TIME TRANSFER USING NEARLY SIMULTANEOUS RECEPTION TIMES OF A COMMON TRANSMISSION*

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Abstract

The concept of time transfer between two geographically separated locations by using nearly simultaneous reception times of a common transmission has been used very fruitfully, e.g., the TV line-10 time transfer system and Loran-C. This paper discusses some germane aspects of the concept and then considers using as some common transmissions a 30-Hz pulse-rate signal from the optical pulsar NP0532, the 60-Hz power-line signal, and the 3.58-MHz television color subcarrier signal.

The theoretical accuracy of each of these methods is discussed along with its coverage and the system feasibility. The day-to-day stability of the differential path delay of each of the above methods was measured or inferred to be ~ 13 μs, ~ 1 ms, and ~ 20 ns respectively.

Key Words (for information retrieval): Atomic clock, Frequency calibration, Frequency stability, Optical pulsars, Remote clock comparisons, Simultaneous reception, Time dissemination, Time stability, Time synchronization, Time transfer, TV color subcarrier, 60-Hz power line.

I. Introduction

Time synchronization or comparison of remote clocks is a common but often difficult to achieve need among the users of precise time signals. Many techniques have been developed and/or employed to satisfy the above need. This paper is an effort to suggest some alternate methods for comparing the readings of remote clocks via simultaneous reception times of signals from a transmitter common to both clocks. The methods studied were restricted also to those with attractive cost benefit ratios. See references [1] through [16].

II. Time Comparison via a Common Transmitter

Figure 1 illustrates this method of remote clock comparison in which time transfer or synchronization is accomplished by receiving signals at A and B at nearly the same time from a transmitter common to both receivers. In many cases clocks A and B are much more stable and accurate than the transmitter clock; nevertheless the transmitted signal as received can be used as a time transfer device. Under certain assumptions the instabilities of the transmitter and the propagation medium to first order contribute neither to the imprecision nor to the inaccuracy of the time transfer system.

As a more detailed analysis, suppose that at a time t_X an identifiable signal, e.g., a pulse or a zero-crossing of a sinusoid, is emitted from the transmitter illustrated in Fig. 1. Let τ_{XA} and τ_{XB} be the propagation and equipment delay times from the transmitter to the time interval counters at A and B respectively. If the readings of clocks A and B are t_A and t_B respectively, then the difference in the readings of the time interval counters will be:

$$[t_A - (t_X - \tau_{XA})] - [t_B - (t_X - \tau_{XB})] = t_A - t_B + \tau_D, \quad (1)$$

where τ_D is the differential propagation delay, $\tau_{XA} - \tau_{XB}$. If τ_D is calculable, then obviously the time difference between clock A and clock B can be accurately determined within the uncertainty of the calculated differential delay. If τ_D is not calculable, then it needs to be measured; e.g., with a portable clock. The stability of τ_D in either case will determine an upper limit for the precision with which the time difference $t_A - t_B$ can be measured by this system. If the propagation and equipment delay paths are similar, the differential delay τ_D may be extremely stable; e.g., for TV timing stabilities of several nanoseconds over several seconds have been achieved within a given transmitter locale [17].

Note that in this simple case the time of emission of the identifiable signal cancels in equation (1). However, in general, the identifiable signal will be repetitive, and A and B can receive events with different transmission times. All that needs to be added to equation (1) is the transmitter emission time difference, Δt_X, of the different events received, which can often be inferred from the repetitive nature of the signal assuming the ambiguity can be resolved. In some cases ambiguity resolution may be difficult [15]. Measuring different events usually places very minimal constraints on the transmitter's stability and accuracy. That is, if δt represents the precision or accuracy desired of the time transfer system, then the stability or accuracy, respectively, of the transmitter need only be better than $\delta t / \Delta t_X$. For example, if time transfer is desired to a precision or accuracy of 1 μs, then Δt_X can be several hundred seconds and still require only 1 part in 10^9 stability or accuracy, respectively, of the transmitted signal.

