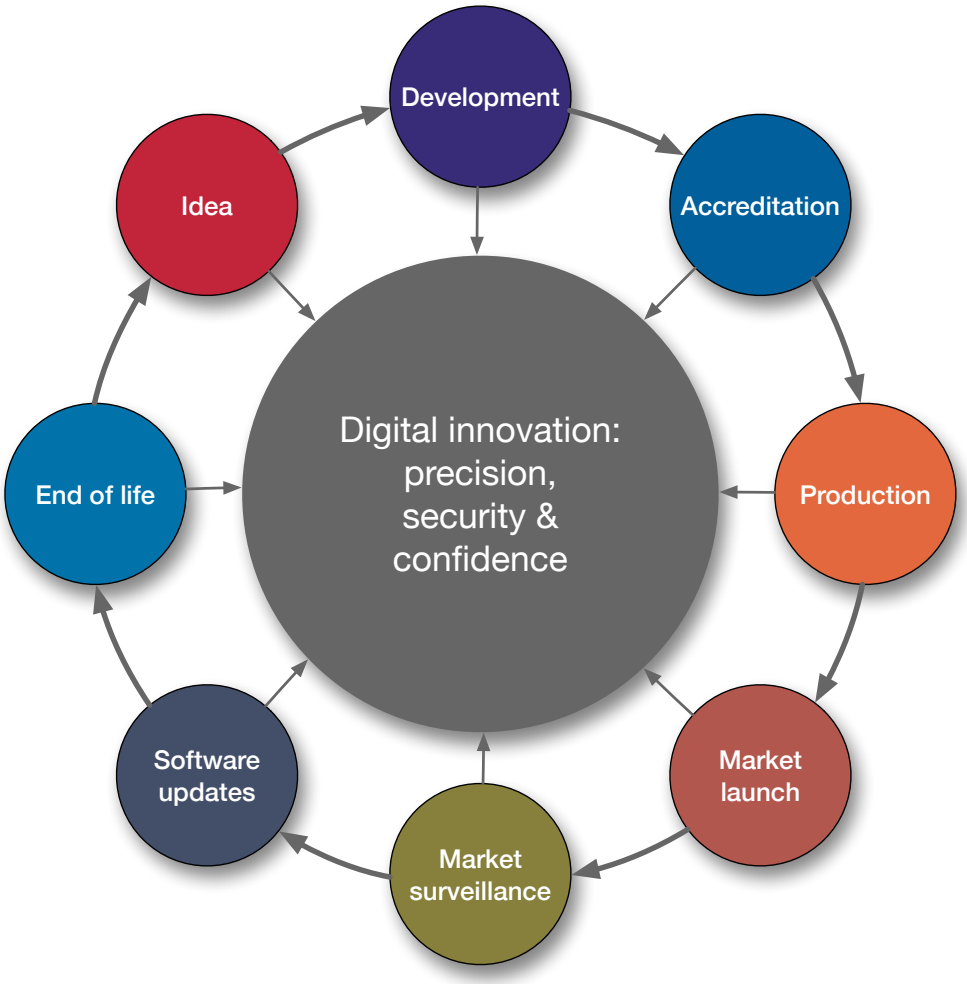
Metrology for the Digitalization of the Economy and Society

The PTB Digitalization Strategy (Status 2018)



Executive summary

Digitalization is an ongoing process that is intensively influencing and lastingly changing all areas of society in very different ways. In Germany's federal states, digitalization has become a ministerial task and is supported financially with billions of euros. The focus here is primarily on broadband expansion, the digitalization of schools and universities, and programs for digital administration. In manufacturing companies, on the other hand, digitalization is seen in the context of industry 4.0, i.e. fully digitally networked production. In addition, companies are developing digitally supported products, with the help of which they are partly opening up new business fields. In research, digitalization is reflected in new branches of research, interdisciplinary cooperation projects and, last but not least, in many new challenges, such as research data management.
Many of these issues are subsumed in a quality infrastructure that will be completely digitized in the future. In this system, processes are handled completely digitally, objects are networked extensively, and intelligent algorithms are used intensively. This digital transformation is already in full swing and will be further accelerated by current technological developments.

As Germany's national metrology institute, the Physikalisch-Technische Bundesanstalt (PTB) plays an active role in many of the above-mentioned issues, challenges and developments due to its great variety of tasks:

- In the field of legal metrology, PTB is actively promoting the comprehensive digitalization of processes and measuring instruments in a process-oriented manner and is supporting industry and market surveillance authorities intensively in the current digitalization fields of intelligent measuring systems (*smart meters*) and electromobility.
- In industrial metrology, PTB is supporting calibration by developing internationally recognized, machine-readable digital certificates with a corresponding infrastructure for the mutual recognition of validity.
- For simulations and so-called virtual measuring instruments, PTB is conducting interdisciplinary research in order to answer the current fundamental questions in a holistic approach.
- For reliable data evaluations, PTB is developing testable algorithms and is working on the harmonization of methods.
- For the sustainable development of a 5G infrastructure, PTB is concerned with the metrological basics of the necessary high-frequency measurement technology.

A joint coordinated procedure as well as the interlocking of the various activities at PTB play a decisive role here.

PTB's digital strategy[1], published in 2017, highlighted four key areas for research and development in which digitalization plays a major role: metrological services, data analysis, communication technology and simulations. Since then, many of the projects described there have already been started and further developed.
Specifically, the following projects, among others, were taken up:

- The European-funded SmartCom project was launched in June 2018 to further develop and make available internationally the foundations laid in 2017 for the *digital calibration certificate (DCC)* and the SI-based digital communication of metrological information. With the current draft of the DCC, the requirements of the new DIN EN ISO/IEC 17025 have been mapped, and a multitude of measured variables can already be displayed. In the first half of 2019, the nationally tested XML schema will then be presented internationally.
- *The European Metrology Cloud* initiative was successfully launched in June 2018 with several European partners. The project will develop demonstrators for a "digital quality infrastructure" for legal metrology, digitally map regulated processes, and develop architectural proposals for distributed measurement devices that interact with this infrastructure.
- The associated junior professorship in the field of "Secure and trustworthy network-connected systems" at the Einstein Center of the Technical University Berlin and PTB was successfully launched.
- The EMPIR-funded Met4FoF project was launched in June 2018 to develop and evaluate metrological foundations for industry 4.0 scenarios.
- In the project entitled "GEMIMEG - Safe and Robust Calibrated Measuring Systems for Digital Transformation", which is mainly promoted by the Fraunhofer HHI and PTB and funded by the BMWi, a new lighthouse project in this field will be developed in the first half of 2019 together

[1] DOI: 10.7795/310.20170401EN

with many well-known partners from industry and research.

