Content

PTB Digitalization Strategy

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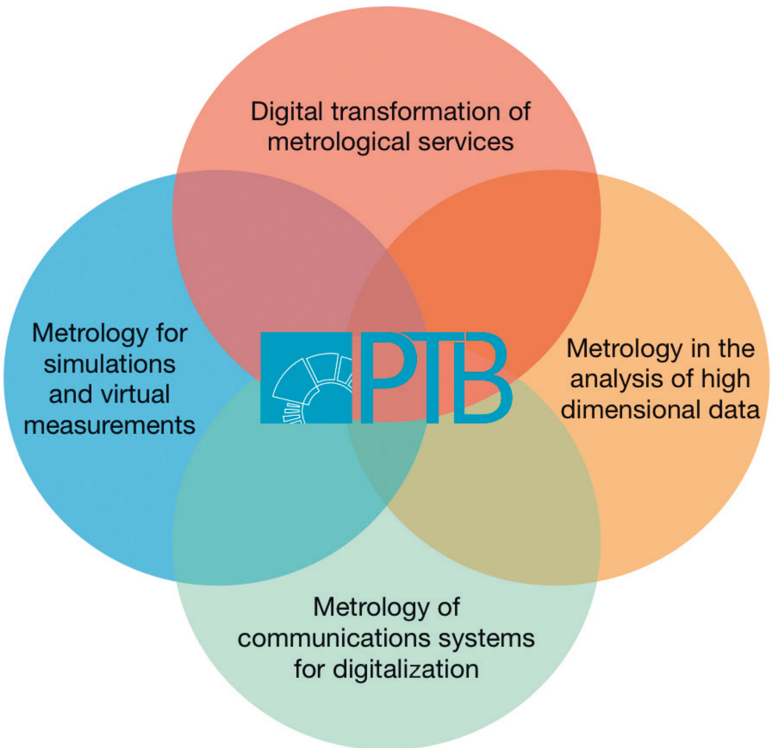
PTB Digitalization Strategy

Editor Sascha Eichstädt[1]

"In the course of economic digitalization (the virtual utilization of resources, "Industrie 4.0", the Internet of Things, etc.), PTB should play a key role in metrology for measurands linked to the Internet and to digitalization, especially in the fields of metrology, standardization and calibration, and for reference quantities in information technologies."

Report of the German Council of Science and Humanities, 2017

1 Dr. Sascha Eichstädt, Working Group "Coordination Digitalization", e-mail: sascha.eichstaedt@ptb.de



"We are willing to develop the quality infrastructure (standardization, accreditation and conformity assessment, metrology, technical product safety and market surveillance) further, since it is, as an integral part of the technological revival in Germany, the brand essence of "Made in Germany". For this purpose, the Physikalisch-Technische Bundesanstalt (PTB) and the BAM Federal Institute for Materials Research and Testing will be further strengthened to be able to hold their ground in global competition with respect to their scientific and technical services."

Key Considerations of Our Innovation Policy, 2017, Federal Ministry for Economic Affairs and Energy (BMWi)

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Executive Summary

Innovation and confidence in an efficient quality infrastructure are the basis of a stable and successful economy and society. The main pillar of an efficient quality infrastructure is the ability to obtain valid data based on high-precision measurements – which is the definition of metrology. The economy and society of the 21st century are in the process of a comprehensive digital transformation: the course is being set to firmly establish the basis for success in the digital arena which is the cornerstone for the development of the economy and society in the digital age. Digitalization is a process which has been developing over several years. Especially the exponential development of computing and storage capacities as well as the increasing speed of data exchange and the cost-effective availability of versatile sensors which can be used flexibly have opened up fully new possibilities when it comes to creating networks between objects and to the exploitation of the data and information stored.

The role of metrology for the digitalization of the economy and society

Measurement values, data, algorithms, mathematical and statistical procedures as well as communication and security architectures represent the basis of digital expansion and transformation. Thus, the ***quality infrastructure (QI)*** – the triad consisting of metrology, standardization and accreditation – and ***legal metrology*** (with conformity assessment, the verification system and market surveillance) will have to be made stronger as they are a prerequisite of the successful digital transformation into an interconnected economy, industry and society. The Physikalisch-Technische Bundesanstalt (PTB) as Germany's national metrology institute has a key role involving various competencies and capabilities. Besides developing and validating measurement procedures ensuring highest precision as well as algorithms and data analysis methods, these tasks also encompass the validation of measurement data by tracing them to the International System of Units (SI). This represents part of the basis of accreditation, of legal metrology within the scope of the Measures and Verification Act (MessEG) and of the Measures and Verification Ordinance (MessEV), of the joint development of national and international standards and of advising the verification authorities within the scope of market surveillance. Against this background, PTB is a main pillar of the national quality infrastructure and of legal metrology, and has set itself the objective of acting as a reliable partner to industry and society within the scope of the digital transformation. The core of this transformation consists, in particular, of the metrology services offered by PTB in the legally controlled area along with the QI services offered as well as the German sensor and measuring instrument industries which are often organized by SMEs.

At the international level, metrology for digitalization is being intensively pushed forwards by means of research programmes and by setting up new capacity groups. For instance, several large groups at NIST (USA), together with public institutions and private economic partners, have been elaborating highly regarded regulatory and administrative foundations for the fields of cloud computing, big data, IT security and machine learning, and have been building the metrological basis for the development of high-performance communication channels (5G) for a long time. NPL (UK) has also been strongly developing the data science field as well as 5G networks and digitalization-related research. Similar activities are currently observed all over the world. PTB will develop its capacities correspondingly, so that it will live up to its role as one of the world's leading metrology institutes and lead the digital transformation and expansion of metrology.

New identified focuses

An exhaustive study based on an intensive internal analysis of PTB's core capacities, on requirements that clients have already expressed and on the results of a visit of PTB to NIST as well as on several experts' discussions has identified new fundamental tasks for PTB in order to promote digital transformation. The following new focal points have been determined:

A. ***The digital transformation of metrological services***

The centre of these tasks is the digital upgrading of the quality infrastructure and of legal metrology, among other things by developing reference architectures, validated statistical procedures for predictive maintenance, an infrastructure for digital calibration certificates and, last but not least, by setting up a "metrology cloud" in the form of a digital quality infrastructure for the harmonization and development of conformity assessment and market surveillance.

B. ***Metrology in the analysis of large quantities of data***

The objective consists in developing metrological analytical methods for large quantities of data and in assessing machine learning methods for big data with an emphasis on existing and increasingly relevant metrological applications for industry in which large quantities of data have to be processed and where high-dimensional information has to be derived (e.g. in imaging procedures and in photonics).

C. ***Metrology of the communication systems for digitalization***

This focus concerns the securing and metrological validation of reliable, secured and efficient communication in complex scenarios. It encompasses the traceability of complex high-frequency measurands for 5G networks, nonlinear and statistical measurands in high frequency, derived measurands in digital communication systems, and complex antenna systems.

D. ***Metrology for simulations and virtual measuring instruments***

By developing analytical methods and licence procedures for interconnected and virtualized measuring systems, the simulation of complex measuring systems (such as optical form-measuring techniques or coordinate metrology) for the planning and analysis of experiments, procedures and measurement standards for automated process control and virtual measurement processes for the automatic assessment of measured data is actively supported.

Implementation strategy

The main pillars for PTB, as a supporter of digital transformation in the economy and society, are, in the first place, interdisciplinary cross-sectoral projects:

Metrology Cloud – Establishing a trustworthy core platform for a digital quality infrastructure by coupling existing data infrastructures and databases and providing all partners with customized access for digitally upgrading legal metrology.

Digital calibration certificate – Developing a secure and standardized digital information structure for universal use in calibration, accreditation and metrology as well as digitally upgrading the whole calibration hierarchy in the quality infrastructure.

Virtual experiments and mathematics-aided metrology – Developing an interdisciplinary, virtual competence group to metrologically support the paradigm change for the use of simulations and data analysis as essential components of measurement procedures.

Moreover, the metrological research for modern high-frequency networks (5G), the expansion of the quality infrastructure to online surveillance, and the metrological support to digitalized precision production are some of the tasks that will have to be furthered in the long term in the respective departments.

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Introduction

The term "digitalization" actually designates the transformation of analogue quantities into discrete values for electronic storage and processing [1]. This term, however, is currently being used more generally to designate the conversion of the whole of society to the use of digital technologies [2] and the increasing involvement of data and machines in business processes by means of digital interfaces. This interconnection allowing the creation of local associations up to global networks also expresses the new quality of this digitalization process. Data are exchanged, analysed and visualized flexibly and automatically between man and machines. This opens up new communication capacities, new business fields for existing companies and has led to fully new industries and research fields. According to a BITKOM study [3], 65 % of German companies think that digitalization will change their existing business models.