There are several important time transfer users employing this near-synchronous reception mode. The International Atomic Time Scale, IAT (BIH), maintained at the Bureau International de l'Heure, employs Loran-C and television signals in this time transfer mode, and achieves precisions of a few tenths of a microsecond between seven international laboratories utilized in the scale [18]. The standard time and frequency radio station WWV is synchronized with respect to the atomic time scale UTC(NBS) to a precision of about 30 ns using the TV line-10 time transfer system developed by the National Bureau of Standards [19]. Some satellite systems employ this mode for time transfer, and long baseline interferometry indirectly employs this mode as data are cross-correlated with impressive precisions in the picosecond region [20]. This paper is an effort to partially explore the capabilities of pulsar signals, 60-Hz power-line signals, and television color subcarrier signals (3.58 MHz), when used in the above time transfer mode.

III. Optical Pulsar Signal as Common Transmitter

A schematic diagram of a pulsar reception system is shown in Fig. 2. The signal averager determines the time interval between the arrival time of the pulsar signal and the local clock. This is accomplished by amplifying the pulsar signal in the photo-tube, then averaging several thousand of the pulses to improve the signal-to-noise ratio. The period of the Crab NP0532 pulsar signal is 33.107 ms, and the pulse width is about 2 ms. The rate of sampling in the signal averager as determined by the frequency synthesizer may be set from an extrapolation of previous pulsar data [21]. One of the present models for the slowing down of this pulsar signal is a "least-squares cubic fit (four parameters) to the phase as a function of time" [22]. Extrapolations based on such models allow longer averaging times to be better utilized in the signal averager except, however, when the pulsar signal makes an occasional jump in rate [23].

The cost of the equipment involved will be determined in large measure by the cost of the telescope, the size of which directly affects the signal-to-noise ratio and typically ranges from 24 inches to 36 inches (~ 60 to 90 cm). There are other less expensive ways of having a large receiver area such as the J. E. Faller multi-lensed receiver telescope [24]. Very inexpensive photo-tubes can be obtained, but $1,000 invested here is very well spent. The signal averager employed at Lawrence Radiation Laboratory (LRL) cost about $10,000 and the frequency synthesizer about $6,000 [21]. Reference clocks that are fully adequate for the job can be purchased for about $8,000 to $20,000.

A resolution of the pulsar signal to about 2 μs is believed achievable [21], [25] with about a 2-hour sampling time and a telescope of about 24-inch (61-cm) diameter. It is further believed that the precisions involved in determining the pulsar signal arrival time are primarily given by the statistics associated with particle (photon) detection and counting, and hence can be characterized as white noise process; therefore, the uncertainty of the arrival time will be inversely proportional to the square root of the sampling interval. The total increase in delay due to the earth's atmosphere is only of the order of 10 nanoseconds, hence the differential delay associated with the atmosphere is totally negligible, as well as calculable assuming the pulsar signal is a plane wave as it arrives at the earth. The accuracy limitation for the differential time delay τ_D due to the spinning earth is also of minor consequence, i.e., one can know earth position (given by the UT1 time scale) to better than 5 ms; this corresponds to an uncertainty on τ_D of less than 8 ns. It is apparent that the reception equipment and the very weak pulsar signal are by far the largest contributors in the uncertainties of τ_D.

The data analyzed in this paper were made available through the kind cooperation of Jerry Nelson and John Middleditch of LRL and are similar to the data published in reference [22]. The data analyzed gave the reception times at LRL and at Harvard University of the pulses from NP0532 (the Crab pulsar). The primary concern of these observers is to study the pulsar's behavior by measuring in an absolute sense the arrival times of the pulsar signals. Such a measurement requires reduction of the data to arrival times at the solar system barycenter by use of an accurate ephemeris for the earth--a non-trivial problem. Difficulties quickly arose when trying to compare the data of one observatory to another because each had a unique fourth-order polynomial to model the pulsar's behavior and a unique assumed best ephemeris for the earth's position. The assumption that the pulsar signal is a plane wave, which is a good one at the 1-μs uncertainty level regardless of where the earth is in its orbit, allows one to avoid these difficulties. Nelson and Middleditch supplied us with a data listing which used the Harvard polynomial fit and the LRL ephemeris for reducing the data as received at both observatories. Even then there appeared to be some difference in the method of properly identifying when the pulse occurred [22].

