MEASUREMENTS AND MEASUREMENT STANDARDS

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Contents

Summary

This contribution is aimed at presenting a broad generalization of information about measurement of physical quantities, and metrology as a science, philosophy, and the basis for the art of measurement. The history of the development of measurements, the state of measurement and metrology yesterday and today, and the trend of their development in the first decade of the twenty-first century are discussed. The international system of measurement traceability is characterized and presented in action. The equivalence of national measurement standards, the international system of units of measurement, and the role of metrology in the support and development of the life of the world community are explained. International measurement traceability and accuracy, as factors for solving the problems of support and development of all aspects of life of the modern community, are presented as an ideological and topical thread connecting the material of this contribution and the subsequent contributions on different fields of measurement.

1. Introduction

The world around us is, first of all, the world of physical quantities existing in reality in the widest range of their values. This is why the range of characteristics describing both natural phenomena and the behavior of devices and instruments produced by humankind is extremely wide. (Figure 1)

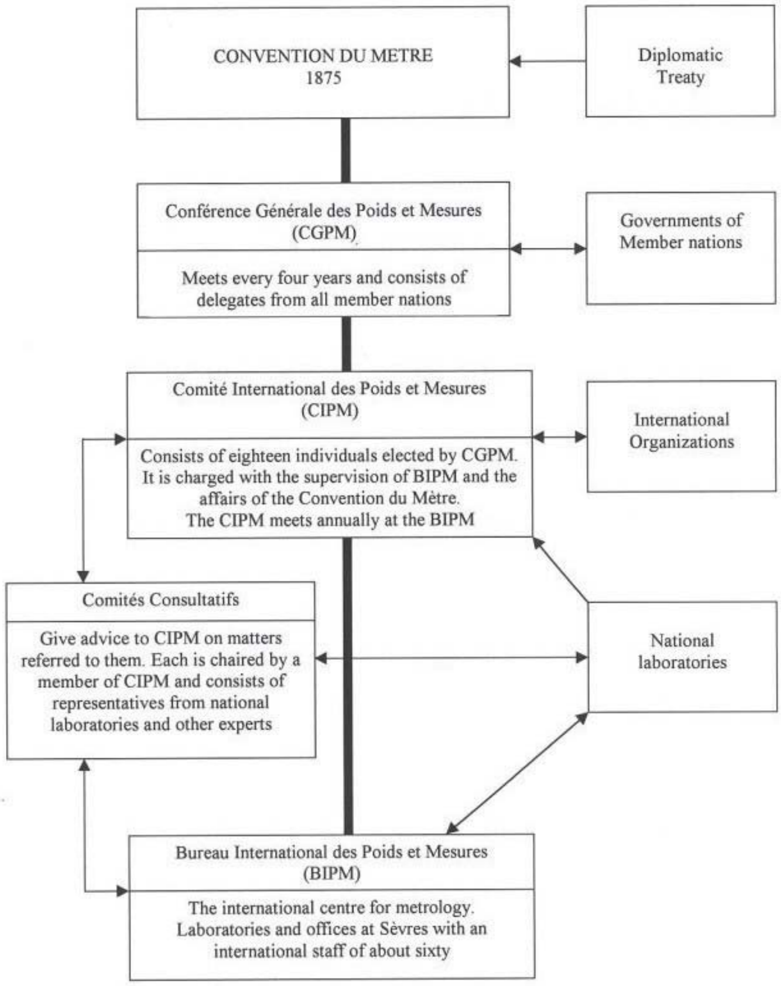

Figure 1. Measurement ranges of physical quantities in science and technology

Physical quantities are characteristics of objects of the material world and processes characterizing different interactions between these objects or their variation with time. This logically follows from the materiality of the world, which manifests itself in the absolute categories of this world as a whole and the attributes of separate objects around us such as space, time, interactions, dimensions, development, thermal state, displacements, and so on.

Humans see their destination in cognition of the world. On the way, experience has led us to the quantitative comparison of physical quantities, that is, to the conclusion that one should measure something in order to know it. Logic led us further: in order to measure, one should choose a measure, establish a single value of the quantity—a unit. Therefore, a demand arose for a standard, material, accurate, and stable embodiment of this unit.