"Perhaps the most significant business disruptions will come from a combination of the connected sensors, devices and objects (Internet of Things), coupled with new ways to analyze, action and monetize the resulting data streams."

atos study "Journey 2020"

New challenges are, however, arising since it is often not possible to transfer existing concepts, standards and approaches to the digital universe and interconnected systems [4]. For instance, in the field of metrology, sensor manufacturers are being increasingly required to supply measurement capabilities rather than only measuring instruments. As a consequence, sensors are increasingly being developed in such a way that they contain additional intelligence and integrated data processing [5]. This, in turn, represents a huge challenge for traceable calibration which is no longer manageable as an approach purely conceived for precise measurement.

The quantity of data which has to be processed due to digitalization is increasing exponentially and can only be made exploitable with a profit by means of suitable mathematical and statistical tools [6,7,8]. The first step most companies take is to visualize the deluge of data in a suitable manner. To this end, the processes that take place in a facility are, for example, represented in a "digital twin" based on sensor data. Methods of "predictive maintenance" [9] go much further by drawing conclusions as to how reliable the system can be expected to be by means of statistical analyses of the data. This can help prevent fixed testing intervals – and thus unnecessary shutdowns of the facility. Such (and other) methods of intelligent and automated realtime data analysis can contribute to significantly increasing efficiency, even in facilities that are already fully automated [10]. This is usually done using model-free data analysis procedures which are "trained" to work with large quantities of data [11], which results in new challenges when it comes to determining the quality of the results obtained. At the same time, even model-based procedures increasingly need new approaches to make established data analysis concepts implementable for this rapidly increasing quantity of data (obtained from, e.g., imaging procedures). In metrology, this challenge expresses itself more and more through the necessity of determining and disseminating measurement uncertainties for high-dimensional quantities. Due to the connection of different data sources and distributed measuring systems with each other, the requirements placed on data analysis in metrology will keep increasing.

"The term "data quality" designates the quality and reliability of data objects themselves. Whenever possible, the uncertainty of a piece of data should be quantified suitably."

Council for Scientific Information Infrastructures, 2016

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Moreover, like in all digitalized applications, the **IT protection objectives of *integrity, confidentiality and availability*** play an essential role to a different extent [12, 13]. The needs for protection thereby differ depending on the concrete requirements of the application. Also, the integrity of measuring equipment (i.e. protection against unauthorized access to measuring equipment and its calibration) plays an important role [14]. The IT protection objectives are of essential importance, especially in the legally regulated area (legal metrology) [4]. In legal metrology, ensuring integrity, confidentiality and availability are an absolute prerequisite for modern information and communication technologies (ICT) to be accepted. Furthermore, requiring the highest possible BSI (Federal Office for Information Security) standards would present manufacturers with unnecessarily high requirements and inhibit innovation and development. Here, PTB can and has to play a key role in elaborating suitable, legally flawless solutions for manufacturers, users and market surveillance.

Just as technical solutions from the non-regulated area will increasingly be applied in the field of legal metrology (e.g. cloud computing or remote maintenance), many of the solutions required for the legally regulated area will become applicable in the non-regulated area, since similar needs can be expected due to demands from users. At the same time, devices with unnecessarily high security measures will hardly make it onto the market. A similar picture can be drawn for legal metrology where manufacturers are increasingly willing to apply modern ICT. The necessary conformity assessment calls for strict rules for data communication and data processing, while providing market surveillance with technologically simple checking possibilities at the same time [15]. This balancing act will have to be mastered in order to enable the digitalization of legal metrology.

“The Federal Ministry for Economic Affairs and Energy (BMWi) expects “Industrie 4.0” to generate added values amounting to more than 30 billion euros per year. 80 % of industrial enterprises say that they will have digitalized their entire value chain by 2020 – which implies investing 40 billion euros per year according to the Industrie 4.0 study conducted by PWC”

BMWi & BMAS “Arbeiten in der digitalen Welt” – “Working in the Digital World”

The major driver of digital transformation is currently industry – which is reflected in concepts such as “Industrie 4.0”, the “Industrial Internet of Things” or “Cyber-Physical Systems” (CPS). A recent study conducted by VDMA [16] has shown that 25 % of the companies operating in the fields of mechanical engineering and plant construction are already supplying novel digital technologies such as cloud services. These companies believe that the main benefit from these technologies results from increasing automation which will eventually lead to the increased competitiveness of German industry. The required knowledge no longer solely resides in pure metrology, but rather in software development and in the analysis of complex data. Thus, plant control and monitoring are increasingly implemented via so-called apps which have to be able to include data that have not been generated by the manufacturer. This requires cross-sectoral implementation and interconnections which can only be based on appropriate and accepted standards. More generally, the trend is going towards companies relying more on collaborating with other partners from industry in order to develop bilateral agreements rather than on conventional means such as standardization. One of the reasons for this is the necessity to act quickly, which results from pressure on the international market. Hence, the study conducted by VDMA recommends that companies do not wait for exhaustive standards to be developed, but rather offer initial solutions [16]. This trend has to be countered with fast, focused, user-friendly and flexible standardization projects.

Besides mechanical engineering and IT, photonics is a key technology for Germany and Europe as places for innovation. As early as 2011, it already contributed a considerable 66 billion euros of production turnover to the EU’s economic output [17]. The upcoming transition towards integrated photonic (micro-)systems and the connection with fast and powerful digital image-processing tools make photonics a strategic technology in an increasing number of markets, in products and processes. These range from controlling (e.g. gesture control, microdisplays) to data acquisition (sensors) and data processing (computational imaging) up to production (3D printing/additive manufacturing (AM), online quality measurements, laser processing) [18]. Photonics thus acts both as a driver and as a user of digitalization. Virtual experiments and simulations, in particular, are a basic tool for planning, optimizing and analysing in the field of photonics. However, there is a significant lack of reliable standards and metrological traceability [17,18]. Based on its excellent existing capabilities and on a targeted extension of its research activities, PTB will be able to play a key role in this area.

The entire field of health is also massively influenced by the ground-breaking evolutions due to digital transformation. In biotechnologies, innovative digitalization concepts are thus helping

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to create resources and active substances in novel process, production and cooperation procedures. Their realization requires cross-sectoral and interdisciplinary cooperation projects with partners in both industry and research. Examples of such cooperation may be cross-sectoral networks in bio-economics with joint objectives and a shared IT infrastructure which aim to develop innovative platforms for resource- and energy-efficient investigations and to elaborate and implement bio-based products and processes. In this context, PTB is already in close contact with major German pharmaceutical companies.

Challenges for PTB as the cornerstone of quality infrastructure and legal metrology

For PTB, the challenge of the digitalization of the economy and of society results from its particular position in the legally regulated part of the quality infrastructure (with the triad consisting of metrology, standardization and accreditation) and legal metrology (with conformity assessment and market surveillance). PTB can and must act as a strong partner and facilitator between industry and standardization, based on its corresponding capabilities in the established fields of metrology and in the new areas of the IT, communications and data analysis landscape, in order to support, further and establish as soon as possible the quality infrastructure and legal metrology in their role as a promoter of innovation and as a guarantor for the sustainability of German quality. The report of the German Council of Science and Humanities correspondingly recommends that PTB

> *"[should] play a key role in metrology for measurands linked to the Internet and to digitalization, especially in the fields of metrology, standardization and calibration, and for reference quantities in information technologies."*
>
> **German Council of Science and Humanities, 2017**

To this end, the German **quality infrastructure** represents an effective sales argument for companies which is often accepted all over the world and which now enjoys international renown as a model of a sustainable traceability chain. Standardization, which, in technical and in part in medical areas, relies on metrology, is paving the way for the (often international) market access of SMEs and for the interoperability of business models. The quality infrastructure – and thus PTB's major task – rests on traceability (metrology), standardization and accreditation. By maintaining close cooperation with numerous partners, PTB guarantees the German economy its leading position by means of reliable and highly precise measurement capacities. For instance, PTB provides DAkkS laboratories with experts and carries out approx. 3500 calibrations per year. PTB participates in more than 400 standardization committees and its president is, at the same time, vice-president of the German standardization body, DIN. PTB plays a central role for the conformity assessment bodies by chairing the Rule Determination Committee and by managing the conformity assessment bodies (KBS). Furthermore, PTB chairs the Deutscher Kalibrierdienst (DKD) and organizes the General Assembly of the Measures and Verification System to ensure that information and experiences are exchanged.