In order to evaluate the capability of the pulsar time transfer system, we attempted to remove any bias due to the difference in method of pulse identification by taking the difference in the pulsar arrival times, Harvard minus LRL, on those nights when both made observations, as follows:

$$T_H(t) - T_L(t') \simeq \Delta T(t), \tag{2}$$

where t and t′ denote the local clock readings at Harvard and LRL respectively. The LRL measurements were usually taken 3 to 4 hours later than the Harvard measurements. Equation (2) assumes that both occurred at the same time, t. This assumption requires that the instabilities of the pulsar not be significant over this interval. This is probably a good assumption [25]. The local clocks at both sites were referenced to the same very stable time scale via a clock at Hewlett-Packard in Santa Clara, California, and the Loran-C navigation chain on the East Coast.

In order to get an idea of the stability characteristics of the differential data, consider the following quantity:

$$\frac{\Delta T(t + \tau) - \Delta T(t)}{\tau} = \frac{\delta\nu}{\nu} \tag{3}$$

where τ is the time interval between nights when the pulsar signal was commonly observed. Plotted in Fig. 3 are the absolute values of these differential fractional frequency deviations for all possible combinations of the $\Delta T(t)$. The dashed line in Fig. 3 is obviously an approximate model for the data and implies a precision capability of about 13 μs. The slope of the dashed line is consistent with the assumption stated earlier that the uncertainty in the reception time is given by the statistics of particle (photon) counting--white noise. If will be noticed that the triangles have a very high density above the line, and one will note that these points are reduced from data belonging to two different sequences--the implication is that something was changed that affected the biases after the first sequence and before the second sequence.

The analysis of the time difference or the comparison of data between two laboratories could be simplified considerably by correcting only for sidereal time, then afterward ascertaining the polynomial model for the pulsar signal and reference frame transfer to the solar system's barycenter. Also, there is some indication that a uniform method of determining the arrival time of the pulsar signal would be worthwhile. Perhaps the present differences in pulsar arrival time determination rest in equipment changes or in differences in equipment.

The pulsar time transfer system has the apparent potential for accurate time transfer on a global basis to within about 2 μs. The LRL group achieves uncertainties of this order on a regular basis [21]. The currently measured time transfer precision is about 13 μs. The drawbacks in this time transfer system are that measurements can only be made at night and cannot be made at all during the last part of May, all of June, and the first part of July. Cloud cover could also be a problem. The signal strength of the source at the earth and the expense of the receiver system to overcome the problem are the significant considerations, since it appears that the precision and the accuracy of the proposed pulsar time transfer system are primarily limited in these areas. Overall the optical pulsar time transfer system seems to be feasible and worthy of being given further consideration because of the high accuracy and precision potentially achievable as weighed against the investment in development and equipment costs.

IV. Power-Line (60-Hz) Signal as Common Transmission

The thesis of this section is that the 60-Hz power-line grid in the USA is basically a phase coherent system; i.e., in the effort to transfer power from one area to another and to deliver power efficiently to the user the phase difference between any two points should remain fairly constant.

We first analyzed the fractional frequency stability of the power-line signal as received in Boulder, Colorado. Figure 4 is a plot of this stability using the square root of an Allan variance as defined in [27], [28] versus the sample time τ. This particular stability measure will be used frequently throughout the remainder of this text and is denoted by $\sigma_y(\tau)$. The stability points plotted may be nominally classified as a flicker noise frequency modulation process [27], [28] with a range of τ from 17 ms to 10^4 s, and at a level of about 5×10^{-5}. The common transmitter stability is adequate in this case to do submillisecond time comparisons of remote clocks if the measurements are made within about one second of each other. The stability was measured at different dates and essentially the same results were obtained as in Fig. 4.

The phase of the 60-Hz power-line signal was recorded over the weekend of 12-15 May 1972 relative to atomic clocks at the Hewlett-Packard (HP) laboratory in Santa Clara, California, and at the NBS laboratory in Boulder, Colorado. The data appeared to correlate to well within one cycle (16.67 ms) of the signal with rare deviations of the order of a cycle. A plot of a section of this data is shown in Fig. 5. The strong phase coherence is obvious.

