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Translation

SYNCHRONIZATION OF PRECISION TIME AND FREQUENCY STANDARDS

By

Gleb Nikolayevich Paliy and Yelena Vitol'dovna Artem'yeva

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[Annotation, introduction, chapters 1-3, 5-7, references and table of contents from book "Synchronization of Precision Time and Frequency Standards", by Gleb Nikolayevich Paliy and Yelena Vitol'dovna Artem'yeva, Izdatel'stvo standartov, 5,000 copies, 168 pages]

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Annotation

[Text] The book describes the principal methods and means of synchronizing high-stability frequency and time standards with major emphasis on new wide-band systems that have enabled synchronization of standards separated by different distances with error of 1 μs or less. A brief description is given of the corresponding measurement facilities, their basic metrological characteristics are indicated, and an examination is made of possible regimes of synchronization of frequency and time standards. Methods are described for synchronizing frequency and time standards situated in direct proximity to one another, methods of transmitting and calculating travel time of the time and frequency signals in the short-wave and VLF bands, methods and means of synchronization in the VHF and microwave bands. Recommendations are made on determining the irradiance of the transmission path, and on measuring signal delay in receiving and recording equipment, methods of processing measurement results and determining the principal metrological characteristics of measurement facilities. Some information is given on national time services, and on the new UTC [universal coordinated time] system.

The book is intended for scientific workers of the appropriate profile, engineering and technical personnel of various time and frequency services, and may also be of use to undergraduate and graduate students of institutions of higher education.

Tables 12, figures 46, references 51.

Introduction

The unit of time, the second, is one of the principal physical quantities in all systems of units, including SI. The unit of frequency, the hertz, is a derivative unit that corresponds to the frequency of a periodic process such that one cycle of this process occurs in one second.

Until the mid twentieth century, local time was determined with respect to the position of a given point of the earth relative to the sun and stars, it being

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originally assumed that rotation of the planet takes place uniformly. The period of rotation of the earth relative to its axis was taken as a natural time standard, the mean solar day, and the second was defined as 1/86400 of a mean solar day. As measurement technology developed and the requirements for accuracy of measurements increased, the definition of the second underwent considerable changes. Even pendulum clocks showed a systematic slowing down of the diurnal rotation of the earth. To improve accuracy of reproduction of the unit of time, it was redefined in 1960 with reference to the motion of the earth around the sun based on the astronomical definition of universal ephemeris time. The second was calculated as 1/3155925.9747 of the tropical year (time between two vernal equinoxes) for January 0 of the year 1900 at 12 hours ephemeris time. This improved the accuracy of time reproduction by nearly two orders of magnitude.

However, the realization of such accuracy required accumulation of results of astronomical observations over a period of one or two years. Besides, it was established by quartz clocks that even with consideration of the regular slowing down of diurnal rotation of the earth the duration of a day was still inconstant, i. e. the very period of revolution of the earth around the sun is subject to irregular fluctuations. The creation of quantum-mechanical sources of electromagnetic waveforms (these sources are based on the capacity of atoms and molecules to emit and absorb energy with transition from one energy state to another) enabled introduction of the concept of the physical or atomic second in 1967. This was defined as the interval of time required for 9192631770 oscillations corresponding to the resonant frequency of the energy transition between levels of the hyperfine structure of the ground state of an atom of cesium-133 in the absence of perturbations by external fields.

The development of masers enabled refinement of the numerical values of the uniform rotation of the earth. It was established that the secular deceleration of the rotation of the earth due to tidal friction over a century leads to a change in the duration of the day by 0.0016 s. Seasonal nonuniformities in rotation of the earth over half a year cause changes in the duration of a day by ±1 ms (with respect to frequency this amounts to $\sim 1 \cdot 10^{-8}$).

But even with acceptance of the atomic second, the astronomical system of time measurement has not been displaced. The two scales mutually complement one another. The time scale based on the atomic second reproduces an abstract uniform time. It is not associated with the position of the earth relative to the sun or other heavenly bodies, and reproduces a unit of time intervals with temporal zero position that is arbitrary, just as the phase of any waveforms is arbitrary. The scale of ephemeris time reproduces elapsed time with respect to the position of the earth in cosmic space, fixes its position, and changes along with a change in the rate of motion of the earth. The scale of ephemeris time reproduces both an interval and an instant of time. The scale of atomic time reproduces a time interval and stores the instant transferred to it by the ephemeris second.

Units of time and frequency are reproduced by time and frequency standards. The purpose of the frequency standard is to reproduce waveforms with a given value of frequency and predetermined metrological characteristics. The purpose of the time standard is to reproduce a time scale, i. e. a sequence of time intervals with set temporal position of the beginning of the interval (instant of time).

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The assurance of unity of measurements of time and frequency is not merely the reproduction of units of these quantities with minimum errors relative to the State time and frequency standard [Gosudarstvennyy etalon vremeni i chastoty; GEVCh]; assurance of unity of measurements is inseparably tied up with the availability of correspondingly accurate means of synchronization and methods of transmitting time and frequency signals. To ensure unity of time measurements it is necessary not only to synchronize time intervals, but also to correlate the signals of the time scale with the GEVCh scale. The signals from the reference standard that are used to bring the time scales into coincidence do not arrive instantaneously, but over a certain time, and consequently a correction for this time must be introduced into the time scale being synchronized.

The synchronization method is dictated by the method of determining the difference of frequencies or phases of the signals of the synchronizing and synchronized standards in combination with different signal transmission channels. This combination depends on the required precision, the errors of the standards, and their relative location. Analysis of these and many other technical factors in application to specific conditions enables determination of the most effective methods and means.

The main facilities for synchronizing frequency and time standards are radio stations operating in various bands. They transmit information on instants and intervals of time:

by pulse signals, each having a characteristic point that coincides with the instant of onset of some event that determines the beginning of readout of the time standard to be synchronized (pulse systems);

by continuous harmonic oscillations, or waveforms with frequencies that periodically alter phase relations (phase systems);

by pulse signals in which the phase of one of the periods of the carrier frequency is combined with the epoch of the time standard to be synchronized (pulse-phase systems).

As a rule, frequency standards are synchronized with respect to the high-precision carrier frequencies of these radio stations.

It becomes possible to use precise time and standard frequency signals transmitted via radio stations to make an exact check on measurement facilities not only with respect to frequency and time, but also with respect to voltage, power and so on.

At the same time, this method does not completely meet the demands of a large range of users with regard to accuracy and reliability. The error of synchronizing frequency and time standards by these signals is due to many factors, primarily instability of the characteristics of transmitting and receiving equipment and the inconstancy of conditions of radio wave propagation. These components will have various weights for different wave bands.

In the very-low frequency band, the radio wave propagation channel can transmit instants of time signals with a small error of the order of 10 μs, but the time-inconstancy of characteristics of the transmitting and receiving equipment and the passband (150-600 Hz) considerably increases the overall synchronization error.

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The influence of these errors is reduced by increasing the collation time and by using a phase method of tie-in with resolution of ambiguity to the period of the carrier frequency. Besides, VLF radio stations are quite large, expensive to make and costly to operate.

The channel of long-wave radio stations provides precision time and frequency signal transmission with small errors, of the order of a few microseconds, but signal transmission can be accomplished to distances of up to 1200-1800 km, and a network of long-wave stations is needed to cover large territories, and these are also cumbersome and expensive.

Transmitting and receiving equipment for the short-wave band has a relatively wide passband and more stable characteristics. However, due to multibeam signal propagation and shifting of the reflecting layers of the ionosphere, there are considerable losses of precision. Only by using special methods of reception, registration and calculation of the time of signal transmission can the synchronization error be reduced to 50-200 μs.

At the present time, considerable theoretical and experimental research is being done to appreciable improve the accuracy of transmitting the dimension of units of time and frequency, mainly by using wide-broadcast television channels, meteoric communication, artificial satellites, and also natural sources of radiation of periodic electromagnetic oscillations from outer space.

This book describes the most typical methods of synchronizing time and frequency standards with consideration of accuracy requirements. Analysis of these methods may be useful in developing more improved methods and means of synchronization.

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CHAPTER 1: PRECISION FREQUENCY AND TIME STANDARDS

1.1. Metrological Characteristics

Of primary significance for frequency standards are metrological characteristics of frequency of the generated waveforms; by the same token, the most important for time standards are metrological characteristics of the reproduced time intervals and instants.

As is true of all other quantities, frequency may have systematic and random patterns of change. To evaluate these, it is necessary to know some frequencies during time intervals τ_{dis} over which it is required to establish the changes that occur.

The frequency of the oscillations at time t (the instantaneous frequency) is the derivative of phase with respect to time

$$f = \frac{1}{2\pi} \frac{d\varphi}{dt}. \qquad (1.1)$$

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If on the extent of some time interval there is little variation in phase and amplitude of the oscillations, then the instantaneous frequency is the frequency of harmonic oscillations in this time interval.

Measurement of the frequency of oscillations, like any physical quantity, requires a time over which the measured quantity is averaged. The frequency is taken as the mean value for the time-averaging interval τ_y, and it is the integral of the instantaneous frequency f on this interval (Fig. 1)

$$f_{t_1} = \frac{1}{\tau_y} \int_{t_1'}^{t_1''} f dt, \tag{1.2}$$

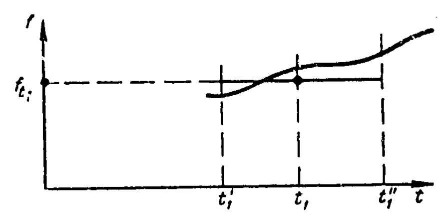

Fig. 1. Frequency averaging in the interval $t_1'' - t_1'$

where t_1', t_1'' are the instants bounding τ_y, and are symmetrically situated relative to instant t_1; $\tau_y = t_1'' - t_1'$. Each frequency is obtained as the mean value over the same averaging intervals. The averaging interval may be equal to the interval of discreteness--the interval over which the metrological characteristics of the frequency standard are determined (Fig. 2).

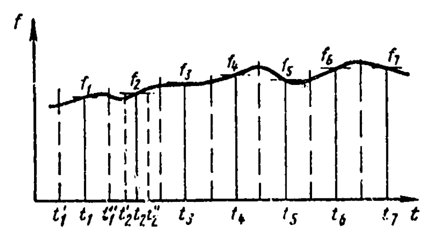

Fig. 2. Discrete series of average frequencies

We can take $\tau_y < \tau_{dis}$ under condition that the frequency in the time interval between measurements ($t_2' - t_1''$, $t_3' - t_2''$ and so on) varies linearly.

The mean value of the frequency over τ_y can be found either by continuous measurement over time $\tau_m = \tau_y$, or by repeated discrete measurement each time over a period $\tau_m < \tau_y$.

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In continuous frequency measurement by the method of direct estimation with the use of a counting-type frequency meter, its reading is the mean frequency over the measurement time equal to the time of averaging ($\tau_m = \tau_y$).

In direct frequency measurement by a differential method, and in direct measurement of the difference frequency F, the mean frequency is obtained as a result of the calculation

$$f = f_n + F, \tag{1.3}$$

where f_n is the nominal frequency.

In discrete measurement, the mean frequency in time τ_y is calculated as the arithmetic average of the resultant values

$$\bar{f} = \frac{\sum_{i=1}^{n} f_i}{n}. \tag{1.4}$$

Continuous frequency measurement can be replaced by discrete measurement in time intervals during which the frequency changes linearly.

The metrological characteristics of the frequency standard are:

nominal frequency f_n,
effective frequency f_e,
frequency error--error of the standard γ,
error of effective frequency S_f,
systematic regular change in frequency in time ν,
variation, random changes of frequency, a.

The nominal frequency is the value that is to be reproduced by the frequency standard; it is the nameplate value.

The effective frequency f_e (or simply f) is determined by comparing the given standard with one of greater precision. During utilization of the standard, the frequency of the generated waveforms varies, and hence f_e differs from f_n.

The frequency of the oscillations is a function of time, and at time t

$$f_t = f_{t_0} + \nu(t - t_0) \pm a, \tag{1.5}$$

where $t - t_0$ is expressed in intervals of discreteness time τ_{dis}.

In precision frequency standards the time dependence of ν can be observed only over long time intervals, and the frequency variation can be described by a second-degree polynomial in which ξ is taken as a linear component of the systematic change in frequency in interval $t - t_0$, and the quadratic component q of this change is negative. Then

$$f_t = f_{t_0} + \xi(t - t_0) + q(t - t_0)^2 \pm a. \tag{1.6}$$

Hence the relative error of the standard is

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$$\gamma_{0_t} = \gamma_{0_{t_0}} + \xi_0 (t - t_0) + q_0 (t - t_0)^2 \pm a_0, \tag{1.7}$$

where

$$\gamma_{0_t} = \frac{f_t - f_n}{f_n};\ \gamma_{0_{t_0}} = \frac{f_{t_0} - f_n}{f_n};$$
$$\xi_0 = \frac{\xi}{f_n};\ q_0 = \frac{q}{f_n};\ a_0 = \frac{a}{f_n}.$$

For small time intervals (of measurement and discreteness), ξ is taken as constant, $q = 0$, and all supplementary measurements are evaluated as random.

The effective frequency is the average value for the time of measurement. If the frequency is measured by the method of direct estimation using a counting-type frequency meter, the averaging is done directly by the frequency meter, and the error of the resultant value is equal to that of the meter. If a differential method is used in which the measured frequency is compared with a calibrated value f_{cal}, the averaging time shall not be less than one period of their difference frequency F, and the measurement result is the number of periods n of the difference frequency over the measurement time

$$f_e = f_{cal} + \frac{n}{\tau_m}, \tag{1.8}$$

The error of the resultant value is

$$S_{0f} = \gamma_0 \frac{\Delta\tau}{\tau_m}, \tag{1.9}$$

where $\Delta\tau$ is the error of measurement of time τ_m,

$$\gamma_0 = \frac{F}{f_e}.$$

In determining f_e as a result of discrete measurements by the method of direct estimation or by the differential method, the measurement is made over the extent of τ_m through equal intervals of time τ. Determined at each measurement is the unit value of f_i, the average over τ_m, and the arithmetic average is taken from values obtained over time $\tau_y = n\tau$ [see formula (1.4)].

The error S_f is the mean square error of the result

$$S_f = \sqrt{\frac{\sum_{i=1}^{n} (f_i - \bar{f})^2}{n(n-1)}}. \tag{1.10}$$

In doing this, the systematic change in frequency over τ_y can be disregarded, or rather τ_y must be selected so that the systematic change in frequency over this time will be small compared with random changes.

The error of the standard is determined for time intervals during which the changes of frequency are less than the error of measurement of the effective frequency.

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The error of the standard can be either determined from the effective frequency, or measured directly (although the measurement of an error sounds somewhat paradoxical). For example if the differential method of comparing the frequency of the standard with a calibrated frequency is used, the difference between the effective and nominal values is measured directly, i. e. the frequency error (if the error of the calibrated frequency can be disregarded).

The effective frequency can be determined by a phase method--measurement of the time interval τ_m during which the phase difference between oscillations has changed by 2π. Then

$$f_e = f_{cal} + \frac{1}{\tau_m}. \quad (1.11)$$

To measure or check the numerical values of changes of frequency of precision standards, discrete measurements are taken of the frequency of the standard over some sample time interval τ_s. By analogy with sampling monitoring, the sample time interval should be such that it can be assumed with a sufficient degree of probability that values of metrological characteristics determined over this time will be retained by the standard until the next check or certification. The times between intervals are established by regulations for different types of standards, and times between certifications are established by the rules of certification of precision frequency standards.

Based on a number of values of frequency obtained in intervals τ_s through predetermined times τ_{dis}, the average values of frequency changes over this time interval are calculated.

Precision frequency standards have a systematic variation that is constant over comparatively short intervals τ_s, that is time-independent, and that can be easily calculated from the formula

$$\xi_0 = \frac{f_n - f_1}{f_n(t - t_0)}, \quad (1.12)$$

where f_n is the effective frequency at the last n-th measurement; f_1 is the same at the first measurement, n is the number of measurements, $t - t_0 = \tau_s$ (expressed in τ_{dis}).

Random changes of frequency are evaluated by the mean square value of the frequency variation

$$a_n = \frac{1}{f_n} \sqrt{\frac{\sum_{k=1}^{n} [(f_{k+1} - f_k) - \xi]^2}{n-1}}. \quad (1.13)$$

The average values of the metrological characteristics of the standard as determined with finite n will be the more exact the greater the n. At n = 10, the deviations of the resultant numerical values of these characteristics from the true values do not exceed 50% [Ref. 1]. Therefore in calculating mean values it is necessary to have at least ten independent measurement results.

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Frequency instability is the term used for the degree of variability of the frequency of the continuously operating standard. As we can see, this is the sum of systematic and random changes. Until recently, the principal characteristic of higher-class frequency standards was constancy, frequency stability numerically characterized by the value of its instability. After quantum frequency standards had been introduced into the time and frequency service, the accuracy of the frequency of reproduced oscillations as characterized by the error of the effective value came to be just as important an indicator. Therefore it would now be more correct to call higher-class frequency standards "high-precision" rather than "high-stability."

Precision time standards (clocks) are based on a precision frequency standard, and therefore the error of the time intervals that they reproduce and their instability are in a one-to-one relationship with the analogous characteristics of the precision frequency standard.

The temporal position of the beginning of a time interval (instant of time) is described by the expression

$$T_t = T_0 + \int_{t_0}^{t} \gamma_0 dt, \quad (1.14)$$

where T_0 is the temporal position of the beginning of the interval at some instant t_0, and γ_0 is the relative error in time interval $t - t_0$.

The constant value of the error of the frequency standard in interval $t - t_0$ leads to a linear rise in the correction of the time standard

$$U_t = \gamma_0 (t - t_0) \quad (1.15)$$

and to a constant rate of going of the frequency standard (clock rate)

$$g = \frac{U_t - U_{t_0}}{t - t_0} = \gamma_0. \quad (1.16)$$

The systematic frequency change described by a second-degree polynomial produces corresponding changes in the correction and rate of going of the time standard. For example the correction at time t is

$$U_t = \gamma_0 (t - t_0) + \frac{1}{2} \xi_0 (t - t_0)^2 + \frac{1}{3} q_0 (t - t_0)^3, \quad (1.17)$$

and the rate of the time standard in the interval $t - t_0$ is

$$g = \gamma_0 + \frac{1}{2} \xi_0 (t - t_0) + \frac{1}{3} q_0 (t - t_0)^2. \quad (1.18)$$

Different combinations of values of γ_0, ξ_0 and q_0 lead to different changes in the errors of the frequency standard and the moment of signals of the time standard.

1.2. Structure of High-Precision Standards

A quartz oscillator is a low-noise generator of stable electric waveforms in which the tank circuit is a quartz crystal that has piezoelectric properties. The

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combination of the large piezoelectric effect of quartz with high homogeneity of crystals, and low dependence of its physical parameters on external conditions ensures high frequency stability of the generated waveforms.

Quartz oscillators are used as precision frequency standards in a variety of electronic measurement systems, and up until quantum frequency standards appeared, groups of quartz oscillators were used as frequency standards.

Frequency instability of the signals of a quartz oscillator is caused by inconstancy of the parameters of the quartz resonator and the excitation circuit arising as a result of internal changes in the oscillatory system, variations in the working conditions and in the oscillator load. Frequency changes can be calculated for different oscillator circuits as a function of the change in individual circuit parameters, variation of interelectrode capacitances and the transconductance of the tube or transistor, or the change in active losses in the circuit [Ref. 2].

The total effect of all factors that influence frequency causes systematic and random frequency variations. Systematic changes occur mainly due to aging of the quartz resonators, and immediately after manufacture may reach 10^{-7}-10^{-8} per day, gradually decreasing to $(1-2)\cdot 10^{-9}$ per month.

In one of the radio centers of the State Time and Frequency Service, the reference frequency standard is a quartz oscillator in a silicon transistor circuit with X-cut quartz-crystal resonator. The influence of external temperature variation on the frequency of the oscillator is eliminated by using double thermostatting, the ΔT of the inner thermostat being $<10^{-3}\,°C^{-1}$. Reliable isolation of the excitation circuit from the external load is accomplished by using common-base amplifiers, and the output stages are accommodated together with the circuit of the next-to-last stage in a separate shield. Each stage of the circuit has a separate supply stabilizer, and in addition there is a common stabilizer for the input supply voltage. As a result of prolonged use it has been established that the mean square deviation of frequency is $a_0 \cong 10^{-12}$, and the systematic diurnal variation of frequency is $\xi_0 \cong (3-4)\cdot 10^{-12}$ [Ref. 3].

By now the theory of the quartz oscillator and methods of constructing it have been fairly well worked out [Ref. 4-6], so that the capabilities of the quartz oscillator with respect to getting high-stability waveforms have been nearly exhausted.

Fundamentally new methods of high-precision reproduction of electromagnetic oscillations have been suggested by radiospectroscopy and quantum electronics [Ref. 7]. Microsystems of atoms and molecules emit or absorb electromagnetic oscillations with frequency depending nearly exclusively on the structure of the microparticle, and therefore being nearly absolutely constant. Microsystems are made up of a comparatively small number of elementary particles (electrons, protons and neutrons), and therefore removal of any of them appreciably changes the properties of the microsystem. The continuous changes of properties inherent in macrosystems are impossible in microsystems.

One of the major properties of a microsystem is the discrete set of values of its internal energy E. In a microsystem isolated from external factors, the energy spectrum always remains invariant. Interaction of atoms and molecules with an

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electromagnetic field may cause a change in the internal energy as a result of transition of the microsystem from one energy state to another by amounts described by the well-known formula

$$h\nu_{nk} = E_n - E_k, \tag{1.19}$$

where h is Planck's constant, ν_{nk} is the frequency of emission or absorption, E_n and E_k are energy levels between which the transition has taken place.

Transitions from one level to another can occur spontaneously, independently of external actions on the microparticles, or can be induced by external radiation. Spontaneous transitions are random. Their principal characteristic is the average time during which the transition occurs, amounting to about 10^{-8} s. The overall spontaneous emission is incoherent, i. e. non-unidirectional and non-monochromatic. In a stimulated transition, when an atom transfers energy to the electromagnetic field, which is intensified as a consequence, the frequency of the induced radiation coincides exactly with that of the stimulating emission. Induced transitions are the basis for operation of quantum generators of monochromatic coherent radiation.

If an active substance with population of an upper level E_2 greater than that of a lower level E_1 is acted on by an electromagnetic field with frequency

$$\nu = \frac{E_2 - E_1}{h},$$

the number of induced transitions from E_2 to E_1 will exceed the number of absorptions with transitions from E_1 to E_2, and as a result the field will be intensified by the internal energy of the atoms. Placement of the active substance in a cavity resonator with large Q tuned to the frequency of the transition $E_2 \rightarrow E_1$ brings about conditions for generation of oscillations.

However, under conditions of thermodynamic equilibrium between the substance and the ambient medium, Boltzmann's law states that lower energy levels are more densely populated than upper levels. Therefore ordinary matter absorbs the energy of the stimulating electromagnetic field rather than amplifying it.

Several methods can be used to upset the equilibrium state and set up population inversion.

The first method is spatial separation of atoms that are on different energy levels. A beam of noninteracting atoms is passed through an inhomogeneous electric or magnetic field. The effect of such a field on an atom depends on energy: with an increase in a continuous field, the energy of the lower level decreases, while that of the upper level increases. As atoms pass through an inhomogeneous field they will tend to approach the region where the resultant potential energy will be minimum. Consequently, the atoms that are on the upper energy level will go toward the weaker field, while atoms on the lower level will go toward the strong field region.

The second method is to disrupt thermal equilibrium by using auxiliary emission (method of pumping). A three-level system (E_1, E_2 and E_3) is subjected to the action of an auxiliary field whose frequency is equal to that of the transition

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between levels E_1 and E_2, and as a result the population of E_3 increases. Inverse population of levels E_2, E_3 is set up, enabling amplification or stimulated emission of waveforms in such a substance.

Each atom has its own inherent set of spectral lines on definite frequencies with different natural widths and shapes. Corresponding to the tip of the spectral line is some resonant frequency that is a reference frequency. Measurement of the frequency of the tip of the spectral line is the basic job of a device designed for operation as a precision frequency standard, called the quantum frequency standard (QFS).

Since the reference frequencies of spectral lines expressed in SI units have values that are inconvenient for practical use, the QFS is based on the principle of stabilizing the frequency of the output of the quartz oscillator with respect to the frequency of electromagnetic radiation upon transition of atoms of a substance from one state to another.

There are several types of QFS that differ with respect to methods of fixing the tip of the spectral lines and arrangements for automatic frequency control of the quartz oscillator.

The active QFS is an arrangement with a maser whose output signal controls the frequency of a quartz oscillator via a phase AFC system. The passive QFS arrangement contains a quantum discriminator whose signals are used to control the quartz oscillator frequency by means of a frequency AFC system.

Most completely developed at present are QFS's based on cesium-133, atomic hydrogen and rubidium-87.

Cesium Frequency Standard

The cesium frequency standard is a passive QFS. The tip of the spectral line is fixed by determining the number of atoms that have undergone a quantum transition [Ref. 8].

The quantum discriminator or atomic-beam tube (ABT) was developed as a result of perfecting the radiospectroscope. Cesium-133 atoms are used as the working substance.

The energy of interaction between magnetic moments of electrons and nucleus appears as one of the components in the overall energy of the cesium atom. As a consequence of the interaction, a hyperfine structure is formed, and the increment of energy of the ground level E_0 is

$$\Delta E_0 = a\bar{I}\bar{J} = \frac{a}{2}[F(F+1)] - [I(I+1) - J(J+1)], \quad (1.20)$$

where a is the hyperfine splitting constant, $I = 7/2$ is the quantum number of the spin moment of the nucleus $\bar{I}$, $J = 1/2$ is the quantum number of the angular moment of the electron shell $\bar{J}$, $F = \bar{I} + \bar{J}$ is the quantum number of the total moment of momentum of the atom. Depending on the mutual orientation of moments, F may take on values of $I + J = 4$ and $I - J = 3$, and as a consequence the ground level is split into two hfs levels.

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In the presence of an external magnetic field, the magnetic moments of the nucleus and electron shell interact with this field, and each hfs level is split into 2F+1 sublevels corresponding to certain states of the atom, and characterized by quantum numbers F and m_F that take on values of 0, ±1. The upper level (F = 4) is split into 2F+1 = 9 sublevels, and the lower level (F = 3) is split into 2F+1 = 7 sublevels. In the case of electromagnetic field action, there may be transitions between the hfs levels.

The cesium QFS uses the transition between levels F = 4; $m_F = 0 \rightleftarrows F = 3$; $m_F = 0$, the frequency of which in Hz is

$$f = 9192631770 + 267 \cdot 10^4 H_0^2, \qquad (1.21)$$

where H_0 is the intensity of the external magnetic field in A/m.

The atomic-beam tube is a radiospectroscopic vacuum device (Fig. 3). The atomic beam is shaped by collimator 1 of the beam source, and enters an inhomogeneous magnetic field set up by permanent magnets 2 of a certain shape--stronger at the north pole, and weaker at the south pole.

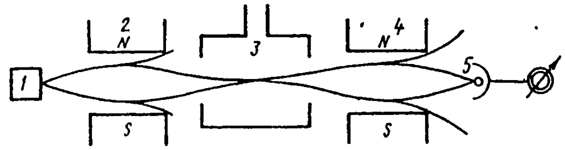

Fig. 3. Atomic-beam tube

Cesium atoms have a magnetic moment, and therefore in a magnetic field they experience the action of a force with direction that depends on the energy state of the atoms.

Fig. 3 shows two rays I and II that bound the atomic beam. There are atoms on two energy levels in both rays. Upon arrival in the inhomogeneous field, the atoms of ray I that are in upper energy state E_2 move toward the weaker field, changing their trajectory and approaching the axis, while atoms on level E_1 move into the stronger field region, deviating further from the axis.

Atoms of ray II experience an analogous effect of the field, resulting in deflection of atoms on level E_2 away from the axis, while atoms on level E_1 approach the axis.

Thus after magnet 2, atoms on level E_2 remain in ray I, and atoms on level E_1 remain in ray II. The second magnetic field of magnet 4 is identical to the first, and therefore as the two rays of the sorted atoms arrive in this field they would diverge away from the axis. But placed between the magnets is cavity resonator 3 in which a constant uniform magnetic field is set up together with a microwave electromagnetic field with frequency equal to that of the quantum transition between levels E_2 and E_1. The cesium atoms, entering the resonator after magnet 2, undergo quantum transitions resulting in the appearance of atoms with level E_1 in ray I,

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while atoms with level E_2 appear in ray II. As these atoms enter the field of magnet 4, they will be deflected toward the axis. Consequently receiver-detector 5 placed on the axis will register a current proportional to the number of atoms that have undergone a quantum transition in the cavity resonator. This number of atoms depends on the detuning of the microwave field frequency relative to the frequency of the atomic transition, and therefore the dependence of receiver current on microwave field frequency has the shape of a spectral line.

A simplified diagram of the Ch1-42 frequency standard is shown in Fig. 4 [Ref. 2].

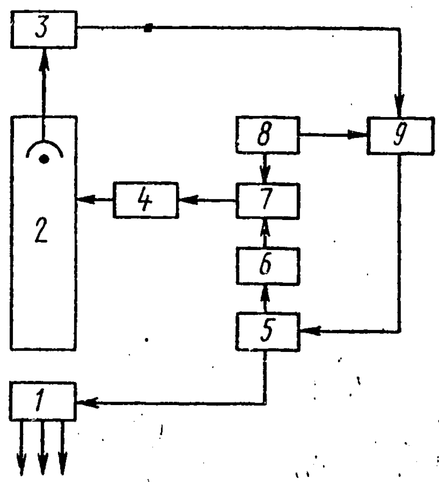

Fig. 4. Simplified block diagram of cesium frequency standard: 1--frequency divider, 2--ABT; 3--amplifier; 4--waveguide input; 5--quartz oscillator; 6--frequency synthesizer; 7--multiplier; 8--low-frequency oscillator (80 Hz); 9--phase detector

The frequency of quartz oscillator 5 is adjusted by a synthesizer and frequency multiplier to the frequency of the atomic transition $f = 9192631770$ Hz, and the electromagnetic field on this frequency is sent to the cavity of the ABT. Under the action of this field, the cesium atoms undergo transitions, and the signal at the output of the ABT taken from the detector determines the deviation of the microwave field frequency from the transition frequency. To determine the direction of the deviation, the voltage from the quartz oscillator is frequency-modulated on a low frequency by voltage from oscillator 8. If the frequency of the microwave field is lower than the transition frequency, the phase of the signal at the output of the ABT coincides with the phase of the modulating voltage, and if the microwave field frequency is higher than the transition frequency, the ABT signal is 180° out of phase.

A constant voltage with magnitude determined by the frequency difference and polarity determined by the sign of the difference is formed on phase detector 9 as a result of adding the voltages from the output of the ABT and the modulating oscillator. This voltage, called the error signal, synchronizes the frequency of the quartz oscillator.

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The mean square hourly frequency variation of the Ch1-42 is $5 \cdot 10^{-11}$, and the daily variation is $2 \cdot 10^{-11}$.

Hydrogen Frequency Standard

The hydrogen frequency standard is an active QFS that contains a hydrogen maser, a phase AFC system and a tunable quartz oscillator [Ref. 9].

As in the ABT on atoms of ^{133}Cs, the hydrogen maser also uses energy transitions between hfs levels. for hydrogen atoms $I = \frac{1}{2}$, $J = \frac{1}{2}$, and therefore $F = \frac{1}{2} - \frac{1}{2} = 0$, or $F = \frac{1}{2} + \frac{1}{2} = 1$. The level $F = 0$ is not split in the external magnetic field, and level $F = 1$ is split into $2F + 1 = 3$ sublevels. Levels with $m_F = 0$ are less dependent than other levels on the external magnetic field, and therefore they are also used in the QFS. Transition between these levels $F = 0$, $m_F = 0 \rightleftarrows F = 1$, $m_F = 0$ corresponds to the frequency

$$f = 1420405751.6 \text{ Hz} + 1720 \cdot 10^4 \, H_0^2.$$

The construction of the hydrogen maser is diagramed on Fig. 5.

