Publishable Summary for 21SCP02 TRaMM
Traceability Routes for Magnetic Measurements

Overview

Magnetic measurements are vital to support European challenges in areas such as electric vehicles; health; power transformation and harvesting; clean, affordable and secure energy; information and sensor technology. However, only very few (4) European NMIs had the capabilities to perform traceable measurements of all of the most important magnetic quantities. Consequently, the adoption of novel technologies and materials was hindered by the lack of local metrological expertise that research and development activities in academia and industry could exploit. An experienced NMI (INRIM) has extended their capability to perform traceable magnetic measurements to two less developed NMIs in this field (CEM, NSAI). This has enabled them to start addressing market and stakeholder requirements in their countries. A smart specialisation concept has also been outlined, which may serve as the basis for future projects. A comprehensive set of lessons and laboratory videos were prepared and made available to the project partners, the stakeholders and the general public through the website and a dedicated YouTube channel. A survey among the stakeholders allowed the consortium to identify magnetic metrology needs that are not currently addressed, and the results were presented at international conferences and have been submitted for publication. Finally, the partners developed strategic development plans, which have already resulted in a new magnetic field metrology laboratory in Spain. In a joint effort, with selected stakeholders and a few other European NMIs, the partners agreed to further develop magnetic metrology in the low-intensity magnetic field range in the next few years, in response to stakeholders needs.

Need

Magnetic measurements are relatively common in academia and in industrial research and development, as they are widely employed for the measurement of magnetic fields and for the characterisation of the magnetic cores in sensors or electronics. In addition, they are used in applications such as earth observation, biomedicine and health and safety requirements regarding exposure to electromagnetic fields (The Electromagnetic Fields Directive 2013/35/EU). However, industrial and scientific communities were unable to fully benefit from traceable and reliable measurement results because of limited access to suitable calibration facilities. With the global magnetic materials market continuously increasing at an annual growth rate of about 9.6 %, it was crucial to develop sustainable magnetic measurement capabilities that will support these end-users.

Even though the calibration of teslameters and coils, or the measurement of the magnetic properties of steel sheets for power applications (electrical motors, transformers) are already standardised, very few (4) European NMIs were capable, for historic reasons, of providing a comprehensive set of measurement and calibration services in these areas, which require very specific instruments and techniques. This was different from other electrical measurements. In addition, new research activities and industrial products, in the fields of biomedicine, theragnostics, water remediation, and security expanded the need for traceable magnetic measurements for e.g. the characterisation of magnetic nanoparticles, rings, ribbons or bulk materials, or for sensing devices involving magnetoelectric phenomena.

Other fields requiring traceable and reliable magnetic measurements are all those where magnetic materials are exploited for energy conversion, harvesting and storage, such as automotive and powertrains, aerospace, and smart grids. All these applications attract both scientific research and industry, and offer development and market opportunities especially for SMEs that wish to be dynamic and innovative, offering breakthrough technologies and solutions to new potential customers and markets. In spite of this exciting innovation and development, easy access to the measurement and calibration capabilities for magnetic field and magnetic material characterisations were still mostly lacking, leaving industry and academia with the unaddressed need to properly validate their technological solutions through traceable magnetic measurements.

Relevant stakeholders belonged to the following categories: academia and research centres working on magnetic materials and applied magnetism (for energy transformation, actuation, sensing, biomedicine); industries belonging to electric vehicle supply chains (electric motors) and power application supply chains (electric motors and transformers); industries belonging to sensor supply chains (magnetic field probes, position, rotation, angle, speed, vibration, etc., detectors, bit detectors and systems for magnetic registration); industries belonging to the magnetic field monitoring supply chain (measurement of magnetic fields in or around industrial equipment, biomedical devices such as NMR, personal exposure meters, etc.); industries involved in medical device manufacturing; industries in the food supply chain (metal detection in food processing); industries involved in electric and electronic components (e.g. microwave components); academia and research centres working on geomagnetism; industries belonging to the steel supply chain (manufacturers and industries processing semifinished products) and to the weakly magnetic steel supply chains (aerospace, naval and military industries).

The stakeholders' high-level needs and the metrology services provided or planned by the NMIs/DIs needed to be determined and aligned (Objective 1). Initially, the developing NMIs (CEM, NSAI) were not able to fulfil these needs due to the lack of relevant resources and experience. They were unable to quickly solve this problem to help their stakeholders. Therefore, an experienced NMI (INRIM) provided the knowhow through customised training for each partner (Objective 2). In addition, each partner developed a plan in order to acquire the capability needed to address their stakeholders' needs. This plan included the definition of a smart specialisation concept, which may be extended and implemented in future projects (Objective 3).