Next a study was made of the differential delay, τ_D, between Boulder and Santa Clara by measuring the zero-crossings of the 60-Hz signal that immediately followed the same second's tick on each of the above atomic clocks, and then taking the difference in these measures. The stability of τ_D was observed for a variety of sample times. The instabilities in τ_D were converted to fractional frequency fluctuations, and a plot of the stability of these is shown in Fig. 6. Achieving 1 part in 10^8 at τ = 1 day makes this 60-Hz time transfer mode extremely competitive with WWV insofar as the stability of the propagation media is concerned.

The stability for longer times was also studied over the above path as well as between the atomic clocks at the WWV transmitter site near Fort Collins, Colorado, and at NBS Boulder, Colorado. This was accomplished, similarly, by measuring the occurrence time of the next zero-crossing of the 60-Hz signal after the date 16:30:00 UTC as determined by each of the atomic clocks at each of the three locations. The results of these data are plotted in Fig. 7 after the differences in the measures were taken to estimate τ_D over the two paths. The actual path lengths are not known but are estimated as being less than 3200 km (2000 miles) and less than 160 km (100 miles) respectively. Also, the actual transmitter source point(s) is (are) not known; hence, τ_D is only known modulo one cycle (16.67 ms). However, from data in Fig. 7 one could suggest that once a particular path was calibrated two remote clocks using this 60-Hz time transfer mode could be kept synchronous to within about 1 ms over fairly large portions of the power-line grid.

Maintaining synchronization assumes that no cycle slippage occurs between the different areas involved. Hewlett-Packard/Santa Clara and Colorado are in "Electronic Power Supply Areas" VIII and VI respectively [29]. A test was conducted to determine if cycle slippage was occurring between the three locations cited above by building dividers to generate a precise 1 pulse per second (pps) from the 60-Hz signal. These dividers were placed at each location and as long as the power was continuously available we detected no cycle slippage over several-day intervals. Occasionally the dividers would jump some cycles due to 60-Hz power-line transients. Low-pass filters were used to suppress this problem.

If the occurrence times of the zero-crossings of the 60-Hz signal with respect to a standard clock could be made continuously available, then a clock at a remote site could be continuously updated to be synchronous with the standard clock. We have not been able to conceive of an inexpensive way of providing these occurrence times. One of the attractions of the 60-Hz time transfer mode is its impressive cost benefit ratio; i.e., the receiver can be built for about $10 (a low-pass filter and a transformer).

The fractional frequency stability of the data plotted in Fig. 7 was also analyzed, and these stability results are shown in Figs. 8 and 9 for the WWV-NBS path and the HP-NBS path, respectively. Note that the WWV-NBS path stability was about 6 times better than the HP-NBS path stability. One may infer that the stability degrades nominally as the distance, which would imply a stability of a few milliseconds across the continent. Being able to compare the frequencies of remote standards at the 1 part in 10^{10} level for a few dollars receiver investment cost makes this 60-Hz time transfer mode additionally worthy for consideration in many applications. The 16.67 ms cycle ambiguity could probably be resolved in most parts of the USA by use of the WWV audio telephone signal, (303) 499-7111.

V. TV Color Subcarrier Signal (3.58 MHz) as Common Transmitter

Figure 10 is a plot of the impressive fractional frequency stability $\langle\sigma_y^2(N, T, \tau, f_h)\rangle^{\frac{1}{2}}$ [27], [28], of the television color subcarrier signal as received at NBS Boulder, Colorado, from one of the TV studios in New York City. The frequency of the color subcarrier is 63/88 of 5 MHz denoted ν_c, and the 5-MHz frequency is derived from a rubidium gas cell frequency standard at the studio. In contrast to the 60-Hz method where it would take many days to get a frequency calibration to within a part in 10^{10}, it would only take about 10 seconds to accomplish the same thing using the ν_c signal. For this reason NBS publishes monthly the frequencies, as measured in Boulder, of the rubidium gas cell frequency standards of the three network studios for which live telecasts are available in Boulder, Colorado [30].