The history of human civilization is closely connected with the development of the measurement culture. This is the process of continuous improvement of methods and means for measurement, and of systems ensuring measurement traceability based on improvements in accuracy and measurement uniformity, motivated by the increasing recognition of the importance of reference measurements as a necessary basis for both economic and state power.

In other words, the entire history of humankind reflects the way that we passed from measurements based on the senses to the scientific fundamentals of measurements that are the most important components of modern metrology, a science of measurements, methods and means for ensuring their traceability, and ways for reaching the required accuracy.

The present activities of modern society in the widest sense, and the corresponding estimation of the role of metrology in acceleration of the scientific and technological progress, throw light on the opportunities and problems of metrology.

Research work and studies searching for new phenomena of nature; investigation of the microcosm and outer space, the ocean, and circumterrestial space; study of the properties of materials; investigations in medicine and biology; ecological monitoring, and so on—all of these are inconceivable without the measurements with which the quantitative relationships in the phenomena under study are determined. The opportunities for a scientist to study, analyze, control, and use natural phenomena depend completely upon the available methods and means for measurement. It is equally valid that not a single technological process can do without measurements. Mass production, the basis of modern industry, is fully dependent on the use of interchangeable parts measured with high accuracy. To make all these measurements, we have at our disposal an enormous stock of measuring means for different purposes: information-measurement systems, computerized measuring complexes, and so on.

The number of measurements required by modern society and instruments necessary to perform them is enormous in developed countries. Thus, according to the available estimates, measurement and operations connected with it account for 4 % of gross national product in industrially developed countries. This figure is several hundreds of billions of US dollars for the European Union. In Russia, several hundreds of millions of different purpose are used at present. This means that tens of billions of measurements are taken every day using these instruments.

Measurements are based on two different definitions:

- Measurement in the narrow sense is an experimental comparison of one measurand to another, known one of the same kind (quality), which is established as a unit. A typical example is the measurement of physical quantities and application of proportional scales.
- Measurement in the broad sense is a search for correlations between numbers and states or processes according to a certain rule.

The wide scope of activities in the field of measurement testifies to their significant role in science and technology in the life of modern society. One can judge the general level of development of a society according to the condition and opportunities of the measuring service and metrological assurance. However, the great masses of measurement data that we obtain through measurements, as mentioned above, are socially significant and useful only if their traceability and accuracy, irrespective of the place, time, and conditions under which they are taken, are assured. Measurement traceability is one of the most important tasks of metrology.

Some outstanding scientists, giving a high estimate to the importance of measurements, wrote the following:

- “Count what is countable, measure what is measurable, and make measurable what is not measurable.” (G. Galileo.)
- “Science begins when people begin to measure; exact science is impossible without measure.” (D. I. Mendeleyev.)
- “Each thing is known only to the extent to which it can be measured.” (W. Kelvin.)

The philosophical significance of measurements is determined primarily by the fact that measurement is an important method used to study natural (physical, chemical, etc.) phenomena and processes. In this sense, metrology occupies a special place among the other sciences, servicing each of them and being closely interwoven with them.

The technological significance of measurements is determined by the fact that measurements provide information about an object under control, which is necessary to realize the technological process, to ensure the quality of products, and to control the object.

Let us turn to the role of measurements in science. Measurements developed over many decades, with a tendency to differentiate the branches of science and technology. This meant the accelerated development of separate fields of measurement, as well as of separate types of measuring instruments and equipment. Such development will certainly continue. However, because of the development of complex information measuring systems, in some instances the opposite situation occurred. The integration of different fields of metrology began to develop too. These tendencies were reflected in the working out of the theory of information, measuring systems intended to study physical quantities of different kinds, the fundamentals for the theory of accuracy of measuring devices, the development of methods to process the measurement results, and the theory of scientific experiment.

Development of measurements and the science of measurement has also led to the establishment of new scientific specialties in information-measuring equipment at universities, such as specialties in mechanical and optical instruments, time-measuring instruments, radioactivity measurement, automatization of investigations, and metrology. The transition from using separate measuring instruments to complex information-measuring systems demands the improvement of metrological education for young scientists of any specialization.

