PRECISION AND ACCURACY OF REMOTE SYNCHRONIZATION VIA PORTABLE CLOCKS, LORAN C, AND NETWORK TELEVISION BROADCASTS*

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Summary

A comparison among three precise timing centers in the United States has been conducted for more than one year using three different synchronization methods. The timing centers involved were the United States Naval Observatory (USNO) in Washington, D. C., Newark Air Force Station (NAFS) in Newark, Ohio, and the National Bureau of Standards (NBS) in Boulder, Colorado. The three methods were cesium beam portable clocks; Loran-C transmissions from Cape Fear, North Carolina, and Dana, Indiana; and ABC, CBS, and NBC network television broadcasts common to the three timing centers.

Cesium beam portable clocks have the capability of accurately and precisely synchronizing remote clocks to within 0.1 μs. This portable clock method, which appears to be one of the most accurate currently available, is used for comparison purposes.

The Loran-C data involved a 3500 km (2180 miles) ground wave path--the longest Loran-C ground wave path that has been studied with the precision and accuracy reported herein. The long-term precision achieved via Loran-C between the three remote precise timing centers was better than 2 μs. The accuracy is limited by the 10 μs ambiguity involved in identifying the proper cycle of the 100-kHz pulse train.

The precision of maintaining remote clock synchronization using network television broadcasts was measured to be $[30 \text{ ns day}^{-1/2}]\, T^{1/2}$ over the range of T from 7 days to about 200 days, but with definite accuracy limitations caused by such factors as occasional network re-routing of the television signals.

An upper limit of the long-term frequency stabilities among the references used at the three timing centers were measured or inferred. Typically the reference at each center was composed of an ensemble of cesium beam frequency standards. The relative stabilities measured for sample times of the order of three months were a few parts in 10^{14}.

Key Words: Cesium beam standards, Frequency standards, Loran-C, Portable clocks, Time synchronization, TV timing.

Introduction

Time and frequency dissemination via television has received much attention during the past four years. Even though some very impressive results have already been obtained using television,[1-6] it seems still to be a pioneer field. In this paper we compare television with two other state-of-the-art methods of time and frequency dissemination--Loran-C and portable clocks--and evaluate some precision and accuracy capabilities of each.

The television method is readily available, very inexpensive, and within the majority of the continental United States it is a common source for many users. Loran-C, being well established and well known for its precision and accuracy,[7,8] has been chosen to compare with the television system. Portable clocks are used as a reference because of their precision and accuracy for remote synchronization--one of the best techniques yet available.[9] The portable clocks referred to in this paper are principally those of the United States Naval Observatory (USNO). We will exclude many other interesting areas such as VLF and satellite, as these have already been covered in some detail.[10-12]

There are three fundamental aspects of time which can be disseminated via these methods. The first is time interval which can be related to frequency--frequency being the inverse period of an oscillation. The second aspect is that of date or clock reading which has often been called epoch. We prefer the use of the word date because epoch has alternate meanings that could lead to confusion. Often we have a master clock, and we wish to communicate its date or time by some technique to a slave station located elsewhere. The third aspect is simultaneity--the practical application of which is clock synchronization, i. e., two clocks have the same reading in some frame of reference.

In principle, if we had perfect clocks, we could synchronize them once and they would remain synchronized forever. There are two basic reasons in practice why the synchronization does not persist. First of all, systematic problems such as frequency drift, frequency offset, and environmental effects on equipment often cause time dispersion. These must be analyzed and solved at each particular location. Secondly, there are different kinds of noise, or what we might call non-deterministic kinds of processes, that affect these time and frequency centers or communication systems. These processes are perhaps a little better classified and more universally present than some systematic effects. We will discuss and apply some useful statistical measures for the time and frequency dispersion of the dissemination systems in question.

Most of the data analyzed in this paper were taken by other people, and we wish to acknowledge the fine work and careful data taking and reporting of the personnel at the Bureau International de l'Heure (BIH), the Neuchâtel Observatory (ON), the U. S. Naval Observatory (USNO), and the Newark Air Force Station (NAFS), as well as of the personnel in addition to the authors at the National Bureau of Standards (NBS).

Methods of Analysis

It is often the case that data are taken at a constant repetition rate with a period of sampling, T; and each data point is an average over a time τ called the sample time. Let the total number of data points taken in a continual data set be M. Further, for every measurement system there is a high frequency cut-off usually called the measurement system bandwidth, f_B, such that noise at frequencies greater than f_B will be attenuated and non-relevant. In the past it has been common practice to compute the standard deviation as a statistical measure of such a data set:

$$\sigma_{\text{std.dev.}} \equiv \left\{ \frac{1}{M-1} \left[\sum_{i=1}^{M} (z_i - \bar{z})^2 \right] \right\}^{1/2}, \qquad (1)$$

where z_i denotes the i^{th} data point and $\bar{z}$ denotes the average of all M of the z_i. For most of the noise processes that are pertinent in time and frequency, it has been shown that $\sigma_{\text{std. dev.}}$ depends upon M, T, τ and f_B,[13-15] and all of these parameters should be noted for each experiment. We have found it convenient to use the Allan variance:[13-15]

$$\sigma^2 \equiv \langle \sigma^2 (N, T, \tau, f_B) \rangle, \qquad (2)$$

where the angle brackets denote the expectation value. If N = M, then eq (2) is exactly the expectation value of the squared standard deviation.

For many pertinent noise processes, we have found that a power law spectral density is a good model, i. e.,

$$S_y(f) = \underline{A} f^{\alpha}, \qquad (3)$$

where f is the Fourier frequency and $\underline{A}$ is the intensity of the noise process. Throughout this paper y denotes the fractional frequency deviations, x denotes the time deviations, and so y is proportional to the derivative of x. Further, it has been shown that if N, f_B, and the ratio $r = T/\tau$ are held constant, then σ_y^2 is equal to $\underline{a}\tau^{\mu}$ with

$$\mu = \begin{cases} -\alpha - 1 & -3 < \alpha \le 1 \\ -2 & \alpha > 1 \end{cases}, \qquad (4)$$

and with $|\tau f_B|^{|\alpha - 1|} \gg 1$.[10,13] For a more detailed explanation of the N, T, and τ dependence, the relationship between μ and α, and the relationship between the frequency domain and time domain coefficients, $\underline{A}$ and $\underline{a}$, see Refs. 14 and 15.

