CAL LAB

THE INTERNATIONAL JOURNAL OF METROLOGY

2022
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Project LiBforSecUse: Quality Assessment of Electric Vehicle Lithium Ion Batteries for Second Use Applications

Metrological Challenges of Plastics Recycling

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ON THE COVER: Emre TUNA, with KAL-MET Calibration in İzmir, Turkey, is running a fully automated force calibration in accordance with ISO376/ASTM E74 using their 2 meganewton hydraulic calibration system.

UPCOMING CONFERENCES & MEETINGS

The following event dates and delivery methods are subject to change. Visit the event URL provided for the latest information.

Jun 15-17, 2022 CIVEMSA. Chemnitz, Germany. IEEE 9th International Conference on Computational Intelligence and Virtual Environments for Measurement Systems and Applications (CIVEMSA). https://conferences.ieee.org/conferences_events/conferences/conferencedetails/53371

Jun 19-24, 2022 International Microwave Symposium (IMS). Denver, CO. IMS is the flagship event in a week dedicated to all things microwaves and RF. The week also includes the IEEE MTT-S Radio Frequency Integrated Circuits Symposium (RFIC) and the Automatic Radio Frequency Techniques Group (ARFTG). https://ims-ieee.org/

Jun 24, 2022 99th ARFTG Microwave Measurement Conference. Denver, CO. The Automatic Radio Frequency Techniques Group (ARFTG) is a technical organization interested in all aspects of RF and microwave test and measurement. https://www.arftg.org/

Aug 20-25, 2022 NCSL International Workshop & Symposium. Grapevine, TX. The annual NCSLI event is your gateway to the decision-makers for the B2B measurement science industry. Connect with those from companies and associations that support the calibration, testing and service industry, including many of the largest in North America. https://ncsli.org/

Aug 29-Sep 1, 2022 AUTOTESTCON. National Harbor, MD. AUTOTESTCON is the world's premier conference that brings together the military/aerospace automatic test industry and government/military acquirers and users to share new technologies, discuss innovative applications, and exhibit products and services. It is sponsored annually by the Institute of Electrical and Electronic Engineers (IEEE). https://2022.autotestcon.com/

Sep 19-21, 2022 IMEKO TC6 International Conference on Metrology and Digital Transformation (M4D). Hybrid with physical attendance in Berlin, Germany. https://www.m4dconf2022.ptb.de/home

Sep 19-22, 2022 MSA Conference. Wellington, New Zealand. Metrology Society of Australasia conferences are a rare opportunity

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EDITOR'S DESK

Good News, Good News

I owe quite a lot to our contributors. They take time away from their busy lives to produce something that will be of value to others. They are our metrology heroes, spreading the good news of measurement! They include a varied assortment of well-experienced technicians, managers, engineers, consultants, and R&D folks, from both commercial and government institutions. Some are even retired or in-between gigs. They don't just write for publications, and sometimes they don't have to write at all (okay, maybe just a little) to spread the good news… they do this through hands-on teaching and presentation.

Every industry has its events and metrology has a lot of events; there exists plenty of opportunity to present or instruct. Here are some compelling reasons to get involved: Learn something new by getting your feet wet. Meet other measurement heroes! Feel good factor. Bragging rights. You get to travel—remember travel?

A measurement community does not exist without those professionals who contribute. And many of those professionals would not be part of our measurement community if it wasn't for organizations who bring people together in order to collaborate, learn, and solve problems.

Lately, I've been reading about how people learn. It turns out, when you feel like you're having to reach for information in your brain, it's actually your neurons that are reaching and branching out to make connections. If you vary how you receive new knowledge—through different modalities—you now have the ability to make more connections, stronger connections, because you're utilizing prior knowledge. In other words, the more you learn and engage, the smarter you get! But you can't do it all through a computer screen, or in isolation. Flip through this issue's pages to learn about what is going on in metrology—research, training, events, and special interests. Discover all the organizations behind metrological activities and think about getting involved… even if it's just a webinar or virtual conference.

We have a couple of research papers to present this time. The first one is intriguing in its practical nature, as well as its potential for calibration labs to pick up as a service they can offer. "Project LiBforSecUse: Quality Assessment of Electric Vehicle Lithium Ion Batteries," was funded by Euramet's EMPIR program, Participating States, and the European Union's Horizon research and innovation program. The authors go into detail of their processes and why they chose to do things the way they did.

To continue the theme of "reduce, reuse, and recycle," the second paper, "Metrological Challenges of Plastics Recycling," takes inventory of the types of materials involved in collection and the sensor technologies needed to help process Europe's (and the world's) post-consumer plastic. The author was kind enough to produce a paper from his poster presentation, originally presented at last year's International Metrology Congress (CIM) in Lyon, France.

Each of these research papers present a problem and solution (or a part of the solution) that can be picked up by business and industry. In this way of investigating and collaborating, they are measurement heroes spreading the Good News!

Before I forget, don't miss Dan Wiswell's *In Days of Old*, where he talks about production of the old meters and the interesting tools and human labor that went into each instrument. It's a real good story.

Happy Measuring,

Sita Schwartz, Editor

to demonstrate calibration, test and measurement products and services to a cross-section of measurement-focused scientists, engineers and technicians from Australia, New Zealand and beyond. https://www.metrology.asn.au/msaconnected/

Sep 26-30, 2022 Metrology for Climate Action. Online Workshop. The workshop, hosted by BIPM and WMO, is open to experts and stakeholders active in the fields of climate science, observations, GHG mitigation and measurement, modelling and measurement science willing to contribute to the development of recommendations on key technical challenge areas for metrology in these fields. https://www.bipmwmo22.org/

Oct 11-13, 2022 IMEKO TC3, TC5, TC16, TC22. Cavtat-Dubrovnik, Croatia. Conferences on the Measurement of: Force Mass & Torque, Hardness, Pressure & Vacuum, and Vibration. https://conferences.imeko.org/event/1/

Oct 25-27, 2022 The Global Flow Measurement Workshop. Aberdeen, UK. To reflect the ongoing changes in the industry, and as we focus on the energy transition and meeting the measurement challenges of vital net-zero greenhouse emissions obligations, "The North Sea Flow Measurement Workshop" has a new name: "The Global Flow Measurement Workshop." https://www.tuvsud.com/en-gb/events/global-flow-measurement-workshop

Nov 2-4, 2022 MATHMET. Paris, France. The 5th edition of the Mathmet international conference will take place at the ENSAM (Ecole Nationale Supérieure des Arts et Métiers). Mathmet 2022 is an event of the European Metrology Network (EMN) for Mathematics and Statistics to promote new analytical and computational approaches in measurement science. https://www.lne.fr/en/events/mathmet-2022

Dec 12-16, 2022 Conference on Precision Electromagnetic Measurements (CPEM). Wellington, New Zealand. The Measurement Standards Laboratory of New Zealand (MSL), in collaboration with the National Measurement Institute of Australia (NMIA), enthusiastically welcomes you to CPEM2022. https://www.cpem2022.nz/

SEMINARS & WEBINARS: Dimensional

Jun 14-15, 2022 "Hands-On" Precision Gage Calibration & Repair Training. Virtual Class. IICT Enterprises. This 2-day training offers specialized training in calibration and repair for the individual who has some knowledge of basic Metrology. Approximately 75% of the workshop involves "Hands-on" calibration, repair and adjustments of micrometers, calipers, indicators height gages, etc. https://www.calibrationtraining.com/

Jun 29, 2022 Seminar #111: Introduction to Dimensional Gage Calibration. Aurora, IL. Mitutoyo. This 1-day classroom course is part of our dimensional metrology curriculum and is a blended learning opportunity to maximize the student's time in the classroom. Adapted from our popular 3-day Dimensional Gage Calibration course, this 1-day version utilizes Mitutoyo America's online video material, which is to be watched prior to attending the classroom course. https://www.mitutoyo.com/training-education/

Jul 12-13, 2022 "Hands-On" Precision Gage Calibration & Repair Training. Virtual Class. IICT Enterprises. This 2-day training offers specialized training in calibration and repair for the individual who has some knowledge of basic Metrology. Approximately 75% of the workshop involves "Hands-on" calibration, repair and adjustments of micrometers, calipers, indicators height gages, etc. https://www.calibrationtraining.com/

Jul 19-20, 2022 "Hands-On" Precision Gage Calibration & Repair Training. Akron, OH. IICT Enterprises. This 2-day training offers specialized training in calibration and repair for the individual who has some knowledge of basic Metrology. Approximately 75% of the workshop involves "Hands-on" calibration, repair and adjustments of micrometers, calipers, indicators height gages, etc. https://www.calibrationtraining.com/

Jul 20, 2022 Seminar #111: Introduction to Dimensional Gage Calibration. Aurora, IL. Mitutoyo. This 1-day classroom course is part of our dimensional metrology curriculum and is a blended learning opportunity to maximize the student's time in the classroom. Adapted from our popular 3-day Dimensional Gage Calibration course, this 1-day version utilizes Mitutoyo America's online video material, which is to be watched prior to attending the classroom course. https://www.mitutoyo.com/training-education/

Aug 2-4, 2022 Seminar #114: Dimensional Gage Calibration. Aurora (Chicago), IL. Mitutoyo America's Gage Calibration course is a unique, active, educational experience designed specifically for those who plan and perform calibrations of dimensional measuring tools, gages, and instruments. https://www.mitutoyo.com/training-education/

Aug 5, 2022 Geometric Dimensioning & Tolerancing Workshop. Lower Hutt, NZ. Measurement Standards Laboratory of New Zealand. This course explores the fundamentals of geometric dimensioning and tolerancing and explains the symbols, modifiers, rules, and concepts of GD&T based on the ASME Y14.5-2018 Standard. https://www.measurement.govt.nz/training/

Aug 9-10, 2022 "Hands-On" Precision Gage Calibration & Repair Training. Bloomington, MN. IICT Enterprises. This 2-day training offers specialized training in calibration and repair for the individual who has some knowledge of basic Metrology. Approximately 75% of the workshop involves "Hands-on" calibration, repair and adjustments of micrometers, calipers, indicators height gages, etc. https://www.calibrationtraining.com/

Aug 11, 2022 Geometric Dimensioning & Tolerancing Workshop. Auckland, NZ. Measurement Standards Laboratory of New Zealand. This course explores the fundamentals of geometric dimensioning and tolerancing and explains the symbols, modifiers, rules, and concepts of GD&T based on the ASME Y14.5-2018 Standard. https://www.measurement.govt.nz/training/

Sep 13-14 2022 "Hands-On" Precision Gage Calibration & Repair Training. Virtual Class. IICT Enterprises. This 2-day training offers specialized training in calibration and repair for the individual who has some knowledge of basic Metrology. Approximately 75% of the workshop involves "Hands-on" calibration, repair and adjustments of micrometers, calipers, indicators height gages, etc. https://www.calibrationtraining.com/

Sep 20-23, 2022 Fundamentals of Geometrical Dimensioning and Tolerancing. Online. National Measurement Institute, Australia. This course is based on ASME Y14.5-2009 standard. You will learn about the symbols, modifiers, rules and concepts of geometric dimensioning and tolerancing (GD&T). https://shop.measurement.gov.au/collections/physical-metrology-training

Sep 22-23, 2022 "Hands-On" Precision Gage Calibration & Repair Training. Bloomington, MN. IICT Enterprises. This 2-day training offers specialized training in calibration and repair for the individual who has some knowledge of basic Metrology. Approximately 75% of the workshop involves "Hands-on" calibration, repair and adjustments of micrometers, calipers, indicators height gages, etc. https://www.calibrationtraining.com/

Oct 5-6, 2022 Dimensional Measurement. Port Melbourne VIC, Australia. National Measurement Institute (NMI), Australia. This two-day course (9 am to 5 pm) presents a comprehensive overview of the fundamental principles in dimensional metrology and geometric dimensioning and tolerancing. https://shop.measurement.gov.au/collections/physical-metrology-training

SEMINARS & WEBINARS: Electrical

Jun 13-16, 2022 MET-101 Basic Hands-on Metrology. Everett, WA. Fluke Calibration. This Metrology 101 basic metrology training course introduces the student to basic measurement concepts, basic electronics related to measurement instruments and math used in calibration. https://us.flukecal.com/training

SEMINARS & WEBINARS: Flow

Sep 20-23, 2022 Gas Flow Calibration Using molbloc/molbox. Phoenix, AZ. Fluke Calibration. Gas Flow Calibration Using molbloc/molbox is a four day training course in the operation and maintenance of a Fluke Calibration molbloc/molbox system. https://us.flukecal.com/training

Sep 21-23, 2022 Flow Measurement and Calibration Seminar. Neufahrn, Germany. TrigasFI. Measuring principles of flow meters for liquids and gases. Accuracy, performance, calibration techniques and procedures. Featuring networking event with Lunch hosted at the Munich Oktoberfest. https://www.trigasfi.de/en/training-and-seminars/

SEMINARS & WEBINARS: Force

Oct 5-7, 2022 Force Fundamentals. York, PA. Morehouse Instruments. This course will cover applied force calibration techniques and potential errors made in everyday force measurements, including errors associated with improper alignment, use of different and/or incorrect adapter types, thread depth and thread loading. This course also covers the importance of calibrating force measurement devices in the manner in which they are being used in order to reduce errors and lower uncertainty. https://mhforce.com/training-programs/

SEMINARS & WEBINARS: General

Jun 27-Jul 1, 2022 Fundamentals of Metrology (5797). Gaithersburg, MD. NIST. The 5-day Fundamentals of Metrology seminar is an intensive course that introduces participants to the concepts of measurement systems, units, good laboratory practices, data integrity, measurement uncertainty, measurement assurance, traceability, basic statistics and how they fit into a laboratory Quality Management System. https://www.nist.gov/pml/weights-and-measures/training

Aug 22-26, 2022 Fundamentals of Metrology (5802). Gaithersburg, MD. NIST. The 5 day Fundamentals of Metrology seminar is an intensive course that introduces participants to the concepts of measurement systems, units, good laboratory practices, data integrity, measurement uncertainty, measurement assurance, traceability, basic statistics and how they fit into a laboratory Quality Management System. https://www.nist.gov/pml/weights-and-measures/training

SEMINARS & WEBINARS: Industry Standards

Jun 20-24, 2022 Forensic Internal Auditing to ISO/IEC 17025:2017. Live Online. ANAB. An integral part of a successful management system is an effective audit program. An audit program is also essential and required to achieve and maintain accreditation. This ISO/IEC 17025 training course provides a detailed review of ISO/IEC 17025:2017 and the related ANAB accreditation requirements for forensic service providers (AR 3125) as well as a review of ISO 19011, Guidelines for Auditing Management Systems. https://anab.ansi.org/training

Jun 21-22, 2022 Understanding ISO/IEC 17025 and AOAC Food Program Guidelines. A2LA WPT. This course focuses on the application of the 17025 requirements and the AOAC INTERNATIONAL Guidelines for Laboratories Performing Microbiological and Chemical Analyses of Food, Dietary Supplements Requirements, in an accredited food testing laboratory setting. https://www.a2lawpt.org/training

Jul 5-6, 2022 (3004) Understanding ISO/IEC 17025 for Testing and Calibration Labs. Online. International Accreditation Service (IAS). This 2-day Training Course examines structural components of the standard. Quality system and technical requirements are grouped in a manner that makes them clear and understandable. https://www.iasonline.org/training/testing-cal-labs/

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Jul 11-12, 2022 Understanding ISO/IEC 17025:2017 for Testing & Calibration Laboratories. Frederick, MD. A2LA WPT. This course is a comprehensive review of the philosophies and requirements of ISO/IEC 17025:2017. The participant will gain an understanding of conformity assessment using the risks and opportunities-based approach. https://www.a2lawpt.org/training

Jul 11-15, 2022 ISO/IEC 17025 Lead Assessor Training. Live Online. ANAB's ISO/IEC 17025 Lead Assessor Training course uses hands on, exercise-based approach to effectively develop and support the necessary competencies required of a lead assessor. The course was revised in response to the change of focus to competence within laboratory-related accreditation standards and is based on ISO 19011 and ISO/IEC 17011 requirements. https://anab.ansi.org/training

Jul 13-14, 2022 Auditing Your Laboratory to ISO/IEC 17025:2017. Frederick, MD. A2LA WPT. This ISO/IEC 17025 auditor training course will introduce participants to ISO/IEC 19011, the guideline for auditing management systems as applied to ISO/IEC 17025:2017. https://www.a2lawpt.org/training

Jul 19-20, 2022 Laboratories: Understanding the Requirements and Concepts of ISO/IEC 17025:2017. Live Online. ANAB. This introductory course is specifically designed for those individuals who want to understand the requirements of ISO/IEC 17025:2017 and how those requirements apply to laboratories. The course covers all requirements of the standard with a focus on what laboratory personnel need to know to understand and apply the requirements of the standard. https://anab.ansi.org/training

Jul 19-21, 2022 Internal Auditing to ISO/IEC 17025:2017 (Non-Forensic). Live Online. ANAB. ISO/IEC 17025 training course prepares the internal auditor to clearly understand technical issues relating to an audit. Attendees of Auditing to ISO/IEC 17025 training course will learn how to coordinate a quality management system audit to ISO/IEC 17025:2017 and collect audit evidence and document observations, including techniques for effective questioning and listening. https://anab.ansi.org/training

Aug 1-5, 2022 Forensic Internal Auditing to ISO/IEC 17025:2017. Live Online. ANAB. An integral part of a successful management system is an effective audit program. An audit program is also essential and required to achieve and maintain accreditation. This ISO/IEC 17025 training course provides a detailed review of ISO/IEC 17025:2017 and the related ANAB accreditation requirements for forensic service providers (AR 3125) as well as a review of ISO 19011, Guidelines for Auditing Management Systems. https://anab.ansi.org/training

Aug 9, 2022 ISO/IEC 17025:2017 For Cannabis Testing Laboratories. Frederick, MD. A2LA WPT. Throughout this course participants from the cannabis industry, (e.g. growers, regulators, testing laboratories) will learn how and why the new ISO/IEC 17025:2017 standard applies to them and how accreditation improves the visibility, creditability, and safety of the cannabis industry. https://www.a2lawpt.org/training