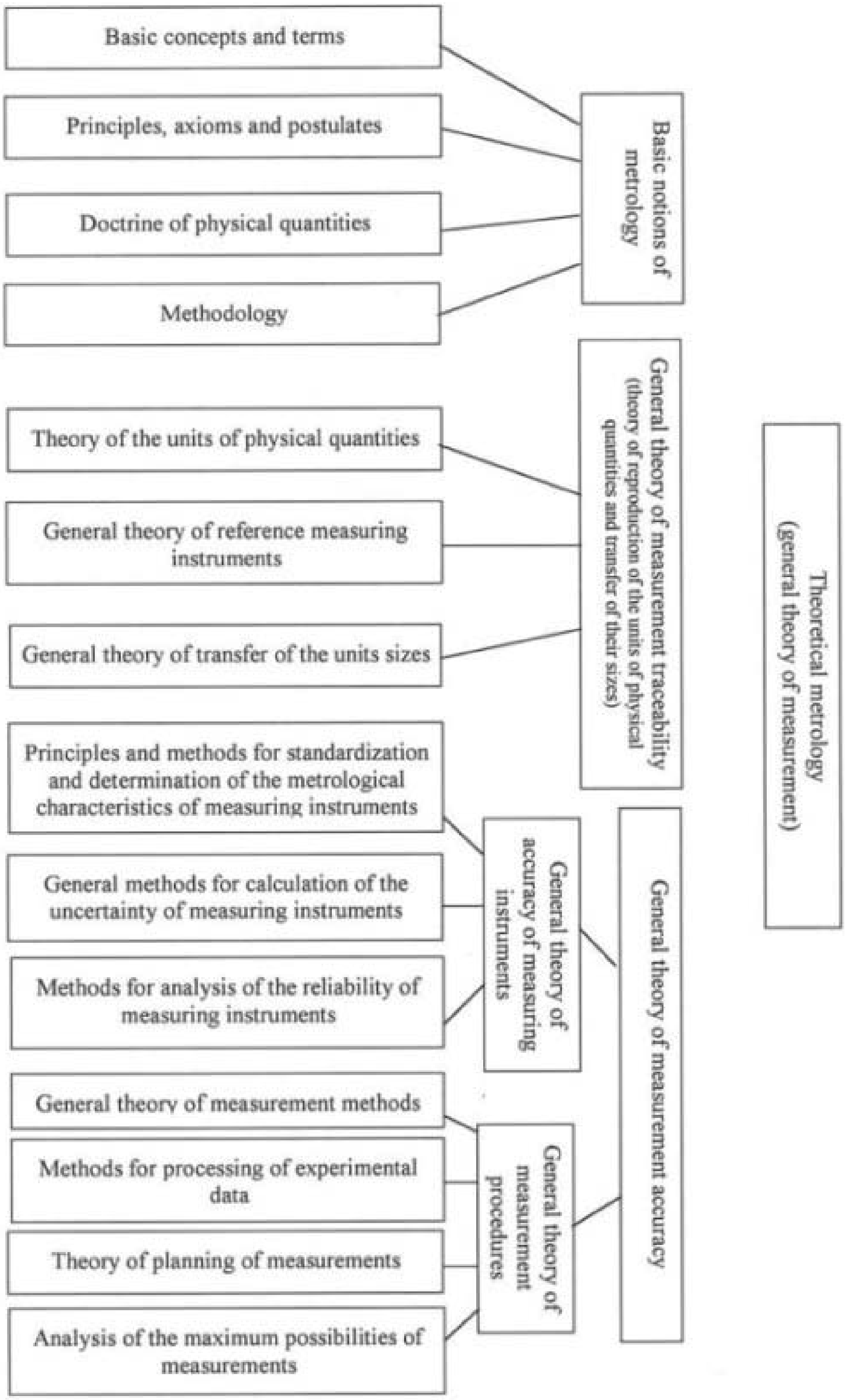

Figure 2. Metrical information in production

Because low-powered, slow, but well-visible measuring instruments are gradually being replaced today by high-productive, fast, but poorly visible instruments, the activities of measuring staff are changing and, hence, the education requirements for people taking measurements are growing. Measurement theory increasingly manifests itself as a decisive educational factor. It concentrates the knowledge of the state of the equipment, reduces countless numbers of metrological phenomena to a countable number of basic methods, principles, and techniques, and makes measurement conceivable. By way of systematic, regular solution of measurement problems using measurement theory, it is possible to optimize the solutions, restricting wrong actions and expenses, and to predict future requirements.

