MEASUREMENTS AND STANDARDS OF TIME AND FREQUENCY

L. K. Issaev
Scientific Research Institute for Metrological Service (VNIIMS), the Gosstandart of Russia, Moscow, Russia

V. M. Tatarenkov
Scientific Research Institute for Physicotechnical and Radiotechnical Measurements (VNIIFTRI), the Gosstandart of Russia, Moscow region, Russia

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Summary

This chapter is a concise exposition of bases for time and frequency measurements up to 2001. The progress in the atomic clocks and generators, invented in the 1950s, has been defining the position and the evolution of time metrology all these years. In 1967, the physical process of the Earth's rotation, which served as a primary standard time source throughout the previous human history, was changed for much more stable and precise intratomic processes, being realized in timing laboratories. The atomic time and

frequency standards have become the main sources and keepers of precise time. The measurement accuracy was million times increased up to the level of $\sim 1 \times 10^{-15}$ in 2001. Besides having the highest accuracy, time and frequency are more available for users of physical quantities. At any time and at any place of the Earth and circumterrestrial space, a user can receive precise frequency and time signals, transmitted by technical means of different countries. The need of many scientific and technological trends in more precise time and frequency is ever growing. This chapter contains the definitions of astronomical time scales and units. The problems of definition and realization of the atomic second, International Atomic Time, Coordinated Universal Time are discussed. The main data on the most frequently used atomic time and frequency standards are given. One also discusses the future prospects, which are very promising - there is a probability of achieving accuracy from 10^{-16} to 10^{-17} in the near future.

1. Introduction

The time measurements and standards are based on the concept, that time is a general current parameter of all the processes and phenomena describing duration and sequence of these processes and phenomena. According to this idea, certain natural process or a process, artificially created and maintained, can be taken as a standard for time determination and measurement. Thus the measurements come for comparison of all the other processes with the standard one. Naturally, the periodic processes, generating a sequence of identical phenomena and being highly stable and widely available for observation and use, correspond to this role best of all. With the help of such a process the unit of time interval - a second, as a defined (under the agreement) number of periods of this process is determined, and the homogeneous indefinitely increasing duration - a time scale is formed. This scale is formed of a sequence of single and numbered intervals without skips and with a point of origin, selected by the agreement.

Since the ancient times the time measurements were based on the observations of phenomena related to physical processes of the Earth's rotation about its axis, around the Sun and the Moon rotation around the Earth. Such phenomena are the following: an alternation of day and night, an annual season change, a month change of a moon phase, and also a periodic change of the star position on the celestial sphere.

These phenomena are the basis of the calendar count of time, in which the time unit interval has duration of a day. The count and continuous time keeping within a day were carried out with the help of a clock, having passed a long way of development starting from solar, water, pendulum clock up to quartz crystal and atomic clock in the XX century. The correctness of the clock rate was controlled by a regular comparison with the rate of the standard process of the Earth's rotation, the data about which were received from astronomical observations of the star position.

The accuracy of time determination achieved by the astronomers was $\sim 10^{-9}$ in relative expression and was principally limited by the irregularity of the Earth's rotation.

In the 1950s the first atomic clock with the intratomic processes was created. These are the processes of quantum transitions from one state into another, which are accompanied by absorption or radiation of quanta with strictly defined energy and frequency. In accordance with the theory of atomic spectra, the frequency of unperturbed quantum transition is expressed through a combination of fundamental physical constants and thus, it is a physical constant itself. At the present time nothing more stable is known in the nature. Therefore atomic processes of quantum transitions are ideal for the selection of any of them as a reference one.

The development and investigation of the first atomic time and frequency standards, based on the transitions in atoms of cesium, molecules of ammonia and atoms of hydrogen have immediately given the excellent results. These standards exceed by tens of times in their capabilities of astronomical measurements in achievable uncertainty of frequency and time intervals.