A very useful time domain measure of frequency stability, which has been recommended by the IEEE subcommittee on frequency stability,[14] is defined as follows:

$$\sigma_y(\tau) \equiv \langle \sigma_y^2 (N = 2, T = \tau, \tau, f_B) \rangle^{1/2}. \qquad (5)$$

This measure has some very convenient experimental and theoretical characteristics. For example, with M values of $\bar{y}_i$ an estimate of $\sigma_y(\tau)$ is:

$$\sigma_y(\tau) = \left[\frac{1}{2(M-1)} \sum_{i=1}^{M-1} (\bar{y}_{i+1} - \bar{y}_i)^2 \right]^{1/2}, \qquad (6)$$

where

$$\bar{y}_i = \frac{x_{i+1} - x_i}{\tau} \qquad (7)$$

and the interval between each discrete time measurement x_i is τ. Also once $\sigma_y(\tau)$ has been calculated, the time dispersion may be estimated by simply calculating the product $\sigma_x(\tau) \equiv \tau \cdot \sigma_y(\tau)$.[14] This estimate is good for white noise FM but is approximately a factor of 1.3 too optimistic for flicker noise FM and is approximately a factor of 1.7 too pessimistic for flicker noise PM with respect to an optimum prediction routine.[16]

An operational measure of time dispersion is $\langle \sigma_x^2(2, T, \tau, f_B) \rangle$. This has the nice physical interpretation that it is a measure of the time dispersion at a time T after synchronization. The sample time τ in this case is usually constrained by the measurement system to be $1/(2\pi f_B)$, and this measure has a smaller range of convergence, i. e., $\alpha > -1$ unless properly normalized (see bias function B_2 in Ref. 15).

The above statistical measures will be used to calculate the precision for the data used in this paper. From these analyses we will draw some conclusions regarding the relative precision of the three time and frequency dissemination techniques herein discussed, i. e., network television, Loran-C, and portable clocks. Accuracy, on the other hand, may be defined as follows: for frequency it is the confidence with which a frequency is known with respect to the currently defined resonance in cesium 133; and for time it is the confidence with which a date is known with respect to a reference time scale such as UTC(BIH).

Time and Frequency Stability of Network TV

Description of TV Line-10 Timing System

After the work of Tolman and others,[1-5] the TV line-10 system was developed by NBS as a passive means of comparing precision clocks, remotely located but periodically tied to common broadcasts from an originating network.[6] An overview of the system is shown in Fig. 1. These broadcasts originate from the New York City studios of any or all of the three commercial TV networks (ABC, CBS, and NBC). The originating networks incorporate independent atomic frequency standards (rubidium) to stabilize their transmissions. The New York signals, broadcast without auxiliary time coding, traverse varied and long paths at microwave frequencies. This relay system is a chain of broadband radio links encompassing the continental United States at line-of-sight distances of some 40 to 60 km between repeaters. The microwave relay system carrying over 95% of the U. S. intercity television programs is known as the TD-2 system.[17] At a terminating station, such as an affiliate local transmitter, the microwave signal from the applicable repeater station is converted to a video signal and re-transmitted by VHF or UHF (commercial TV) to a local service area. Reception points of such broadcasts for our data were the U. S. Naval Observatory (USNO), Washington, D. C.; Newark Air Force Station (NAFS), Newark, Ohio; and the National Bureau of Standards (NBS), Boulder, Colorado.

This version of TV timing uses line-10 of the odd field in the 525-line system M as a passive transfer pulse.[3,6] This pulse occurs during the blanking retrace interval between successive fields; line-10 was chosen for timing as it is the first horizontal sync pulse following the equalizing and vertical sync pulses and therefore is easy to identify with simple logic circuits. Figure 2 shows a typical equipment alignment for line-10 synchronization. Almost any type of television receiver, black and white or color, is suitable for reception of the signals used for timing. The auxiliary equipment required can cover a broad range of specifications, but typically would include a line-10 synchronized pulse generator (available at a cost of about $165), a digital counter-printer (about 0.1 μs resolution), and a clock whose frequency is known to an accuracy of a few parts in 10^9 and which has an output of 1 pulse per second (1 pps). A functional block diagram of the line-10 identification circuitry is shown in Fig. 3.

The timing system employed to collect the data used in this paper works as follows: At the same date, to an accuracy which is much better than the 17 ms needed, counters are started at all laboratories with a 1 pps tick from their local reference atomic clocks. Near this time a line-10 horizontal sync pulse is broadcast from one of the New York City originating TV transmitters. After diverse delays through both common and separate microwave links, the sync pulse--received by the laboratories at different times due to the delay and clock differences--stops the corresponding counters. The difference, then between each pair of counter readings at any two receiving laboratories, remains constant except for instabilities in the propagation delay and/or instabilities or relative frequency offsets among the reference atomic clocks.

Similarly, any laboratory can compare their clocks to the UTC(USNO) and UTC(NBS) scales through a duplicate reception-recording system once their clock has been set to within 17 ms of either of the above, and the propagation path has been calibrated. (As the period of one modular TV frame is about 33 ms, it is necessary to resolve ambiguity at the receiving site to about 17 ms.) NBS distributes the line-10 daily measurements in terms of UTC(NBS) in the Monthly NBS Time Service Bulletin.[18] The USNO distributes line-10 data in terms of UTC(USNO-MC) in the weekly Series 4 Time Services Bulletin.[19] These publications will publish future changes, modifications to the TV system, or other factors affecting a user in the field.

Advantages of line-10 timing include 1) simplicity and minimum cost of comparison equipment; 2) low cost of maintaining synchronization with long range precision of better than 10 μs; 3) no effect on regular TV networks and with no external cost to user; 4) three TV networks with atomic clock references provide redundancy and backup data in case one TV channel shows a microwave reroute; and 5) a method for simultaneous maintenance of μs synchronization of several clocks diversely located within the service area of a common transmitter, without regard to national programming. These advantages must be tempered by such factors as 1) microwave paths can be interrupted without notice; 2) there is limited simultaneous viewing time of nationwide network programs; 3) present network distribution does not allow common programming with west coast transmission lines, although local synchronization from a common transmitter can be effected; 4) system is not compatible with tape delayed programs; and 5) the system ambiguity is 33 ms. (Note that time-of-day is "ambiguous" to one day.)