- The combination and the mutual integration of the developments in SmartCom and the *Metrology Cloud* are being accompanied scientifically.
- PTB is intensively involved in the activities of the Berlin universities in the field of machine learning and is actively promoting joint application-oriented research.
- A professorship in the field of "Uncertainty and Machine Learning" at TU Berlin and PTB will start in 2019.
- The pilot phase for PTB's electronic file (e-file) was started in the autumn of 2018. The start of the active operation is planned for June 2020. PTB works in close coordination with other departmental research institutions in order to guarantee efficient implementation.
- In the main area on "Simulations and virtual measuring instruments", PTB is actively promoting the further development of its reference methods VCMM and SimOptDevice. In addition, PTB has created a new internal platform as a competence center: Metrology for Virtual Measuring Instruments (VirtMess). This will further strengthen interdisciplinary exchanges and the joint development of solutions.
- PTB established a project group in 2017 to develop and implement efficient research data management. It is developing guidelines and software tools as well as advising PTB researchers. International coordination within the framework of EURAMET has already been initiated.
- The European Centre for Mathematics and Statistics in Metrology (MATHMET) is currently being integrated into EURAMET as the *European Metrology Network.* PTB is greatly involved and has set itself the goal of developing and implementing a *software quality framework* and cooperation in the field of high performance computing (HPC).
- As part of its "5G and millimetre wave" strategy, PTB already started the area designated "Spectrum analysis of nonlinear systems" as part of its trainee program at the beginning of 2018. Preparations are currently underway for several cooperation projects with industry and research.
- The International Cooperation Department has adopted a specifically tailored digital strategy, which will be consistently implemented from 2019 onwards.

This status report shows the developments since the digitalization study of 2017, places them in the context of a cross-sectoral strategy and discusses new questions. In addition, this document presents the overriding core objectives of PTB's digitalization strategy, which place the current developments in a long-term context.

Basic objectives of the PTB digitalization strategy

1) Ensuring uniformity and trust in metrology in a digitized world

The essential legal core tasks of PTB are to ensure the uniformity of metrology (Units and Time Act), to make sure that DIN EN ISO/IEC 17025 is complied with and to ensure measurement accuracy, measurement stability and testability (MID, Measurement and Verification Act). International harmonization is strongly supported in these areas. In the course of digitalization, a large number of new challenges have arisen for these tasks, which PTB is actively facing.
These include:

- securing confidence in measurements and processes in digital infrastructures;
- the development of suitable "digital standards", such as reference data, for the validation of algorithms;
- the harmonization of digital formats for the dissemination of metrological information, such as DCCs for digitally networked industries.

2) Efficient and secure use of digital technologies

PTB is developing and using digital technologies both for its own working methods and for the processes in quality infrastructure. It sees the concepts of *security by design* and *privacy by design* as indispensable for securing trust. These include:

- the introduction of the e-file with sophisticated rights management;
- the provision of advanced central IT services;
- the development of the *Metrology Cloud* for legal metrology processes.

3) Sustainable usability of research results and data

Data-driven research and business models can only be implemented if reliable data is accessible and can be used sustainably. Therefore, PTB deals among other things with:

- a comprehensive concept for research data management;
- the development and implementation of a *software quality framework*;
- the consistent use of metadata and vocabulary in the digital environment.

4) Holistic approach to the treatment of measuring instruments and measurement data

In a digitally networked economy and industry, holistic concepts for the handling of measurement data and the networking of measuring instruments are necessary. Therefore, PTB is developing, among other things, concepts for:

- the consistent digital transformation of legal and industrial metrology;
- *metrology by design* for reliable measured values right from the acquisition stage;
- the consideration of the entire life cycle of a measuring instrument.

5) Active participation of all employees in the digitalization process

Digital transformation can only succeed if no one is left behind and digital innovation is encouraged. For this purpose, PTB is developing a number of initiatives which include:

- formats for the active support of digital pioneers;
- a wide range of training and learning opportunities;
- innovative formats for co-design and participation.

Introductory remarks

Following the adoption and publication of the PTB digitalization strategy in June 2017, PTB started implementing the projects straight away. Central strategic reserves and third-party funding were used specifically for this purpose. In July 2017, a new staff group for the "Coordination of Digitalization" was founded in order to gather information and coordinate interdepartmental projects. Since then, this group has been technically accompanied by a central project steering group consisting of the department heads who are primarily involved. In addition to coordinating and accompanying the technical projects, the task of this staff group is to advance PTB's digital strategy both technologically and technically. To this end, the group has set up a central Internet and Intranet site as an information platform, organized several colloquia, launched internal pilot projects, actively promoted national and international networking and acquired a European third-party funding project.

Similarly, great progress has already been made in all areas of PTB's digital strategy of 2017. The digital transformation of the quality infrastructure requires a holistic consideration of data security, suitable data formats, data availability and a legal framework, see Figure 1. From the point of view of metrology, digital consumption meters, a common language for networked meters and the availability of suitable metrological platforms play a decisive role. The interaction of the requirements and the areas of responsibility is reflected in many of PTB's developments.

The current status of implementation is shown below. The four new focal areas developed in the 2017 study will be discussed: "Digital transformation of metrological services", "Metrology in the analysis of large amounts of data", "Metrology of communication systems for digitalization" and "Metrology for simulations and virtual measuring instruments".

