PHASE RADIO METEOR EQUIPMENT FOR TIME AND FREQUENCY STANDARDS COMPARISON

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Abstract

The main results of the work on radio meteor channel application for high-precision time and frequency standards comparison carried out at Kharkov are described. The error sources, ways of decreasing them, and the method's potential are analyzed. Samples of equipment developed and introduced are considered.

MODERN STATE OF THE RADIO METEOR COMPARISON METHOD

The basis of the high precision radio meteor comparison method (RCM) is that the time of radio signal propagation between corresponding points in direct and reverse directions in the first approximation is considered to be equal (the signal reflected by the "useful" meteor trail exists for tens to hundreds of seconds).

At present the RCM, along with the methods using transportable quantum clocks (TQC) and satellite radio navigation systems (GPS, GLONASS), ensures the comparison error of the order of tens of nanoseconds. In this case the RCM surpasses the indicated methods in such characteristics as measurement productivity, self-sufficiency, operation, efficiency, concealment, and stability to ionospheric perturbations.

The work on the RCM was started in Kharkov **[1]** soon after the first publications devoted to this problem **[2]**, and were carried out in the following directions:

- theoretical and experimental investigations of the possibilities to increase the RCM accuracy (investigation of the meteor radio channel characteristic precision, analysis, and synthesis of the comparison algorithms; search for ways to decrease the signals and equipment errors; refinement of techniques for measurement results processing) **[3-6]**;
- development, manufacturing, and testing of radio meteor comparison complexes (RMCC) **[7-8]**;
- development and refinement of radio meteor comparison systems (RMCS) of time standard scales **[9-10]**.

As a result of the work carried out, the RCM has found practical application in Russia and Ukraine. Since 1985 the RMCS of the primary standards functions in Ukraine and Russia **[9]**. In 1989 the comparison cycles Poznan - Kiev - St. Petersburg and Zelenchookskaya station (the radio telescope of the Academy of Sciences) - Kharkov (relaying point) - St. Petersburg were carried out with a transportable equipment version application. In 1993 the primary standard was incorporated into the RMCS (Kiev) **[10]**. The RMCS structure is shown in Figure 1. The RMCS is equipped with the RMCC "METKA-5, 6, 6M" developed in Kharkov. The characteristics are shown in Table 1.

Table 1

Parameters	Equipment				
	METKA-1	METKA-5...7	METKA-4	Phase	METKA-11
Working frequency, MHz	57.3				45.5
Impulse power, kW	50	20...40	3	10	2...4
Signal type	6 pulses code	16 pulses code	4 LFM packets	PM + DFS	PM + DFS
Signal duration, μs	5	16x2	4x50	15x26-PM, 2x500-DFS	10x13-PM, 5x265-DFS
Comparison error, ns	300	15...30	10...30	< 1	< 1
Spectrum width, MHz	0.4	1	2.5	1	0.2

LFM = linear frequency modulation; PM = phase modulation; DFS = double frequency signal.

The investigation of the meteor channel precision characteristics, signal and equipment errors, and results of the comparison algorithm analysis and synthesis carried out recently have shown that the method's possibilities are far from having reached its limit.

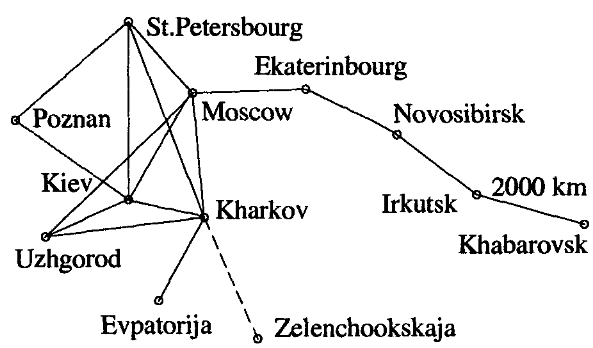

Fig. 1. The map of the RMCS time and frequency standards.