The fractional frequency stability of ν_c was studied for longer sample times, for different networks, and at different times of the day. The range of these stability results is plotted in Fig. 11, and is a reasonable extension of the results plotted in Fig. 10. An effort was made to study the differential delay τ_D of ν_c by use of the atomic clock at Boulder and the atomic clock at WWV as the remote site, but unresolved noise problems thwarted the experiment--possibly due to the high intensity radiation fields at the WWV site. Though the stability of the differential delay τ_D of ν_c as received at two remote sites may not be much better than the data plotted in Fig. 10 and Fig. 11, it should not be any worse. The implication from these data is that the potential exists to keep two clocks remotely located synchronized to about 1 ns once calibrated if they have mutual access to the same ν_c signal. In practice the signal probably needs to be line-of-sight from a common transmitter to both clock locations to achieve this potential.

Some of the problems generally encountered are as follows: 1) Live color TV is not continuously available; 2) phase jumps occur with commercials and with changes in studio cameras and in peripheral equipment; 3) as color adjustments are made at the studio, at the local TV station, or in your own receiver, phase shifts will be introduced in ν_c; and 4) the cycle ambiguity of ν_c (about 279 ns) is difficult to resolve.

On the positive side if the above problems could be resolved the cost benefit ratio is extremely desirable. If the measurements were made at the same time each day (same studio and network configuration) the first three problems listed above would be partially or effectively solved. The 279 ns ambiguity problem may be solvable by observing its relationship to a particular horizontal or vertical synchronization pulse occurring at nearly the same date. The ambiguity of the vertical interval is 33.366 ... ms and is easily resolved in many ways. A study was conducted of the phase relationship between the zero-crossing of ν_c and the line-10 horizontal synchronization pulse over several days and the results are plotted in Fig. 12. These results give some hope that the cycle ambiguity in ν_c could be resolved. There is a need for an experiment involving remote atomic clocks to finally test the idea.

Time transfer using ν_c or the common transmitter requires a fair degree of sophistication on the part of the user. However, the cost benefit ratio is very impressive and may make it worth the effort. If the proposed NBS active TV time code becomes a reality [31], [32], most aspects of time transfer via ν_c would become redundant, and user ease highly favors the active code.

VI. Conclusion

We have partially explored the capabilities of three novel common transmitters as may be used in the above time transfer mode. 1) The optical transmissions from the Crab pulsar NP0532 may be utilized to transfer time via the above mode on a global basis with a theoretical accuracy of a few microseconds. The measured time stability of the differential delay between the east and west coast of the USA was 13 μs. The anticipated receiver cost is about 20 to 30 thousand dollars provided a suitable telescope is available. 2) The 60-Hz power-line system--even though it has very poor phase stability--has an impressive differential delay stability. The stability of the differential delay of this coherent power-line grid was measured to be in the submillisecond region in the western section of the USA. The receiver cost is about ten dollars. 3) The TV color subcarrier signal (3.57954 ... MHz) appears to have stabilities in the nanosecond region over thousands of miles with, however, some difficulty in removing the cycle ambiguity. The receiver cost is the price of a color TV set, a few hundred dollars.

The cost benefit ratio of all three of the above proposed systems makes them very competitive and worthy of serious consideration for utilization in the field of time and frequency dissemination.

An exotic time and frequency dissemination system of the future may employ in part the above time transfer mode with a potential of nanosecond precision and nanosecond accuracy of date transfer. Such a system might employ a belt of three geostationary satellites around the globe. Each satellite may have an rf communications transponder and triggerable pulsed laser irradiating the earth. Using trilateration with a grid of synchronous ground station clocks the position of the satellite could be determined to a few centimeters, and thence communicated along with the dates of occurrence of the laser's pulses to the appropriate receiving equipment. A laser signal seems desirable because of available bandwidth, accurately calculable path delay, and some comparative cost considerations.

