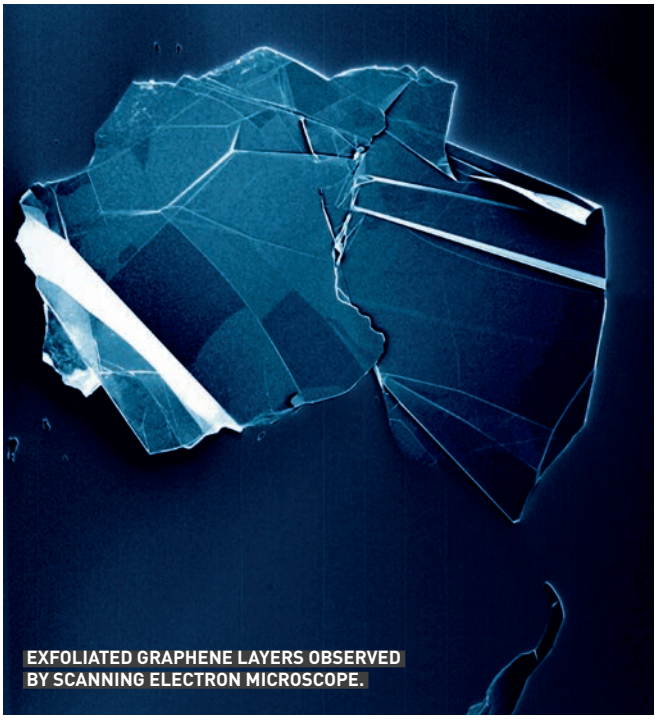
From new materials to artificial intelligence, from nanotechnology to lighting and energy, LNE and the French national metrology laboratories help industry to characterise, assess and standardise its innovations.

GRAPHENE: DEDICATED METROLOGY TO ACCELERATE APPLICATIONS

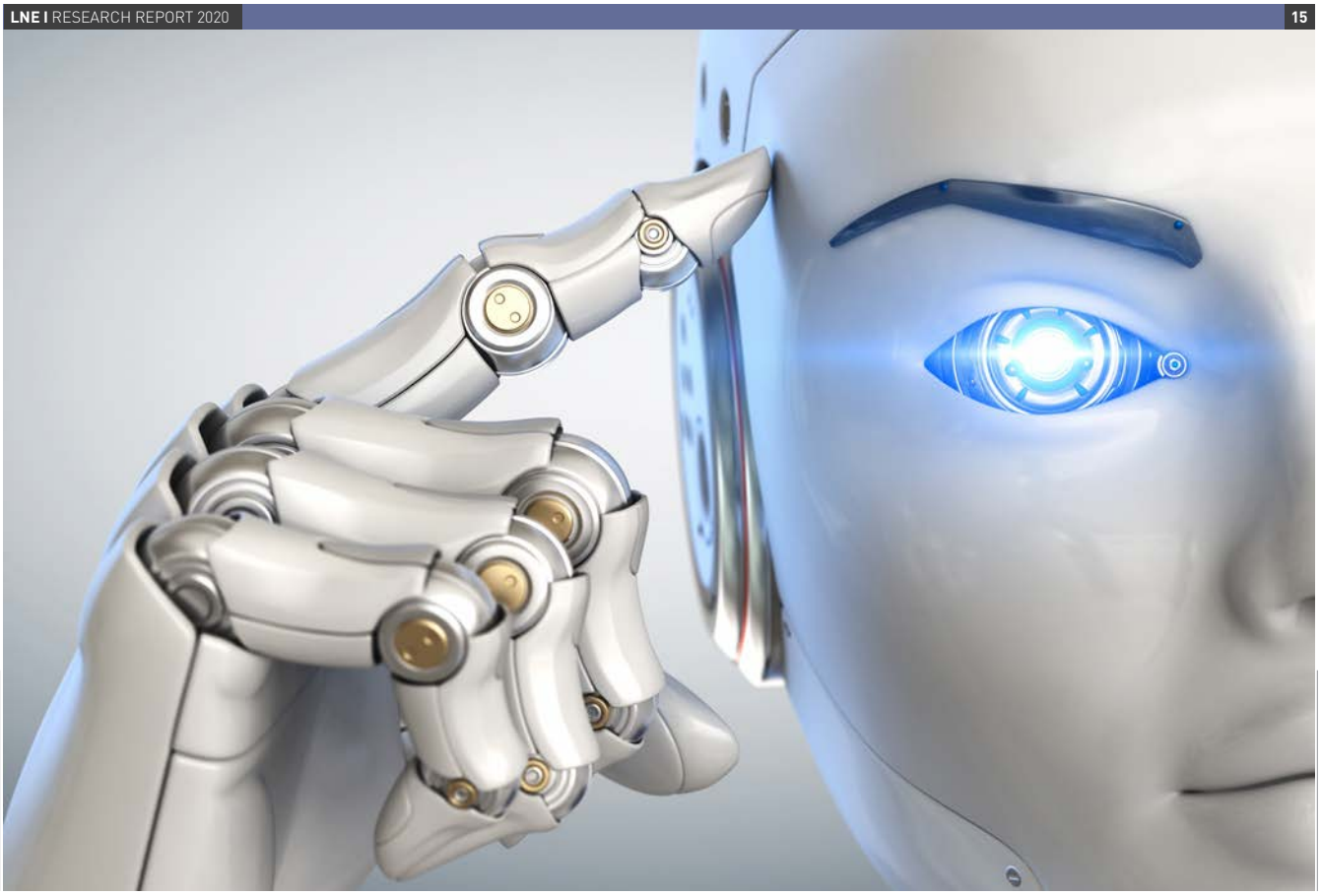
Graphene has exceptional physical and chemical properties. Nevertheless, the lack of robust methods for its characterisation is holding back the emergence of applications, although these are expected in many fields. To remedy this, LNE's Graal project, which began in 2019 and will last four years, aims to develop reliable and SI-traceable measurement protocols for the physical-chemical properties of graphene-based materials.
In dealing with different properties, (structural, thermal, electrical or chemical, some of which are
"extreme", such as the monoatomic thickness of the carbon sheet), specialists opted for a hybrid metrology approach that includes various microscopy, spectroscopy, radiometry and surface analysis techniques that can be combined. Some are metrologically proven, such as the AFM and SEM, for which LNE has developed a national reference. However, others still need to be perfected in terms of metrology. Last year, the LNE-Nanotech institute team worked with the Graphene XT manufacturer, for which it characterised thin films and liquid dispersions of graphene. In addition, French metrologists carried out measurements on FFP2 masks in order to assess the risk of the release of graphene oxide particles with virucidal properties.
"The idea is to be able to carry out characterisations of graphene, whether pure or in more complex forms, and integrated into different materials or finished products," explains Alexandra Delvallée of LNE. Her colleague Félicien Schopfer adds: *"Our approach combines the implementation of specific advanced metrology and more traditional tests aimed at supporting industrialists in their needs, right up to finished products for quality control, performance or risk assessment."* The best way to take advantage of the extraordinary properties of graphene! ■