INVESTIGATION OF METEOR CHANNEL INSTABILITY AND POSSIBILITY OF PHASE MEASUREMENTS

To investigate the short-term instability of signal delay in the meteor channel (V_τ), we have used the results Tof phase measurements on the carrier and difference frequencies of the coherent double-frequency signal (DFS) of the developed RMCC "Phase." The sample mean values for $|V_\tau|$ were as follows: $|V_\tau|$ = $(2.5....3)10^{-7}$ in the detection and ranging regime; $|V_\tau|$ =$(0.5...1)10^{-7}$ in the corridor. The maximum values were $(1...2)10^{-6}$ and $(5...7)10^{-7}$, respectively. The law of $|V_\tau|$ distribution was close to the exponential one. In (5...10)% of cases, significant differences in $|V_\tau|$ for various frequencies and complexes took place; this can be explained by irreversibility of the signals delay in separate meteor trails.

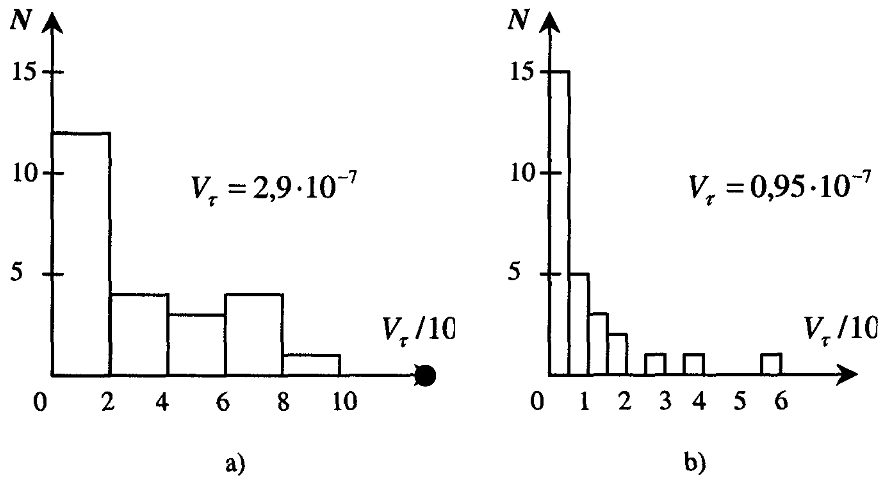

Fig. 2. Measurement results signal delay instability: location mode (a) and comparison mode (b).

The results of the experimental investigations of the short-term phase instability of the signal delay in the meteor radio channel have allowed the substantiation of the choice of phase principle of radio meteor comparison equipment construction.

The analysis of the RCM potential precision for the phase measurements was carried out with reference to the universal case of the coherent discrete component frequency signal (CDCFS) (see Figure 3). Relations for the CDCFS effective frequency (ω_{ef}) were obtained; they define its potential error in the temporal position measurement:

$$\sigma_t = (q\ \omega_{ef})^{-1},$$

where q is the signal-to-noise ratio.

Having denoted the parameters of every *i*th element of the CDCFS as: angular frequency $\omega_{0/i}$, energy *Ei*, and envelope effective frequency $\omega_{ef/env/i}$ we have obtained three forms of the relations notation for ω_{ef} calculation:

$$\omega_{ef}^{\ 2} = \sum_{i=1}^{N} \nu_i(\omega^2_{0/i} + \omega^2_{ef/env/i}) =$$

$$\omega_0^{\ 2} + \sum \nu_i((\omega_{0/i} - \omega_0)^2 + \omega^2_{ef/env/i})) =$$

$$\omega_0^{\ 2} + \sum_{i=1}^{N}\sum_{j=1}^{N} \nu_i\, \nu_j\, (\omega_{0/i} - \omega_{0/j})^2 + \sum \nu_i\, \omega^2_{ef/env/i}, \quad (1)$$

where $\nu_i = Ei / E$ is the *i*th element weight energy coefficient, ($\sum \nu_i = 1$); and $\omega_0 = \sum \nu_i \cdot \omega_{0/i}$ - is the spectrum energy center of gravity.