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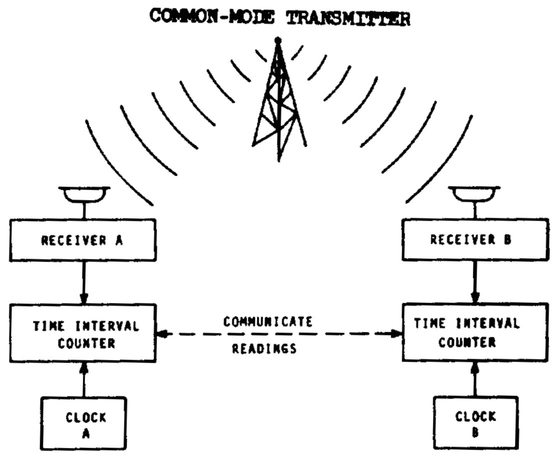

Fig. 1 Illustration of the concept of precise time transfer using nearly simultaneous reception time of signals from a common transmitter.

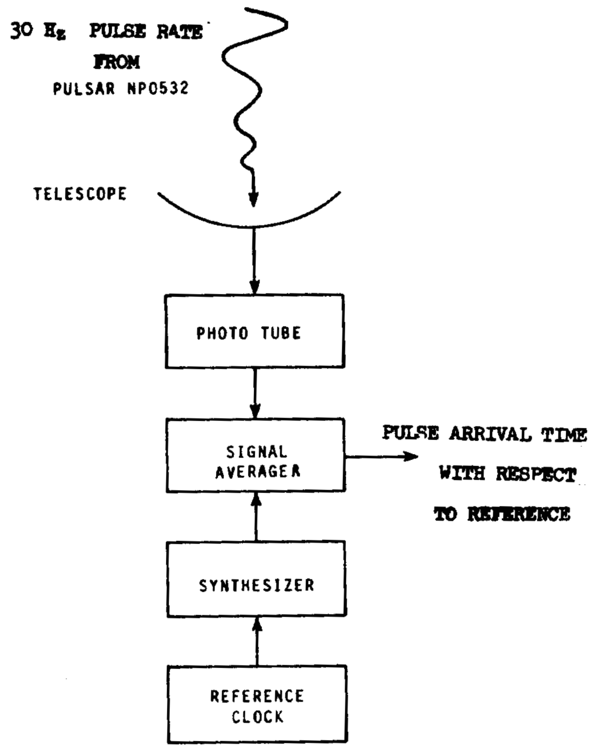

Fig. 2 Schematic of pulsar reception system. The synthesizer causes the signal averager to scan the incoming signal from the photo-tube at an estimated pulsar rate.

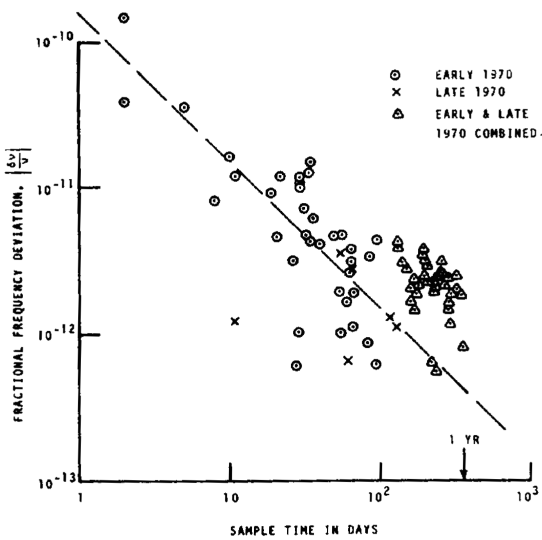

Fig. 3 The differential fractional frequency between the clocks at the Harvard and the Lawrence Radiation Laboratory's observatories as deduced from the arrival time at both observatories of the optical pulsar signal NP0532. The dashed line implies an rms time error of about 13 μs and the slope is inversely proportional to the sample time--consistent with the assumption that the reception times are perturbed by a white noise.