In time metrology, official transition to the primary role of atomic processes took place in 1967, when the 13 th CGPM accepted a new definition of the second - an atomic second, and in 1971, when the 14 th CGPM accepted a definition of a new time scale - the International atomic time (TAI). The atomic second is the duration of 9 192 631 770 periods of radiation, corresponding to the transition between two hyperfine levels of the ground state of the cesium - 133 atom. Now both the second in the International System of Units (SI) and the International time scale TAI are established and maintained with the help of atomic clocks. The era of atomic time has begun.

The inventions of Nobel laureates I.I. Rabi, N.G. Basov, A.M. Prokhorov, C.H. Townes, A. Kastler, N.F. Ramsey, W. Paul, N.G. Dehmelt have become the basis for creation and development of atomic time and frequency standards.

For half a century, since the invention of the first atomic clocks, an unprecedented advance of their accuracy has been achieved: every ten years the accuracy was 10 times increased! No saturation is visible for this advance. As a result, the accuracy of time and frequency measurement by 2001 was increased million times from the level of astronomical determination, i.e. from $\sim 10^{-9}$ to $\sim 10^{-15}$. Time and frequency exceed other physical quantities in accuracy by several orders. The high accuracy required a careful consideration of both motion and gravitation effects, and therefore the modern metrology of time and frequency is based on a special and general relativity theory.

Alongside the increase in accuracy both the problems of synchronization of remote clocks and dissemination of precise time and standard frequencies over long distances to users in any place and at any time are successfully resolved. Now the uncertainty comparison of clocks, separated from each other by a thousand kilometers, can be reduced to a nanosecond level or even less. The dissemination of standard time and frequency signals covers the whole Earth and the circumterrestrial space. The main means for transmission of these signals are special radio stations and the global satellite navigation systems GPS (USA) and GLONASS (Russia) from the 1980s. With the help of the systems a user can determine time with an uncertainty of less than 100 ns and position - a few meters.

2. Time Units and Scales

2.1. Astronomical Times

2.1.1. Universal Time

Universal Time (UT) is based on the Earth's rotation around its axis with respect to the Sun. It is the time that conforms, within a close approximation, to the mean diurnal motion of the Sun as observed on the prime meridian which is Greenwich. UT is determined from astronomical observations of the diurnal motions of the stars. The time scale determined from such observations is denoted as UTO. It is dependent on the place of observation on the Earth surface caused by the polar motion.

Another form of Universal Time (UT1) is a corrected UT0 with consideration to variations of the observer's meridian caused by the polar motion. The time scale UT1 is more uniform than UT0. UT1 is proportional to the angle of diurnal rotation of the Earth. The proportionality coefficient was chosen historically as equal to 24 hours that corresponds to the duration of the mean solar day. The initiation of the day UT1 is chosen so that 0h UT1 corresponds to midnight in Greenwich. The definition of the UT1 unit is as follows: the second is the fraction 1/ 86 400 of a mean solar day. This was the SI second up to 1960. It could be realized with an uncertainty of a few parts in 10^{-9}. The uncertainty is restricted by the irregularity of the Earth's rotation. UT1 was the basis of legal time up to 1972, when a transition to the atomic time took place. At present Universal Time UT1 and the pole coordinates of the Earth's rotation are considered to be one of the parameters of the Earth's orientation in space. These parameters are necessary for transition from the terrestrial to the celestial coordinates and vice versa. They are widely used in astronomy, in calculation of satellite orbits, in navigation, geodesy and geophysics. In time metrology UT1 is used for establishing Coordinated Universal Time.

2.1.2. Ephemeris Time

Ephemeris Time (ET) is derived from the theory of the Earth's rotation around the Sun, and it is a time-like argument of this theory. The observation of ephemeredes of the Sun, the Moon and planets helped its realization. The ET unit is an ephemeris second, defined as "the fraction 1/ 31 556 925. 9747 of the tropical year on 1900 January 0 at 12 hours ephemeris time". It was the SI second from 1960 to 1967. ET was not used as a practical time scale, due to the low accuracy of its realization. The uncertainty was about 0.1 second at the annual averaging of the Moon observations. It was obtainable only through the residuals with regard to UT1, and later - with regard to the atomic time. ET was used for astronomical applications until 1977, when it was replaced by terrestrial dynamic time, which was in its turn replaced by Terrestrial Time (TT) in 1991.