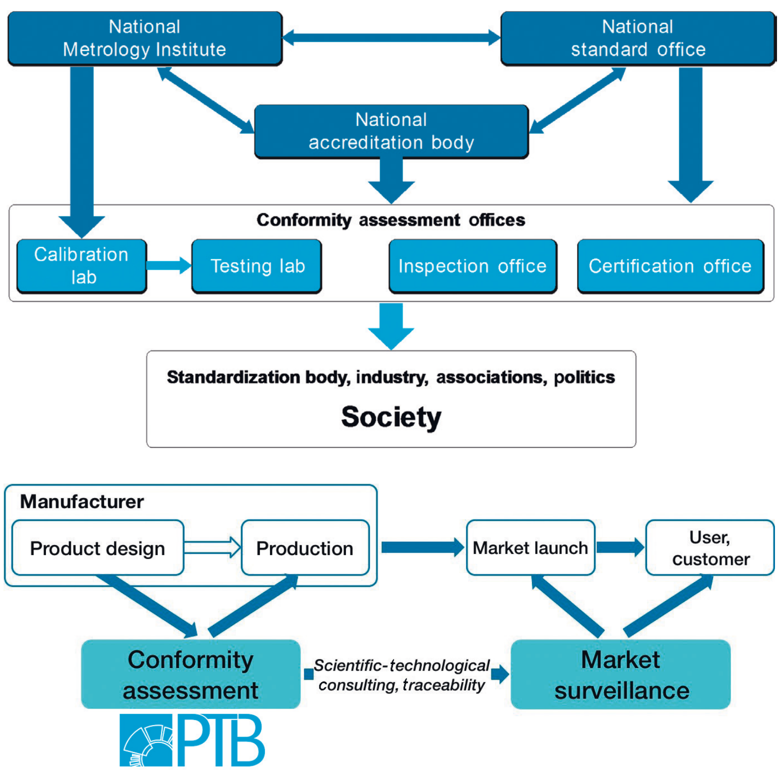

Figure 1:
PTB's role in the German quality infrastructure (top) and in legal metrology and market surveillance (bottom).

The digital transformation of products and the application of digital processes in **conformity assessment** are currently leading to a drastic increase in new challenges (e.g. for the calibration process) and require the digital transformation of the entire traceability chain. Using intelligent sensors as a product in the quality infrastructure requires suitable traceability taking both the physical properties of the transducer and the integrated digital pre-processing of the measurement data into account. At the same time, the digital transformation of the administrative processes in the traceability chain, in accreditation and conformity assessment demands appropriate standardization and a centralized, trustworthy entity for the certification of digital calibration certificates.

"Reference quantities are becoming increasingly important for the digitalized economy. Against the background of the dynamic development of cloud-based services, the demand for calibrations of digital systems is becoming increasingly urgent. [...] In this context, support to activities geared to the development of metrology for digitalization is being intensified."

German Council of Science and Humanities, 2017

Legal metrology – together with conformity assessment prior to placing products on the market as well as the verification system and market surveillance whilst in use – is the guarantor for mutual trust between clients and manufacturers. More than 170 million measuring instruments and an annual turnover amounting to approx. 150 billion euros – in Germany alone – especially in the fields of consumption meters (electricity, water, gas, fuel, etc.) and of the scales used for commercial transactions show how important legal metrology is for society and the economy [19]. At the European level, the regulatory framework is the "Measuring Instruments Directive" (MID) 2014/32/EU, which has been transposed into German national law by means of the Measures and Verification Act [20] and of the Measures and Verification Ordinance [21]. At the European level, conformity assessment (and standardization) both benefit firstly from the networks established in the form of various committees and associations. Secondly, the EU's **"New Approach"** in the field of conformity assessment has paved the way for declarations of conformity to be recognized and accepted throughout the EU and for the corresponding inspections to be limited to essential requirements [22]. This implies a certain degree of openness to new technologies and a strengthening of European standardization and of the European single market. In the legally regulated fields, the increasingly complex IT and communications technologies used in measuring instruments, however, are leading to an exponential increase in the time and effort spent on conformity assessment and to tremendous requirements for the verification system and for market surveillance. The risk that manufacturers might consider the latter as an obstacle to innovation is therefore increasing. What is urgently needed here are suitable types of reference architecture in order to accelerate the conformity assessment process and to support the verification and the market surveillance systems. Moreover, it is absolutely indispensable to establish a digital, cloud-based range of solutions with a centralized entity as a trustworthy basis for the digital transformation of the processes in legal metrology.

"PTB is experiencing strong support in its effort to initiate the setting up of reference architecture for secure cloud computing and to ensure its central coordination. [...] Cloud metrology should [...] contribute to implementing digital concepts for the coordination, concentration, simplification, harmonization and quality assurance of metrological services for all stakeholders in Europe."

German Council of Science and Humanities, 2017

Due to the rapidly progressing digital transformation, companies are faced with numerous new challenges which the vast majority of them consider as the most important challenge to maintaining their own competitiveness. From the examples of successful digital transformation quoted on the "Plattform Industrie 4.0" [23], it becomes obvious that the requirements placed on companies to implement this digital transformation lie mainly in the following fields:

- capabilities in the field of IT and software;
- modelling and virtual measurement process or "digital twins";
- real-time data storage and cloud services;
- autonomous systems;
- development and integration of apps, and
- establishing a link between the virtual and the physical world (CPS).

In the meantime, these technologies have outgrown the so-called hype phase and have entered everyday industrial use [16]. The technologies needed for disruptive developments [24] in the foreseeable future are, partially, already available in a wide range and will, according to the study

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[24], lead to further changes in the business world and in industry within the next 2 to 3 years. Companies are getting ready for these changes – and this to a large extent and at a rapid pace, according to the VDMA IMPULS study [16]. In contrast, digital transformation at PTB – and thus of large parts of the QI and of the verification authorities of the federal states – has clearly not reached such a developed state yet. Without an extensive, efficient and fast reaction, this deficit puts the quality infrastructure as a whole at risk of being considered as an obstacle to innovation – and thus of losing its significance.

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Digitalization Topics: New Tasks of PTB

The continuous exchanges between politics, the economy and research are a prerequisite for a successful digital transformation, since only joint effort will enable us to cope with the challenges of digitalization. By gathering and interconnecting all relevant partners [25], the **"Plattform Industrie 4.0"** thereby represents the core of German national initiatives. The diverse topics are addressed in groups, and the interconnections between the partners are coordinated by a central management team. In this context, the most significant area for PTB is standardization, in particular, since PTB plays a key role by participating in more than 400 committees, both at national and at international levels, and has considerable influence, as shown by the report of the German Council of Science and Humanities. During a discussion between experts of PTB and representatives of the platform, this role was definitely confirmed, and the admittance of PTB to the platform was clearly approved. Meanwhile, PTB has been represented on the mirror committee for standardization where it will be able to contribute its longstanding experience and contacts in this field. By means of targeted research activities geared to the new challenges of digitalization and of digital transformation, PTB will be able to continue to efficiently play the key role it is currently playing in this process.

The German Federal Government and the federal ministries are supporting digital transformation via a number of packages of measures and promotion measures. For example, the lack of information identified in SMEs is addressed in a targeted manner by continuously developing so-called **"Mittelstand 4.0"** competence centres and by means of various support programmes [26]. PTB could indirectly support these projects via measures such as the digital transformation of the calibration system or by supplying reference architecture, which would contribute to digital business processes being accompanied by corresponding digital interfaces with an appropriate security level in the measuring chain and in the quality infrastructure.

Testing centres provide SMEs particularly with the possibility to assess new technologies without having to bear any risk themselves and to develop solutions with competent partners. This area is therefore being intensely promoted by the Federal Ministry of Education and Research (BMBF) and by the **"Labs Networks Industrie 4.0"** (LNI4.0) association [27, 28]. PTB already distinguishes itself by its numerous cooperation projects with SMEs in which technology and know-how are transferred in the form of joint projects and licensing. By developing and offering technological solutions to deal with the challenges of digital transformation, PTB will be able to secure its position as a supporter of the German industry and economy. For this purpose, close cooperation with LNI4.0 is planned in order to use synergy effects and to increase the visibility of what PTB is offering. A first round of discussions with LNI4.0 has already taken place. The link between LNI4.0 and standardization via the **"Standardization Council 4.0"** (SC4.0) [29] and the numerous international mirror committees on which PTB is already represented are particularly important for PTB, since the technologies thus developed allow long-term support to the entire quality infrastructure. In this respect, the development of suitable testing centres at PTB benefits the German economy in two ways. In a first step, PTB, Siemens and interested partners are planning to set up a **testing field "Digital Transformation in the Quality Infrastructure"**. Moreover, existing internal activities of PTB which could, in the future, be offered as testing centres together with LNI4.0 are identified in order to support the digital transformation of the German economy in a targeted manner. For instance, it seems obvious that another testing centre of PTB in the field of virtual measuring instruments, based on the uncertainty determination specific to the measurement task for complex 3D measuring systems, would be welcome.

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In the field of biotechnologies, the Federal Ministry of Education and Research (BMBF) supports the creation of network projects with topics ranging from basic and advanced training to standardization; these are promoted within the scope of the "Nationale Forschungsstrategie BioÖkonomie 2030" programme via the "Innovationsräume Bioökonomie". On the initiative of industry, PTB will get involved in the "Digitalisierung der Biotechnologie" (Biotechnology digitalization) project application concerning the traceability of measured values, secure data transfer and standardization.