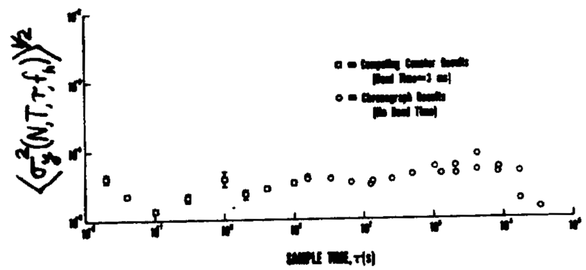

Fig. 4 Fractional frequency stability as a function of sample time of the 60-Hz power line measured at Boulder, Colorado. The vertical scale is the square root of an Allan variance with N = 2, T = τ for the circles, T - τ ~ 3 ms for the squares, and a system bandwidth f_h of about 30 Hz.

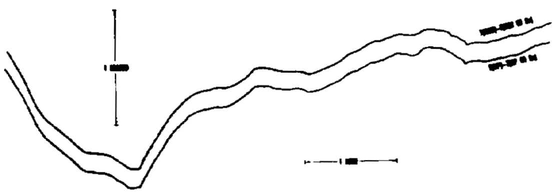

Fig. 5 A plot showing the detailed similarity of the time fluctuations of 60-Hz (power-line) clocks at NBS/Boulder, Colorado, and HP/Santa Clara, California. The 60-Hz clock at each site was compared with a local atomic clock.

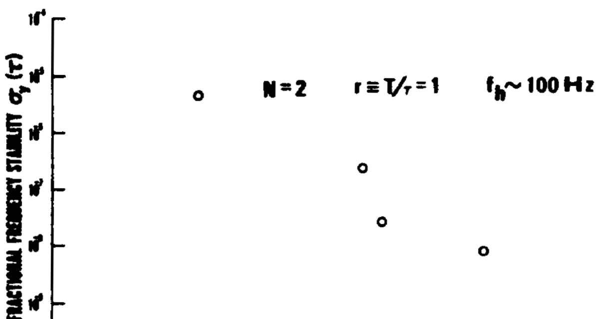

Fig. 6 Fractional frequency stability as a function of sample time of the differential delay of the 60-Hz power line between Boulder, Colorado, and Santa Clara, California.

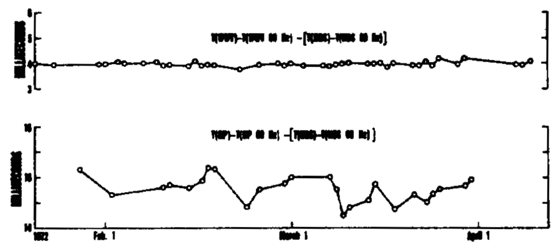

Fig. 7 Time fluctuations of the differential delay, τ_D, of the 60-Hz power-line signal. The upper plot shows the delay (modulo one cycle) between a 60-Hz clock at the WWV station near Fort Collins, Colorado, and a 60-Hz clock at the NBS laboratory at Boulder, Colorado.

The lower plot shows the delay (modulo one cycle) between a 60-Hz clock at the HP laboratory in Santa Clara, California, and the one at NBS Boulder, Colorado.

At each measuring site the 60-Hz clock was compared with a local atomic clock.

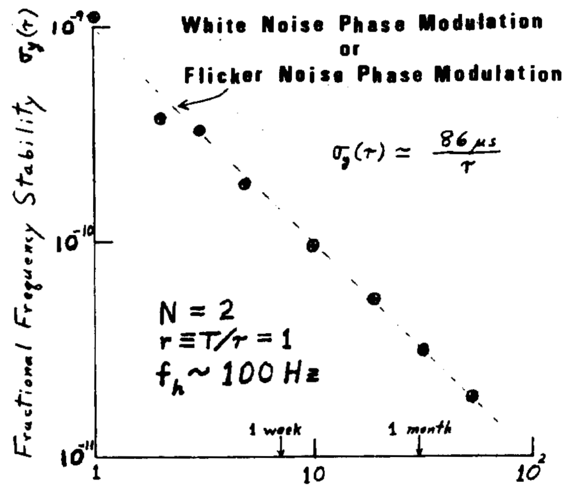

Fig. 8 Fractional frequency stability as a function of sample time of the differential delay of the 60-Hz power line between Boulder, Colorado, and Fort Collins, Colorado.