Aug 15-18, 2022 Understanding ISO/IEC 17025:2017 for Testing & Calibration Laboratories. Virtual. A2LA WPT. This course is a comprehensive review of the philosophies and requirements of ISO/IEC 17025:2017. The participant will gain an understanding of conformity assessment using the risks and opportunities-based approach. https://www.a2lawpt.org/training

Aug 16-17, 2022 Understanding ISO/IEC 17025:2017 for Testing & Calibration Laboratories. Frederick, MD. A2LA WPT. This course is a comprehensive review of the philosophies and requirements of ISO/IEC 17025:2017. The participant will gain an understanding of conformity assessment using the risks and opportunities-based approach. https://www.a2lawpt.org/training

Aug 22-25, 2022 Auditing Your Laboratory to ISO/IEC 17025:2017. Virtual. A2LA WPT. This ISO/IEC 17025 auditor training course will introduce participants to ISO/IEC 19011, the guideline for auditing management systems as applied to ISO/IEC 17025:2017. https://www.a2lawpt.org/training

Aug 23-24, 2022 Validation and Verification of Analytical Methods. Live Online. ANAB. This course provides an introduction to validation and verification of analytical methods. The common elements of a validation/verification plan and a general approach to performing a validation or verification are presented. The pertinent requirements in ISO/IEC 17025 and ISO/IEC 17020 for method validation and verification are also reviewed. https://anab.ansi.org/training

Aug 30-31, 2022 (3004) Understanding ISO/IEC 17025 for Testing and Calibration Labs. Online (ME and South Asia). International Accreditation Service (IAS). This 2-day Training Course examines structural components of the standard. Quality system and technical requirements are grouped in a manner that makes them clear and understandable. https://www.iasonline.org/training/testing-cal-labs/

Sep 13-14, 2022 Laboratories: Understanding the Requirements and Concepts of ISO/IEC 17025:2017. Live Online/Milwaukee, WI. ANAB. This introductory course is specifically designed for those individuals who want to understand the requirements of ISO/IEC 17025:2017 and how those requirements apply to laboratories. The course covers all requirements of the standard with a focus on what laboratory personnel need to know to understand and apply the requirements of the standard. https://anab.ansi.org/training

Sep 13-15, 2022 Internal Auditing to ISO/IEC 17025:2017 (Non-Forensic). Live Online/Milwaukee, WI. ANAB. ISO/IEC 17025 training course prepares the internal auditor to clearly understand technical issues relating to an audit. Attendees of Auditing to ISO/IEC 17025 training course will learn how to coordinate a quality management system audit to ISO/IEC 17025:2017 and collect audit evidence and document observations, including techniques for effective questioning and listening. https://anab.ansi.org/training

Sep 20-23, 2022 Forensic Internal Auditing to ISO/IEC 17025:2017. Live Online/Milwaukee, MI. ANAB. An integral part of a successful management system is an effective audit program. An audit program is also essential and required to achieve and maintain accreditation. This ISO/IEC 17025 training course provides a detailed review of ISO/IEC 17025:2017 and the related ANAB accreditation requirements for forensic service providers (AR 3125) as well as a review of ISO 19011, Guidelines for Auditing Management Systems. https://anab.ansi.org/training

SEMINARS & WEBINARS: Management & Quality

Jul 18, 2022 Managing Risk in Your Organization. Virtual. A2LA WPT. This course introduces the participants to risk-based thinking from an international standards perspective. The participant will learn risk concepts from ISO 31000 and ISO 9000 and become familiar with industry tools used to assess and manage risk in the ISO conformity assessment arena. https://www.a2lawpt.org/training

Aug 8-9, 2022 Quality Fundamentals. Virtual. A2LA WPT. During this course, the participant will gain an understanding of the basic concepts of quality fundamentals terms and quality principles. The participant will also map a quality management system, practice the PDCA process, develop objectives, action plans, and compare job descriptions to personnel competencies, goals to key performance indicators and stakeholder relationship components with best practices. https://www.a2lawpt.org/training

Sep 1-2, 2022 (3022) Internal Audit Course for All Standards. Online (ME and South Asia). International Accreditation Service (IAS). This 2-day Training Course examines auditing principles and techniques and facilitates the practice of required internal audit skills. It is based on internationally-recognized approaches to conducting conformant internal audits. https://www.iasonline.org/training/ias-training-schedule/

SEMINARS & WEBINARS: Mass

Jul 11-21, 2022 Advanced Mass Seminar (5799). Gaithersburg, MD. NIST. The 9-day, hands-on Advanced Mass calibration seminar focuses on the comprehension and application of the advanced mass dissemination procedures, the equations, and associated calculations. https://www.nist.gov/pml/weights-and-measures/training

Aug 1-12, 2022 Mass Metrology Seminar (5801). Gaithersburg, MD. NIST. The Mass Metrology Seminar is a two-week, "hands-on" seminar. It incorporates approximately 30 percent lectures and 70 percent demonstrations and laboratory work in which the participant performs measurements by applying procedures and equations discussed in the classroom. https://www.nist.gov/pml/weights-and-measures/training

SEMINARS & WEBINARS: Measurement Uncertainty

Jun 13-14, 2022 Applied Measurement Uncertainty for Calibration Laboratories. Virtual. A2LA WPT. During this course, the participant will be introduced to several tools and techniques that can be applied in the calibration laboratory environment to efficiently and effectively create measurement uncertainty budgets which comply with ISO/IEC 17025 requirements. The tools presented are generic in nature such that they may be applied in a variety of calibration laboratories. https://www.a2lawpt.org/training

Jun 15-17, 2022 Introduction to Estimating Measurement Uncertainty. Online. National Measurement Institute, Australia. This course will give you a clear step-by-step approach to uncertainty estimation with practical examples; you will learn techniques covering the whole process from identifying the sources of uncertainty in your measurements right through to completing the uncertainty budget. https://shop.measurement.gov.au/collections/physical-metrology-training

Jun 28-29, 2022 Measurement Confidence: Fundamentals. Live Online. ANAB. This Measurement Confidence course introduces the foundational concepts of measurement traceability, measurement assurance and measurement uncertainty as well as provides a detailed review of applicable requirements from ISO/IEC 17025 and ISO/IEC 17020. https://anab.ansi.org/training

Jul 11-13, 2022 Measurement Uncertainty: Practical Applications. Live Online. ANAB. This course reviews the basic concepts and accreditation requirements associated with measurement traceability, measurement assurance, and measurement uncertainty as well as their interrelationships. https://anab.ansi.org/training

Aug 3, 2022 Measurement, Uncertainty and Calibration Workshop. Lower Hutt, NZ. Measurement Standards Laboratory of New Zealand. This course gives a broad high-level overview of measurement and calibration principles, and calculation of uncertainty. https://www.measurement.govt.nz/training/

Aug 8-10, 2022 MET-302 Introduction to Measurement Uncertainty. Everett, WA. Fluke Calibration. This course will teach you how to develop uncertainty budgets and how to understand the necessary calibration processes and techniques to obtain repeatable results. https://us.flukecal.com/training

Aug 10, 2022 Measurement, Uncertainty and Calibration Workshop. Auckland, New Zealand. Measurement Standards Laboratory of New Zealand. This course gives a broad high-level overview of measurement and calibration principles, and calculation of uncertainty. https://www.measurement.govt.nz/training/

Aug 18-19, 2022 Applied Measurement Uncertainty for Calibration Laboratories. Frederick, MD. A2LA WPT. During this course, the participant will be introduced to several tools and techniques that can be applied in the calibration laboratory environment to efficiently and effectively create measurement uncertainty budgets which comply with ISO/IEC 17025 requirements. The tools presented are generic in nature such that they may be applied in a variety of calibration laboratories. https://www.a2lawpt.org/training

Sep 13-15, 2022 Uncertainty, Sampling and Data Analysis: Understanding Statistical Calculations. Live Online. ANAB. This course provides an introduction to statistical concepts and techniques used for the collection, organization, analysis, and presentation of various types of data. The course touches on both descriptive statistics and inferential statistics, including how to compute measures of central tendency and dispersion, and how to assess the relationship between two variables. https://anab.ansi.org/training

Sep 19-20, 2022 Measurement Confidence: Fundamentals. Live Online. ANAB. This Measurement Confidence course introduces the foundational concepts of measurement traceability, measurement assurance and measurement uncertainty as well as provides a detailed review of applicable requirements from ISO/IEC 17025 and ISO/IEC 17020. https://anab.ansi.org/training

Sep 21-23, 2022 Measurement Uncertainty: Practical Applications. Live Online. ANAB. This course reviews the basic concepts and accreditation requirements associated with measurement traceability, measurement assurance, and measurement uncertainty as well as their interrelationships. https://anab.ansi.org/training

SEMINARS & WEBINARS: Photometry & Radiometry

Aug 1, 2022 Spectrophotometer Calibration Workshop. Lower Hutt, NZ. Measurement Standards Laboratory of New Zealand. This course covers the calibration of benchtop spectrophotometers including wavelength accuracy, photometric accuracy and stray light characterization. It is highly interactive and includes hands on sessions to develop practical skills. https://www.measurement.govt.nz/training/

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SEMINARS & WEBINARS: Pressure

Aug 2, 2022 Pressure Calibration Workshop. Lower Hutt, NZ. Measurement Standards Laboratory of New Zealand. This workshop is a practical one-day session dealing with all aspects of pressure gauge and transducer calibration. https://www.measurement.govt.nz/training/

Aug 9, 2022 Pressure Calibration Workshop. Auckland, New Zealand. Measurement Standards Laboratory of New Zealand. This workshop is a practical one-day session dealing with all aspects of pressure gauge and transducer calibration. https://www.measurement.govt.nz/training/

Aug 29-Sep 2, 2022 TWB 1061 Principles of Pressure Calibration Web-Based Training. Fluke Calibration. This is a short form of the regular five-day in-person Principles of Pressure Calibration class. It is modified to be an instructor-led online class and without the hands-on exercises. It is structured for two hours per day for one week. https://us.flukecal.com/training

SEMINARS & WEBINARS: Software

Jul 11-15, 2022 MC-206 Basic MET/CAL® Procedure Writing. Everett, WA. Fluke Calibration. In this five-day Basic MET/CAL Procedure Writing course, you will learn to configure MET/CAL software to create, edit, and maintain calibration solutions, projects and procedures. https://us.flukecal.com/training

Jul 25-27, 2022 MC-203 Crystal Report Writing. Everett, WA. Fluke Calibration. A three-day course on the basics of Crystal Reports using MET/TEAM®. https://us.flukecal.com/training

Jul 28 & Aug 18, 2022 Software Verification and Validation. Webinar (5800). NIST. Session I and Session II. These two 2 hour sessions on Software Verification and Validation will focus on the use of Microsoft Excel in calibration laboratories and examine the ISO/IEC 17025:2017 requirements related to software. https://www.nist.gov/pml/weights-and-measures/training

Aug 15-19, 2022 TWB 1051 MET/TEAM® Basic Web-Based Training. Fluke Calibration. This web-based course presents an overview of how to use MET/TEAM Test Equipment and Asset Management Software in an Internet browser to develop your asset management system. https://us.flukecal.com/training

Sep 12-16, 2022 MC-207 Advanced MET/CAL® Procedure Writing. Everett, WA. Fluke Calibration. This course covers advanced topics and requires an existing knowledge of MET/CAL calibration software. https://us.flukecal.com/training

Oct 3-7, 2022 TWB 1031 MET/CAL® Procedure Development Web-Based Training. Fluke Calibration. Learn to create procedures with the latest version of MET/CAL, without leaving your office. This web seminar is offered to MET/CAL users who need assistance writing procedures but have a limited travel budget. https://us.flukecal.com/training

SEMINARS & WEBINARS: Temperature & Humidity

Aug 1, 2022 Infrared Radiation Thermometry Workshop. Lower Hutt, NZ. Measurement Standards Laboratory of New Zealand. This is a practical course covering problems with the use and calibration of infrared radiation thermometers, including reflections, absorption, emissivity, and instrumental effects. https://www.measurement.govt.nz/training/

Aug 4, 2022 Temperature Measurement and Calibration Workshop. Lower Hutt, NZ. Measurement Standards Laboratory of New Zealand. This course covers the use, care, and calibration of liquid-in-glass, platinum resistance, thermocouple, and radiation thermometers. https://www.measurement.govt.nz/training/

Aug 5, 2022 Humidity and Moisture Calibration Workshop. Lower Hutt, NZ. Measurement Standards Laboratory of New Zealand. This practical one-day course will introduce you to humidity generation, calibration and measurement, along with the conceptual framework for understanding the various limitations in humidity measurements. https://www.measurement.govt.nz/training/

Aug 11, 2022 Temperature Measurement and Calibration Workshop. Auckland, New Zealand. Measurement Standards Laboratory of New Zealand. This course covers the use, care, and calibration of liquid-in-glass, platinum resistance, thermocouple, and radiation thermometers. https://www.measurement.govt.nz/training/

Aug 12, 2022 Humidity and Moisture Calibration Workshop. Auckland, NZ. Measurement Standards Laboratory of New Zealand. This practical one-day course will introduce you to humidity generation, calibration and measurement, along with the conceptual framework for understanding the various limitations in humidity measurements. https://www.measurement.govt.nz/training/

Sep 12-14, 2022 Advanced Topics in Temperature Metrology. American Fork, UT. Fluke Calibration. A three-day course for those who need to get into the details of temperature metrology. This course is for experienced calibration technicians, metrologists, engineers, and technical experts working in primary and






CALENDAR

secondary-level temperature calibration laboratories who would like to validate, refresh, or expand their understanding of advanced topics in temperature metrology. https://us.flukecal.com/training

Oct 3-5, 2022 Practical Temperature Calibration. American Fork, UT. Fluke Calibration. A three-day course loaded with valuable principles and hands-on training designed to help calibration technicians and engineers get a solid base of temperature calibration fundamentals. https://us.flukecal.com/training

SEMINARS & WEBINARS: Vibration

Sep 13-15, 2022 Fundamentals of Random Vibration and Shock Testing. Longmont, CO. This three-day Training in Fundamentals of Random Vibration and Shock Testing covers all the information required to plan, perform, and interpret the results of all types of dynamic testing. Some of the additional areas covered are fixture design, field data measurement and interpretation, evolution of test standards and HALT/HASS processes. https://equipment-reliability.com/open-courses/

SEMINARS & WEBINARS: Volume

Aug 29-Sep 2, 2022 Volume Metrology Seminar (5812). Gaithersburg, MD. NIST. The 5-day OWM Volume Metrology Seminar is designed to enable metrologists to apply fundamental measurement concepts to volume calibrations. A large percentage of time is spent on hands-on measurements, applying procedures and equations discussed in the classroom. https://www.nist.gov/pml/weights-and-measures/training

SEMINARS & WEBINARS: Weight

Aug 2, 2022 Balances and Weighing Workshop. Lower Hutt, New Zealand. Measurement Standards Laboratory of New Zealand. This course provides training to assist laboratory personnel demonstrate quality assurance in their measurements. https://www.measurement.govt.nz/training/

Aug 9, 2022 Balances and Weighing Workshop. Auckland, New Zealand. Measurement Standards Laboratory of New Zealand. This course provides training to assist laboratory personnel demonstrate quality assurance in their measurements. https://www.measurement.govt.nz/training/

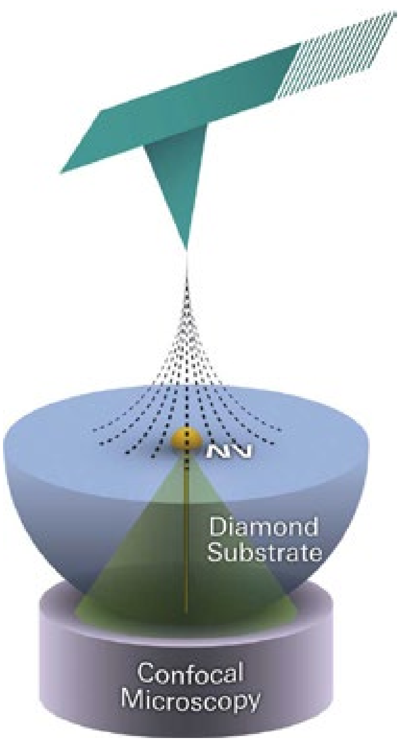
Sep 8, 2022 Calibration of Weights and Balances. Lindfield NSW, Australia. National Measurement Institute (NMI), Australia. This course covers the theory and practice of the calibration of weights and balances. It incorporates hands-on practical exercises to demonstrate adjustment features and the effects of static, magnetism, vibration and draughts on balance performance. https://shop.measurement.gov.au/collections/physical-metrology-training

Visit **www.callabmag.com** for upcoming metrology events & webinars!

Quantum-Calibrated Magnetic Force Microscopy

PTB News 1.2022, 17 January 2022 – A classical measurement system for measuring magnetic field distributions, which vary spatially on the nanometer scale, was calibrated by means of an atomic quantum sensor for the first time. This new calibration procedure does not depend on simplifying model assumptions and allows more reliable measurements of magnetic field distributions with high spatial resolution.

To develop future magnetic components such as sensors and data storage devices, industry needs traceable magnetic field measuring systems with the best possible spatial resolution. The most widespread method for measuring magnetic field distributions on the nanometer scale is magnetic force microscopy (MFM). In MFM, a magnetic tip is moved a few nanometers above a sample surface while measuring the force which acts on the tip in the magnetic field of the sample. To be able to calculate the magnetic field strength from this force in SI units, the magnetic properties of the tip must be known very accurately. For this purpose, simplifying models combined with measurements on magnetic reference samples have been used to date.