Stability of the USNO, NBS TV Path

The TV paths being considered are from two to four thousand kilometers in length. The particular problem mentioned above of an occasional TV network re-route will cause an effective change in the delay. So it is highly advantageous to use all three networks so that such a change can readily be identified. Conveniently, we do have three networks so that outliers and delay changes are easily recognized. During the analysis period studied, which was from 25 June 1969 to 30 December 1970, there were only about two network delay changes per year per network, so it is not a serious inconvenience. The television time measurements using the line-10 method were made at 2025 UT, 2026UT, and 2027 UT (one hour earlier during Daylight Savings Time) on NBC, CBS, and ABC, respectively and nominally every work day at each of the three laboratories.

Figure 4 is a plot of the fractional frequency stability, $\sigma_y(\tau)$ versus the sample time τ in days for the TV paths between Washington, D. C. and Boulder, Colorado, for each of the three networks (this assumes the reference time scales are negligible). An ensemble of commercial cesium beam frequency standards and dividers to generate atomic time (AT) were used at each location as the 1 pps time reference, i. e., AT(USNO-MEAN) and AT(NBS).[20-23] The dashed line in Fig. 4 corresponds to flicker noise phase modulation and appears to be a reasonable model for the fluctuations between Washington, D. C., and Boulder, Colorado. Calculating the time dispersion, $\sigma_x(\tau)$ for the dotted line gives the following equation:[14]

$$\sigma_x(\tau) = 62 \text{ ns} [6 + 3 \log_e(2\pi \tau f_B) - \log_e 2]^{1/2}, \quad (8)$$

where τ is in seconds; f_B for a color TV is about 3.2 MHz.

The fractional frequency difference, y, between AT(USNO-MEAN) and AT(NBS) calculated over the period of analysis was:

$$\frac{\nu_{AT(USNO-MEAN)} - \nu_{AT(NBS)}}{\nu_{AT(NBS)}} = \begin{cases} 4.48 \times 10^{-13} \text{ via ABC} \\ 4.43 \times 10^{-13} \text{ via CBS} \\ 4.56 \times 10^{-13} \text{ via NBC.} \end{cases} \quad (9)$$

The precision of these measurements is about $\pm 3 \times 10^{-14}$ as may be seen from the stability measured at τ = 224 days.

Since there are three essentially independent networks, they can be combined optimally by weighting each one inversely proportional to its variance. We chose the variance at τ = 7 days, since it has the best confidence, to calculate the weights of 0.52, 0.38, and 0.10 for ABC, CBS, and NBC, respectively. This is optimum in the sense of giving a minimum variance, and it should be noted that these coefficients need to be calculated for each pair of receiving laboratories or effectively for each TV path. The squares in Fig. 4 represent the stability using this optimum weighting procedure. The squares in Fig. 5 show the time fluctuations of the weighted three network TV data between USNO and NBS as measured each Wednesday. Each of these points represents a 40s average. A one second measurement gives almost as good precision, but the averaging allows one to recognize outliers. The interval between the measured line-10 horizontal sync pulses is 1.001s and hence there is a walk between a standard 1 pps and the line-10 pulse of 1 ms per second (modulo 33 ms). This is easily accounted for in the counter printer system shown in Fig. 2.

TV and Cesium Beam Stability at NAFS

The same line-10 TV network method was employed as outlined above at Newark Air Force Station (NAFS) in Newark, Ohio. Their time reference was a commercial cesium beam frequency standard and clock. Both USNO and NBS data were used to study the path stability between Washington, D. C., and Newark, Ohio, and between Boulder, Colorado, and Newark, Ohio, over the periods from 24 September 1969 to 16 December 1970 and from 17 September 1969 to 30 December 1970 respectively.

Figure 6 shows the fractional frequency stability $\sigma_y(\tau)$ for both paths using all three TV networks optimally weighted. The squares are the stability for the USNO, NAFS TV path with weights of 0.36, 0.57, 0.07 for ABC, CBS, and NBC respectively. The circles are the stability for the NBS, NAFS TV path with weights of 0.29, 0.36, and 0.35 for ABC, CBS, and NBC respectively.

The slope indicated by $\alpha = 0$ is probably the noise of the TV line-10 time transfer system, but the type of noise is unexpected, i. e., white frequency FM or random walk of phase noise. Calculating $\sigma_x(\tau) = \tau\sigma_y(\tau)$ gives:

$$\sigma_x(\tau) = (0.13 \text{ } \mu\text{s day}^{-1/2}) \tau^{1/2} \quad (10)$$

where τ is in days. An explanation of this random walk of phase noise could be some step changes in the delay for which there was no accounting.

Note that the stability gets worse for τ larger than 100 days with a maximum at τ equal to about 1/2 year for both the squares and the circles. This part of the stability plot is probably due to a seasonal or annual effect on the time reference cesium standard at NAFS.

Wiener Filtering of TV Data

In Fig. 6 the dashed line representative of $\alpha = 0$ (white noise FM) appears to be a good model for the instabilities in the TV data over the two paths mentioned above. If one can assume that the dashed line representative of $\alpha = -2$ (random walk of frequency noise) is a good noise model for the cesium beam reference standard, then it has been shown that a Wiener filter may be applied to the data.[11, 24] Assuming that the $\alpha = 0$ process is noise and the $\alpha = -2$ process is signal, i. e., we wish to have a best estimate of the behavior of the cesium reference as observed through the noise of the TV line-10 time transfer system, then the filter takes on a very simple form, i. e., an exponential. We mean by best estimate a minimum mean squared error for the signal $\langle[\hat{s}(t) - s(t)]^2\rangle$ where s(t) is the true behavior of the cesium beam reference standard and $\hat{s}(t)$ is the Wiener filtered estimate.

The models for the noise and signal are:

$$S_{y(\text{noise})}(f) = A f^0, \quad (11)$$

and

$$S_{y(\text{signal})}(f) = B f^{-2} \quad (12)$$

respectively, and the form of the Wiener filter for the discrete case is as follows:

$$\hat{x}_i = \frac{\sum_{j=-\infty}^{i} x_j e^{-\frac{i-j}{\xi}}}{\sum_{j=-\infty}^{i} e^{-\frac{i-j}{\xi}}}, \quad (13)$$

where

$$\xi = \frac{1}{2\pi}\sqrt{\frac{A}{B}} \qquad (14)$$

and ξ is normalized to the same units as i and j, i.e., days, weeks, etc. A convenient recursive filter that approximates eq (13) is:

$$\hat{x}_i = \frac{1}{\xi+1}[x_i + \xi\, \hat{x}_{i-1}]. \qquad (15)$$

For the signal and noise processes given by eqs 11 and 12, using Ref. 14, ξ takes on the value

$$\xi = \frac{1}{\sqrt{3}}\, \tau_I , \qquad (16)$$

where τ_I is the value of τ corresponding to the intercept of the dashed lines in Fig. 6. For these particular data sets, ξ had values of 7 weeks and 9-1/4 weeks for the Washington, D. C. to Newark, Ohio, and the Boulder, Colorado to Newark, Ohio, paths respectively.