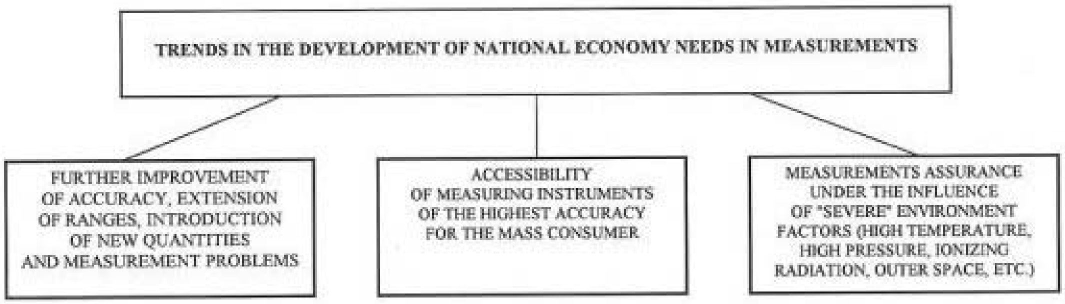

Figure 3. Development of measuring instruments, working fields and educational requirements

Until now, training of specialists and improvement of their qualifications have been hardware-orientated. However, to effectively apply modern technology today, orientation to software systems is more important. It is necessary to understand the processes, rather than the instruments.

The accumulation of new scientific knowledge and experience in the field of measurement of quantities, determination of regularities, and generation of signals with preset characteristics makes modern metrology a science of both measurement of quantities and determination of dependencies. Modern metrology, in its development, uses complex empiric methods of cognition, as well as various methods of other sciences. Theoretical metrology, a scientific basis of metrology, is a common base for numerous and complex measurements in different fields.

In a scientific experiment, or in the process of production in order to take measurements, it is necessary to determine: (a) what is to be measured, that is, what is the object of measurement, and what physical quantities characterize it, (b) what it is to be measured with, that is, what measuring means are optimum for receiving the required result, and, lastly, (c) what is the required measurement accuracy. In other words, the measurement problem must be formulated first.

If we take the leading branches of modern industry as the possible customers for solutions of different measurement problems—namely such branches as atomic, thermal, electrical power engineering, instrument-building, space research, electronics, and transport, as well as agriculture, environmental protection, medicine, research in the field of electrical magnetism, thermodynamics, mechanics, optics, and so on—then their highest requirements as to the accuracy of physical quantity measurements can be characterized in general by the data given in Figure 4 and Figure 5.