Schematic representation of the measurement setup used for calibrating an MFM tip by means of a quantum sensor. The MFM tip (turquoise) generates a magnetic stray field which can be measured precisely over a single NV center (yellow) in a diamond substrate (blue). If the tip is scanned over the NV center, its stray field distribution is obtained – and thus quantum-accuracy information on its magnetic imaging properties is also gained. Credit: PTB

Within the scope of a cooperation project between PTB and the University of Ulm, the magnetic properties of such a magnetic tip have now been characterized precisely for the first time by means of a quantum sensor. This nitrogen vacancy (NV) center sensor consists of a single atomic lattice defect in a diamond crystal whose optical spectrum depends on the external magnetic field. In the experiments performed, the magnetic tip was scanned in a plane over the NV center, and the optical spectrum was measured at each point. Based on these measurements, a map of the magnetic field emanating from the tip was derived. The tip's magnetic properties that are relevant to magnetic force microscopy were then determined from this map. After this procedure, the tip was quantum calibrated and could be used for precise and reliable magnetic field measurements on the nanoscale.

In further investigations, it is also planned to set up such a measuring system to characterize MFM tips at PTB. In this way, it would be possible to perform MFM measurements using quantum-calibrated tips directly at PTB in the future.

Contact: Hans Werner Schumacher, Department 2.5, Semiconductor Physics and Magnetism, hans.w.schumacher(at)ptb.de.

Scientific publication: B. Sakar, Y. Liu, S. Sievers, V. Neu, J. Lang, C. Osterkamp, M. L. Markham, O. Öztürk, F. Jelezko, H. W. Schumacher: Quantum calibrated magnetic force microscopy. Phys. Rev. B, 104, 214427 (2021)

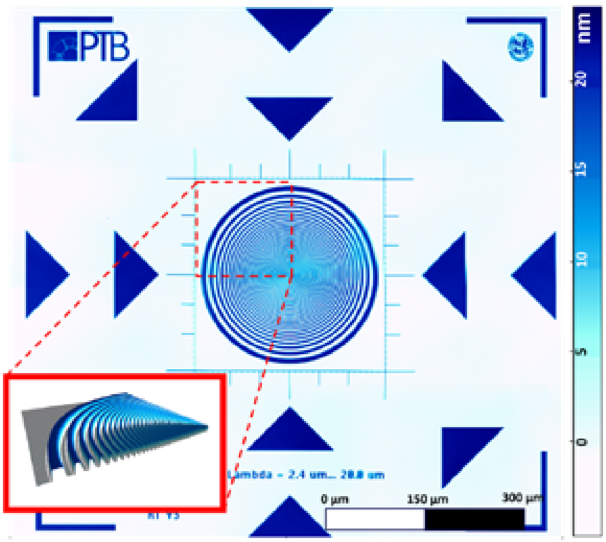
Source: https://www.ptb.de/cms/en/presseaktuelles/journals-magazines/ptb-news.html

A Material Measure for Optical Surface Measurement

PTB News 1.2022, 17 January 2022 – The measurement responses of optical measuring devices to surface topography can be described by the instrument transfer function (ITF). At PTB, a novel material measure has been developed to characterize two-dimensional instrument transfer functions (2D-ITF) of optical measuring instruments. This material measure is flexible and easy to use. Moreover, it shows high reproducibility and robustness.

Optical areal surface topography metrology tools are often used for noncontact and fast measurements of precision surfaces such as optical mirrors of X-ray or lithography devices. However, using such tools often raises a fundamental question in optical measurements, 'Are we getting the right answer?'

To answer this challenging question, PTB, in collaboration with Zeiss-SMT, has developed a novel material measure to characterize the 2D-ITF of areal surface topography measuring tools within the scope of the 3D-Stack EMPIR project. Among other things, this new standard features circular structural patterns. Such rotationally symmetric patterns are advantageous for characterizing ITFs along different angular directions, i.e., for investigating the angular anisotropy of measuring instruments. Three different kinds of patterns have been implemented in the design: circular step patterns, circular chirp patterns whose spacing continuously changes, and circular discrete grating patterns. They are designed to represent three kinds of spatial signals for ITF characterization in a complementary way. The patterns have radii ranging from 30 µm to 300 µm and wavelengths from 0.1 µm to 150 µm. They may be combined to



Material measure with circular chirp patterns (section: 3D view of the structures).

meet measurement requirements for various instruments that may have very different bandwidth characteristics and fields of view. The design of this material measure is therefore highly flexible and suited to various applications.

Besides the material measure, software has also been developed for the calibration process and the subsequent data evaluation. This combination allows the 2D-ITF of optical surface measuring devices to be characterized conveniently in just a few minutes. The application of the newly developed method at PTB's industrial partners shows the advantages of its high repeatability and robustness, along with its excellent flexibility and ease of use.

Contact: Gaoliang Dai, Department 5.2, Dimensional Nanometrology, (gaoliang.dai(at)ptb.de).

Scientific publication: G. Dai, Z. Jiao, L. Xiang, B. Seeger, T. Weimann, W. Xie, R. Tutsch: A novel material measure for characterizing two-dimensional instrument transfer functions of areal surface topography measuring instruments. Surface Topography: Metrology and Properties 8, 045025 (2020)

Source: https://www.ptb.de/cms/en/presseaktuelles/journals-magazines/ptb-news.html

JILA Atomic Clocks Measure Einstein's General Relativity at Millimeter Scale

NIST News, February 16, 2022 – JILA physicists have measured Albert Einstein's theory of general relativity, or more specifically, the effect called time dilation, at the smallest scale ever, showing that two tiny atomic clocks, separated by just a millimeter or the width of a sharp pencil tip, tick at different rates.

The experiments, described in the Feb. 17 issue of Nature [https://www.nature.com/articles/s41586-021-04349-7], suggest how to make atomic clocks 50 times more precise than today's best designs and offer a route to perhaps revealing how relativity and gravity interact with quantum mechanics, a major quandary in physics.

JILA is jointly operated by the National Institute of Standards and Technology (NIST) and the University of Colorado Boulder.

"The most important and exciting result is that we can potentially connect quantum physics with gravity, for example, probing complex physics when particles are distributed at different locations in the curved space-time," NIST/JILA Fellow Jun Ye said. "For timekeeping, it also shows that there is no roadblock to making clocks 50 times more precise than today — which is fantastic news."

Einstein's 1915 theory of general relativity explains large-scale effects such as the gravitational effect on time and has important practical applications such as correcting GPS satellite measurements. Although the theory is more than a century old, physicists remain fascinated by it. NIST scientists have used atomic clocks as sensors to measure relativity more and more precisely, which may help finally explain how its effects interact with quantum mechanics, the rulebook for the subatomic world.

According to general relativity, atomic clocks at different elevations in a gravitational field tick at different rates. The frequency of the atoms' radiation is reduced — shifted toward the red end of the electromagnetic spectrum — when observed in stronger gravity, closer to Earth. That is, a clock ticks more slowly at lower elevations. This effect has been demonstrated repeatedly; for example, NIST physicists measured it in 2010 [https://www.nist.gov/news-events/news/2010/09/nist-pair-aluminum-atomic-clocks-reveal-einsteins-relativity-personal-scale] by comparing two independent atomic clocks, one positioned 33 centimeters (about 1 foot) above the other.

The JILA researchers have now measured frequency shifts between the top and bottom of a single sample of about 100,000 ultracold strontium atoms loaded into an optical lattice [https://www.nist.gov/physics/what-are-optical-lattices], a lab setup similar to the group's earlier atomic clocks [https://www.nist.gov/video/strontium-clock-animation]. In this new case the lattice, which can be visualized as a stack of pancakes created by laser beams, has unusually large, flat, thin cakes, and they are formed by less intense light than normally used. This design reduces the distortions in the lattice ordinarily caused by the scattering of light and atoms, homogenizes the sample, and extends the atoms' matter waves, whose shapes indicate the probability of finding the atoms in certain locations. The atoms' energy states are so well controlled that they all ticked between two energy levels in exact unison for 37 seconds, a record for what is called quantum coherence.

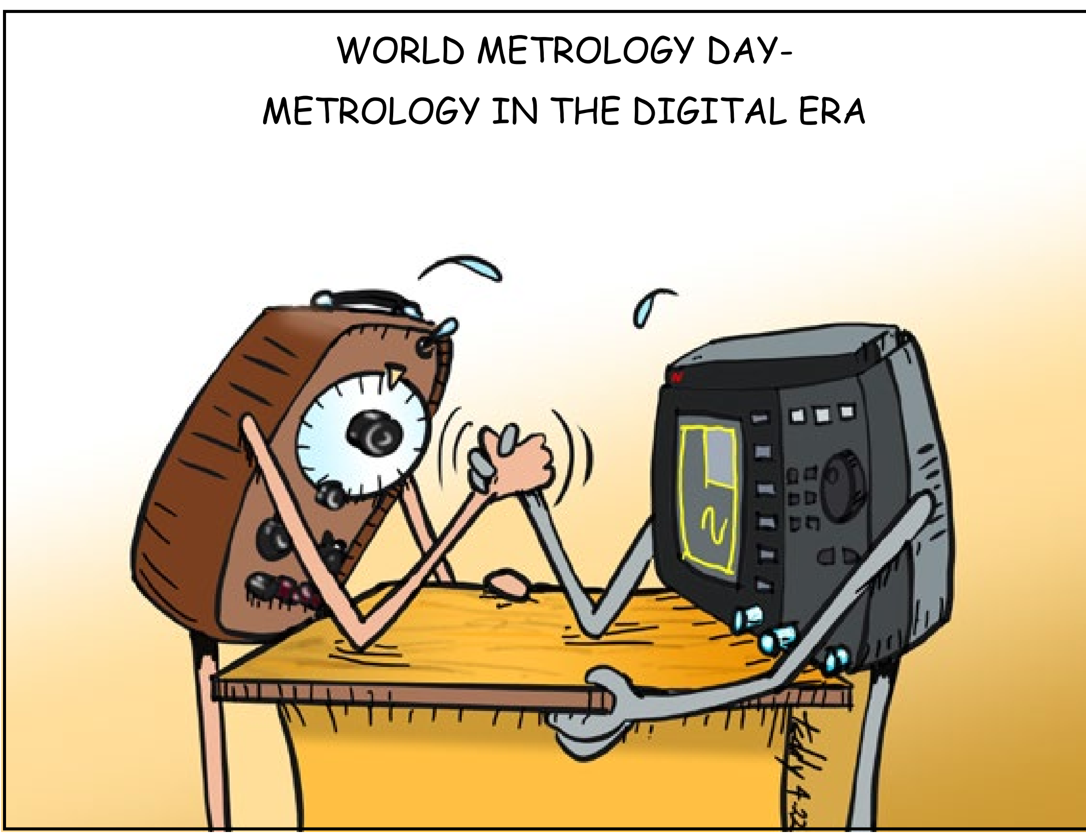
Crucial to the new results were the Ye group's imaging innovation [https://www.nist.gov/news-events/news/2018/03/jila-team-invents-new-way-see-quantum-world], which provided a microscopic map of frequency distributions across the sample, and their method of comparing two regions of an atom cloud rather than the traditional approach of using two separate clocks.

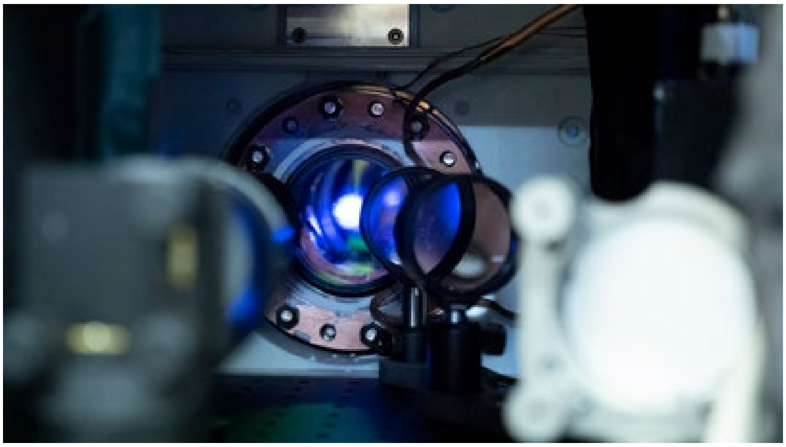
The measured redshift across the atom cloud was tiny, in the realm of 0.0000000000000000001, consistent with predictions. (While much too small for humans to perceive directly, the differences add up to major effects on the universe as well as technology such as GPS.) The research team resolved this difference quickly for this type of experiment, in about 30 minutes of averaging data. After 90 hours of data, their measurement precision was 50 times better than in any previous clock comparison.

"This a completely new ballgame, a new regime where quantum mechanics in curved space-time can be explored," Ye said. "If we could measure the redshift 10 times even better than this, we will be able to see the atoms' whole matter waves across the curvature of space-time. Being able to measure the time difference on such a minute scale could enable us to discover, for example, that gravity disrupts quantum coherence, which could be at the bottom of why our macroscale world is classical."

Better clocks have many possible applications beyond timekeeping and navigation. Ye suggests atomic clocks can

CAL-TOONS by Ted Green teddytoons@icloud.com





JILA researchers measured time dilation, or how an atomic clock's ticking rate varied by elevation, within this tiny cloud of strontium atoms. Credit: R. Jacobson/NIST

serve as both microscopes to see minuscule links between quantum mechanics and gravity and as telescopes to observe the deepest corners of the universe. He is using clocks to look for mysterious dark matter [https://www.nist.gov/news-events/news/2020/11/advanced-atomic-clock-makes-better-dark-matter-detector], believed to constitute most matter in the universe. Atomic clocks are also poised to improve models and understanding of the shape of the Earth through the application of a measurement science called relativistic geodesy [https://www.nist.gov/news-events/news/2018/11/nist-atomic-clocks-now-keep-time-well-enough-improve-models-earth].

Funding was provided by the Defense Advanced Research Projects Agency, National Science Foundation, Department of Energy Quantum System Accelerator, NIST and Air Force Office for Scientific Research.

Source: https://www.nist.gov/news-events/news/2022/02/jila-atomic-clocks-measure-einsteins-general-relativity-millimeter-scale

Project LiBforSecUse: Quality Assessment of Electric Vehicle Lithium Ion Batteries for Second Use Applications

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This paper introduces the European project LiBforSecUse, which is focused on metrology requirements for impedance spectroscopy of commercial Li-ion cells for second life applications. It focuses specifically on the achievements in the workpackage dealing with traceability of low impedance analyzers for cell impedance spectroscopy. Several low impedance mΩ-range impedance standards are described. Next, a reference digital sampling impedance bridge for mΩ-range and frequencies from 0.01 Hz to 5 kHz is presented. Finally, preliminary results of an international, interlaboratory comparison of low impedance measurements are presented.

1. Introduction

Lithium-ion batteries are the energy storage technology of choice in electric vehicles due to their high energy density, cycling stability, high efficiency and continuously decreasing cost. However, one of their drawbacks is that the capacity of each cell in a battery pack tends to decrease steadily with time during operation due to degradation of the electrode materials. Most vehicle manufacturers specify a limit on this 'capacity fade' of 70-80 % of the original capacity, after which the battery pack must be removed from the vehicle as the driving range is no longer sufficient. There is a growing market for repurposing of such battery packs for 'second life' applications such as residential and industrial power storage, where the energy and/or power demands are not as stringent as those in automotive applications.

An important parameter in the characterisation of battery performance and lifetime is state-of-health (SoH), which is usually defined as the ratio of the remaining capacity of the cell to its original capacity. Cells in the same module of a battery pack should exhibit similar SoH, otherwise performance, lifetime and safety can be compromised. In order to qualify battery cells for 'second life' applications in a cost-effective manner, it is necessary to evaluate their SoH rapidly, accurately and non-destructively. Electrochemical impedance spectroscopy (EIS) has been proposed as a potential technique for rapid evaluation of SoH but to date its application has been hampered by the lack of an underpinning metrological framework, including traceability, quantified measurement uncertainties and defined measurement procedures.

The LiBforSecUse project set out to address these issues by developing validated impedance-based measurement procedures aimed at reducing the measurement uncertainty in SoH from 10 % to 3 %. This paper summarizes a key component of the project, which was the establishment of traceable impedance measurements in the mΩ and sub-mΩ range to underpin the calibration of EIS spectrometers. Reference impedance standards, calibration setups and the results of an interlaboratory comparison are presented and discussed.

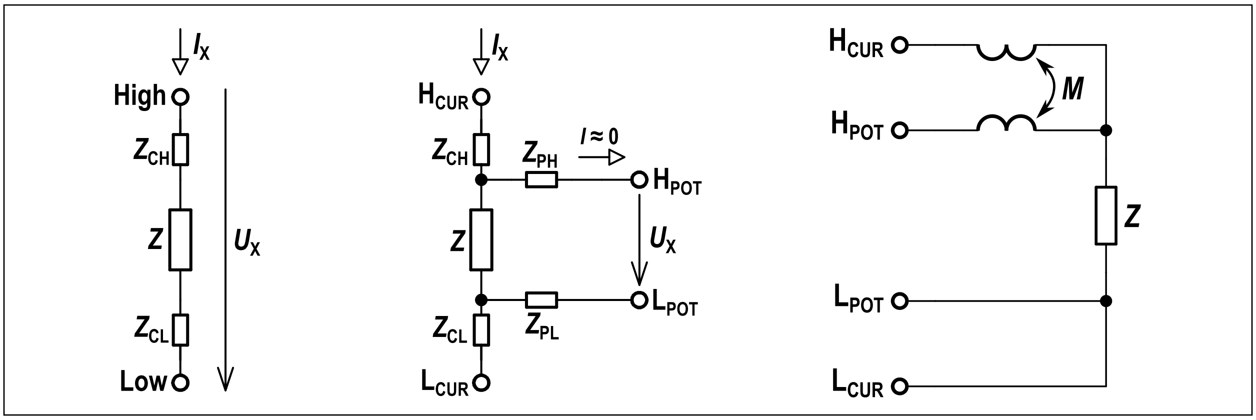

Figure 1. Two terminal (left), four terminal connection (center), effect of mutual coupling (right).