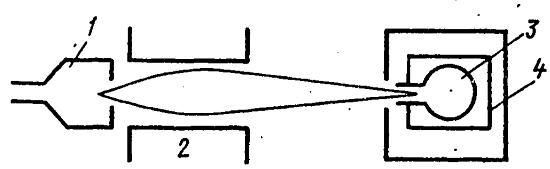

Fig. 5. Construction of hydrogen maser:
1--atomic beam source; 2--magnets; 3--accumulator flask;
4--cavity resonator

Hydrogen in nature exists in the form of molecules, and therefore as it enters atomic beam source 1 it is subjected to the action of a high-frequency electric discharge to dissociate the molecules. The hydrogen atoms streaming out in a parallel beam are incident on the inhomogeneous field of magnet 2, which is weakest on the axis of motion of the atomic beam, and increases with distance from the axis. Due to the presence of a magnetic moment, the hydrogen atoms that are on the upper energy level ($F = 1$, $m_F = 0$) will approach the axis as they enter such a magnetic field, while those on the lower energy level ($F = 0$, $m_F = 0$) will be deflected away from the axis. The excited atoms are focused on the input to cavity resonator 4, tuned to a frequency of approximately 1420.405 MHz. In the cavity the excited atoms undergo an induced transition to the lower energy level, resulting in amplification of the electromagnetic field in the cavity, so that newly arriving atoms interact with the amplified field. In this way a feedback is set up between the atoms entering the cavity, which may lead to stimulated emission of electromagnetic oscillations under certain conditions when the Q of the cavity is sufficient. However, since the energy radiated by even the most intense beam of hydrogen atoms is very small, it is impossible to bring hydrogen atoms to a state of stimulated emission by using resonators alone, even with the highest Q.

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To increase the number of radiative transitions, a quartz accumulator flask 3 with very small input opening is placed in the cavity. Upon entering the flask, a hydrogen atom may undergo several tens of thousands of collisions with the teflon-covered walls of the flask before a quantum transition occurs, i. e. the atom may interact with the resonator field for several seconds. In this case the probability of a stimulated transition is considerably increased.

To ensure prolonged stay of hydrogen atoms in the accumulator flask, there is a considerable increase in vacuum requirements in the vicinity of this flask--$(1\text{-}5)\cdot 10^{-5}$ Pa. Since the pressure may be appreciably higher in other parts of the hydrogen maser, the vacuum system of the device is two- or three-chambered with a separate evacuation chamber.

The duration of interaction of atoms with the resonator field makes the spectral line quite narrow (0.5-0.3 Hz). The Q of the line is $Q_l = 10^9$. However, due to the Doppler effect, chaotic movement of the hydrogen atoms in the accumulator flask may cause appreciable line broadening. This broadening is eliminated by appropriate choice of the flask diameter: the distance between its walls should be less than a wavelength of the stimulated emission.

The Ch1-44 hydrogen standard is series produced. A simplified block diagram of the device is shown in Fig. 6 [Ref. 2].

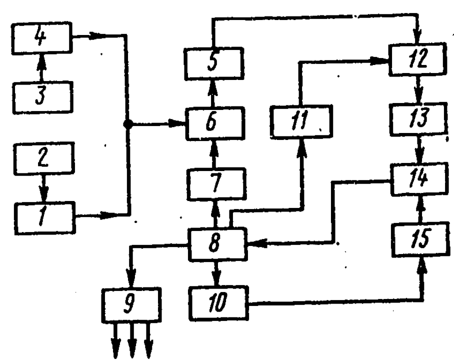

Fig. 6. Simplified block diagram of the Ch1-44 hydrogen frequency standard:
1, 4--ferrite diode; 2, 3--hydrogen maser; 5--i-f amplifier (20.405 MHz); 6, 12--mixer; 7--multiplier by 280; 8--quartz oscillater (5 MHz); 9--dividers by 5 and 10; 10--divider by 5; 11--multiplier by 4; 13--i-f amplifier (405751.6 Hz); 14--phase detector; 15--frequency synthesizer

The vacuum space of each hydrogen maser consists of two chambers. The pressure in the first is maintained at $(4\text{-}6)\cdot 10^{-4}$, while that in the second is held at $4\cdot 10^{-5}$ Pa. The beam of atoms is shaped by a collimator consisting of 300 channels, each 500 μm in diameter. Sorting is done by a six-pole magnet 80 mm long with distance of 3.2 mm between poles. Diameter of the accumulator flask is 150 mm, diameter of the input channel is 6.5 mm, and its length is 65 mm. The resonator

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is placed in a thermostat, where a constant temperature is maintained with deviation of ±0.03°C. The frequency of the quartz oscillator is controlled by a phase AFC system.

The output signal of hydrogen maser 3 with frequency of 1420.4057516 MHz is sequentially converted to intermediate-frequency signals on 20.4057516 MHz and 405.7516 kHz by mixing (heterodyning) with quartz-oscillator heterodyne signals on 1400 and 20 MHz. Arriving at phase detector 14 are the converted signal from the hydrogen maser with frequency of 405751.6 Hz, and the signal from the quartz oscillator converted by synthesizer 15 to the same frequency. At the output of the phase detector an error signal is produced that tunes the frequency of the quartz oscillator to that of the hydrogen maser.

Mean square hourly and daily frequency variations are $(2-5)\cdot 10^{-13}$.

Rubidium Frequency Standard

The method of optical pumping [Ref. 10] is used to set up population inversion of energy levels. In rubidium atoms, three energy levels are used with two transitions, the frequency of one f_{23} lying in the optical band, while that of the other f_{12} is in the r-f region.

The rubidium vapor is exposed to intense light with frequency corresponding to transition $E_2 \rightarrow E_3$, causing the population of level E_3 to rise, and the system is brought to equalization of populations on levels E_2 and E_3 (the rubidium vapor becoming transparent). Then the same working substance, rubidium vapor, is exposed to an electromagnetic microwave field with frequency equal to that of the transition $E_1 \rightarrow E_2$. Absorbing the energy of the field, the rubidium atoms make the transition from level E_1 to E_2, increasing the population of E_2 at the expense of E_1. A difference in populations of E_2 and E_3 arises once more, and the transparency of the substance decreases in proportion to the number of atoms making the transition from level E_1 to E_2. This number is maximum when the frequency of the microwave field coincides with that of transition f_{12}. The curve showing the dependence of optical transparency as a function of microwave field frequency takes the form of the spectral line of rubidium atoms with peak at frequency f_{12}.

The series-produced Ch1-43 instrument uses atomic transition $F = 2,\ m_F = 0 \rightleftarrows F = 1\ m_F = 0$ in the hyperfine structure of the ground state of the rubidium-87 atom on frequency of 6884.682614 MHz.

In a spectral lamp filled with ^{87}Rb a high-frequency oscillator sets up a discharge and the frequency spectrum emitted by the lamp contains a frequency equal to that of the microwave transition. The light from the lamp, passing through optical and thermal filters (the former suppresses the line corresponding to the frequency of transition $E_1 \rightarrow E_3$, and the latter obstructs the path of the heat flux from the lamp), enters an absorption cell, excites the rubidium atoms, raising them to the upper level, and is incident on a photodiode.

The absorbing cell is a glass flask with flat end faces filled with rubidium vapor. It is placed in a cylindrical resonator with grating end faces for transmitting pumping light; this cavity is tuned to the microwave transition frequency.

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As a result of chaotic motion of the rubidium atoms in the absorbing cell, just as in the accumulator flask of the hydrogen maser, considerable broadening of the spectral line takes place as a consequence of the Doppler effect. But since the electron shell of the rubidium atom is more complicated than for hydrogen, the Doppler effect cannot be suppressed merely by proper choice of the dimensions of the flask. And the rubidium atoms in the cell are doped with inert gases, the rubidium atoms having less sensitivity to collisions with these inert gas atoms than to collisions with the walls of the flask. A simplified block diagram of the Ch1-43 rubidium standard is shown in Fig. 7 [Ref. 2].

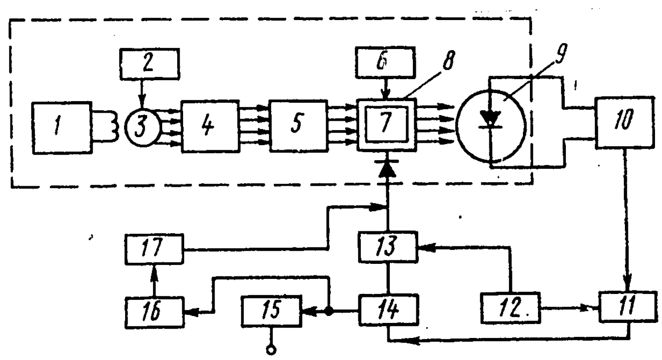

Fig. 7. Simplified block diagram of Ch1-43 rubidium frequency standard:
1--exciter of spectral lamp; 2--lamp thermostat; 3--spectral lamp; 4--thermal filter; 5--optical filter; 6--thermostat; 7--absorption cell; 8--resonator; 9--photodiode; 10--amplifier; 11--phase detector; 12--low-frequency oscillator; 13--multiplier; 14--quartz oscillator; 15, 16--divider; 17--frequency synthesizer

The frequency of quartz oscillator 12 is brought by multiplier 10 and synthesizer 17 to the transition frequency, is modulated by the voltage of low-frequency oscillator 12, and is coupled by a loop into cavity resonator 8. The absorption of light by rubidium vapor in cell 7 depends on deviation of the frequency of the microwave signal from the transition frequency. And since the microwave signal is frequency-modulated, the light beam passing through the cell from light source 3 is also modulated by this frequency. The light beam acts on photodiode 9, and an error signal is produced at the output of this photodiode with the frequency of the modulating signal cophased with the modulation frequency if the microwave field frequency is less than that of the transition, and 180° out of phase if the microwave field has a frequency higher than that of the transition. The signal from the output of the photodiode passes through amplifier 10 and is summed in phase detector 11 with the signal of the modulating oscillator, forming a constant voltage at the output proportional the the frequency difference of the microwave field and the quantum transition; the polarity determines the sign of this difference. The voltage regulates the frequency of the quartz oscillator with respect to the quantum transition frequency.

The mean square hourly variation of the frequency of the Ch1-43 is $5 \cdot 10^{-11}$.

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CHAPTER 2: TYPES OF SYNCHRONIZATION OF PRECISION FREQUENCY AND TIME STANDARDS

Synchronization is what we call adjustment of the period of synchronized oscillations to the period of synchronizing signals. Synchronization of a frequency standard means adjustment of the frequency f_c of the oscillations that it reproduces to the value $f_{\text{э}}$ associated with the frequency of the synchronizing standard assigned an integral value n that may be multidigital. Consequently, in synchronization it is necessary to satisfy the equality

$$nf_c - f_{\text{э}} = 0 \text{ or } f_c - f_{\text{э}} = 0. \tag{2.1}$$

For practical purposes, these equalities are not equal to zero, and their value is the synchronization error

$$nf_c - f_{\text{э}} = \psi_f \text{ or } f_c - f_{\text{э}} = \psi_f. \tag{2.2}$$

The frequency errors of both the synchronized and synchronizing standards are inconstant in time. If it is assumed that at the point of collation they are respectively described by the relations

$$\underset{t}{\gamma_{0.c}} = \underset{t_0}{\gamma_{0.c}} + \nu_{0.c}(t - t_0) \pm \underset{t-t_0}{a_{0.c}} \tag{2.3}$$

and

$$\underset{t}{\gamma_{0.\text{э}}} = \underset{t_0}{\gamma_{0.\text{э}}} + \nu_{0.\text{э}}(t - t_0) \pm \underset{t-t_0}{a_{0.\text{э}}}, \tag{2.4}$$

then the relative synchronization error is

$$\psi_{0_f} = (\gamma_{0.c} - \gamma_{0.\text{э}})_t = (\gamma_{0.c} - \gamma_{0.\text{э}})_{t_0} + (\nu_{0.c} - \nu_{0.\text{э}})(t - t_0) \pm \sqrt{a_{0.c}^2 + a_{0.\text{э}}^2}. \tag{2.5}$$

Synchronization of time standards means coincidence or mutual tie-in of the time scales that they reproduce (a sequence of time-coincident signals), i. e. satisfaction of the equality

$$\underset{t}{T_{\text{э}}} - \underset{t}{T_c} = 0. \tag{2.6}$$

If it is assumed that the time standards are based on frequency standards described by expressions (2.3) and (2.4), then the temporal positions of the time scales that they reproduce will be described by the expressions

$$\underset{t}{T_c} = \underset{t_0}{T_c} + \gamma_{0.c}(t - t_0) + \frac{1}{2}\nu_{0.c}(t - t_0)^2 \tag{2.7}$$

and

$$\underset{t}{T_{\text{э}}} = \underset{t_0}{T_{\text{э}}} + \gamma_{0.\text{э}}(t - t_0) + \frac{1}{2}\nu_{0.\text{э}}(t - t_0)^2. \tag{2.8}$$

The error of synchronization or error of tie-in of such time standards is

$$\psi_t = (T_c - T_{\text{э}})_t = (T_c - T_{\text{э}})_{t_0} + (\gamma_{0.c} - \gamma_{0.\text{э}})(t - t_0) + \frac{1}{2}(\nu_{0.c} - \nu_{0.\text{э}})(t - t_0)^2. \tag{2.9}$$

The process of synchronization of time standards includes synchronization of the oscillators (frequency standards) and adjustment of the phase of the synchronized signals.

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The synchronization system contains: 1) a mixer that sums the waveforms and produces a synchro-information signal functionally related to the frequency difference of the summed waveforms or to the phase difference; 2) a controlling element or controlling circuit for regulating the frequency and phase of the standard to be synchronized by the mixer output (synchro-information signal); 3) channels for signal transmission from the synchronizing and synchronized standards to the mixer (Fig. 8). Depending on the synchronization conditions, the elements of the system can be made with a variety of hardware.

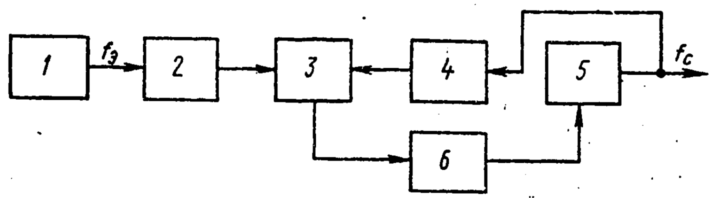

Fig. 8. Block diagram of the synchronization system: 1--synchronizing standard; 2, 4--transmission channels; 3--mixer; 5--synchronized standard; 6--controlling element

Let us consider three methods of synchronization: 1) induced synchronization where the synchro-information acts continuously on the standard to be synchronized; 2) semi-autonomous, where the synchro-information acts periodically on the standard to be synchronized; 3) autonomous, where there is no synchro-information.

The first method is used if the error of the standard being synchronized is greater than the error introduced by the signal transmission channels, which is negligibly small compared with the error of the synchronizing standard. Such conditions are encountered nearly exclusively in the circuits of oscillators that are frequency-stabilized.

The second method is used in stabilizing standards that have commensurate errors but are territorially separated. In this case, special channels are used for signal transmission, and the influence of the channel parameters on the transmitted signals cannot be disregarded. That is why the synchro-information is used to correct the standard being synchronized over definite time intervals rather than continuously.

The third method can be used if the errors of the synchronized and synchronizing standards are of the same order of magnitude, and neither standard is associated with the other by synchro-information during operation.

2.1. Induced Synchronization

Induced frequency synchronization is based on a closed automatic control system, where compensation of the deviation of the controlled quantity from a set value takes place with respect to the difference between these values as determined by the method of comparison [Ref. 11].

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An automatic frequency control (AFC) system is used in cases where the error introduced by the transmission channels can be disregarded. This is feasible if the synchronizing and synchronized standards are situated in direct proximity to one another (i. e. they make up a single unit), or if the time of automatic synchronization is such that the error introduced by the transmission channel is negligible, or finally, if the given error can be automatically compensated.

In the case considered here, the synchronization circuit is made up of the mixer proper, and the controlling element. A block diagram of such a system is shown in Fig. 9.

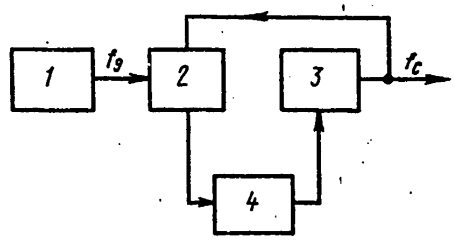

Fig. 9. Block diagram of AFC:
1--synchronizing standard; 2--mixer; 3--synchronized standard; 4--controlling element

The output (synchronized) frequency f_c has a predetermined functional relation to the input (conventional standard) frequency $f_э$ at an invariable or constant value of the latter. The frequency to be synchronized is sent through the feedback circuit to the mixer together with the standard frequency. A control signal is produced at the mixer output with amplitude determined by the mismatch--the difference between frequencies f_c and $f_э$.

The change in phase of the oscillations $\Delta\phi$ is unambiguously related to the change in frequency of these oscillations $\Delta\omega$. Therefore the change in both frequency and phase can be used to produce a control signal at the output of the mismatch sensor. That is, automatic frequency control is possible with two kinds of mismatch sensors: a phase detector with tuning to a definite phase, and a frequency detector-discriminator with tuning to a definite frequency. In accordance with this, two AFC groups are formed: phase AFC and frequency AFC.

The result of action of either scheme is the same: the frequency of the standard to be synchronized is regulated with respect to the source of synchronizing waveforms. But the phase and frequency AFC systems themselves are different both with respect to the circuit design and with respect to their regulating action. The phase AFC system is in a state of stable equilibrium only when the controlling factor is constant, while the voltage at the output of the phase detector remains constant only when the phases of the voltages being compared are invariable, which necessitates equality of frequencies. In the frequency AFC system in the steady state, the controlling factor can be constant only when the frequency difference is constant. Consequently in the frequency AFC system there is always a difference between the frequencies of the synchronized and synchronizing waveforms.

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In the frequency control process, this difference must be adjusted to the discriminator tuning frequency

$$f_{д} = f_0 - f_{э}, \quad (2.10)$$

where f_0 is the value of the frequency to which the standard is to be synchronized.

The voltage appearing across the mixer load has the difference frequency of the standard, f_c or $f_э$. This voltage acts on the discriminator, which is located at the output of the mixer. A controlling voltage is formed at the discriminator output. When $f_c = f_0$, this voltage is equal to zero and the frequency AFC system does not operate.

The process of frequency establishment when the frequency AFC system is connected to the oscillator being stabilized begins at the time when the difference is equal to some beginning mismtach $f_c - f_0 = \Delta f_{beg}$. Under the action of the voltage coming from the discriminator output, the controlling element changes the frequency of the oscillator being synchronized toward the side opposite (in sign) to the initial mismatch, resulting in reduction of the difference.

The phase difference of two waveforms can remain constant in time only in the case where the frequencies of these two waveforms are the same. If the frequencies of the waveforms are unequal, but differ by a constant value, the phase difference is

$$\varphi = (\omega_c - \omega_э)t + \varphi_0 = \Delta\omega t + \varphi_0, \quad (2.11)$$

where ϕ_0 is the initial phase difference, ω_c and $\omega_э$ are the frequencies of the synchronized and synchronizing oscillators respectively.

If the frequency difference is not constant in time, the instantaneous phase difference is

$$\varphi = \int \Delta\omega dt, \quad (2.12)$$

and hence

$$\Delta\omega = \frac{d\varphi}{dt}. \quad (2.13)$$

The constancy of the phase difference guarantees equality of the frequencies of two waveforms; this is the design basis of the phase AFC system.

The structural difference of block diagrams of frequency and phase AFC systems dictates the different physical processes that take place in these systems.

In phase AFC systems a variable-frequency voltage appears at the output of the phase detector that is transmitted to the controlling element of the oscillator to be synchronized.

The beginning mismatch $\Delta\omega_{beg}$ of the oscillator being synchronized should not exceed the stopband for efficient operation of the system. In this case a constant phase

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difference is set up in the system, i. e. equality of frequencies ω_c and ω_g is assured. Hence the stopband also determines the locking-in band, the maximum mismatch of the oscillator to be synchronized at which phase AFC will accomplish synchronization.

Phase shifts in the automatic control channel cause delay of the controlling signal.

The voltage across the output of the phase detector is determined by the phase difference of the signals being compared. Therefore when the frequencies of these signals are equal, the voltage across the output of the phase detector is constant. On the other hand, if the frequencies are not equal, the change in phase difference is determined by expression (2.12), and the voltage across the output of the phase detector is a function of time.

It is not only the useful driving waveforms that act on an actual AFC system, but also interference. Interference causes changes in the frequency of the synchronized oscillator relative to the average value of the frequency in the steady state, and this change is equal to the mean square error.

Additional elements must be introduced into the circuit in order for the AFC system to track the useful signal with the greatest possible accuracy and not react to interference.

Masers are systems with phase AFC. The converted signal from the quartz oscillator is added to the signal from the maser in the mixer. The difference-frequency signal that arises at the output of the mixer acts on the phase detector simultaneously with the converted signal of the quartz oscillator; an error signal is produced that is used to adjust the quartz oscillator frequency to the maser frequency.

In frequency standards with quantum discriminator, the quartz oscillator is synchronized by a frequency AFC system.

2.2. Semi-Autonomous Synchronization

When the oscillators are spatially separated, and the signals are transmitted from the synchronizing oscillator by different channels (cable lines, radio channels of all waves bands, television channels, satellites, meteoric channels and so on), since no methods for automatic elimination or compensation of errors have as yet been found on the present stage of investigation of destablizing factors introduced due to the inconstancy of parameters of such channels, automatic induced synchronization of precision frequency measures is impossible. Therefore semi-autonomous synchronization is used, necessarily with the participation of a human operator who analyzes the results of comparison of the synchronizing and synchronized frequency standards and introduces needed corrections.

In the general case, the block diagram of synchronization of spatially separated frequency and time standards takes the form shown in Fig. 10. The two standards 1 and 2 are connected by a channel. The mixer-receivers are devices that pick up the signals simultaneously from the two standards and produce a signal in which one of the parameters is related in a definite way to the difference of the frequencies or phases of the received signals. Such devices may be standard radio

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and television receivers, standard oscilloscopes, and also special receivers--phase comparators and frequency comparators.

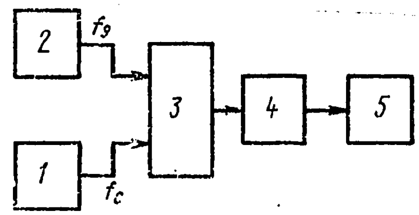

Fig. 10. Block diagram of synchronization of spatially separated frequency standards:
1--standard to be synchronized; 2--synchronizing standard; 3--converter; 4--comparator; 5--display

Cable lines are used in synchronization by a time and frequency calibrated reference for laboratory standards intended for radio transmission of exact time and reference frequency signals, and in synchronization of precision standards situated at small distances from each other within the confines of a single institution, or a single time and frequency service.

A cable line is equivalent to a two-terminal pair network with distributed parameters R, L, C and g.

Inconstancy of these parameters causes a change in frequency of the transmitted signals and their transmission time.

In practice, signals can be transmitted over cable lines to distances of 10-100 km with frequency variation of $(1-2)\cdot10^{-9}$ and variation of transmission time of $(1-2)\cdot10^{-4}$ s.

Radio communication channels are used in synchronizing time and frequency standards separated by distances of from 50-100 to 10,000-15,000 km or more. Depending on the distance between the standards and the required synchronization accuracy, different radio wave bands and correspondingly different methods of transmission are used.

Signals from the synchronizing standard are sent over one of the transmission channels and arrive at the comparator-receiver, where the difference of frequencies or phases of the signals of the synchronizing and synchronized standards is determined. If the synchronizing signals are transmitted over cable lines, they go directly to the comparator after amplification. On the other hand, if transmission is by radio communication channels, the signals go to the reception device, with circuit determined by the radio band of the received signals, and from there to the comparator.

In semi-autonomous synchronization, signals from the synchronizing standard are periodically received at the point of location of the standard being synchronized. The time between receptions (discreteness time) is established depending on the

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required synchronization accuracy, the ratio between the metrological characteristics of the two standards, and the signal transmission error.

The metrological characteristics of the standard to be synchronized must be calculated on the basis of certain measured effective frequencies. Therefore the time between signal receptions must not exceed the time during which the metrological characteristics of the standard are determined. The error of the effective frequency is made up of the error of frequency comparison and the error introduced by the transmission channel. Systematic errors introduced by the transmission channel are eliminated by making appropriate corrections, and random errors are added in with the comparison errors.

For example with error S_{0f} of determination of the effective frequency, and error S_{0l} introduced by the transmission channel, the total error is

$$S_0 = \sqrt{S_{0_f}^2 + S_{0_l}^2}. \qquad (2.14)$$

If the effective frequency is determined by the differential method, the necessary measurement time with consideration of S_{0l} is calculated by formula

$$\tau_0 = \gamma_0 \frac{\tau}{\sqrt{S_{0_f}^2 - S_{0_l}^2}}. \qquad (2.15)$$

If the effective frequency is determined as a result of discrete measurements, the necessary number of measurements n is established from the relation

$$n(n-1) = \frac{1}{f_n^2} \frac{\Sigma (f_i - f_n)^2}{S_0^2 - S_{0_l}^2} \qquad (2.16)$$

or, assuming $n \gg 1$,

$$n = \frac{1}{f_n} \sqrt{\frac{\sum_1^n (f_i - f_n)^2}{S_0^2 - S_{0_l}^2}}. \qquad (2.17)$$

The overall error should be 3-10 times smaller than the permissible synchronization error.

When metrological characteristics are already known, measurements can be done after still greater time intervals. In this case the measurements can be considered control measurements, and the method of semi-autonomous synchronization becomes a method of autonomous synchronization.

2.3. Autonomous Synchronization

If the synchronizing and synchronized standards have identical metrological characteristics and their laws of time variation are also identical, then a single determination of the phase difference of the generated signals is sufficient in principle to synchronize such standards.

Most closely approaching such conditions in practice is the QFS, although this device also has small but systematic frequency variations. At the present stage,

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the instability of the QFS is much less than the error of determination of parameters of signal transmission channels and their inconstancy. Therefore a method of autonomous synchronization is used to synchronize frequency standards based on the QFS: the standards are not connected by transmission channels, and the frequencies of the waveforms that they generate remain invariable over a permissible range. For control purposes, the frequency must be periodically compared with that of the synchronizing standard (the period is determined by the reliability of retention of the metrological characteristics of the standard to be synchronized). Synchronization of time standards based on the QFS also necessitates periodic control measurements of the temporal position of the signals. Besides, the measurements must be made after each cutoff of the standard, even briefly.

With consideration of the fact that the standard being synchronized must copy all changes in the characteristics of the synchronizing standard, both standards must be periodically combined in some way during autonomous synchronization as well. It is most effective to use portable time and frequency standards for this registration. Such a frequency standard based on the QFS--atomichron or rubidium clock--is synchronized to the synchronizing standard, and then transported by air to the point of location of the standard to be synchronized, where this synchronization is carried out [Ref. 12].

CHAPTER 3: METHODS OF DETERMINING FREQUENCY DIFFERENCE OF SYNCHRONIZED AND SYNCHRONIZING STANDARDS

3.1. Method Based on Results of Determining the Effective Frequency of the Standard to be Synchronized

The effective frequency $f_Д$ can be determined by the method of direct evaluation using a frequency meter, or by a differential method by comparing the frequenices of the synchronized and synchronizing standards (GOST 13628-68 "High-Stability Oscillators. Methods and Means of Checking the Frequency of Electric Signals"). The former method is the simplest; a counting-type frequency meter is used for measurement with an external source, which may be the synchronizing standard. In this case the error of determination of the frequency of the synchronized standard is only the error of discreteness of the frequency meter,

$$S_{0_f} = \frac{1}{f_э \tau_н}. \tag{3.1}$$

If a frequency meter without external source is used for measurement, the error due to discreteness is combined with the error of the reference oscillator of the frequency meter

$$S_{0_f} = \delta_{o.r} + \frac{1}{f_э \tau_н}. \tag{3.2}$$

The accuracy of determining $f_Д$ of the synchronized standard is increased by doing n repeated measurements in time τ_y, during which variation of measurement conditions can be disregarded. The error in this case is reduced by a factor of $\sqrt{n}$.

When the differential method is used, it is necessary that the summation of the waveforms of the synchronized and synchronizing standards produce beats; the beat frequency is then measured and used to determine the frequency difference of the two standards.

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It is known that when scalar oscillations $v_1 = V_1 \cos 2\pi f_1 t$ and $v_2 = V_2 \cos 2\pi f_2 t$ are added, the resultant waveform is

$$v = V\cos(2\pi f_1 t - \varphi), \quad (3.3)$$

where

$$V = V_1 \sqrt{1 + 2h\cos 2\pi(f_1 - f_2)t + h^2}; \quad (3.4)$$

$$\varphi = \operatorname{arctg}\frac{h\sin 2\pi(f_1 - f_2)t}{1 + h\cos 2\pi(f_1 - f_2)t}; \quad (3.5)$$

$$h = \frac{V_2}{V_1}.$$

These formulas are valid for any f_1 and f_2, but if $f_1 - f_2 \ll f_1$, the resultant waveform is perceived as alternations of waveforms of the same frequency with amplitude varying periodically on the difference frequency. Such signals are conventionally called beats. Beats may also be produced by combining waveforms with frequencies that are appreciably different. For example the sum of two mutually perpendicular vector waveforms

$$\vec{v}_1 = \vec{V}_1 \cos 2\pi f_1 t \text{ and } \vec{v}_2 = \vec{V}_2 \cos 2\pi f_2 t,$$

whose frequencies are $f_1 = lf_0 + \Delta_1$, $f_2 = kf_0 + \Delta_2$, where l and k are integers, and $\Delta_1 < f_1$, $\Delta_2 < f_2$, are described by the equation

$$\cos\left(k\arccos\frac{V_1}{v_1} - l\arccos\frac{V_2}{v_2}\right) = \cos 2\pi(k\Delta_1 - l\Delta_2)t. \quad (3.6)$$

For each instant of time t, this equation describes some figure on plane $\vec{v}_1\vec{v}_2$. If $k\Delta_1 = l\Delta_2$, the figure is invariant. If $k\Delta_1 \neq l\Delta_2$, the figure is deformed with period

$$T = \frac{1}{k\Delta_1 - l\Delta_2} = \frac{1}{kf_1 - lf_2}. \quad (3.7)$$

If $F = \frac{1}{T} = (kf_1 - lf_2) \ll f_1$ or f_2, the resultant waveforms are perceived as beats.

Beats of two electric signals are produced by mixers, which may be an electric circuit that alters the spectrum of signals acting on it, and isolates the component of the difference frequency from this spectrum, or a cathode-ray tube that does not change the spectrum of the summed waveforms, but enables observation of beats.

If the frequencies of the synchronized and synchronizing standards lie in a range of 100 Hz-1 MHz, the difference frequency can be measured with an electronic oscilloscope (from Lissajou figures or from a circular scan; in the latter case an electronic oscilloscope with radial scale on the screen is used).

By this means, frequency differences of less than 2-3 Hz can be determined by measuring the time of part of a period or of an integral number of periods of the difference-frequency waveforms.

Measurements by Lissajou figures are possible at a ratio of nominal values of the frequencies of the synchronized and synchronizing standards up to 1:10; measurement time cannot be less than the period of the beats.

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The rate of periodic change in the Lissajou figure is proportional to the frequency difference being measured. The beginning of the period is taken as the instant when the Lissajou figure becomes a single line. The timer is energized at this instant. The timer is disconnected when the Lissajou figure again becomes a line oriented in the same way as the initial line. The time indicated by the timer determines the beat period.

It is not possible to determine the sign of frequency deviation of the synchronized standard directly from measurements. It is determined either by changing the frequency of the synchronized standard in a known direction, or by using an auxiliary oscillator.

Measurements with respect to a circular scan are possible at a ratio of the nominal frequencies of the synchronized and synchronizing standards up to 1:100; measurement time may be less than the period of the beats.

When voltages are applied to the circular beam scan and to the brightness modulator with corresponding regulation of their levels and the brightness of the electron beam, one (when the nominal values of $f_{C.H}=f_{Э.H}$) or m bright points (when $f_{C.H}/f_{Э.H}=m$) are formed on the screen that move in a circle with a velocity proportional to the beat frequency. The instant of readout is taken as the time when a point crosses any marker of a scale on the screen. At this instant a timer is energized, and it is switched off when the point crosses the same marker of the scale if the time of a whole period of beats is being measured, or any other marker of the scale if the time of a part of the beat period is being measured.

The sign of frequency deviation of the synchronized standard is determined directly during the measurement from the direction of motion of the points around the circle.

The beat frequency is calculated from the formula

$$F = \frac{n}{\tau_H}, \quad (3.8)$$

where n is the part of a period or whole number of periods of the beats in time τ_H.

When $f_{C.H}=f_{Э.H}$ and $f_{C.H}=lf_{Э.H}$, the frequency error of the synchronized standard is equal to the beat frequency.

$$\gamma_c = F. \quad (3.9)$$

When $kf_{C.H}=f_{Э.H}$, the error is determined from the formula

$$\gamma_c = \frac{F}{k}. \quad (3.10)$$

If the synchronized and synchronizing frequencies lie in a range of 100 kHz-30 MHz, the difference frequency can be measured by a heterodyne method, using a nonlinear frequency mixer (see Fig. 10).

Measurements by the heterodyne method are possible at a ratio of nominal frequencies up to 1:200; measurement time cannot be less than the period of oscillations of the difference frequency.