At the European level, an increasing number of cooperation projects and promotion initiatives have been developed. The European partners cooperate with each other following the principles of the EU strategy of a "Digital Single Market" [30] in which the objective is to establish unlimited digital trade, develop rules and standards that are able to keep up with technological advances, and seize measures aiming to enable the European economy and industry to exploit all opportunities provided by digitalization to the full. In addition to supporting selected research projects (e.g. within the scope of "Horizon 2020" [31, 32]), it is also planned to develop a strategy for a "European Open Science Cloud" within the scope of the "European Cloud Initiative" [33]. Whereas the GovData platform and the current legislative initiatives at the federal level are presently limited to administrative data, the "European Open Science Cloud" is explicitly to make research results available free of charge [33]. The first step will consist in disclosing research data obtained for new research projects from the Horizon 2020 programme. Since PTB is involved in numerous European projects realized within the scope of the Horizon 2020 programme, this development represents considerable challenges for PTB's research data management, and these challenges will have to be addressed promptly. This necessity has also been identified by the German Council of Science and Humanities that has recommended that urgent measures be taken. PTB has already taken initial steps in this direction.

Legal metrology

In the field of legal metrology (i.e. conformity assessment, verification system, market surveillance), digitalization has mainly manifested itself through the increasing spreading of so-called "intelligent measuring systems" (e.g. smart meters) – which is partly due to the **"digitalization of the energy transition"** – distributed measuring systems and cloud infrastructures [35, 36]. All in all, considerable effort will be required in order to further the digital transformation of the legal metrology system (and of the quality infrastructure), since the digitalization of industry depends on it in a number of areas. Thus, PTB divisions accommodating departments which are responsible for the testing of physical properties within the scope of their legal metrology tasks, have registered an increasing number of applications from industry concerning digital intelligent sensors, distributed measuring systems and cloud infrastructures. At present, the integration of modern IT and communications technologies into measuring instruments for regulated fields is still being hampered by high requirements in the approval and conformity assessment processes. Manufacturers are therefore increasingly considering the regulation and approval processes as an obstacle to innovation, and they fear these could represent a competitive drawback in the long run. PTB can support this process by **developing legally compliant reference architecture** which offers acceptable solutions with appropriate security and simple verification methods for basic technologies of new technological fields. Manufacturers using the reference architecture supplied by PTB for their measuring instruments can expect a speedy approval process and can, thus, market their innovations faster. At the same time, this reference architecture ensures compliance with the required security standards and the verifiability which is necessary for market surveillance. Especially the development of the architecture for the legally compliant division of the software of the measuring instrument into a legally relevant part and a free part allows the manufacturers to develop new, innovative solutions, regular software updates and individual client customization in the free part of the software without having to go through the approval process again.

The trend is clearly going towards measuring instruments with distributed – and for some of them even virtualized – components and towards the use of **cloud services**. This applies to an even greater extent to legal metrology. The division into units for the acquisition, processing and indicating of measured values alone provides manufacturers with various possibilities, but presents market surveillance with considerable technical obstacles. Today in dosimetry for example, mobile, web-based dosimeters are used almost without exception. Thereby, the mobile dosimeter, which is connected to a desktop computer, contacts one of the manufacturer's cloud infrastructures via the Internet. From the acquired data, the computer can generate measurement results, store them in a database, and update the instrument's software in order to adjust the calibration parameters. This approach has now become the state of the art; it is, however, compatible neither with the German calibration regulations nor with the radiation protection guidelines.

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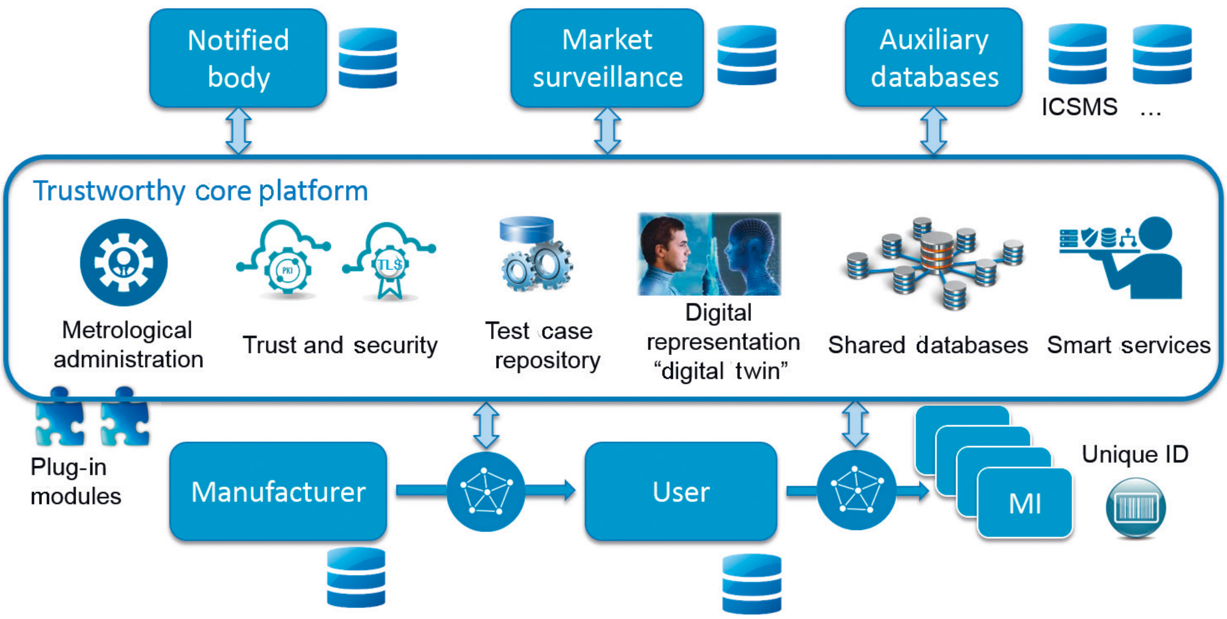
In addition, the distributed, interconnected and partly virtualized infrastructure already with 170 million measuring instruments in Germany alone in the fields of approval and market surveillance offers numerous possibilities for the use of big data solutions based on the data generated during the lifetime of the measuring instrument. These databases are currently widely distributed, not interconnected and very heterogeneous (measurement data, administrative data, service data). The digital upgrading of the legal metrology system can be achieved by establishing a digital quality infrastructure as a **"metrology cloud"**: coupling existing data infrastructures, differentiated access of all partners to the "metrology cloud" as a database and secure access place, new concepts for the coordination, concentration, simplification, harmonization and quality assurance of metrological services. Starting with a reliable basis of this digital infrastructure at PTB, it is planned to progressively develop the "metrology cloud" into a "European metrology cloud" to support the concept of a "Digital Single Market". This idea will be initiated by the application for a three-year European joint project within the scope of the EMPIR programme under the Horizon 2020 programme. This trustworthy core platform includes the digital representation of every single type approval or measuring instrument, ensure secure communication and clear identification, provides support services for market surveillance and will contribute to streamlining administrative processes. In its report, the German Council of Science and Humanities thereby emphatically supports the concept of a "European metrology cloud".

In acts and ordinances that are in direct connection with PTB's competences (e.g. concerning the type approval of cash gaming machines (payout machines) (SpielV) or the conformity assessment of measuring instruments (MessEG, MessEV)), **IT security expertise** reports are required; these must be issued by BSI, a test centre authorized by BSI or similar. However, in legal metrology, assets worth protecting are defined and with this, assessment strategies are needed which are not part of the topics covered by BSI, a BSI-approved test centre or similar. This gap can be bridged by a service unit within PTB. The "Cash Gaming Machines" working group already assesses and supports IT security expertise in the processes of the manufacturers of cash gaming machines within the scope of the type approval in accordance with the Gaming Ordinance (SpielV). The "Metrological Software" working group assesses and supports risk analyses for software and IT components of the manufacturers of measuring instruments within the scope of conformity assessment. Both working groups are responsible for updating and publishing topical attack vectors. BSI publishes general threats on a regular basis, however, assets worth protecting in the legally regulated area are often so specific that only PTB can identify relevant threat scenarios. This task also includes the counselling of BSI-approved test centres or similar in elaborating the security expertise reports. This development seems to suggest that within the scope of the "Digital Agenda", further tasks of PTB that are part of its legal metrology mission will be affected by the necessity of the assessment of IT security risks. For this purpose, it is envisaged to create a "Metrological Security Expertise and Risk Analysis" working group having the characteristics of an internal service provider to act independently as a **BSI-approved test centre** for all of PTB.

Centralized data provision is an absolute prerequisite for the efficient use of modern big data analytical procedures as are already being used very successfully to increase efficiency in those

Figure 2: Concept of the "metrology cloud" as a trustworthy core platform.



areas of metrology that are not legally regulated. The concepts of **"predictive maintenance"** developed in that area can, in principle, also be applied to increase efficiency in the fields of metrology, verification and calibration where currently fixed deadlines prevail which are based on random sampling tests. By developing appropriate statistical modelling methods, it would be possible to establish continuous prognostics and to guarantee the quality of the measurement accuracy of the entire measurement infrastructure – even for metrology and verification. To this end, however, preliminary research activities at PTB would be necessary to prepare a sustainable modification of the Measures and Verification Act. The "Mathematical Modelling and Data Analysis" department already advises professional associations, DAkkS laboratories and market surveillance bodies, providing them with statistical expertise and procedures. The concepts that had to be developed for "predictive maintenance", however, involve far more than this.