SUSTAINABLE NANOMANUFACTURING: SOON THERE WILL BE A DEDICATED EUROPEAN NETWORK

From the synthesis of single objects to their insertion in various systems within value chains: performance, risks, social acceptability, regulation, life cycle, etc. - many issues are associated with nanomanufacturing.
To deal with them, the European NanoFabNet project, in which LNE is participating, started in 2020 and will run for at least two years. The long-term objective is to set up a hub that brings together all the players concerned (industrialists, government bodies, laboratories, NGOs, etc.) on the European continent scale to share and prioritise needs and to set up various service activities to meet them.
As LNE's Georges Favre explains, *"This first year has particularly highlighted very major requirements in terms of the validation, harmonisation and standardisation of characterisation and test methods, for which LNE and the other national metrology laboratories are on the front line."* They will thus be key players in a future "one-stop shop" reserved for nanomanufacturing in an ethical and sustainable perspective. ■



EXFOLIATED GRAPHENE LAYERS OBSERVED BY SCANNING ELECTRON MICROSCOPE.



IN ARTIFICIAL INTELLIGENCE, LNE IS NOW ESSENTIAL

The growth of AI requires the implementation of dedicated assessment methods. The laboratory is working on this through various projects.

How to characterise and test the performance or measure the acceptability of an application integrating artificial intelligence? While AI is growing fast, LNE specialists are resolutely committed to the emergence of assessment methods for AI systems, as illustrated by several current projects at the laboratory.

Last year saw the start of the European AIR project, in which LNE is a partner. It aims to develop an integrated system on which a so-called analogue AI will be directly installed to process data from a short- and medium-range radar system. *"The aim is to be able to remotely detect the breathing and heart rate of people for medical applications,"* adds Rémi Régnier of LNE. The task of the researchers will be to characterise the performance of the device with the ultimate goal of developing a method for assessing analogue AIs that does not exist today.

As of this year, the laboratory has also been involved in the European MISEL project. The aim is to develop a very low power "smart retina" for applications in robotics in particular. Specifically, this will consist of four layers: one for detection, the second for processing short-term memory and the last two for image analysis. *"The idea is to mimic the functioning of the visual cortex,"* explains Olivier Galibert of LNE. The laboratory's researchers will focus on developing metrics to assess the performance of the detection layer and the two calculation layers. This performance may thus be compared with systems that are more efficient but also much less flexible with regard to use.

For some months, LNE has also been a partner in the European ROBOTICS4EU project, which aims to develop tools to assess the acceptability of robots by society. *"On the basis of a European mapping of "best practices" linked to the development of robotics, as well as a survey of players in the field to identify their needs, the goal of specialists is to develop a model that will enable the objective assessment of the acceptability of robots according to different aspects,"* explains Agnès Delaborde of LNE. This is an issue for manufacturers, political decision-makers and end-users alike.

Finally, this year saw the creation of a chair involving various laboratories and industrialists for the development of an artificial intelligence assessment platform.

