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TIME & FREQUENCY COORDINATION USING UNSTEADY, VARIBLE-PRECISION MEASUREMENTS ON METEOR BURST SYNCHRONIZATION AND COMMUNICATION EQUIPMENT

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Abstract – **Paper presents methods of overcoming problems of automated time & frequency coordination by meteor burst channel that are caused by its peculiar behavior. Possibility of achieving high coordination precision shown by experiments on synchronization equipment constructed in Kazan State University is described. The main problem treated is reliable carrier frequency phase resolution in time coordination measurements. Results may help construct meteor synchronization equipment for distances 1500—1800 km with errors less than 0.3 nanoseconds.**

Keywords – **Meteor, synchronization, time, phase, equipment**

I. INTRODUCTION

Successful experiments on time transfer by meteor burst (MB) channel have been carried out in Kazan State University (KSU) for a long time. The latest sets of MB synchronization equipment [1] constructed for high precision phase measurements showed that potential time transfer error does not exceed fractions of nanoseconds. Some experiments actually allowed tracing the relative time shift between distant clocks with errors less than 0.3 ns. Such precision, along with independence, simplicity and cost-effectiveness, makes meteor synchronization eligible and in some cases even preferable to satellite systems.

The synchronization equipment uses two-way time transfer method and multiple carrier frequency measurements for achieving high precision time coordination. One of the main factors affecting its potential precision is channel non-reciprocity (NR), representing the difference between propagation conditions of waves transmitted in opposite directions [2, 3]. Phase NR errors of the MB channel estimated by theoretical research and experiments do not exceed 0.5 ns., values higher than that can theoretically happen only in the worst cases, rare in practice. Two-way transfer method also practically excludes ionospheric NR errors. This is possible because meteor traces are used as passive retransmitters and signals are transmitted both ways on the same frequency in the range of 40-60 MHz.

The NR error can vary from burst to burst and even during the same meteor, depending on its nature. In the first case error remains stable on intervals of meteor existence but changes randomly on different meteors. That type NR is caused mostly by winds shifting the meteor trail. In the second case error changes dynamically and is caused by changing reflection conditions of the forming meteor trail. Some types of NR, like those caused by polarization effects, span both cases. These errors together with purely random noise errors currently limit the precision of time transfer at 0.3-0.5 ns., but it is possible that this value can be further reduced because some type NR errors still did not actually show up in the experiment and others can be estimated and excluded by additional algorithms with equipment modernization.

It must be stated here that all synchronization experiments on the described equipment have been performed mostly on latitudinal routes, where magnetic field of the Earth does not affect the polarization of carrier radio waves, one of the causes of increasing NR errors. Can the actual NR errors reach the possible theoretical values on longitudinal routes is still a problem for further investigation.

A distinctive feature of MB synchronization equipment constructed in KSU is keeping meteor registration thresholds intentionally low. The signal to noise ratio in MB channel varies in the range 30-40 dB on different traces, making different ways of weeding out errors possible. First approach is to keep the registration threshold high and perform the synchronization using only high-energy meteor bursts that give precise, but rare single-meteor measurements. This can be useful if synchronization purposes do not require immediate results and may be performed infrequently, perhaps not more than once an hour. KSU equipment uses the second approach, registration threshold is extremely low, close to the average noise level and high enough only to exclude false triggering from non-meteor or noise sources. It makes use of every meteor trace for synchronization purposes and relies on secondary processing algorithm for filtering out whatever possible from measurements. That approach not only uses the given energies more efficiently, but also affords additional opportunities in the phase ambiguity resolution technique described later.

In this paper we base the estimates on the experiment carried out in 1992 on Moscow-Kazan route. The minimal signal to noise ratio for that experiment has been chosen so that noise error of a single carrier phase measurement did not exceed 0.5 ns. Decreasing the noise error was left to averaging measurements on the interval of one meteor. The average meteor yields about 15 measurements, so noise error on single meteor can be decreased to 0.1 ns. Estimates of NR errors showed that they did not exceed 0.3 ns. and most of them can be traced to wind-caused NR. Dynamic NR errors did not exceed the average noise errors and could not have been estimated separately. No corrections have been made to reduce the NR errors at the time of experiment.