The dots in Fig. 7 are the weighted three network values measured each Wednesday for each of the above two paths. The solid lines are the result of an application on these data of the Wiener filter given by eq 13 with the sum being taken over about 1-1/2 time constants, i.e., the past 10 and 14 values respectively for the above two paths. Note the slope of one part in 10^{13} and the strong correlation between the two paths both before and after filtering.

Time Dispersion of Optimum Processed TV Data

Taking the difference between the two solid lines in Fig. 7 gives us a filtered estimate of time fluctuations between AT(USNO-MEAN) and AT(NBS). If we now apply a Wiener filter to the TV line-10 data plotted in Fig. 5, we have a direct path filtered estimate of the same fluctuations. Taking the difference between these two estimates leaves as a residual the filtered noise of the TV line-10 time transfer system and the associated measurement equipment. This residual is plotted in Fig. 8. Note, the data fall within a very sensitive vertical range of ± 1 μs. The Wiener filter applied to the USNO, NBS path[11] assumes that the instabilities of the TV line-10 time transfer system are characterized by flicker noise PM($\alpha = 1$, see Fig. 4), and that the signal, AT(USNO-MEAN) - AT(NBS), is limited by flicker noise FM($\alpha = -1$) at a level for $\sigma_y(\tau)$ of about 1×10^{-13}. The latter assumption, though inconsistent with the 3×10^{-14} value of $\sigma_y(\tau)$ from Fig. 4, was based on two reasons: first, frequency changes of this order have been observed between the two scales (see Fig. 5, November, 1970); and second, the filter has a similar time constant to the other two paths.

When the data in Fig. 8 are analyzed using the time dispersion measure previously discussed, we get the results shown in Fig. 9. The white noise FM model represented by the dashed line seems to be a reasonable model at a level of:

$$\sigma_x(2, T, \tau, f_B) = (30\,\text{ns day}^{-1/2})T^{1/2}, \qquad (17)$$

with T having a range from 7 days to about 200 days.

For comparison we analyzed the same data to determine $\sigma_x(\tau) \equiv \tau\, \sigma_y(\tau)$:

$$\sigma_x(\tau) = (46\,\text{ns day}^{-1/2})\tau^{-1/2}, \qquad (18)$$

where τ is in days. Using Refs. 14 and 15, the theoretical ratio of $\sigma_x(\tau)$ to $\sigma_x(2, T, \tau, f_B)$ may be calculated for white noise FM as equal to $\sqrt{2} = 1.414$, whereas the experimental value from eqs (17) and (18) is 1.5. For either equation the dispersion is less than 1 μs after one year.

Time and Frequency Stability of Loran-C

Stability of USNO, NBS Loran-C Path

The circles in Fig. 5 represent the time difference fluctuations AT(NBS) - AT(USNO-MEAN) via a 3,500 km Loran-C path going from Cape Fear, North Carolina, to USNO and to Dana, Indiana, and from Dana, Indiana, to Boulder, Colorado. Dana, Indiana is phase controlled to within 0.2 μs with respect to Cape Fear using as the phase reference point Warner Robins AFB in Georgia.[26] The circles represent the Loran-C measurements as made every fifth day. The triangles are the USNO portable clock trips between USNO and NBS with a reported accuracy of date transferral of 0.1 μs.[19]

The circles in Fig. 10 are the fractional frequency stability, $\sigma_y(\tau)$ for the Loran-C data plotted in Fig. 5. The circles in Fig. 11 are an estimate of the time dispersion, $\sigma_x(\tau) \equiv \tau\, \sigma_y(\tau)$ for the same data. The squares in Fig. 11 are the same estimate of time dispersion for the TV line-10 data shown in Fig. 5.

Stability of European and Atlantic Loran-C Paths

Some data were made available at the courtesy of the Neuchâtel Observatory (ON) using Loran-C to compare two commercial cesium standards located at ON each against UTC(BIH) and UTC(USNO). Given a set of measurements between three independent standards, the stability of each may be estimated.

Using this approach, while realizing that part of the Loran-C path is common to the two ON cesium standards, an estimate of $\sigma_y(\tau)$ was made for the USNO, ON path across the North Atlantic and to Neuchâtel, Switzerland, represented by the pluses (+) in Fig. 10. Similarly an estimate of $\sigma_y(\tau)$ was made for the BIH, ON Loran-C path and are represented by the triangles (Δ) in Fig. 10. It is interesting that the much longer Atlantic Loran-C path from USNO to ON is more stable than the USNO, NBS continental Loran-C path.

Loran-C and TV Stability via BIH

The BIH maintains the International Atomic Time Scale IAT(BIH). This scale is based on a weighted set of the atomic time scales of the major laboratories of the world which keep such scales and which have a date communication link to the BIH via Loran-C or TV.

Using the data published by the BIH in Circular-D, we performed a stability analysis of the time scale data for these major laboratories versus the BIH. The four most stable time reference laboratories were chosen in order to see the instabilities in the Loran-C system and the results are plotted in Fig. 12. It should be noted that IAT(BIH) is dependent upon each of the contributing time scales, hence the stabilities shown are nominally optimistically biased.

The atomic time scale of the Physikalisch-Technische Bundesanstalt (PTB) is communicated to the BIH via European TV and Loran-C from Braunschweig, Federal Republic of Germany, to Paris, France. The Royal Greewich Observatory (RGO) is in Herstmonceux, England.

It is interesting to note the comparable stabilities of the four laboratories even though they are located at greatly different distances over the earth. The white noise FM is typical of cesium beam frequency standards but for much smaller τ values and at much lower levels. This noise is apparently nominally representative of the Loran-C and TV instabilities as observed at the BIH except for the NBS data which is more nearly represented by flicker noise PM. The white noise FM again implies step changes in delay for which there is no accounting.