"It will be a matter of developing metrics for assessing the performance of AIs, but also tools for understanding the algorithm decision-making logic that often resemble "black boxes", a field we call explicability," explains Guillaume Bernard. In concrete terms, the partnership will be built around various doctoral and post-doctoral programmes, pre-doctoral internships and meetings and conferences. For example, from 2021 onwards, a joint thesis between LNE and the Avignon IT Laboratory will tackle the explicability of automatic speech transcription systems. In this field, as in all others where AI is becoming a must, LNE intends to become a reference organisation. ■

MOBILE ELECTRONICS: METROLOGY TO MEET THE CHALLENGE OF ENERGY CONSUMPTION

The emergence of 5G and the Internet of Things is accompanied by a sharp increase in energy consumption associated with the information and communication sector, 20% of which can be attributed to personal mobile devices. In this context, the European ADVENT project, coordinated by LNE and completed in 2020, aimed to develop multi-scale metrology (from the material to the system) enabling the assessment, in situ and in operation, of the energy characteristics of the components of these devices.

At the materials level, LNE's metrologists therefore developed nanometric standards to ensure the traceability of capacitance measurements through SMM (Scanning Microwave Microscope) of advanced nanomaterials, such as piezoelectric materials. As François Ziadé of LNE points out, *"From a situation where there was nothing, we now have the possibility of measuring capacitance in a range from the attofarad to several femtofarad with an uncertainty of around 10%."*

In addition, French specialists developed a power sensor for components with an operating frequency of around 42 GHz, one of the frequencies selected for 5G. Developed on an electronic chip, this sensor provides the opportunity to bypass connection constraints affecting measurements and will enable the calibration of integrated industrial sensors. The result is the possibility of carrying out measurements with an uncertainty of a few tens of micro watts in a field where metrologists were also starting from scratch. This development will help industrialists to better define power sensors, which are essential in both current and future mobile electronics. ■

FUNDAMENTAL METROLOGY AND DISSEMINATION OF THE SI

Improving the accuracy of fundamental standards remains at the heart of LNE's activities and those of the laboratories in the French National Metrology Network. This includes both fundamental physics research and developments for the dissemination of units to end-users or the adaptation of national references to new applications.

ATOMIC AND NUCLEAR DATA: ITS MEASUREMENT AND ASSESSMENT ENSURED OVER THE LONG TERM

LNE-LNHB's work contributes to international efforts to improve atomic and nuclear data. The laboratory also plays a central coordinating and editing role in gathering them and making them available to users.

Radioactivity metrology must face up to a unique challenge to establish the becquerel unit. Each radionuclide has its own identity with specific decay modes, particle types, energies and emission intensities. In order to determine how a certain amount of a radionuclide decays over time, it is necessary to identify all of its decay pathways as precisely as possible, in particular the energy spectra of the particles emitted. Detailed metrological knowledge of radionuclide decay is therefore essential in metrology, but is also of great importance in medicine, fundamental physics, power generation or national defence applications. The measurement and assessment of this atomic and nuclear data is carried out in France by LNE-LNHB, a key laboratory in the world of radioactivity metrology.

In order to provide users with the best possible information in the area, LNE-LNHB coordinates the *Decay Data Evaluation Project* (DDEP). This informal international project started in 1995 and aims to assess and summarise all global nuclear data for radionuclides of metrological interest. The recommended value and its determination uncertainty are carefully established for each quantity of interest by the DDEP group. These values can be consulted through various publications, including those of the BIPM. For over twenty years, LNE-LNHB has been developing a substantial database and a set of tools to make it accessible from its website (http://www.lnhb.fr/donnees-nucleaires/). Through ongoing dialogue, this dissemination activity strives to meet the needs of the different users as efficiently as possible, year after year. Some of this work is carried out within different projects, and 2020 saw the completion of some of them. Thus, LNE-LNHB physicists developed the Nuclide++ module for the GEANT4 Monte-Carlo simulation code. This simply allows all DDEP data to be used in this reference code for simulations of radiation-matter interactions, whether to study the response of a detector to a source or that of a biological tissue to an internal or external radiotherapy treatment. In parallel, Abhilasha Singh defended her doctoral thesis on the metrological study of the shape of the beta spectra of different radionuclides, through the implementation of a low-noise spectrometer with very high angular coverage. The results were compared with those obtained by other methods and with the theoretical predictions made based on the BetaShape code, developed in the laboratory by Xavier Mougeot, a new version of which has been available for a few months. This researcher also defended his Authorisation to Direct Research on this theme in 2020.

Atomic and nuclear data assessments, as well as some of the measurements carried out at LNE-LNHB, are financed by State funds allocated to French Metrology. In view of the importance of these studies, it was decided to ensure their durability by including them in the laboratory's permanent programme of activities, starting this year. As Mark Kellett, head of the Activity Metrology Laboratory within LNE-LNHB, points out: *" This visibility is essential to ensure our work in the context of the DDEP, work which is essential to many communities but rarely in the spotlight. Thanks to our dissemination activities, these funds also make it possible to highlight all our activities and, in so doing, to develop new projects with our partners, while aiming to maintain LNE-LNHB's expertise in radioactivity metrology at the highest level worldwide."* ■

THE OPTICAL SECOND WILL SOON BE BEYOND QUANTUM LIMITS

Continuing its research work on so-called optical atomic clocks, LNE-SYRTE is approaching the ultimate limits of precision in time measurement.