2. Impedance Traceability

It is well known that measurements of EIS spectra by different laboratories are not always comparable. Often, even measurements performed within a single institution may be incomparable among several test setups with e.g. different wirings. Therefore, the first and fundamental work package of the project LiBforSecUse was focused on ensuring traceability of low impedance measurements specifically for EIS. This process had several steps:

i) Preparation of a good practice guide for low impedance measurements.
ii) Development and construction of reference impedance standards simulating lithium cell impedance (so called “dummy cells”).
iii) Development of a reference low impedance calibration setup.
iv) Calibration of reference standards.
v) Calibration of EIS meters by the reference standards.
vi) Interlaboratory comparison verifying steps (i) to (v).

2.1 Good Practice Guides

Two good practice guides were produced in the scope of the work package. The first guide was focused on precision low impedance measurements using the reference low impedance calibration setup [2] described below. The second guide was focused on good practice in measurement of cells using EIS spectrometers [3]. Both guides, among other things, discuss good practice in wiring a range of cells and standards to various EIS and RLC meters and the interferences and errors that can be expected. Key problems are summarized in the following paragraphs.

Two types of EIS/RLC meters are available for measurement of cell impedance spectra. The first type is measurement in simple 4-wire/terminal (4T) configuration as we know it from DC resistance metrology. The second group of meters, usually general RLC meters, uses so called 4 terminal-pair (4TP) coaxial cable connection to the unit under test (UUT). There is a fundamental difference between the two. 4T connection is simple, however it is not possible to fully eliminate effective mutual inductance *M* between potential and current leads. This always leads to a certain reactance (X_s) measurement error. With typical test leads used in EIS, it is reasonable to expect up to ±50 nH mutual inductance uncertainty. This is roughly $\Delta X_s = \pm 1.5\ \text{m}\Omega$ at 5 kHz. It is possible to reduce the error by twisting the leads, placing current and potential bundles perpendicular to each other and keeping distance between them (see guides for details). The SHORT correction that is used to eliminate residual series impedance, including this parasitic coupling as it is known from impedance metrology, is not always applicable for EIS meters. The idea of SHORT correction

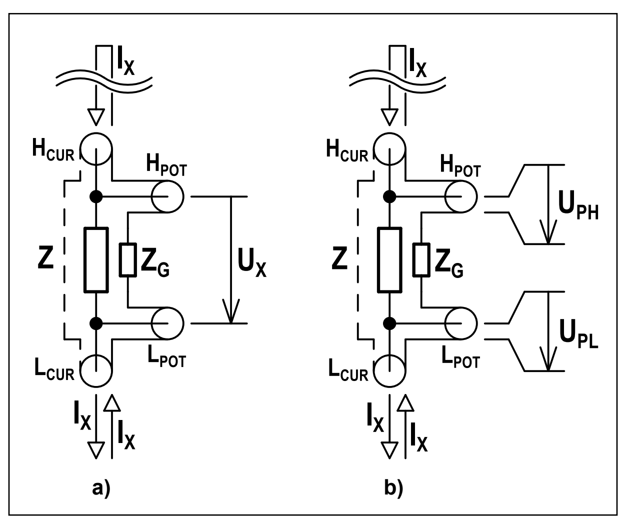

Figure 2. a) 4TP standard measured in 4T configuration, b) 4TP standard measured in 4TP configuration.

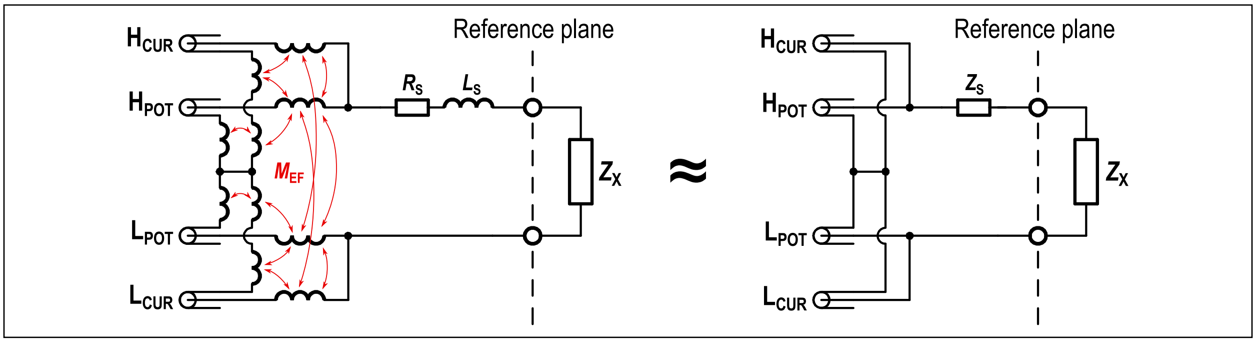

Figure 3. Principle of SHORT correction.

is to connect the leads in as close as possible to ideal zero-ohm arrangement, measure the residual series impedance Z_s as shown in Figure 3 and then subtract this residual Z_s value from all subsequent measurements on the UUT. The problem is that most EIS meters do not have the SHORT correction function, so this can only be done manually in postprocessing of the data. Furthermore, rearranging the test leads from UUT measurement to SHORT connection changes their geometry and thus the residual coupling M, so the error reduction is limited.

Therefore, the 4TP connection was introduced in precision impedance metrology. This adds coaxial shielding to the test leads and ideally even to the impedance standards to be measured. The idea is that the measuring RLC bridge is forcing return current through the coaxial shields of current coaxes which is equal to the forward current via live conductors. Therefore, magnetic radiation from the current coaxes should cancel out and thus parasitic voltage induced in the potential leads or coaxes is minimized. It is useful to note that in 4TP configuration, the impedance is calculated from voltage drops on potential coaxial ports U_{PH} and U_{PL} as shown in Figure 2b, instead of only from the potential difference U_X between the live conductors as shown in Figure 2a. This means the UUT shield impedance Z_G becomes part of the measured impedance; however, this effect can be neglected by changing the standard construction [2]. Nevertheless, the 4TP connection facilitates getting close to the UUT without much interference and then the four coaxes can be converted to the desired 4T or 2T connection. Residual series impedance in the adapter can be suppressed by SHORT correction in the same way as for 4T measurement.

The problem related to any practical EIS/RLC measurement is that we cannot choose the meter terminal configuration or UUT terminal configuration. The measurement must be performed with what is available. Thus, the good practice guides describe several practical examples of interconnection between 4T/4TP bridges and different standards or cells and suggest some measures to reduce errors.

2.2 Reference Impedance Standards - Dummy Cells

Calibration of EIS meters or RLC meters for EIS requires reference impedance standards. These calibration impedance standards mimicking the impedance of lithium-ion cells, sometimes called "dummy cells," are specific in value, operating range and also terminal arrangement. Typical cell impedance may vary from values below 1 mΩ for large, high current cells up to tens of milliohms or even above 100 mΩ for small, discharged, aged cells. Although there are many impedance standards usable in this range, there are a few challenges specific to EIS. First, real cells exhibit not only "pure" resistance or reactance (capacitors or inductors) but also strongly frequency-dependent impedance with arbitrary phase angles. In addition to simulating the correct impedance value, it is also beneficial to have a terminal arrangement similar to the particular cell geometry. This is especially helpful for low impedance measurements as even small mutual inductances between the test leads and/or the cell itself will translate into relatively high parasitic reactance. Furthermore, Li-ion cells always have some DC bias voltage around 4 V, so when calibrating EIS meters it is wise to check its impedance measurement accuracy dependence on applied DC bias voltage from the UUT (cell or impedance standard) at least at a few impedance values. To our knowledge there are no commercially available "dummy cells" having DC bias simulation and there is definitely no established impedance metrology in the presence of DC bias voltage. Thus, one of the goals of the project was to develop at least one standard with controllable DC bias.

Several approaches were tested in the scope of the project:

i) Passive resistive standards based on coaxial current shunts.

ii) Passive reactance standard with variable DC bias.

iii) Active impedance simulators based on impedance multipliers.

iv) Active digital sampling impedance simulator.

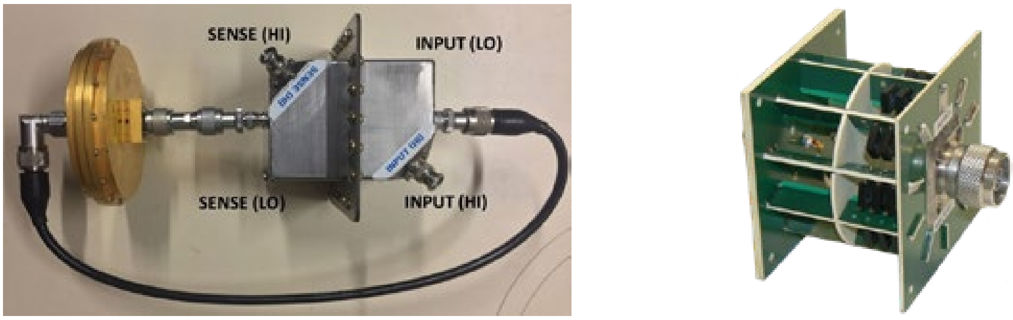

Figure 4. Calculable disk coaxial shunt with adapter to 4TP developed by LNE (left). Cage type current shunt of CMI production (right).

2.2.1 Passive Resistive Standards

The first group of standards that were developed and tested were standards based on coaxial current shunt designs common in AC current or AC power metrology. There are numerous designs possible, however there are two main groups: a) calculable, and b) secondary. The calculable standards are typically based on metal films (or wires) in a geometrical arrangement for which it is possible to calculate the frequency dependence of complex impedance either numerically or analytically. One example that was developed and tested in the scope of this project is a disk shunt developed by LNE shown in Figure 4 [12]. The passive resistive standard is based on a completely calculable structure defined in a 2TP configuration using a resistive disk made of a resistive alloy positioned at the end of a coaxial line. The resistive disk that defines the resistance value has been fabricated using the vacuum deposition technique and its optimization allows obtaining an ac-dc variation of a few μΩ/Ω and a few μrad on the phase up to 1 MHz. The complete structure of the standard is defined in a 4TP configuration with BNC connectors using an adapter box to 4TP based on the approach described in [14].

Secondary standards are general artifacts of various constructions usually designed to have as flat as possible frequency dependence and minimal response to current loading (temperature). Mostly, they are based on a cage design that is being reiterated by commercial manufacturers and NMIs in many different forms. Typically, these standards can be manufactured with impedances down to few milliohms and they are assembled using as many as over a hundred precision resistors, which makes them quite expensive. Nevertheless, they can be calibrated using the ac-dc difference technique and partially modelled, so they can provide outstanding uncertainty in the order of ppm and microradians in angle in a frequency range from DC to at least tens of kilohertz. However, all these standards were developed for other purposes, so they are equipped with two coaxial ports on the opposite sides of the standard. This is the optimal solution, reducing mutual coupling between current input and potential output, but it makes them hard to connect to 4TP bridges or even 4T EIS meters if the terminals are far apart. Therefore, these can be complemented by an adapter box to classical 4TP connection based on [14].

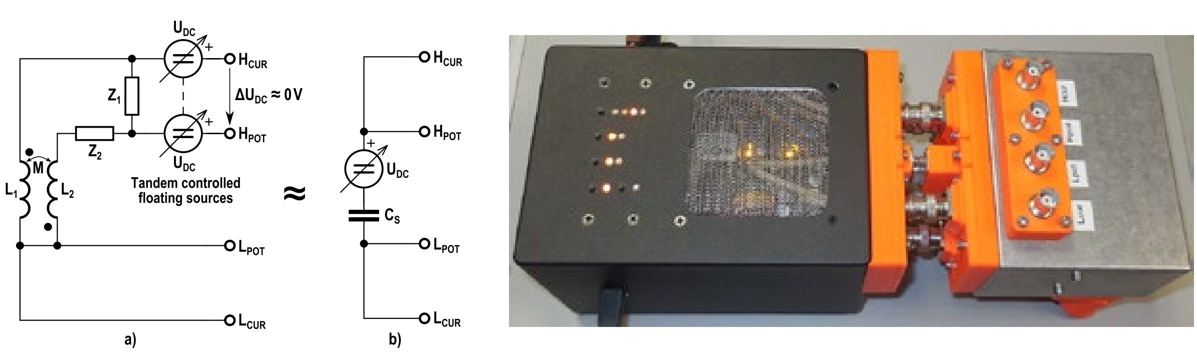

Figure 5. Capacitance simulator based on mutual inductor with “ideal” controllable DC bias source developed by CMI.

2.2.2 Passive Reactance Standard With Variable DC Bias

Another idea developed and tested in the scope of this project was a reactance standard based on mutual inductance equipped with a variable DC bias source. It is not a simple task to realize metrologically usable self-inductance below a few microhenries as the coil would be too small and a considerable portion of the reactance would be actually caused by coupling to terminals and external leads. However, this can be easily achieved by mutual inductors. This is a pair of coils where one is used for current input and the other is used for sensing potential. It is quite simple to realize inductances down to the nanohenry range using this approach. Another advantage is that the mutual inductor has very small phase angle errors compared to self-inductance, where wire resistance would dominate the impedance at low frequencies. The standard developed in this project used a simple trick—inversion of polarity of the secondary coil, which inverts the apparent reactance and thus the standard appears as a large capacitance to the EIS/RLC meter.

Furthermore, the standard was accompanied by a variable floating DC bias source that was designed not to affect the standard's impedance. This was achieved by inserting two isolated, but tandem-controlled, DC sources in the current and potential circuit. The current path DC bias source has to handle full peak measurement current of up to ±2.5 A at up to 5 V bias, however its finite internal impedance does not affect the apparent impedance of the standard, because it is not in the potential sensing circuit. There is an independent precision DC bias source inserted in the potential circuit. Since there is almost no current flowing via the potential DC bias source, its internal impedance should not introduce additional voltage drop and thus does not affect the simulated impedance. The whole circuit appears, from the EIS meter side, as an impedance with a variable series source of DC bias with zero internal impedance. This makes the standard optimal for testing EIS meter error dependence on applied DC bias. Details of the standard were published in [10] and the prototype design was open sourced [9].

2.2.3 Active Impedance Simulator Based on Impedance Multipliers

Another approach to simulating low impedances is the use of active simulators based on operational amplifiers. Two topologies were tested. One topology developed at PTB used a low resistance standard as a reference and an active modifying circuit simulating typical cell impedance. The whole solution was encapsulated in a box mimicking a large lithium-ion cell with two screw terminals. This is the ideal solution as it is possible to directly check EIS meter accuracy without changing the geometry of the test leads and thus parasitic reactances. The standard also contained an internal switch, enabling simulation of several different impedance characteristics as well as short circuit for eliminating the EIS meter leads coupling problem.

Another approach developed at RISE was based on active impedance multipliers with power operational amplifiers. This technique allowed multiplication of precision and stable capacitance of 1 μF to roughly 1 F in two steps. The principle of operation and a prototype are shown in Figure 6.

2.2.4 Active Digital Sampling Impedance Simulator

The last approach developed and tested in the scope of this project was an active digital sampling simulator developed at METAS called *iSimulator*. The simulator is an extension of a previous version that was developed for higher impedances [13]. A simplified diagram of the new simulator is shown in Figure 7. The idea is that the RLC meter (UUT) supplies current I_{LC} to a calculable reference impedance Z_{CB}. The voltage drop at Z_{CB} is digitized by the PXI setup's digitizer channel V_i. Software (SW) controlling

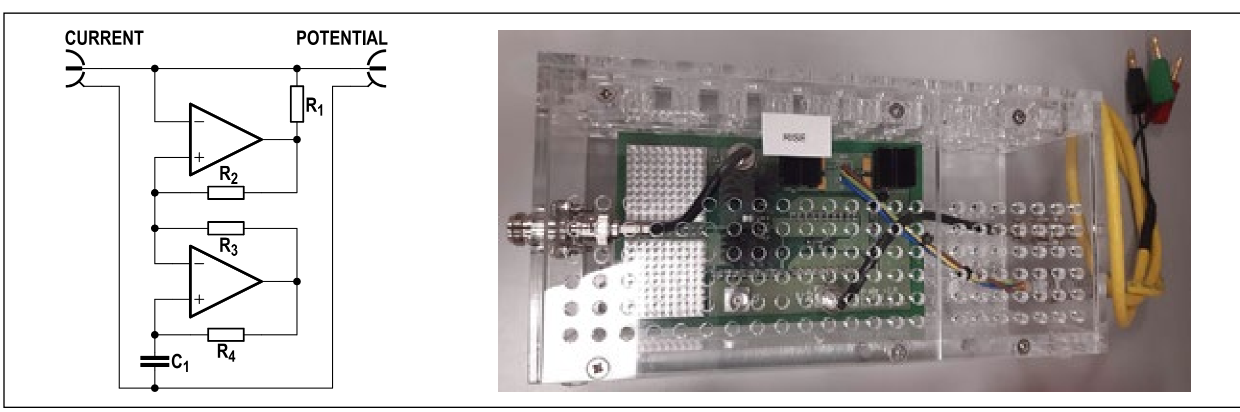

Figure 6. Low impedance simulator based on impedance multipliers developed at RISE.