Time Accuracy of TV Line-10, Loran-C, and Cesium Portable Clocks

The ordinate shown in Fig. 5 for the TV line-10 system, for the Loran-C, and for the portable clocks is arbitrary since over these paths only the portable clocks have accurate date transferral capabilities. For the paths being considered both the TV line-10 system and Loran-C need a path delay calibration in order to maintain sub-microsecond synchronization. Loran-C delays can often be calculated to better than 1 μs for areas within ground-wave coverage. For the TV line-10 system the path delay may be readily calculated to within about 1 μs only when both receiving points are line-of-sight to the same TV transmitter. On the other hand, the cycle ambiguity for Loran-C can be 10 μs whereas it is only 33 ms for the TV line-10 system. This means that the cycle ambiguity could be removed very easily on the TV line-10 system using WWV whereas the 10 μs ambiguity of Loran-C can be more difficult to remove.

Figure 11 shows the time dispersion characteristics for cesium beam portable clocks presently available. Note that the dispersion degrades to be that of either TV or Loran-C for τ values of a few weeks. For portable clocks τ may be interpreted as the time since the last date calibration. It is obvious for this and other reasons that portable clock trips should be made quickly for the best accuracy in date communication.

Short-Term Frequency Stability of TV, Loran-C, and Portable Clocks

It is often desirable to have available a reference standard frequency for calibrating the frequency of a clock, or of a frequency counter, etc. In color television broadcasting, a color "subcarrier" of 63/88·5 MHz (3.58 ... MHz) is transmitted on the VHF or UHF signal. It is used as a reference signal in the color television receiver to demodulate the chrominance sidebands. Since the major U. S. networks generate the color subcarrier with rubidium frequency standards, this color subcarrier may be used as a reference standard frequency. Frequency stability measurements of the color subcarriers of all three major U. S. networks (originating in New York) have been made at the NBS laboratories in Boulder.[24] In most cases it appears that the overall measurements system is capable of resolving the 3.58 ... MHz time (phase) differences to less than 10 nanoseconds. This corresponds to determination of frequency difference of about one part in 10^{11} in 17 minutes. NBS designed instrumentation both to synthesize the output of a 1 or 5 MHz local frequency standard to 3.58 ... MHz and to compare phases of the local synthesized signals to the received subcarrier frequency. A plot of the stability of some of the best data received in Boulder, Colorado, are represented by the squares marked CBS in Fig. 13. Typically the stability was a factor of two or three times worse than this. The Dana, Indiana Loran-C stability as monitored in Boulder, Colorado, is represented by the circles, and the portable clock stability by the triangles.

It is interesting to compare the relative stabilities (precision) of the three methods for a sample time, τ, of about 200 s. The values of $\sigma_y(\tau)$ are about 10^{-10}, 10^{-11}, 4×10^{-12} for Loran-C, TV color subcarrier, and cesium portable frequency standard, respectively. The TV color subcarrier provides a very inexpensive and precise method for frequency calibration. The accuracy of a measurement in all three cases is limited by the accuracy of the reference standard employed as well as by the precision of the measurement. To improve the usefulness of the TV color subcarrier method it would be an easy matter for NBS to publish daily measurements of the absolute frequencies of the three networks' rubidium gas cells.

Figure 13 also shows for comparison purposes the previous data discussed comparing AT(USNO-MEAN) and AT(NBS) via Loran-C and via TV line-10 time transfer system. The circles at the right are the stabilities via Loran-C and the squares at the right are the stabilities via line-10 TV.

Conclusions

The three network TV line-10 systems properly filtered may be used in a large majority of the United States to keep clocks synchronized to within an rms precision of:

$$\sigma_x(\tau) = (46 \text{ ns day}^{-1/2})\,\tau^{-1/2} \qquad (19)$$

with τ at least in the range from 7 days to about 200 days. The clocks are assumed to have been synchronized previously. The TV color subcarrier may be used as a frequency reference with a precision capability of:

$$\sigma_y(\tau) = (3.5 \times 10^{-10}\ s^{2/3})\ \tau^{-2/3} \qquad (20)$$

where τ has at least the range of values from $10s \le \tau \le 200s$.

The long-term fractional frequency stability of Loran-C and the three network TV line-10 systems are comparable with the Loran-C stability at a level of about:

$$\sigma_y(\tau) = (1.9 \times 10^{-12}\ \mathrm{day}^{2/3})\ \tau^{-2/3} \qquad (21)$$

where τ has at least the range from 1 day $\le \tau \le$ 200 days Both systems provided precision capabilities of a few parts in 10^{14} for sample times of one-half year and longer and with rms time dispersions of less than 1 μs after one year.

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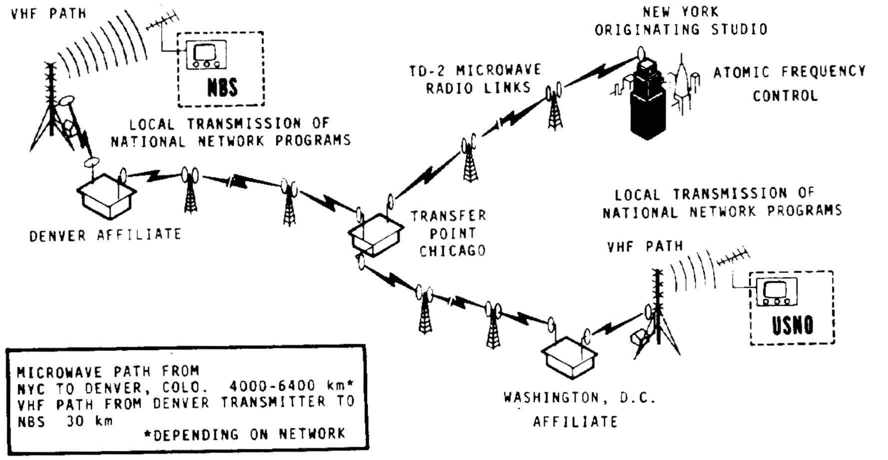
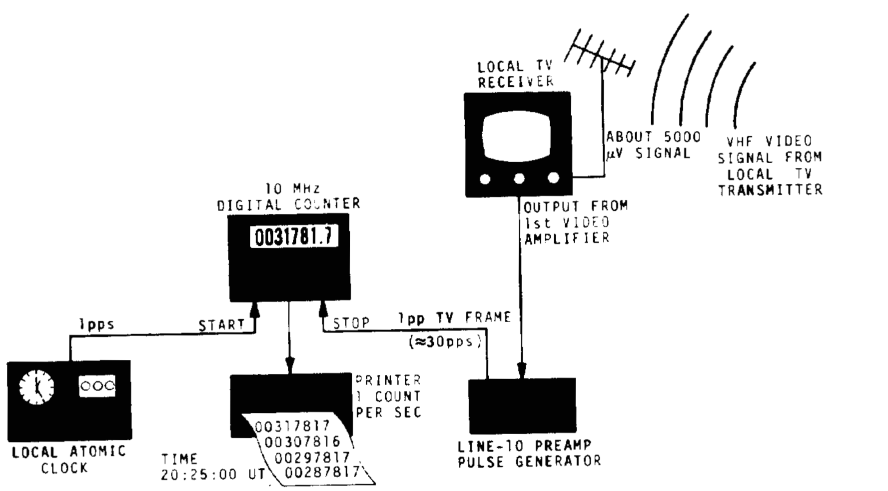