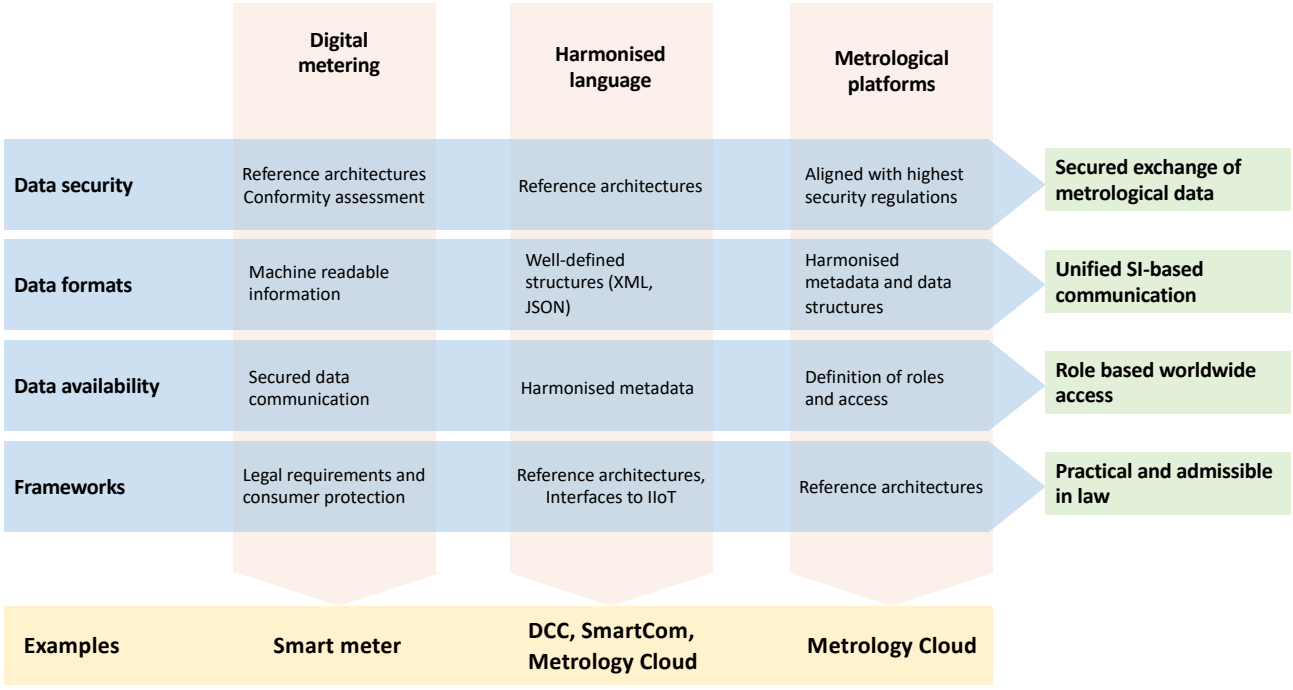


Figure 1 Requirements matrix for digital processes in the quality infrastructure.

Digital transformation of metrological services

Together with several European partners, PTB started the ***European Metrology Cloud*** (EMC)[2] project in June 2018. The first phase of the project is designed for three years and will develop demonstrators for a "digital quality infrastructure" for legal metrology, digitally map regulated processes and develop architectural proposals for measuring instruments that interact with this infrastructure. This project is closely interlinked with the EU-funded EMPIR project 17IND02 called "Communication and validation of smart data in IoT networks" (**SmartCom**[3]), which is also designed for three years. Within the SmartCom project, the foundations for the *digital calibration certificate* and the uniform SI-based Internet of Things (IoT) communication of metrological data are being promoted, along with the online validation of algorithms and the development of metrological requirements for communication in the IoT. An essential part of the cooperation of both projects – EMC and SmartCom – is the integration of the DCC into the *Metrology Cloud*. The corresponding solutions will be implemented in a joint research project starting at the beginning of 2019.

Towards the end of the EMC and SmartCom projects, practically usable, prototype-like infrastructures and reference architectures should be available. With the help of practical examples of applications, these projects will specifically pave the way for their rapid deployment in real applications. Particularly in the field of industrial metrology, the lower degree of regulation means that the solutions developed in SmartCom can be expected to be used quickly in practice.

One of the central digitalization projects for Germany as a business location is the introduction of ***smart meter gateways*** (SMGW) in the course of digitizing the energy revolution. By law, PTB is one of the pillars supporting SMGW design, and it ensures measurement accuracy as well as confidence in measured values and measuring instruments. The first *smart meter gateways* have already been certified by PTB with regard to their metrological characteristics. The central element of the SMGW is the ability to communicate measurement data and access information about connected measuring instruments via the Internet. In the EMC in particular, communicating with intelligent measuring systems via SMGW is therefore also aimed at. To implement the EMC in practice, PTB is represented in the relevant committees on intelligent measurement systems led by the BMWi and the German Federal Office for Information Security as well as being closely networked with the DKE and the national and European trade associations active in the respective field. The implementation and further development of the EMC will also be

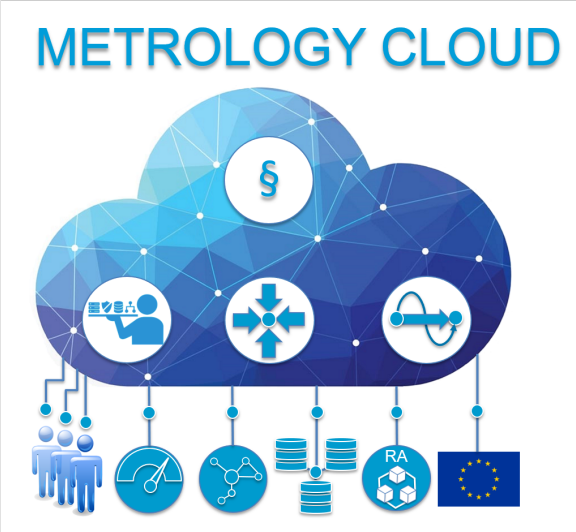


Figure 2 The European Metrology Cloud should provide a digital quality infrastructure for the highly regulated area of legal metrology in order to streamline processes through digitalization, provide a central point of contact and pave the way for data-based services.

[2] Details at https://digital.ptb.de/MetrologyCloud

[3] Details at https://www.ptb.de/empir2018/smartcom/home

supported by a junior research group entitled “Secure and trustworthy network-connected systems”, which started work in April 2018 in cooperation with TU Berlin. By embedding this work in Berlin's "Einstein Center Digital Future", it has been integrated into the cutting-edge developments of Berlin's universities and other research institutions from the very beginning.

Since June 2018, general reference architectures have already been designed for the *Metrology Cloud* for measuring instruments connected to the Internet in legal metrology at the highest risk level – in each case for embedded systems and cloud computing structures. These form the basis for prototypical, **instrument-specific measuring instrument developments** in the project. The "digital representation" of the measuring instrument in the *Metrology Cloud* forms the communicative core for all stakeholders. A first demonstrator was presented to the project consortium at the start of the project. It fundamentally demonstrated the processes selected in the project for digital transformation together with a reference architecture for embedded systems. ***Distributed ledger technology*** (DLT) or blockchain and PKI-based processes are used to guarantee trustworthiness and security in the *Metrology Cloud* for the digital mapping of regulated processes in legal metrology and the associated data exchange between stakeholders. Corresponding proof-of-concept implementations of the concepts developed and agreed with the stakeholders are expected by mid-2019. PTB's experience in defining requirements for intelligent measurement systems together with the BSI is incorporated here. The EMC concept study and the demonstrators will lead to exchanges and consultations, along with the coordination and refinement of digitalization. This will take place with the state calibration authorities and representatives of the manufacturers' associations both nationally and at the European level.