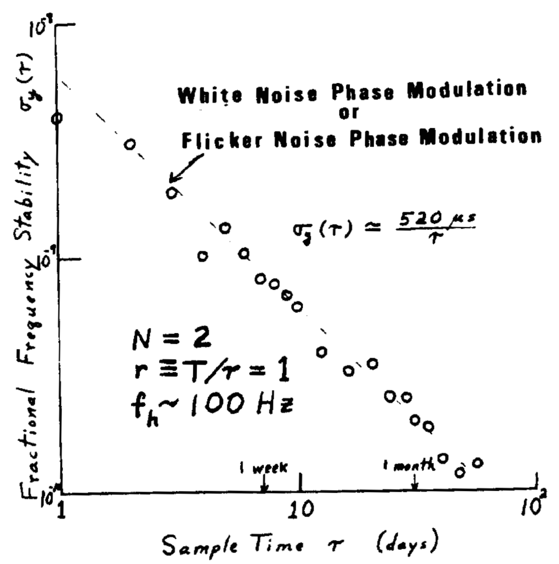

Fig. 9 Fractional frequency stability as a function of sample time of the differential delay of the 60-Hz power line between Boulder, Colorado, and Santa Clara, California.

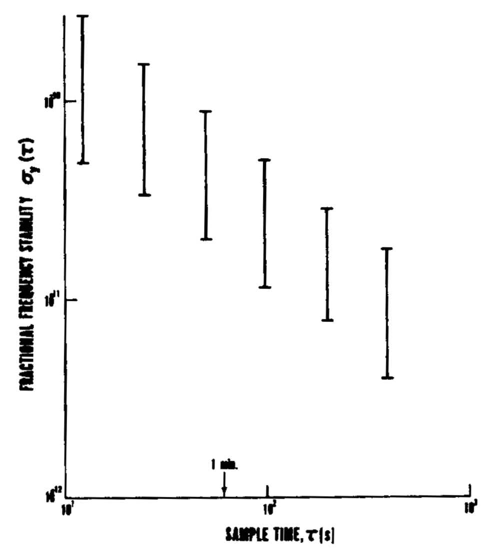

Fig. 11 Range of fractional frequency stabilities of the TV color subcarrier signals as received in Boulder, Colorado, from all of the network studios in New York City, New York, and which were available at Boulder.

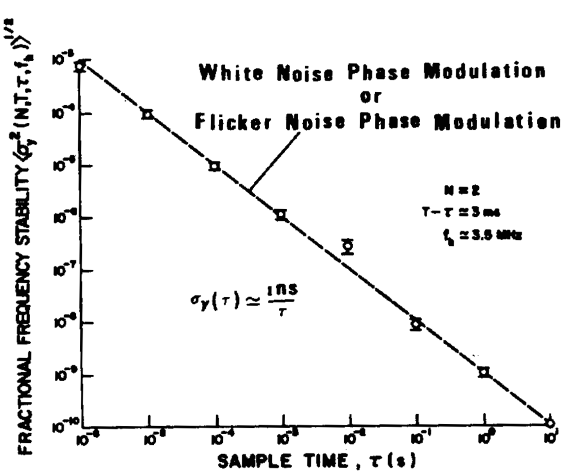

Fig. 10 Fractional frequency stability of the TV color subcarrier signal as received in Boulder, Colorado, from a network studio in New York City, New York.

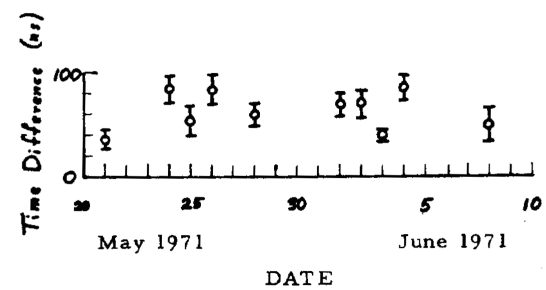

Fig. 12 A plot showing the nominal day by day fluctuations of the time difference between the occurrence of a TV line-10 horizontal synchronization pulse and the next zero-crossing of the color sub-carrier signal from a live network telecast.