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This method enables isolation and measurement of the difference frequency both directly between the fundamental frequencies of the synchronized and synchronizing standards, and between the frequencies of their harmonics.

A special mixer or all-wave radio receiver is used for the measurements; in the case of harmonics, distorters of the waveshape of their oscillations are used.

When signals on close frequencies are sent simultaneously to the input of the mixer, a voltage modulated by the difference frequency appears at its output. Depending on the magnitude of the difference frequency, it is measured either by counting the number of periods of beats over a time determined by a timer, or by a counting-type frequency meter.

The error of the synchronized frequency is calculated by the formula

$$\gamma_c = \frac{kf_c - lf_э}{k} = \frac{F}{k}, \tag{3.11}$$

where k, l are the numbers of the utilized harmonics of the synchronized and synchronizing frequencies respectively.

The error of the differential method of measurement is due chiefly to the error of measurement of the difference frequency. In direct measurement of the beat frequency F, the error is determined by the error of the frequency meter $\Delta F/F$. In indirect measurement, the error is due to imprecision of time measurement ($\Delta\tau_1$) and imprecision of registration of the number of beats (Δn); for the calculations we use the law of summation of the mean errors:

$$S_f = F\sqrt{\left(\frac{\Delta n}{n}\right)^2 + \left(\frac{\Delta\tau_1}{\tau}\right)^2}. \tag{3.12}$$

In practice, it is difficult to separate errors $\Delta\tau_1$ and Δn, and therefore the overall error of time measurement is estimated

$$\Delta\tau = \sqrt{\Delta\tau_1^2 + \Delta\tau_2^2},$$

where $\Delta\tau_2 = \frac{\Delta n}{F}$, and the error is calculated by the formula

$$S_f = F\frac{\Delta\tau}{\tau} \text{ or } S_{0_f} = \frac{F}{f_{c.н}} \cdot \frac{\Delta\tau}{\tau}. \tag{3.13}$$

Values of $\Delta\tau$ lie in a range of 0.3–0.5 s for different beat frequencies (0.3–5 Hz).

If the frequency difference is less than 0.01 Hz, the comparator may be a phase discriminator with registration of periods of the difference frequency on a chart recorder. The electric circuit of this method can provide a linear rise in amplitude of the difference frequency over the entire period with an abrupt drop at the end of the period (Fig. 11). Therefore, to determine the frequency error of the standard that is being synchronized, the time of the periods is read out from the output of the chart recorder, and the difference frequency is calculated. On Fig. 11, $T_1 = T_2 = T_3 = T_4 = T$; $N = 4$; $\tau_n = NT = 4 \cdot 21600 = 86400$ s. If $f_c = 100$ kHz, the relative error of the synchronized standard is $\gamma_{o.c} = 4.6 \cdot 10^{-10}$.

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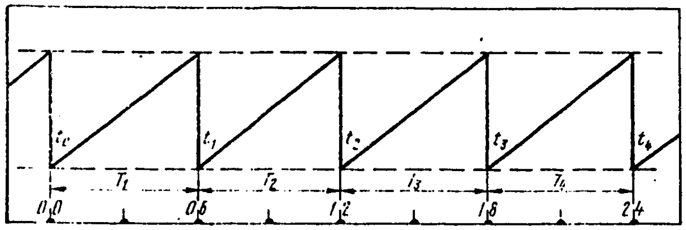

Hours of the day

Fig. 11. Change in amplitude of difference frequency at phase discriminator output

3.2. Method Based on Measurements of Change in Phase Difference of Waveforms of Synchronizing and Synchronized Standards

In the phase method of determining the error of the standard being synchronized, exact time signals produced by the synchronizing standard are used. An oscilloscope or counting-type frequency meter is used to observe the phase difference of oscillations of the synchronized and synchronizing standards.

Determination of the error of the synchronized frequency from exact time signals consists in fixing instants T_1 and T_2 of signals of exact time relative to signals of the standard to be synchronized after time interval τ. To do this, an image of the signal is produced on the oscilloscope screen by scanning it with the signal of the standard being synchronized, and using a phase shifter to achieve registration between the beginning of the signal of the synchronizing standard and the beginning of the scan, noting the respective positions Π_1 and Π_2 of the phase shifter.

The relative error of the standard being synchronized is calculated by the formula

$$\gamma_{o.c} = \frac{T_2 - T_1}{\tau} = \frac{\Pi_2 - \Pi_1}{\tau}. \tag{3.14}$$

The error of establishment of time interval τ and the error of registration of signal times cause errors in determination of the effective frequency of the standard being synchronized in accordance with formula (3.13).

CHAPTER 5*: SIGNAL TRANSMISSION METHODS USING VLF RADIO CHANNELS

5.1. Transmitting Facilities

By convention, myriametric radio waves are those with wavelengths of 10-30 km, which corresponds to radio signal frequencies of 10-30 kHz. These limits are not rigorous, as radio waves in a frequency band of 6-60 kHz propagate by a similar mechanism.

*Chapter 5 was written by Candidate of Technical Sciences M. V. Bolotnikov.

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It is known from the routes of propagation of radio waves that when a signal propagates in non-ideal media or close to their boundaries, attenuation decreases with increasing wavelength. Because of this, VLF radio channels are used to synchronize frequency and time standards separated by distances of more than 10,000 km.

However, in transmission of long-wave signals of the order of kilometers or more, considerable difficulties arise. The monograph by S. I. Nadenenko [Ref. 20] points out that the radiation impedance of a transmitting antenna that characterizes its efficiency decreases rapidly with decreasing ratio of antenna height l_a to the wavelength of the emitted signal

$$E_\Sigma = 160\pi^2 \frac{l_a^2}{\lambda^2}. \qquad (5.2)$$

Formula (5.1) is more conveniently represented as

$$R_\Sigma = 160\pi^2 f^2 \frac{l_a^2}{c^2},$$

where the speed of light $c = 3 \cdot 10^8$ m/s.

The height of antenna towers of the largest VLF stations is no more than 500 m, i. e. no more than 5% of the wavelength. To ensure efficient radiation, such antennas are "capacitance top-loaded" [Ref. 20]. Here the capacitance is a system of horizontal wires stretched between the central tower and somewhat shorter peripheral towers. The total capacitance C of a multiple-tower VLF antenna with developed system of horizontal wires may reach 0.1 μF. The combination of inductance of the wires with the capacitance of the horizontal web forms a parallel oscillatory tank with distributed parameters. During transmission, this tank is tuned to resonance with the exciter signal by special large-scale tuning coils. The wave impedance ρ of the antenna under these conditions is determined by its total capacitance C,

$$\rho = \frac{1}{2\pi f C}, \qquad (5.2)$$

and the Q of the antenna tank

$$Q = \frac{\rho}{R_\Sigma} = \frac{c^2}{320\pi^3 l_a^2 f^3 C} = \frac{2,14 \cdot 10^{13}}{l_a^2 f^3 C}$$

is inversely proportional to the cube of the frequency of the transmitted signal. The passband of the antenna is

$$\Pi = 320\pi^2 \frac{l_a^2}{c^2} f^4 C = 4,62 \cdot 10^{-14} f^4 l_a^2 C. \qquad (5.3)$$

Taking $l = 500$ m, for a frequency of $f = 20$ kHz we get $\Pi = 200$ Hz, and for $f = 10$ kHz it is 12.5 Hz.

The main purpose of VLF radio stations is long-range radio communications. Time signals are transmitted by these radio stations during specially selected broadcasting sessions or in a combined schedule. Because of the very high cost of VLF transmitters, and especially antennas, a rather limited number of VLF stations of comparatively low power have been built specifically for synchronization.

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5.2. Methods of Time Signal Transmission

Two principal methods are used for transmitting exact time signals in the VLF range: pulse modulation and sequential transmission of coherent carrier frequencies.

In time signal transmission by the former method (in mode A-I) synchronization accuracy is influenced by the narrow-band nature of the antenna systems and by the quite considerable level of natural interference. As shown by calculations (see Section 5.1), the risetime τ of the signal radiated from the antenna on a frequency of 20 kHz will be 3-5 ms, and on a frequency of 10 kHz $\tau = 50$-100 ms. Natural interference in the VLF band is mainly due to lightning discharges and is markedly pulsed. The average level of interference at the latitude of Moscow is of the order of 0.5-1 mV/m in the 1 kHz band. As will be shown below, the field strength of VLF radio signals from most transmitters in this band at a distance of 3,000-6,000 km is 0.5-1.5 mV/m. For a receiver pass band of 1 kHz, the signal-to-noise ratio at its output is 1-3, and the accuracy of registration of the instant of pulse arrival at the reception antenna can be estimated by the formula [Ref. 20]

$$\sigma_t \approx \frac{\tau}{q}; \ \sigma_t > 1 \ \text{ms}. \tag{5.4}$$

By observing the received signal on the screen of an oscilloscope with afterglow, an experienced operator can determine the position of the received pulse relative to the local time scale with error of the order of 200-300 μs. Errors that arise due to inexact knowledge and delay instability in the receiver can be eliminated with fair accuracy if this delay is measured by using a special simulator of received signals before the synchronization sequence starts.

In virtue of simplicity of the reception equipment, the pulse method of synchronization in the VLF band is being extensively used in complexes and systems where the permissible synchronization error is 0.5 ms or more.

The method of sequential transmission of coherent carrier frequencies improves synchronization accuracy by more than an order of magnitude, but involves considerable complications of transmitting and reception equipment. The method was originally developed and implemented in application to problems of the Omega VLF radionavigation system for the U. S. Navy [Ref. 22]. To explain the working principle, let us consider a hypothetical system that sequentially transmits coherent monochromatic signals with frequency of 12.5, 12.6, 13 and 15 kHz. In the shaper of the transmitter, these signals are phased in such a way that they simultaneously pass through zero 100 times per second, and once per second this coincides synchronously with the second pulse of the master clock at the station. Let there be some time storage device at the reception point with scale that lags behind that of the master clock by T_0, and let an analogous time grid be formed from its signals as well. The time of signal propagation from the transmitter to the receiver on all frequencies will be taken as identical and equal to τ_p.

The phase difference of the received and local signals with frequency f_i at the reception point is

$$\varphi_i = f_i(T_0 + \tau_p) - n_i = \frac{T_0 + \tau_p}{T_i} - n_i,$$

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where T_i is the period of signal with frequency f_i, $n = \text{entier}(T/T_i)$ is the whole number of periods of T_i contained in time interval $T = T_0 + \tau_p$. Let us note that here and below for purposes of greater compactness in writing them out, the values of the phases and phase differences are expressed in fractions of the period of the corresponding signal.

The difference of phase shifts for two different frequencies is

$$\Psi_{ij} = \varphi_i - \varphi_j = (f_i - f_j)T - (n_i - n_j)$$

or

$$\Psi_{ij} = \frac{T}{T_{ij}} - n_{ij},$$

where T_{ij} is the period of the effective difference frequency F_{ij}, and $n_{ij} = n_i - n_j$ is the whole number of such periods in interval $T = T_0 + \tau_p$.

Thus knowledge of the phase shift Ψ_i on some carrier frequency f_i or of the difference of such shifts Ψ_{ij} enables determination of the corresponding shift of time scales with an uncertainty that is a multiple of T_i or T_{ij}. With a reduction in frequency difference, the band of unambiguous readout of the measured interval increases, but there is a simultaneous increase in the error of measurement of this interval

$$\sigma_{ij}^2 = \sqrt{\sigma_{\varphi_i}^2 + \sigma_{\varphi_j}^2}\,\frac{1}{F_{ij}}.$$

To resolve the uncertainty, it is necessary to determine the number of periods n_i. Let us assume that the measured shift of the local scale and the received signals $T = T_0 + \tau_p$ is less than the period of the least of the difference frequencies T_{21}. Then from the corresponding difference of the phase readouts Ψ_{21} we can unambiguously find the measured shift $T = \Psi_{21}T_{21}$. Hence the number of periods of the next difference frequency T_{31} in the measured interval is

$$n_{31} = \text{entier}\,\frac{\Psi_{21}T_{21}}{T_{31}}. \tag{5.5}$$

In this case, the measured interval

$$T \approx (n_{31} + \Psi_{31})\,T_{31}$$

can be determined with accuracy corresponding to the higher difference frequency F_{31}. Performance of these calculations is in no way limited by the fact that physically the difference frequencies F_{ij} are not formed in the receiver, and the phase readouts Ψ_{ij} are calculated from the results of measurements made on the corresponding carrier frequencies f_i and f_j. In the general case

$$m_{l+1,1} = \text{entier}\,\frac{\Psi_{l1}T_{l1}}{T_{l+1,1}}. \tag{5.6}$$

Calculations by formula (5.6) are done until transition to readout on carrier frequency f_1. Ultimately

$$T = \sum_{l=3}^{r} m_{l1}T_{l1} + (m_1 + \varphi_1)\,T_1. \tag{5.7}$$

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where p is the number of sequentially transmitted carrier frequencies, m_1 is the number of periods of the carrier frequency as calculated for the maximum difference frequency F_{p1}, m_{31} is the quantity previously denoted in formula (3.5) as n_{31}.

Formula (5.6) has a serious flaw: if readout on a greater difference frequency $F_{i+1,1}$ is close to unity, it is quite possible as a consequence of unavoidable measurement errors that the whole number $m_{i+1,1}$ will be incorrectly determined. More stable with respect to errors of this kind is the relation

$$m_{i+1,1} = N\left[\frac{\Psi_{i1} T_{i1}}{T_{i+1,1}} - \Psi_{i+1,1}\right], \tag{5.8}$$

where N is the operation of determining the nearest whole number. Regardless of the specific values of Ψ_{i1} and $\Psi_{i+1,1}$,

$$\Gamma = \frac{\Psi_{i1} T_{i1}}{T_{i+1,1}} - \Psi_{i+1,1} \tag{5.9}$$

will be a whole number in the absence of measurement errors. In practice, this quantity differs from a whole number increasingly with increasing error of measurement of the phases of the carrier frequencies.

Ambiguity is correctly resolved if the error of determination of Γ (denoted by δ_Γ) for the given measurement series satisfies the inequality $\delta_\Gamma < 0.5$. Physically, this means that the error of readout on frequency $F_{i,1}$ assumed in the time expression must not exceed ½ the period of the next higher difference frequency $F_{i+1,1}$.

From formula (5.9) we get the following relation between δ_Γ and the errors of phase measurement of the carrier frequencies

$$\delta_\Gamma = \frac{T_{i1}}{T_{i+1,1}}(\delta_{\varphi_i} - \delta_{\varphi_1}) - (\delta_{\varphi_{i+1}} - \delta_{\varphi_1}) = \varkappa(\delta_{\varphi_i} - \delta_{\varphi_1}) - (\delta_{\varphi_{i+1}} - \delta_{\varphi_1}).$$

Taking the errors of phase measurement on sequentially transmitted carrier frequencies as mutually independent and equal in mean-square value, we get

$$\sigma_\Gamma = \varkappa\sqrt{2}\,\sigma_\varphi\sqrt{1 - \frac{1}{\varkappa} - \frac{1}{\varkappa^2}}, \tag{5.10}$$

where σ_ϕ, σ_Γ are the mean square errors of measurement of phases and of determining Γ respectively. Assuming that these errors are distributed according to normal law, we can determine the probability of correct resolution of ambiguity for one transition between readings on adjacent difference frequencies by the formula

$$p = \Phi\left(\frac{0.5}{\sigma_\Gamma}\right), \tag{5.11}$$

where $\Phi(\kappa)$ is the probability integral. The ratio $\varkappa = \frac{T_{i+1}}{T_{i+1,1}}$, which to a great extent determines the probability of correct resolution of ambiguity, is called the coefficient of transition, or the scale ratio.

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Let us consider a practical example. Let the measured phase shifts be $\phi_1 = 0.65$, $\phi_2 = 0.56$, $\phi_3 = 0.11$, $\phi_4 = 0.99$. Data processing is done in the following order.

1. Phase shifts on effective difference frequencies are determined by the formula

$$\Psi_{i1} = \varphi_i - \varphi_1 (+1).$$

Here the phase of the lower-frequency signal is subtracted from that of the higher-frequency signal. If the phase difference is negative, unity is added,

$$\Psi_{21} = 0{,}56 - 0{,}65 = -0{,}09 (+1) = 0{,}91;$$
$$\Psi_{31} = 0{,}11 - 0{,}65 = -0{,}54 (+1) = 0{,}46;$$
$$\Psi_{41} = 0{,}99 - 0{,}65 = 0{,}34;$$
$$\Psi_{51} = \varphi_1 = 0{,}65.$$

2. The whole numbers of periods of the difference frequencies contained in the measured displacement of time scales are determined

$$m_{31} = N\left(0{,}91 = \frac{10000}{2000} - 0{,}46\right) = N(4{,}09) = 4;$$
$$m_{41} = N\left(0{,}46 = \frac{2000}{400} - 0{,}34\right) = N(1{,}96) = 2;$$
$$m_{51} = m_1 = N\left(0{,}34 = \frac{400}{80} - 0{,}65\right) = N(1{,}05) = 1,$$

where the numbers 10,000, 2,000, 400, 80 are the periods of the difference frequencies and the first carrier frequency expressed in microseconds. For our example $\kappa = 5$.

3. The time interval to be measured is calculated

$$T = 4 \cdot 2000 + 2 \cdot 400 + (1 + 0{,}65) \cdot 80 = 8932 \ \mu s.$$

The error of the reception equipment when using the multiscale synchronization method (usually digital phase meters) is made up of the error caused by noises and the discreteness error. The first of these can be calculated from the relation

$$\sigma_{ш} = \frac{1}{2\pi q_{ф}},$$

where q_ϕ is the signal-to-noise ratio with respect to field strength in the band of the phase meter [see formula (5.3)]. The effective passband of the digital phase meter is determined in turn by the duration f_n of signal transmission on the given carrier frequency

$$П_{ф} = \frac{1}{2\pi t_n}.$$

Let $t_n = 300$ s. Then even at a signal-to-noise ratio of 0.05 in a 1 kHz band,

$$q_{ф} = q_{1кГц} / \sqrt{2\pi 1000 t_n} \approx 50$$

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[subscript 1кГц = 1 kHz] in the phase meter passband which corresponds to error due to noises that is equal to 0.003 period, or expressed in time--0.024 μs.

A much greater error is associated with determining the exact time of propagation on the carrier frequencies. This error can be conventionally divided into two components: random σ_p and systematic δ_p. The random error is understood to be that due to chaotic changes in the phase of the arriving signal under fixed conditions on the path from the transmitter to the receiver. As implied by data of years of observations, such changes, and consequently σ_p, fluctuate from 1.5 (daytime, summer), to 4 μs (nighttime, winter) [Ref. 23]. The systematic error in determination of phase velocity on transmitted frequencies is fundamental, and under unfavorable conditions may reach 30-50 μs on paths up to 6000 km long.

If δ_p is the same on all frequencies, it has no effect on the probability of correct resolution of ambiguity. In this case the σ_ϕ appearing in formula (5.10) can be defined as

$$\sigma_\varphi = \sqrt{\left(\frac{\sigma_p}{T_1}\right)^2 + \sigma_{ш}^2 + \frac{d^2}{3}}, \qquad (5.12)$$

where d is the discreteness of phase readout by a digital phase meter.

Using formulas (5.11) and (5.12) we evaluate the probability of correct resolution of ambiguity for one transition in the hypothetical system we are considering. Setting $d = 0.01$, $\sigma_p = 2$ μs (0.0250 period on frequency of 12.5 kHz), we get

$$\sigma_\varphi = 0,035; \; P = \Phi\left(\frac{0,50}{0,175}\right) = \Phi(2,84) > 0,99.$$

So correspondingly for $\sigma_p = 4$ μs we get $P \approx 0.9$.

From a formal standpoint, the result should have been raised to a power equal to the number of transitions (four in our case). However, on low difference frequencies the correlation of measurement errors is so strong that the corresponding transitions are always made unambiguously. The loss of this unambiguous property can occur only with transition from the greatest difference frequency to the carrier frequency. Such an occurrence gives rise to a measurement error equal to the period of the carrier frequency (in our case 80 μs).

The existence of two fundamentally different methods of time signal transmission in the VLF band necessitates two approaches to the problem of calculating the time of propagation of transmitted signals. To determine corrections for delay in the propagation channel with the purpose of refining phase readings, it is necessary to know the phase velocity v_p, which enables us to find the total phase shift of the signal that has covered a distance l from receiver to transmitter,

$$\varphi_{\Sigma_p} = \varphi_{i_p} + n_{i_p} = \frac{l}{v_p} f_i. \qquad (5.13)$$

Formula (5.13) is also frequently written as

$$\varphi_{\Sigma_p} = \frac{1}{2\pi} k_i l,$$

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where $k_l = \frac{\omega_l}{v_p} = 2\pi\frac{f_l}{v_p} = \frac{2\pi}{\lambda_l}$ is the so-called propagation constant, or wave number. For free space, this symbol will be used without a subscript.

To determine the pulse signal delay, its group velocity v_g should be known, i. e. the velocity of displacement of energy from the transmitting to the receiving antenna. In this case, $\tau_p = \frac{l}{v_g}$.

If the phase velocity of the signal is independent of its frequency, the group velocity is exactly equal to the phase velocity. If such a dependence does hold between them, then there is a difference that is the stronger the greater the rate of change in v_p as frequency changes

$$v_g(f) = v_p(f) + \frac{\partial v_p(f)}{\partial f} f \qquad (5.14)$$

or as signal wavelength changes in free space

$$v_g = v_p(\lambda) - \lambda \frac{\partial v_p(\lambda)}{\partial \lambda}.$$

From the relations given in Section 5.3 it follows that $0 < \frac{c - v_g}{c} < 3 \cdot 10^{-3}$, in virtue of which the group velocity of pulsed VLF signals can be taken as equal to the speed of light in the case of an error in signal registration.

Thus we must have an opportunity to determine v_p to solve the problem of determining propagation time in the VLF band.

5.3. Elements of the Theory of VLF Propagation in the Spherical Earth-Ionosphere Waveguide

VLF radio waves propagate in the concentric earth and ionosphere that are walls, as it were, of a spherical waveguide. A strict mathematical description of the signal with the ionosphere with actual consideration of its properties does not permit us to find an analytical solution for signal parameters even when the characteristics of the propagation channel are known. Unfortunately, information that is currently available relative to the region of the ionosphere of significance for the propagation of VLF waves, ionization layers at an altitude of 50-100 km, does not enable a sufficiently exact description of the physical processes that take place therein.

The lower ionisphere, closed off as it is from the principal sources of ionization by upper layers, is less subject to the influence of a change in ionizing factors, and consequently is more stable than the upper ionosphere. The altitude dependence of electron concentration N_e for typical daytime conditions is shown in Fig. 20a, and for nighttime conditions--in Fig. 20b [Ref. 24]. The field of the VLF radio signal for the actual profile of the ionosphere can be calculated only by numerical methods, using a computer.

The waveguide nature of VLF radio signal propagation causes simultaneous excitation of several wave modes near the antenna that differ with respect to the altitude

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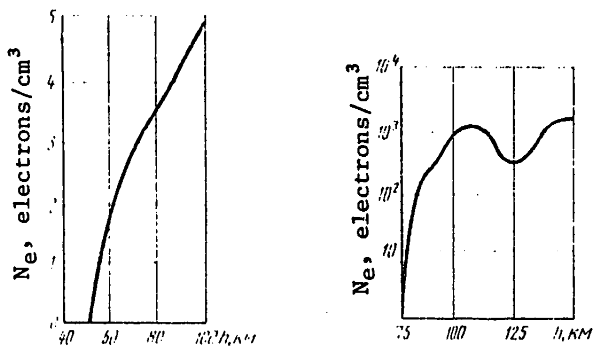

a b

Fig. 20. Altitude dependence of electron concentration in the lower ionosphere for typical daytime (a) and nighttime (b) conditions

dependence of the corresponding components of field intensity. The lower the mode number n, the less the fluctuations observed in this dependence. Each mode is characterized by a modulus λ_n and a phase $\phi\lambda_n$ of the coefficient of excitation, a phase velocity v_n and an attenuation β_n. The dependence of the field strength vector $\vec{E}_n$ on distance to the transmitter is

$$\vec{E}_n(l) = E_0(l) \frac{\theta}{\sqrt{\sin\theta}} \frac{\sqrt{\lambda R_3}}{h} A_n e^{-i2\pi\varphi_n}, \tag{5.15}$$

where

$$E_0(l) = \frac{300\sqrt{P}}{l} \tag{5.16}$$

is the field strength that would have been set up by a transmitter of power P under an infinitely conductive unbounded plane [in formula (5.16) E_0 is expressed in mV/m, P in kW and l in km], Θ is the ratio of the distance l from the transmitter in proportion to the radius of the earth R_3, h is the effective altitude of the ionosphere,

$$A_n = \Lambda_n e^{-\beta_n l}; \quad \varphi_n = 0{,}125 + \varphi_{\Lambda_n} + \frac{l}{v_n} l \tag{5.17}$$

are respectively the relative amplitude and phase of the given mode. The amplitude A and phase ϕ of the resultant field are determined from the relations

$$A = E_0(l) \frac{\theta}{\sqrt{\sin\theta}} \frac{\sqrt{\lambda R_3}}{h} \left[\left(\sum_n A_n \cos 2\pi\varphi_n\right)^2 + \left(\sum_n A_n \sin 2\pi\varphi_n\right)^2\right]^{\frac{1}{2}}, \tag{5.18}$$

$$\varphi = \operatorname{arctg} \frac{\sum_n A_n \sin 2\pi\varphi_n}{\sum_n A_n \cos 2\pi\varphi_n}. \tag{5.19}$$

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Thus to determine the phase and amplitude of the field at the reception point it is necessary to determine the parameters of the most intense modes and to perform vector summation of the fields that they produce in accordance with formulas (5.18) and (5.19). In view of the considerable difficulty of general solution of such a problem, idealized models of the channel with different degrees of complexity are used for approximate evaluation of the parameters of the modes.

A model with ideally reflective earth and ionosphere enables estimation of the phase velocities of the modes only. In this case, the strict solution for $f \leqslant 16$ kHz corresponds most nearly to the relation

$$v_n = c\left[1 + \frac{(2n-1)^2\lambda^2}{32h^2} - \frac{h-\lambda}{2R_3}\right], \tag{5.20}$$

h being the only parameter of the model.

In practice, instead of the absolute value of the phase velocity v_n, we often use its difference from the speed of light expressed relatively. In this case

$$\alpha_{n_0} = \frac{v_n}{c} - 1 = \frac{(2n-1)^2\lambda^2}{32h^2} - \frac{h-\lambda}{2R_3}. \tag{5.21}$$

From formulas (5.20), (5.21) we see that at comparatively lower altitudes of the ionosphere the phase velocities of some modes may be greater than the speed of light. This does not in any way contradict the famous assumption of relatively theory since the value of v_n only describes the spatial distribution of the phase of the field at a certain instant, and is not the velocity of propagation of any physical object. Any signal that is a change in phase or amplitude of the field near an antenna will lead to a reception point with group velocity that is always less than the speed of light.

A model with a sharply bounded ionosphere that accounts for nonideality of reflection from the walls of the equivalent waveguide permits evaluation of all four parameters of each mode, but in the general case requires numerical solution of the problem on a computer. The parameters of the model are: altitude h of the ionosphere, conductivity of the earth σ_3, and conductivity of the ionosphere σ_i. Instead of σ_i, the literature conventionally uses the so-called characteristic frequency of the ionosphere

$$\omega_r = \frac{\sigma_i}{\varepsilon_0},$$

where $\varepsilon_0 = \frac{1}{36\pi} \cdot 10^{-9}$ F/m is the dielectric constant of free space.

Since losses are small in practice in the earth and ionosphere, we can get approximate formulas for estimating mode parameters. In doing this, it is permissible to use the representation

$$\alpha_n = \alpha_{n_0} + \Delta\alpha(\sigma_3) + \Delta\alpha(\omega_r), \tag{5.22}$$

$$\beta_n = \beta(\sigma_3) + \beta(\omega_r), \tag{5.23}$$

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i. e. the influence of earth and ionosphere on the characteristics of mode propagation shows up independently in the first approximation. We give the corresponding formulas without derivation

$$\Delta\alpha(\sigma_3) = -0{,}25\frac{1}{h\sqrt{\sigma f}}; \tag{5.24}$$

$$\beta(\sigma_3) = 0{,}046\frac{1}{h}\sqrt{\frac{f}{\sigma}}. \tag{5.25}$$

Let us note that the values of $\Delta\alpha(\sigma_3)$ and $\beta(\sigma_3)$ are the same for all modes of the radio signal.

$$\Delta\alpha(\omega_r) = -0{,}70\cdot 10^{-3}(2n-1)^2 g\left(\sqrt{L}-\frac{1}{\sqrt{L}}\right); \tag{5.26}$$

$$\beta(\omega_r) = 0{,}0192\frac{(2n-1)^2}{\lambda} g\left(\sqrt{L}-\frac{1}{\sqrt{L}}\right), \tag{5.27}$$

where
$$g=\left(\frac{\lambda}{h}\right)^3\left[1+\frac{32h^3}{(2n-1)^3R_3\lambda^2}\right];\quad L=\frac{\omega_r}{6283f}.$$

In formulas (5.25), (5.27), the altitude of the ionosphere and signal wavelength are expressed in km, conductivity in mS/m, signal frequency in kHz, and attenuation in dB/km. To evaluate the modulus and phase of the coefficients of excitation we can use the relations

$$\Lambda_n = \frac{40\lg e}{(2n-1)^2}\frac{h^3}{R_3\lambda^2}; \tag{5.28}$$

$$\varphi_{\Lambda_n} = -\frac{\pi}{6}\frac{h^3}{R_3\lambda^2(2n-1)^2}. \tag{5.29}$$

Analysis of these formulas shows that the attenuations of modes increase rapidly with increasing mode numbers. Because of this, at sufficiently great distances from the transmitter the phase and amplitude of the field are determined by the one or two most intense modes. This circumstance, which appreciably simplifies the summation of modes according to formulas (5.18), (5.19), is used in presentation of the method of calculating the VLF transmission path (see Section 5.4).

A three-parameter model $\{h, \sigma_3, \omega_r\}$ with proper selection of parameters enables calculation of the phase velocities of modes and the total phase delay of a signal with relative error of no more than $(3\text{-}5)\cdot 10^{-4}$ for paths $l \geqslant 2000$ km. Since it is practically impossible to measure h, σ_3 and ω_r independently, their values are estimated from measured parameters of the field at the reception point. At the present time it is usually assumed that h = 70 km for day and 90 km for night, and $\omega_r = 2\cdot 10^5$. The conductivity of the earth in S/m, depending on the type of underlying surface, is:

sea.	8
prairie, wet ground. . .	$5\cdot 10^{-3}$
prairie, dry ground. . .	$1\cdot 10^{-3}$–$2\cdot 10^{-4}$
fresh water.	$1\cdot 10^{-3}$

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mountains. . . . . $1 \cdot 10^{-4}$–$3 \cdot 10^{-5}$
permafrost . . . . 3–$5 \cdot 10^{-5}$
permanent ice. . . . . . . less than $1 \cdot 10^{-5}$

TABLE 1

Phase velocities of first three modes without consideration of losses in the walls of the equivalent spherical waveguide

n	For day (h = 70 km)					For night (h = 90 km)				
	$\alpha_{n_0} \cdot 10^3$ at f, kHz									
	10	15	20	25	30	10	15	20	25	30
1	2,62 2,89	—1,35 —0,94	—2,86 2,31	—3,63 2,95	—4,07 3,25	—1,25	—3,96	—5,01	—5,56	—5,9
2	48,5	19,09	8,66	3,61	0,92	26,2	8,28	1,95	—0,55	—1,80
3	140,6	60,10	31,70	18,11	10,92	81,7	32,7	15,8	7,95	3.37

TABLE 2

Corrections to values of phase velocity with consideration of nonideality of reflection from the ionosphere

n	For day					For night				
	$\Delta\alpha \cdot 10^3$ at f, kHz									
	10	15	20	25	30	10	15	20	25	30
1	0,35	0,15	0,14	0,12	0,07	0,30	0,22	0,120	0,08	0,07
2	1,41	0,37	0,30	0,15	0,10	0,70	0,20	0,16	0,14	0,08
3	3,46	0,81	0,62	0,32	0,16	1,45	0,38	0,30	0,18	0,10

TABLE 3

Attenuations of modes due to interaction with ionosphere

n	For day					For night				
	$\beta \cdot 10^3$, dB/km at f, kHz									
	10	15	20	25	30	10	15	20	25	30
1	3,42	2,54	2,25	2,11	2,06	2,81	2,29	2,24	2,02	1,99
2	12,79	6,32	4,34	3,37	2,89	6,65	4,09	2,93	2,64	2,39
3	31,53	13,89	8,57	5,87	4,56	14,21	5,51	5,29	3,87	3.22

Knowing the parameters of the propagation channel, we can readily calculate the components of $\Delta\alpha(\sigma_3)$ and $\beta(\sigma_3)$ from formulas (5.24), (5.25). Tables 1–4 summarize the values of α_{n_0}, $\Delta\alpha(\omega_r)$ and $\beta(\omega_r)$, which are more difficult to calculate. It was pointed out above that formula (5.21) gives fairly accurate values of α_{n_0} for

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TABLE 4

Coefficient of excitation of the first mode* and its phase

f, kHz	Λ_1, dB		φ_{Λ_1}, fraction of cycle	
	daytime	nighttime	daytime	nighttime
10	−2,09	−4,43	0,005	0,01
15	−4,74	−9,91	0,011	0,024
20	−8,16	−17,41	0,019	0,042
25	−13,37	−27,2	0 032	0,065
30	−20,18	−40,9	0,048	0,098

*For modes with other numbers Λ_n and ϕ_{Λ_n} can be calculated from the formulas

$$\Lambda_n = \frac{\Lambda_1}{(2n-1)^2}; \quad \varphi = \frac{\varphi_{\Lambda_n}}{(2n-1)^2}.$$

$f \leqslant 16$ kHz. For the frequency range of 20-25 kHz, the values of α_{n0} are understated by $(0.6\text{-}0.7)\cdot 10^{-3}$.