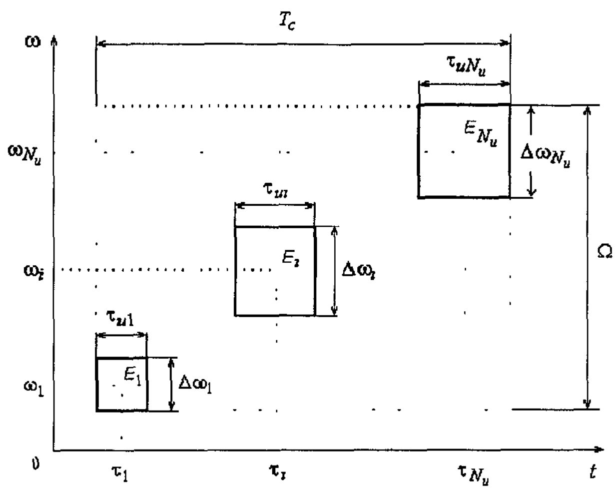

Fig. 3.

The relations (1) show that the CDCFS effective frequency is defined by three sources: the central frequency w, difference frequencies of the elements, and effective frequencies of the elements' envelopes. Two latter sources are connected with the envelope, that is, why the effective frequency of the CDCFS envelope forms:

$$\omega^2_{ef/env} = \sum_{i=1}^{N}\sum_{j=1}^{N} \nu_i \nu_j (\omega_{0/i} - \omega_{0/j})^2 + \sum_{i=1}^{N} \nu_i \omega^2_{ef/env/i}, (j \neq i)$$

With q >> 1 the CDCFS potential precision can be realized with an optimal processing and measurements of the temporal position of every element by the envelopes and phases with a subsequent weight averaging of these measurements.

In addition to a high potential precision, the phase principle advantages in the comparison equipment construction are as follows: the possibility to form high-precision defining signals and heterodynes from the signals of the primary standards being compared; simplicity and high precision of devices for estimating the CDCFS temporal position; and symmetry of the measuring signal having the harmonic form.

The analysis of theoretical and experimental investigations of the channel delay irreciprocity sources (polarization phenomena in the presence of propagation in ionosphere and reflection from a meteor trail and relativistic effects as well) has shown that the measurements carried out with application of the modern meteor comparison equipment do not allow the confirmation, for the time being, the simulation estimates of irreciprocity.

The estimates of relativistic corrections Δ_{rl} mean values obtained with the results of **[11]** for the RMCC main corridors amount to: Kharkov-Moscow – 0.175 ns; Kharkov-Uzhgorod – 3.43 ns; Uzhgorod-Moscow – 3.17 ns; Irkutsk-Novosibirsk – 4.27 ns; Irkutsk-Khabarovsk- - 7.03 ns. The conceptual possibility of Δ_{rl}

experimental definition exists in measuring the shift scales of three or more primary standards using the "ring" algorithm, in particular, in the "triangle." But in the "triangles" of the operating RMCS (Kiev - Kharkov - Moscow and Kharkov -Uzhgorod - Moscow), Δ_{rl} was not identified experimentally as the "METKA-6" complex exceeded the above-mentioned estimates of the relativistic corrections. The "convergence" of the comparison results amounted to ±3 ns in the indicated "triangles."

WAYS OF REDUCING THE RMC EQUIPMENT ERRORS

To reduce the equipment systematic errors (ESE) depending on the difference of signals delay in the sections of reception and radiation of the RMCC (τ_r - τ_{rd}) signals, a number of methods were offered for their measurement, correlation, and compensation **[4,5]**. But these methods do not allow one to measure the ESE sources resulting from the instability of the signal formation devices and irreciprocity of the signals delay in the antenna-feeder devices (AFD). The latter source is identified and studied quite recently and it deserves a special consideration.