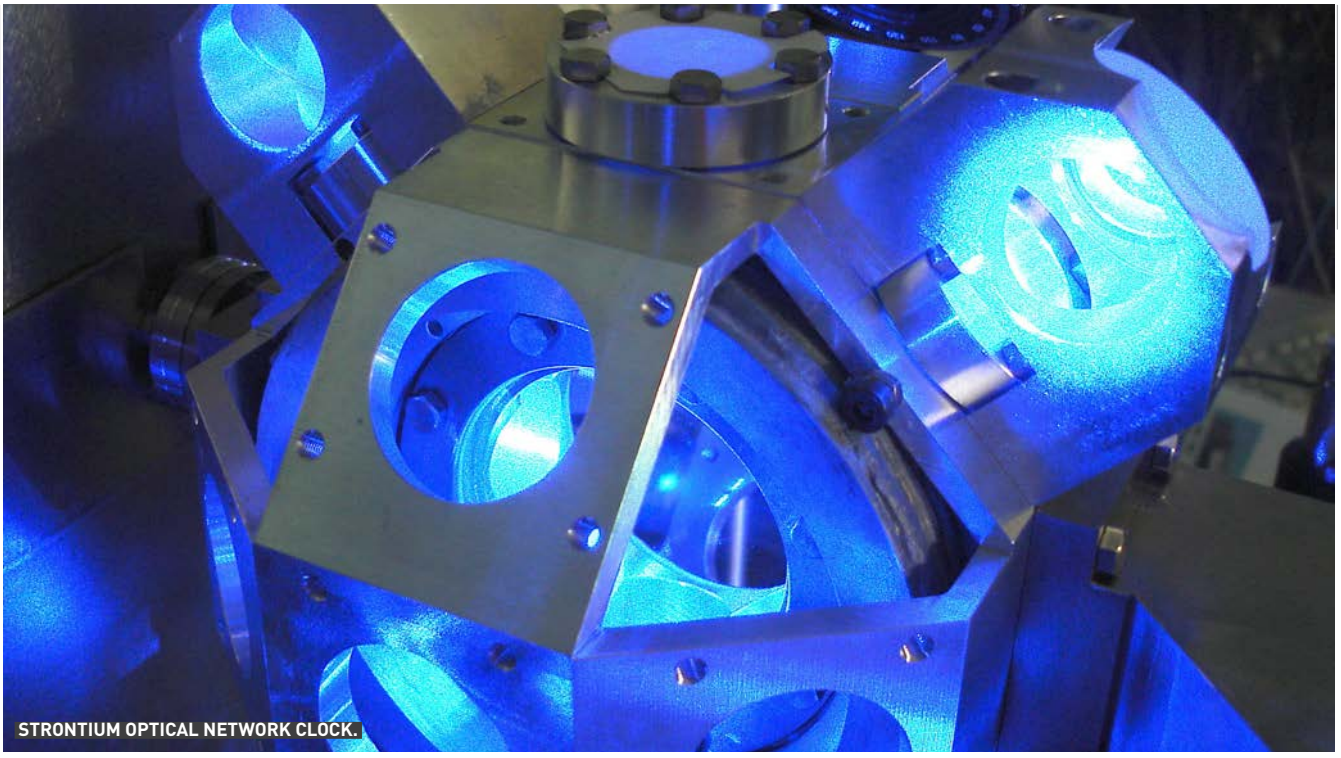
Defined based on the transition frequency between two energy levels of the caesium atom, located in the microwave range, the second is today determined with a relative uncertainty in the order of 10^{-16}. As a result, today the second is the most accurately defined unit of the SI. However, the progress made in recent years in the field of atomic clocks suggests the possibility of a new definition of the unit of time that is at least 10 times more precise. How? By using atomic transitions at higher frequencies, located in the so-called optical part of the electromagnetic spectrum. One possibility for their implementation is to use strontium clocks, two examples of which LNE-SYRTE has developed at the highest level worldwide for several years. However, for these to become the new reference standard, specialists still need to master all the subtleties.

To this end, last year, French metrologists notably continued their work aiming to better control the effect of collisions between strontium atoms and the residual gas in the vacuum vessel that contains them. In order to determine the chemical nature of this gas, on which the way in which collisions affect the transition frequency of their clocks depends, they developed a model and compared it with new measurements with gases such as nitrogen or argon. In addition, LNE-SYRTE researchers continued to participate in comparisons of optical clocks from different European time metrology laboratories.

This exercise is essential to ensure their robustness in the long term.

Finally, physicists worked on taking into account the "fundamental" limits that affect the stability of their clocks. More specifically, the random quantum properties of atoms mean that the measurement of their frequency with a laser is marred by an intrinsic uncertainty. Nevertheless, to lower the value, it is possible to take advantage of another quantum property that allows atoms to be placed in a so-called entangled state such that they no longer form a collection of isolated particles, but rather an irreducible entity with no conventional equivalent. *"The strontium atoms then "respond" in unison to the laser's stimulus, and the accuracy of their frequency measurement increases,"* explains Jérôme Lodewyck of LNE-SYRTE.