Thus, two main kinds of errors appeared most prominently: 1) random noise errors, varying from meteor to meteor and through the same meteor with errors not more than 0.5 ns. and mostly less, 2) NR errors caused by wind, stable on the length of meteor trace, but random from meteor to meteor, with errors about 0.3 ns.

II. Synchronization Technique and Equipment

A. Multiple Frequencies Phase Method

Transmission of relative time shift between distant clocks is based on the following method. Time marks are represented by packets of coherent, relatively narrow-band radio impulses, transmitted on several carrier frequencies. Time shift is calculated using the envelope positions of the received impulses and interrelation of their carrier wave initial phases. First and the least precise estimate of the time shift is made by envelope position of the received signal. This estimate is unambiguous and serves as a starting point of the following later phase ambiguity resolution procedure. Initial phases of carrier waves and their differences, corresponding to phases of fake differential frequencies, yield more precise, but ambiguous measurements. Higher differential frequencies increase measurement precision and decrease the phase ambiguity period. Several carrier frequencies enable step by step ambiguity resolution procedure that starts from the envelope position measurement, and proceeds from lower to higher differential frequency measurements. Reliable ambiguity resolution can be achieved if the ratio of differential frequencies does not exceed 4-5, so carrier frequencies must be chosen accordingly. The final step in the resolution procedure goes, if possible, from the highest differential to carrier frequency phase measurements.

The highest differential frequency must be about 10 MHz to achieve the required ratio. Such span between carrier frequencies can be hard to implement because it requires more complex equipment, making different transceivers obligatory for higher and lower carrier frequencies. Another problem of higher span that becomes the same level with the carrier frequencies is growing difference between propagation conditions of carrier waves.

It is desirable therefore to make the maximal differential frequency as low as possible and use filtration to help achieve the estimate that will enable safe ambiguity resolution of the carrier frequency phase. Thus, the weakest step in the ambiguity resolution procedure is going from the highest differential to carrier phase measurements.

From now on the ambiguity resolution on lower differential frequencies is considered safe, maximal differential frequency unambiguous, and the term *resolution* refers to carrier frequency phase ambiguity resolution.

B. Exclusion of Propagation Time

Exclusion of the unknown wave propagation time is based on two-way transmission of time marks. It is a modified for phase measurements version of the algorithm described in [4].

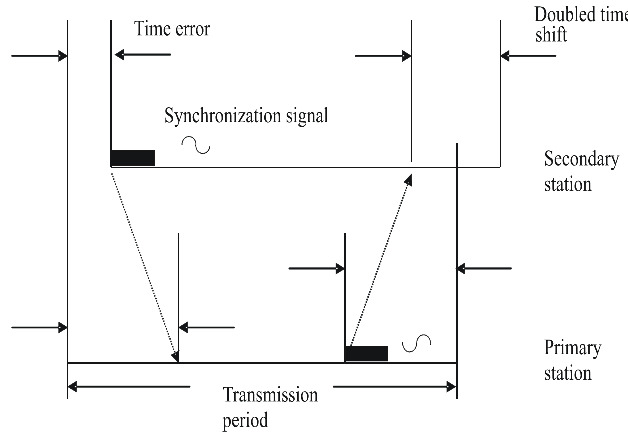

Fig 1. Two-way time transfer.

First, the secondary station transmits its time to the primary station using the appropriate meteor burst. The primary station calculates the time of the signal reception, then retransmits the signal, inverting its phase, the same amount of time ahead of the next mark. Phase inversion serves the same purpose as the beforehand signal retransmission. At the secondary station time between the received signal and the nearest time mark yields doubled relative time shift, initial phases of the signal are doubled accordingly.