In the active comparison systems, the combined AFD are used for radiation and reception to exclude the errors caused by different angular coordinates of the trajectories of signal passage between the points. Here, on the basis of the known antenna reversibility property, the signal delays in the AFD in radiation and reception are assumed to be equal and, hence, do not affect the ESE.

The AFD delay irreciprocity was established experimentally with "detection and ranging in succession" of two RMCC of "METKA-8" type. The cable length variation, the AFD change, and element replacement in the commutator led to the ESE up to 20...30 ns.

Irreciprocity of delays in the AFD is explained by the signal form variations due to differences in regimes of the cable matching in reception (the antenna-cable-commutator-receivers input resistance) and in radiation (the transmitter-commutator-cable-antenna).

As an ideal matching of the AFD (that should be the simplest solution of the problem) is impossible, experimental investigations were continued and theoretical analysis of the signal form distortions with mismatching in the AFD and subsequent anomalies in the delays was also carried out.

For the predetermined parameters of the signal source [$s_1(t)$, $\underline{Z}_i$], the load [$\underline{Z}_l$] and the cable [$\underline{Z}_W$, V_p, α, L], the real delay of the signal τ_d as defined (see Figure 4). The influence of the cable mismatching on the ESE was estimated with an abnormal delay τ_a, defined as the difference between the real and ideal delays:

$$\tau_a = \tau_d - L/V_p .$$

In the case of active resistance of the circuit (R_i, R_l, R_W), the temporal method of analysis was used. Here the output signal had the following form:

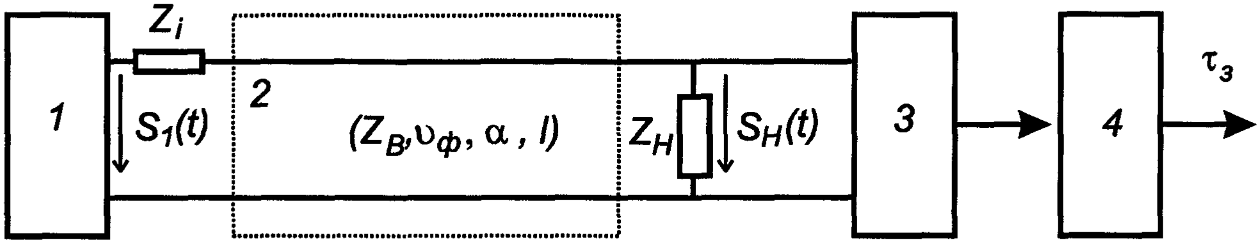

Fig. 4. Block diagram: 1 – known form signal source $S_1(t)$; 2 – cable; 3 – detector; 4 – indicator of signal's temporary provision.

$$s_l = R_l\,(R_\iota + R_l)^{-1}\,[(1-\sum_{k=1}^{N}(p_ip_l)^k\cdot\exp(-k\alpha L)]\cdot s_1(t- L/ Vp) +$$

$$+\sum_{k=1}^{N}(p_ip_l)^k\cdot\exp[\,-(2k+1)\,\alpha L)]\cdot s_1(t - (2k+1)\,L/ Vp)],$$

where $p_i = (R_i-R_W)(R_\iota+R_W)^{-1}$, $p_l = (R_l-R_W)(R_i+R_W)^{-1}$ are the coefficients of reflection from the source and the load, respectively.

As $|p_i\cdot p_l| << 1$ is real, we can confine ourselves to the first component in the sums (k=1) when performing calculations.