5. 4. Daily Variations of Phase and Amplitude of Signal at Reception Point

The principal conclusions and relations of Section 5.3 have been derived on the basis of the assumption that either daytime or nighttime conditions obtain on the entire path from the transmitting to the reception point. Such routes are called equiluminant. They correspond to values of phase and amplitude that are nearly invariant in time. In reality, the path between transmitter and receiver crosses the line between night and day (terminator) twice daily. Exceptions are paths with one end lying in the polar region, which dictates anomalous conditions of illuminance (absence of total day or total night, continual day or continual night).

The period of crossing the line between day and night is called the transition period, and transmission paths at this time are non-equiluminant. During the transition period, the phase and amplitude of the field change rather rapidly, passing from the daytime to the nighttime value and vice versa. At sufficiently great distances from the transmitter, where the interference of terms of the mode series has no effect, these variations are trapezoidal. P. Ye. Krasnushkin, who was the first to observe the curve of diurnal phase variation and to give it an interpretation based on the mode approach [Ref. 25], called it the phase trapezoid.

In daylight the phase velocity as a rule is greater than at night, while the signal phase at the reception point is greater in the nighttime than during the day. The peak-to-eak diurnal fluctuations of the phase--the amplitude of the phase trapezoid --at a distance can be defined as

$$\Delta\tau = \frac{l}{c}(\alpha_{\text{дн}} - \alpha_{\text{ноч}}) = \frac{l}{c^2}(v_{\text{дн}} - v_{\text{ноч}}), \qquad (5.30)$$

[subscripts дн, ноч denote "day" and "night" respectively] where $v_{\text{дн}}$, $v_{\text{ноч}}$ are the phase velocities of leading modes for daytime and nighttime conditions.

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Let distance l be great enough that the first mode is the leading mode both during the day and at night. Then on the basis of formula (5.21) we get

$$\alpha_{дн} - \alpha_{ноч} = \frac{\lambda^2}{32\bar{h}^2} \cdot 2\frac{h_{ноч} - h_{дн}}{h} + \frac{h_{ноч} - h_{дн}}{2R_3}, \qquad (5.31)$$

where $\bar{h}$ is the mean altitude of the ionosphere, equal to 80 km. Substituting numerical values of parameters in formula (5.31), we get

$$\alpha_{дн} - \alpha_{ноч} = 0{,}244 \cdot 10^{-5}\lambda^2 + 1{,}57 \cdot 10^{-3}.$$

Most points on the territory of the USSR get reliable reception of signals from a VLF radio station in Great Britain situated about 100 km to the north of London, and operating with call letters GBR on a carrier frequency of 16 kHz. Since this frequency corresponds to a wavelength of 18.75 km, with consideration of formula (5.31) we get $\Delta\tau = 8.1l$ μs (distance l is expressed in thousands of km). The distance from station GBR to Moscow is about 2550 km, which should correspond to an amplitude of the phase trapezoid of the order of 21 μs. The resultant value agrees well with experimental data of the authors for this route. Analogously, for the GBR-Irkutsk route we get $\Delta\tau = 8.1\ 5.220 = 42.3$ μs; in Ref. 26, diurnal phase variations of the order of 37-45 μs were determined for this longer route.

In cases where different modes predominate during the day and at night, the data of tables 1 and 2 should be used for calculating the diurnal phase variation.

5.5. Method of Calculating Phase and Amplitude of a Signal (Correlation of Mode and Ray Approaches and Their Limits of Applicability)

The method of calculating the field of a VLF radio signal must include the following principal stages:

1) determination of mode parameters;
2) determination of ratios of levels of the terms of the mode series at the reception point;
3) selection of the leading mode or making a decision on the necessity of adding several terms of the mode series;
4) calculating the phase and amplitude of the signal with respect to the leading mode or by using a relation that accounts for several modes.

In calculating the phase it is usually considered that the phase velocities of the most significant modes as a rule differ from the speed of light in free space by no more than $(5\text{-}7)\cdot 10^{-3}$. This enables us to express the total phase delay or its corresponding apparent time of propagation as

$$\tau_{ф} = \frac{l}{c}(1+\alpha) = \tau_0 + \tau_{доп};\ \varphi = \frac{fl}{c}(1+\alpha) = \varphi_0 + \varphi_{доп}, \qquad (5.32)$$

[subscript доп = additional] τ_0, ϕ_0 are calculated with respect to the speed of light, and the corrections to these values are called the additional phase advance and additional propagation time respectively. Based on the feasibility of representation of expressions (5.32), it is advisable to calculate the phase in three stages:

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calculation of the time of propagation to the reception point "at the speed of light";

determination of the additional propagation time with respect to the leading mode or by summation of several modes;

calculation of the total phase of the field.

We will give a detailed exposition of the method based on an example of calculation of a specific transmission path.

Initial data: transmitter is the GBR radio station; reception point in the vicinity of Moscow; radiation power of the transmitter 60 kW; signal frequency 16 kHz; the route passes almost entirely over dry land, plains without mountains or permafrost; path length 2610 km; reception time 15^h00^m Moscow time in June.

Parameters of the equivalent waveguide: the nomogram of Fig. 36 shows us that the entire transmission path is completely illuminated during the reception period, and therefore $h = 70$ km. In accordance with the data on pp 40-41, $\sigma_3 = 5$ mS/m for the given type of terrain. Based on recommendations in the literature, we take the characteristic frequency of the ionosphere as $\omega_r = 2 \cdot 10^5$ s^{-1}.

Let us determine the parameters of modes.

1. Auxiliary parameters associated with signal frequency:

$$T = \frac{1000}{f} = 62.5 \ \mu s, \ \lambda = \frac{300}{f} = 18.75 \ km, \ \omega = 6.283f = 1.05 \cdot 10^5 \ s^{-1}.$$

2. Phase velocities of the first three modes without consideration of losses ($v_n = c(1 + \alpha_n)$). Since the signal frequency f lies between the two tabulated values f_T, f_{T+5}, we use linear interpolation:

$$\alpha_{n_0}(f) = \alpha_{n_0}(f_T) + \frac{f - f_T}{5} [\alpha_{n_0}(f_T + 5) - \alpha_{n_0}(f_T)]. \tag{5.33}$$

For the first mode we get

$$\alpha_{1_0}(16) = \left[-1{,}35 + \frac{1}{5}(-2{,}86 + 1{,}35)\right] \cdot 10^{-3} = -1{,}65 \cdot 10^{-3},$$

for the second $\alpha_{2_0} = -17.01 \cdot 10^{-3}$, and for the third $\alpha_{3_0} = -54.54 \cdot 10^{-3}$.

3. Attenuations of modes:

components of attenutation that are due to the finite conductivity of the earth,

$$\beta_n(\sigma_3) = 0{,}046 \frac{1}{R_3} \sqrt{\frac{f}{\sigma_3}} = 1{,}47 \cdot 10^{-3} \text{ dB/km};$$

the component of attenuation due to nonideality of reflection from the ionosphere is found by interpolating the data of Table 3 using a formula analogous to (5.33). After interpolation we get

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$$\beta_1(\omega_r) = 2.54 \cdot 10^{-3} \text{ dB/km}, \quad \beta_2(\omega_r) = 6.32 \cdot 10^{-3} \text{ dB/km}, \quad \beta_3(\omega_r) = 13.89 \cdot 10^{-3} \text{ dB/km}.$$

4. Coefficients of excitation of modes:

$$\Lambda_1 = -5{,}45 \cdot 10^{-3} \frac{h^3}{\lambda} = -5{,}45 \cdot 10^{-3} \frac{34300}{350} = -5{,}35 \text{ dB};$$

in accordance with Table 4

$$\Lambda_2 = -0.6 \text{ dB}; \quad \Lambda_3 = -0.2 \text{ dB}.$$

5. Relative levels of modes at the reception point:

in accordance with formulas (5.23) and (5.16) for the first mode

$$\beta_1 = (1{,}47 + 2{,}54) \cdot 10^{-3} = 4{,}01 \cdot 10^{-3} \text{ dB/km};$$
$$A_1 = -5{,}35 - 4{,}01 \cdot 10^{-3} \cdot 2610 = -5{,}35 - 10{,}47 = -15{,}82 \text{ dB};$$

for the second

$$\beta_2 = (1{,}47 + 6{,}32) \cdot 10^{-3} = 7{,}79 \cdot 10^{-3} \text{ dB/km};$$
$$A_2 = -0{,}6 - 7{,}79 \cdot 10^{-3} \cdot 2610 = -20{,}83 \text{ dB};$$

for the third

$$\beta_3 = (1{,}47 + 13{,}89) \cdot 10^{-3} = 15{,}36 \cdot 10^{-3} \text{ dB/km};$$
$$A_3 = -0{,}2 - 15{,}36 \cdot 10^{-3} \cdot 2610 = -37{,}29 \text{ dB};$$

6. Error of calculating the phase of the field with consideration of only the first (leading) mode:

$$\delta_\varphi \leqslant \frac{1}{2\pi} 10^{-(A_1 - A_2)/20} = \frac{1}{6{,}28} \cdot 10^{-5{,}01/20} = \frac{1}{1{,}8 \cdot 6{,}28} = 0{,}087 \text{ cycle}.$$

7. Corrections to the phase velocity for the leading mode. In accordance with formula (5.24)

$$\Delta\alpha(\sigma_3) = -\frac{0{,}25}{70} \sqrt{\frac{1}{5 \cdot 16}} = -0{,}35 \cdot 10^{-3}.$$

Interpolation of data of Table 2 gives $\Delta\alpha(\omega_r) = -0.15 \cdot 10^{-3}$.

8. Final value of the phase velocity of the leading mode:

$$\alpha_1 = \alpha_{1_0} + \Delta\alpha_1(\sigma_3) + \Delta\alpha_1(\omega_r) = -(1{,}65 + 0{,}35 + 0{,}15) \cdot 10^{-3} = -2{,}15 \cdot 10^{-3}.$$

9. Phase of the coefficient of excitation of the leading mode:

according to formula (5.29), $\phi_{\Lambda_1} = 3° \cong 0.01$ cycle, which corresponds to 0.6 μs.

10. Additional propagation time

$$t_{доп} = T(0{,}125 + \varphi_{\lambda_1}) + \alpha_1 \frac{l}{c} = (0{,}01 + 0{,}125) \cdot 62{,}5 + \frac{2{,}15 \cdot 10^{-5} \cdot 2610}{0{,}3} = 28{,}8\ \mu s.$$

11. Total apparent time of propagation

$$\tau_{p_\Sigma} = t_{доп} + \frac{l}{c} = t_{доп} + \frac{l}{0{,}3}(1 + 0{,}7 \cdot 10^{-3}) = 28{,}8 + 8705{,}1 = 8733{,}9\ \mu s.$$

12. Complete phase of the field

$$\varphi_{p_\Sigma} = \tau_p / T = 8733{,}9/62{,}5 = 139{,}74 \text{ cycles}.$$

13. Correction for phase delay of signal during propagation

$$\varphi_p = \varphi_{p_\Sigma} - \text{entier}(\varphi_{p_\Sigma}) = 139{,}74 - 139 = 0{,}74.$$

The resultant number is the sought correction for signal propagation in the earth-ionosphere waveguide.

14. Signal amplitude is determined by using the results already found. First the constant factor is found that depends on transmitter power P, wavelength λ and altitude of the ionosphere h

$$B = \frac{300\sqrt{P\lambda}}{h\sqrt{R_3}}.$$

For our case

$$B = 300 \frac{\sqrt{60 \cdot 18{,}75}}{70\sqrt{6378}} = 1{,}81 \text{ mV/m}.$$

Then the factor that depends only on the distance from the transmitter is determined

$$u(l) = \frac{1}{\sqrt{\sin \frac{l}{R_3}}} = \frac{1}{\sqrt{\sin \frac{2610}{6378}}} = 1{,}63.$$

The field strength of the signal at the reception point is

$$E(l) = Bu(l) \cdot 10^{A/20}.$$

In accordance with point 5, A = -15.82 dB. Finally

$$E(l) = 1{,}63 \cdot 1{,}81 \cdot 10^{-0{,}791} = 2{,}95/6{,}20 = 0{,}475 \text{ mV/m}.$$

This example demonstrates an important advantage of the mode approach at sufficiently great distances from the transmitter: it has the capability of accounting for one mode alone, and thus makes it comparatively simple to calculate the amplitude and phase of the field at the reception antenna. At short distances, where it is necessary to account for several terms of the mode series, this advantage disappears. The difficulty of the mode approach is inversely proportional to the length of the transmission path, which is opposite to the situation for the ray method considered in Chapter 4.

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Let us recall that the ray method at distances of the order of 500-1000 km permits consideration of only one or two rays that have arrived at the reception point with different numbers of reflections [Ref. 27]. On short routes the ray approach can be successfully used instead of the mode approach or on an equal basis with it. As the distance from the transmitter increases, there is a sharp increase in the number of rays with approximately equal amplitudes that are incident on the reception antenna. Besides, at a considerable distance from the transmitter, the fundamental limitations of the ray method also begin to make themselves felt. When it is used in implicit form, it is assumed that the signal travles in an finitesimally thin ray, and after colliding with the walls of the equivalent waveguide it changes direction of propagation in accordance with the law of mirror reflection. However, in reality, even in free space, the signal travels to the reception point as if through some channel that narrows at the transmitting and receiving antennas and widens out on the middle distances between them.

The maximum width of the channel d_{max} may be taken as equal to the diameter of the so-called first Fresnel zone [Ref. 28],

$$d_{max} = \frac{\sqrt{\lambda l}}{2}.$$

The width of the channel can be disregarded, and it can be considered a ray only in the case where it is less than the height of the equivalent waveguide

$$d_{max} = \frac{\sqrt{\lambda l}}{2} \ll h. \tag{5.34}$$

From expression (5.24) we get a formula for the radius of the zone of applicability of the ray approach:

$$l \ll \frac{4h^2}{\lambda}. \tag{5.35}$$

Calculations by formula (5.35) show that in the VLF range, the ray approach can be used in pure form only at distances up to about 500 km in daytime and 1000 km at night [Ref. 27 (this paper gives a detailed description of the ray method as applied to the VLF band)].

With transition to higher-frequency bands the radius of the zone of applicability of the ray approach increases. Mode damping practically ceases to grow as mode number increases, and there is an increase in the number of propagating modes. In comparison all this negates the noted principal advantage of the mode approach.

Thus the mode and ray approaches mutually complement one another, enabling comparatively simple engineering calculation of transmission paths over a wide range of frequencies and distances from the transmitting antenna.

5.6. Error of Calculating Propagation Time

The error of calculating the phase and group velocities of VLF radio signals is dictated mainly by two factors: inadequacy of the model of the propagation channel, and inexactitude of knowledge of its parameters.

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The structure of the error due to inadequacy of determining the difference of the phase velocity of the mode from the speed of light is given rather well by a series of the form

$$\alpha = \alpha_{\text{пл}} + \sum_s \Delta\alpha_s, \qquad (5.36)$$

where $\alpha_{\text{пл}}$ corresponds to the simplest model--a plane waveguide with ideal reflection from the walls; $\Delta\alpha_s$ is the correction sequentially introduced in accounting for the actual properties of the propagation channel. Series (5.36) slowly converges to the value corresponding to the actual behavior of the field of a VLF radio signal. The number of terms is large (in principle it is infinite); however, each specific model has a corresponding sum of a finite number of terms of the series. The sum of the dropped terms, or the approximate value of the first of these is the error due to inadequacy of the model. Thus $\Delta\alpha_1$ is the error due to nonequivalence of the planar ideal waveguide to a spherical waveguide; $\Delta\alpha_2$ is the error of the spherical waveguide with ideal reflection as compared with a model that accounts for losses in the earth and ionosphere, and so on. The next step in refinement of the model is transition from a stepwise approximation of the ionosphere to consideration of the actual behavior of the altitude dependence of the concentration of charged particles and the frequency of collisions (correction $\Delta\alpha_3$).

An important factor is consideration of the horizontal component of the earth's magnetic field H_l. This disrupts azimuthal symmetry of the model, so that the corresponding correction $\Delta\alpha_4$ will depend on the direction of the path. Attempts have also been made to account for deep layers of the earth, terrain relief, vegetation on the transmission path and so on.

The rough values of the corrections due to non-equivalence (inadequacy) for $f = 20$ kilohertz are: $\Delta\alpha_1 = -5\cdot10^{-3}$, $\Delta\alpha_2 = -0.3\cdot10^{-3}$, $\Delta\alpha_3 = \pm0.25\cdot10^{-3}$, $\Delta\alpha_4 = \pm0.5\cdot10^{-3}$.

It must be borne in mind that the actual parameters of the channel are in one-to-one correspondence only with the parameters of a nonexistent ideal model that accounts for all terms of series (5.36). The parameters of all existing models are effective, and have a certain dependence on signal frequency. As a rule, these parameters are not determined by direct measurement, but are rather chosen in accordance with the principle of best conformity of the field amplitude and phase calculated with their use to the values observed in reality. Such an approach is called the "inverse problem method" [Ref. 25]. This is the way in particular that we have found the daytime and nighttime altitudes of the ionosphere frequently quoted in this chapter (70 and 90 km) for the model with stepwise approximation of the behavior of electron concentration--the model with a sharply bounded ionosphere.

The more perfect the model, the wider will be the range of frequencies, and the more accurate will be the correspondence of predicted results to experimental data of investigation of the signal field on different transmission paths. However, refinement of the model requires more and more information on the parameters of the actual path of propagation--in particular on the ionosphere. The possibility of getting information on the lower ionosphere without analyzing the results of amplitude and phase measurements in the VLF band is quite limited, and boils down to point probing with geophysical rockets at a few scattered points [Ref. 24].

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Because of this, a reasonable compromise is needed between complexity and accuracy of the model. If the error of calculation of phase velocities of the modes is to be of the order of $(0.5\text{-}1)\cdot 10^{-3}$, it would be advisable to stop at the three-parameter model $\{h, \sigma_3, \omega_r\}$ discussed in this chapter with sharply bounded ionosphere. When parameters have been appropriately chosen, the model enables calculation of time of propagation with error of the order of 1-3 μs on a 1000 km transmission path in daytime conditions. At nighttime and in the transition period, model $\{h, \sigma_3, \omega_r\}$ and others that have been studied are less exact than under daytime conditions (for example, the error of the model that we have selected may reach 5-6 μs over 1000 km). Nonethelss, the good agreement between the calculations of Section 5.4 and experimentally measured amplitudes of the phase trapezoid is evidence that the given rough value is the upper limit of the computational error.

The additional error of calculation due to inexact knowledge of the parameters of the model can be estimated by standard methods of error theory, which we leave to the reader. Most appreciable in practice is the error due to inexact knowledge of the altitutde of the ionosphere $\Delta h_n(\Delta h)$. The formula for calculating this additional error takes the form

$$\Delta\alpha_1(\Delta h) = \frac{\lambda^2}{16h^2}\frac{\Delta h}{h} - \frac{\Delta h}{R_3}. \qquad (5.37)$$

Formula (5.31) implies that in the middle part of the VLF band, $\Delta\alpha_1(\Delta h)/\Delta h$ is of the order of 0.1·10^{-3} km^{-1}.

Since such error components as instrument error, and the error due to statistical fluctuations of the phase at the reception point amount to a few microseconds and are weakly dependent on distance [Ref. 29], the cited error (1-3 μs per 1000 km) is what determines the realistically attainable accuracy of synchronization with the use of VLF radio channels. For typical transmission paths (l = 3000-6000 km) the error of synchronization in the VLF band may reach 10-15 μs.

All the given values of synchronization error apply to the case of determination of the position of the time scale of the reception point relative to the scale of the transmitting point. The error of mutual tie-in of the scales of two reception points for which the mutual distance l_{mut} is much less than the distance to the transmitter is much lower because of the compensation of common systematic components. For a rough estimate of this effect we can use the semi-empirical formula

$$\delta_{mut}/\delta_{rec} \cong \sqrt{l_{mut}/l}, \qquad (5.38)$$

where δ_{mut} is the error of mutual synchronization of the scales of the reception points; δ_{rec} is the error of synchronization of each of the reception points with respect to signals of the transmitting station. Thus for a typical case ($l_{mut}/l \cong 0.25$), we get $\delta_{mut}/\delta_{rec} \cong 0.5$.

CHAPTER 6: METHODS OF SYNCHRONIZING SPATIALLY SEPARATED FREQUENCY AND TIME STANDARDS IN THE UHF AND MICROWAVE BANDS

Regular transmissions of television broadcasts and communications in these bands rely on radio relay lines, intercity cable lines and artificial satellites.

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Propagation of radio waves in these bands is within the limits of direct visibility for surface radio relay channels (within a range of 50-150 km), and practically unlimited when three artificial satellites are used. In long-range transmissions over surface channels in these bands, intermediate relay broadcast stations are used that extend the lines between two points on the surface of the earth.

These existing channels of television broadcasting and communications are used likewise for synchronizing and transmitting time and frequency units to users.

Radio communications regulations have set aside three frequency bands for these systems: 8-th (30-300 MHz), 9-th (300-3000 MHz) and 10-th (3000-30000 MHz). Radio wave propagation in these bands is influenced by atmospheric inhomogeneities, turbulence, inconstancy of the parameters of atmospheric waveguides and also the sporadic E_s layer. As will be shown below, when using radio relay lines the influence of these parameters produces an error of 0.1 μs or less. When using artificial satellites, the effect of the ionosphere will show up in Faraday rotation of the plane of polarization. In the 9-th band, the coefficient of refraction will also depend on humidity, temperature and pressure, which differ in different regions, and at different times and seasons.

6.1. Using Reflections From Meteor Trails

For purposes of synchronization by reflection from meteor trails, frequencies of 40-100 MHz are used in the 8-th band. Meteor trails that can reflect radio waves are formed at an altitude of 50-100 km due to the fact that the earth's atmosphere is continually penetrated by tens of billions of solid particles with mass of 0.01-0.001 mg from outer space moving at a velocity of 12-70 km/s relative to the earth. As they penetrate the earth's atmosphere, the meteoric particles are heated by repeated collisions with molecules of air. Atoms are removed from the surface of the particles and undergo collisions with molecules of air, resulting in heating of the ambient medium and ionization of atoms. As a consequence of ionization where a meteor has passed, a trail is formed that contains free electrons that over a time of 0.01-1.5 s can reflect radio waves of the 8-th band.

It can be assumed in a first approximation that the number of particles penetrating the atmosphere in a unit of time is related to their mass; $n = k/m$, where m is the mass of a particle; n is the number of particles with mass greater than m; k is a coefficient that depends on time of day, season of the year and other factors.

The average number of trails n_{tr} crossing 1 m^2/s is calculated by the formula $n_{tr} = 160/N_e$, where N_e is the number of electrons per meter (10^{14}-10^{16}).

The meteor trail has a number of specific properties that must be taken into consideration when using it to synchronize time and frequency standards:

the meteor trail has a limited lifetime (a few second or less);

The occurrence of meteor trails is random over the course of a day, and their distribution is determined by solar activity;

the energy flux of radio waves reflected from a meteor trail is sharply directional. During its lifetime, the trail takes a sinuous configuration due to wind action, and

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the reflected beam in some cases of coherent scattering of radio waves by an undercompacted trail (electron density $q \ll 10^{12}$ electrons per cm of trail length) is dispersed.

In the case of such a mechanism of scattering, the following may be possible causes of phase instability:

diffraction effects associated both with the process of trail formation due to the finite velocity of meteors, and with the process of trail destruction under the action of diffusion;

displacement of the reflecting region under the action of winds in the atmosphere.

Ionized meteor trails reflect signals almost specularly, the reflected signal being characterized by an initial surge of amplitude, and rapid decay in accordance with an exponential function. This type of signal makes up about 44% of the total number of reflections. Upon reflection from overcompacted trails, the falling part of the amplitude of the reflected signal shows peaks and valleys due to the action of high-altitude stratospheric winds. Besides this, the reflections from overcompacted trails ($q > 10^{12}$ electrons per cm of trail length) last for long times--up to several seconds--and during this time the turbulent wind twists and breaks the ionized column, resulting in multibeam propagation.

The number of meteoric reflections during signal transmissions depends on the extent of the path, the time of day and the season of the year (Fig. 21) [Ref. 30].

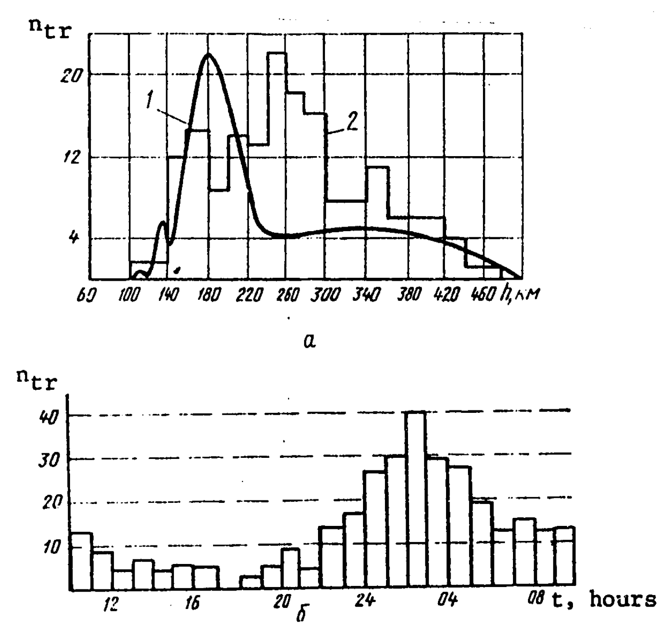

Fig. 21.. Population of meteoric reflections as a function of altitude (a) and time of day (b) [Ref. 30]

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The number of single sessions of synchronization by n_{tr} varies depending on the time of day (Fig. 21b) and the orientation of antenna systems (Fig. 21a). The data of Fig. 21 apply to deflection of the antenna 22° toward the north. When the antenna is turned 22° toward the south, there is a noticeable increase in n_{tr} in the period from 12^h to 18^h. The observed diurnal variations of n_{tr} confirm the advisability of reorienting antennas with a change from nighttime to daytime measurements.

On Fig. 21a, curve 1 shows the calculation, and curve 2 shows the experimental behavior of the number of meteoric reflections as a function of range (altitude) for the main lobe of the antenna radiation pattern.

Studies of Ref. 31-33 showed that the channel of meteoric communication has a relatively broad passband (0.2-0.8 MHz), high security of transmission, and is not overly subject to the influence of ionospheric perturbations thanks to the directional properties of antennas and the simplicity of sending and receiving equipment. These advantages allow this system to be successfully used for synchronizing time and frequency standards at a distance of up to 1200-1400 km.

The point of occurrence of a meteor trail is random and not subject to prediction, and therefore the path and time of signal transmission is determined only experimentally by using simultaneous opposed transmissions and receptions of signals (methods of two-, three- and four-beam transmissions). During a synchronization session, the transmitters are practically in a state of radiation, and the reception devices fix the occurrence of a meteor trail on the transmission path with unilateral and bilateral passage of time signals.

The first experimental transmissions were done on a frequency of 73 MHz with a transmitter having 80 kW pulse power and directional antennas: four seven-element cophased arrays of the wave channel type. The transmitted time signals were pulses from a master timer with pulse recurrence rate of 100 Hz and duration of 10 μs. Variation in altitude of reflection from the meteor trail was 86-105 km. The field strength at the reception point was of the order of 10 μV/m.

In this research, clock synchronization was by a method of simultaneous transmission and registration of time signals (two-beam method). A disadvantage of the method is the necessity of exchanging results of registration over an additional communication channel.

Subsequently, duplex synchronization methods with unilateral or bilateral rebroadcasting were used for such systems in synchronization of time standards. Fig. 22 shows a system for synchronizing the time scale of point Б by using reflection from meteor trails. Time signals from a clock at point A are transmitted after reflection from the meteor trail to point Б and returned to point A together with time signals tranmitted from point Б. Simultaneously with emission of the time signal from point A, a reversible counter is triggered there that operates in the addition mode (forward count). The time signal from point Б switches the counter at point A to the subtraction mode, and the time signal transmitted from point A, after it has been rebroadcast from point Б, stops the pulse count of the counter. Half the difference of the count gives the discrepancy of the time scales reproduced at points A and Б.

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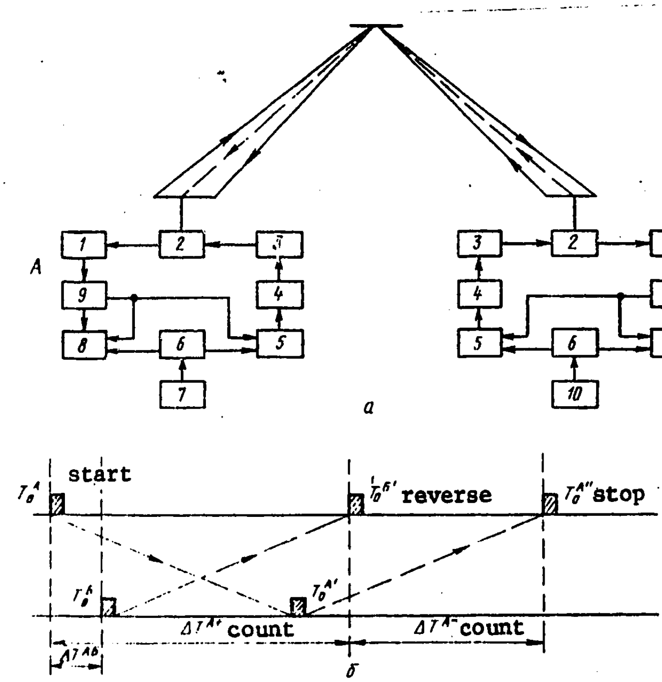

Fig. 22. System for synchronizing time scales using reflection from meteor trails:
a--block diagram of reception and transmission equipment; b--diagrams of signal transmission; 1--receiver; 2--antenna commutator; 3--UHF transmitter; 4--modulator; 5--submodulator; 6--matching device; 7--synchronizing standard; 8--reversible counting-type frequency meter (in the mode of time interval measurement); 9--interference-killing and commutation equipment; 10--time standard to be synchronized

Thus clock synchronization is done automatically without additional exchange of information between points. In addition, such a method enables verification of the correctness of the setting of the synchronizing clock at the point being synchronized, which in this case may be unattended.

With identical equipment at both points, the method gives high precision of clock synchronization.

Experimental work on Moscow-Gor'kiy and Moscow-Khar'kov transmission paths [Ref. 34] has shown that clocks can be synchronized with an error of less than 1 μs when meteor trails are used.

6.2. Use of Television Channels

Intercity cable and radio relay lines are characterized by a broad passband, a signal-to-noise ratio of 50 dB, high stability of the parameters of equipment and

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transmission channel (which in turn ensures high constancy of the time of passage of exact time signals over long distances), and by the capability of direct measurement of the time of signal transmission.

Thanks to the wide passband, the risetime of the transmitted pulses at the reception point is of the order of 0.2 μs or less.

Bandwidth is determined by the ratio of the message spectrum ΔF and the signal spectrum W. The latter in turn is determined by the selected type of modulation and signal duration T. For narrow-band systems

$$\Delta F = W \text{ and } \Delta FT = WT \cong 1,$$

while for wide-band systems

$$W >> \Delta F \text{ and } WT \cong 100\text{–}1000.$$

Frame and line synchronization signals and signals of other types are transmitted together with the picture signals to stabilize the image on television screens. As they are introduced into the makeup of the television signals, they can be used to transmit information on the instants of exact time signals in a variety of television systems differing chiefly in the order and rate of analysis and synthesis of image elements.

The following image-scanning techniques are known: linear (sequential), interlaced, diagonal and spiral.