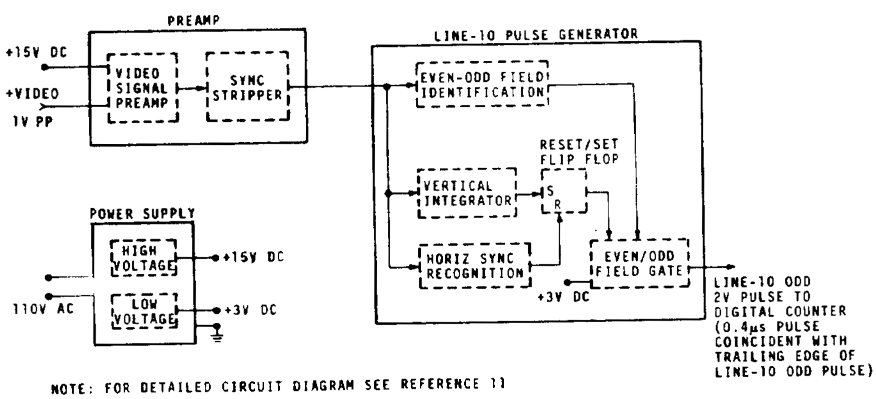


Fig. 3 - Functional block diagram of TV line-10 identification circuitry

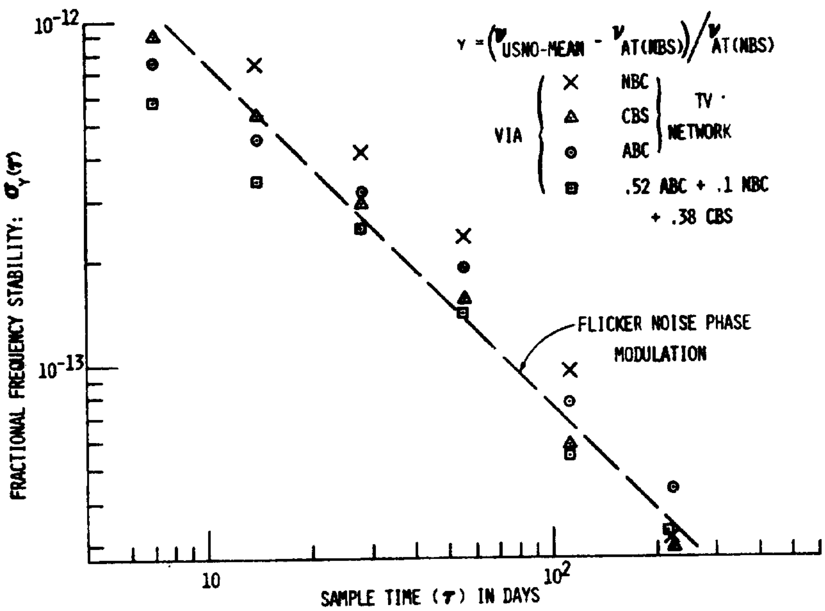


Fig. 4 - Fractional frequency stability, $\sigma_y(\tau)$, of the AT(USNO-Mean) - At (NBS) time scales compared by the 3-network TV line-10 technique.

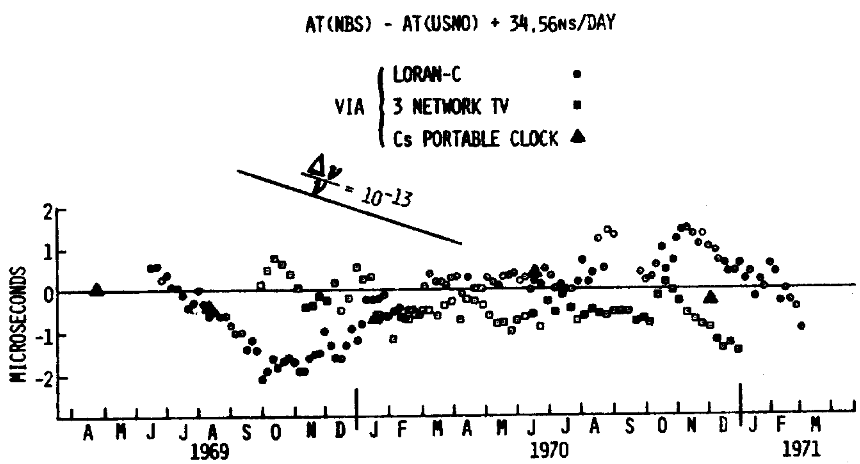
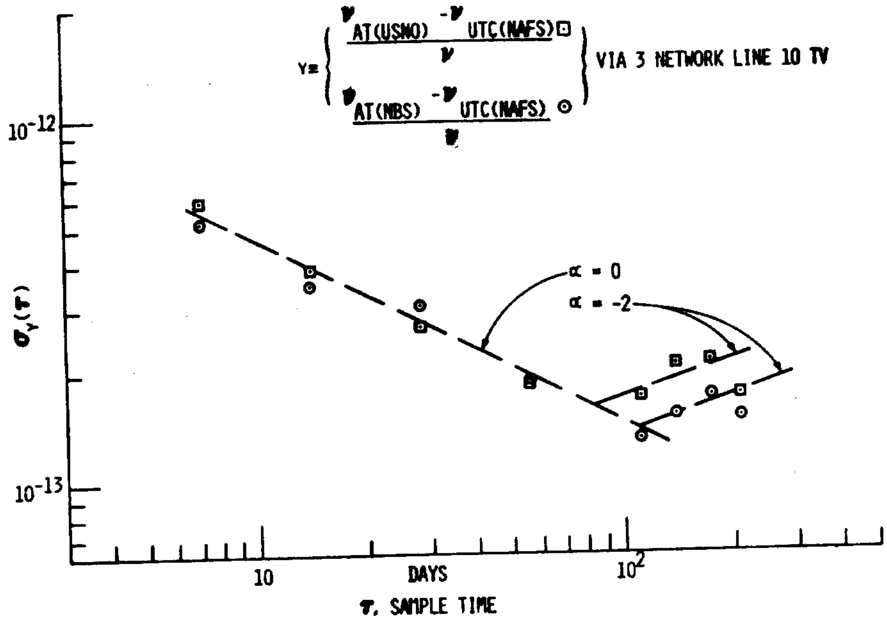