2.1.3. Pulsar Time

In 1967, periodically repeated signals of radio-emission coming from the outer space were detected. These signals are identified with the emission of quickly rotating neutron stars - the pulsars. The repetition period of pulses, coming to the Earth from different pulsars, varies from a few seconds to milliseconds, and it has a high accuracy for some pulsars. Naturally, one could not help using this remarkable natural phenomenon for timing. The investigation of millisecond pulsars shows that the rotation rate and the repetition period of emission pulses slowly varies linearly with time, and that after correction for linear deceleration these pulsars are a clock, the stability of which reaches the stability of the best atomic clocks at time averaging of about one year. The deceleration of pulsar rotation, which is due to the rotation energy loss for emission, does not permit their use as a primary source of time and for determination of the second. But the pulsar clock, based not on the atomic processes, makes it possible to check the stability of the atomic time scale at the very long time intervals and may build up a uniform atomic-pulsar scale in the future.

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Biographical Sketches

Issaev Lev Konstantinovich, graduated from the Moscow Physico-Technical Institute (MPhTI) in 1960, became Candidate of technical sciences in 1973, and Doctor of technical sciences in 1995. From 1960 when he got the post of senior engineer in factory laboratory and then from 1965 - a senior scientist and chief of laboratory, VNIIFTRI (Institute for Physico-Technical and Radio-Technical Measurements), Chief of the Metrology Department, Vice-President of Gosstandart of Russia, now being the supreme scientist of VNIIMS (Institute for Metrological Service, Gosstandart of Russia) he was involved in different aspects of metrological activities. He is Professor of Legal Metrology and the Chair in Academy for Standardization, Metrology, Certification and Quality Control, Gosstandart of Russia. In addition at the present time he is the Member of the International Committee of Weights and Measures and the Vice-President of the International Committee of Legal Metrology. His scientific interests include: general problems of measurements, legal metrology, measurement techniques, time and frequency, reference materials etc.

L.K. Issaev has more than 120 publications, being the editor and a co -author of two monographs: "Metrology and Standardization in Certification" (in Russian, 1996, IPC Publishing House of Standards, Moscow), "Standardization, Assurance of Measurement Uniformity, and Assessment of Conformity-Principles of Quality" (in Russian, 2001, IPC Publishing House of Standards, Moscow). Also he is a co -author and the editor of the English-Russian dictionary "Metrology and the Technique for Precise Measurements", (1983, "Russian Language", Moscow) and "Russian-English-French-German-Spanish Vocabulary for Basic and General Terms in Metrology" (1998, IPC Publishing House of Standards, Moscow). L.K. Issaev is the Merited Metrologist of the Russian Federation, the Winner of the Governmental Prize for Science and Technology and the Vice- President of the Russian Metrology Academy from 1993.

Tatarenkov Victor Mikhailovich, graduated from the physical faculty of the Moscow State University in 1959, becoming Candidate of physical -mathematical sciences in 1964, Doctor of technical sciences in 1983, and Professor in Time and Frequency Metrology in 1990.

From 1960 till 1966 he was working at P.N. Lebedev Physical Institute, where he investigated the ammonia beam maser with two cavities. Since 1966 till the present time he has been working at VNIIFTRI: the chief of laboratory "Laser Frequency Standards", from 1986 - the chief of division "Time and Frequency"; from 1992 - the director of the Institute of Metrology for Time and Space; from 2001 - the associate director of this institute.

His scientific interests include: time and frequency measurements, quantum frequency standards in radio and optical ranges, measurements of lasers frequencies. He has about 80 publications. V.M. Tatarenkov is the Winner of the State Prizes for Science and Technology of Russia.