Thus, in 2020, specialists developed a highly sensitive measurement system that can produce these states through an interaction between light and atoms that does not destroy their quantum properties, which is a prerequisite for its implementation to increase the performance of optical clocks. *"In this way, it is possible to reduce the measurement time required to "question" a clock as to its frequency, and thus to get a little closer still to the possibility of defining the second with an uncertainty of around 10^{-18} as is envisaged in principle with an optical clock"*, says the physicist. This will put the "optical second" even more within reach. ■



STRONTIUM OPTICAL NETWORK CLOCK.

EMPIR PROGRAMME: EUROPEAN METROLOGY AT THE SERVICE OF SOCIETY

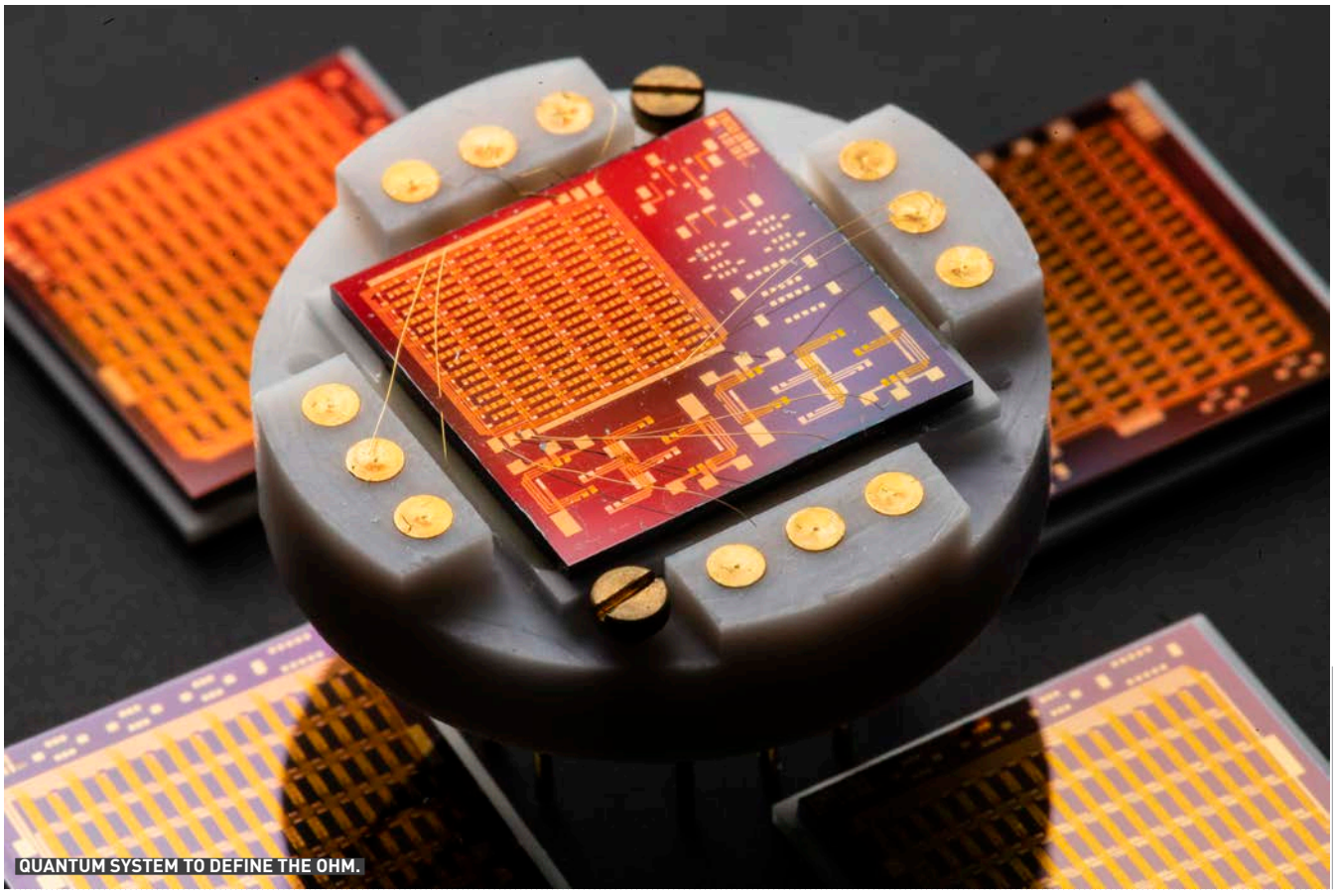
The EMPIR European metrology programme is coming to an end. It has helped to reshape the face of metrology on the continent. Resolutely cooperative, it is now entirely focused on major societal issues.

After seven years of calls for projects, between 2014 and 2020 (with projects still under way until 2024), the EMPIR programme is coming to an end. For this programme dedicated to metrology within the European Commission's 8th Framework Programme for Research and Innovation, Horizon 2020 (H2020), the beginning of 2021 is naturally a time for taking stock.