In the case of a random nature of resistance ($\underline{Z}_i$, $\underline{Z}_l$, $\underline{Z}_W$), the frequency method of analysis was used; here, the complex coefficient of the circuit transmission was converted to the form:

$$\underline{K}(\omega) = \underline{S}_l/\underline{S}_1 = \underline{Z}_l/(\underline{Z}_l + \underline{Z}_\iota)^{-1}[ch(\gamma L)+\underline{Z}'sh(\gamma L)]^{-1},$$

where $\gamma = \alpha + j\beta$ is the coefficient of propagation in the cable; $\beta = \omega/V_p$ is the coefficient of the phase; $\underline{Z}' = \underline{Z}_W/\underline{Z}_1 + \underline{Z}_2/\underline{Z}_W$ is the relative resistance; and $\underline{Z}_1 = \underline{Z}_l + \underline{Z}_\iota$, $\underline{Z}_2 = \underline{Z}_l\cdot \underline{Z}_\iota/(\underline{Z}_l + \underline{Z}_\iota)$.

The relative distribution $\underline{Z}$ represents the dimensionless parameter characterizing mismatching of the cable both on the part of the load and on the part of the source. If $\underline{Z}_i = \underline{Z}_W$ or $\underline{Z}_l = \underline{Z}_W$, then $\underline{Z}' = 1$. Here, the abnormal delay does not depend on the cable's length; it is defined by the signal distortion in the circuit with a complex coefficient of transmission:

$$\underline{K}_0(\omega) = \underline{Z}_l/(\underline{Z}_l + \underline{Z}_i)^{-1}.$$

Not only the abnormal delays of the signals envelopes, but the abnormal delays of the coherent carrier frequency phases were annualized. In this case, the real signal's delay was defined as

$$\tau_d = \varphi(\omega_0)/\,\omega_0,$$

where $\varphi(\omega_0)$ is an argument $\underline{K}(\omega)$ on the frequency ω_0.

Simulation was carried out for the main types of signals, different types of loads and resistances, and the main methods of the signal's temporal position measurement with the use of relative dimensionless delays τ'_{a}, τ'_{c} ($\tau'_{a} = \tau_{a}/\tau_{s}$, $\tau'_{c} = L/(V_{p} \cdot \tau_{s})$; τ_{s} is the signal duration.

The main results of the simulation are as follows (see Figure 5):

1) for the real values of the active resistances R'= 0.7...1.3, the abnormal delays are negligibly small for 0.8 $<\tau'_{c}<$0.01 and the maximum absolute values of abnormal delays correspond to the relative delay of the cable $\tau'_{c} \in$ 0.2...0.3;

2) the dependencies of the abnormal radio pulses delays on the cable's length are of quasi-harmonic nature, with a period corresponding to the cable's delay for a half-period of the signal carrier frequency;

3) for the complex $\underline{Z}_{l}$ the abnormal radio pulse delay dependencies in the cable length have the constant component and the additional "amplitude modulation";

4) three of the main methods (by subtraction of the delayed signal, by two fronts, by FFCh slope) of the signal temporal position measurement are practically equally sensitive to the abnormal delays; the measurements by the gravity center have the largest values of the abnormal errors and the measurements by the maximum of the signal and by the leading edge have the smallest values of the abnormal errors.

The simulation results are confirmed experimentally. The measurements were carried out for three types of antennas: four cophased waveguide channels array (Figure 6a); single four-elemental waveguide channel (Figure 6b); shortened oscillator (Figure 6c).

The plots' period $\tau_{a}(\tau_{c})$ ($\approx$ 8 ns) corresponds to the half period of the carrier frequency –57.3 MHz. The array with $\tau_{a/max} \approx$25 ns had the maximum values of abnormal delays; the shortened oscillator had the minimum values ($\tau_{a/max} \approx$3 ns); then it was used as a measuring antenna for the ESE identification.

The abnormal delays measurements in the receiving channel were carried out by the analogous methods. Here, the abnormal delays level within 1...2 ns was obtained at the expense of a more careful matching of the receiver input circuits.

Thus, for the cable real lengths and the AFD matching quality, the abnormal delays can reach units of percents of the pulse duration; this amounts to tens of a nanosecond. This can lead to the ESE of the same order.