As the *European Metrology Cloud* project progresses, the way legal metrology works will change significantly. The *Metrology Cloud* is widening the dialogue of all stakeholders on how existing regulated processes can be streamlined through digital technologies. This wider dialogue also covers how these processes can be digitally transformed in a trustworthy and secure way so that they become end-to-end digital procedures. In this way, all the groups involved are to be found in the joint solution. This will guarantee market and technology acceptance and thus help to reduce obstacles to innovation.

The currently issued "analogue" calibration certificate represents a core competency in the calibration hierarchy as well as in quality management and accreditation.

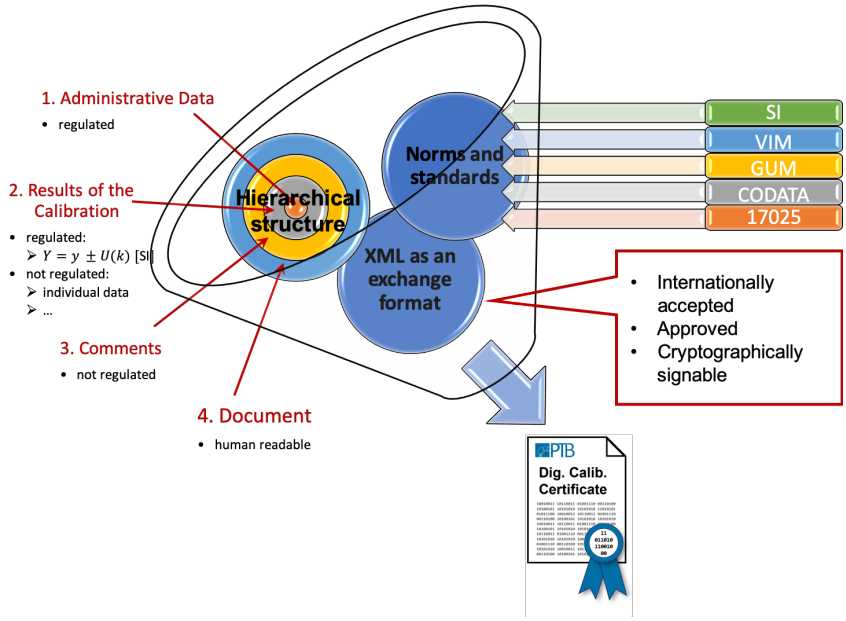


Figure 3 The basic concept of the digital calibration certificate (DCC), which is based on the implementation of existing norms and standards in metrology, a hierarchical structure and the use of an XML schema.

However, the use of the information contained in it is usually only possible manually, because it is restricted to paper. Digitally supported manufacturing and quality monitoring processes are enabled by the digital, human- and machine-readable format of the **digital calibration certificate**. In addition, this multiplies the amount of information that can be made directly available.

An initial XML schema for the DCC was already available at the end of 2017. This first draft was further developed within the framework of a broad exchange process within PTB as well as in discussions with the DAkkS, accredited DKD calibration laboratories and industry. PTB's silicon spheres are currently being supplied together with a DCC and a **digital twin** (*DT).*

By the end of 2018, an example of a complete chain of digital calibration certificates from PTB to industry had been designed and was available for further practical tests. The current version of the XML schema now maps the new DIN EN ISO/IEC 17025 covering the administrative data of a calibration. The part for the calibration results is also ready for use for the real numbers. Thus, in principle, a large number of previous calibrations can also be displayed in the DCC. The next challenge is to specify the measurement results with complex numbers that are required, for example, in the high-frequency range. At the same time, together with calibration laboratories of PTB and other partners, the further adaptation of the DCC to the individual calibration requirements will be implemented. One result of this work will be the creation of a collection of *good practices* for users of the DCC. A decisive role in the design and implementation of the XML schema will be played by PTB's participation in numerous committees, in particular in the standardization working group of Germany's "Plattform Industrie 4.0". Within the framework of a national workshop on the DCC at the beginning of June 2019, the digital calibration certificate will be made available to a broad public. The aim of the workshop is to set the course for the coordinated further development of the DCC. This will be followed in mid-2020 by an international workshop that will initiate the worldwide roll-out of DCCs. At the same time, PTB has already intensively started international cooperation on digital calibration certificates in order to coordinate their essential requirements. Within the SmartCom research project, there are discussions on the DCC with other metrology institutes, also outside Europe. At the European level, PTB initiated the EURAMET project entitled "TC-IM 1448 - Development of digital calibration certificates" in order to intensify exchanges with European partners. In addition, there are concrete bilateral plans with ROSSTANDART within the framework of the cooperation agreements with PTB.

At the end of 2018, PTB, together with the Fraunhofer Heinrich Hertz Institute and a number of other partners from research and industry, started "**GEMIMEG**", a BMWi-funded preliminary project, in which, among other things, the use of the DCC as a means of secure identity management in industry 4.0 will be examined. Additionally, 5G measurement technology and camera-based measurement in an industrial environment will also be discussed. The project started at the end of 2018 and has a duration of 6 months. It aims to identify essential requirements and research needs for "Safe and robust calibrated measurement systems for digital transformation" in user workshops and to develop a proposal for a lighthouse project. The technologies developed are also to be used in a digitally upgraded "Wind Energy Competence Centre", thus enabling a first test field in real operation in the near future.

PTB has furthermore established a new focal point for research called "Heterogeneous Sensor Networks", which is also based on an EU project called "Metrology for the factory of the future" (Met4FoF). From the beginning, the Met4FoF project has worked in close coordination with the SmartCom project mentioned above in order to interlink the extraction of metrological information (Met4FoF) with its communication (SmartCom). The *metrology-by-design* concept with the SI-based communications of metrological data as in SmartCom is thus linked with "smart traceability" from Met4FoF as a concept for an intelligent measuring instrument which can deliver traceable measurement data, including uncertainty data, in real time.

Together with the integration of SmartCom and the *Metrology Cloud* project, this results in a concept for metrology on the Internet of Things that is graduated according to the regulatory framework conditions, see figure 4. With this concept, PTB covers almost all application areas from highly regulated measuring instruments to digital sensors in the networked production of the future.