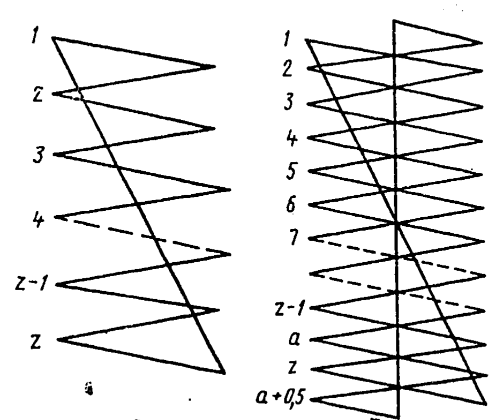

Fig. 23. Image scanning

In sequential scanning (Fig. 23a), the elements are analyzed by continuous tracing of the transmitted image in sequence along each line. The number of lines in a frame may be constant, in which case

$$\frac{f_z}{f_K} = z, \qquad (6.1)$$

where z is the number of lines of the scan.

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In the case of interlaced scanning (Fig. 23b) there is no such relation between scanning frequencies, and

$$\frac{f_z}{f_\kappa} = m(a+b), \tag{6.2}$$

where m is the scanning multiplicity, and a is an integer; b is any number.

In a television broadcast system it is assumed that m = 2, b = 0.5, a = 312, i. e. in each image field there are 312.5 lines, and as a result during frame scanning the lines of both fields of one frame are automatically shifted.

Interlaced scanning is used in the Soviet Union. Fig. 24 shows signals of the first and second fields of a television image.

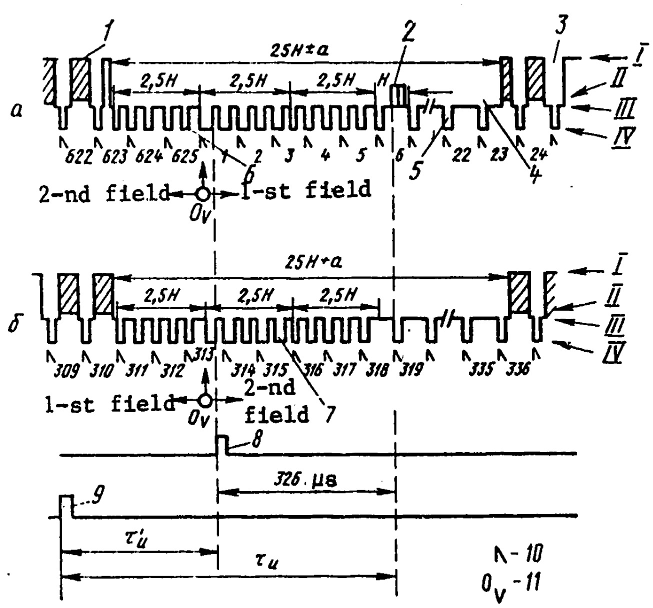

Fig. 24. Complete television signal at the beginning of each first (a) and second (b) field:
I--white level; II--black level; III--blanking level; IV--synchronizing pulse level; 1--line signal; 2--time signal; 3--line blanking pulse; 4--frame blanking pulse; 5--line synchronizing pulse; 6--leveling pulse; 7--frame synchronizing pulse; 8--pulse shaped from cutoff of frame synchropulse; 9--local clock seconds pulse; 10--beginning of line; 11--beginning of field; a--duration of line quenching pulse 12 ± 0.3 µs; numerals indicate frame line numbers

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The duration of the entire frame quenching pulse is $25H = 25 \cdot 64$ μs (where H is the duration of a line). In interlaced scanning, the frames of the television image alternate at a repetition rate of 25 frames per second. The line scanning frequency is $f_z = 15625$ Hz. Nominal field scanning corresponds to the ratio $f_{field} = 2f_z/625 = 50$ Hz.

The following lines are set aside for service use:

16 and 329--identification signals;
17, 18, 330 and 331--test line signals;
19, 20, 21, 332-333 and 334--signals for in-house use;
7, 8, 9, 10, 11, 12, 13, 14 and 15 (in the first field), 320, 321, 322, 323, 324, 325, 326, 327 and 328 (in the second field of a frame)--color synchronization signals. Chrominance signals are a subcarrier modulated by two color-difference signals that alternate from line to line. The subcarrier frequencies used in different systems are: 4.429687 MHz (NTSC), 4.43361875 MHz (PAL), and the SECAM-3 system has two zero subcarriers (4.25 and 4.40625 MHz) located alternately on the trailing flats of the line quenching pulses.

Test signals are used to monitor the white level by means of square pulses, and to evaluate:

the amplitude-frequency response of the video channel by means of a signal with six bursts of sinusoidal waveforms situated sequentially in order of increasing frequencies along the line (0.5, 1.5, 3.0, 4.5, 5.0 and 6.0 MHz);

the transient response of the video channel in the video frequency range by means of sine-square pulses with duration of 0.16 μs;

nonlinearity of the amplitude response of the video channel by means of a sawtooth signal with superposed sinusoical waveform on a frequency of 1.2 MHz.

The television program is radiated by the telecenter on fixed carrier frequencies individually for the image and sound in separate radio channels. For the Moscow Television Technical Center (TTC), the 1-st, 3-rd, 8-th and 11-th television broadcast channels are assigned. The nominal values of carrier frequencies for image and sound are summarized in Table 5.

Existing systems for transmitting dimensions of time and frequency units over television broadcast channels are differentiated into passive and active systems depending on the method of coding information on the moment of time [Ref. 35, 36].

In passive systems, characteristic television synchropulses or special marking pulses transmitted as part of the television signal are used as auxiliary signals that are simultaneously registered at the synchronization points. Information on measurement results is exchanged over an auxiliary communication channel, or else the information on measurement results is transmitted from one point to the other by a special code that is part of the television signal.

In active systems, characteristic television synchropulses (most frequently used is the trailing edge of the first frame synchronizing pulse during frame quenching)

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TABLE 5

Nominal values of carrier frequencies

Channel №	Channel frequency band, MHz	Carrier frequency, MHz	
		Image	Sound
1	48,5—56,5	49,75	56,25
2	58,0—66,0	59,25	65,75
3	76,0—84,0	77,25	83,75
4	84,0—92,0	85,25	91,75
5	92,0—100,0	93,25	99,75
6	174,0—182,0	175,25	181,75
7	182,0—190,0	183,25	189,75
8	190,0—198,0	191,25	197,75
9	198,0—206,0	199,25	205,75
10	206,0—214,0	207,25	213,75
11	214,0—222,0	215,25	221,75
12	222,0—230,0	223,25	229,75

or seconds-marking pulses transmitted as part of the television signal carry direct information on the instant of time in the unified system of the State Time and Frequency Standard [GEVCh]. Registration of these signals at the reception point by an oscilloscope with driven sweep or a time-interval indicator makes it possible to superimpose the the instant of output of the second-marking pulses of the local clock with the second-marking pulses of the GEVCh clock (with consideration of the time for the signals to travel over the radio relay line or intercity cable line) without any auxiliary information.

The error of tie-in of time scales reproduced at spatially separated points has the same order of magnitude with use of either system since it is determined mainly by inconstancy of the time of signal travel over the radio relay or intercity cable lines.

On the other hand, the systems differ in effectiveness from the standpoint of reliability of the results, simplicity of measurements, cost, flexibility, working reliability and so on. The active system is preferable.

The method of synchronizing time and frequency standards over television channels is realized by the State Time and Frequency Service [Gosudarstvennaya sluzhba vremeni i chastoty; GSVCh] of the USSR [Ref. 37]. An active system has been set up at the Moscow TTC based on a precision time and frequency reference standard that ensures constancy of instants of output of time signals and frame synchropulses from the television transmitter antenna in the unified system of GEVCh. A block diagram of transmission of highly stable synchronization signals from synchrogenerators at the TTC and incorporation of time signals into the television signal is shown on Fig. 25.

The following methods can be used to control operation of the synchrogenerators at the TTC from time and frequency reference standards:

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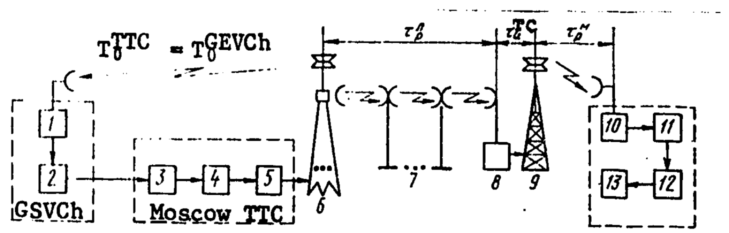

Fig. 25. Synchronization by television:

1--GEVCh; 2--transmitting correcting device; 3--reception correcting device; 4--reference frequency standard; 5--central equipment room; 6--Ostankino radio transmitter; 7--radio relay line; 8--terminal radio relay station; 9--local telecenter; 10--PShT-1P recording receiver; 11--selector for isolating first cut-in of the frame synchropulse and time signals; 12--time-interval measuring device; 13--digital printer

1) a voltage from the reference standard is sent to the synchrogenerator instead of the internal generator voltage;

2) synchrogenerator is changed to the driven mode from simplified synchronization signals (SS or SSTs [expansions not given]) formed from a voltage with frequency of 100 kHz from the reference standard.

These signals are used simultaneously for internal synchronization of all equipment of the television center. The SS signal is a mixture of line synchropulses with duration of 2 μs (f_z = 15625 Hz) and frame synchropulses with duration of 28 μs (f_K = 50 Hz). In addition to these pulses, the SSTs signal also contains pulses of 28 μs duration (f_{sig} = 12.5 Hz) intended for chrominance synchronization of the telecenter equipment.

The second method of controlling operation of the synchrogenerator not only synchronizes and cophases the line synchropulses, but also maintains the temporal position of the synchropulses and the field pulses of the television signal. The method used at the TTC for centralized synchronization of all equipment at the center keeps the instant of output of the frame synchropulses from the television transmitter antenna in register with the signals from the time and frequency reference standard regardless of the nature of formation of television transmissions (direct transmission from a studio, motion picture film, magnetic tape). The automatic control system used in present-day black-and-white video tape recorders sets the phase of synchropulses reproduced from magnetic tape relative to the phase of the signal from the reference standard with an error of ±0.2 μs, and in color video tape recorders--with an error of ±30 ns [Ref. 38, 39, and also State Standard GOST 7845-72].

In future, with full implementation of centralized synchronization of all image sources in the telecenter, time signals introduced into line amplifiers of TTC central equipment must be present in the television signal throughout the working time of the telecenter.

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Time signals and bursts of reference carrier frequencies transmitted as part of television signals of reverse polarity to synchropulses are pulses of 2 μs duration with recurrence rate of 25 Hz, the pulses arriving at the beginning of each second being prolonged to 10 μs. The time signals are accommodated in the central part of the sixth line of the first field of the television signal (see Fig. 24). The second-marking time signals follow 326 μs later than the cutoffs of the frame synchropulses; this time can be different, and is established depending on the point of insertion of the second-marking signal. The set delay remains constant during all transmissions, and is determined by the GSVCh.

Choice of Synchronization Method

Selection of the method depends on the type of registration of signals at the synchronization point, and on the method of information coding. In the case of an active synchronization method, a procedure can be used that is based on recording either time signals transmitted as part of the television signal, or the first cutoff, the pulses being transmitted from a scale synchronized with the GEVCh.

In the first variant of the method, the discrepancy of the local time scale reproduced at a point to which a Soviet-wide television program is transmitted over radio relay lines and intercity cable lines relative to the GEVCh scale is determined from the expression

$$\Delta T_T^{Б} = \tau_и - \left(\frac{l}{v_{cp}} + \tau_a^{TC} + \tau_p^{M} + \tau_з\right) \pm \delta, \qquad (6.3)$$

where $\tau_И$ is the time interval measured at the synchronization point between the second-marking pulse of the local clock and the second-marking pulse differentiated from the television signal; $\frac{l}{v_{cp}} = \tau_p^{П}$ is the signal travel time over a radio relay line or intercity cable line from the Moscow TTC to the terminal radio relay station; τ_a^{TC} is the signal travel time from the terminal radio relay station to the antenna of the transmitting station of the local telecenter; τ_p^{M} is signal travel time from the antenna of the local telecenter to the antenna of the synchronization point (see Fig. 25); τ_3 is the delay time of the recording receiver at the synchronization point; δ is the error of establishing the instant of output of signals from the transmitting antenna at the Ostankino station.

For points located in the zone of direct reception of television programs transmitted by Ostankino, the discrepancy of scales of time standards can be determined from the formula

$$\Delta T_T^{M} = \tau_и - (\tau_p^{M1} + \tau_з) \pm \delta, \qquad (6.4)$$

where τ_p^{M1} is signal travel time from the Ostankino antenna to the reception antenna at the synchronization point.

When using the second variant of the method, to eliminate ambiguity of readout with discreteness of 20 ms on the one-second interval, it is necessary to presynchronize the time scale with respect to signals transmitted by short-wave, long-wave and VLF radio stations with an error of 1-5 ms.

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In the case of the passive method, a procedure is used in which synchropulses are recorded at two points, where these pulses have not been synchronized and are not tied in to the GEVCh, and the instant of output of frame synchropulses from the transmitting antenna of the radio station varies by a random law. Time scales for points situated within the range of action of a local telecenter or for remote points to which a television program is transmitted over radio relay lines or intercity cable lines can be synchronized under condition that the same frame synchropulses are recorded at both points. In this case, the inequality

$$\Delta T'_{\text{м}} + (\tau_{\text{р}}^{\text{л}} + \tau_{\text{р}}^{\text{м}} + \tau_{\text{a}}\text{TC} + \tau_{\text{з}}) < \frac{20}{3} \text{ ms} \qquad (6.5)$$

must be satisfied, where $\Delta T'_M$ is the error of presynchronization of the time standard.

The discrepancy of the scale of the local time standard relative to the GEVCh scale is determined from formula (6.3) at $\tau_{И} = \tau'_{И} - \tau_0$, where τ_0 is the time interval measured in Moscow.

In all transmissions, the temporal position of the cutoff of the first frame synchropulse with respect to the GEVCh scale remains constant. The user gets the values of $\tau_{\text{Р}}^{\text{Д}}$, τ_0 and δ by request according to the procedure outlined in the Transmission Schedule.

In mutual synchronization of time standards, when the standard to be synchronized is any reference standard, and characteristic synchropulses are simultaneously registered at the point of location of the time standards, the discrepancy of the time scales is determined from the formula

$$T_T^A - T_T^Б = (\Sigma\tau_{\text{з}}^{TA} - \Sigma\tau_{\text{з}}^{TБ}) + \frac{l_T^A - l_T^Б}{v_{\text{г}}} + (\tau_{\text{п-р}}^A - \tau_{\text{п-р}}^Б), \qquad (6.6)$$

where $\Sigma\tau_3^{TA}$ and $\Sigma\tau_3^{TБ}$ is the overall delay of frame synchronization in the transmitting and rebroadcasting equipment between points A and Б; $\frac{l_T^A - l_T^Б}{v_{\text{г}}}$ is the difference of travel time of signals from the transmitting telecenter to the points where the synchronizing and synchronized time standards are located; $v_{\text{г}}$ is the group velocity of radio wave propagation; $\tau_{\text{п-р}}^A - \tau_{\text{п-р}}^Б$ is the difference of delays in the recording receivers of points A and Б.

Synchronization Error

The synchronization accuracy in such a method is considerably dependent on the operation of the selector and the circuit for gating the frame synchronization pulses, and on the resolution of the time-interval measuring device.

The error of tie-in of time scales with the use of active and passive methods is of the same order of magnitude [Ref. 40]. This can be attributed to the fact that the principal errors arise due to inaccuracy of determining the signal travel time on the transmission path from Moscow to the local telecenter, and from the telecenter to the tie-in point, and due to delay in the equipment of the telecenter and the tie-in point, which is equally detrimental to the results of calculation of the discrepancy of time scales relative to the GEVCh scale.

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Error of synchronizing scales of time standards

$$\delta\Delta T_T = \delta\tau_{\text{н}} + \delta\frac{l}{v_{\text{cp}}} + \delta\Sigma\tau_3. \tag{6.7}$$

Overall error

$$\sigma\Delta T_T = \sqrt{(\delta\tau_{\text{н}})^2 + \left[\delta\left(\frac{l}{v_{\text{cp}}}\right)\right]^2 + \Sigma(\delta\tau_3)^2}, \tag{6.8}$$

where $\delta\tau$ is the registration error, δl is the error of determining the distance between Moscow TTC and the tie-in point, δv_{cp} is the error of determining the mean group velocity of radio wave propagation, $\delta\tau_3$ is the error due to instability of signal delay time at the telecenter, in intermediate relay stations and in the recording receiver.

To determine the possible error of synchronization of time standards when using television signals, it is necessary to evaluate the influence of all destabilizing factors of the transmission channel. The principal ones are the following:

1. Error of registration δ_1 or measurement of time intervals between the signal of the local time standard and the received signal. This error is determined by the error of the measurement method and the resolution of the time-interval measuring device.

2. Instability of reception equipment of the reception points δ_2.

3. Error of determining the signal travel time from the antennas of television transmitters to antennas of the reception points δ_3 and δ_4.

4. Change in temporal position of signals during travel through the channels of radio relay lines δ_5.

5. Instability of delay of equipment at the television centers δ_6 and δ_7.

Let us consider quantitative evaluation of the enumerated major components of errors of synchronization of time standards [Ref. 41-44].

1. In practice, δ_1 can be reduced to 0.02 μs, considering that a counting-type frequency meter with high counting rate is used as the time-interval measuring device. If the count rate is 1 MHz, resolution will be 0.01 μs. The second component of δ_1 will be determined by the rise time or fall time of the signals transmitted through television channels, and by the signal-to-noise ratio.

The mean square error is

$$\sigma_{\Phi} = \frac{T_{\Phi}}{q\sqrt{2n}},$$

where T_{Φ} is the rise time of the signal, q is the signal-to-noise ratio, and n is the number of signals used for the measurement.

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For a rise time of 0.3 μs, $n = 1$ and $q = 10$, error $\sigma_\Phi \cong 0.02$ μs.

2. Error $\delta_2 = 0.06$ μs.

3. Errors δ_3 and δ_4 can be determined from the following considerations.

The value of τ_p^M is determined either by calculation or experimentally.

In calculation, v_{cp} is taken as equal to the speed of light, and l is found from the coordinates of the reception point.

This method is most frequently used only for cases of intracity synchronization when τ_p^M is established with direct transmission through the ether from the telecenter to the antenna of the reception point without relays. In intracity broadcasting, τ_p^M can also be determined by using laser range finders or by measuring with the parallax method. For Moscow points the parallax angles are differences of zenith distances measured from the synchronization point to three tiers of the TTC television tower. The mean square errors of the average values of the zenith distances of one of the points as calculated from internal convergence of measurement results in receptions and semi-receptions are: for tier I $\Delta = \pm 2.6$; II $\Delta = \pm 3.1$; III $\Delta = \pm 2.9$. The distance l from the GEVCh to the television tower was obtained twice from the values of reference bases (Fig. 26): with respect to basis I-III of 260 m, $l' = 32681$ m; and for basis II-III 178.5 m, $l'' = 32756$ m. The final value is taken as the weighted average between these two results (the weights are inversely proportional to the lengths of the bases), $l = 32712$ m.

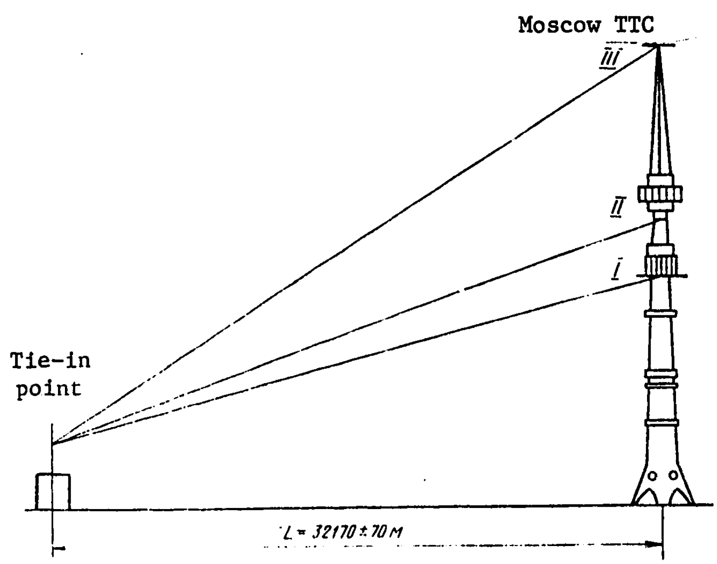

Fig. 26. Parallax method of distance measurement

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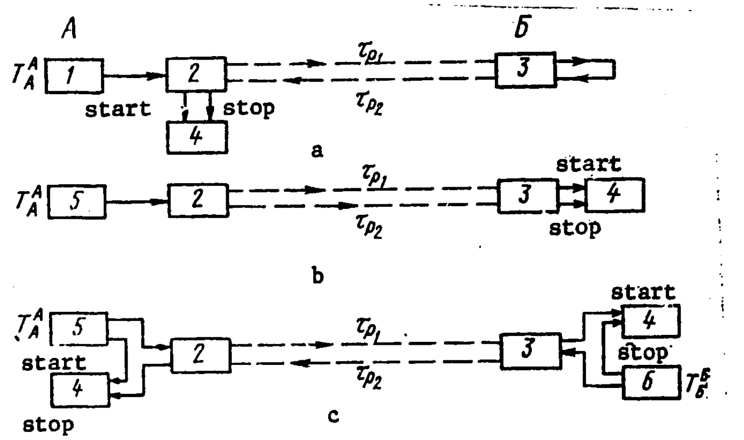

Fig. 27. Diagram of determination of signal travel time over main television channels:
1--pulse generator; 2, 3--relay stations; 4--counting-type frequency meter; 5, 6--precision time standard

For remote synchronization points to which television programs are sent via relay rebroadcast lines or intercity cable lines, the loop method is used (Fig. 27a) comprising forward and reverse television channels, i. e.

$$\tau_{p_1}+\tau_{p_2}=\Delta T_A^A \qquad (6.9)$$

when

$$\tau_{p_1}=\tau_{p_2};\quad \tau_p^A=\frac{\Delta T_A^A}{2}.$$

In the presence of a purely physical pair, where $\tau_{p_1}^A \neq \tau_{p_2}^A$, additional measurements are made by the arrangement of Fig. 27b, whence

$$\tau_{p_1}-\tau_{p_2}=\Delta\tau_A^Б. \qquad (6.10)$$

Simultaneous solution of equations (6.9) and (6.10) gives

$$\tau_{p_1}^A=\frac{\Delta T_A^A+\Delta T_A^Б}{2}; \qquad (6.11)$$

$$\tau_{p_2}^A=\frac{\Delta T_A^A-\Delta T_A^Б}{2}. \qquad (6.12)$$

In the presence of a single duplex channel, the measurements are done in the following order: a loop is set up to determine the value of ΔT_A^A at point Б, and the value of $\Delta T_Б^Б$ at point A. In addition, alternate measurements are made at points Б and A by the arrangement of Fig. 27c, using synchronized precision time standards at point A (5) and point Б (6) with registration of the received signal on the local clock. From measurements

$$T_A^A+\tau_{p_1}=\Delta T_A^Б, \qquad (6.13)$$

$$T_Б^Б+\tau_{p_2}=\Delta T_Б^A, \qquad (6.14)$$

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from measurements by the loop

$$T^A_A + \tau_{p_1} + \tau_{p_2} = \Delta T^A_A, \quad (6.15)$$

$$T^B_B + \tau_{p_2} + \tau_{p_1} = \Delta T^B_B. \quad (6.16)$$

After solving equations (6.16)-(6.16)

$$\tau^a_{p_1} = \Delta T^A_B - \Delta T^B_B, \quad (6.17)$$

$$\tau^a_{p_2} = \Delta T^B_A - \Delta T^A_A. \quad (6.18)$$

The error of measuring signal travel time in radio relay lines, as in the preceding cases, is determined mainly by the error of registration, or by the instrumental error of the recording device, which amounts to 0.01 μs (for counting-type frequency meter 4 at a counting frequency of 100 MHz).

4. Error δ_5 is due mainly to instability of signal delay time upon passage through radio relay stations; $\delta_5 = 0.5\sqrt{n}$, where n is the number of relay points of a radio relay line.

5. Error $\delta_6 = \delta_7 \cong 0.4$ μs.

If we assume that all the factors determining the temporal position of television synchropulses as they are recorded at time standard synchronization points have a mutually independent random influence, the total synchronization error using nonspecialized equipment is

$$\sigma = \sqrt{\delta_1^2 + \delta_2^2 + \delta_3^2 + \delta_4^2 + \delta_6^2 + \delta_7^2} = 0{,}18\sqrt{1 + 0{,}2n}. \quad (6.19)$$

A change in residual attenuation of radio relay line channels, deviation of amplitude-frequency and phase-frequency responses from monotonic, and asymmetric limitation of the spectrum of amplitude-modulated signals (δ_5) occur fairly slowly compared with the duration of a session of time and frequency standard synchronization. In this connection there is a possibility of reducing the synchronization error, particularly on transmission paths of 2000-3000 km, by measuring the signal transmission time through the radio relay line immediately during or after the synchronization session.

In the case of intracity synchronization, the error is about 0.01 μs.

Signal Reception and Recording Equipment

Fairly simple recording receivers are used in all methods of synchronizing time and frequency standards. The principal components of this equipment are a standard television set, a counting-type frequency meter and a selector for isolating the required signal from television synchropulses.

Let us consider the PShT-1M recording receiver. This instrument can synchronize time and frequency standards from reception, isolation and recording of time signals (1 and 25 Hz) transmitted as part of a television signal;

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from reception, isolation and registration of the cutoff of television frame synchronizing pulses;

from collating the frequency of a precision standard with the GEVCh scale, using television synchropulses or time signals or sine-wave signals, using the differential method of collation. For an averaging time interval of 20 minutes on a frequency of 1 MHz, the error of the collation method is (8-10)$\cdot 10^{-11}$.

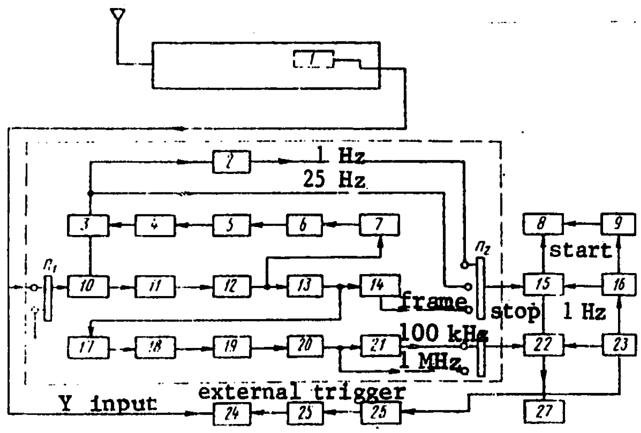

Fig. 28. Block diagram of PShT-1M:

1--Video amplifier of Yunost'-603 television; 2--differential amplifier; 3--coincidence stage; 4--gating pulse generator; 5--kipp oscillator; 6, 10, 14--signal amplifiers; 7--integrating circuit; 8--digital printer; 9--electronic clock; 11--shaper stage; 12, 20--Schmitt trigger; 13--differentiating amplifier; 15--signal stop stage; 16, 21, 25--frequency dividers; 17-19--frequency multipliers by 2.8 and 4; 22--phase detector; 23--time and frequency standard to be synchronized; 24--oscilloscope; 26--phase shifter; 27--chart recorder

A block diagram of the PShT-1M is shown in Fig. 28. A Yunost'-603 standard series-produced television set is used as the receiver.

From a control point of the video amplifier with positive polarity and amplitude of at least 1 V, the complete television signal goes to switch $П_1$. After amplification, this signal is sent to stage 11 in which the level of the synchronizing pulses is fixed with limitation on the quenching level. This ensures unchanged amplitude of the signals from the output of 11 when there are fluctuations in the amplitude of the output signals. The signals are then sent to Schmitt trigger 12 to make the synchronizing pulse edges steeper. After the Schmitt trigger, the cutoffs of the frame synchronizing pulses are isolated from the television synchromixture by differentiating amplifier 13. The time constant of the differentiating circuit of the amplifier is selected so that line synchronization pulses with duration of 5 μs pass through it without distortion, while frame synchronizing pulses with duration of 30 μs are differentiated, and stop signals are formed from their cutoffs by amplifier 14 working in the limiting mode.

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Under all working conditions, stage 15 is triggered from a seconds-marking pulse of the local clock. These pulses come from frequency divider 16, the stop pulses being sent to the input of this divider.

To get reference frequencies of 10 kHz and 1 MHz, the device incorporates a system of multipliers that convert the line frequency (15625 Hz) to 1 MHz, and a frequency divider 21. A distinguishing feature of multiplier systems is that the first stage has a quartz filter for frequency $2f_z = 31250$ Hz, and signals of the complete synchromixture are sent to the input of this filter after differentiating amplifier 13. Differentiation of the synchromixture is necessary to protect the frequency multiplier from the influence of the pulses that take care of conversion from frame synchronizing pulses to trailing controlling pulses.

Reference frequencies from the output of the instrument can be used to check various precision frequency-measuring equipment and for prolonged collation of the frequency of the standard (for example by phase detector 22 and chart recorder 27 or by oscilloscope, using Lissajou figures).

To collate the frequencies of high-stability frequency standards, it is sufficient to take a few readings of the temporal position of frame synchropulses or time signals relative to pulses of the local time and frequency standard through set time intervals (in the active method), or to register the position of the frame synchropulses for standard time intervals (in the passive method).

Synchronization by Television Channels Outside the USSR

In the United States, specialists at the National Bureau of Standards (NBS) since 1969 have used a method of simultaneous registration of characteristic synchropulses with subsequent exchange of information on the measurement results for synchronizing radio stations that transmit exact time signals and reference frequencies. Outside the USSR, television signals were first used for comparing remote clocks in 1965 by specialists of Czechoslovakia (Prague) and East Germany (Potsdam) [Ref. 37].

In transmissions, television channels of three firms are used: ABC, CBS and NBC. The method that is used does not require that the transmitting television station be informed of its participation in the measurements [Ref. 45].

In 1970 the NBS worked out a method of introducing code information into a television signal on time and frequency by binary phase modulation of a 2 MHz subcarrier stabilized by a cesium standard for a passive system of clock collation. On the seventeenth line of the first and third frame quenching pulses after the beginning of each second, a 1-2-4-8 binary-decimal code containing 32 binary digits transmits the hours, minutes and seconds of universal time. On the 17-th line of the second frame quenching pulse a six-bit code is transmitted that corresponds to the number of microseconds from the beginning of the preceding second to the beginning of the code. On all remaining 17-th lines, sine-wave signals are transmitted on a frequency of 2 MHz for phase synchronization of the quartz oscillator at the reception point. The synchronization error with use of this method did not exceed 0.1 μs on a 45-km transmission path.

In 1972, the NBS did a series of experimental transmissions of "active" signals in coded form over U.S. television communication lines. Running time information

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is coded into a binary-decimal signal and transmitted in the second half of the first line. A sine-wave signal with frequency of 1 MHz is transmitted in the first half of this line that is coherent in phase with the standard frequency signal of the NBS and is used to get information on exact time and frequency. In the broadcast studio of the television network, an atomic frequency standard is installed to synchronize the television synchrogenerator and the generator of coded time signals.

6.3. Using Artificial Satellites

Some Information on Artificial Satellites

Artificial satellites of various types--communications, television, meteorological, navigational, geodetic--can be successfully used for synchronizing precision time and frequency standards separated by great distances and situated in inaccessible northern and mountainous regions or on ships.

Exact time and frequency signals can be transmitted directly from the satellite if it carries precision time and frequency standards (this kind of satellite is called "active"), or reflected from the satellite, which in this case acts as a passive or active reflector (relay). An example of a passive satellite is the Echo-1 launched in 1960 in the United States--an inflated balloon with aluminum coating to ensure high reflectivity of radio signals. An example of an active satellite is the Anna-1B launched in the United States in 1962 for mutual tie-in of ground-based points (light beacon). Relay satellites such as Molniya (USSR, 1965), Relay and Telstar (United States) operate on the relay station principle, rebroadcasting signals transmitted from the ground.

Depending on their purpose, artificial satellites move around the earth in different orbits distinguished by the following parameters:

inclination of the plane of the orbit to the plane of the earth's equator (at an angle of 90° the orbit is polar);

shape of orbit (circular or elliptical);

altitude of orbit above the earth's surface.

The shape of the orbit is determined by the velocity at which the satellite is injected into a near-earth orbit. At orbital velocity (7912 m/s) a rocket becomes a satellite and will move along an arc of an ellipse with eccentricity $e<1$, or of a circle when $e=0$. In the latter event, both foci of the ellipse coincide, and are situated at the earth's center of gravitation. According to Kepler's first law, one of the foci of an ellipse must be located at the earth's center of gravitation (O in Fig. 29). The second focus O' is accordingly located at the same distance from the apogee of the satellite orbit as the center O is from the perigee.