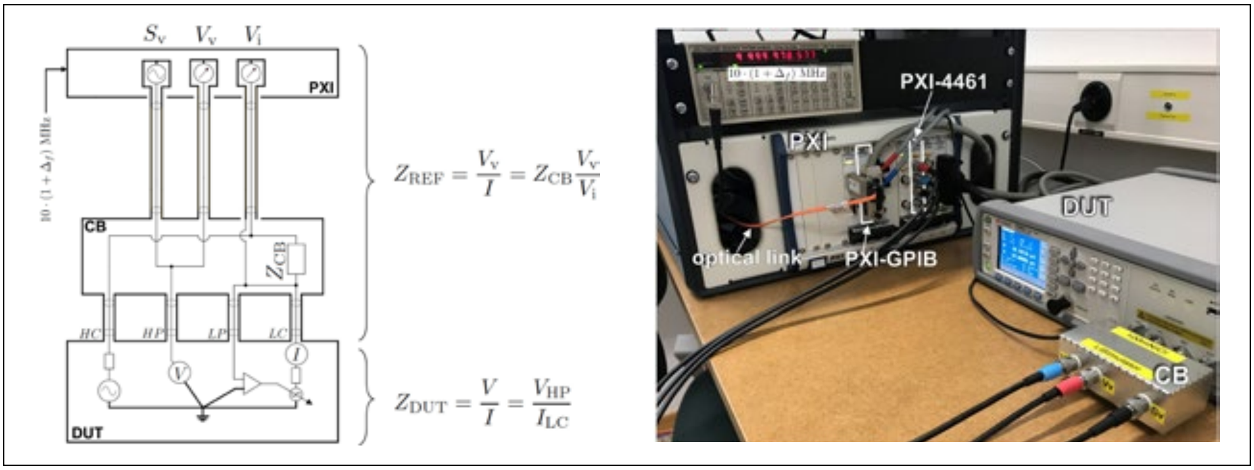

Figure 7. Principle of operation and example of iSimulator setup developed at METAS with calibrating impedance bridge Keysight E4980A.

the PXI setup phase locks to the V_i signal (UUT driver signal) and sets the arbitrary generator's S_v voltage and phase angle so the UUT meter measures a voltage V_{HP} proportional to the desired simulated impedance Z_{REF}. In this way it is possible to simulate any impedance value anywhere in the full complex plane. This allows to check UUT accuracy in detail and not only at a few discrete points mostly concentrated either around the real axis (resistor) or the imaginary axis (capacitors and inductors). However, the disadvantage of the system is its limited usability with some RLC/EIS meters. The SW feedback loop requires a certain time to settle, so EIS/RLC meters that do not provide a continuous stable drive signal, e.g. due to ranging checks, may not be usable with this setup. This was practically tested on a Keysight E4980A.

2.3 Reference Impedance Calibration Setup

The developed standards had to be properly characterized. NMIs are often equipped with digital sampling impedance bridges designed even for low impedances, however EIS calls for extremely low frequencies down to at least 0.01 Hz. Typical impedance bridges incorporate transformers which are obviously not capable of operating at such low frequencies. Therefore, a specialized digital sampling impedance bridge had to be developed. Requirements were the following:

i) Frequency range at least 0.01 Hz to 5 kHz.
ii) AC rms current up to at least 1 A.
iii) Measurement in the presence of DC bias voltage up to at least 5 V.
iv) Measurement range down to at least 1 mΩ with target uncertainty below 1% at 1 mΩ.
v) Based on commonly available instruments.
vi) Measurement of impedance in 4 terminal or 4 terminal-pair (4TP) topologies.

It was decided to make it as simple as possible and base it on commonly available components so the whole setup could be replicated at other NMIs. The main challenge of the design was measurement of very small ac voltage drops at the UUT in the presence of a large DC bias voltage. It was not possible to simply use AC coupling at frequencies below 1 Hz, so it was decided to test the performance of various digitizers when digitizing directly DC+AC voltage. Several digitizers were considered. The first choice were sampling multimeters Agilent 3458A [5]. They offer great performance at very low frequencies due to their stability, however the performance in the presence of DC bias is not optimal due to limited resolution [11]. Surprisingly, the low-end digitizers NI 9238/9239 [6] for the compact-DAQ platform turned out to have acceptable performance in the desired frequency range up to 5 kHz even with DC bias [11]. However, in order to maximize performance, the setup was in the end accompanied by DC bias eliminators in order to remove DC bias from the digitized waveforms, which greatly improved digitizer resolution and thus bridge performance even at very low impedances below 1 mΩ. Furthermore, active guard drivers for the digitizers were used to eliminate ground leakage currents. Examples of the two setups are shown in Figure 8.

However, the 4TP topology shown on the right in Figure 8 had one major drawback. Its performance was limited by common mode voltage on both digitizers DMM 2 and DMM 3, so even small differences in linearity resulted in high measurement errors. So, another unusual modification described in [11] was tested. The digitizers were rearranged so the UUT voltage was measured basically by two 4T bridges. One measures voltage drop at live terminals of the UUT (Z_2) and the other measures the ground terminal difference of the UUT. Both are summed together to satisfy the 4TP impedance definition. Thus, the technique was named 2x4T. More details can be found in [11] or [2].

The measurement uncertainty of the setup was analyzed.

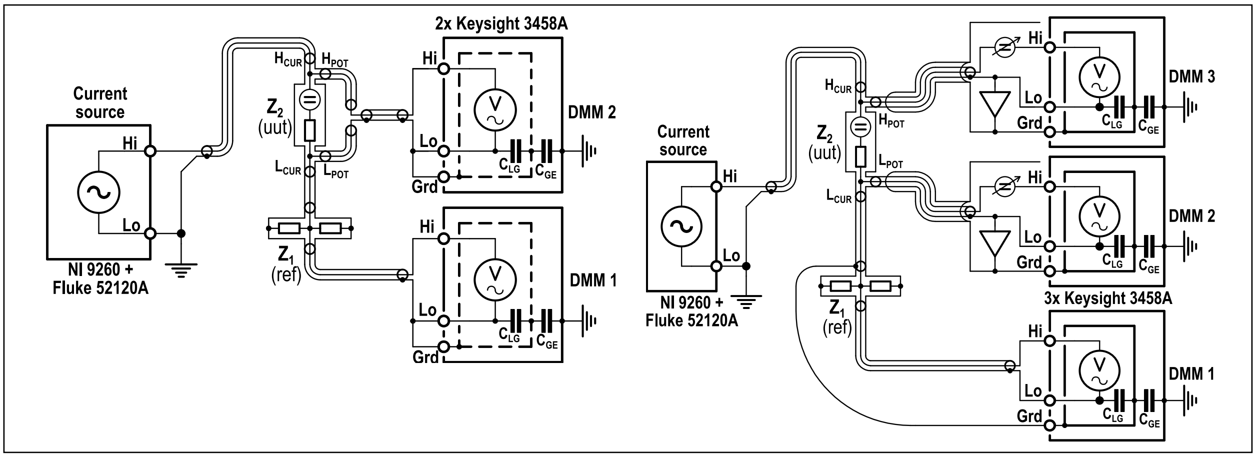

Figure 8. 4-terminal and 4 terminal-pair topology of impedance digital sampling impedance bridge.

A complete Spice model of the setup, including parasitic mutual couplings between bridge components, was made and Monte Carlo calculation performed. The resulting uncertainty in impedance at 1 mΩ was as follows:

vii) R_s and X_s expanded uncertainty below 0.005 % of modulus |Z| up to 400 Hz.

viii) R_s and X_s expanded uncertainty below 0.05 % of modulus |Z| up to 5 kHz.

These uncertainties fully satisfy the project's requirement of 1 % uncertainty. The measurement capability was verified by a series of measurements on known impedance standards. Some of the measurements were presented in [11].

2.3.1 Open Z Bridge SW Tool

The designed bridge core is an open source SW tool TWM [7] that was developed in the scope of the previous EMPIR project TracePQM [4]. The TWM tool is used to control digitizers and calculate various parameters from the digitized voltage and current waveforms. So, for this project, it was simply extended by new digitizer drivers for NI 9238 modules and by a new algorithm TWM-LowZ that simplifies measurement of impedance (or complex voltage ratio). The TWM tool itself is capable of measurement at single frequency and current. However, for effective and comfortable use, it is ideal to have the capability to automatically control signal source (frequency and current) and to automatically sequence measurement of whole frequency or current characteristics as with regular EIS meters. Thus, another SW tool named "Open Z bridge" was developed [8]. This tool uses the TWM Server API to control it, so the whole bridge SW consists of two interconnected applications.

The Open Z bridge tool has no ambition to solve all problems related to measurement of low impedance, however it is a convenient tool for some measurements. Despite the fact that the bridge was designed mainly for calibration of reference standards at low frequencies, it is of course usable even for direct measurement of cell impedance spectra. Its main features are the following:

i) Automatic measurement of frequency sweep, current sweep, DC bias current sweep or combined frequency/current sweep.

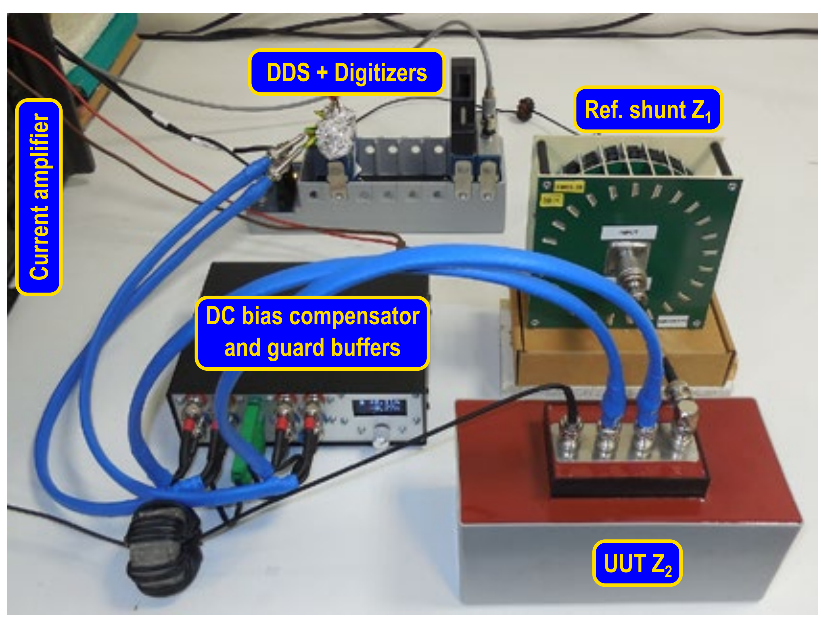

Figure 9. Setup of low impedance digital sampling bridge measuring 4TP capacitor (UUT).

ii) Digitizing and signal processing via the TWM tool using algorithms TWM-LowZ (low impedance) or TWM-InpZ (high impedance).

iii) Supports several signal sources (NI9260, Tektronix 3100, Agilent 33120A, Fluke 5000 series calibrators).

iv) Measurement of impedance or complex voltage ratio.

v) Exporting simple reports to XLS file.

vi) Usable for measurement and direct generation of several correction files for the TWM tool.

vii) Full documentation and good practice guide available.

viii) Open source project in LabVIEW 2020.

2.4 Interlaboratory Comparison

Several small interlaboratory comparisons were held in the scope of the LiBforSecUse project. The first comparison was focused on characterization of the developed impedance standards. CMI and RISE participated. The comparison showed acceptable agreement, typically from 100 nΩ to 2 μΩ, on both resistance and reactance. An example is shown in Figure 11. However, it also demonstrated the importance of proper and clearly defined interconnections between the bridge and the UUT. There was good agreement on all 4T and coaxial standards. However, poor agreement was observed for the 4TP standards most likely because of different terminal wiring configuration of the participants.

Another comparison was focused on calibration of EIS meters. Two resistance standards of impedances 1 mΩ and 10 mΩ were used to calibrate the EIS meters. Then, a 3 mΩ resistor and a dummy cell standard with impedance around 1.5 mΩ to 4.5 mΩ were measured and the results compared. Preliminary results showed two major problems. First, the EIS instruments mostly exhibited errors lower than the standard deviation of the repeated measurements (noise). Second, the lack of manual ranging function of the EIS meters made error correction using measurement of known standards 1 mΩ and 10 mΩ questionable because EIS meter error evaluation and UUT measurement might be performed on different physical ranges, meaning that the error correction attempt might actually increase the errors. Preliminary results showed no error improvement using range error corrections as expected. On the other hand, the SHORT correction of residual series impedance, mainly caused by the mutual inductance phenomenon, reduced the errors of comparison participants by an order of magnitude or more. The spread of reactance due to different wiring of standards would be up to ±1 mΩ without correction, versus less than ±40 μΩ at 5 kHz with SHORT correction. Therefore, one relevant conclusion of the comparison is the need for SHORT correction to be performed. Another relevant outcome was finding that all used EIS meters (Biologic VMP3, Zahner Zenium and Gamry Ref 3000) exhibited errors deep within their specifications.

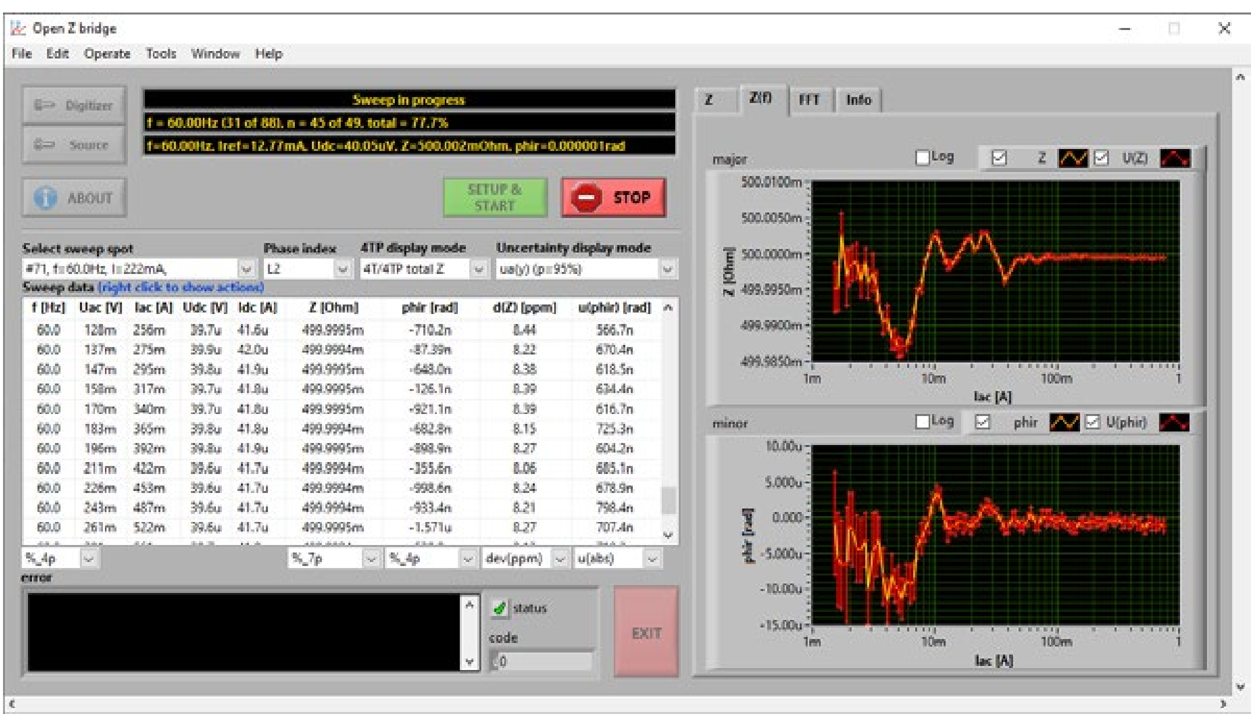

Figure 10. Open Z bridge main panel.

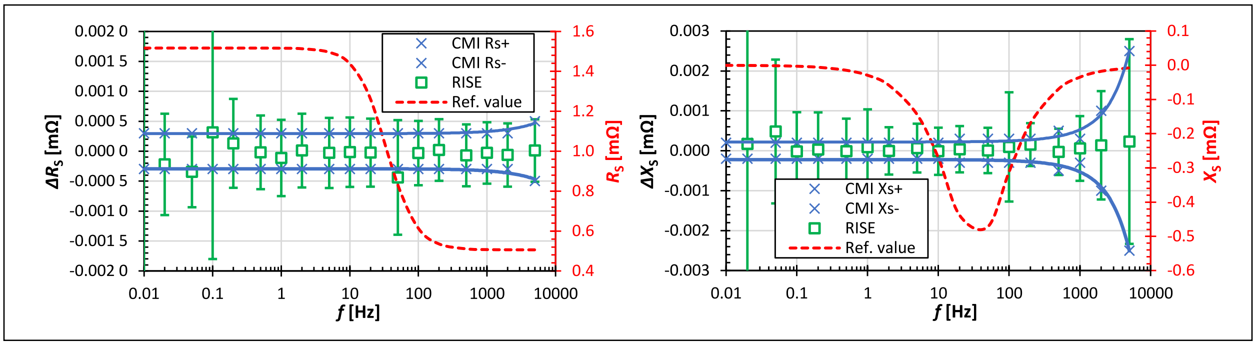

Figure 11. Comparison of simulated impedance of < 1.5 mΩ between CMI and RISE. The blue lines are expanded (k = 2) uncertainty limits of the CMI measurements, the green points are absolute deviations of the RISE-CMI measurements.

Finally, a third comparison with actual lithium-ion cells was performed. Impedance spectra at various states of charge were measured by several labs. The purpose of this comparison was to check if the measurement procedures lead to compatible measurements among the laboratories. The data are however still being processed, so no results or conclusions are available at the time of writing this article. The data will be available after the end of the project.

3. Conclusion

Partners of the EMPIR project LiBforSecUse successfully developed metrology of mΩ-range impedance in the full complex plane in support of electrochemical impedance spectroscopy of lithium cells. Good practice guides explaining problems related to low impedance measurement were prepared. A set of impedance standards of mΩ-range values covering pure resistances, reactances and impedances with arbitrary phase angles were developed. All the standards were characterized using a newly developed digital sampling impedance bridge. Detailed descriptions of the standards and the bridge were published (see references). Three interlaboratory comparisons were held in order to confirm newly developed capabilities. The comparisons showed agreement of impedance measurements among the participants mostly below 1 % which was the target uncertainty of this project. SHORT correction was identified to be able to reduce EIS measurement errors by more than an order of magnitude. Preliminary results have been summarized in this article and a detailed report will be available after the end of the project.