Quality infrastructure

Digitalization affects quality infrastructure **(metrology, standardization and accreditation)** in its entirety. Here, the greatest challenges seem to concern standardization and the calibration system as metrological parts of accreditation. At the "National IT Summit 2015" of the German Federal Government, the position paper **"Leitplanken für die digitale Souveränität"** (Guardrail for digital sovereignty) was presented [37]. This paper lists the three major prerequisites for maintaining competitiveness: efficient and secure infrastructure, mastering key capabilities and technologies, and digital sovereignty with framework conditions open to innovation. In all of these three areas, ensuring reliability and confidence in correct measurements are expressly demanded from the quality infrastructure in its entirety. This concerns, for one thing, the communications infrastructure in which the reliability of high-frequency measurements will be a pre-condition for the sustainable development of the communication network [38]. For another, the entire calibration system is also expected to provide efficient framework conditions that are open to innovation and technology in order to promote innovation [4]. Mastering key capabilities in the fields of calibration, IT security, metrology and data analysis is thereby the basis of a standardization system that is geared to actual needs. Correspondingly, the German government made use of its G20 presidency to take up the topic of **standardization in digital transformation** as a key topic [39]. During discussions among experts, which took place at PTB, the term of **"platform capitalism"** was mentioned several times as a warning against the market dominance of a few companies that may result from this process and may put – not least – SMEs at considerable risk. This phenomenon can only be countered by means of flexible and reliable standardization. This is particularly important in the context of a globalized economy so that German or European companies do not see their possibilities for action limited by other global competitors. Furthermore, a topical IEC white paper lays down that the vision of an "Internet of Things" with highly automated operating participants can only be successful due to suitable standards [40].

In the field of **accreditation**, PTB plays a key role for accredited laboratories due to the required traceability to the SI. Task distribution between PTB and DAkkS (Deutsche Akkreditierungsstelle – German accreditation body)

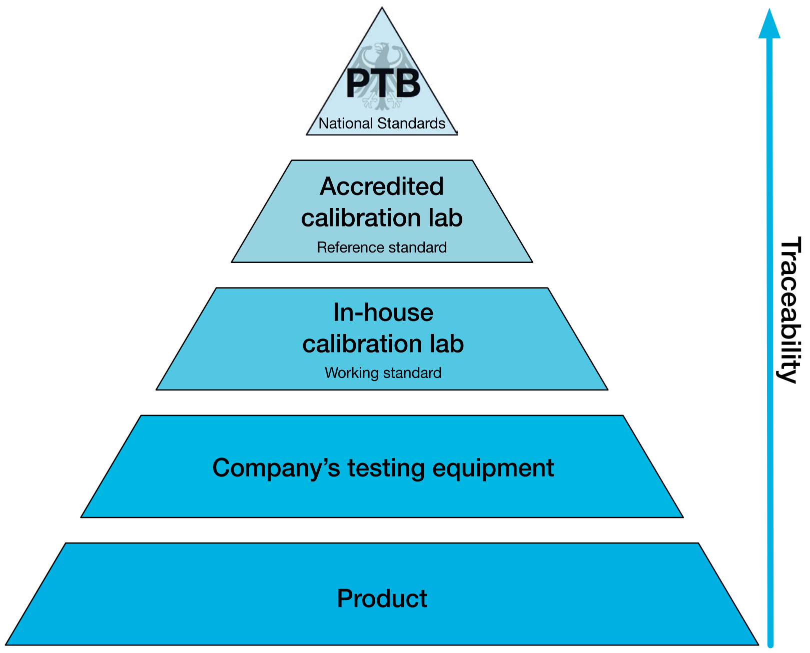


Figure 3:
Calibration hierarchy in the Federal Republic of Germany.

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with more than 400 accredited laboratories (as well as market surveillance with the verification authorities) is in line with the German calibration hierarchy – with PTB spearheading it – and with the international ISO 17025 standard [41], which lays down the main requirements that are placed on accredited laboratories. This standard is, in principle, conceived in such a way that it is open to technologies and allows digital formats to be used. Against the background of digitalization, the aspects of digital information and communication channels are gaining in importance, last but not least in order to meet the growing requirements of industry. Due to the digital transformation of the calibration system, PTB thus has the opportunity of considerably supporting the digitalization of the economy and of industry. This means that digital business processes are accompanied by corresponding digital interfaces within the measuring chain and the quality infrastructure.

For PTB as the body in charge of the top level of the traceability hierarchy, developing a **digital calibration** certificate is therefore the most important task. In accordance with the second wave of digitalization, a calibration certificate is not only the electronic document acting as a counterpart to the current hard copy, but rather a virtual representation of the information which is relevant for the calibration certificate. In particular, this means that the data for the application of the calibration (e.g. scaling factor, temperature ranges, linearity) must be available in such a format that they can be read out and processed automatically by a machine. This opens up the possibility of automating the use of the calibration information in industry 4.0 scenarios. For instance, a sensor could be used in a plant by simply adding it to the existing sensor network; the control software of the plant used in this context would then adapt automatically, based on the digital calibration information (plug'n'measure). The "digital twin" of the sensor is thus generated automatically from the digital calibration certificate. For digital calibration certificates to be developed, to establish themselves and to become widely used, it is necessary to lay down rules with regard to aspects concerning the structures, the content, permitted measurement units, interfaces, the validity and security of the data transfer as well as the digital stamp and signatures. Hereby, authenticity and cryptographic security (e.g. by digital signature management) play a decisive role. EU regulation eIDAS-VO 910/2014 has recently set the legal framework for the EU-wide recognition and legal assignment of digital signatures and stamps.

"The digitalization of all areas of science and the high dynamics of digital technology require standardized procedures, especially with regard to data and metadata, exchange formats, interfaces, data models, mark-up languages and vocabulary."

Council for Scientific Information Infrastructures, 2016

Whereas a digital calibration certificate realizes the correct dissemination of the units vertically along the traceability chain within the calibration hierarchy, concepts for the correct horizontal exchange of data are also necessary. This means, among other things, that concepts for the SI-based dissemination of information and data in **IoT networks** have to be developed and implemented. The flawless automated interpretation of data requires, besides flawless data transfer, a reliable interpretation of the data with regard to their size, dimension, unit and, if applicable, to the indica-

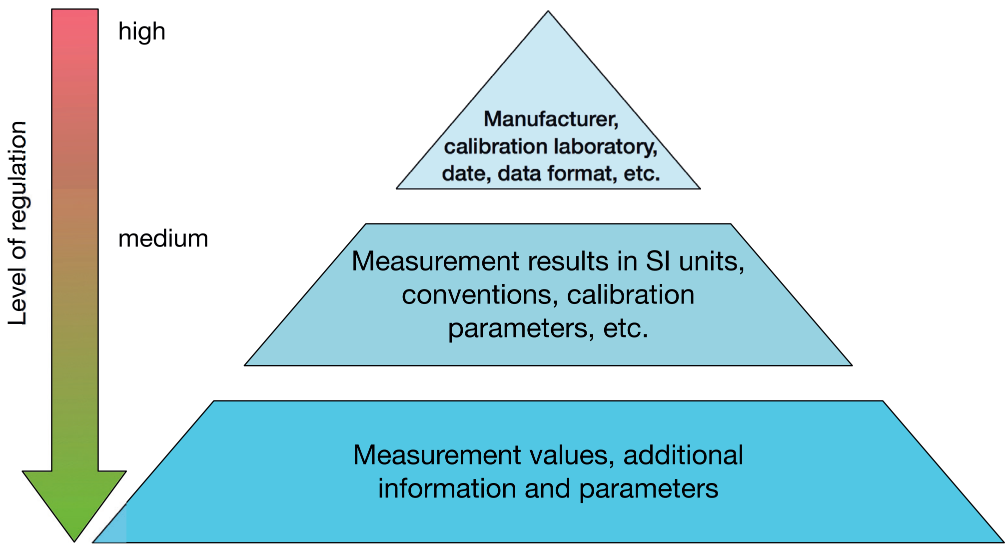

Figure 4: Concept of a standardized digital calibration certificate.

tion of the **measurement uncertainty** which can be read out by a machine. To date, however, data formats have been used either together with the numerical values for data types without consistent implementation or existing approaches have either been proprietary, specifically for a given scientific field or for a programming language and are thus not interoperable. Due to the development of a **standardized metadata format**, the interoperable exchange of metrologically relevant information concerning the numerical data can be ensured for a reliable automated interpretation and evaluation of numerical factual data. The metadata format used for this purpose should be open, widely applicable and flexible with regard to its implementation by formulating basic requirements which are necessary for the smooth exchange of factual data in automated information networks. Such metadata formats would also be helpful when it comes to ensuring the interoperability of databases for the analysis of big data [42]. As a rule, big data analyses imply data from different sources being analysed for purposes such as data correlation. Hereby, attention must be paid to the data being compatible with each other (unit, dimension, measurement uncertainty) in order to obtain reliable analysis results. In metrology, initial efforts (e.g. of NIST, USA) have been limited to make different data sources findable, since interoperability is considered as an extremely high obstacle. For instance, an international cooperation project involving several National Metrology Institutes (NMIs), with the significant involvement of PTB, has been working on an "International Metrology Resource Registry" as a database for metadata in order to increase the findability of metrological databases [43]. As a rule, application-specific solutions are developed for the interoperability of databases; these are then evaluated for a concrete situation. The creation of adequate harmonized formats would significantly support automated data analysis. NIST's first trial with the "UnitsML" [44] data format, however, failed mainly due to a lack of human resources according to NIST's own statement. During its development, the interoperable representation of factual data has also turned out to be very high, which requires corresponding capabilities and long-term commitment.