The equation of the ellipse on the plane in polar coordinates is

$$r=\frac{a(1-e^2)}{1+e\cos Q_{\text{пи}}}, \qquad (6.20)$$

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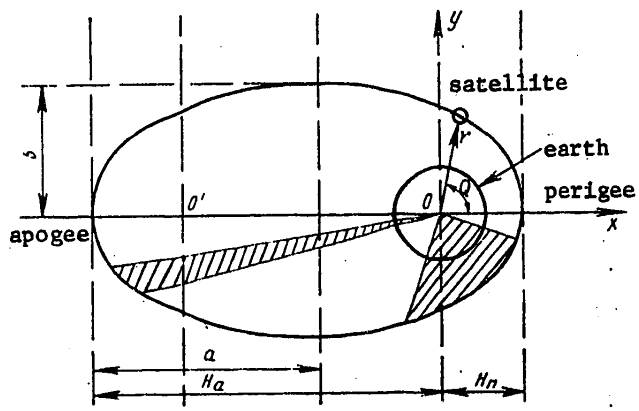

Fig. 29. Satellite orbit

where a is the semimajor axis of the ellipse; Q_{aH} is true anomaly of motion; the eccentricity of the ellipse is

$$e = \sqrt{1 - \frac{b^2}{a^2}} = \frac{H_a - H_\pi}{2a},$$

where b is the semiminor axis of the ellipse; H_a and H_π are the respective distances from the apogee and perigee to the earth's center of gravitation.

As the initial velocity of injecting the satellite into orbit increases, the parameters of the ellipse change, and the second focus of the ellipse O' approaches the center of gravitation of the earth, at a certain velocity coinciding in the center of the earth with focus O, which transforms the ellipse into a circle. This is determined by Kepler's second law. The law of areas enables us to calculate how satellite velocity will vary over its entire path, and states that the radius vector of the satellite sweeps out equal areas in equal time intervals (shaded areas on Fig. 29).

In undisturbed motion of a satellite revolving in a circular orbit of radius r, using equilibrium of forces of gravitation and centrifugal force

$$k\frac{Mm}{r^2} = \frac{mv_\kappa^2}{r},$$

we find the circular velocity of motion of the satellite in cm/s,

$$v_\kappa = \sqrt{\frac{kM}{r}}, \qquad (6.21)$$

where $k = 6.67 \cdot 10^{-8}$ $cm^3/(g \cdot s^2)$ is the constant of gravitation, $M = 5.974 \cdot 10^{27}$ g is the mass of the earth, and m is the mass of the satellite in g.

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The velocity of a hypothetical satellite moving in a circular orbit with radius equal to the equatorial radius of the earth $R_3 = 6.371 \cdot 10^8$ cm would be $7.912 \cdot 10^5$ cm/s.

The period of revolution of a satellite moving in a circular orbit of radius r,

$$T = \frac{2\pi r}{v_к}. \quad (6.22)$$

For our imaginary satellite, T = 84.48 minutes.

The velocity of motion of a satellite in an elliptical orbit is

$$v_э = v_{к.a} \sqrt{\frac{1 + 2e\cos Q + e^2}{1 - e^2}}, \quad (6.23)$$

where $v_{к.a} = \frac{630}{\sqrt{a}}$ is the velocity of satellite motion in km/s in a circular orbit of radius r equal to the semimajor axis of the elliptical orbit; Q is the angle between directions from the center of the earth to the perigee of the orbit and to the point where satellite velocity is to be determined.

Since $Q_a = -1$, while $\cos Q_п = 1$, [subscript a = apogee, п = perigee] the velocity at the apogee is $v_a = v_{к.a} \sqrt{\frac{1-e}{1+e}}$, and at the perigee it is $v_п = v_{к.a} \sqrt{\frac{1+e}{1-e}}$ and the ratio of these velocities is inversely proportional to the ratio of the distances

$$\frac{v_п}{v_a} = \frac{H_a}{H_п}, \quad (6.24)$$

i. e. the velocity of the satellite at apogee will be lowest, and at perigee will be maximum.

According to Kepler's third law, the squares of the time of revolution of satellites are proportional to the cubes of the semimajor axes of their orbits

$$\frac{T_э^2}{T_0^2} = \frac{a^3}{R_3^3}, \quad (6.25)$$

since we always have $a > R_3$, we have $T_э > T_0$ as well.

At a given gravitational constant, it is only the semimajor axis of the ellipse that influences the change in period of revolution of a satellite.

The flight velocity at which a rocket begins to move circumferentially over the earth's surface is called the orbital velocity. With increasing altitude, circular velocity decreases, at first sharply, and then more slowly. For example, at an altitude of 200 km it is 7791 m/s, and at an altitude of 2000 km it is 6903 m/s. With a further increase in initial velocity, eccentricity increases. At e = 1, the orbit of rocket motion becomes a parabola with focus coinciding with the center of gravitation of the earth. At e > 1 the orbit becomes a hyperbola.

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At an altitude of 36,000 km above the the level of the earth, when the plane of the orbit coincides with the equatorial plane of the earth, a satellite remains suspended over a definite spot on the surface of the earth; such a satellite is called stationary. Its period of revolution is 24 hours.

When escape velocity is reached (11.2 km/s) the rocket becomes an artificial solar satellite.

The accuracy of synchronization of frequency and time standards is considerably influenced by the orbit of the satellite, its position relative to the location of the points of synchronization, and its velocity of displacement in orbit. Most favorable are satellites that have high-altitude elliptical orbit or with a stationary orbit.

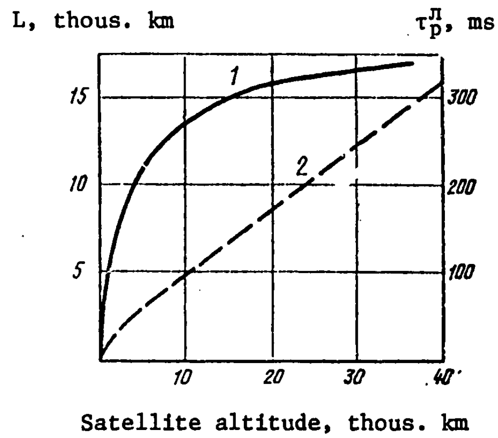

Fig. 30. Dependence of satellite position on distance between standards being synchronized (1) and signal travel time (2)

Fig. 30 shows the dependence of satellite altitude on the distance between the points of synchronization and on the travel time of signals relayed by the satellite.

Ref. 45 gives the results of experimental synchronization of precision rubidium clocks via geostationary satellite ATS-1 and ATS-3 between NASA tracking stations at Rossman North Carolina and Mojave California in 1971. The method of simultaneous transmission and reception of time signals (two-beam method) was used in synchronization. A frequency of 4119 MHz was used for transmission from point A to the satellites, and frequency of 6301 MHz--for rebroadcast via the satellite. Bandwidth was 30 MHz. A check by transported clocks showed that synchronization error was 50 ns.

Molniya Satellites

In the Soviet Union, the Molniya-1 and Molniya-2 relay satellites are extensively used for transmitting television programs and for communications. Transmission of time signals via such satellites enables synchronization of time and frequency standards at a maximum distance between them of 14,000-16,000 km.

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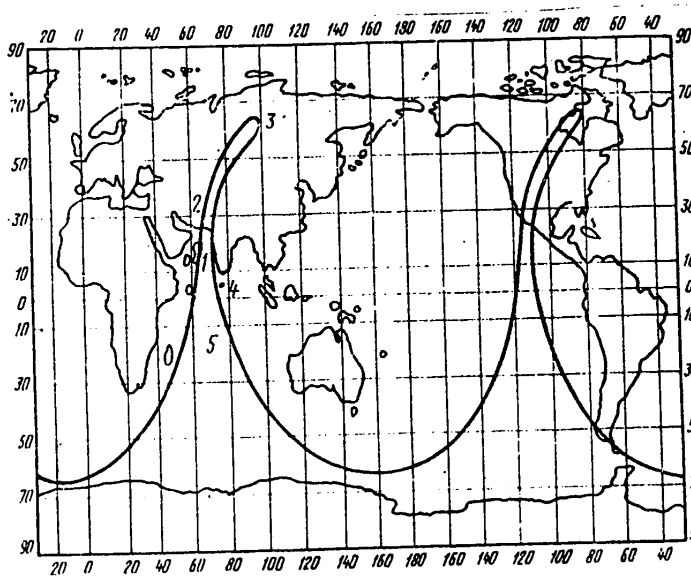

Fig. 31. Satellite orbit in Mercator projection

Fig. 31 shows the orbit of a Molniya-1 satellite in Mercator projection on a map of the earth [Ref. 46]. Even and odd turns of the satellite are shown with ascending nodes of 60° east long. and 120° west long. The period of each turn is about 12 hours. The point of intersection of the equator by the projection of the odd turn is denoted by 0 (60° east long.). The parameters of the orbit are $H_a = 40{,}000$ km in the northern hemisphere and $H_П = 500$ km in the southern hemisphere. The map also shows satellite altitudes of about 6,000 km (points 1 and 5), 10,000 km (points 2, 4), 15,000 km and higher (between points 2 and 4 and at point 3). From 0 to 60° east long., mutual visibility of the satellite between Moscow and Vladivostok lasted 7-10 hours.

With use of Molniya-1 satellites as relays over the territory of the USSR, a network of Orbita reception points operates for reception of television programs from the satellites and transmission through local telecenters and radio relay lines.

The energy characteristics of the line can be calculated from the following formulas.

Power of ground-based transmitter

$$P_п = \frac{P_c 4\pi R^2 L \Pi}{G_{пер} \eta_{пер} A_{пер}}, \qquad (6.26)$$

where P_c is the sensitivity of the receiver, $L = L_T L_И L_ф$ is the product of losses in the troposphere (L_T), ionosphere ($L_И$) and onphase fluctuations ($L_ф$), $\Pi = \Pi_н \Pi_{ав} \Pi_п \cong 2.2$ is the product of losses due to nonuniformity of the antenna radiation pattern ($\Pi_н$), inaccuracy of self-aiming ($\Pi_{ав}$) and polarization losses ($\Pi_п$), $G_{пер}$ is antenna gain, $\eta_{пер}$ is the efficiency of the antenna, $A_{пер}$ is the effective area of the antenna.

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Sensitivity of the ground-based receiver

$$P_c = \frac{P_n G_{np} \eta_{np} A_{np}}{4\pi R^2 L \Pi}. \qquad (6.27)$$

[subscript np = receiver]. It is realized in prticular by using parametric amplifiers and amplifying the signal on an intermediate frequency of 70 MHz.

The ground-based station is equipped with a reflecting parabolic antenna installed in rotating supports.

6.4. Using the Orbita Reception-Point System for Global Synchronization of Time Scales

By using television channels via Molniya-1 or Molniya-2 relay satellites and Orbita reception-point systems, time and frequency standards are synchronized with the use of a complete duplex satellite television trunk and two-beam or three-beam tie-in methods.

In this case, operation between points Г and Б is possible under condition that there is a transmitter at point Г and right of access to the satellite (Fig. 32).

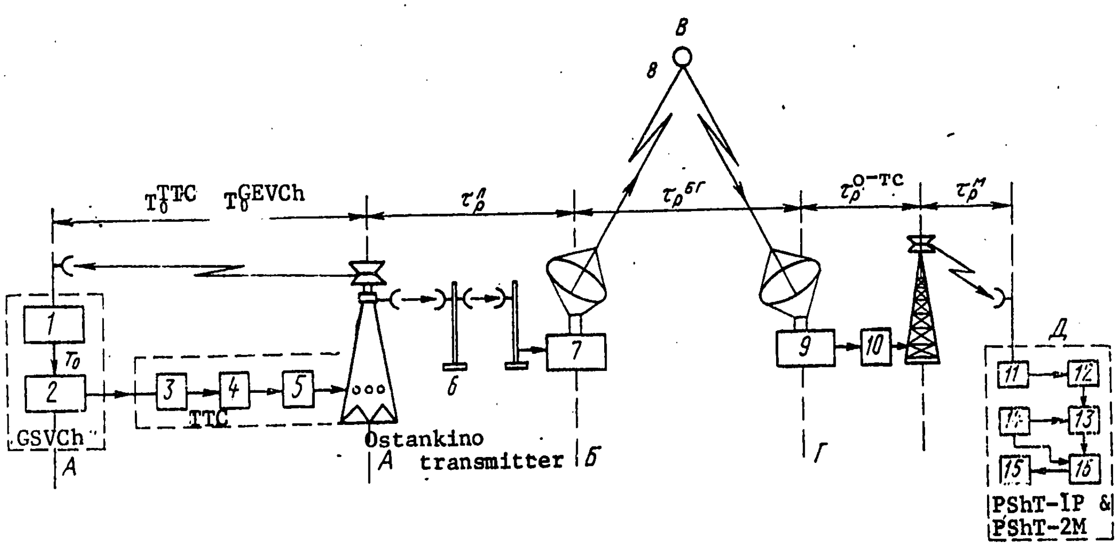

Fig. 32. Block diagram of synchronization over channels of the Orbita reception-point system

1--GEVCh; 2--transmitting correcting device; 3--reception correcting device; 4--reference frequency standard; 5--central equipment room; 6--connecting radio relay line; 7--transmitting antenna; 8--Molniya satellite; 9--reception antenna; 10--local telecenter; 11--television receiver; 12--selector for isolating cut-in of frame synchropulses and time signals; 13--time interval measurement device; 14--local time and frequency store; 15--digital printer; 16--electronic clock

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Time and frequency standards are synchronized in the period of transmission of a conventional television program at any point on the territory of the USSR and other nations covered by the Orbita reception-point system. In 1975 there were more than 60 such points analogous to point Г.

Also used is a system that differs in principle from the time-scale synchronization system with respect to ground-based television channels. In this case a line operates on segment БГ with considerable continuous variation of signal travel time, which must be taken into consideration during the synchronization session. On other segments, signal travel time always remains constant.

Transmission time is chosen in such a way that the television synchropulses and time signals of 1 and 25 Hz are formed from the reference standard of the TTC synchronized with the GEVCh, and are transmitted as part of the television signal.

When satellites are used, the signal travel time τ_p^0 to the reception point may be calculated or determined experimentally.

In calculation, we first determine the path of signal travel between transmission and reception points from ballistic data of the satellite orbit during registration, and the coordinates of the reception points, after which we calculate

$$\tau_p^{БГ} = \frac{l^{БГ}}{v_p} + \tau_з. \qquad (6.28)$$

where l is the length of the path of signal travel, v_p is the velocity of signal propagation, τ_3 is delay time in the equipment on the satellite.

The error of determining $\tau_p^{БГ}$ in this case is due mainly to the error of the ballistic data (since the orbital parameters of the satellite vary during satellite motion as a consequence of the influence of various perturbations), and also to a change in signal travel velocity through the ionosphere depending on the state of this medium.

The experimental time τ_p of signal travel is determined by the method of bilateral transmissions and receptions using a complete television trunk [Ref. 47].

According to the results of simultaneous registration of received signals at points Б and Г, $\tau_p^{БГ}$ is calculated from the formula

$$\tau_p^{БГ} = \tau_p^{ГВГ} + \tau_c = \frac{(T^Г - T'_Б) + (T^Б - T'_Г)}{2}. \qquad (6.29)$$

Formula (6.29) is valid for the case where the relay unit is nearly immobile (at apogee), i.e. $\tau_p^{БВГ} = \tau_p^{ГВГ}$. If these paths are not equal, the value of $\tau_p^{БВГ}$ must be additionally estimated. To do this, consider the segment of satellite motion in its orbit at the instant of synchronization (Fig. 33a). Since the distance from points Б and Г to the satellite is not the same, the signals will be relayed at different instants (positions p' and p"), which results in inequality of times $\tau_p^{ББ}$, $\tau_p^{ВБ}$ and $\tau_p^{ГВ}$, $\tau_p^{ВГ}$. The calculation can be done with adequate accuracy by the graphic-analytical method of Ref. 47. In doing this, we first determine the velocity of satellite displacement for discrete values of angle Q (Fig. 33b)

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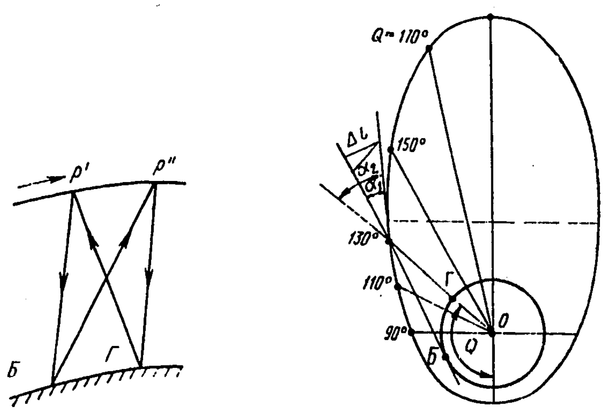

a b

Fig. 33. Graphic-analytical method of determining synchronization error:
a--segment of satellite motion in orbit; b--points of determining velocity of satellite motion in orbit

$$v_{исз} = \sqrt{\frac{kM\,(1 + 2e\cos Q + e^2)}{a\,(1 - e^2)}}, \qquad (6.30)$$
$$a = \frac{H_а + H_п + 2r}{2};$$
$$e = \frac{H_а - H_п}{2a}.$$

[subscript исз = satellite]

For each of the discrete positions of the satellite (value of Q discrete), Fig. 33b is used for graphically determining the maximum difference of distances between the satellite and points of the earth's surface Δr, which corresponds to the difference of distances from the satellite to the earth along the normal and along the tangent to the earth's surface (for example, for point B, Δr = БВ - ГВ). The signal travel time over distance Δr is Δt = Δr/c ($c = 3\cdot10^5$ km/s), and distance ΔH traversed by the satellite in time Δt is ΔH = Δtv.

Distance ΔH is laid off to scale along the tangent to the orbit at the point of observation of the satellite, and the difference of the paths of signal travel to either side is graphically determined,

$$\Delta H' = \Delta H\cos\alpha_1 + \Delta H\cos\alpha_2,$$

where α_1 and α_2 are the angles between the tangent and directions of the satellite to points on the earth.

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Then the tie-in error due to inequality of paths with transmission to one side or the other will be

$$\Delta\tau_p = \frac{\Delta H(\cos\alpha_1 + \cos\alpha_2)}{2c}. \quad (6.31)$$

Table 6 summarizes results of calculation for an orbit with parameters H_a = 40,000 km and $H_п$ = 550 km and for the most unfavorable location of points at different angles Q.

TABLE 6

Synchronization error using bilateral method

Q	v_1, m/s	$\Delta\eta$, km	Δt, ms	ΔH, m	$\Delta H'$, m	$\Delta\tau_p$, μs
90	9,4	4300	14,3	135	210	0,35
110	7,4	5200	17,3	128	215	0,36
130	5,6	5600	18,7	105	168	0,28
150	3,7	6000	20,0	74	115	0,19
170	2,1	6200	20,6	43	35	0,06

Thus the maximum error $\Delta\tau_p$ upon emission of signals at the same instants does not exceed 0.4 μs, and when the apogee segment of the orbit is used (in a range of Q = 150-210°), it does not exceed 0.2 μs.

In the case of nonsimultaneous emission of signals by driving and driven points, an additional error $\Delta\tau_{доп}$ arises that depends not only on the coordinates of the ground points and the satellite, but also on the mismatch of the driving and driven clocks. When the mismatch is less than 10 ms, $\Delta\tau_{доп}$ does not exceed 0.25 μs even in the most unfavorable cases. Therefore tie-in should be done in two stages: preliminary tie-in with error of no more than 5 ms, and final tie-in when the error may be of the order of 0.1-0.2 μs.

In synchronizing time and frequency standards over channels of the Orbita reception-point system, it is necessary to distinguish channels with constant signal delay in the equipment and radio relay line (АБ and ГД), and variable delay (ГВГ) during signal travel from the transmitting point to the antenna of the Orbita reception point (see Fig. 32).

The discrepancy of the time scale at point Д with registration of the seconds-marking signal transmitted as part of the television signal will be determined by the expression

$$\Delta T_Д = \tau_и^Д - (\tau_р^{БГ} + \tau_р^{О-ТЦ} + \tau_р^м + \tau_з^Д), \quad (6.32)$$

where $\tau_И^Д$ is the discrepancy of the seconds-marking signal of the local scale of point Д relative to the signal received in the Orbita network, $\tau_р^{О-ТС}$ is the time of signal travel from the antenna of an Orbita reception station to the antenna of the local telecenter.

The user determines the value of $\tau_р^М$ at the point of the standard to be synchronized, and the total travel time of of signals $\tau_р^Д$, $\tau_р^{БГ}$, $\tau_р^{О-ТС}$ is given to the consumer by request at the recommended synchronization time.

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Recommended recording sessions most generally correspond to a satellite position close to apogee, since in this case there is an imporvement in accuracy of determining the position of the satellite in orbit, and a reduction in requirements for accurate determination of the time of registration of the received signal relative to the local scale.

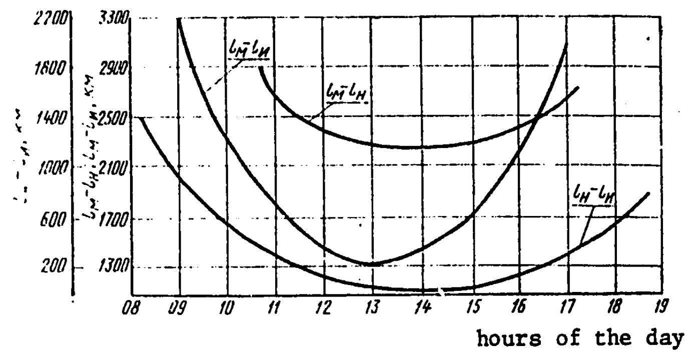

Fig. 34. Range difference from satellite to synchronization point

Fig. 34 shows range differences l_M-l_H (satellite-Moscow) - (satellite-Irkutsk); l_M-l_H (satellite-Moscow) - (satellite-Novosibirsk); l_H-l_H (satellite-Novosibirsk) - (satellite-Irkutsk) as a function of time of location of the satellite near apogee. As we can see from Fig. 34, over a two-hour period, l_H-l_H changes by 9 km, which amounts to 27 μs. Consequently, mutual synchronization of two points under these conditions can be done with high precision.

Signal travel time on section БГ ($\tau_p^{БГ}$) is computer-calculated for the recommended synchronization time in accordance with data of a network of precision TV orbit monitoring [PTOM] and regularly reported to the user. Users for whom the error must not exceed ten microseconds are provided with nomograms and periodically given necessary initial data.

PShT-1M and PShT-2M equipment can be used for recording instants of time signals or synchropulses transmitted through the Orbita reception-point network. In contrast to equipment used for recording the instants of time signals or synchropulses transmitted over channels of radio relay lines and intercity cable lines, reception of time signals with variable delay necessitates exact (with deviation in a range of 0.1-1.0 ms) marking of the time of signal registration. Therefore the PShT-2M equipment is provided with an electronic clock (see Fig. 32).

6.5. Synchronization Error due to Inconstancy of Radio Wave Propagation

In determining $\tau_p^{БГ}$ it is necessary to evaluate the influence of ionized layers, since signals will travel through these layers at different angles for different synchronization points, and the signal travel time in the ionosphere as a result of reduction and variation of group velocity will change as compared with the speed of light; this time can be written as follows:

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$$\Delta\tau_{p}^{nr} = \tau_{p}^{nr} - \tau_{0}^{nr} = \frac{1}{2c}\left(\frac{f_{\kappa p}}{f}\right)^{2} A(\Theta)\left[\frac{2}{3}h_{max} + h_{e}\right], \qquad (6.33)$$

where f_{Kp} is the critical frequency for the ionosphere, f is the carrier frequency of the radio station, h_{max} is the half-thickness of the layer in the parabolic approximation, h_e is the constant of measurement of electron density above the maximum. The coefficient A(Θ) shows by how many times the equivalent distance traversed by the radio wave changes with oblique incidence as compared with vertical

$$A(\Theta) = \frac{R(h)}{\sqrt{R^2(h) - R_3^2\cos^2\Theta}}, \qquad (6.34)$$

where $R(h) = R_3 + h$ is the altitude of the point in the ionosphere.

Values of A(Θ) in the range of altitudes where the influence of the ionosphere is appreciable are:

Angle of elevation ...	0°	10°	15°	30°	45°	60°	75°	90°
A	3.00	2.57	2.40	1.75	1.40	1.13	1.03	1.00

Analysis shows that signal delay on frequencies of 200-300 MHz with passage through the ionosphere may be 15-30 μs, and on frequencies higher than 10 GHz may be 1 μs and be determined with an error of 0.1 μs.

As the carrier frequency of the transmitter increases, fluctuations decrease in proportion to the square of the frequency. The delay of time signals in the ionosphere on frequencies below the UHF band reaches appreciable values that are difficult to take into consideration because the distribution of electron concentration above the maximum has not yet been adequately studied.

According to CCIR documents, carrier frequencies of more than 4 GHz are now being used for satellite relay broadcasters.

CHAPTER 7: RECOMMENDATIONS ON SYNCHRONIZING TIME AND FREQUENCY STANDARDS

7.1. Synchronization Facilities

The choice of the means (as well as the method) of synchronization depends on the predetermined accuracy of synchronization, the relative location of the synchronized and synchronizing standards, the conditions of operation of the synchronized standard and the makeup of auxiliary equipment.

Frequency standards can be synchronized by the carrier frequencies of Soviet shortwave stations (with call letters RWM, RAT, RTA, RKM, RID, RCH, RIM), long-wave stations (RBU, RTZ, RW-166), by television channels, and by signals transmitted by Soviet and non-Soviet radio stations in different radio wave bands. The times and programs of transmissions by these stations are published by the Interagency Unified Time Service Committee in "Schedules of Exact Time and Reference Frequency Signal Broadcasts."

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Time scales can be synchronized by time signals transmitted by the same stations, and also over wire channels, ground-based television channels, satellites and meteoric communication.

For purposes of automatic synchronization, use can be made of carrier frequencies and time signals transmitted in the long-wave, VLF and UHF bands with an error that is determined by the station.

Time standards can also be automatically or manually synchronized with error of 10-100 ms (depending on the point of location of the standard to be synchronized) by using time-check signals (six points) transmitted via wide-broadcast stations in the same TUC system as the exact time signals. The beginning of the last (sixth) signal corresponds to 00 min 00.00 s--the beginning of the hour. In contrast to exact time signals, time-check signals are transmitted without consideration of their travel time from the supply scale to the radio broadcast stations. These signals can be received by using standard recording receivers.

It is also possible to indicate running time to 0.1 s in a current-time code transmitted as part of the time signals of some radio stations, or as part of television signals.

Table 7 shows comparative characteristics of major transmission facilities for synchronizing time and frequency standards that are in use and under development. As can be seen from the Table, the highest accuracy can be achieved by using: a) wide-band systems (in virtue of constancy of the characteristics of the transmission channel, the steepness of the leading edge of the pulse signal at the reception point and high signal-to-noise ratio); b) stable narrow-band systems with registration of the phase of transmitted sinusoidal signals.

When standards are located at a distance of up to about 30 km, synchronization should be done by signals from the synchronizing standard that are transmitted via ground-based television channels, wide-band wire lines and radio stations in the long-wave and VLF bands (for short-wave radio stations, it is recommended that frequencies below 2.5 MHz be used).

When standards are located at a distance of 300-3000 km, it is more advisable to use signals from the synchronizing standard that are transmitted over ground-based television channels, and radio stations in the short-wave, long-wave and VLF bands.

At distances of 3000-6000 km transmission should be by radio stations in the short-wave and VLF bands and via satellite with operation in the UHF and microwave bands.

At distances of more than 6000 km, signals are used that are transmitted via short-wave radio stations and satellites (active and relay) in the UHF and microwave bands.

In general form, the transmission channel consists of transmitting devices, antennas, the medium between antennas and the recording reception equipment.

Auxiliary facilities include radio receivers for various bands, television receivers with special attachment for isolating time signals from the synchromixture, counting-type frequency meters (in the case of pulsed signals) or phase meters and phase

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TABLE 7

Comparative characteristics of transmission facilities for synchronizing time and frequency standards

Transmission facility	Signal transmission method	Parameters of transmission facility			Distance between synchronization points	Transmission error	Nation using transmission facilities
		Frequency band	Bandwidth	Transmitter power			
Transportable quantum time and frequency standards	Direct comparison	-	-	-	-	Depends on accuracy of transported clock. Of the order of tenths of a microsecond	USSR, USA and others
Short-wave radio stations	Transmitting exact time and reference frequency signals	2.5-30 MHz*	3-8 kHz	5-80 kW	Less then 10-15 thous. km	Hundredths of a microsecond	About 50 stations in operation around the world
Long-wave radio stations	Ditto	30-300 kHz	0.8-5 kHz	20 kW-2 MW	Less than 3-5 thous. km	Tens of microseconds	Various nations of Europe
Long-wave navigational systems	Transmitting short pulses filled by carrier frequency	30-300 kHz	Less than 24 kHz	0.2-3 MW	1500 km of surface wave	1 μs (surface wave)	Loran-C stations (USA) in different regions of northern hemisphere
VLF radio stations	Transmitting carrier frequency; phase registered with instants of time signals	10.2-30 kHz	100-600 Hz	Less than 1.5 MW	5-6 thous. km	2 μs per 1000 km + 2 μs (systematic error) 1-5 μs (random error)	Omega system (USA) and others

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TABLE 7 (continued)

Transmission facility	Signal transmission method	Parameters of transmission facility			Distance between synchro-nization points	Transmission error	Nation using transmission facilities
		Frequency band	Bandwidth	Trans-mitter power			
Systems using reflection from meteor trails	Opposed transmissions (two-beam and three-beam)	40-90 MHz	200-1000 kHz	10-200 kW in pulse	Less than 1400 km	Microseconds and frac-tions of a microsecond	USSR and USA
Television broadcast channels	Using charac-teristic pulses of TV signals (pas-sive systems)	UHF	6 MHz	10-100 kW	Within zone of action of TV network	Microseconds	Used in many nations
Ditto	Transmitting time signals as part of TV signal (ac-tive systems)	-	-	-	-	-	USSR and USA
Artificial satellites (relays)	Opposed and unilateral transmissions	1-6 GHz	6-12 MHz	1-50 W (on-board)	Less than 16,000 km	Microseconds and frac-tions of a microsecond	Experimental transmitters in USSR and USA
Artificial satellites with on-board store	Unilateral reception	1-6 GHz	0.8 - 5 MHz	1-50 W (on-board)	Global	Tens of microseconds	Ditto
Geostationary satellites	Ditto	4-6 GHz	-	-	Less than 16,000 km	Tens of microseconds	Experimental system (USA)

*An international agreement sets aside frequencies of 2.5, 5 and 10 MHz with passband of ±5 kHz, and of 15, 20 and 25 MHz with passband of ±10 kHz.

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comparators (in the case of a sine wave), synthesizers, chart recorders, timers and other indicator devices.

During signal travel, electromagnetic waveforms undergo changes in amplitude and phase. The function with signal transmission through a channel made up of n links is equal to the product of the transfer functions of the links, i. e.

$$\bar{K} = k_1 k_2 k_3 \ldots k_n = (k_1 k_2 k_3 \ldots k_n) e^{-j(\varphi_1+\varphi_2+\cdots+\varphi_n)} = k e^{-j\varphi},$$

where k_1, k_2, k_3,..., k_n are the moduli of the transmission coefficients; ϕ_1, ϕ_2, ..., ϕ_n are the corresponding phases.

In a system with distributed parameters, instead of the phase ϕ_k we have the phase constant α_k multiplied by the length of the k-th link of the line l_k or by the product $v_k\tau_k$, where v_k and τ_k are the velocity and time of signal travel in the given link. Then at the end of the channel

$$\bar{S}_n = S_0 e^{j\left(\omega t + \sum_{i=1}^{n} \varphi_i + \sum_{i=1}^{n} \alpha_i v_i \tau_i\right)},$$

where S_0 is the signal at the channel input, $\sum_{i=1}^{n} \varphi_i$ is the total change in phase due to the lumped constants of the channel, and the sum $\sum_{i=1}^{n} \alpha_i v_i \tau_i$ is the same quantity due to the distributed constants of the channel.

In transmitting high-stability frequencies and time intervals, the constant phase shift due to lumped and distributed constants of all elements of the channel does not cause any change in the transmitted high-stability frequency only if all parameters are stable thorughout the measurement period. When transmitting time signals, there is a change of signal times due to phase shifts in circuits with lumped constants, and as a consequence of the finite value of the radio wave propagation velocity.

All these changes during synchronization of frequency standards or time standards must be strictly accounted for, and their resultant effect responsible for the synchronization error must not exceed a predetermined value.