References

[1] EMPIR Project LiBforSecUse. https://www.ptb.de/empir2018/libforsecuse/project/overview/

[2] Mašláň, S. et al. "Guide to Low Impedance Measurements using Digital Sampling Setup." https://zenodo.org/record/5960848

[3] Seitz, S. et al. "Best practice guide on the measurement of the impedances of Li-ion battery cells and the conduction of correlated life cycle tests." https://zenodo.org/communities/libforsecuse/

[4] EMPIR project TracePQM: Traceable Power Quality Measurements. http://tracepqm.cmi.cz/

[5] Keysight. "3458A Digital Multimeter, 8.5 Digit." https://www.keysight.com/zz/en/product/3458A/digital-multimeter-8-5-digit.html

[6] National Instruments. "NI-9238-C Series Voltage Input Module." https://www.ni.com/pdf/manuals/376138a_02.pdf

[7] Mašláň, S. et al., "TWM Traceable PQ Wattmeter." https://github.com/smaslan/TWM

[8] Mašláň, S. "Open Z bridge." https://github.com/smaslan/open-z-bridge

[9] Mašláň, S. "Capacitive Reactance Simulator Based on Mutual Inductor." https://github.com/smaslan/Z-sim-mutual

[10] Mašláň, S. 2020. "High capacitance simulation using mutual inductors," Paper presented at IMEKO TC-4, Palermo, Italy, September 14-16, 2020. https://www.imeko.org/publications/tc4-2020/IMEKO-TC4-2020-32.pdf

[11] Mašláň, S. 2020. "Design of digital sampling impedance bridge for battery impedance spectroscopy," Paper presented at IMEKO TC-4, Palermo, Italy, September 14-16, 2020. https://www.imeko.org/publications/tc4-2020/IMEKO-TC4-2020-32.pdf

[12] Ouameur, M., F. Ziadé and Y. L. Bihan. 2019. "Toward a Calculable Standard Shunt for Current

Measurements at 10 A and Up To 1 MHz." *IEEE Transactions on Instrumentation and Measurement* 68, no. 6: 2215-2222. doi: 10.1109/TIM.2018.2884553

[13] Overney, F. and B. Jeanneret. 2017. "Calibration of an LCR-Meter at Arbitrary Phase Angles Using a Fully Automated Impedance Simulator." *IEEE Transactions on Instrumentation and Measurement* 66, no. 6: 1516-1523. doi: 10.1109/TIM.2017.2652500

[14] Kibble, B. P. 2019. "Four terminal-pair to anything else!" *IEEE Colloquium on Interconnections from DC to Microwaves* (Ref. No. 1999/019): 6/1-6/6. doi: 10.1049/ic:19990102.

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Metrological Challenges of Plastics Recycling

Martti Heinonen
VTT MIKES (Finland)

Europe aims at climate neutrality by 2050; to achieve this, plastic recycling needs to be increased through better processes and technologies. There is an increasing need for measurement technology that enable efficient identification of different plastic types mixed with other waste. Due to variety of materials in waste, measurements are challenging and quality control is difficult. On the other hand, material volumes are large and increasing, which calls for efficient on-line measurement and quality control methods. In this work, current sensor technologies used in plastics recycling were reviewed and needs for new measurement and calibration technologies were analyzed. Our review shows that among various sensing technologies developed for plastics recycling, NIR/VIS are most widely applied in commercial sorting systems. Hyperspectral and multi-sensing technologies with AI-based data analysis were concluded to have largest future potential. Significance of proven quality increases with expanding business and with technology development. Efficient and feasible calibration methods including certified reference material supplies should be developed.

Introduction

The annual global production of plastics increased from 348 to 359 million tons in 2017 to 2018. Totally 62 million tons was produced in Europe in 2018. At the same year, 9.4 million tons of plastic post-consumer waste was collected for recycling [1]. The recycling rate globally is estimated to be 14 – 18 % [2]. However, we need to increase this because recycling of plastics has an important role in achieving the goals of EU Green Deal that aims making Europe climate neutral in 2050 [3]. Today, plastics is mostly recycled into secondary raw material by applying a mechanical recycling process. This means that collected plastics waste is shredded/grinded, sorted, washed, dried and extruded [4-8]. The basic structure of the secondary raw material remains the same as in the collected waste. Due to inhomogeneity, produced secondary raw material can only be used in limited number of applications. Significant advancement is expected from chemical recycling in which waste is converted into fuels or petrochemical feedstock. Pilot plants applying chemical recycling are running in several countries and developments for scaling up are on-going [9-13]. Measurements play an important role in running plastics recycling: many sensor technologies are applied in sorting materials and controlling processes. Due to variety of materials in waste, measurements are challenging and quality control is difficult. On the other hand, material volumes are large and increasing, which calls for efficient on-line measurement and quality control methods. Research is needed for developing new measurement technologies and appropriate metrology tools for quality control that enable efficient process operation and ensure reliability of data for fair trade. This paper reviews the current sensor technologies used in plastics recycling and studies needs for new measurement and calibration technologies.

Plastics to be Monitored

Plastics are composed of organic polymers that are formed by very large molecules. These macromolecules are multiples of simpler chemical units called monomers [14,15]. Majority of needed plastics belong to the category of thermoplastics including polyethylene terephthalate (PET), high density polyethylene (HDPE), low density polyethylene (LDPE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS) and acrylonitrile butadiene styrene (ABS). The chemical composition of a thermoplastic material does not change when heated. Plastic materials may also contain plasticizers, fillers and additives for improving different properties [16].

Sensor Technologies for Detecting Plastics

Automatic separation and sorting are important for efficient plastic recycling because different types of plastics need to be separated from mixed waste and from each other. Photonic sensor technologies are used for characterizing materials in sorting units [6,17]. These technologies are based on detecting the interaction between electromagnetic radiation and molecules/atoms in the material flow. Due to material specificity, the interaction provides spectroscopic fingerprints for different types of plastics. In practice, however, an unknown mixture of different kinds of materials is very challenging target due to overlapping spectroscopic signals and ambiguity of spectral data. Furthermore, black plastic is a specific problem because it cannot be reliably measured at near infrared wavelength region [18,19]. Development of machine learning and AI algorithms for spectral and visual data analysis has been significantly advancing plastics identification and enabling further advancements through combining different sensor technologies.

Spectroscopy techniques applying near infrared (NIR) and visible (VIS) wavelengths as well as x-rays are applied in commercial sorting units [6,20,21]. Other technologies demonstrated in industrial plastic recycling applications include mid-infrared (MIR) and Raman spectroscopy [21,22]. Terahertz detection is being developed for plastic recycling applications [17,24-26]. Laser-induced breakdown spectroscopy (LIBS) has especially been developed for waste electrical and electronic equipment (WEEE) recycling applications [27-30]. Similar to Fourier transform infrared (FTIR) spectroscopy, it is mainly laboratory techniques at the moment [17,22]. Recently, hyperspectral detection in near and mid infrared regions has increasingly been developed for plastics sorting applications.

Table 1 summarizes relevant sensor technologies and a few features of them in plastic detection applications. NIR and hyperspectral imaging are discussed further below. An assessment of commercially available automated sorting technologies was reported by 4R Sustainability, Inc. in 2011 [31]. To get an updated view on currently commercially available technologies, commercial offerings of various recycling system manufacturers were explored in the work reported here. The study was limited to sensor-based plastic sorting systems. As a result, Table 2 lists examples of sorting systems for different applications with information about applied measurement technologies and claimed performances. It should be noted that given sorting efficiency figures are for the whole sorting units and represent the best achievable value as manufacturers have published information. The actual efficiency depends on the input waste mixture and plastic types to be identified.

Near Infrared (NIR) Technology

NIR wavelength region covers from about 750 nm to 2500 nm. Chemical bonds N-H, O-H and C-H absorb strongly radiation of this wavelength region, which enables identification of organic compounds [17,33,34]. With appropriate spectral data analysis, plastic types can be detected and quantified. In in-line plastic sorting applications, material on a conveyer belt is illuminated by a NIR light source and absorption spectrum of reflected light is measured with a NIR spectrometer. As both purity (i.e. amount of output target material relative to amount of total output [6]) and throughput are important in sorting facilities, fast measurements are needed. In high-speed conveyor belts identification should be made within milliseconds [35].

Nowadays NIR spectroscopy is the main technique implemented in sensor-based plastic sorting units. Its major disadvantage is unreliable detection of black plastic because

Type	Typical spectral range	Advantages	Disadvantages	TRL[1]
NIR	0.9 – 2.5 μm	Mature technology, non-destructive, applicable for in-line monitoring	water interference, not for black plastic	9
NIR-HSI	0.9 – 1.7 μm	see NIR, spatial distribution data	see NIR	8
MIR-HSI	2.9 – 4.2 μm	spatial distribution data, non-destructive, applicable for in-line monitoring and for inorganic compound detection	water, CO2 and glass interference	7
VIS	0.4 – 0.7 μm	non-destructive,	small penetration depth, not for black plastic	9
Raman	3.6 – 50 μm	no water or CO2 interference	sample auto-fluorescence, accurate focusing needed, punctual measurement	6
XRF	< 1 nm	atomic information, large penetration depth	ionizing radiation, applicable only to PVC	9
LIBS	0.2 – 1 μm	atomic information, applicable also for metal identification	accurate focusing needed, destructive, punctual measurement	4
FTIR	2.5 – 25 μm	non-destructive	water, CO2 and glass interference, not for black plastic	
THz	100 – 1000 μm	high penetration range	low specificity, water sensitive	

Table 1. Summary of spectroscopic sensor technologies in plastic recycling applications.
[1]TRL = Technology readiness level estimated in [6] for each technology in waste sorting units. The TRL scale ranges from 1 to 9 and is described in [32].

Application	Technology	Claimed features	Manufacturer / Reference
Recycling plastic bottles and trays	NIR, VIS	• Sorting system • separates plastic types, colors and shapes, as well as metals and foreign objects • rejection accuracy of up to 99%	• Sesotec, Germany • https://www.recyclingproductnews.com/article/34354/latest-sesotec-optical-sorting-system-provides-high-level-accuracy-at-throughputs-to-eight-tons-per-hour, visited 7.7.2021
Sorting of mixed colour plastic materials	VIS (CCD camera)	• Sorting system • sorting accuracy 99.99 %	• Zhonke, China • https://www.colorsorter-cn.com/sale-8081929-plastic-optical-sorter-recycling-machine-with-high-sorting-accuracy.html, visited 7.7.2021
Sorting plastic flakes and pellets	VIS (CCD camera)	• Sorting system • sorting accuracy up to 99.99 % if stream to be sorted has impurity less than 5 %	• Hefei Angelon Electronics, China • https://resource-recycling.com/plastics/2016/11/29/equipment-spotlight-accurately-sorting-plastics-by-color/, visited 7.7.2021
Sorting of PE, PP, PET, HDPE, PS, PVC and 3-7 mixed plastics; flakes and bottles	NIR, VIS	• Sorting system • minimum flake size: 2 mm • purity above 95 %	• Tomra, Norway • https://recycling.tomra.com/blog/sorting-technology-to-cope-with-the-increase-of-the-nations-waste, visited 7.7.2021 • https://vdrs.com/tomra-optical-sorting/, visited 7.7.2021
Measurement, analysis, and classification of samples of PE, ABS, PVC, PS, PA, PP, PC, and PET	HSI-VIS HSI-NIR HSI-MIR	• Camera system for sorting • also black plastic identification	• Specim, Finland • https://www.specim.fi/downloads/Plastics-sorting-with-Specim-FX-cameras.pdf, visited 7.7.2021
Plastics from mixed waste, sorting by polymer (PP, PE, PVC, PET) and by shape, size and colour	VIS HSI-NIR	• Sorting system • Purity up to 98%	• zenrobotics, Finland • https://zenrobotics.com/wp-content/uploads/2019/04/zenrobotics_brochure-1.pdf, visited 7.7.2021
Sorting WEEE	XRF, VIS, HSI-NIR	• Sorting system • sorting quality not by contaminations including water	• Redwave, Austria • https://redwave.com/, visited 7.7.2021
Plastics sorting: mixed waste, WEEE	laser spectroscopy (absorption, fluorescence, Raman)	• Sorting system • rejection rate of over 98%	• Unisensor, Germany • https://www.unisensor.de/en/products/product-details//powersort-200-1.html • https://cdn.uc.assets.prezly.com/0f2e33b7-8ac6-449f-92ba-c75e1e1657d1/-/inline/no/, visited 7.7.2021

Table 2. Examples of commercially available sensors-based solutions for plastic recycling.

the reflection intensity is very low due to strong absorption by colorants [6,28,35]. NIR has potential to provide further information about plastic degradation and additives [17, 36]. The penetration depth of NIR is a few millimeters at maximum [17]. Thus, the obtained information originates from the surface only. Due to absorption peaks of water in the NIR wavelengths, water on the sample surface may interfere with a measurement and distort the measurement result.

Hyperspectral Imaging (HSI) Technology

In hyperspectral imaging (HSI), spectral data over a wide wavelength region is created for each pixel of a 2D picture. Using appropriate color coding, a visual presentation of chemical compounds on the target surface can be created. Recently, this technology has significantly been advanced by developments in computing capacity and algorithms for analyzing spectral data, including machine learning algorithms [17,35,37-40]. In recycling applications, HSI provides enhanced efficiency in in-line material detection of mixed waste.

Many of HSI systems developed for recycling applications apply a line scale (push broom) operation [6,17,38], i.e. spectral information of pixels in a single line is collected at a time using a line scan camera. When targets move on a conveyer belt, full 2D pictures with pixel specific spectral data are created.

Both near infrared and mid-infrared detection based HSI-systems have been developed for plastic recycling applications [6,17,35,37-40]. The advantage of MIR over NIR is its applicability to black plastic measurements. However, NIR technology is already relatively mature and less expensive than MIR. HSI has also been combined with fluorescence spectroscopy to analyze technical black plastic particles after grinding relevant to WEEE and automotive industry waste [18].

Needs for Measurement Quality in Plastics Recycling

In plastic recycling processes, there is an increasing need for measurements aiding sorting, i.e. for discriminating material between different plastic types and other waste. Because of a limited number of sorting categories for a single sorting stage, there may be several stages in series in a process to achieve the aimed sorting output as shown in a schematic diagram of Figure 1. Further measurements are needed to control the quality of sorted plastic material. From the quality control point of view, these measurements

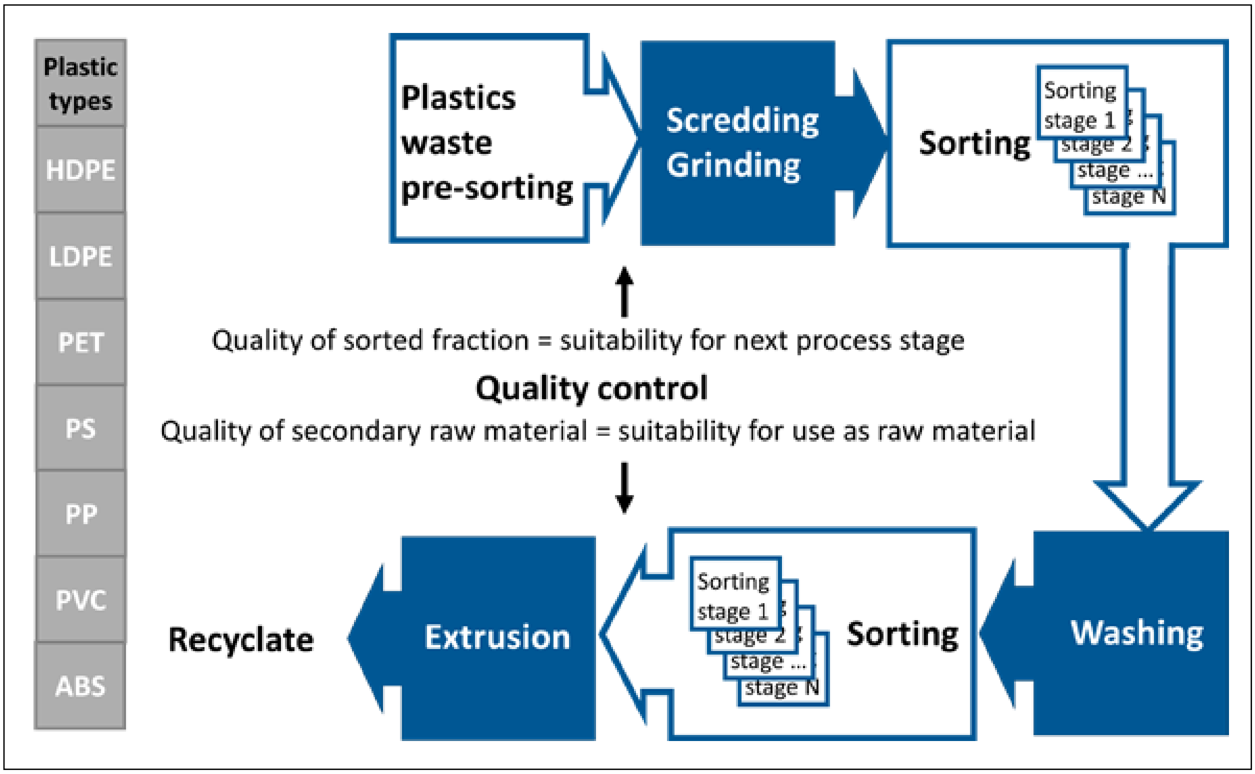

Figure 1. Schematic diagram of a mechanical plastic recycling process and quality control targets. Most relevant types of plastic are listed in the grey column.

are more important because the results affect both process control and the trade value of the produced secondary raw material. Although variations in the chemical matrix and physical properties in the measurement target are much more limited than in the input mixed waste, required measurement reliability is more difficult to achieve due to more strict requirements for contaminants and other measurement parameters. Quality control measurements are naturally also needed to support trade of recycled plastic materials and manufacturing processes using secondary raw materials.

After exploring the theoretical limits of a circular recycling value chain for plastic packages in the Netherlands, T. Brouwer et al. [41] proposed in 2020 classification of recycled plastics with acceptance values for degradation and contamination. As non-polymer contaminants do not melt during processing, the limit for such contamination was set to 50 ppm. The same limit applies for other contaminants in food packaging applications. In non-food applications the contamination criteria were set to levels of 1 – 20 % depending on the contaminant and application. According to the survey of T. Brouwer et al., the polymetric purity of washed milled goods in 2017 ranges from 87 % to 99 % for different plastic waste types [41].