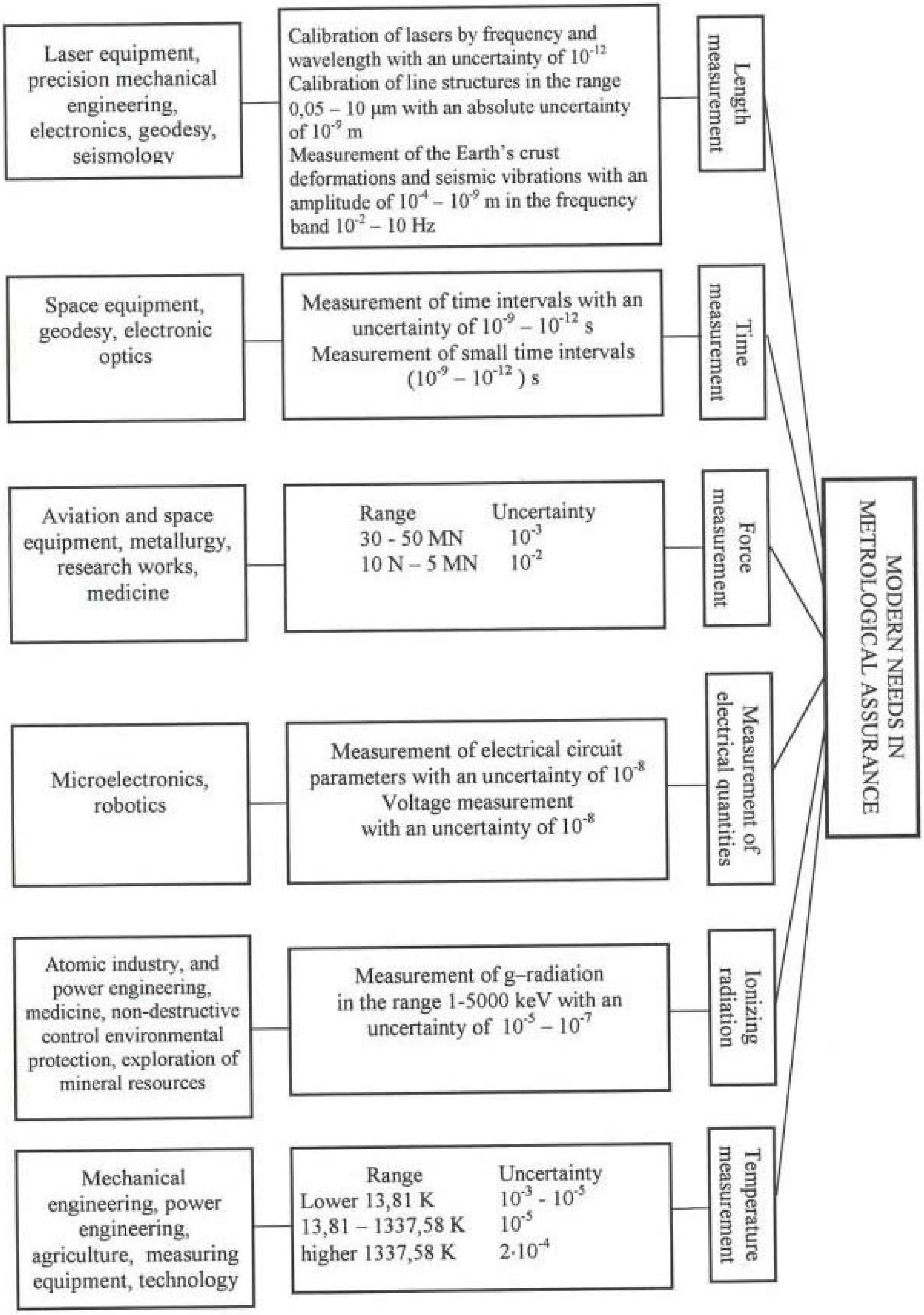

Figure 4. Modern needs in metrological assurance

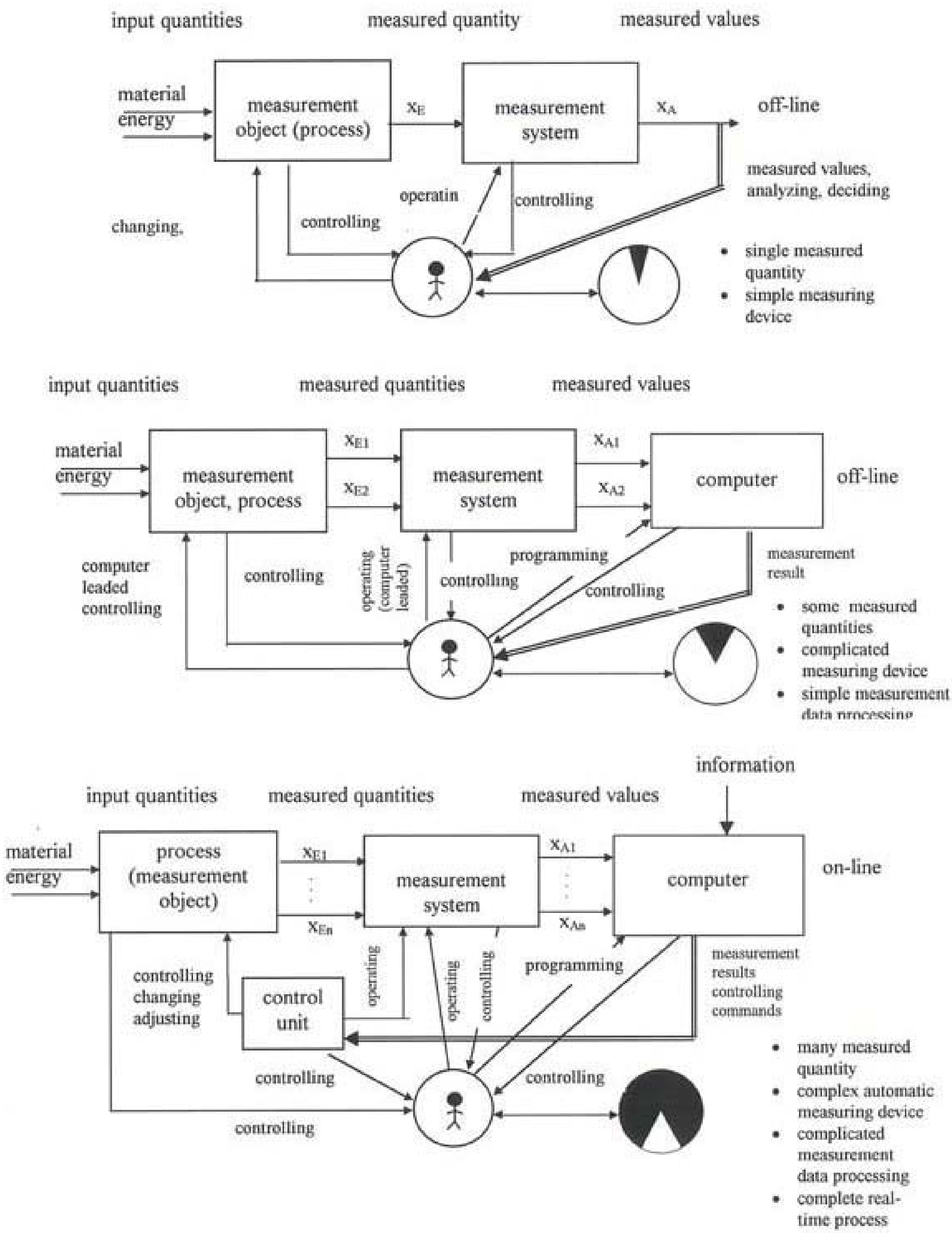

Figure 5. Trends in the development of national economic needs in measurements

All of these measurement problems can be solved only with the existence of a widely ramified and well-organized infrastructure, equipped with modern instruments—called a national system of measurements. Moreover, the boundless number of measurement results can be socially significant and helpful only if their traceability, reliability, and accuracy are assured.

In the subsequent sections of this contribution, we will describe the problems in this field and how modern scientists and practitioners solve them.

2. Metrology: Science, Philosophy, and Scientific Basis for the Art of Measurement

2.1 "Going Uphill, Glance Behind": Measurements Yesterday and Today: A Brief History

Among the notable historical figures in the creation of measuring systems, one can distinguish Imkhotep (twenty-eighth century BC), who built Jocer's pyramid and was the author of the system of uniform measures in Egypt, and Pythagoras (570–550 BC), an outstanding mathematician and astronomer, who considered Earth and the other planets to be spheres.

Aristarchus of Samos (beginning of the third century BC) was a prominent metrologist and astronomer who brilliantly solved the problem of measuring the distance from Earth to the Moon, the Sun, and other stars. Aristarchus of Samos, in fact, laid down the foundations for the present astronomical unit of length (AU), using which the distance between objects of the Solar System is often expressed even today. The method for measurement of the length of an Earth meridian was formulated in the works of Eratosthenes of Cyrene (276–194 BC), whose measurement disagrees with modern data only by 1.1 %.