Fig. 5 - Relative time fluctuations of the AT(NBS) - AT(USNO-Mean) time scales compared by the Loran-C, 3-network TV line-10, and cesium portable clock technique.



Fig, 6 - Fractional frequency stability, $\sigma_Y(\tau)$, or the Boulder-Newark and the Washington, D.C.-Newark paths via the 3-network TV line-10 technique.

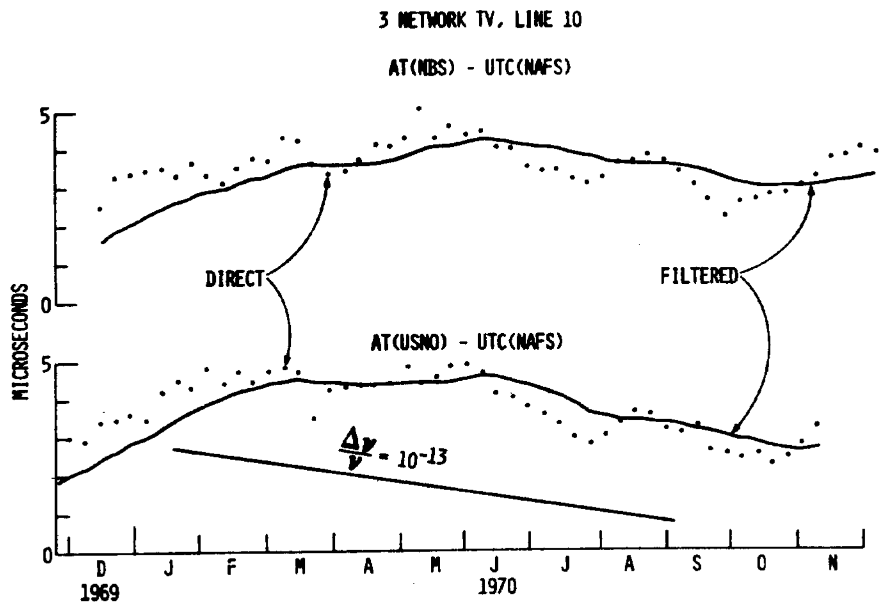
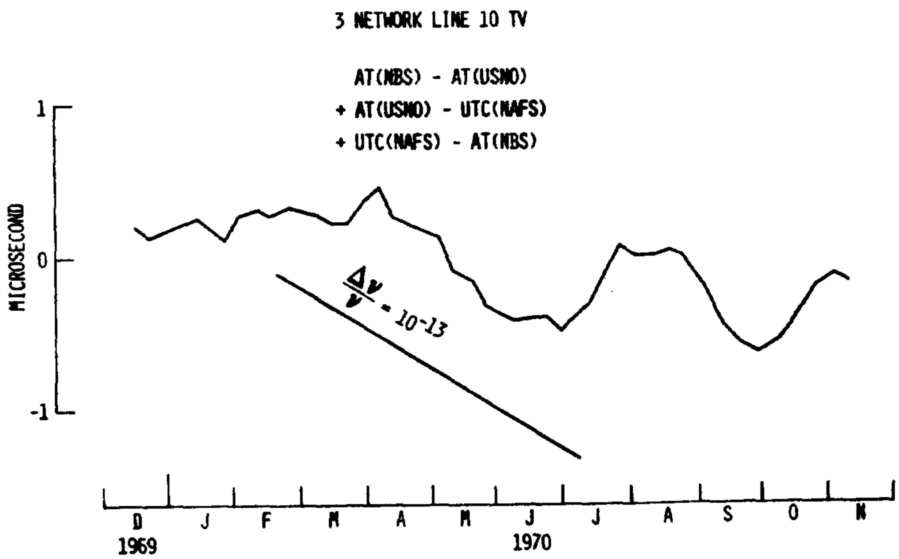


Fig. 7 - Time fluctuations (direct and filtered) of the Boulder-Newark and the Washington, D.C.-Newark paths via the 3-network TV line-10 technique



Fig, 8 - Residual time fluctuations of the 3-network TV line-10 technique between Boulder, Newark, and Washington, D.C.

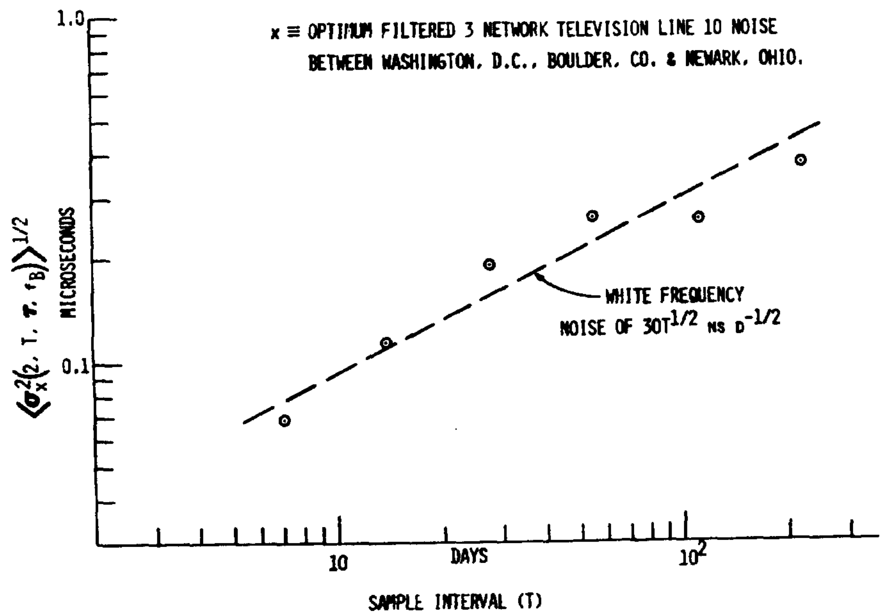


Fig. 9 - The rms time error versus sample interval of the filtered 3-network line-10 noise between Washington, D.C., Boulder, Colorado, and Newark, Ohio.