According to [42], the quality standards provided by DerGrünerPunkt in Germany [43] are widely considered as benchmark in industry. Maximum total amount of impurities defined by those standards ranges from 2 % to 30 % by mass. European RecyClass initiative has published criteria for recyclability [44] that specify minimum relevant plastic material content to 95 % and maximum amount of residues to 5 % for best quality. Both DerGrünerPunkt and RecyClass provide also further criteria to several characteristic parameters. Various other standards were reported by A. Grant et al. [45] in their survey of quality standards applied to sorted fractions of plastics. The target material content is mostly 94 % to 98 % depending on the material while the lowest target is 80 % according to this survey.

Current European standards for characterization of recycled plastics list various mandatory and optional parameters to be determined [46-52]. These standards are applied in carrying out reference measurements to support plastic recycling but they do not state criteria nor estimation for the measurement reliability. According to these standards, material content and contamination should be determined using manual laboratory methods described in these standards or other specified standards. From the technologies described in the previous chapter, only FTIR and NIR are addressed in these standards.

T. Brouwer et al. call for improved efficiency in automatic sorting [41] to respond to the increasing worldwide need for increasing significantly plastic recycling. Along with this, efficient automated reference measurement methods are needed to be developed and standardized.

Metrological Traceability to Support Plastic Recycling

Metrological traceability is defined as "property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty" [53]. It is the key feature of measurement data with known level of reliability. The reliability is characterized by measurement uncertainty that comprises errors and non-idealities in the measurement instrument, setup, method, conditions etc. and the uncertainty arising from the reference used in the calibration of the instrument. To obtain robust metrological traceability in the plastic recycling domain, we need to have:

- measurement methods and instruments providing demonstrated measurement uncertainty meeting the quality requirements of the intended application, and
- calibration methods that provide metrological traceability with sufficient uncertainty.

When considering the measurement technologies currently available for sorting, it is obvious that a lot of development is still needed to achieve required level of reliability, speed and diversity when sorting various plastic waste mixtures. As described above, many different technologies have been developed and are already on market but further development is needed especially to reduce errors due to interference between different chemical compounds and to enable fast in-line detection. Hyperspectral imaging at different wavelength region seems to have a great future potential. Also, combining several sensor techniques seems to be a promising approach. Both of these are boosted by the development of artificial intelligence based data analysis techniques.

To provide efficient and feasible calibration scheme for inline measurements, automatic sampling systems are needed. Errors due to sampling and sample handling need to be minimized to keep overall measurement uncertainty at an acceptable level. Alternatively, certified reference material sets could be developed to be used for calibrating instruments monitoring the sorting output. With accredited supplier and appropriate sample handling, sufficient accuracy can be achieved in applications where contamination level is low and the number of materials of interest is very limited.

When the calibration expands with expanding plastic recycling business, also the reference measurements need to be more efficient. To enable analysis of increasing amount of reference samples, automatic analysis and sample handling methods with efficient data analysis will be needed.

Summary

Various sensor technologies have been developed for plastic recycling process applications. Many of them, however, are still in the development phase. NIR/VIS are most widely applied in commercial sorting systems. Usually, a single technology can only detect a few plastic types in a reliable way. The major challenges for the measurements are set by the needed measurement speed, spectroscopic interferences between different chemical compounds and overall reliability and uncertainty estimation. Hyperspectral and multi-sensing technologies with AI-based data analysis are considered to have largest future potential.

Significance of proven quality increases with expanding business and with technology development. To support reliable measurements, fast and feasible calibration methods are needed for both in-line and laboratory measurements. It is also evident that we will need certified reference materials and improved validated sampling techniques.

References

[1] Plastics Europe. 2019. *Plastics – the Facts 2019: An analysis of European plastics production, demand and waste data*. https://plasticseurope.org/wp-content/uploads/2021/10/2019-Plastics-the-facts.pdf

[2] OECD Environment Directorate. 2018. *Improving Plastics Management: Trends, policy responses, and the role of international co-operation and trade.* OECD Environment Policy Paper no. 12. https://www.oecd.org/environment/waste/policy-highlights-improving-plastics-management.pdf

[3] Hesselink, Tom and Emil van Duuren. 2021. *The green deal: A game changer for the waste management and plastics industries*. KPMG Advisory N.V. https://assets.kpmg/content/dam/kpmg/nl/pdf/2021/sectoren/green-deal-plastic-recycling.pdf

[4] Ragaert, Kim, Laurens Delva, and Kevin Van Geem. "Mechanical and chemical recycling of solid plastic waste," *Waste Management* 69 (2017) 24–58, https://doi.org/10.1016/j.wasman.2017.07.044

[5] British Plastics Federation. "How is Plastic Recycled? A Step by Step Guide to Recycling." Accessed March 10, 2022. https://www.bpf.co.uk/plastipedia/sustainability/how-is-plastic-recycled-a-step-by-step-guide-to-recycling.aspx

[6] Sormunen, Tuomas and Sari Järvinen. 2021. *Report on the state-of-the-art and novel solutions in sorting of post-consumer plastic packaging waste*, VTT Technical Research Centre of Finland. VTT Research Report No. VTT-R-00582-21. https://cris.vtt.fi/en/publications/report-on-the-state-of-the-art-and-novel-solutions-in-sorting-of-

[7] Fischer, Joerg, Kieran Evans, and Gerlinde Wita. "Plastics recycling: Insights, challenges, and future trends." Webinar by PerkinElmer. https://www.perkinelmer.com/uk/library/plastics-recycling-insights-challenges-and-future-trends.html

[8] Schyns, Zoe and Michael Shaver. 2021. "Mechanical Recycling of Packaging Plastics: A Review." *Macromol. Rapid Commun.* 42, 2000415. https://doi.org/10.1002/marc.202000415

[9] Bailey, Mary Page. 2021. "Canadian partners exploring new chemical recycling pilot plant for agricultural plastic waste." Chemical Engineering, November 10, 2021, https://www.chemengonline.com/canadian-partners-exploring-new-chemical-recycling-pilot-plant-for-agricultural-plastic-waste/?printmode=1.

[10] Paladino, Ombretta and Arianna Moranda. 2021. "Human Health Risk Assessment of a pilot-plant for catalytic pyrolysis of mixed waste plastics for fuel production," *Journal of Hazardous Materials* 405, 5 (March) 124222. https://doi.org/10.1016/j.jhazmat.2020.124222

[11] "New pilot plant for chemical recycling of plastics at Brightlands Chemelot Campus," Agro & Chemistry, News, April 28, 2020. Accessed March 10, 2022. https://www.agro-chemistry.com/news/new-pilot-plant-for-chemical-recycling-of-plastics-at-brightlands-chemelot-campus/

[12] "European project results in chemical recycling pilot plant." Chemical Recycling News, June 14, 2021. Accessed March 17, 2022. https://www.chemicalrecycling.eu/news/european-project-results-in-chemical-recycling-pilot-plant/

[13] Das, Sreeparna. 2021. "Chemical Recycling Poised to Take Off, Plastics Technology," RECYCLING, January 9, 2021. Accessed March 17, 2022. https://www.ptonline.com/articles/chemical-recycling-ready-to-take-off

[14] *Encyclopaedia Britannica*, https://www.britannica.com/science/polymer. Accessed March 17, 2022.

[15] *IUPAC Gold Book*, 2005–2022. International Union of Pure and Applied Chemistry. Accessed March 17, 2022. https://goldbook.iupac.org/terms

[16] Deloitte Sustainability. 2017. *Blueprint for plastics packaging waste: Quality sorting & recycling.* Accessed

March 17, 2022. Final report, Deloitte Conseil, https://www2.deloitte.com/content/dam/Deloitte/my/Documents/risk/my-risk-blueprint-plastics-packaging-waste-2017.pdf

[17] Cuauhtémoc Araujo-Andrade, Elodie Bugnicourt, Laurent Philippet, Laura Rodriguez-Turienzo, David Nettleton, Luis Hoffmann, Martin Schlummer. 2021. Review on the photonic techniques suitable for automatic monitoring of the composition of multi-materials wastes in view of their posterior recycling." *Waste Management & Research* 39, no. 5: 631–651. DOI: 10.1177/0734242X21997908

[18] Gruber, Florian, Wulf Grählert, Philipp Wollmann, and Stefan Kaskel. 2019. "Classification of Black Plastics Waste Using Fluorescence Imaging and Machine Learning" Recycling 4, no. 4: 40. https://doi.org/10.3390/recycling4040040

[19] Becker, Wolfgang, Kerstin Sachsenheimer and Melanie Klemenz. 2017. "Detection of Black Plastics in the Middle Infrared Spectrum (MIR) Using Photon Up-Conversion Technique for Polymer Recycling Purposes." *Polymers* 9: 435. DOI: 10.3390/polym9090435

[20] Brunner, S., P. Fomin and Ch. Kargel. 2015. "Automated sorting of polymer flakes: Fluorescence labeling anddevelopment of a measurement system prototype." *Waste Management* 38 (April): 49–60. DOI: 10.1016/j.wasman.2014.12.006

[21] Neidel, Trine Lund and Jens Bjørn Jakobsen. 2013. *Report on assessment of relevant recycling technologies.* COWI A/S. Accessed March 17, 2022. https://cupdf.com/document/report-on-initial-assessment-of-relevant-recycling-technologies-catalouge-21.html?page=1

[22] Bae, Jong-Soo, Sung-Kwun Oh, Witold Pedrycz and Zunwei Fu. 2019. "Design of fuzzy radial basis function neural network classifier based on information data preprocessing for recycling black plastic wastes: comparative studies of ATR FT-IR and Raman spectroscopy," *Applied Intelligence* 49: 929–949. DOI: 10.1007/s10489-018-1300-5

[23] Roh, Seok-Beom, Sung-Kwun Oh, Eun-Kyu Park and Woo Zin Choi. 2017. "Identification of black plastics realized with the aid of Raman spectroscopy and fuzzy radial basis function neural networks classifier." *Journal of Material Cycles and Waste Management* 19: 1093–1105. DOI: 10.1007/s10163-017-0620-6

[24] "Fusing Terahertz and MWIR Technologies to Recycle E-waste Black Plastics." Mitacs Projects. Accessed March 17, 2022. https://www.mitacs.ca/en/projects/fusing-terahertz-and-mwir-technologies-recycle-e-waste-black-plastics

[25] "TACTICS: Terahertz computer tomography for plastics extrusion." 2020. Accessed March 17, 2022. Project public summary page from the ATTRACT Showroom website, https://phase1.attract-eu.com/showroom/project/terahertz-computer-tomography-for-plastics-extrusion-tactics/

[26] "Sorting of black plastics for recycling." 2022. Accessed March 17, 2022. Fraunhofer-Gesellschaft, https://www.blackvalue.de/en.html

[27] Tang, Yun, Yangmin Guob, Qianqian Sunb, Shisong Tangb, Jiaming Lib, Lianbo Guob and Jun Duan. 2018. "Industrial polymers classification using laser-induced breakdown spectroscopy combined with self-organizing maps and K-means algorithm." *Optik* 165: 179–185. DOI: 10.1016/j.ijleo.2018.03.121

[28] Costa, Vinícius Camara, Jeyne Pricylla Castro, Daniel Fernandes Andrade, Diego Victor Babos, Jose Augusto Garcia, Marco Aurelio Sperança, Tiago Augusto Catelani and Edenir Rodrigues Pereira-Filho. 2018. "Laser-induced breakdown spectroscopy (LIBS) applications in the chemical analysis of waste electrical and electronic equipment (WEEE)." *Trends in Analytical Chemistry* 108: 65-73. DOI: 10.1016/j.trac.2018.08.003

[29] Stefas, Dimitrios, Nikolaos Gyftokostas, Elli Bellou and Stelios Couris. 2019. "Laser-induced breakdown spectroscopy assisted by machine learning for plastics/polymers identification." *Atoms* 7: 79. DOI: 10.3390/atoms7030079

[30] Costa, Vinicius Câmara and Fabíola Manhas Verbi Pereira. 2020. "Laser-induced breakdown spectroscopy applied to the rapid identification of different types of polyethylene used for toy manufacturing." *Journal of Chemometrics* 34: e3248. https://doi.org/10.1002/cem.3248

[31] 4R Sustainability, Inc. 2011. *Demingling the mix: An assessment of commercially available automated sorting technology.*

[32] "HORIZON 2020 – WORK PROGRAMME 2014-2015, General Annexes." Extract from Part 19 - Commission Decision C. (2014) 4995.

[33] Zhu, Shichao, Honghui Chen, Mengmeng Wang, Xuemei Guo, Yu Lei and Gang Jin. 2019 "Plastic solid waste identification system based on near infrared spectroscopy in combination with support vector machine." *Advanced Industrial and Engineering Polymer*

Research 2: 77e81. DOI: 10.1016/j.aiepr.2019.04.001

[34] Masoumi , Hamed, Seyed Mohsen Safavi and Zahra Khani. 2012. "Identification and classification of plastic resins using near infrared reflectance spectroscopy." *International Journal of Mechanical and Industrial Engineering* 6: 213 - 220.

[35] Signoreta, Charles, Anne-Sophie Caro-Bretelleb, José-Marie Lopez-Cuestaa, Patrick Iennyb and Didier Perrin. 2020. "Alterations of plastics spectra in MIR and the potential impacts on identification towards recycling." *Resources, Conservation & Recycling* 161: 104980. DOI: 10.1016/j.resconrec.2020.104980

[36] van Engelshoven, Yuri, Pingping Wen, Maarten Bakker, Ruud Balkenende, and Peter Rem. 2019. "An Innovative Route to Circular Rigid Plastics" Sustainability 11, no. 22: 6284. https://doi.org/10.3390/su11226284

[37] Bonifazi, Giuseppe, Giuseppe Capobianco, Roberta Palmieri and Silvia Serranti. 2019. "Hyperspectral imaging applied to the waste recycling sector." *Spectroscopy Europe* 31, no. 2.

[38] Luciani, Valentina, Giuseppe Bonifazi, Peter Rem, and Silvia Serranti. 2015. "Upgrading of PVC rich wastes by magnetic density separation and hyperspectral imaging quality control." *Waste Management* 45: 118–125. DOI: 10.1016/j.wasman.2014.10.015

[39] Ulrici, A., S. Serranti, C. Ferrari, D. Cesare, G. Foca, and G. Bonifazi. 2013. "Efficient chemometric strategies for PET–PLA discrimination in recycling plants using hyperspectral imaging," *Chemometrics and Intelligent Laboratory Systems* 122: 31–39, DOI: 10.1016/j.chemolab.2013.01.001

[40] Signoret, Charles, Anne-Sophie Caro-Bretelle, José-Marie Lopez-Cuesta, Patrick Ienny, and Didier Perrin. 2019. "MIR spectral characterization of plastic to enable discrimination in an industrial recycling context: I. Specific case of styrenic polymers." *Waste Management* 95: 513–525. DOI: /10.1016/j.wasman.2019.05.050

[41] Brouwer, Marieke T., Eggo U. Thoden van Velzen, Kim Ragaert, and Roland ten Klooster. 2020. "Technical limits in circularity for plastic packages." *Sustainability* 12: 10021. doi:10.3390/su122310021

[42] Ingenieurgemeinschaft Innovative Umwelttechnik GmbH. 2019. *Report. Study about plastic sorting and recycling.* Accessed: March 17, 2022. https://plastikviden.dk/media/212448/study-about-plastic-sorting-and-recycling.pdf

[43] Accessed March 17, 2022. https://www.gruener-punkt.de/en/downloads

[44] Accessed March 17, 2022. https://recyclass.eu/recyclass/design-for-recycling-guidelines/

[45] Grant, A., M. Cordle, and E. Bridgwater. 2020. *Quality of recycling: Towards an operational definition*. European Union. doi:10.2760/225236

[46] *Plastics. Recycled plastics. Characterization of Polyethylene (PE) recyclates.* European Standard EN 15344:2021.

[47] *Plastics. Recycled Plastics. Characterization of polystyrene (PS) recyclates.* European Standard EN 15342:2007.

[48] *Plastics. Recycled Plastics. Characterisation of Polypropylene (PP) recyclates.* European Standard EN 15345:2007.

[49] *Plastics. Recycled plastics. Characterization of poly(vinyl chloride) (PVC) recyclates.* European Standard EN 15346:2014.

[50] *Plastics. Recycled plastics. Determination of solid contaminants content.* CEN Technical Specification CEN/TS 17627:2021.

[51] *Plastics. Re-cycled plastics. Determination of selected marker compounds in food grade recycled polyethylene terephthalate (PET).* CEN Technical Specification CEN/TS 16861:2015.

[52] *Plastics. Recycled plastics. Characterization of poly(ethylene terephthalate) (PET) re-cyclates.*European Standard EN 15348:2014.

[53] JCGM. 2012. *JCGM 200:2012: International vocabulary of metrology – Basic and general concepts and associated terms (VIM), 3rd edition.* https://www.bipm.org/documents/20126/2071204/JCGM_200_2012.pdf/f0e1ad45-d337-bbeb-53a6-15fe649d0ff1?version=1.8&download=true

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Pieces Parts

Dan Wiswell
Cal-Tek Company, Inc.

About thirty years ago I was doing some spring cleaning and decided to bring a few tables worth of items to a large flea market in south-central New Hampshire. I had an assortment of old tools and some household items, but on a whim, I also brought some antique electrical instruments from my collection. I got there early and hadn't been set up very long when two older ladies came up to my display. They looked at my instruments and asked if I had found them at some estate sale. I told them that I had been collecting them for many years. Turning around, they looked into the crowd and disappeared for a while but returned with two other ladies. I won't soon forget the near loving looks of what I perceived to be affection when they looked at each instrument. One said to the others that she remembered making wire-wound resistors with a Leeds and Northrup bridge that I had on display. The eldest of the group was eighty-six years old and asked me many questions about where I had found the meters and instruments, and then more pointedly asked if I knew what they were all used for. Luckily, I was able to answer her questions and as I did the looks from all four ladies began to soften. They had all worked in the instrument industry, the eldest worked at Beede Instruments in 1928. In the following half hour, I learned more about the way things were in my industry than I had previously imagined in all my time as a metrologist. They told me stories of the companies that they and their friends had worked in. I learned that just prior to the market crash of 1929, business was so good that they couldn't find applicants talented enough to do some of the work, so some manufacturers paid women to assemble meter movements at home at piece-work rates. One of the ladies told me that her mother taught her how to build moving-coil assemblies at her sewing table at home. She used those skills for nearly the entire rest of her career.