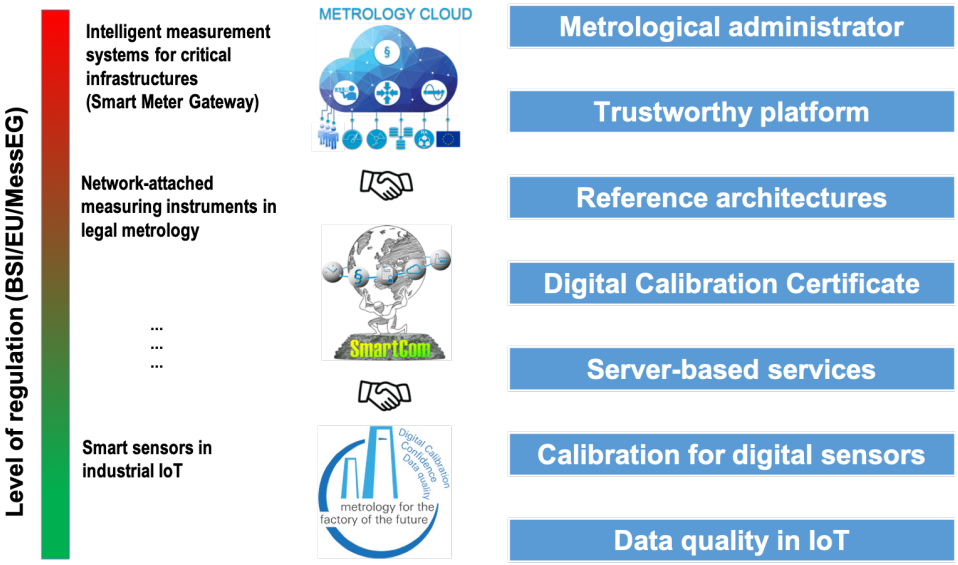


Figure 4 Graduated concept of PTB for metrology in the Internet of Things.

To be able to offer its customers digital, web-based platforms for order processing in the field of conformity assessment and calibration in the near future, PTB founded a project group called the "**Digital Customer Platform"** at the beginning of 2018. This project group is expected to pilot a software solution together with the *Information Technology Centre Bund* in the near future. The necessary administrative preparations are currently underway. The customer platform will contain the web-based submission of orders and customer contact, as well as a ticket system and the provision of further information on order processing. For this purpose, the customer platform is to be linked to the electronic file (e-file) of PTB from the very beginning. At the end of 2015, PTB established the E-files project group to implement electronic file management. PTB's e-files are using the eGov-Suite software of the Fabasoft company, which is also used in many federal authorities. PTB has been cooperating with the Robert Koch Institute (RKI) for some time in this regard. A reference solution entitled FAKT (a subaspect of the eGov suite) was created on the functionalities of the RKI solution. PTB's solution was implemented on the basis of this reference solution. The RKI will update its system in 2019 on the basis of FAKT. Other departmental research institutes are also planning to implement their e-file solutions based on FAKT. In the second half of 2018, the **e-file** started pilot operations in the areas of EU projects and procurement. A conformity assessment will follow at the beginning of 2019. In the course of the pilot phase, questions regarding the use of digital signatures will also be evaluated in accordance with the eIDAS Regulation, as well as in collaboration with external partners. The start of effective operation is expected on 1 June 2020. Comprehensive training documents are already being prepared for this. The roll-out will be accompanied by a team of experts in the field of **metadata and thesauri** in order, on the one hand, to optimize the search functions in the e-file and, on the other hand, to promote the PTB-wide consistent handling of keywords, metadata and technical terms in digital platforms. With the networking of heterogeneous data in the course of digital transformation, reliable metadata will play a decisive role in the reusability of data.

This aspect also plays a major role in PTB's **research data management,** which represents another important component of PTB's digital strategy. For this purpose, PTB already founded a cross-sectoral project group in mid-2017 and built up the personnel in this area. At the end of 2017, a comprehensive concept study[4] on the topic was completed, which now forms the basis for the development and implementation of a PTB concept. As an initial step, a web-based tool for the development and administration of data management plans was developed to support PTB researchers in the organization of third-party-funded projects. At the same time, the concrete needs and workflows of the departments were recorded to enable the simplest and most efficiently possible recording, archiving and provision of relevant research data. The EU FAIR[5] principles will be followed from the outset, ensuring that the data is: findable, accessible, interoperable and reusable. PTB will also actively participate in the development of uniform standards for the description and notation of numerical factual data. This includes the development of a modular metadata schema and the corresponding controlled vocabularies, which will be multilingual and provided with *persistent identifiers right from the start.* PTB will

[4] Details can be found at https://digital.ptb.de

[5] Details can be found at https://go-fair.org

advance the process by submitting a prototype and it is striving for a timely cooperation with the technical communities and scientific committees on an international level. To this end, PTB has already initiated a EURAMET project entitled “TC-IM 1449, Research data management and the European Open Science Cloud” at the European level in order to promote the exchange of *good practices* and to support a harmonized approach to research data management.

Metrology in the analysis of large amounts of data

Trust in digital innovation is only possible through trust in the data and algorithms used. Due to the large number of sensors available and their increasing use in sensor networks, the broad application of imaging processes in industry and medicine as well as the increasing use of simulations, the requirements for quality assurance in novel digital procedures are growing rapidly. For example, specifications for measuring systems in industrial applications for the traceable calibration of radiation bodies are currently being discussed in standardization committees. These calibrations of measuring systems result in data rates of about 3.5 TB within 90 minutes. The collection and processing of such amounts of data are not a technical challenge in principle. However, the existing established and internationally harmonized methods and procedures for the evaluation of measurement data and the determination of measurement uncertainties are not designed for this purpose. In cooperation with MATHMET, The European Centre for Mathematics and Statistics in Metrology, PTB is developing core competences and applications for third-party funding with a focus on high-dimensional problems and **machine learning**, see Figure 5. The projects are supported by a professorship of "Uncertainty and Machine Learning" currently in preparation in cooperation with TU Berlin. The projects in the field of machine learning and high-dimensional data analysis will be technologically supported by a central IT group focusing on the requirements of scientific computing. Among other things, this group operates a central PTB cluster for high-performance computing, which is continuously being further developed.

Trust in algorithms is an absolute prerequisite for their sustainable and reliable application, especially in the field of medicine. This applies, in particular, to the processes from the field of machine learning, which will be increasingly used in the future and which also include *deep learning* and *artificial intelligence* (AI). In the future, the task of metrology institutes and regulatory bodies will be to provide reference methods and reference data. For this purpose, PTB will coordinate an EMPIR project from mid-2019, in which the use of reference data sets for the evaluation of algorithms on electrocardiograms (ECGs) will be specifically investigated.