And at this time, one thing is certain: with EMPIR, there will be a before and after in the European metrology landscape. As summarised by Maguelonne Chambon, LNE Director of Scientific and Technological Research, *"EMPIR has quite simply changed the way metrologists work in Europe."*

Specifically, EMPIR has enabled the coordination of all metrology projects on the continental scale. Better still, thanks to EMPIR, the European metrology community is now a key player in meeting current major economic, environmental and societal challenges. A programme in which French metrologists can hold their heads up high.

Historically, EMPIR is a continuation of the European metrology projects that began in the late 2000s. Thus, in 2008, with a budget of 64 million euros, the iMERA-Plus project demonstrated to the European Commission the capacity of the European metrology community to set up R&D projects. Hence the continuation of the EMRP which, with a budget of 400 million euros,



QUANTUM SYSTEM TO DEFINE THE OHM.

CLEAN ROOM.

enabled researchers from 23 countries to participate in 119 projects between 2009 and 2013. Following on from it, grouping 28 countries and with a budget of 600 million euros (half from the European Commission and the other half from the Member States) divided between 236 projects, EMPIR logically continued to support the growth of European metrology.
For its part, over 7 years, France committed 27 million euros to EMPIR, in other words, 8.5% of the total funding by the states, for a higher rate of return of 9.64%. More specifically, LNE and French metrology laboratories received funding of 18.16 million euros from the Commission, corresponding to a rate of return of 8.8% among European NMI/DIs. For their part, the other entities (academic laboratories, industrialists, etc.) associated with EMPIR projects have a rate of return of 11.4%, with an allocated budget of 10.6 million euros. In terms of projects, French metrology participated in 113 of them and led 24, in other words, 21.4% of those in which it was involved.
In Maguelonne Chambon's opinion, *"There are two reasons for these favourable figures with regard to French metrology. Firstly, our work is based on a solid foundation of knowledge in many areas. Secondly, our researchers have demonstrated their great capacity to adapt to the new paradigm proposed by the European Commission's programmes."* Because over time, the task of metrologists has changed.
The director continues: *"Fifteen years ago, we used to talk about metrology by quantity or by unit: the second, the metre, the kilogram, etc. And the work of metrologists consisted of developing and maintaining references, among other things. But with the EMRP and even more so with EMPIR, their activity has expanded considerably. Starting from the concrete needs of users, it is a matter of proposing concrete solutions for disseminating units, also of addressing all the quantities derived from them and finally of providing answers to cross-disciplinary and societal issues."*
In concrete terms, the EMPIR programme was structured into three main sections: a fundamental section based on the International System of Units (SI), another on major societal challenges such as the environment, health and energy, and a third specific to metrology issues for industry.
In terms of fundamental progress, the period covered by EMPIR was distinguished by the redesign of the SI, which saw four of its seven units change definition. Moreover, all of them were redefined on the basis of a fundamental constant of physics whose value had to be definitively set. In this endeavour, French metrologists played an active role through their work on the redefinition of the kilogram, the kelvin and the ampere.
In the spirit of the EMPIR programme, specialists also tackled the question of the dissemination of these new units.
"For example, it is not enough to have a new definition of the kelvin based on the Boltzmann constant of thermodynamics. We must also make it possible for industrialists to use it," says, for example, Maguelonne Chambon. In addition, several projects were carried out on derived thermal units, in particular with the aim of producing references that make it possible to define the thermal resistance of materials, data that is essential for effectively tackling the thermal renovation of buildings in the context of the fight against global warming and the improvement of energy efficiency. Similarly, the second can be mentioned, which is currently the subject of major fundamental work with a view to its upcoming redefinition; at the same time,

EXPERIMENTAL PLATFORM FOR THE ASSESSMENT OF THE PERFORMANCE OF AIR QUALITY MICROSENSORS.

specialists are working on fibre-optic links enabling the dissemination of very high-precision frequency signals, intended for both universities and for companies.

With regard to major societal challenges, *"French metrology has been up to the task,"* says Maguelonne Chambon. *Including on issues where we were not necessarily well identified and where we have seen a rise."* This is particularly the case in the field of health, where, since 2016, a directive has required medical analysis laboratories to connect to traced references for the dosing of biomarkers. *"By force of circumstance, this has had the effect of bringing us closer to these entities that previously did not know us well,"* explains the researcher. In addition, several projects focused on ionising radiation, such as radiotherapy, where metrology is clearly critical for patients. *"There is also the field of nanometrology, which is cross-disciplinary to health and the environment,"* continues the specialist. *"What is interesting is that just 15 years ago, we could not have imagined all these needs. They were clearly dictated to us by society."* This is still the case for many projects in geodesy, on navigation and localisation, quantum technologies or appearance. *"Linked to the human eye, we had to define atypical quantities for the last of these themes,"* explains Maguelonne Chambon. *"We had taken little interest in them even though they are very important to industrialists."*