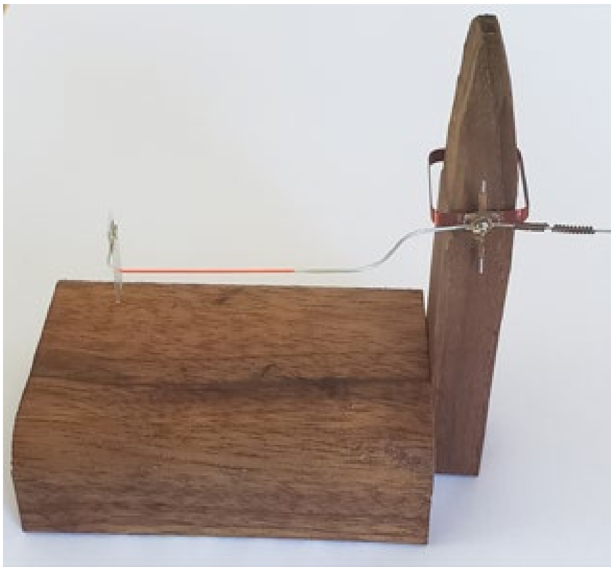
I think that many people take a kind of short-handed look at how things may have been in days gone by. Reading about history in grade school, decades of time are often compressed into a few paragraphs and never truly relate the experiences of the daily lives of those from previous generations. The reality is that the world has always been more complex that most people imagine. Time has seen the passing of entire industries as technology has marched forward casting a myriad of trades into obsolescence in a natural selection kind of way. This process has sped up tremendously in the throw-away reality that we live in today. But in days of old, nearly everything broken was repaired and products were designed to be repairable. Just as in other industries, instrument manufacturers had service departments to serve the aftermarket needs of their clientele. Many of these manufacturers sold their products through distributors that also had service departments which created another ancillary market for spare parts. The electro-mechanical manufacturing industry was supported by a broad network of specialty component manufacturers and custom tool makers, each with their own distribution networks. Meter manufacturers contracted the services of machine shops for many of the basic components that went into each product such as pivots, jewels and hairsprings. These are the kinds of details that are often forgotten by time.

Instrument distributors used to carry inventories of what were called "mod meters." These basic meters were designed to be easily modified so that they could be used in a variety of customers' applications. An example of a mod meter can be seen in the picture below.

This is a Weston Model 271. Many thousands of these meters were modified and ranged to measure a host of different parameters. Notice that the example shown has a blank scale. A meter like this would enter a value-added production process where it would be outfitted with a custom scale that would often include the logo and other artwork provided by the customer. The meter would also have an internal circuit added to interface with the equipment that it was intended to be used in. This may include series or parallel resistor networks, rectifiers or other components, to meet the requirements of each application. Meters like this could also be modified to indicate in reverse by suppressing the mechanical zero-correctors or have its hairsprings changed out so that the customer could have positive and negative meter indications with a zero-centered scale.

IN DAYS OF OLD

As a young metrologist in the 1970s, I remember that all my fellow metrologists used a wooden mandril to support meter movements as they were being worked on. Trying to fit in, I made one for myself and brought it into work. When my boss saw it, he laughed and gave me one of his older ones. I guess I tucked my creation away, because I was surprised recently when one of my metrologists found it in a box above our lab and asked me what it was. To the right, is my first feeble attempt at making a meter movement mandril. I wish I still had the superior one that my boss gave me.



I also wish that I had the presence of mind to have been able to gather up as much of the ephemera from my earlier days of working in various laboratories as I could have done. It may be for the better though, as it might now be like dragging along Jacob Marley's chains. If I had, I'd be able to relate a much more complete picture of what life was like to live a day in the life of an old-world metrologist. Pictured below are a few of the components and tools that were widely used back in those times.

This picture by itself shows many things. Pivots and hair springs. Spring adjuster tools made by P.K. Nueses Inc. These particular tools were made very early on in that company's history, as Arlington Height Illinois was the location of their original factory. These tools were used to shape hair springs.

In those days you could buy replacement pointers, pivots, jewels and all of the other replaceable parts that kept the meter repair industry going. All of these things got damaged or went missing and could be replaced. Everyone working at the benches around me back then had an assortment of balancing weights, as well as a collection of specialized fasteners, screws and other hardware.

I used to hold my breath as I watched in amazement when the more experienced metrologists deftly removed damaged hair springs and then expertly reattached new ones with an economy of motion.

Something strange seems to have happened in the intervening years that stretch between the early day of my career and the present time. Tens of thousands of pieces of equipment have all merged into one continuous learning experience. Snippets of conversations that occurred decades ago still help me to manage my laboratory through each working day. And fortunately, as I'm sure is the case with many of us, until they repeal Ohm's Law we all still have a job.

Dan Wiswell (dcwiswell@repaircalibration.net) is a self-described Philosopher of Metrology. He is President/CEO of Cal-Tek Company, Inc. and Amblyonix Industrial Instrument Company.

New Rohde & Schwarz LCX Family of LCR Meters

Munich, 15-Mar-2022 – Rohde & Schwarz launches its new LCR meter family of high performance general purpose impedance testers covering a wide range of applications. With its supported frequency range from 4 Hz to 10 MHz, the R&S LCX is suitable not only for the vast majority of devices operating at conventional 50 or 60 Hz domestic power frequencies or 400 Hz for aircraft, but also for everything from low frequency seismic sensors to high power communication circuits operating at several Megahertz.

For engineers selecting suitable capacitors, inductances, resistors, and analog filters to match the device application, the R&S LCX models provide high precision impedance values with market-leading accuracy. Equally, higher speed measurements at production-use accuracy for quality control and monitoring are also supported. All the essential software and hardware required for production environments is available, including remote control and result logging, as well as rack mounting for the instrument, and a full range of test fixtures for handling components.

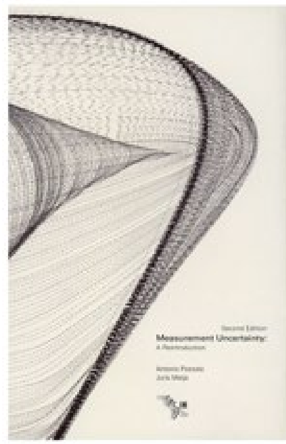
The auto-balancing bridge technology used by the R&S LCX supports conventional impedance measurements by measuring the AC voltage and current for the device under test, including the phase shift. This is then used to calculate complex impedance at any given operational point. As a general purpose LCR meter, the R&S LCX covers many applications, such as the measurement of equivalent series resistance (ESR) and equivalent series inductance (ESL) of electrolytic capacitors and DC-link capacitors. Furthermore, users can test transformers and measure DC resistance in addition to the full range of impedance measurements. To investigate components with impedance values varying at different frequencies and levels, option R&S LCX-K106 supports dynamic impedance measurements with the frequency, voltage or current as the swept parameter.

The R&S LCX family is launched with two models; the R&S LCX100 covers a frequency range from 4 Hz to 300 kHz, the R&S LCX200 a basic frequency range from 4 Hz to 500 kHz with options to cover all frequencies up to 10 MHz. Both models feature a large capacitive touchscreen and virtual keyboard to support tap-and-test for all main measurements. Alternatively, voltage, current, and frequency values can be set using the rotary knob. Less frequently used functions are menu-operated. Settings, results, and statistics can be displayed on the screen or output for automated post-processing. Up to four measurements can be selected and plotted versus time, with minimum and maximum values included in the display for at-a-glance pass/fail analysis.

For investigating impedance in a wider range of materials, the MFIA impedance analyzer from Zurich Instruments AG, a subsidiary of Rohde & Schwarz, complements the R&S LCX perfectly. With the MFIA researchers can characterize semi-conductors or undertake material research into materials including dielectrics, piezoelectrics, ceramics and composites, as well as tissue impedance analysis, cell growth, food research, microfluidics, and wearable sensors.

The R&S LCX family of LCR meters is part of the R&S Essentials portfolio and is now available from Rohde & Schwarz and selected distribution partners. For further information on the R&S LCX visit https://www.rohde-schwarz.com/product/lcx. For more information the LCR meter portfolio from Rohde & Schwarz, including the MFIA from Zurich Instruments AG, visit https://www.rohde-schwarz.com/lcr-meters.

2nd Ed. Released for Measurement Uncertainty: A Reintroduction



A much enlarged second edition of *Measurement Uncertainty: A Reintroduction*, by Antonio Possolo (NIST) and Juris Meija (NRC Canada) was released April 6, 2022. An inter-American collaboration, the publisher is Sistema Interamericano de Metrologia (SIM) in Uruguay, with the National Resource Council of Canada (NRC) and the National Institute of Standards and Technology (NIST) as sponsors. Additionally, members of the measurement community from institutions throughout North, Central, and South America provided materials and feedback in the creation of this edition.

Besides being a reference and instruction on measurement uncertainties, the authors mean to capture the widening influence of metrology in recent decades. As stated in the Preface, "We take an eclectic and inclusive view of measurement, recognizing its vital and pervasive role in science and technology, also in the arts." Indeed, as detailed examples range from the interpolating of chirping crickets to calibration of the radiocarbon dating of the Shroud of Turin. They in turn do not prescribe to rigid ideology, but instead pull from the wide range of models and methods to best address a specific need; "to select models and employ data reduction techniques that are verifiably adequate for the data in hand."

In the span of 256 pages, the authors offer a distilled and sweeping overview of measurement uncertainties, including multiple measurement examples that can apply to a broad range of interests, coverage of statistical models and methods, and tools and references that can be found online through embedded links.

Of the uncommon pricing of the hard copy, Antonio Possolo notes "The price is not a mistake -- it is a bargain the likes of which you have not seen in a long time. Look at it this way: some coffee drinks cost more than this book." The PDF version is copyrighted by NRC and licensed under Creative Commons guidelines, making it free for individuals to download for their own use.

"Our goal is to make the book accessible to interested colleagues the world over, especially in the developing countries, and particularly in the Americas. For this reason we have opted for a black-and-white version" Possolo adds.

Measurement Uncertainty: A Reintroduction is freely available for download at https://doi.org/10.4224/1tqz-b038. A hardcopy issue is also available for $6.54 (plus shipping) from https://www.amazon.com/gp/product/0660428660/.

NEW PRODUCTS AND SERVICES

Keysight M9484C Vector Signal Generator

SANTA ROSA, Calif. April 26, 2022 - Keysight Technologies, Inc. (NYSE: KEYS), a leading technology company that delivers advanced design and validation solutions to help accelerate innovation to connect and secure the world, today launched a new four-channel vector signal generator, with frequency up to 54 GHz that offers up to 5 GHz of radio frequency (RF) bandwidth and low phase noise in a single instrument.

Keysight's new M9484C VXG vector signal generator, expands the company's VXG series portfolio with real-time capabilities to support demanding wireless industry applications. The M9484C VXG signal generator, with a V3080A vector signal generator frequency extender, expands the frequency range up to 110 GHz to address the needs for the latest and evolving standards.

New 5G mobile communications, 6G research, satellite communications and radar applications use a wide range of frequencies, up to and including millimeter wave (mmWave) spectrum. Testing these applications requires signal generation equipment capable of creating millimeter-wave signals at extremely high bandwidth. These new applications also adopt multi-antenna techniques, such as spatial diversity, spatial multiplexing and beamforming to achieve diversity, multiplexing and antenna gains for high-throughput and robust communications.

Keysight's new M9484C VXG signal generator enables customers to reduce test system setup complexity and achieve accurate and repeatable multi-channel measurements in a single instrument. Key customer benefits include:

- A scalable architecture that enables the most demanding wideband and multichannel test signals with frequencies up to 110 GHz.
- A fully integrated, calibrated and synchronized signal generator that delivers low phase noise and minimizes measurement uncertainty.
- Real-time signal processing and comprehensive signal creation that enables complex test scenarios and simplifies test complexity for receiver and performance tests.

Keysight's new M9484C VXG signal generator generates high frequency, wide channel bandwidth signals in multiple coherent channels. These capabilities enable engineers to:

- Innovate designs that enable higher frequencies, wider bandwidths and multichannel applications, and ensure they meet the latest and evolving standard test requirements.
- Simplify measurement setup and complex calibration routines associated with multi-box solutions with a one-box approach, saving time and reducing measurement errors related to changing equipment configuration and cabling.
- Eliminate signal impairments caused by traditional analog I/Q modulators with a new DDS architecture and deliver advanced signal fidelity for wideband signal generation.

More information about the Keysight VXG signal generators is available at www.keysight.com/find/m9484c.

Yokogawa AQ6380 Awarded Highest Class Score

February 9, 2022 - Yokogawa Test&Measurement, a pioneer and leader in precision optical measurement, is pleased to announce that the latest addition to its optical spectrum analyzer line, the AQ6380 Highest Performance OSA has received the highest score, 4.5/5.0, in the Lab/Production Test Equipment class by 2022 Lightwave Innovation Reviews.

An esteemed and experienced panel of judges from the optical communications community recognized Yokogawa Test&Measurement as a high-scoring honoree, with the judges describing the AQ6380 as a "…grating-based optical analyzer with market leading resolution and wavelength range as well as enhanced automation for many measurement workflows."

"On behalf of Lightwave Innovation Reviews, I would like to congratulate Yokogawa Test&Measurement on their high-scoring honoree status," said Lightwave Associate Publisher and Editorial Director, Stephen Hardy. "This competitive program allows Lightwave to celebrate and recognize the most innovative products impacting the optical communications community this year."

The AQ6380 OSA's optical wavelength resolution (down to 5 picometers) enables optical signals in close proximity to be clearly separated and accurately measured. Waveforms that were previously not visible using a standard OSA, such as modulation side peaks in the laser spectrum, can now be accurately detected using the AQ6380. This capability is often crucial to engineers who develop and validate next-generation high-speed optical signal sources. Additionally, the new RAPID sensitivity mode enables CW light sub-second measurement speeds up to 20 times faster than the previous highest resolution model, which reduces test time and increases productivity.

The AQ6380 OSA's key differentiator is that it combines high resolution (5 pm), high wavelength accuracy (+/- 5 pm), high sensitivity (-85 dBm), fast measurement speed (sub-second), and a broad wavelength range (1200 to 1650 nm) into a single grating-based instrument.

To learn more about the Yokogawa Test&Measurement AQ6380 Highest Performance Optical Spectrum Analyzer, please visit https://tmi.yokogawa.com/us/solutions/products/optical-measuring-instruments/optical-spectrum-analyzer/aq6380-optical-spectrum-analyzer/

The Need for Model-Driven Metrology Software Engineering

Michael L. Schwartz
Cal Lab Solutions, Inc.

I am going to try and take a huge concept in software engineering and design, break it down into its core functions, then show how it applies to metrology software in less than 850 words.

So let me start with a brief evolution of software engineering, where back in the 1950s through 1970s most of the software applications built were function-based applications. Programmers would create a "function int main(string args){...}" and call in from a command line or some other application. Then they would write a series of sub-functions inside the application and call them as needed to complete a defined task.

From the 1980s until 2000, most of these function-based applications were migrated into Object-Oriented-Programs (OOP), where the idea of objects containing both data and functions used with the data were mixed. This created more robust code in the applications and increased the code re-usability, as it was built around well-defined objects. Things like a textbox, found in a windows application or on a web page could be reused from application to application. This moved tasks like drawing the box, receiving keyboard input, displaying the data to the user, etc. from the application programmer to the operating system or browser code. All because of better code readability!

From the 1990s to today, many of the applications started using generics and/or annotation in their code. Usually, they are called decorator classes, because they add features to the objects, kind of like how a pine tree becomes a Christmas Tree because of how it is decorated. One great example of this is the serialization of an object, allowing the user to save it or load it to and from a file. This serialization of the object copies all the data into a stream allowing it to be moved or saved for another/future use.

In .NET, this task is as simple as adding "<Serializable()>" to the top of the object; it now has all the code needed to save and create itself to and from a file. All the programmer has to do is tell it where to write or read the file from.

The difference between Function and OOP-based programming vs. the concept of generics is when and how the code is added that can serialize the object to and from a file. In the 80s, the programmer would have had to know about the requirement to serialize to a file and write the code to read and write the object to and from an I/O stream. But as generics came into use, the programmer just had to add the annotation to any existing class and all the work was done.

The object can be decorated just like the Christmas Tree. And not with just one decoration, as there are several generic decorations that can be added to an object: read and write to XML or JSON file, create a REST Interface, store in a data table, and tons of tools and more each day.

The above examples are based on data storage, because that is what most computers do, data storage and data access. How the data is persisted, created, read, and saved to the filing system is the largest part of what computers do.

The above examples work on Linux, Windows, Mac, Android, etc. They work on almost all databases, such as MS SQL Server, PostgreSQL, My-SQL, Oracle, etc. They have adaptations in .NET, Java, Pascal, C++, etc… and they can move data from and to any system.

This needs to be the focus for metrology software companies in the 21st century. We need to start focusing on models that work in tandem with each other. Building more reusable tools, sharing ideas, and reusing common ideas and metrology-based software models.

We have been working with the NCSLI 141 Committee to create better software models for metrology. Over the past few years, we have discovered commonalities and created tools that will help bring model-driven engineering to the world of metrology software.

The next few Automation Corners will be dedicated to creating better models for metrology. And if you are attending any of the metrology conferences this year, please look me up… I would love to chat about what is needed in a better data model.

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