To a considerable extent the abnormal delays manifest themselves in the circuit: the transmitter-cable-antenna, as for obtaining an acceptable efficiency, the output resistance of the transmitter is $\underline{Z}_{i} >> \underline{Z}_{W}$ and the antenna resistance in the frequency band of the signal differs from the wave resistance by no less than 1.1...1.2 of its value.

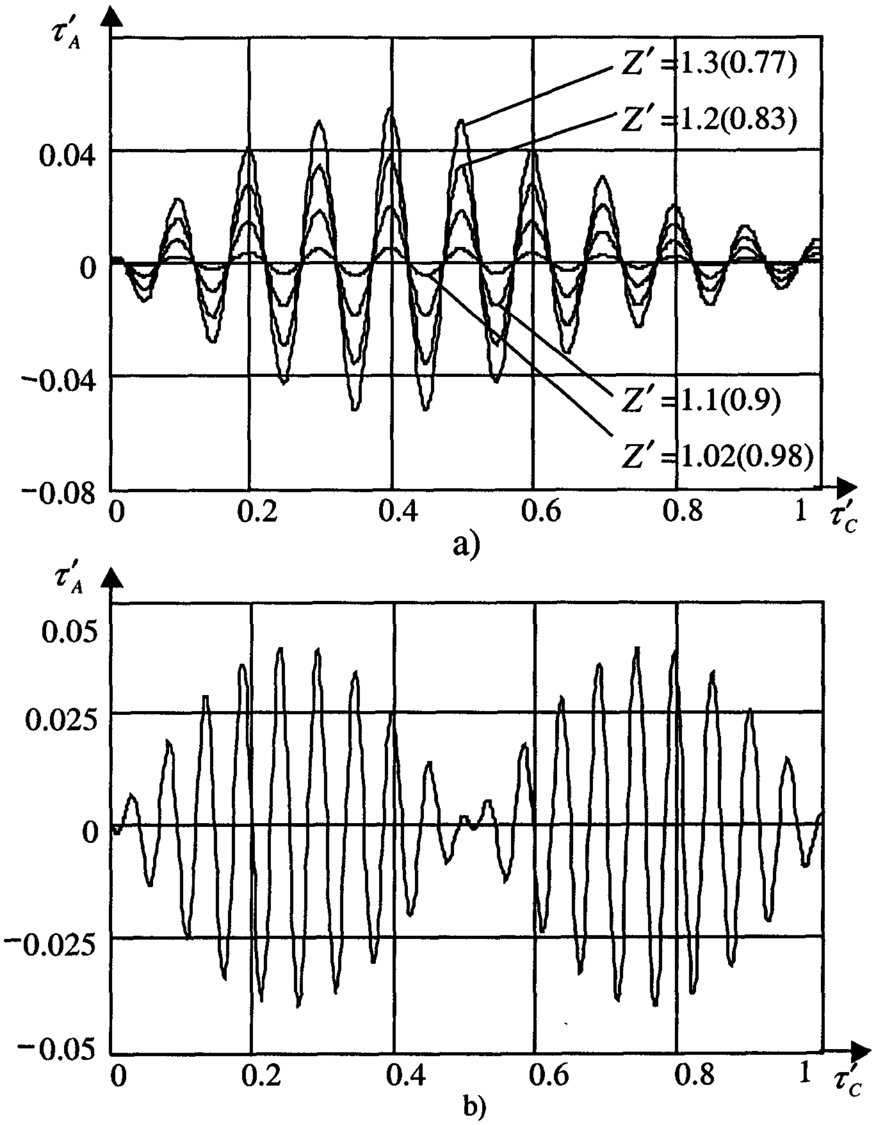

Fig. 5: a) Gaussian radio impulse; b) Double frequency signal.