In addition, PTB is intensively involved in the field of machine learning in several research and industrial projects. The focus is always on ensuring reliability and trust in the results of the algorithms by consistently incorporating measurement uncertainties and data quality. Current fields of application at PTB are classification procedures in the field of battery research and medical imaging. PTB is extensively linked with the Berlin university landscape and is actively involved in several cooperation projects. For example, PTB is an associated partner in the Math+ excellence cluster of Berlin universities, which was approved in 2018. Here it will above all accompany the practical suitability of mathematical methods for industry-related applications.

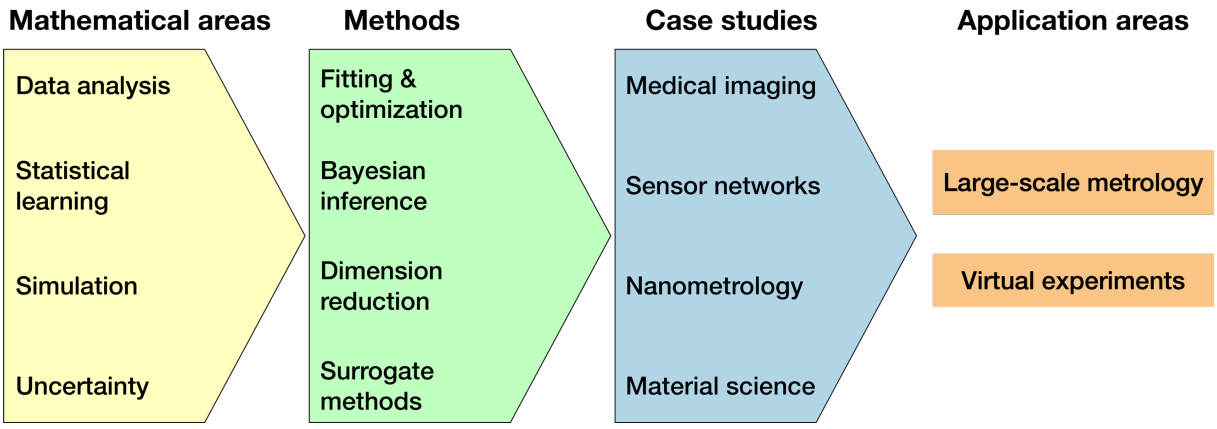


Figure 5 Concept of developments in the field of mathematical modelling and data analysis.

Metrology of communication systems for digitalization

The availability of reliable, efficient and flexible communication channels is a frequently cited prerequisite for the success of digital transformation. The current global focus is on building a 5G infrastructure. Confidence in the reliability of innovative communication solutions and their sustainable development is only possible if their characteristics can be measured. Validated, traceable calibration and measuring equipment is necessary, in particular, for the verifiability of future legal requirements, but also for securing market access for the corresponding measurement technology.

To this end, PTB started the area designated "Spectrum analysis of nonlinear systems" as part of its trainee program at the beginning of 2018. In parallel, PTB, as part of a DFG research group, will submit an application on "Metrology for Terahertz-Communications", which deals with antenna and transmission channel measurement technology in the mm and THz wave range. In addition, PTB has already held initial discussions with the Bundesnetzagentur (Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway - BNetzA) for the traceability of the broadband measurements offered by the BNetzA. The possibility of setting up a metrologically validated test track in order to evaluate the methods used is currently being discussed here. For this purpose, an arbitrary waveform generator and a real-time oscilloscope will be procured as part of the investment in the largest equipment, with which any high-bit-rate digital data streams can be generated and displayed before and after transmission through the high-frequency channel. In mid-2018, PTB also started measurements on systems for **5G technology.** In the future course of this work, smart and multiple-input-multiple-output (MIMO) antenna systems up to the mm-wave range will be investigated. The aim is to expand these projects into a broad research project called "Metrology for 5G and beyond". Cooperation talks are already underway with the *Zentralverband Elektrotechnik- und Elektronikindustrie e.V.* (ZVEI), various groups in the Information Technology Society of the VDE Association for Electrical, Electronic and Information Technologies in the field of high-frequency technology, the Fraunhofer HHI and other bodies. In addition, very good contacts exist with the manufacturers of high-frequency measuring instruments, with which base stations and terminals of the new mobile radio standards are examined for interoperability and compliance with the specifications in development and production.
Since the end of 2018, PTB has also been actively involved in the preparations of a 5G region in the Wolfsburg-Braunschweig area.

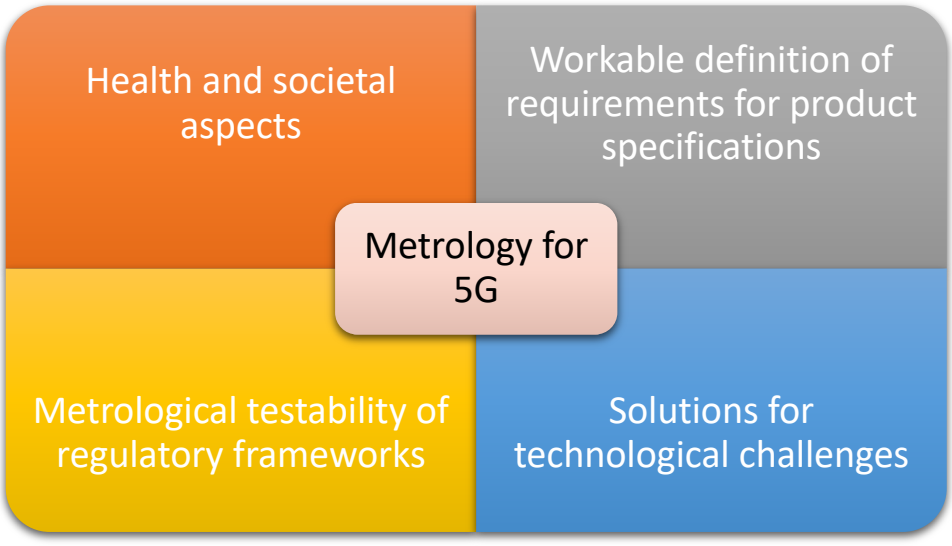


Figure 6 Aspects and requirements of the metrological infrastructure for 5G.

Metrology for simulations and virtual measuring instruments

In the course of digitalization, the importance of simulations and *in-silico experiments* is increasing rapidly. In many areas, so-called "virtual measurements", such as simulations based on physical-mathematical modelling and statistical methods, are now in everyday use. For example, some companies use virtual images of components and simulations of the design process for planning and quality assurance. In other areas, simulations serve to gain a better understanding of the real experiment, to plan new experiments or to evaluate existing experiments. Simulations are also increasingly being used as an essential part of measurement, usually as part of an inverse problem.
In the context of this development, the task of metrology is to secure confidence in simulation results if they are to be used in the same way as real measurements. Concrete existing examples at PTB include the tilted-wave interferometer (TWI) from Mahr or the virtual coordinate measuring machine (VCMM) from PTB.