Unfortunately, the history of the Middle Ages does not present any systematized information about the uniform systems of weights and measures. However, the fundamental experiments of Leonardo da Vinci, Galileo, Newton, Copernicus, and Lomonosov should be entered on the credit side of metrology. After this, we can trace the establishment of some national measurement systems in England, Russia, and other countries.

In Russia, in 1730, (sixty years earlier than in France), attempts were made to introduce the decimal system. However, it was the decision taken by the French Academy of Science and confirmed by the French government that, in fact, revolutionized the world's measurement system. In 1790, Talleyrand, who became a famous diplomat and the Minister of Foreign Affairs in France, made a report in the National Assembly about the necessity of introducing the metric system of measures. On the May 8, 1790, the National Assembly adopted the decree about the reform of measures. The French Academy of Science discussed the problem of choosing natural measures and proposed one part in ten million of the quarter of a meridian arc as a unit of length. An area equal to a square with sides of length 10 m was proposed as a measure of surface. The cubic measure, intended to measure volume, was equal to one cubic meter. The liter, equal to one thousandth of a cubic meter, was chosen as a capacity measure for both liquid and dry substances. The name "liter" originated from the Greek word *litra*, meaning a pound. The base unit of weight became the gram, equal to the absolute weight of pure water with the volume of 0.000001 of a cubic meter. Lavoisier and others reproduced the kilogram as the mass of a cubic decimeter of water. Their prototype of the kilogram, which we use today, was, in fact, equal to the mass of about 1.000028 dm^3 of water. Although this value is obviously very close to 1 dm, the difference turned out to be significant enough to worry metrologists for many years. As the liter was not exactly equal to the mass of 1 dm^3, this difference was preserved till 1964, when the liter was determined exactly equal to the mass of 1 dm^3.