Objectives

The overall objective of this project was to make traceable magnetic measurements more widely available in the EU, by disseminating the knowledge and expertise of an expert NMI (INRIM) to those NMIs with less developed capabilities (CEM, NSAI) that have market and stakeholder needs in this field. This project aimed at establishing the foundations for the development of relevant and reliable magnetic measurement and calibration services at CEM and NSAI by raising their level of understanding of the fundamental techniques used in this field.

The specific objectives of the project were:

1. To identify existing stakeholder needs in the area of magnetic measurements and related calibration services and to establish contact with other European NMIs in order to understand their current capabilities and future plans. To analyse the alignment between the stakeholders' high-level needs and the metrology services provided or planned by the NMIs/DIs.
2. To transfer knowledge and expertise related to magnetic measurement and calibration techniques from the expert NMI (INRIM) to the developing NMIs (CEM, NSAI) by delivering training that is customised to include the capabilities that they need to acquire in order to address the stakeholders' needs.
3. For each partner to develop a plan, including the sourcing of suitable hardware, the development of measurement procedures and quality schemes, in order to acquire the capability needed to address the stakeholders' needs. The plan will include definition of the smart-specialisation concept and coordination among the participating NMIs and other NMIs/DIs to pave the way for the future development of smart specialisation in magnetic measurements and calibration services, possibly through follow-on projects.

Results

1. *To identify existing stakeholder needs in the area of magnetic measurements and related calibration services and to establish contact with other European NMIs in order to understand their current capabilities and future plans. To analyse the alignment between the stakeholders' high-level needs and the metrology services provided or planned by the NMIs/DIs.*

This project searched for stakeholders from universities, research centres, other NMIs, and different supply chains, such as: measurement equipment manufacturers (flux meters, tesla meters, NMR equipment, fluxgates, etc., but also medical equipment); space; automotive; health (hospitals or companies monitoring the environmental magnetic field surrounding medical or industrial equipment); electronics; food processing. Fifty-one stakeholders from 13 different European countries agreed to receive further information on the development of this project. Their needs were identified through two ad-hoc questionnaires that were

submitted to them, and a list of capabilities that NMIs need to have in order to address not only the current needs, but also those for the foreseeable mid- to long-term was compiled. These needs and the European NMIs' capabilities and future plans were analysed to determine their alignment. This information was used to determine the knowledge and expertise that needed to be transferred to the developing NMIs (CEM, NSAI) in Objective 2. Eventually, a report was prepared and published on the project's website, detailing the alignment between the stakeholders' high-level needs for magnetic measurements and calibration services and the metrology services provided or planned by the NMIs/DIs (deliverable D1).

From the 20 stakeholders that provided feedback through the questionnaires, a partial misalignment between what is currently offered by NMIs and what is currently and will shortly be needed by stakeholders, in terms of magnetic measurements and calibrations, pointed to the need to develop metrological expertise, laboratories, standards and capabilities in the following areas:

i. Calibration of probes and sensors, also of novel kinds, on a wide range of field strengths, including low field intensities (which are currently difficult to trace to primary standards) and high field intensities (which are difficult to implement in laboratories).

ii. Calibration of probes and sensors, also of novel kinds, on a wide frequency range, not limited to 50 kHz which is the current highest frequency limit of the available CMCs.

iii. Characterisation of the magnetic properties of components and finished products, for certification, comparison of different manufacturers and suppliers, etc.

iv. Characterisation of complex material types (e.g. nanoparticles), where not only the measurement process, but also the sample preparation procedures need to be documented and standardised.

Besides these new areas of development, the traditional measurement and calibration capabilities for Hall probes, fluxgates, soft and hard magnetic materials are still of widespread importance, therefore requiring the development of expertise on this in more European countries. At the end of the project, this objective was achieved, the stakeholders' needs were collected and published on the website as deliverable D1, and the misalignment with the current metrological offering in the EU was analysed.