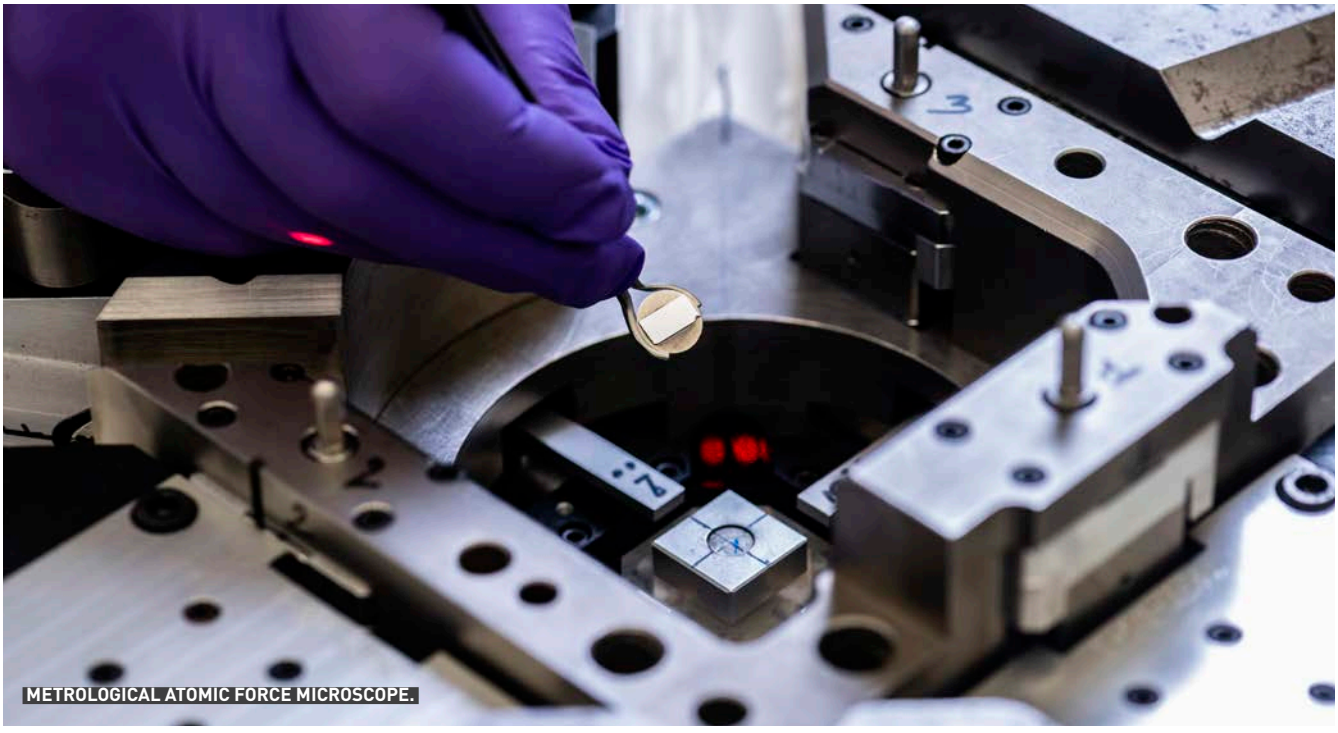
Industrialists also showed particular interest in EMPIR's so-called pre-standardisation projects, which are devoted to work upstream of standardisation and to which 10% of the programme's budget was allocated. The initial observation was that there was little interaction between metrology research and standardisation committees, which sometimes led to aberrations with standards that were impossible to implement due to a lack of metrological means to enforce them. *"With respect to air quality, buildings or even micro-fluidics, lighting or electrical networks, we carried out surveys and interviews with professionals in order to meet their needs as closely as possible,"* explains the scientist. A platform was also created to collect them, a platform between EURAMET and CEN-CENELEC, which France chaired throughout the programme.

In addition to bringing industrialists together, EMPIR also had the effect of strengthening existing links between the metrology community and other research entities and creating new ones. 90 million euros were allocated to these by the European programme, with the aim of enabling collaborations to benefit from skills that are complementary to those of metrology laboratories. *"This measure has been very beneficial,"* says Maguelonne Chambon. *"In addition to the CNRS and the CEA, we therefore approached various universities, university hospitals and INSERM, as well as industrialists, such as Air Liquide and Thales, which we had as service providers, but which we had not necessarily identified as partners for R&D. We also established links with SMEs, such as POLLEN."*

One thing is certain: as a result of the EMRP and EMPIR programmes, European metrology has reached a high level of maturity characterised by a strong capacity for cooperation between the various parties involved. It is in this context that the European Commission's 9th Framework Programme for Research and Innovation, Horizon Europe, started at the beginning of this year, with a budget of 700 million euros for its metrology component. It should be noted that this will also be the last one, obliging the bodies that coordinate it and benefit

« French metrology has been up to the task including on issues where we were not necessarily well indentified and where we have seen a rise.»
Maguelonne Chambon, Director of Scientific and Technological Research.