Furthermore, automated approvals via digital interfaces will play an important role in supporting business-to-business processes. With TraCIM [45], for example, PTB currently offers the automated testing of algorithms, based on reference data of PTB, for certain tasks in coordinate metrology. This system allows the automated remote testing of an algorithm followed by the issuing of a corresponding test mark. In the future, many industrial companies will expect PTB to provide such services, since these companies will have already digitalized their own processes in exactly the same way.

In many areas digital transformation is currently the source of conflicts between technological possibilities and the legal framework conditions in place. Examples of such conflicts are production plants which are subject to explosion protection regulations, where PTB, according to its legal tasks, plays an important (and in some cases even a globally leading) role while sharing the work with BAM (Federal Institute for Materials Research and Testing). Pursuant to 2014/34/EU as the legal transposition of IEC 60079, manufacturers are obliged to subject the electronic devices they use to a strict conformity assessment procedure. The guidelines this procedure is based on presuppose that stationary instruments are used, whereas an increasing number of mobile devices (e.g. tablets) are used, especially for maintenance purposes. In this context, PTB is required to develop suitable reference architecture to implement the digital modernization of explosion protection. For example, by developing adequate **software-based solutions**, it is possible to offer alternatives by applying a safety classification which is adapted to the concrete case instead of applying rigid rules. Legally compliant requirements and reference systems at PTB contribute to preventing the use of devices that have not been approved.

In a similar manner, new tasks arise in various other fields from PTB's legal assignments. An increasing number of connected measuring systems and real-time analyses are used in fields such as medicine or environmental monitoring, whereas traceability is still mainly geared to laboratory diagnosis. New digital technologies allow **online monitoring** in medicine (point-of-care diagnostics) and in environmental analyses (water, air, vehicles). Furthermore, digital communication channels open up the possibility of remote maintenance, remote diagnostics and remote calibration. Monitoring the correctness of the measured values, especially in the field of medicine, is just as important for such online systems as in stationary laboratory diagnostics. This calls for the development of methods for the remote-controlled calibration of measuring instruments, but also for concepts of reliable data security and transfer and for the traceability of measurement results in the online or in the on-board mode. PTB supplies the national standards for quality assurance in laboratory diagnostics and is therefore required to further play this role also for modern diagnostic and analytical methods. PTB must expect new tasks, especially with regard to the exhaust gas analysis of combustion engines, due to the occurrence of digital manipulation.

The dissemination of legal time is one of PTB's sovereign tasks. Against the background of digital transformation, a series of novel challenges, but also opportunities have arisen in this context.

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Thus, real-time capable methods for the analysis of large amounts of data (big data analysis) would provide new insights into continuously recorded measurement data in order to assess high-precision optical clocks. At the same time, the interconnection of digitalized industries and markets has led to new challenges with regard to the dissemination of time. Hence, as early as 2018, the European regulation of algorithm-controlled financial trade will come into force via the **MiFID II Directive**, which will require traceable time stamps with 1 µs resolution and no more than 100 µs deviation from UTC. There is no metrological infrastructure in the form of accredited laboratories for this purpose in Germany as of yet. NMIs are already performing interlaboratory measurements of signal runtimes by means of transportable, calibrated detectors with low uncertainty in order to determine the UTC contributions. One possibility to support the German financial industry would therefore be to develop calibration procedures for use in the network of financial institutes, based on the method used for comparisons between NMIs and to develop monitoring and documentation methods. Thanks to the qualification and accreditation of calibration laboratories, this task could then be passed onto external laboratories on a long-term basis. Preparations for this support by PTB have already begun.

In "Internet-of-Things" networks, data are permanently acquired and processed centrally. Especially in "Industrie 4.0" environments with a real-time-capable data analysis ambition for automated production, **time synchronization** plays a decisive role [46]. In principle, adequate time stamps can be derived from a local time reference which can then be assigned to the data. In company-wide and global networks, this approach, however, requires such time references to be synchronized if globally acquired data are to be temporally correlated. In areas where time synchronization is technically necessary or legally required, like in telecommunications or the power industry, the effort to synchronize the time references has to be made by the companies, and corresponding hardware must be used. The prerequisite for the wide use of corresponding technologies, such as the NTP protocol (time indication via networks with a variable packet runtime) or the **PTP protocol** (with a focus on increased accuracy and locally limited networks), is an easy implementation. Thus, numerous manufacturers of active network components now increasingly use PTP hardware solutions in their devices. PTB will have to reflect these changes adequately when disseminating legal time. Furthermore, developing a modified version of the **WebSocket protocol** as a complement to NTP is useful, since it supports various browsers and programming languages and enables simple implementation in software. It is therefore perfectly designed for use in IoT, even in the industrial field where web technologies are widely used. By developing a corresponding WebSocket service of its own, PTB would be able to disseminate time for large-scale application in IoT and other networks.

Metrology in the analysis of large quantities of data

All analyses and studies have one thing in common, namely that only adequate data analysis can generate knowledge – or rather information. The BMWi is therefore supporting the **"Smart Data – Innovation based on data"** [6] promotion initiative with 30 million euros for the development of efficient procedures geared to obtaining economically utilizable information from the flood of raw data. Besides IT security, the efficient handling of the increasing quantities of data is a core topic of digitalization [47]. The increasingly interconnected corporate landscape equipped with cheap data storage facilities, digital sensors and inexpensive data communication systems has led to an exponential increase in the quantity of data [48]. New phrases have even been coined to designate data: they are called the "21st century's oil" or "fertile soil".

"The vast majority of all data (in fact up to 90 %) has been generated in the last two years"

Realising the European Open Science Cloud 2016

Hence, new measurement procedures – such as those used in medical imaging, industrial CT or radiance measurements of luminous and reflecting surfaces – have led to **rapidly increasing data quantities**. In many cases, the dimensionality of the measurand to be determined has increased correspondingly. For instance, PTB's near-field goniophotometer can measure the luminous flux of a light source with spatial resolution. In this case, the measurand is extremely high-dimensional and is therefore not manageable for the established procedures of the quality infrastructure. Such high-dimensional data are used, for example, for virtual drafts of the geometry of light-transmitting building elements in simulations. Against the background of digital transformation in industry, traceability to the SI – and thus PTB – will have a decisive role to play in this context in the future.

Interdisciplinary research at PTB is paving the way for a number of specialized projects and guidelines in fields such as mathematical modelling, statistical data analysis and procedures for the determination of measurement uncertainty.

These are organized in a central department called "Mathematical Modelling and Data Analysis". By cooperating in committees for the harmonization of metrological data analysis, PTB is continuing to support the intertwining of the different application fields. Due to the increasing quantities of data, to the dimensionality of the measurands and to analytical procedures that have become more complex, PTB is faced with rapidly growing requirements. An increasing number of applications represent challenges for the evaluation of measurement data by complex data structures with high dimensionality, variability and volatility as well as strongly varying **data quality**. Procedures for the determination of measurement uncertainties, which are widely accepted in metrology, are already reaching their limits in terms of dimensionality and computing time. Digitalization and computer-based measurement procedures are enhancing this trend and leading to constantly increasing quantities of data and parameter spaces in distributed measuring systems, complex **computer simulations** or multi-parameter medical data (in imaging, protein and genetic analyses and biochemistry). The connection between the measurement and the evaluation of the measurement data is becoming closer and closer, leading to the growing importance of mathematical and statistical procedures. Transferring established and accepted procedures to situations with large quantities of data (e.g. by means of simulations) and long computing times (e.g. due to demanding models) is a huge challenge. Scalable mathematical and statistical tools must therefore be developed to act as complements to established procedures in order to enable a smooth transition between small and large quantities of data.