A device based on the mirror inversion of the signal (MIS) was offered for the ESE measurements, including irreversibility of delays in the AFD and instability of the signal formation devices. With the help of a movable measuring antenna, the device receives the signals radiated by the RMCC and after the MIS the device re-radiates them. In the case of the signal's symmetrical form, this allows one to carry out measurements of the following value with the RMCC

$$\tau = (\tau_r - \tau_{rd}) + 2t_0 + \Delta,$$

where τ_r, τ_{rd} are, respectively, full delays of the RMCC reception and transmission paths including the AFD and the signals formation devices; t_0 is a moment of time; the MIS is carried out relative to it; and Δ is the ESE of the MIS device. Thus, it is possible to define the complete ESE of the RMCC if the parameters t_0 and Δ are known and stable. The stability of t_0 and Δ is ensured at the expense of the primary standard's signals and the MIS digital realization application in the device.

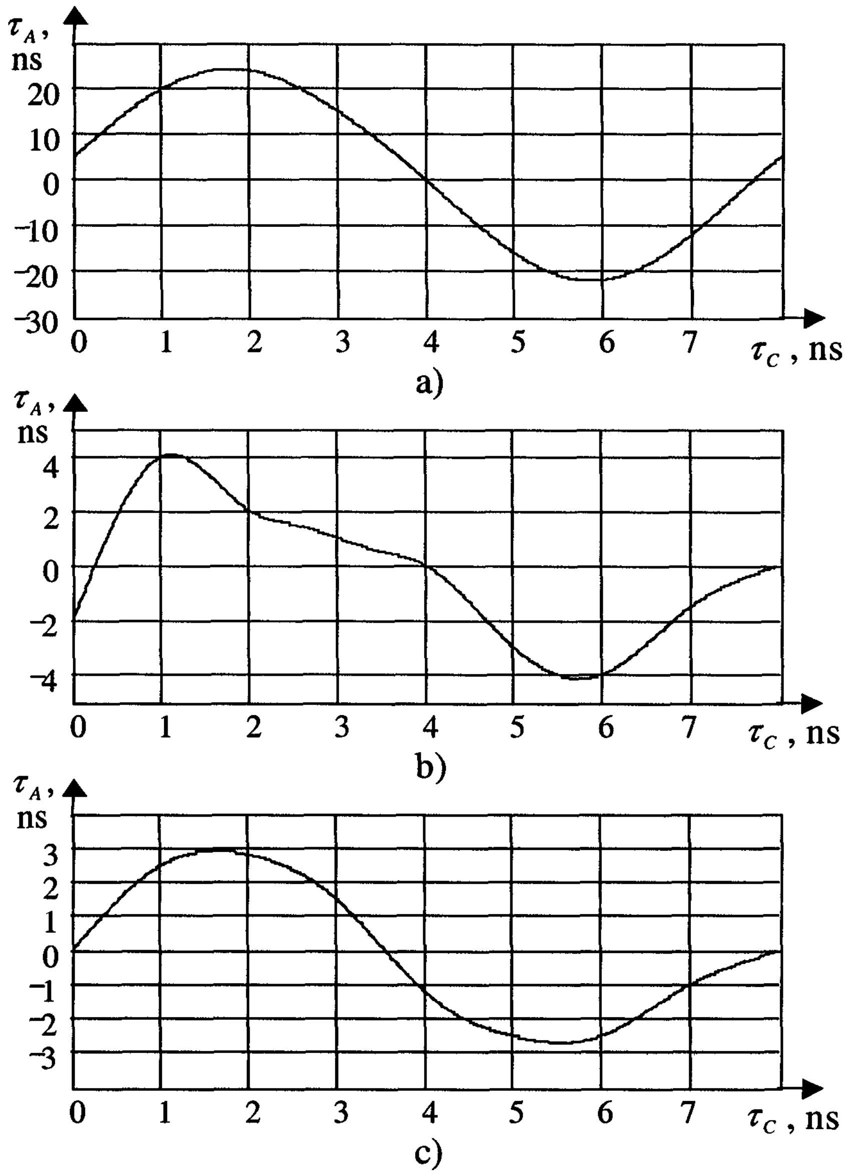

Fig. 6.