In a national workshop on "**Metrology for Virtual Measuring Instruments**" organized by PTB in March 2018, the following overarching questions and cross-sectional tasks were identified for these and other application examples:

1) How do you ensure trust in simulation results?
2) How can virtual and real measurements be compared?
3) What standards are required for interfaces, metadata and data formats?
4) How can virtual experiments for complex measurement systems with large amounts of data be handled using machine learning methods?

PTB's treatment of these issues requires continuous and intensive interdisciplinary cooperation. In addition, the visibility of PTB's expertise in this field is to be increased to further improve standardization and cooperation with external partners. For this reason, PTB has established the **VirtMess Competence Center** focusing on "Metrology for Virtual Measuring Instruments", in which PTB's existing expertise is gathered, and interdisciplinary exchanges are continuously promoted. The Competence Center will also further strengthen exchanges and cooperation with external partners in this area. This will be accomplished by jointly representing those involved externally and by organizing regular workshops. The existing excellent competence of PTB's departments in the field of virtual measurements and simulations is thus being sustainably strengthened and is becoming more widely visible.
Among other things, the existing virtual PTB measuring instruments for tactile coordinate measurements (VCMM) and optical measurement technology (SimOptDevice) will be included.

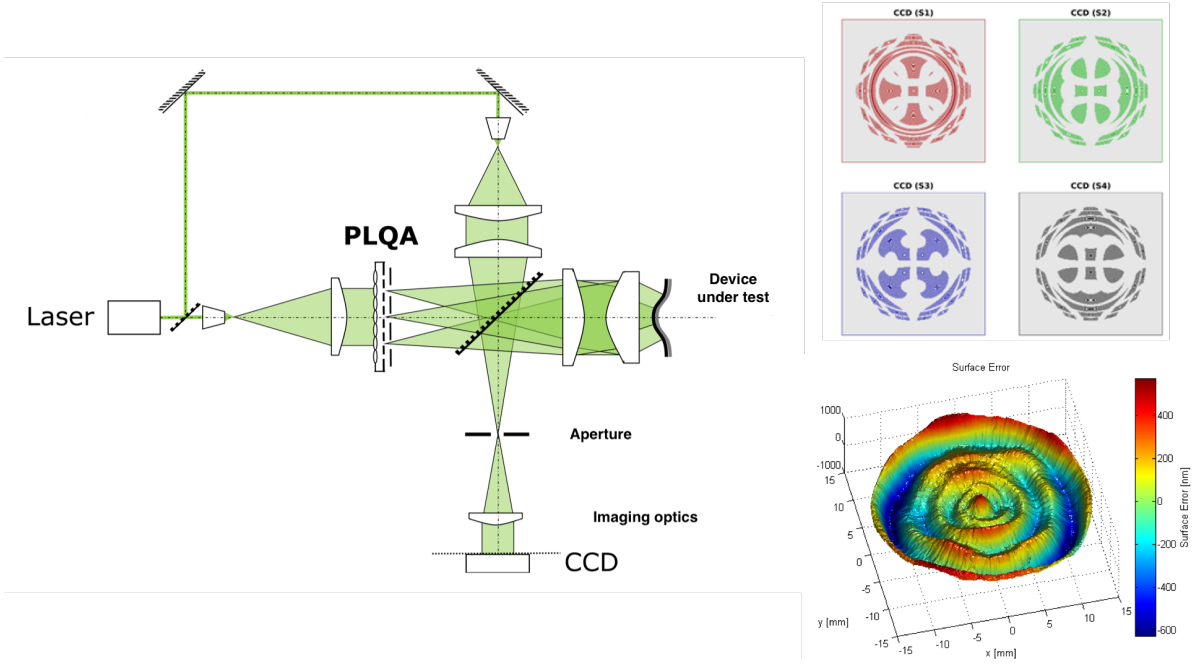


Figure 7 The tilted-wave interferometer (TWI) as an example of an integration of real and virtual measurement.

These instruments reflect the great competence of PTB in the field of physical-mathematical simulation methods and are continuously being further developed, primarily driven by third-party-funded projects. Among other things, the development of a concept for a test field for the use of VCMM in 3D coordinate measurement is currently underway, while an extension for the consideration of diffraction effects is being prepared for SimOptDevice. In the course of the preparations for the Competence Center, a large number of possible interdisciplinary cooperation projects have already been identified and elaborated. In addition to the development of metrological digital twins and their linkage with the digital calibration certificate, new mathematical-physical simulation methods under the consideration of measurement uncertainties also play a role.

Further challenges and outlook

The work and projects taken up since the Digitalization Study in 2017 form the basis for the future design of PTB's digitalization strategy. In many cases, these projects have laid the foundation for further developments and are creating the necessary conditions for comprehensive digitalization.

Thus, in the future PTB will also intensively deal with methods of AI in the priority area focusing on the "Analysis of large amounts of data", based on developments in the field of machine learning. Metrology forms the basis for business and industry. Today's global economic life would not be possible without the reliable transfer of units and the setting of global standards. Classical metrology achieves these goals by providing high-precision measurement methods, reference data and validated evaluation methods. However, this portfolio will no longer do justice to future developments as classical metrology is increasingly influenced by AI. Metrology is already increasingly dominated by software and algorithms for analyzing the measurement data obtained, and AI methods are already being used in some areas. Ensuring the reliability of metrology in the future will require a massive transformation of tasks in metrology today. Mathematical and statistical methods will play an essential role in this transformation. Uniform data formats of the measurement data and reliable communication protocols will also be indispensable so that AI can use the measurement data without deviating from the desired course and without misinterpretations. Mastering these developments successfully is a great challenge for metrology. While AI enables completely new possibilities, e.g. in the control and optimization of large, networked systems, risks must also be eliminated, especially in applications in safety-relevant areas (e.g. autonomous driving). While classical algorithms can be verified mathematically, self-learning algorithms cannot be verified in the same way. This requires new, reliable, recognized and standardized measurement methods. Metrology, with its expertise in the field of registration and legal metrology, its broad research potential, and not least its growing know-how in mathematics and AI, plays a central role here.

Reference data and reference methods also play a decisive role in the reliable use of AI methods in the field of biochemistry and personalized medicine. To this end, PTB will be involved in a national innovation area called "BioDigit" starting in 2019. BioDigit, with its goal of "triggering sustainable bioeconomy", aims to develop innovative platforms for resource and energy-efficient research, as well as the development and implementation of bio-based products and processes. This is founded on knowledge-based methods, comprehensive digitalization, education, technology transfer and effectiveness studies. With the help of reference methods and reference measurements, PTB wants to contribute to a digital workflow that extends from giving a diagnosis to individual therapy.