Actual measurement of doubled time shift affects the phase ambiguity resolution problem, because the resulting ambiguity period becomes half of the corresponding frequency period.

C. Equipment Parameters

Experimental meteor synchronization and communication equipment sets Kama-5 and Kama-7 constructed in Kazan State University have never actually reached mass production. Nevertheless valuable experimental data achieved during several years of development that can be used for further increasing the equipment possibilities.

Basic equipment specifications of Kama-5 are the following [1].

1) The maximum range of signal transmission is 1500-1800 km.

2) Average power used does not exceed 500 Wt during transmission and 200 Wt in the waiting mode.

3) Bandwidth includes 4 channels, each 25 kHz wide with maximal span between channels 0.5 MHz.

4) Equipment affords time coordination between two distant clocks, with precision about 2-5 ns. for absolute and 0.3 ns. for relative time shift measurements. Coordination precision of 7 ns. is reached during 15 minutes of measurement accumulation. It can be further decreased to values about 2-2.5 ns. on intervals of 2-3 hours. Relative time shift between time scales is measured with precision of 0.5 ns. by carrier frequency measurements, if the relative time shift does not exceed 4-6 ns. on intervals between meteors.

The maximal carrier frequency span of 0.5 MHz makes the ratio of differential to carrier frequencies more than 100 and does not allow carrier frequency phase resolution by averaging measurements on one meteor trace.

For such measurements the equipment set Kama-7 has been constructed with additional carrier frequency spans of 2.5 and 10 MHz, but problems not related to meteor burst channel prevented organization of the experiments in the late 1990s.

D. Experimental Carrier Frequency Phase Measurements.

Potential synchronization precision is evident when carrier frequency measurements are used. Two sample carrier frequency measurements made during the experiment on Kama-5 are shown on Fig. 2 and Fig. 3. All four used frequencies are presented, in all cases the full ambiguity period does not exceed 18 nanoseconds.

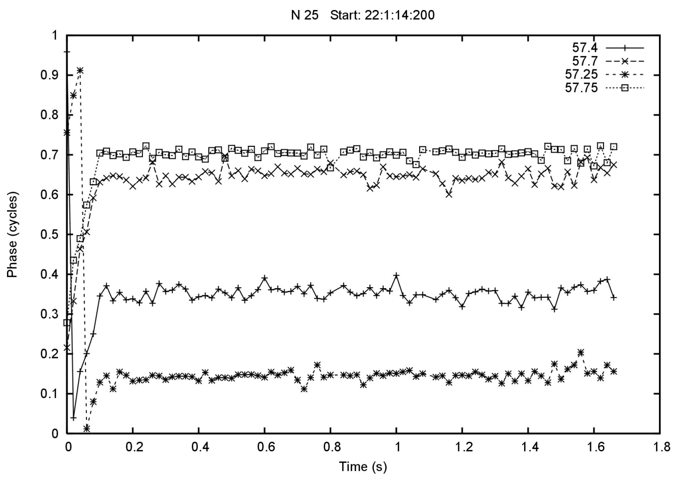

Fig 2. Sample carrier phase measurement.

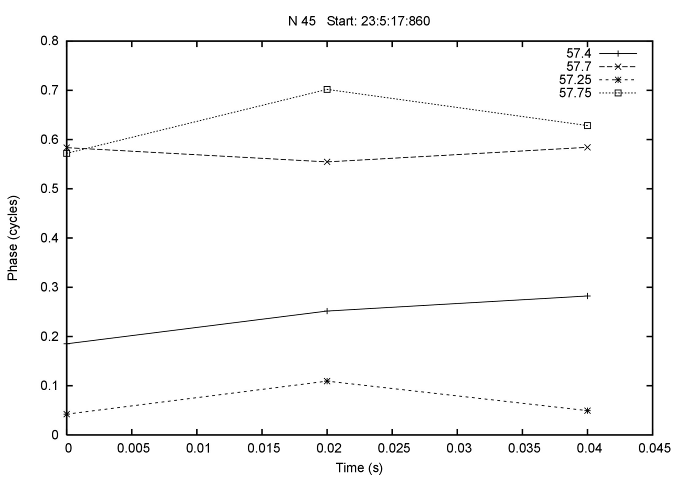

Fig 3. Sample carrier phase measurement.