2. *To transfer knowledge and expertise related to magnetic measurement and calibration techniques from the expert NMI (INRIM) to the developing NMIs (CEM, NSAI) by delivering training that is customised to include the capabilities that they need to acquire in order to address the stakeholders' needs.*

The developing NMIs (CEM, NSAI) have acquired the knowledge and expertise common to all magnetic measurements and calibration services in order to address the stakeholders' needs. Follow-up training was provided, targeted to specific magnetic materials and calibration capabilities. The training was supported with ad-hoc training material (lessons, presentations, technical documents, videos, etc.), that were also shared with stakeholders, and made publicly available online. The results of the survey described in Objective 1 allowed the partners to develop an innovative training programme to transfer knowledge from INRIM to CEM and NSAI, focussing not only on the traditional measurement and calibration methods exploited for magnetic quantities, but also on novel aspects where measurement techniques, typically belonging to research laboratories, needed to be inserted into a well-established metrological context to make them useful to address the stakeholders' needs. The training programme, therefore, has been developed through a PhD course, attended by CEM and NSAI researchers, aimed at giving the fundamentals of magnetism and magnetic measurements, but also the deeper critical analysis of magnetic measurement procedures that was required to understand how the new metrological challenges that emerged from the questionnaires will impact the metrological chain in this field. Additionally, a set of training videos, based both on traditional and innovative measurement and calibration techniques, has been created.

After the initial training with the PhD course and video lessons, a 4-day training event was organised at INRIM's laboratories, which was attended by CEM and NSAI researchers. During this event, the calibration and characterisation techniques available at INRIM's magnetic laboratories were made available to the trainees, who were able to use them with the aid of experienced scientists in the field. Later on, two specific training events, one at CEM and the other at NSAI, were addressed to their respective researchers, focussing on their available equipment and laboratories, and on their development perspectives. At the end of the project, the objective was achieved: the magnetic measurements and characterisation knowledge was

transferred to the partners, and a comprehensive set of training videos was produced and published online, for use of stakeholders, other NMIs, and of the general public.

3. *For each partner to develop a plan, including the sourcing of suitable hardware, the development of measurement procedures and quality schemes, in order to acquire the capability needed to address the stakeholders' needs. The plan will include definition of the smart-specialisation concept and coordination among the participating NMIs and other NMIs/DIs to pave the way for the future development of smart specialisation in magnetic measurements and calibration services, possibly through follow-on projects.*

Each partner has prepared a development plan, which includes the sourcing of suitable hardware, and the development of measurement procedures and quality schemes, in order to acquire the capability needed to address the stakeholders' needs. The plan also includes a definition of the smart specialisation concept and coordination among the participating NMIs, and other NMIs/DIs, to pave the way for the future development of smart specialisation in magnetic measurements and calibration services, possibly through follow-on projects. The plan was published on the project's website. A first outcome has been the submission of a Potential Research Topic application on the metrology of low-intensity magnetic fields for the Research Potential 2024 call, involving this project's partners, several of its stakeholders, and additional European NMIs. At the end of the project, the objective was achieved: the strategic implementation plans of INRIM, CEM and NSAI have been compiled, and a smart specialisation concept has been envisaged and published on the project website as deliverable D3. The smart specialisation concept was already exploited to form a group of interested parties (NMIs and stakeholders beyond those of this project) that submitted a Potential Research Topic application to the 2024 Research Potential call to extend magnetic field metrology to the low-intensity range.

Impact

The project and its results were presented at the:

i. EURAMET TC-EM committee (low frequency subcommittee), in October 2022 (presentation and aim of the project) and in May 2023 (consolidated, although not yet final results of the stakeholders surveys).

ii. IMEKO TC4 conference in September 2022 (target: mostly scientists, metrological community).

iii. AIM conference in January 2023 (target: IEEE scientific association, mostly scientists from academia).

iv. CIM conference and expo in March 2023 (target: mostly European industry).

v. IMEKO TC4 conference in September 2023 (target: scientists, metrological community, industry).

A publication with the final results of the stakeholder survey has been submitted to ACTA IMEKO, and is currently under review.

Fifty-one stakeholders joined the project, covering industry, academia and public research organisations from 13 different European countries. Two questionnaires (one closed-form and one open-ended) have been submitted, and their responses, coming from 20 stakeholders, allowed the consortium to conceive the training programme from CEM and NSAI researchers. A PhD course and eighteen videos have consequently been prepared and published online, with free access, both on the project's website and on a dedicated YouTube channel, presenting theoretical and experimental aspects of magnetic calibrations and measurements. Their publication on the BIPM e-learning platform is underway. A promotional video addressed to the general public has also been prepared and shared online.