One possibility here is **dimensionality reduction**, where the structures existing in the data are exploited in a targeted manner to reduce the amount of data whilst maintaining the same content in terms of information. In this context, deep knowledge of the measurement is just as indispensable as the joint development of more efficient measurement procedures and evaluation methods. This requires collaboration between the "Mathematical Modelling and Data Analysis" department and the experimental departments in joint research projects. In numerous applications, new computer-aided measurement procedures in the "Photometry and Applied Radiometry" department have led to considerable quantities of data in calibration, as is the case, e.g., in the metrological detection of the so-called "radiating body" of a light source, where a single measurement generates approx. 100 GB of measurement data. Extensions of the basic measurement procedures, which additionally enable spectrally resolved measurements, are expected for the near future; they will result in another considerable increase in the amount of data. The German Council of Science and Humanities also considers that there is a significant need for research in this field:

> *"The measurements generate huge quantities of multidimensional data; it is, however, not certain what processable information can be derived from them. It would be helpful to intensify the research efforts with regard to data interpretation and data use."*
>
> **German Council of Science and Humanities, 2017**

In applications where it does not make sense to reduce data dimensionality due to the applications aimed at, practicable and reliable methods must be developed for the **transfer of large amounts of data**. The problem is not so much the data storage or the data transmission speed, but rather finding a suitable data format. At PTB, for example, traceable measurements of reflection standards are supplied, as needed by a number of device developers and calibration and testing laboratories. Here, a uniform, standardized data format is necessary for measurements of the bi-directional reflectance distribution function of surfaces; this format must be able to image the high-dimensional, complex data, including the measurement uncertainties and the information about the surface suitably and to allow reliable data analysis. Thereby, a flawless computer-aided interpretation of the data must be ensured. Based on the measuring infrastructure and on experience of the "Imaging and Wave Optics" department as well as on its long-standing, successful cooperation with the "Mathematical Modelling and Data Analysis" department, it is possible to develop adequate data formats and analytical methods for this purpose.

Data mining methods and other correlation procedures are widely used methods in areas such as real-time analysis in "Industrie 4.0". Thereby, sensor data are continuously evaluated and compared with each other. In metrology, an example of this is the **data correlation analysis** of photovoltaic modules along their value chain. By developing adequate measurement and traceability methods, data analysis procedures can be developed which would, for example, enable an early reaction in the event of a fault and allow a link to be established between lower efficiency in a solar park and wafer production, for example. Since this presupposes profound knowledge and developments with regard to the measurement procedures as well as the development of suitable mathematical and statistical procedures, here again, joint research of the "Photometry and Applied Radiometry" and "Mathematical Modelling and Data Analysis" departments is necessary.

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Examples of high-dimensional measurement results are also encountered in many fields of nanometrology, like signal contrast modelling by means of Monte Carlo methods for the evaluation of measurements on nano-objects in scanning electron microscopes. Furthermore, imaging procedures generating large amounts of data, which also have to be processed, are increasingly used in dimensional metrology and optical surface metrology. Determining the influences of uncertainty in these fields is sometimes only possible by means of demanding **simulation calculations**. As a rule, these require dimensionality reduction to facilitate the handling of the data. Similar approaches are increasingly applied in the field of production where, e.g., optical measurement methods are used. This requires the development of methods allowing statements about the quality of the measurement uncertainty when using dimension-reducing procedures. Thereby, generic procedures must always be developed based on concrete applications, and thus in cooperation with the elaboration of the measurement procedure. By selecting the measurement points adequately, adapted measurement procedures can even lead to a sufficient dimensionality reduction.

In research, a rapidly growing number of publications is observed in the field of big data analysis and automated **big data** analysis, due to, e.g., machine learning and artificial neural networks [11, 49]. Currently developed methods are usually based on the established theory of artificial neural networks, but use an increasing number of hidden layers between the input and the output [11]. These methods are generally designated as **"deep learning"**. Due to the increasing availability of specialized hardware, of open-source software and of very large amounts of data, "deep learning" methods are becoming relevant in a growing number of fields [40]. From the quality infrastructure viewpoint – and especially from the viewpoint of metrology – the aspect of the reliability of the results is highly relevant. Such data analysis procedures have, however, not yet been dealt with from a metrology point of view. Investigating the reliability of data analysis and developing methods for the quantitative evaluation of the results' quality are subjects that are currently being dealt with in research, outside metrology as well, for instance at the Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute (HHI) in Berlin [51]. As a general rule, the development of methods for the determination of uncertainties and statements about the quality in "deep learning" is, however, still in its infancy. In critical areas, there is the additional issue of the susceptibility to the manipulation of results of machine learning by tampering with the input data. This field of research is called "adversarial learning" [52] and will be relevant for metrology in the future.

Metrology of the communication systems for digitalization

The availability of reliable, efficient and flexible communication channels is a frequently mentioned prerequisite for successful digital transformation, see for example [38]. The expansion of **5G technology** is being intensively pushed forwards, in particular. The Verband der Elektrotechnik, Elektronik und Informationstechnik (VDE – Association for Electrical, Electronic & Information Technologies) thus quotes experts from these sectors as considering a roll-out of 5G in Germany as realistic even before 2020 [53]. In their analysis "Key Issues for Digital Transformation in the G20", the G20 have also emphasized the need for a fast expansion of 5G by means of targeted public promotion and have even recommended that the roll-out goal be fixed for 2018 [39]. Currently, the term "5G technology" usually designates radiofrequency communication technologies in the upper megahertz or in the gigahertz frequency range. There is no final 5G standard at present, which means that it is not certain yet what concrete requirements must be met. The "Next Generation Mobile Networks Alliance", for instance, defines the requirements placed on a 5G standard as follows: the availability of very high data rates (from 100 Mbit/s to 1 Gbit/s), even for large groups of simultaneous users; several hundreds of thousands of simultaneous wireless connections; a considerably more efficient exploitation of the spectral range as compared to 4G; considerably lower latency as compared to LTE, and enhanced transmission efficiency [38].

> *"5G will operate in a highly heterogeneous environment characterized by the existence of multiple types of access technologies, multi-layer networks, multiple types of devices, multiple types of user interactions, etc."*
>
> **NGMN White Paper 5G**

As a rule, in 5G communication and digital modulation, the **high-frequency measurands** are very complex, nonlinear, stochastic and high-dimensional. For instance, quadrature amplitude modulation (QAM) with large numbers of constellations (64 – 4096) is playing an enhanced role in high-frequency communication engineering. The required transmission and reception techniques must be characterized with great accuracy in order to minimize transmission errors. An efficient use of the electromagnetic spectrum in terms of range, channel capacity and channel density thus requires nonlinear and stochastic characteristics in the spectral range (harmonic content, signal-to-noise interval, degree of passive intermodulation, oscillator phase noise, etc.) to be known. Traceable measurements of these nonlinear and stochastic measurands are therefore the precondition for the **calibration of high-frequency measuring instruments** and for the setting up/development of digital communication systems.

Traceability has, to date, nearly only been available for basic measurands (unmodulated continuous-wave signals, linear characterization), although commercial devices for nonlinear characteristics have also been developed in Germany. Including such measuring instruments into the calibration hierarchy would provide the relevant companies with a significant competitive advantage. The need for an extension of the accreditation scope of the DAkkS laboratories to nonlinear and stochastic measurands is therefore increasing due to digitalization. According to the calibration hierarchy, however, the precondition for this is the traceability of such measurands at PTB.

Furthermore, antenna arrays with MIMO technology (multiple input multiple output) up into the millimetre wave range [54] are playing an important role in antenna measuring techniques due to the transformation into 5G networks. Ensuring the reliability of such systems requires the emitting and receiving technique used to be metrologically characterized and the measuring instruments used for characterization to be traceably calibrated. For instance, it is necessary to investigate the technical implementation of the signal focusing of time-varying channels at the most diverse frequencies and propagation conditions (massive MIMO).

Developments towards self-configuring, intelligent systems with great requirements being placed on the interoperability in highly complex communication protocols are leading to the need for the traceability of signal parameters such as the modulation level and modulation deviation, the error vector magnitude (EVM) and the error rates (modulation/bit/frame error rate). In order to develop the measuring equipment and antenna systems correspondingly, it is necessary to know the channel runtimes, the channel transmission loss and the pulse drift of every individual propagation channel exactly. The availability of corresponding metrological services in Germany would represent a competitive advantage in a market that is currently still dominated by the USA and China. Preliminary work done by PTB in this area concern the THz Communication Lab, EVM measurements by means of digital real-time oscilloscopes, the calibration of vector signal analysers, the measurement of electrically transformed optical **modulation characteristics**, and first activities on the characterization of "smart antennas".

Other institutes such as NIST have long acknowledged the required research effort and have massively invested (approx. 300 million US dollars) into the "Communications Technology Lab" and into the **"mmWave, 5G & beyond"** research programme [55]. NIST's activities are scheduled to take at least 20 years of research. NPL is also massively developing its research activities in this field and has just founded the "Nonlinear Microwave Measurements and Modelling Laboratories" joint research centre with the University of Surrey[2].