MODERN RMCC AND RCM PERSPECTIVES

The complexes "Phase" and "METKA-11" designed according to the phase principle rank among the most perfect RMCC of the last generation. For establishing a contact and eliminating an ambiguity of the phase measurements, the pulses phase-manipulated (PM) by Barker code are used in the complexes, and for high precision phase measurements by the envelope and coherent frequencies, the DFS is used.

The measurement error on the PM signal (≈ 60 ns) allows estimation of the phase measurement ambiguity by the DFS envelope having the spectrum width equal to 1MHz. In its turn the measurement error by the DFS envelope (< 10 ns) allows one to eliminate ambiguities of the phase measurements by the carriers with a corresponding accumulation of measurement results and stability of modern standards. Thus, the resulting measurements error accounts for less than 1 ns. The limitation in obtaining such an error is the ESE alone.

The distinctive features of the RMCC "METKA-11" are as follows: relatively small spectrum width (0.2 MHz); application of the signal's digital processing; measurement of the complete ESE with a device with the MIS; introduction of an additional regime, i.e. of data transmission. The indicated features of the RMCC "METKA-11" allow one to obtain confidently a measurement error less than 1 ns (see Figure 7); they promote solution of the problem of the complex electromagnetic compatibility with the operating systems of a metric wave band and broaden the possibilities of the equipment functional application.

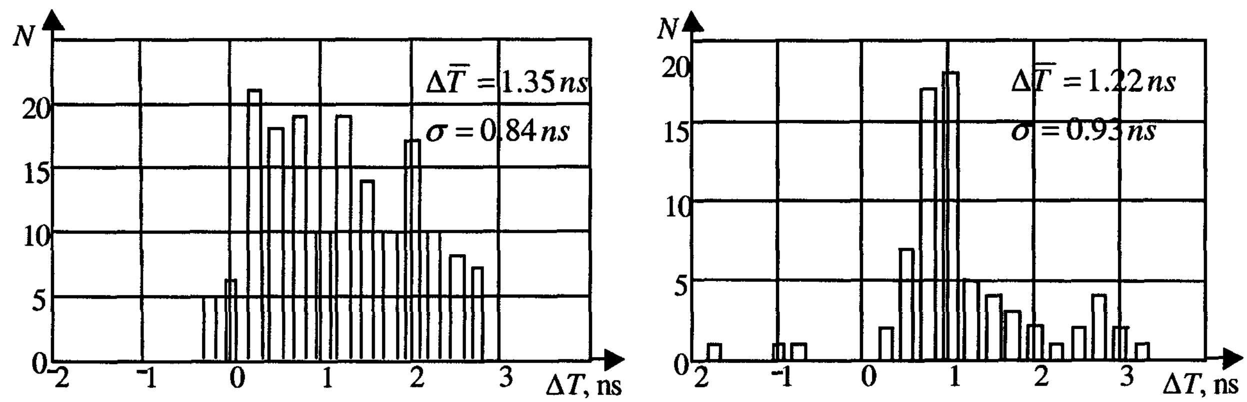

Fig. 7.

Besides the data transmission, the following additional functions of radio meteor comparison equipment are real: measurement of frequency difference and frequency primary standards short-term instabilities; measurement of primary standard scales shift within direct visibility; and conjugation with the communication satellite systems for carrying out the time scales comparison.

Application of the new high-precision radio meteor equipment for time scales comparison can not only raise the functioning RMCS efficiency, but promote its structure and broadening of possibilities. The RMCC application is of a considerable scientific and practical interest for mutual calibrations of comparisons carried out with the GPS and GLONASS systems (in the differential regime), and with communication satellite systems (in the duplex regime). As the analysis showed, the distances from the functioning RMCS points to the leading metrological centers of Europe do not exceed the limiting ones for the RCM. That is why the RCM application does not require organization of the relaying stations.

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