III. Filtration of Measurements

Accumulation of differential frequency measurements until reliable resolution becomes possible does not always work because of short-term instability of frequency standards used. If the relative time shift on intervals between successive measurements does not exceed a fraction of carrier frequency ambiguity period, the short-term instability can be traced by carrier frequency and effectively excluded. But peculiarities of meteor burst channel, first of all its unsteadiness, hamper such procedure.

Achievement and maintaining the ambiguity of carrier frequency measurement requires smart filtration procedure that uses all information about process on every resolution step. The first thing we describe will be a model of measurements and underlying time shift properties.

A. Synchronization Procedure Model

A simple model of the synchronization procedure includes frequency standard and unsteady radio channel, providing measurements of doubled time difference described earlier.

In the experiment a cesium frequency standard has been used at the secondary station. Instability of widely used cesium standards is described by white gaussian frequency noise, parameters are known and can be found in specifications. In case of discrete measurements it can be represented as gaussian frequency errors with dispersion inversely proportional to intervals between measurements. We also suppose that instability remains constant on intervals less than one second.

Difference of time on distant clocks τ can be represented as

$$\tau(t) = \tau_0 + \frac{df}{f_0} + \int_0^t \rho \, dt \quad , \qquad (1)$$

where ρ is the relative frequency noise that describes the instability of frequency standard, τ_0 the initial time shift, f_0 the nominal frequency of the standard, df_0 the constant nominal frequency shift.

For discrete measurements in MB channel time difference model, suitable for optimal linear filtration [5] is

$$\begin{pmatrix} \tau \\ \frac{df}{f_0} \end{pmatrix}_{k+1} = \begin{pmatrix} 1 & dt_k \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \tau \\ \frac{df}{f_0} \end{pmatrix}_k + \begin{pmatrix} 0 & dt_k \\ 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} 0 \\ \gamma \end{pmatrix}_k , \quad (2)$$

where dt_k interval between measurements, γ normally distributed random variable that describes the current frequency standard instability on the interval dt_k.. Dispersion of γ can be presented as $N_0/2dt_k$, where $N_0/2$ characterizes the frequency standard.

Discrete measurements we represent as

$$Z_{k+1} = \begin{pmatrix} 2 & 0 \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \tau \\ \frac{df}{f_0} \end{pmatrix}_{k+1} + \begin{pmatrix} v_{2\tau} \\ v_\gamma \end{pmatrix}_{k+1} , \qquad (3)$$

where $v_{2\tau}$ is the current doubled time difference measurement, v_γ the current relative frequency shift measurement.

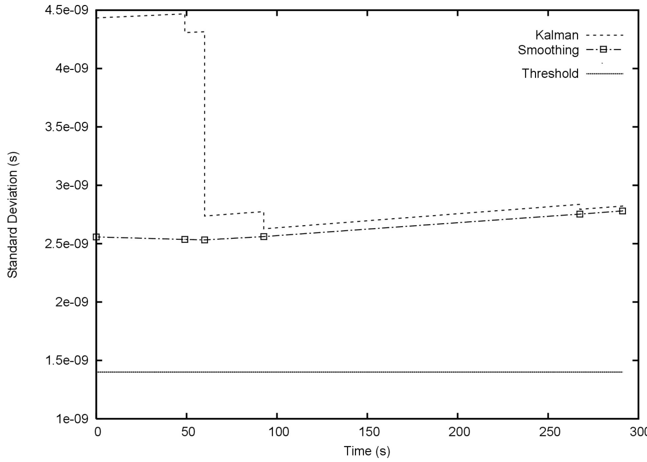

Fig. 4. Start of ambiguity resolution session.