Early impact on user communities

The three NMIs that participated in this project have analysed the alignment between their stakeholders' high level needs and the metrology services provided or planned by other NMIs/DIs. This enabled them to plan their development, in collaboration with INRIM, in order to meet these needs (Objective 1). As a result, the future development of CEM's and NSAI's measurement and calibration facilities will be driven by the expectations of the stakeholder community and this will avoid overlap with the metrology services that are currently provided or planned by other NMIs/DIs.

CEM and NSAI have developed the level of knowledge needed to address the stakeholders' needs in the field of magnetic measurements and calibration services (Objective 2). In addition to developing reference standards and calibration setups (after the end of the project), which can be accessed by users who require reliable and traceable measurement results (e.g. academic and research centres working on magnetic materials, medical device manufacturers, measurement equipment manufacturers, companies and agencies involved in the monitoring of the magnetic fields surrounding medical or industrial equipment, etc.), the developing NMIs, as well as creating impact for themselves, have reached the position to generate impact by offering sound technical advice to those involved in magnetic measurements. This means that stakeholders now have local, affordable access to the new consultancy services that they need. CEM was already able to set up instrumentation for magnetic measurements or calibrations before the end of the project, whereas NSAI established a proficient collaboration with the nearby Trinity College Dublin, which has a strong expertise in magnetic measurements. Therefore, their stakeholders can immediately benefit from these NMIs' new capabilities.

The definition of the smart-specialisation concept paves the way for the future development of smart specialisation in magnetic measurements and calibration services (Objective 3). It is expected that the smart specialisation concept will create impact by widening the offering of magnetic measurement and calibration capabilities in the European Union, both through an increased number of expert NMIs in the field, and through an increased awareness, among the stakeholders, of the availability of these capabilities. This will raise stakeholder awareness of the importance of traceable measurements, and it will improve the quality of research outcomes. It will also be possible for the partners to become reference collaborators with academic research centres and with industrial partners that need specific magnetic measurements or calibrations to develop, test or market a certain material, product, technological device, or service. The early impact will therefore be to lift those restrictions that are currently slowing down or hindering the adoption of new technologies, processes or materials by the stakeholders, from a magnetic measurement and calibration point of view.

To promote the uptake of the project's outcomes by the user community, all of the training material and published documents (such as measurement and calibration needs, specialisation plans, etc.) produced within the project's framework (including hands-on training videos) were shared with EURAMET TC-EM and other NMIs and were made publicly available via the project website, a dedicated YouTube channel, and soon on BIPM's e-learning platform.

The project also organised a 1-day stakeholder workshop in February 24. The workshop involved 6 invited speakers who are expert in magnetic field metrology, magnetic materials characterisation and standardisation, and 52 participants (25 in person and 27 online), from many of the project's stakeholders. As an early impact, these stakeholders were informed about the results of the project, about the development plans of the involved NMIs, of the availability of the training material, and about up-to-date resources and competences in magnetic metrology.

Furthermore, the NMIs participating in the project, several of their stakeholders, and a few additional European NMIs submitted a Potential Research Topic application to the Research Potential 2024 call, focussing on low-intensity magnetic field metrology.

Longer term economic, social and environmental impacts

In the longer term, the impact of the project is threefold. Firstly, NMIs that have not been trained during the project's timeframe will be able to benefit from training material in the future. This is already the case for at least one NMI that was not participating in this project, but who co-authored a submitted Potential Research Topic application. Although INRIM does not plan to maintain a training facility for continuous use, it will be available after the end of this project for direct collaboration with other NMIs that would be interested in magnetic measurements and calibration facilities. This will improve the common knowledge base, and extend the network of metrology institutes that will be capable of distributing measurement and calibration expertise on magnetic materials and devices across the EU.

Secondly, the knowledge base established at the NMIs that have participated in this project will enable them to be key players in new actions and future development opportunities. This will include participation in research projects where magnetic measurement capabilities are required, participation in forthcoming projects aiming at smart-specialisation, and the expansion of their capabilities to address new stakeholder needs in the field of magnetic measurements.

Finally, more reliable traceable magnetic measurements will positively impact society and the environment.

For example, reliable magnetic measurements will allow for a much more accurate estimate of the converted energy losses in power applications (with less wasted power), an optimisation of the performance of magnetic materials in technology applications (with reduced raw material requirements and final product weight, which is especially important in the automotive and aerospace industries) and in biomedicine (with optimisation of the amount of magnetic material required to achieve a certain therapeutic or diagnostic result), and an improved performance of safety critical devices that exploit magnetic materials in the information technology industry (cryptography, anti-counterfeiting, anti-adulteration, etc.).

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