Data-driven research projects will also emerge in the future. In these cases, the technical expertise is not used to develop new experiments. Instead, existing data may be re-evaluated and correlated by other people's experiments in order to answer specific questions. This is a completely new approach that is only made possible by open science and open data. PTB actively supports this process and has committed itself, among other things, to the expansion of open research data. This includes comprehensive research data management with the corresponding organizational and technological bases. This process is accompanied by a broad-based project group and internationally networked strategy development. This also includes the creation of uniform standards for the indication of measurands and units of measurement in the description of numerical factual data. With internationally agreed documents, such as the *Guide to the Expression of Uncertainty in Measurement* (GUM) or the *Vocabulary in Metrology* (VIM), documented vocabularies are already available that uniformly present the basic terminology of metrology. In the course of digitalization, however, further specific vocabularies are required, for instance for finding information through algorithms. Examples of this are vocabularies and standardized term lists with *persistent identifiers* (PID) which can help to create metadata that is machine-readable and accessible worldwide in a language-neutral manner. PTB is meeting this challenge concretely by creating metadata schemas and vocabularies that enable a clear, complete and platform-independent information transfer for science and industry, while at the same time maintaining the necessary flexibility for future development. In the area of calibration data, the DCC is a concrete example of the implementation of these goals. Similar approaches are also being investigated in sensor-software communication and in the feeding of metadata into a data portal as well as in other areas.

In the course of the digitalization of industry, the linking of different data sources is also moving into focus in the development of new processes and business models. PTB's planned Photovoltaic (PV) Competence Center will focus on the investigation, development and application of spectrally and

angularly resolved monitoring concepts and measurement technology to improve measurement technology for the performance testing of solar parks. The received online data as well as the historical data should be made available online as open data, so that other groups can use this data, e.g. as high-precision support points for satellite evaluations. To this end, the design of the PV Competence Center will be closely linked to the development of the digital calibration certificate and research data management from the outset.

The linking and networking of sensor data and information play a decisive role, especially when sensor networks are used. Such networks represent a challenge for metrology in many respects. Sensor networks, for example, have to be treated like individual measuring instruments and novel measured variables have to be considered. The Met4FoF EMPIR project is already raising the question of the metrological consideration of the frequently used *condition monitoring*. The essential question is the exact definition of the actual measurand. In addition, there is the flexible use of a sensor network, often through the use of edge and fog computing. Flexible and robust modelling and method tools are required for metrological observations and the evaluation of measurement data. As part of a BMBF-funded project, PTB, together with Fraunhofer FOKUS and other partners, will implement the further development and implementation of existing methods of sensor modelling and the analysis of sensor networks for concrete industrial test fields at the beginning of 2019. This project combines the work of Met4FoF with PTB's expertise in the field of mathematical modelling data analysis in order to realize application-oriented metrological approaches in fully networked production.

Likewise, the increasingly camera-based measurement methods, for example in production engineering and quality control, pose enormous challenges to the underlying metrological infrastructure. Optical measurement methods are increasingly preferred to tactile measurement methods because of their shorter measurement times and area-based object detection. The latter still represents the recognized reference in many areas, but optical and camera-based methods are increasingly catching up in terms of accuracy and reliability. In addition, many camera-based measurement methods are opening up new possibilities for the direct application of AI methods, for example, for automated quality control through pattern recognition. Within the framework of "GEMIMEG", a BMWi-funded project, PTB and its project partners will carry out a comprehensive assessment of the research requirements in this area with the help of user workshops.

The security of information and data is an essential aspect of all PTB activities and projects. In addition to *metrology by design* as the principle of considering metrological aspects throughout the entire product life cycle, *security by design* and *privacy by design* play a central role at PTB. These apply to internal digitalization processes as well as to research and development projects. For example, the identification of protection requirements and risk analyses along with the derivation of corresponding measures for the PTB work processes are self-evident tasks when introducing digital tools and processes. New challenges are arising from the increasing networking of PTB infrastructures with external partners and service providers. Thus, the use of commercial cloud services by PTB researchers poses organizational and technical challenges. In the future, meeting these challenges will not only require interdisciplinary cooperation, but also continuous and sustainable awareness and responsibility building. PTB thus also consistently takes up recommendations such as those of the German Rectors' Conference (HRK)[6]. Information and data security also play an important role in the developments for the digital transformation of processes in legal metrology. Besides the compliance with strict regulatory and legal requirements, the protection of data and information is a prerequisite for acceptance by stakeholders in the quality infrastructure. PTB is developing methods based on *distributed ledger technologies* and blockchain technologies in order to digitally represent the processes between the partners in legal metrology. In future, these will also be intensively evaluated in other areas, such as the mutual recognition of calibration certificates.

In its activities and projects in digitalization, PTB has relied from the very beginning on intensive and comprehensive international cooperation. Thus, PTB is currently coordinating the establishment of a European network for the digitalization of metrological services. As a first step, EURAMET projects were initiated in the Technical Committee on "Interdisciplinary Metrology". In the first half of 2019, this will lay the foundations for the establishment of a

[6] https://www.hrk.de/positionen/beschluss/detail/informationssicherheit-als-strategische-aufgabe-der-hochschulleitung/ (November 2018)

EURAMET network (EMN) by organizing joint workshops. In addition, PTB and Rosstandart are currently drawing up a cooperation agreement for 2019-2021, which will include several joint digitalization projects, which will be accompanied by a joint working group named "M4D".
Besides these activities, PTB's International Cooperation Department is pushing ahead with the digitalization of the quality infrastructure worldwide. To this end, a comprehensive digitalization strategy is currently being developed, which is also oriented to the strategy of the Federal Ministry for Economic Cooperation and Development (BMZ). An essential element of this specialized PTB strategy is the implementation of a *digital by default* approach in all projects. This means that in all cooperation and development projects in this area, the digital transformation is being taken into account from the very beginning. There will furthermore be a number of very specific digitalization projects with partner countries.

In a similar way, PTB is engaged with many international and national partners in close exchanges and in a large number of cooperation projects. The common core objective is to ensure trust and reliability in international metrology in the digital age.

Contact us
Physikalisch-Technische Bundesanstalt
Bundesallee 100
38116 Braunschweig

Dr. Sascha Eichstädt
Presidential Staff Office
Phone: 0531 592-2008
E-mail: sascha.eichstaedt@ptb.de
https://digital.ptb.de