Metrology for simulations and virtual measuring instruments

In several application fields of metrology, simulations and virtual experiments have already been established for some time. In **coordinate metrology** for example, simulation-based measurement uncertainty determination is covered by ISO 15530-4 for well-defined measurement tasks [56]. With the **"Virtual Coordinate Measuring Machine VCMM"**, an evaluation software program for coordinate measuring instruments, PTB has a reference procedure at its disposal which it developed itself and which large manufacturing companies such as Zeiss and Hexagon have implemented in their coordinate measuring instruments and which has also already been transferred to DAkkS calibration laboratories [57]. The measurement data are evaluated automatically, and the measurement uncertainties are also determined automatically, efficiently and with digital interfaces for further processing inside the connected infrastructure. PTB, being independent of manufacturers and enjoying a leading position as a trustworthy institute throughout the world when it comes to developing simulation-based evaluation software for measurement uncertainty determination, can rely on ideal conditions for further developing the application possibilities. The final objective is to transfer the method used for the VCCM to all relevant classes of measuring instruments that are relevant in production in order to provide valid statements concerning the measurement uncertainties obtained with the measuring instruments and sensors used in the production industry pursuant to "Industrie 4.0". In this context too, strategic cooperation is envisaged between the "Coordinate Metrology" department and the "Mathematical Modelling and Data Analysis" department in order to push forwards the development of generic methods for the simulation-based evaluation of measurement data.
In the field of optical measurement procedures, PTB has the ideal preconditions for the development of a holistic simulation tool for optical form measuring devices [58]. These preconditions take the form of PTB's worldwide leading position in optical, two-dimensional asphere technology

[1] http://www.tcl.tu-bs.de/
[2] http://n3m-labs.org

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and its simulation tool **"SimOptDevice"**, which has already been successfully used in numerous research projects; this tool is used for optical ray tracing taking static mechanical influences into account. In principle, the modular setup and the availability of the software sources allow the wide use of this tool for virtual experiments inside PTB. Certain measurement procedures must even categorically be based on a physically correct simulation. The **"tilted wave interferometer"**, which was developed at the University of Stuttgart and has also been operated at PTB for asphere metrology, uses a simulation of the beam path to determine the deviation of the object under test from a digitally determined design template [59, 60]. Hereby, the virtual measurement result obtained by means of the simulation is compared with the actual result in order to obtain the actual surface structure of the object under test from these deviations. One of the greatest challenges of such experiments is to ensure traceability to the SI units. Due to the complexity of the physical setup and of the simulation procedures used, there is a significant need for research in this area.

Algorithms are also increasingly being used to acquire and exploit data from integrated connected measuring systems of quality monitoring and **automated production control**, for example in the integration of methods of additive manufacturing in the production industry, the objective being to increase efficiency and to maintain competitiveness. This results in new tasks for traceability and measurement uncertainty influences of integrated connected measuring systems, among other things by developing standards for use in application-oriented measurement and control. Especially **additive manufacturing procedures** are becoming increasingly used as a complement to established methods in the industrial environment – for example in order to increase efficiency. Due to their layer-like manufacturing characteristics, such procedures offer good leeway for more freedom in the design and for optimization according to different criteria. The development of appropriate "in-process measurement procedures" to control additive manufacturing and the metrological characterization of the manufacturing precision, however, represent huge challenges. PTB is currently investing in corresponding production facilities – for one thing for efficient and more flexible manufacturing in PTB's own "Scientific Instrumentation" department, for another for the realization of metrological research projects. Initial research activities at PTB have already been realized within the scope of the "Traceable in-process dimensional measurements" research project which was funded by the EU and was completed in 2016. As a consequence of the connected measuring systems, the customers of sensor manufacturers are increasingly asking for **intelligent measuring systems** which – when equipped with the necessary software – generate results automatically and partly autonomously, and can interact with other sensors and facilities (purchasing measurement values rather than measuring instruments). The further increasing need for accuracy and reliability of the measurement results leads to a growing number of measuring instruments having to be calibrated with digital interfaces and integrated evaluation software (e.g. in acoustics and dynamic applications). The measuring equipment and measurement procedures available at metrology institutes to date are not normally equipped to examine measuring instruments in which the indicated value has already been pre-processed. This presents NMIs with new challenges, especially when neither the evaluation algorithms, nor the analogous raw data can be directly retrieved. Here, both new measuring capabilities and novel approaches of conformity evaluation are becoming necessary.

Technological infrastructure

The new sets of tasks identified for PTB for the major part presuppose a change in the IT infrastructure. For instance, the planned creation of a "metrology cloud" requires **efficient server systems** with very high IT security and continuous maintenance in order to sustain the existing confidence in PTB as a "trustworthy core" within the concept. The same is true of the digital calibration certificate concept and of the digital interfaces to reference data of PTB.

In order to set up an electronic document filing system, as required by the digital transformation, PTB has already started preparing for the introduction of an **e-file** system. The planned document administration makes a central, server-based administration of internal documents available which encompasses cooperative working, digital signatures, access control and archiving methods. For this purpose, the workflow for all of PTB's internal document-based business processes has been adapted to the e-filing system by an interdisciplinary organization working group. Initial internal pilot projects are expected to start at the beginning of 2018 with a progressive roll-out until approx. the end of 2020. The planned concepts of a digital calibration certificate and of digital customer interfaces are already to be taken into consideration for the required process structure to ensure that the systems are compatible.

Analysing large amounts of data and dealing with high-dimensional mathematical and statistical issues require an adequate **IT service for computationally intensive processes**. In this context, it is necessary to be able to offer high-performance computing (HPC) solutions available across the borders of divisions and departments, parallel computing, high-availability scalable storage and special IT services. If these technologies are developed sustainably, this could be realized for specialized services by developing internal pricing schemes. The Federal Institute for Materials Research and Testing (BAM) is currently also elaborating such a concept. PTB and BAM have already started exchanging information and experiences, and it is planned to pursue this exchange in the future. At NIST in the USA, there is already an internal range of IT services for the **cloud-based storage** and archiving of publically accessible research data; these services are based on an internal pricing scheme. NIST's experience has, however, shown that the prerequisites for such services to actually be used are access to the services being as simple as possible and a good cost/benefit ratio. This can be realized for example by establishing capabilities in the development of software in order to centralize the work done to develop interfaces to data, databases and parallel computing, and the standardization of the software libraries for scientific cross-sectional tasks. At the national level, there are currently several initiatives (such as that of the German National Research and Education Network – Deutsches Forschungsnetzwerk (DFN)) aiming to develop cloud infrastructures in the form of "infrastructure as a service" (IaaS) and to make them centrally available [61]. PTB could immensely benefit from such structures in the form of basic agreements. What IaaS offers, however, does not replace the necessity to develop software interfaces and to service them in the long term. Otherwise, the services purchased cannot be exploited to the full, since the technological requirements for their profitable utilization are comparably high.

In addition to the performance of the computing systems and their storage capacity, a sustainable and uniform **research data management** concept is considered a "condition for excellent research" (German Rectors' Conference; an association of universities in Germany). Correspondingly, there are a growing number of promotion initiatives, such as that of the BMBF for research and the elaboration of solutions to the challenges of research data management. In addition, the Deutsche Forschungsgemeinschaft (DFG) at the national level and the European Commission are elaborating specifications to oblige funded projects to make the research data obtained within the scope of the projects publicly available. At the European level, the **European Open Science Cloud** initiative is the start of a ground-breaking advance towards a harmonized European research data landscape. The competent committee's recommendation therefore reads: "We recommend that use of present and future instruments in research programming, including Horizon 2020, should only support projects that properly address data stewardship issues for open data." An efficient infrastructure for the handling of research data will thus become indispensable in the near future for PTB as an important project partner in numerous Horizon 2020 projects. Corresponding internal preliminary talks on this subject have already begun. Thereby, the first requirements identified were that centralized IT services should be made available to ensure the security of research data in the long term; moreover flexible access (for persons or groups of persons) to data should be granted and interfaces for external access to appropriate data should be enabled.

"Against the background of the increasing data intensity of science, data curation – as a prerequisite for the later re-use of the data – is rapidly gaining in importance."

Council for Scientific Information Infrastructures, 2016

One of the goals of the European initiatives is to document data and to make them findable. One of the essential prerequisite for this is to have **harmonized metadata structures** and data standards. At the national level, the **GovData** initiative, which aims to define a uniform format for public administrative data, represents the first step in that direction. In the meantime, various kinds of data formats and metadata structures have become available. It is, in part, possible to develop automated procedures to generate so-called "rich metadata" – for example based on well-defined processes concerning the generation of the data. This, however, usually represents a continuous task for

"highly qualified staff with both technical and IT skills to ensure the interoperability of the datasets inside a repository. These criteria cannot be met by the mere depositing of uncurated data by researchers, which reduces the value creation potential within the life cycle of the data"

Council for Scientific Information Infrastructures, 2016

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