7.2. Synchronization Methods

The choice of synchronization method depends in great measure on the working conditions of the standard to be synchronized, and the capabilities for receiving signals from the synchronizing standard. For example if the standard to be synchronized operates periodically, and synchronization is required each time it is energized, The method must ensure one-time synchronization with error no greater than the permissible error. On the other hand, if the standard to be synchronized operates continuously, synchronization with the permissible error can be achieved by averaging the results of repeated sequential comparisons of the frequency of the standard to be synchronized with the signals of the synchronizing standard.

The requirements placed on the channel for synchronization of frequency standards are not the same as those for time standards. When synchronizing frequency standards

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it is necessary to take consideration of the inconstancy of lumped and distributed constants of all elements of the channel only for the time interval of synchronization. In synchronizing time standards, consideration must also be taken of the constant phase shift caused by systematic and random changes in the parameters of the channel from the instant of establishing the signal travel time in the transmission channel.

Synchronization of time standards (or tie-in of time scales) must be distinguished from tie-in of the instants of time signals. Tie-in of time scales includes two operations: synchronizing the frequency of electric oscillations or time intervals, and tie-in of the instants of time scale signals. Tie-in of the instant of the time signal amounts to one-time phasing of the signal of the standard to be synchronized without synchronizing the time-scale intervals. After one-time tie-in, the instants of the time signals will be continuously shifted relative to the instants of synchronization by $\Delta_0 = \gamma_0$ (the relative error of the frequency of the synchronizing measure), i. e.

$$t_{\text{н.об}} = t_{\text{н.с}} + t_{\text{н.с}}\Delta_0, \qquad (7.1)$$

where $t_{\text{н.об}}$ is the interval between time signals emitted from the radio transmitter antenna from the reference standard, $t_{\text{н.с}}$ is the interval between time signals of the standard to be synchronized.

Synchronization of frequency standards or time-scale intervals is done by a method of direct measurement of the frequency of the standard to be synchronized or by the method of frequency comparison using counting-type frequency meters, the heterodyna or phase method in transmissions of sine waves or time signals from the synchronizing standard; synchronization of time standards is done mainly by the phase method, using special synchronization signals or time signals.

7.3. Synchronizing Frequency Standards

Order and Conditions of Synchronization

Frequency standards are synchronized in the following order:

a) the optimum method and means of synchronization are selected from among those summarized in Table 7, depending on the metrological characteristics of the frequency standard to be synchronized, the makeup of the recording receiver equipment and the location of the frequency standard;

b) the time for synchronization is selected with consideration of the maximum constancy of parameters of the transmission channel;

c) the necessary time interval of frequency comparison is determined (see Table 8 or 9);

d) the error of the recording receiver is determined;

e) frequencies are compared, and the principal metrological characteristics of the standard are determined under selected measurement conditions;

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f) the frequency is corrected by a regulating element or a special frequency adjustment module.

Synchronization Error

In synchronizing frequency standards, errors should be accounted for and minimized that are due to: change in the state of the ionosphere during the synchronization interval; the synchronization facilities that are used; the method of reception and registration; the error of the frequency standard to be synchronized; the selected time for synchronization.

The error of synchronizing the frequency standard is determined by errors of the transmission channel ($\delta_{01}f$), the synchronizing standard with consideration of transmitting equipment ($\delta_{02}f$), the standard to be synchronized ($\delta_{03}f$), the method of synchronization and the receiving recording equipment ($\delta_{04}f$) and frequency regulation of the standard being synchronized ($\delta_{05}f$). Since these errors are independent of one another, and each of them is random, the relative synchronization error

$$\Psi_{0f} = \sqrt{\delta^2_{01f} + \delta^2_{02f} + \delta^2_{03f} + \delta^2_{04f} + \delta^2_{05f}}. \tag{7.2}$$

The transmission error due to inconstancy of the characteristics of time and frequency signals in different radio wave bands, as has been shown above, is due in large measure to the state of the atmosphere surrounding the earth, including the ionosphere, to the conductivity of the underlying surface, the geographic location of the transmission path, time of day, season of the year, solar activity, magnetic storms in progress and other factors that influence conditions of radio wave propagation in various bands.

Approximate values of errors of the transmission channel δ_{01f} for different bands:

	Equiluminant path	Non-equiluminant path
Short-wave	$(1-5)\cdot10^{-9}$	$(1-8)\cdot10^{-8}$
Long-wave	$(1-5)\cdot10^{-11}$	$(1-10)\cdot10^{-11}$
VLF	$(3-8)\cdot10^{-11}$	$(5-40)\cdot10^{-11}$
UHF	$(1-10)\cdot10^{-13}$	$(1-10)\cdot10^{-13}$

The values for the long-wave range are cited for a surface wave when the duration of the measurement time interval is in accord with the data of tables 8 and 9 (see below); the values for the VLF range are cited for transmission paths of 1000-3000 km.

Fig. 35 shows an example of the results of daily comparison of the frequency of a standard being synchronized with the carrier frequency of short-wave radio stations on 10 and 15 MHz situated at a distance of 2000 km from the reception point. Considering that the instability of the carrier frequency on the antenna of the radio station is of the order of 10^{-11}, we can state that the given curves characterize mainly the inconstancy of conditions of radio wave propagation. As we can see from the graphs, during the period when the transmission path is totally illuminated or totally in darkness, the difference of frequencies being compared reaches $(1-5)\cdot10^{-9}$, while this difference is $(1-5)\cdot10^{-8}$ when the path is unevenly lighted.

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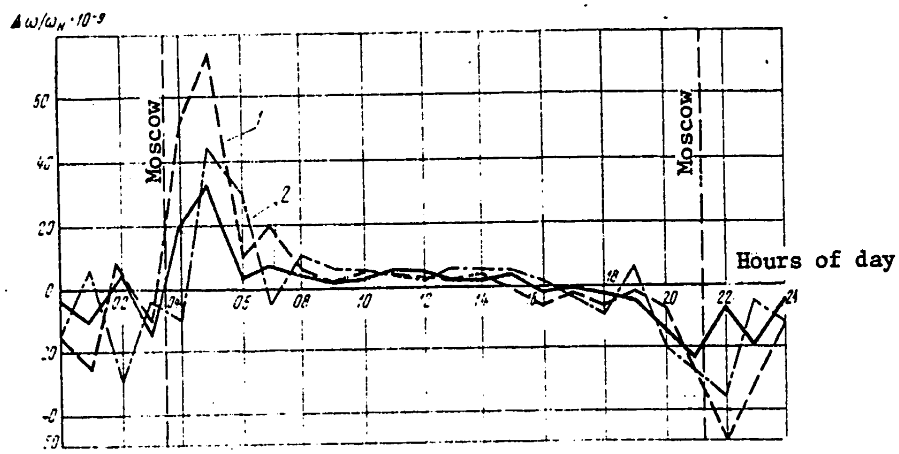

Fig. 35. Frequency comparisons with respect to a short-wave radio station (carrier frequency 10 MHz) on Moscow-Novosibrsk transmission path (June):

1--calculated date; 2--experimental data

In Novosibirsk, Sverdlovsk and Tbilisi during a solar eclipse when the complete shadow of the moon crossed over the territory of the USSR, measurements were made of the changes in the carrier frequency of radio station RWM (15 MHz). The maximum change in frequency was noted for the Moscow-Tbilisi route ($6.7 \cdot 10^{-8}$), and for Moscow-Novosibirsk the change was $5.3 \cdot 10^{-8}$.

To synchronize frequency standards, a radio station is used that ensures predetermined accuracy, and provides sufficient field strength at the reception point for reliable synchronization. For the VLF band, the field strength must be at least 300 μV/m in the receiver band of 500-1000 Hz, and 20-50 μV/m in the band of 20-50 Hz; for frequencies of the long-wave band (50, 662/3 and 200 kHz)--at least 100 μV/m in the band of 100-500 Hz, and at least 50 μV/m in the band of 10-100 Hz; for frequencies of 2.5, 5, 20, 15 and 20 MHz and those displaced from the nominal frequency by ±4 kHz--at least 2-10 μV/m, depending on the interference level.

If frequency reception is impeded by the presence of interference, special devices are used: quartz bandpass filters, external or loop antennas, shielded antenna housings.

The time of day that is suitable for radio signal reception when the path of radio wave propagation does not cross the terminator (the boundary between the daytime and nighttime sides of the earth) can be determined by a nomogram (see Fig. 36). Since the terminator line is a fairly broad twilight zone, the boundaries of the favorable part of the day are to some extent uncertain, resulting in an error of the order of ±(20-30) minutes.

The error of the synchronizing frequency standard δ_{02f} is determined by the error of the frequency standard set up at the transmitting point (radio station), and the

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TABLE 8

Minimum time intervals for comparing frequency standards (values of τ_H are approximate)

Relative error of standard being synchronized	Time interval τ_H, s for band		
	short-wave	long-wave	VLF
10^{-11}	-	60,000	86,400
10^{-10}	-	10,000	36,000
10^{-9}	-	1,000	3,600
10^{-8}	-	200	400
10^{-7}	20	60	120
10^{-6}	10	20	60
10^{-5}	5	10	30
10^{-4}	2	5	20

TABLE 9

Minimum time intervals for comparing frequency standards with respect to exact time signals (values of τ_H are approximate)

Relative error of standard being synchronized	Time interval τ_H, s			
	short-wave	long-wave	VLF	TV channels
10^{-11}	-	-	-	3,600
10^{-10}	-	-	-	1,600
10^{-9}	-	86,400	-	120
10^{-8}	-	12,000	30,000	30
10^{-7}	800	500	1,200	10
10^{-6}	200	100	300	5
10^{-5}	80	40	100	2
10^{-4}	40	20	50	1

instability of parameters of the radio transmitter and antenna. To reduce these components, devices are used at the transmitting station that stabilize the phase of the signal on the antenna. The overall error $\delta_{02}f$ is usually indicated in "Schedules of Exact Time and Reference Frequency Broadcasts."

The error of the synchronized standard $\delta_{03}f$ is indicated in nameplate data.

Error $\delta_{04}f$ is determined by the equipment used, and the error of time of registration and synchronization.

The error of frequency regulation of the synchronized standard $\delta_{05}f$ is determinined by the resolution of the tuning element in manual alignment, and by the stopband in automatic alignment.

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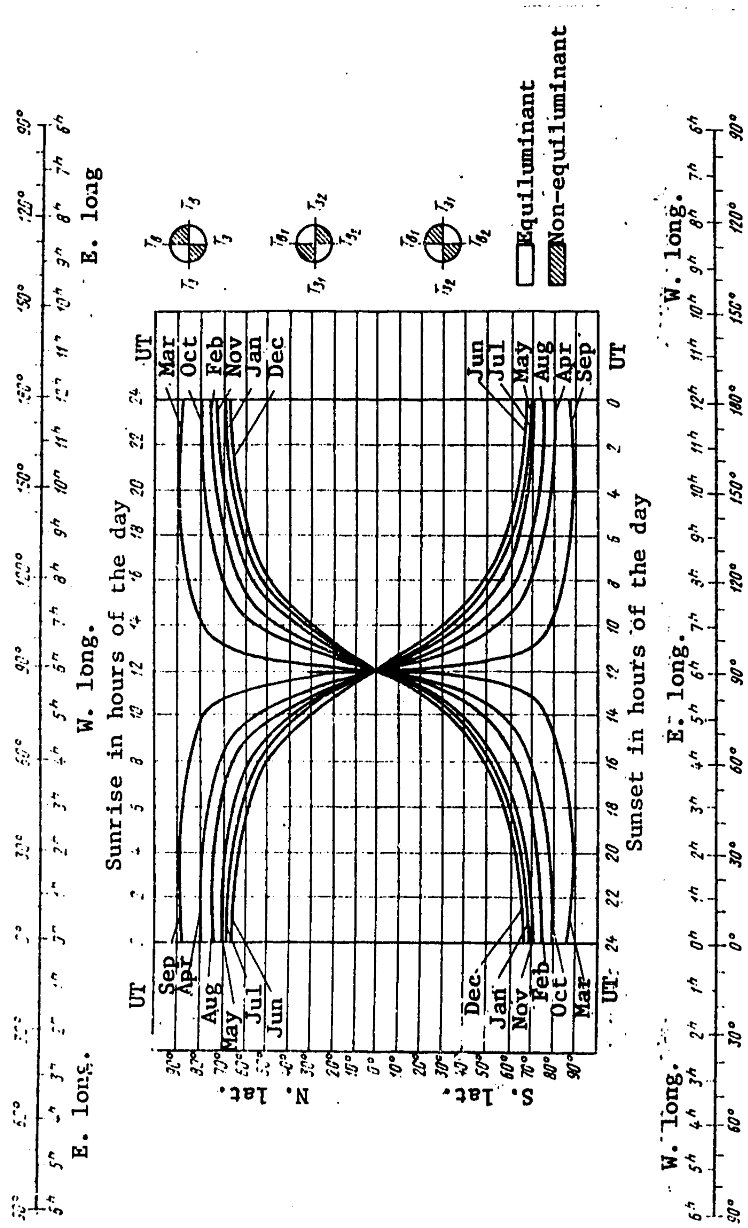

Fig. 36. Nomogram for determining time of equiluminant transmission paths

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Synchronization of frequency standards with error from 10^{-4} to 10^{-7} is done with respect to carrier frequencies of short-wave, long-wave and VLF radio stations. In the case of short-wave radio stations, a heterodyne method is used for comparing the reference frequency with the frequency of the standard to be synchronized or with its harmonics; when long-wave or VLF stations are used, frequencies are compared by a heterodyne or differential method.

Synchronization of frequency standards with error from 10^{-7} to 10^{-10} is done with respect to the carrier frequencies of long-wave and VLF stations, using phase, differential or heterodyne methods of comparison. Use of the first method is preferable.

Synchronization of frequency standards with an error of 10^{-10} and less can be achieved only with strict accounting for destabilizing factors of the transmission channel, the error of the phase method of comparison, registration and processing of the results of comparisons.

The time intervals for comparing frequencies to be synchronized when using reference frequencies transmitted via radio stations in the short-wave, long-wave and VLF bands are established by Table 8 with consideration of the fact that the total error of the synchronizing standard and the synchronization method must be at least three times lower than the error of the standard to be synchronized.

Table 8 gives data with consideration of inconstancy of conditions of radio wave propagation for an equiluminant transmission path and recording error.

The time interval for comparison when using time signals as dependent on the relative error of the frequency standard to be wynchronized is established by Table 9.

The data in Table 9 are given with consideration of inconstancy of the conditions of radio wave propagation for equiluminant paths or in the course of a day (86,400 seconds). The error of signal registration: for the short-wave band 40 μs, for the long-wave band 20 μs, for VLF 100 μs, for TV channels 0.1 μs.

The actual value of the frequency of the standard being synchronized is calculated from the following formulas.

When using a counting-type frequency meter in the frequency-measuring mode

$$f_д = f_{д.ЧЭС} \pm \psi_{ЧЭС}, \qquad (7.3)$$

where $f_{д.ЧЭС}$ is the reading of the frequency meter in Hz, and $\psi_{ЧЭС}$ is the error of the frequency meter in Hz.

When the differential or heterodyne method of measurements is used

$$f_д = f_н + C \pm \psi_c, \qquad (7.4)$$

where f_H is the nominal frequency of the standard being synchronized in Hz, $C = -\Delta$ is the correction to the frequency of this standard in Hz, equal in magnitude and opposite in sign to the difference between the nominal and actual frequencies;

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The quantity Δ may have either a positive or negative sign; ψ_C is the error of the method in Hz.

When using the phase method of measurements

$$f_д = f_н\left(1 + \frac{\delta\varphi}{\tau_н} \cdot 10^{-6}\right) \pm \psi_c, \qquad (7.5)$$

where τ_H is the interval of measurement time in s, $\delta\phi$ is the discrepancy of signal phases in μs over the interval of time measurement.

When using a counting-type frequency meter in the mode of measurements of time intervals between pulses of the synchronized and synchronizing frequency standards, or measurements with respect to time signals

$$f_д = f_н\left(1 + \frac{\delta T}{\tau_н}\right) \pm \psi_c, \qquad (7.6)$$

where δT is the change in the time interval between signals over time τ_H, s.

The relative error of synchronization $\psi_{O.C} = \psi_C/f_H$; it must be an order of magnitude less, or at least three times less, than the relative error of the frequency of electric oscillations of the standard to be synchronized, i. e.

$$\psi_{о.с} < \frac{1}{3}\,\gamma_0.$$

Formulas (7.5) and (7.6) are used for calculations of the actual value of the frequency of the standard to be verified over the time measurement interval, while the averaged actual frequency over the course of a day is determined from the formula

$$f_д = f_н\left(1 + \frac{\delta\varphi_C}{0{,}864} \cdot 10^{-11}\right), \qquad (7.7)$$

where $\delta\phi_C$ is the phase discrepancy of the signals in μs over a day.

When the phase discrepancy is measured in degrees,

$$f_д = f_н + \frac{\delta\varphi}{360\tau_н}. \qquad (7.8)$$

The method of processing the results of comparison by the phase technique is explained in Section 7.5.

Determining the Time of the Equiluminant Transmission Path

To determine the time of the equiluminant path it is necessary to know the hours of sunrise and sunset, which depend on the season of the year, and on the coordinates of the points where the transmitting radio station and the standard to be synchronized are located [Ref. 48].

To plot the nomogram (Fig. 36), a BESM-4 computer is used to calculate times of sunrise and sunset for latitudes from +85° to -85° with a step of 5° for the middle

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of each month by the following approximate formulas of spherical astronomy:

$$\begin{aligned} \operatorname{tg}\delta_0 &= \operatorname{tg}\varepsilon \sin\alpha_0; \\ t_0 &= \arccos(-\operatorname{tg}\varphi \operatorname{tg}\delta_0); \\ T_B &= t_0;\ T_3 = 24^h - t_0, \end{aligned} \tag{7.9}$$

where α_0, δ_0 are the time of right ascension and declination of the sun, $\varepsilon \cong 23°.4$ is the tilt of the ecliptic to the equator, ϕ is the geographic latitutde, t_0 is the hour angle of the sun at sunrise, T_B, T_3 are times of sunrise and sunset.

The values of α_0 were calculated from the formula for mean right ascension. To calculate values close to the middles of the months, the formula was transformed to the approximation

$$\alpha_0 = 17^h.6 + 2^h m,$$

where m is the ordinal number of the month. The error of the resultant value of α_0 does not exceed 17 min.

The curves of the nomogram plotted by using the values calculated from formulas (7.9) are graphs of the times of sunrise (sunset) as a function of latitude with respect to the local mean time scale. To convert to universal (Greenwich) time, it is necessary to consider the longitude of the point (subtract the value of east longitude or add the value of west longitude). This operation is accomplished by using the upper and lower longitude scales. The change in times of sunrise and sunset from month to month increases with increasing latitude. And at the same time, there is an increase in the twilight period at higher latitudes. Therefore, considering the physics of the phenomenon, it makes no sense to interpolate between curves of two successive months, and it is sufficient to take the curve relating to the middle of a given month.

Work with the nomogram should be done in the following order:

find the point of intersection of the horizontal line corresponding to one of the points (for example the transmitting point) with the curved line that corresponds to the given month;

go up or down from this point to the midline of the nomogram 0°, i. e. find the projection of this point;

join the projection point to the point of the upper scale of the nomogram that corresponds to the longitude of the site, and beneath this point read out the time of sunrise T_{B_1}; join the same point of the projection to the [appropriate] point of the lower scale of longitudes, and read out the time of sunset T_{3_1} above this point.

The time of sunrise and sunset for the other point (T_{B_2} and T_{3_2}) is determined in exactly the same way.

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To determine the part of the day that is favorable for measurement (equiluminant path), it is necessary to construct a cyclic diagram of order of succession of sunrises and sunsets at the two points [see example to the right on the nomogram].

If the sunrises and sunsets succeed one another in the order "rise-rise-set-set", the equiluminant path will lie between times T_B-T_3 and T_3-T_B. If the order of succession of sunrises and sunsets is "rise-set-rise-set", the equiluminant path will lie in intervals T_{B_1}-T_{3_2} and T_{B_2}-T_{3_1} or T_{3_2}-T_{B_1} and T_{3_1}-T_{B_2}, i. e. between neighboring sunrises and sunsets at the different points.

The following must be taken into consideration.

1. The nomogram gives universal (Greenwich) time, and 3 h must be added to convert to Moscow time.

2. If the horizontal scale corresponding to the latitude of the site does not intersect the curve of the corresponding month, this means that it is polar day or polar night at the given point at this time of year (in accordance with the inscription on the nomogram). In this case, the only favorable interval for measurements is the part of the day when it is daytime or nighttime respectively at the other point.

3. Measurement conditions are unfavorable during twilight, and therefore the period of the equiluminant path should be somewhat shortened on both ends.

7.4. Synchronization of Time Standards (Time Scales)

Order and Conditions of Synchronization

Time standards are synchronized in the following order:

a) depending on the metrological characteristics of the time standards, the makeup of the recording reception equipment and the location of the standard to be synchronized, the optimum method and means of synchronization are chosen from among those cited in Table 7;

b) the time of synchronization is selected with consideration of maximum constancy of the parameters of the transmission channel;

c) in accordance with tables 8 and 9, the necessary time interval is determined for synchronization of the frequency standard that is the basis for setting up the time scale;

d) the error of the recording reception equipment is determined;

e) the signal delay is determined in the recording reception equipment;

f) the signal travel time from the antenna of the transmitting station to the antenna of the location of the standard to be synchronized is calculated or experimentally determined;

g) the frequencies are compared, and the principal metrological characteristics of the standard are determined under selected measurement conditions;

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h) the instants of the signals of the time scale are brought together with the signal transmitted from the synchronizing standard;

i) corrections with respect to the frequency and instants of the time signals are calculated and introduced by means of regulating elements (frequency control, phase shifter or discrete delay module);

j) synchronization of the time standard is checked by one or two other radio stations;

k) synchronization results are marked on a graph.

Synchronization Error

In synchronizing time standards, it is necessary to account for and minimize errors due to: change in state of the ionosphere on the transmission path during the interval of signal registration at the reception point; selection of the time and time interval of synchronization; error of determining the signal travel time in the transmission channel and its change during synchronization; the error of determining the time of signal delay in the receiving and recording equipment; the error of the method of comparing, recording and processing measurement results; the error of the time standard being synchronized and the periodicity of synchronization; the error of regulating the intervals and instants of the signals of the time scale to be synchronized.

The error of synchronization of time standards is determined by errors of synchronization of the time-scale interval or the frequency of the reference standard for formation of the time scale (see Section 7.3)--ψ_{0f}; of determining the time of signal travel from the antenna of the synchronizing standard to the antenna of the synchronized standard--δ_{0t1}; of the synchronizing standard--δ_{0t2}; of the standard being synchronized--δ_{0t3}; of recording the instants of time signals--δ_{0t4}; of determining travel time delay of the time signals in the recording receiver equipment--δ_{0t5}; of determining and making the correction to instants of signals of the time scale to be synchronized--δ_{0t6}:

$$\psi_{0t} = \sqrt{\psi_{0f}^2 + \delta_{0t1}^2 + \delta_{0t2}^2 + \delta_{0t3}^2 + \delta_{0t4}^2 + \delta_{0t5}^2 + \delta_{0t6}^2}. \quad (7.10)$$

In selecting the radio station, consideration is taken of the fact that the time signals from this station must be clearly audible, the leading edge of the signals should not be distorted by interference and multibeam propagation of radio waves, and the transmission path should be equiluminant.

Time standards with error of 10-100 ms can be synchronized with respect to signals of civil time (six points) transmitted by radio broadcast stations; with error of 100-300 μs--with respect to time signals of short-wave radio stations on the territory of the USSR and the neighboring seas; with error of 40-70 μs--with respect to time signals of long-wave radio stations RTZ and RBU (radius up to 1200-1500 km from Moscow and Irkutsk) and other non-Soviet long-wave and VLF stations, including the Loran-C long-wave and the Omega VLF navigation systems; with error of 0.5-2 μs--with respect to TV and satellite channels. Time-scale intervals or frequency of the reference standard are synchronized in the order given in Section

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7.3, and the instants of signals of the time scale being synchronized are normalized with respect to exact time signals, or with respect to the phase of the carrier frequency marked to resolve ambiguity.

In some cases, where high precision of synchronization is not required or where a single tie-in of the scale is to be done (in the case of a periodically energized time scale), the operations of synchronizing time intervals and normalizing the instants of local time-scale signals are combined by repeated sequential registrations of the instants of received time signals with the signals of the time scale to be synchronized. Each time after determining the deviation, corrections are made by correcting elements without correcting the frequency of the reference standard.

The error of travel time of the signals δ_{0t1} is determined with consideration of all destabilizing factors (see chapters 4-6), or is evaluated from experimental data. For the short-wave, long-wave and VLF ranges the most appreciable influence is from illumination of the transmission path. As an example, Fig. 37 shows the change in signal travel time of signals during the course of a day on a transmission path from Moscow to Rugby (U.K.) in the summer (radio station GBR, frequency 16 kHz). The greatest change in signal travel time between day and night is 45 μs.

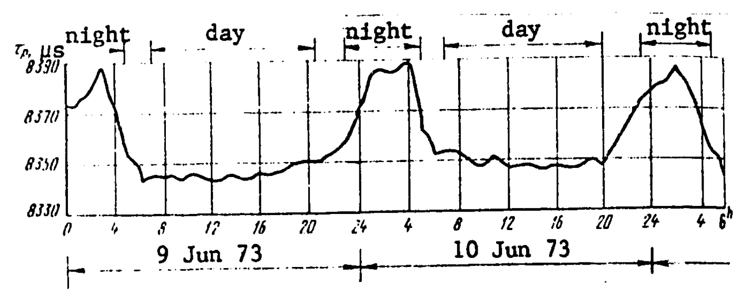

Fig. 37. Change in signal travel time on Rugby-Moscow transmission path

The travel time of time signals can be approximately determined for the short-wave band from Fig. 38a, and for the long-wave band--from Fig. 38b. The curves are plotted from experimental data. The error of determining τ_p by using Fig. 38a is ±150 μs, and for 38b--±50 μs.

Error δ_{0t2} of the synchronizing time standard is determined by the error of the time standard set up at the transmitting point and by the instability of delay of signal travel time in the transmitting equipment with consideration of a special stabilizing device. The total error is usually indicated in "Schedules of Exact Time and Reference Frequency Signal Transmissions."

Error δ_{0t3} of the standard being synchronized is indicated in the nameplate data.

The recording error δ_{0t4} is determined by the resolution of the recording device, the method of comparing time scales, the shape of the leading edge of the signal and the signal-to-noise ratio at the reception site.

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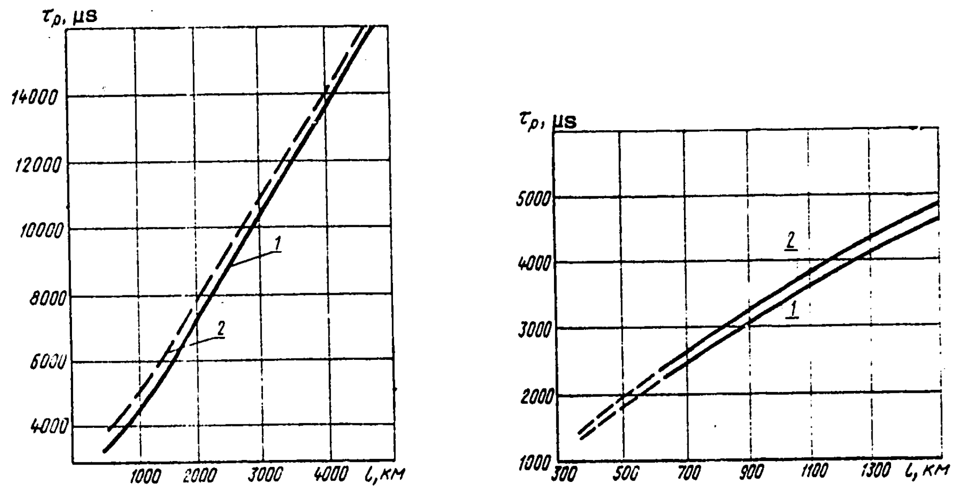

Fig. 38. Signal travel time as a function of distance between antennas of synchronized and synchronizing standards on an equiluminant transmission path: 1--daytime; 2--nighttime

For short-wave radio stations, this shape will vary because of multibeam propagation of radio waves. Fig. 39 shows the shapes of time signal pulses at the reception point. In recording time (Fig. 39a) the recording error may reach 50-80 μs, and in recording the signal (Fig. 39b)--300 μs or more. For practical purposes, a signal of this shape is not recommended for synchronization.

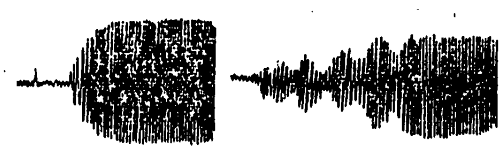

Fig. 39. Shape of leading edge of signals at the reception point with transmission by short-wave radio stations

Fig. 40 shows the leading edge of a signal in the long-wave range at the antenna of radio stations RES--10 kHz (1) and RBU--66⅔ Hz (2).

In the case of interference with ratio of 5:1 and realistic phase fluctuation at the reception site, the recording error is 30-50 μs at a distance of up to 1200 km.

If the exact time signals being used to synchronize the time standard have some spread at the reception site characterized by variance σ_ε^2, reliable determination of the instant of the received signal necessitates averaging the instants over as

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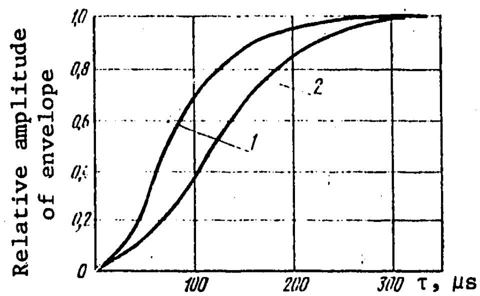

Fig. 40. Leading edge of time signal on antenna of long-wave radio stations

long a time interval as possible, consistent with σ_ξ^2 and depending on reception conditions, interference level and the fluctuations of the leading edge of the signal.

If a time scale is to be synchronized for a time during which the instants of signals of the scale being synchronized must not deviate from the instants of exact time signals by a predetermined value of σ_ξ^2, an interval can be established during which it is advisable to carry out averaging and synchronization of instants of the time scale signals.

If the error of synchronization of time signals is preassigned, the average time during which it is advisable to carry out tie-in after the (2n - 1)-th received time signal to the average value of the instant of these signals is

$$t_{cp} = \frac{\sum_{i=1}^{2n-1} t_i}{2n-1} = t_{c.B}\delta_{03f}(n-1) + t_0 + \frac{\Sigma\xi_i}{2n-1}, \qquad (7.11)$$

where n is the number of recorded instants of time signals; ξ_i is the fluctuation of time signals at the reception site; $t_{c.B}$ is the interval between time signals radiated from the transmitter antenna.

But $t_{c.B}\delta_{03f}(n-1) + t_0$ is the correction at the n-th instant, and consequently is the more exact the greater the n, since its variance is equal to $\sigma_\xi^2/(2n-1)$. If we displace the instants of the time-scale signals by t_{cp} after the (2n - 1)-th signal, then the interval between the new position T_{2n-1} and T'_{2n-1} will be equal to $\frac{\Sigma\xi_i}{2n-1} + t_{c.B}\delta_{03f}(n-1)$. The spread of values of this interval obtained from the possible values of ξ_i and δ_{03f} is what determines the accuracy of synchronization. Then the recording error due to averaging of the fluctuation of instants of the signals at the reception site is

$$\sigma_{\phi} = \sqrt{\frac{\sigma_\xi^2}{2n-1} + t_{c.B}^2\sigma_{03f}^2(n-1)^2}. \qquad (7.12)$$

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It can be seen from formula (7.12) that there is an optimum value n_{opt} that ensures maximum recording accuracy with averaging of the recording results.

One of the appreciable components of the synchronization error is the error of determining the signal travel time in the radio reception equipment δ_{0ts}, which depends mainly on the width of the passband, and can be determined for each specific receiver. Fig. 41 shows $\tau_{3.\text{пр}} = \phi(\Delta F)$ for the R-250 M radio receiver.

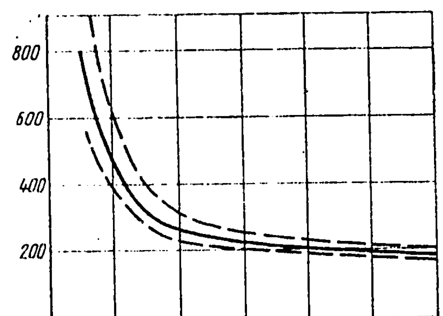

Fig. 41. Typical behavior of signal delay time in receiver for different passbands

Signal delay time in the receiver equipment is

$$\tau_{3.\text{пр}} = \tau_{3.c} + \Delta\tau_3, \tag{7.13}$$

where $\tau_{3.c}$, $\Delta\tau_3$ are the systematic and random components of delay time of the phase or envelope of the signal

The time τ_1 of travel of a sine-wave signal through the circuit corresponds to the phase angle $\phi = \omega\tau$. If τ is constant in the frequency band, the phase shift in the circuit in this band varies linearly as a function of frequency. Deviation of the phase shift $\omega\tau_{3.c}$ from linearity is comprised of the systematic and random changes of τ_3.