The obviously progressive nature of the metric system of measures worked out in France aroused considerable scientific and practical interest throughout the world. In 1869, three Russian Academicians, O. Struve, B. Yakobi, and G. Wild, addressed themselves to the Paris Academy of Science with a proposal to establish an international commission on the meter, in which proposals could be worked out to ensure the introduction of the metric system of weights and measures as an international one. This proposal was approved, and after some preliminary preparations, in 1875, a special international diplomatic conference was convened, which adopted the first international global agreement called the Convention du Mètre. Seventeen countries participated in this conference and signed the convention, establishing a special scientific institution—BIPM, the International Bureau of Weights and Measures, near Paris—that was called upon to develop and keep the international standards of units.

In correspondence with the adopted definitions, the standards of the meter and the kilogram were reproduced in the BIPM: the meter as the distance between two lines on a platinum-iridium rod, and the kilogram as a cylindrical weight with diameter and height equal to 39 mm, made of the same alloy. They were manufactured and tested in the BIPM, and from 1889, they were given, according to sortition, to the countries participating in the Convention du Mètre. Two standards were given to each participant (one as a national standard, and the other as its copy), which facilitated the introduction of the metric system throughout the world.

At the national level, the end of the nineteenth century and the beginning of the twentieth century were marked by the establishment of a number of large scientific metrological centers:

- 1893: D. I. Mendeleyev transformed the Depot of Reference Weights and Measures, established in 1842, into the Main Chamber of Weights and Measures in Russia.
- 1878: the PTR (Physikalische Technische Reichsanschtaldt) was established in Germany.
- 1900: the NPL (National Physical Laboratory) was established in the UK.
- 1901: the NBS (National Bureau of Standards) was established in the USA.

Modern metrological offices were also formed in the other countries.

The intensive development of measurements and metrology at national and international levels started in connection with the rapid development of the world economy in the first decades of the twentieth century, which was partly slowed down only during the Second World War.

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Biographical Sketch

Yuri V. Tarbeyev was born on August 9, 1931, in the town of Chusovoy of the Perm region. In 1955, he graduated from the Faculty of Electrical Engineering of the F. E. Dzerzhinsky Higher Naval Engineering School in Leningrad (now St. Petersburg). In 1955–1960, he served in the navy of the USSR. In 1963, he finished his postgraduate course and he was awarded a degree of the Candidate of Science. In 1981, he became a doctor of science, in 1982, a professor.

Since 1967, Y. Tarbeyev has been working at the D. I. Mendeleyev Institute for Metrology (VNIIM):

1967–1971: Head of the laboratory;

1971–1975: First Deputy Director on Research Work;

1975–1997: General Director of VNIIM;

Since 1997: Scientific Head of VNIIM.

In 1992, he was elected an Academician and the first President of the Russian Metrological Academy.

Y. Tarbeyev is an Honored Scientist and Technologist of the Russian Federation, and academician of the Russian Engineers' Academy, the New York Academy of Science (1994).

Y. Tarbeyev organized, managed, and participated in the fundamental research activities in the field of scientific metrology and basic work on establishment of the national measurement standards in Russia. He worked out methods and means for the accurate measurement of the parameters of electrical and magnetic field, hydrophysical equipment, voltage, and current calibrators. He developed the information-measuring system for unique investigations in the world ocean (1967–1975), and founded the research direction of electromagnetic field measurements in liquid media.

Y. Tarbeyev lectures at the Leningrad State University and the North-West Polytechnical Institute. At present, he is the head of a chair at the St. Petersburg State Technical University.

In 1978–1991, he was the Chairman of TC8 "Metrology," of the International Measurement Confederation (IMEKO).

In 1994–1998 he was a member of the Comité International des Poids et Mesures (CIPM).

Y. Tarbeyev is a member of the editorial boards of the journals *Izmeritelnaya Tekhnika* (published in Russia) and *Measurement*, and the editor-in-chief of the journal *News of the Metrological Academy*.