from it to think of a way beyond the Commission's framework programmes as of now, in order to perpetuate the synergies that they have created, when it comes to an end in 2027.
Thus, in 2019, EURAMET launched a series of European Metrology Networks (EMN). Their role is to analyse needs and implement coordinated strategies between the different players and users of metrology with respect to the aspects of research, infrastructure, knowledge transfer and services. To date, EMNs cover the following topics: mathematics and statistics for metrology, traceability for medical analysis, quantum technologies, smart power networks, climate and ocean observation and gases for energy. Others are in preparation, whether on radiation protection regulations, advanced manufacturing, the use of ionising radiation in the field of medicine, "green" energies or pollution. In a nutshell, they focus on all the major challenges defined by the European Commission for Horizon Europe.
"Having learned to cooperate, we must now better coordinate ourselves in the long term," says Maguelonne Chambon. *"The ultimate goal must now be the creation of common platforms enabling the pooling of metrology resources on a European scale. In addition, we still need to increase our visibility, so that our potential partners understand well in advance that they cannot do without metrology."* Nor can society as a whole. Thanks to EMPIR, the work is clearly under way. Now it must be established over the long term. ■



METROLOGICAL ATOMIC FORCE MICROSCOPE.

QUALIFICATION TO SUPERVISE RESEARCH (HDR)

LNE-LNHB/CEA

Xavier Mougeot, 17 January 2020
«Low interaction transitions in ionising radiation metrology: from fundamental physics to applications». ■

DISTINCTION

CNRS MEDAL OF INNOVATION 2020

Arnaud Landragin, Director of the SYstèmes de Référence Temps-Espace (SYRTE) laboratory,

recognised for his work in the field of atomic gravimetry and its transfer to industry (development of ultra-precise sensors for geoscientific applications).

The winning innovation is a cold atom interferometric sensor; the subject of a patent, it was the origin of the Muquans company, which now markets absolute cold atom gravimeters, which are compact and transportable and provide performance (sensitivity, stability, etc.) that is unrivalled on the global market. ■

DOCTORAL THESIS DEFENCES

LNE-LCM/LNE

Loïc Crouzier, 17 July 2020
«Development of a new hybrid approach combining AFM and SEM for the dimensional metrology of nanoparticles».

LNE-SYRTE/OP

Joannès Barbarat, 21 September 2020
«Development of a visible, compact, fibre-reinforced, frequency-stabilised IR & laser source».

Étienne Savalle, 16 November 2020
«Testing general relativity with clocks in space, and exploring the possibilities of detecting dark matter with cold atoms in space and on the ground».

LNE-LNHB/CEA

Abhilasha Singh, 25 September 2020
«Metrological study of the shape of beta spectra and experimental validation of theoretical models».

LNE-LADG

Marc-Antoine Lambert, 18 December 2020
«Contribution to the study of flows in cylindrical sonic nozzles». ■

NEW CALIBRATION SPHERE FOR SECONDARY VACUUM. IT REPLACES THE REFERENCE SPHERE, IN THE BACKGROUND, AFTER MORE THAN 50 YEARS OF SERVICE AT SOGEV (SOCIÉTÉ GÉNÉRALE DU VIDE) AND THEN AT LNE FROM THE MID-80S.

THE FRENCH NATIONAL METROLOGY NETWORK

NATIONAL METROLOGY LABORATORIES

LNE-LCM/LNE-Cnam

The joint metrology laboratory of LNE and the Conservatoire National des Arts et Métiers works in the fields of length, optical radiation, temperature and thermal quantities, mass and related quantities (pressure, force, torque, acoustics, accelerometry, viscosity).

LNE

LNE is responsible for areas such as electricity-magnetism, chemical metrology and mathematics and statistics, in addition to the activities of the LCM.

LNE-LNHB/CEA

The Laboratoire National Henri Becquerel at the Commissariat à l'Énergie Atomique et aux Énergies Alternatives is responsible for producing references in the field of ionising radiation, i.e., dosimetry and radioactivity.

LNE-SYRTE/OP

The Laboratoire des Systèmes de Référence Temps-Espace at Observatoire de Paris - PSL is responsible for the production of time-frequency references.

LNE PARTNER LABORATORIES

LNE-CETIAT

The Centre Technique des Industries Aérauliques et Thermiques is responsible for hygrometry, liquid-water flow measurement and anemometry.

LNE-ENSAM

The École Nationale Supérieure d'Arts et Métiers de Paris is in charge of dynamic pressure references.

LNE-IRSN

The Institut de Radioprotection et de Sûreté Nucléaire is responsible for neutron dosimetry.

LNE-LADG

The Laboratoire Associé de Débitmétrie Gazeuse, for gas flow measurement.

LNE-LTFB

The Laboratoire Temps-Fréquence de Besançon is in charge of the transfer of time and frequency references, in particular for phase spectral density measurements and time and frequency stabilities.

LNE-TRAPIL

The Trapil laboratory is responsible for liquid hydrocarbon flow measurement references.

Registered office: 1 rue Gaston Boissier - 75724 Paris Cedex 15 - France - Tel.: +33 (0)1 40 43 37 00
lne.fr - metrologie-francaise.lne.fr - info@lne.fr

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