When a pulse signal is being transmitted, τ_3 must be constant for frequencies in the passband for retention of pulse shape in the phase relations. Otherwise it is difficult to determine signal delay time due to distortion of the envelope.

During signal transmission, the signal envelope depends on the steepness of the phase characteristics of the transmission channel; the average phase delay is usually determined from the relation $\tau_{3.\text{ср}} = \phi/\omega$, and the signal envelope delay ("signal delay time" or "group signal travel time") is defined as

$$\tau_{3.\text{сиг}} = \frac{d\varphi}{d\omega} = \tau_{\text{ср}} + \omega \frac{d\tau_{\varphi}}{d\omega}, \tag{7.14}$$

i. e. the delay of the envelope is equal to the phase delay on the fundamental frequency plus a term that accounts for the change in delay in the frequency passband

and that is determined by the passband of the channel, the accuracy of tuning to the carrier frequency, and to a lesser extent by signal amplitude and shape.

The foregoing arguments show how difficult it is to exactly measure the delay time of the signal envelope.

It would be possible to get the most exact results in measuring the phase shift with respect to points in a predetermined frequency band and plotting a graph of the delay characteristic. But this is a very laborious process.

We give below a block diagram of practical measurements of the time delay of a time signal in radio reception devices either when a low-frequency voltage arrives directly at the radio receiver input from an oscillator (voltage keyed by square pulses), or when antennas are used for radiation and reception through the ether.

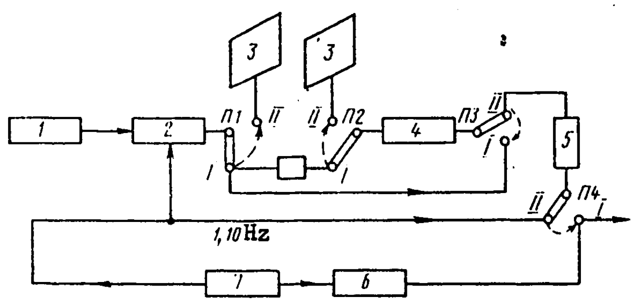

Fig. 42. Diagram of measurement of signal delay time in radio receivers:

1--standard signal generator; 2--time signal simulator; 3--antennas; 4--receiver; 5--oscilloscope with external triggering; 6--device with variable delay; 7--pulse generator

In the former case, a signal from a simulator (Fig. 42) may be sent directly to the receiver input, all switches [П1-П4] being set in position I. In the latter case, the switches are set in position II.

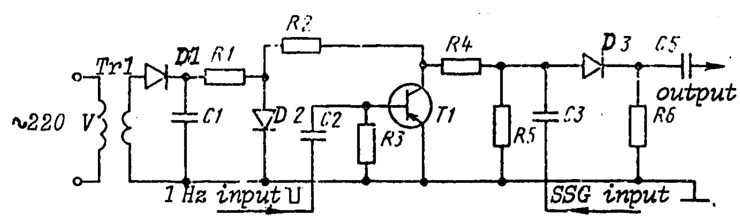

Fig. 43. Schematic diagram of time signal simulator

Fig. 43 shows a schematic diagram of a time signal simulator. Time frequency generators are provided by an rf-oscillator operating in the band of the radio stations, or television broadcast channels. The time signal simulator is an electronic switch based on a semiconductor diode. In the initial state, the transistor is closed, and

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the negative potential from its collector load is fed through resistor R4 (10 kΩ) to the cathode of the diode. When a negative pulse arrives at the base of the transistor, it is opened, and the blocking voltage is removed from the diode. The high-frequency voltage from the rf-oscillator passes to the output plug of the simulator. The duration of the output radio signal of the simulator is determined by the duration of the input pulse.

Signals from the simulator output are fed to the antenna input of the receiver being studied. The delay time of the receiver is measured by an oscilloscope with calibrated scan. Signals from the output of the intermediate-frequency amplifier of the receiver are fed to the vertical amplifier input of the oscilloscope. The oscilloscope is triggered by the seconds-marking pulses of the local clock. The zero-amplitude point of the signal is shifted away from the reference line on the oscilloscope screen, and the time τ_3 is read out with respect to the calibrated scan of the oscilloscope.

When more accurate measurements are needed in the recording receiver, the signals from the simulator are sent to the antenna of the receiver. The measurements themselves are made in the same order as in the first case.

When determining signal delay time in equipment, repeated measurements must be made, and each time the receiver must be tuned and the amplitude at the input must be regulated. The arithmetic mean of the group delay time is

$$\bar{\tau}_{з.р} = \frac{\sum_{i=1}^{n} \tau_{з.р\,i}}{n}, \qquad (7.15)$$

and the error of determining τ_3 is

$$\delta\bar{\tau}_{з.р} = \sqrt{\frac{\sum_{i=1}^{n} (\tau_{з.р\,i} - \bar{\tau}_{з.р})^2}{n-1}}. \qquad (7.16)$$

As we can see from Fig. 41, for the frequency band from 4 to 12 kHz τ_3 is nearly constant, and it increases sharply for the frequency band below 3 kHz. Therefore when signals are being received in the frequency band below 3 kHz, $\tau_{3.r}$ must be accounted for and precisely monitored since it will have an appreciable effect on the overall error of time-scale tie-in.

The error of determining and making the correction to the instants of the time scale δ_{0t6} is determined by phasing and precision of registration of the instants of signals of the synchronizing and synchronized time standards, and by the definition of the correction.

The instants of the time signals are considered simultaneous when the instants of signals of the local time scale lead the received time signal by the signal travel time from the reference time standards (radio stations) to the standards being synchronized.

A time standard will be synchronized if the following equation is satisfied and all components of the total synchronization error have been minimized:

$$\tau_{ч}^{м} - (\tau_{з.пр} + \tau_{р}) = \Delta T_{ш}^{м} = 0, \qquad (7.17)$$

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where $\Delta T_{ш}^{M}$ is the discrepancy of instants of time-scale signals.

To increase accuracy, all synchronization operations must be repeated 10 times, and the average should be determined

$$\overline{\Delta T_{ш}^{M}} = \frac{\sum_{i=1}^{n} \Delta T_{ш}^{M}}{n}. \qquad (7.18)$$

If exact time signals transmitted by two or more stations that are equivalent in accuracy can be received at the site of the reception point at a given time, and the leading edge of such signals is of the same quality (signal-to-noise ratio more than 5:1), then tie-in should be done with respect to two or three stations for greater reliability. For this purpose:

a) the beginning of the received signals must be combined 10 times with the signals of the time standard to be synchronized with respect to the first and second stations, the readings recorded, and $\overline{\Delta T_{ш1}^{M}}$ and $\overline{\Delta T_{ш2}^{M}}$ must be calculated;

b) if these values do not differ by more than 10%, the arithmetic mean should be calculated:

$$\overline{\Delta T_{ш1,2}^{M}} = \frac{\overline{\Delta T_{ш1}^{M}} + \overline{\Delta T_{ш2}^{M}}}{2}; \qquad (7.19)$$

on the other hand, if the mean values with respect to the two stations differ by more than 10%, all synchronization operations should be repeated.

After determining $\overline{\Delta T_{ш1,2}^{M}}$ or $\overline{\Delta T_{ш1,2,3}^{M}}$ a phase shifter or discrete delay should be used to change the instants of the time-scale signals by the resultant amount taken with the reverse sign.

When using the phase method of time scale synchronization, only one station should be used, and to improve the accuracy and reliability of the results of the measurements, the synchronization time interval must be increased.

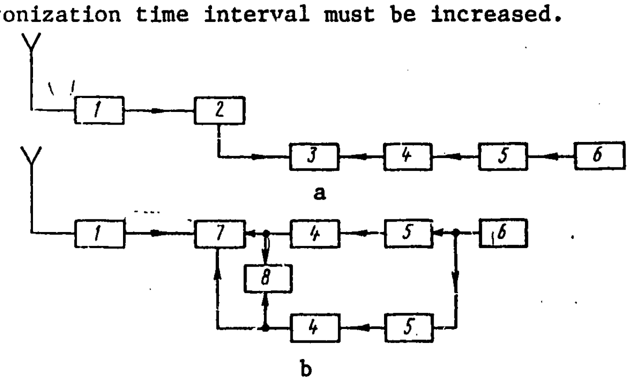

Fig. 44. Block diagram of equipment for synchronizing time standards with respect to time signals:
1--radio receiver; 2--i-f or low-frequency amplifier; 3--slave-sweep oscilloscope; 4--discrete delay device; 5--time-scale shaper; 6--frequency standard; 7--two-beam electronic oscilloscope; 8--counting-type frequency meter

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Fig. 44 shows block diagrams of equipment for synchronizing time standards with respect to exact time signals. Let us consider the one that uses devices with discrete delay (Fig. 44a).

The voltage of the received time signal goes from the output of i-f or low-frequency amplifier 2 to single-beam oscilloscope 3 with slaved sweep. Signals from the time scale to be synchronized with recurrence rate of 1 or 10 Hz, depending on the repetition rate of the received signal are sent through device 4 with discrete delay (type Ch6-37) to the trigger terminal of the oscilloscope (slave sweep mode). By varying the delay with which the beginning of the rise in the leading edge of the signal is fed to the beginning of the scan, we determine the discrepancy of the instants of time signals of the standard to be synchronized relative to the instants of the received time signals.

Fig. 44b shows a block diagram using a counting-type frequency meter in the mode of measurement of time intervals with different received waveforms. In the presence of two-beam oscilloscope 7 and a second divider channel with phase-shifting device, synchronization is done in the following order. The received time signal is sent to two-beam oscilloscope 7 with slaved sweep. To synchronize the oscilloscope, a seconds-marking pulse is sent from the time scale to be synchronized, which is simultaneously the start signal for counting-type frequency meter 8. Time signals (reference mark) from the output of the additional divider channel are sent to the second beam of the oscilloscope and to the frequency meter (stop). By rotation of the phase shifter, the seconds-marking signal (reference mark) is fed to the beginning of the rise in the leading edge of the received time signal. The value of τ_H is determined from the readings of frequency meter 8 in the mode of time interval measurement.

7.5. Methods of Processing Results of Measurements Made by the Phase Method

When the phase method of synchronization is used, the phase difference of signals of the synchronizing and synchronized standards is registered by conventional phase meters. The measurements are taken over standard time intervals τ_C.

The average frequency of the standard to be synchronized is

$$\bar{f} = \frac{1}{2\pi\tau_c} \int_{t_1}^{t_2} \varphi(t)\,dt. \qquad (7.20)$$

The principal advantage of this method is in continuous averaging of the phase of the frequency standard.

If time standards are synchronized discretely rather than continuously, the measured real value of the frequency is determined as a function of phase dispersion at the reception site and the preset accuracy of synchronization.

The averaged real value of the frequency over standard time intervals normalized to the middle of a measurement time interval of N days is determined as follows.

The established measurement time interval $t_n^{(N)} - t_0^{(N)}$ is broken down into n identical intervals $t_{i+1}^{(N)} - t_i^{(N)}$, where $i = 0, 1, 2, \ldots, (n-1)$.

At time $t_i^{(N)}$, a measurement (in μs) is made of the phase difference between the reference frequency and the frequency of the standard to be synchronized (the phase time lead is determined) $\phi_i^{(N)}$.

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Then $\Delta_0 = \frac{f_н - f_{\text{л}}}{f_н}$ on intervals $t_{i+1}^{(N)} - t_i^{(N)}$ will be defined as

$$\Delta_{0i}^{(N)} = \frac{\varphi_{i+1} - \varphi_i^{(N)}}{t_{i+1}^{(N)} - t_i^{(N)}} 10^{-6}. \qquad (7.21)$$

the average value of this quantity on the interval $t_н^{(N)} - t_0^{(N)}$ normalized to the middle of this interval is

$$\overline{\Delta_0^{(N)}} = \frac{1}{n} \sum_{i=0}^{n-1} \frac{\varphi_{i+1}^{(N)} - \varphi_i^{(N)}}{t_{i+1}^{(N)} - t_i^{(N)}} 10^{-6}. \qquad (7.22)$$

M days after these measurements, a standard measurement interval $t_н^{(N+M)} - t_0^{(N+M)}$ is selected that is equal to the N-day measurement interval and is situated at the same place of the time scale, i. e. $t_н^{(N+M)} - t_0^{(N+M)} = t_н^{(N)} - t_0^{(N)}$ where $t_0^{(N+M)} = t_0^{(N)}$. Then analogous measurements are made and used in the calculation of

$$\overline{\Delta_0^{(N+M)}} = \frac{1}{n} \sum_{i=0}^{n-1} \frac{\varphi_{i+1}^{(N+M)} - \varphi_i^{(N+M)}}{t_{i+1}^{(N)} - t_i^{(N)}} 10^{-6}. \qquad (7.23)$$

Knowing the quantities defined by formulas (7.22) and (7.23) at the same instant on different days, we can calculate the relative diurnal systematic frequency variation

$$\nu_0^{(M)} = \overline{\Delta_0^{(N+M)}} - \overline{\Delta_0^{(N+M-1)}}, \qquad (7.24)$$

and the change in the relative diurnal systematic frequency variation

$$2q_0^{(M)} = \frac{\nu_0^{(M)} - \nu_0^{(1)}}{M-1}; \qquad (7.25)$$

at M = 2

$$q_0^{(2)} = \frac{\nu_0^{(2)} - \nu_0^{(1)}}{2}. \qquad (7.26)$$

If the time interval is expressed in days, and the phase advance in microseconds, the averaged relative 24-hour change in frequency is

$$\Delta_0 = \frac{\varphi(t) - \varphi(t-1)}{0,864} 10^{-11}; \qquad (7.27)$$

when the phase advance is measured in degrees

$$\Delta_0 = \frac{\varphi(t) - \varphi(t-1)}{f_н t_н 360}. \qquad (7.28)$$

By determining the values of Δ_0 over equal time intervals (24 hours) in a set period, we can calculate all principal metrological characteristics of the frequency standard by the formulas, using one of the methods of frequency measurements.

Experience has shown that the methods of mathematical statistics provide the best means of determining metrological characteristics of time and frequency standards.

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Practical formulas are given below for calculating the metrological characteristics of frequency standards from the results of continuous testing over several days.

In processing experimental data with a considerable inherent random spread, the best result is attained by constructing a line of regression [Ref. 49] using the method of least squares. The specific nature of frequency standards is such that the systematic change in their frequency with time as a rule is very well described by a linear law, or at least by a square law. Besides, in prolonged testing of frequency standards, measurements are usually made every day at the same time, so that a standard measurement interval can be introduced.

Let us select some standard interval of measurement i (e. g. 24 hours) that takes integral values i = 1, 2, 3,..., n (usually n = 15 days).

Let $\Delta_{0i} = \frac{f_Д - f_Н}{f_Н} = \frac{T_i - T_{i-1}}{86400}$ be experimental values of the relative deviation of the effective frequency $f_Д$ of the standard away from the nominal value f_H at points i. Then the linear regression

$$\Delta_0(i) = \Delta_0 + \nu_0 i \qquad (7.29)$$

is determined by parameters Δ_0, ν_0 calculated from formulas

$$\nu_0 = \frac{12}{n(n^2-1)}\left(\sum_{i=1}^{n} i\Delta_{0i} - \frac{n+1}{2}\sum_{i=1}^{n}\Delta_{0i}\right), \qquad (7.30)$$

$$\Delta_0 = \frac{1}{n}\sum_{i=1}^{n}\Delta_{0i} - \frac{n+1}{2}\nu_0. \qquad (7.31)$$

In the case of a square law of systematic change in frequency, the line of regression

$$\Delta_0(i) = \Delta_0 + \nu_0 i + q_0 i^2 \qquad (7.32)$$

is determined by parameters Δ_0, ν_0, q_0 that in this case are calculated by formulas

$$\Delta_0 = \frac{3}{n(n-1)(n-2)}\left[(3n^2+3n+2)\sum_{i=1}^{n}\Delta_{0i} - 6(2n+1)\sum_{i=1}^{n} i\Delta_{0i} + 10\sum_{i=1}^{n} i^2\Delta_{0i}\right], \qquad (7.33)$$

$$\nu_0 = \frac{6}{n(n^2-1)(n^2-4)}\left[3(n+1)(n+2)(2n+1)\sum_{i=1}^{n}\Delta_{0i} - 2(2n+1)(8n+11)\sum_{i=1}^{n} i\Delta_{0i} + 30(n+1)\sum_{i=1}^{n} i^2\Delta_{0i}\right], \qquad (7.34)$$

$$q_0 = \frac{30}{n(n^2-1)(n^2-4)}\left[(n+1)(n+2)\sum_{i=1}^{n}\Delta_{0i} - 6(n+1)\sum_{i=1}^{n} i\Delta_{0i} + 6\sum_{i=1}^{n} i^2\Delta_{0i}\right]. \qquad (7.35)$$

As to the dimensionality of the quantities: Δ_0 is dimensionless, ν_0 [day^{-1}], q_0 [day^{-2}].

For linear regression, the rate of going of the time scale of the investigated time standard (in microseconds) relative to the reference scale is

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$$T(i) = T_0 + 8{,}64 \cdot 10^{10}\left(\Delta_0 i + \frac{1}{2}\nu_0 i^2\right), \quad (7.36)$$

and for square-law regression

$$T(i) = T_0 + 8{,}64 \cdot 10^{10}\left(\Delta_0 i + \frac{1}{2}\nu_0 i^2 + \frac{1}{3}q_0 i^3\right), \quad (7.37)$$

where T_0 is the instant of the time signal at $i = 0$. Dimensionality of the quantities Δ_0 [μs/day], ν_0 [μs/day^2], q_0 [μs/day^3].

Let us give a specific example of investigation of a rubidium frequency standard over television channels 1300 km from the GEVCh. Measurement results and processing data are summarized in Table 10.

TABLE 10

Results of measurement processing, μs

i	T_i	ΔT_i	$\Delta_{0i} \cdot 10^{11}$	$i\Delta_{0i} \times 10^{11}$	i^2	$i^2\Delta_{0i} \times 10^{11}$	$\Delta_0(i) \times 10^{11}$	$[\Delta_{0i} - \Delta_0(i)] \times 10^{11}$	$[\Delta_{0i} - \Delta_0(i)]^2 \times 10^{22}$
1	2	3	4	5	6	7	8	9	10
0	—22,6	—	—	—	—	—	—	—	—
1	—17,4	5,2	6,0	6,0	1	6,0	6,0	0,0	0,00
2	—13,1	4,3	5,0	10,0	4	20,0	5,3	—0,3	0,09
3	—9,5	3,6	4,2	12,6	9	37,8	4,6	—0,4	0,16
4	—6,8	2,7	3,0	12,0	16	48,0	4,0	—1,0	1,00
5	—4,7	2,1	2,5	12,5	25	62,5	3,3	—0,8	0,64
6	—3,5	1,2	1,4	8,4	36	50,4	2,7	—1,3	1,69
7	—2,8	0,7	0,8	5,6	49	39,2	2,1	—1,3	1,69
8	—2,3	0,5	0,6	4,8	64	38,4	1,5	—0,9	0,81
9	—1,9	0,4	0,5	4,5	81	40,5	1,1	—0,6	0,36
10	—1,6	0,3	0,3	3,0	100	30,0	0,6	—0,2	0,04
11	—1,3	0,3	0,3	3,3	121	36,3	0,2	0,1	0,01
12	—0,7	0,6	0,7	8,4	144	100,8	—0,2	0,9	0,81
13	—1,0	—0,3	—0,3	—3,9	169	—50,7	—0,6	0,3	0,09
14	—2,3	—1,3	—1,5	—21,0	196	—294,0	—0,9	—0,6	0,36
15	—3,6	—1,3	—1,5	—22,5	225	—382,5	—1,2	—0,3	0,09
16	—5,6	—2,0	—2,3	—36,8	256	—588,8	—1,5	—0,8	0,64
17	—7,2	—1,6	—1,8	—30,6	289	—520,2	—1,7	—0,1	0,01

For the case of linear dependence, we sum columns 4 and 5, and substitute these sums in expressions (7.30) and (7.31) at n = 17:

$$\Delta_0 = \frac{1}{17} \cdot 17{,}9 \cdot 10^{-11} + 9 \cdot 4{,}5 \cdot 10^{-12} = 5{,}1 \cdot 10^{-11};$$

$$\nu_0 = \frac{12}{17 \cdot 288}\left(-23{,}7 \cdot 10^{-11} - 9 \cdot 17{,}9 \cdot 10^{-11}\right) = -4{,}5 \cdot 10^{-12}.$$

Summing columns 4, 5 and 7 for square-law dependence, we get $\sum_{i=1}^{17} \Delta_{0i} = 1{,}79 \cdot 10^{-10}$; $\sum_{i=1}^{17} i\Delta_{0i} = -2{,}37 \cdot 10^{-10}$; $\sum_{i=1}^{17} i^2\Delta_{0i} = -1{,}32 \cdot 10^{-8}$. Substituting these values and n = 17 in formulas (7.33), (7.34), (7.35), we get

$$\Delta_0 = \frac{3[(3 \cdot 289 + 51 + 2)17{,}9 \cdot 10^{-11} + 210 \cdot 23{,}7 \cdot 10^{-11} - 13200 \cdot 10^{-11}]}{17 \cdot 16 \cdot 15} = 6 \cdot 10^{-11};$$

$$\nu_0 = \frac{6[3 \cdot 18 \cdot 19 \cdot 35 \cdot 17{,}9 \cdot 10^{-11} + 70(8 \cdot 17 + 11)23{,}7 \cdot 10^{-11} - 540 \cdot 1320 \cdot 10^{-11}]}{17 \cdot 288 \cdot 285} = -7{,}4 \cdot 10^{-12};$$

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$$q_0 = \frac{30[18 \cdot 19 \cdot 17,9 \cdot 10^{-22} + 108 \cdot 23,7 \cdot 10^{-22} - 6 \cdot 1320 \cdot 10^{-12}]}{17 \cdot 288 \cdot 285} = 1,6 \cdot 10^{-13}.$$

The rate of going of the time scale of the given standard, μs,

$$T(i) = T_0 + 5,2i - 0,32i^2 + 0,04i^3, \quad (7.38)$$

from which we see that the daily rate of going of the time scale is equal to +5.2 μs/day, the change in the diurnal variation is -0.32 μs/day^2, and the deviation of the change in the diurnal variation is +0.004 μs/day^3.

To calculate the mean square error, we sum column 10, and then calculate

$$\sigma = \sqrt{\frac{8 \cdot 49 \cdot 10^{-22}}{16}} = 7,3 \cdot 10^{-12},$$

to determine the linear dependence, other values must stand in columns 8-10. These are calculated by the formula

$$\Delta_0(i) = (5,1 - 4,5i)\, 10^{-11}. \quad (7.39)$$

The mean square error $\sigma = 8.5 \cdot 10^{-12}$. From a comparison of these two values we see that the square-law dependence should be given preference.

The metrological characteristics of the frequency standard can be calculated by a method of graphic interpolation.

If dependence $\Delta_0(i)$ can be interpolated by a straight line [see formula (7.29)], then we can write the following two equations for determining parameters Δ_0, ν_0:

$$\left.\begin{aligned} \Delta_0 + \nu_0 &= \Delta_{01} \\ \Delta_0 + n\nu_0 &= \Delta_{0n} \end{aligned}\right\}, \quad (7.40)$$

and solving these, we get

$$\Delta_0 = \frac{n\Delta_{01} - \Delta_{0n}}{n - 1}, \quad (7.41)$$

$$\nu_0 = \frac{\Delta_{0n} - \Delta_{01}}{n - 1}. \quad (7.42)$$

If dependence $\Delta_0(i)$ is interploated by a parabola in accordance with expression (7.32), then we determine parameters Δ_0, ν_0, q_0 by solving the three equations

$$\left.\begin{aligned} \Delta_0 + \nu_0 + q_0 &= \Delta_{01} \\ \Delta_0 + m\nu_0 + m^2 q_0 &= \Delta_{0m} \\ \Delta_0 + n\nu_0 + n^2 q_0 &= \Delta_{0n} \end{aligned}\right\}, \quad (7.43)$$

$$\Delta_0 = \frac{nm(n - m)\Delta_{01} - n(n - 1)\Delta_{0m} + m(m - 1)\Delta_{0n}}{(n - m)(n - 1)(m - 1)}, \quad (7.44)$$

$$\nu_0 = -\frac{(n^2 - m^2)\Delta_{01} - (n^2 - 1)\Delta_{0m} + (m^2 - 1)\Delta_{0n}}{(n - m)(n - 1)(m - 1)}, \quad (7.45)$$

$$q_0 = \frac{(n - m)\Delta_{01} - (n - 1)\Delta_{0m} + (m - 1)\Delta_{0n}}{(n - m)(n - 1)(m - 1)}. \quad (7.46)$$

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In formulas (7.41) and (7.42) we substitute $n = 17$, $\Delta_{01} = 6 \cdot 10^{-11}$, $\Delta_{017} = -1.8 \cdot 10^{-11}$ (see Table 10), and we get

$$\Delta_0 = \frac{17 \cdot 6 \cdot 10^{-11} + 1{,}8 \cdot 10^{-11}}{16} = 6{,}5 \cdot 10^{-11},$$

$$\nu_0 = \frac{-1{,}8 \cdot 10^{-11} - 6 \cdot 10^{-11}}{16} = -4{,}9 \cdot 10^{-12}\ \text{day}^{-1}.$$

In formulas (7.44)-(7.46) we substitute $n = 17$, $m = 9$, $\Delta_{01} = 6 \cdot 10^{-11}$, $\Delta_{09} = 0.5 \cdot 10^{-11}$, $\Delta_{017} = 1.8 \cdot 10^{-11}$ (see Table 10), and we get

$$\Delta_0 = \frac{17 \cdot 9 \cdot 8 \cdot 6 \cdot 10^{-11} - 17 \cdot 16 \cdot 0{,}5 \cdot 10^{-11} - 9 \cdot 8 \cdot 1{,}8 \cdot 10^{-11}}{1024} = 5{,}7 \cdot 10^{-11},$$

$$\nu_0 = \frac{208 \cdot 6 \cdot 10^{-11} - 288 \cdot 0{,}5 \cdot 10^{-11} - 80 \cdot 1{,}8 \cdot 10^{-11}}{1024} = -9{,}4 \cdot 10^{-12}\ \text{day}^{-1},$$

$$q_0 = \frac{8 \cdot 6 \cdot 10^{-11} - 16 \cdot 0{,}5 \cdot 10^{-11} - 8 \cdot 1{,}8 \cdot 10^{-11}}{1024} = 2{,}5 \cdot 10^{-13}\ \text{day}^{-2}.$$

Experimental data show that parameters Δ_0, ν_0, q_0 are calculated more accurately by the method of least squares than by the method of graphic interpolation.

7.6. Constructing Trapezoids of Changes in τ_p From Results of the Differential Measurement Method

Synchronous recording of field strength and difference frequency is demonstrated on the example of operation of radio station RES in Moscow (100 kHz) and a local radio station at a reception site in Omsk (Fig. 45).

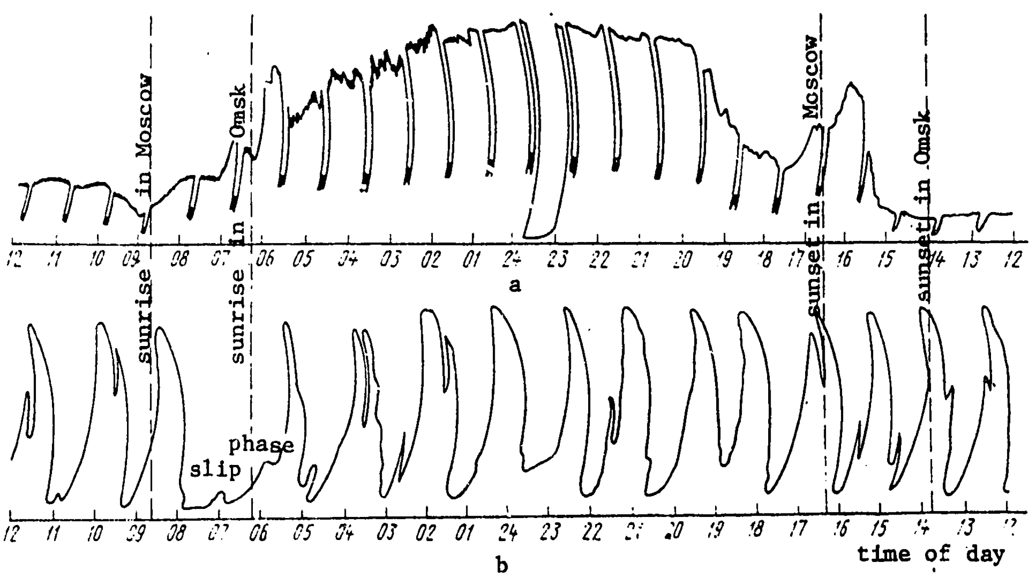

Fig. 45. Synchronous recording:
a--of field strength; b--of difference frequency (beat frequency)

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From Fig. 45 we can see that during the course of a day the field strength at the reception point varies strongly, and that during sunrise, when there is a sharp increase in field strength, phase slip takes place at the reception site due to a change in duration of the period of the difference frequency.

If the instants of zero amplitude of the difference frequency t_0, t_1, $t_2, \ldots, t_n$ are recorded, the difference of two displaced instants determines the duration of the beat period, i. e. $t_1 - t_0 = T_1$, $t_2 - t_1 = T_2, \ldots, t_n - t_{n-1} = T_n$. The beat frequency is defined as $\Delta n = 1/T_n$, or in relative quantities $\Delta_{0n} = 1/T_n f_H$

The relative error of the averaging frequency over ten beat periods (for the case shown in Fig. 45--for 14 periods) is calculated from the formula

$$\Delta_0 = \frac{n}{f_H \sum_{i=1}^{n} T_i} = \frac{14}{10^6 \cdot 23 \cdot 3600} = 1,69 \cdot 10^{-9}. \qquad (7.47)$$

The duration of the average period $T_{cp} = 5914.3$ s, and since each of the beat periods differs by ΔT_n from the average period T_{cp}, this means that the phase changes by $\Delta\phi = \phi_1 - 2\pi$. The total phase change in radians over n periods is

$$\varphi = 2\pi \frac{\sum_{i=1}^{n} \Delta T_n}{T_{cp}}. \qquad (7.48)$$

For graphic representation of the change in phase on measurement time interval ΔT_{cp}, a graph is plotted (Fig. 46) from tabulated values of $\Delta T_n = T_n - nT_{cp}$, where $n = 1, 2, 3, \ldots, 14$ (Table 11). Plotting is ruled by the formula $\Delta\tau_p = \Delta_0 \Delta T_n$.

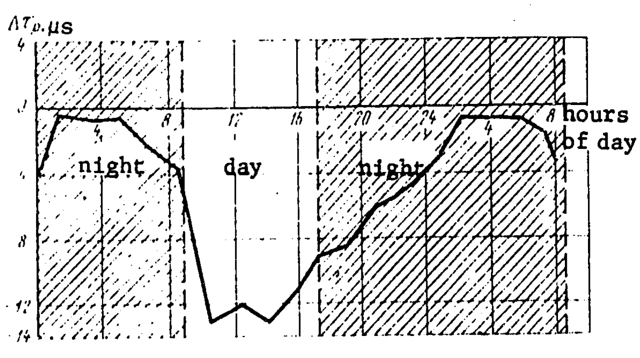

Fig. 46. Change in signal travel time of radio station RES on Moscow-Omsk transmission path as a function of the time of day

Considering the high stability of the standard being synchronized, all changes in ΔT_n can be attributed to inconstancy of the conditions of radio wave propagation.

The curve of Fig 46 shows a practical reflection of the way that signal travel time depends on the time of day.

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TABLE 11

Processing measurement results

n	T_n,	nT_{cp}, s	$\Delta T_n = T_n - nT_{cp}$, s	n	T_n, s	nT_{cp}, s	ΔT_n $T_n - nT_{cp}$, s
1	5700	5914	−214	8	43200	47312	−4112
2	10800	11828	−1028	9	49200	53226	−4026
3	15600	17742	−2142	10	55800	59140	−3340
4	21000	23656	−2556	11	61200	65054	−3854
5	25800	29570	−3770	12	66600	70968	−4368
6	32400	35484	−3084	13	72000	76882	−4882
7	37200	41398	−4198	14	78000	82796	−4796

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