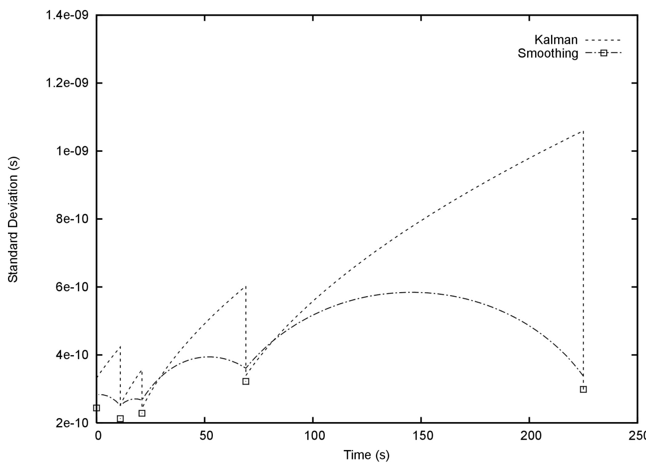

Fig. 5. Optimal estimates of the time difference after ambiguity resolution.

Current time difference measurement in our case is a phase measurement on maximal differential or carrier frequencies.

Measurements of the relative frequency shift are obtained indirectly if the current interval between meteors is short. Short intervals allow mutual phase resolution of two successive carrier frequency measurements and their difference is thus unambiguous. The difference divided by the interval gives current relative frequency shift. Any of the carrier frequencies not used for calculating the maximal differential frequency can yield an independent measurement.

B. Carrier Frequency Phase Ambiguity Resolution

Random noise errors that are relatively small on carrier frequency measurements become the main source of estimate error on differential frequencies.

Sample synchronization session starts with a period of accumulation, when differential frequency measurements gradually decrease the error of optimal estimate. When the smoothing filtration estimate gets low enough, carrier frequency ambiguity resolution takes place. Fig. 4 shows the optimal linear estimates at the start of ambiguity resolution session. Dispersions of single-meteor measurements needed for optimal filtration equations were taken from the results of the experiment. The chosen threshold makes ambiguity resolution error less than 0.001.

Accumulation of differential frequency measurements is effective only if it actually lowers the resulting estimate error. Whether smoothing estimate error decreases is dependent on measurement and estimated process (in our case the varying time difference between clocks) error ratio, as well as intervals between measurements.

For differential frequency chosen too low the estimate error can never reach the given threshold. Modeling of resolution procedure with parameters close to experimental allowed to pick the lowest differential frequency 2.5 MHz which makes resolution possible in 5-15 minutes on the average with probability of resolution error no more than 0.001. Further decreasing the maximal differential frequency quickly leads to inability of resolution however long the accumulation interval.

The resulting time coordination precision after carrier frequency ambiguity resolution is illustrated by time shift estimates on Fig. 5. Actual real-time ambiguity resolution is made by Kalman's estimate and possible only when the error of Kalman's estimate does not exceed the required threshold. When that happens accumulation of measurements starts again.

IV. Conclusion

Meteor burst channel can successfully be used for high precision time coordination between distant clocks. Experimental meteor synchronization and communication equipment constructed in Kazan State University showed the possibility of time transfer on distances up to 1800-2000 km. with precision of 0.3 ns. and better.

Relatively simple modernization of the existing equipment set makes real-time synchronization possible after only 5-15 minutes of initial phase measurement ambiguity resolution procedure. Modeling of the ambiguity resolution process using actual experimental data on phase measurements allowed choosing a possible span between carrier frequencies used, thus making complex equipment changes unnecessary.

Given description of the synchronization process allows estimation of synchronization errors and probability of losing the carrier frequency measurement ambiguity on the unsteady meteor burst channel.

Acknowledgment

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