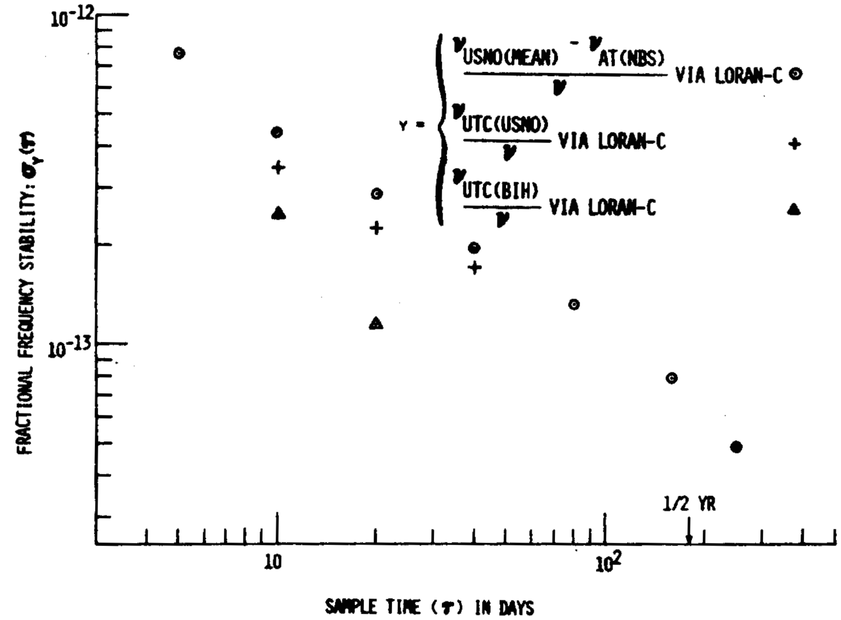


Fig. 10 - Apparent Loran-C stability: over continental U.S. path denoted by the circles; over North Atlantic path denoted by pluses; and as received at ON and BIH denoted by the triangles.

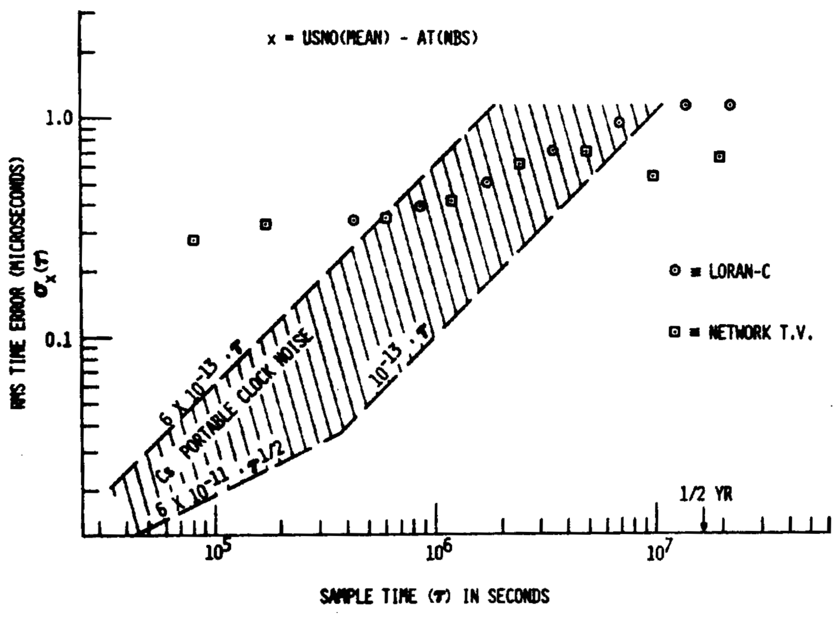


Fig. 11 - Estimation of the rms time dispersion versus sample time for Loran-C 3-network TV line-10, and cesium portable clock techniques with USNO and NBS as the time references.

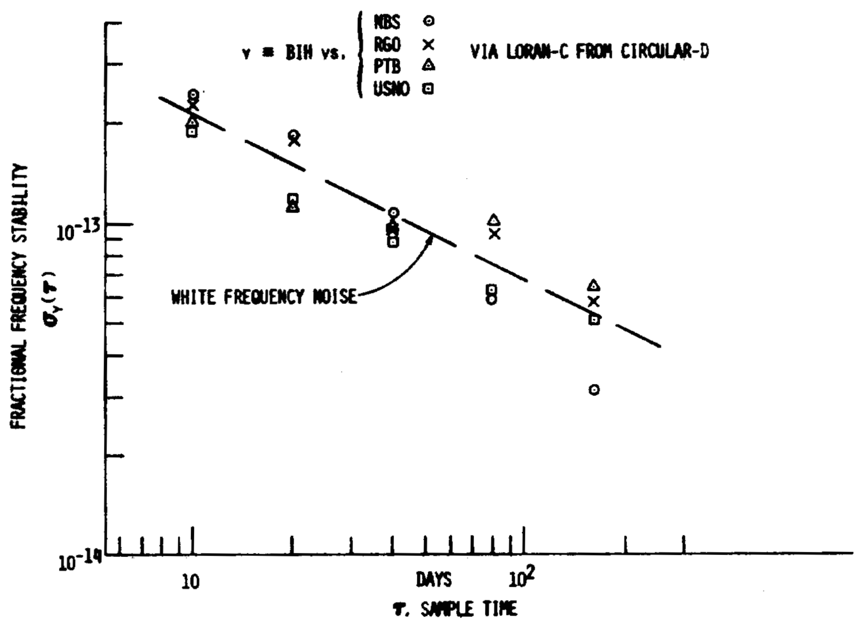


Fig. 12 - Apparent Loran-C stability as observed at the BIH from NBS, RGO, USNO, and PTB.

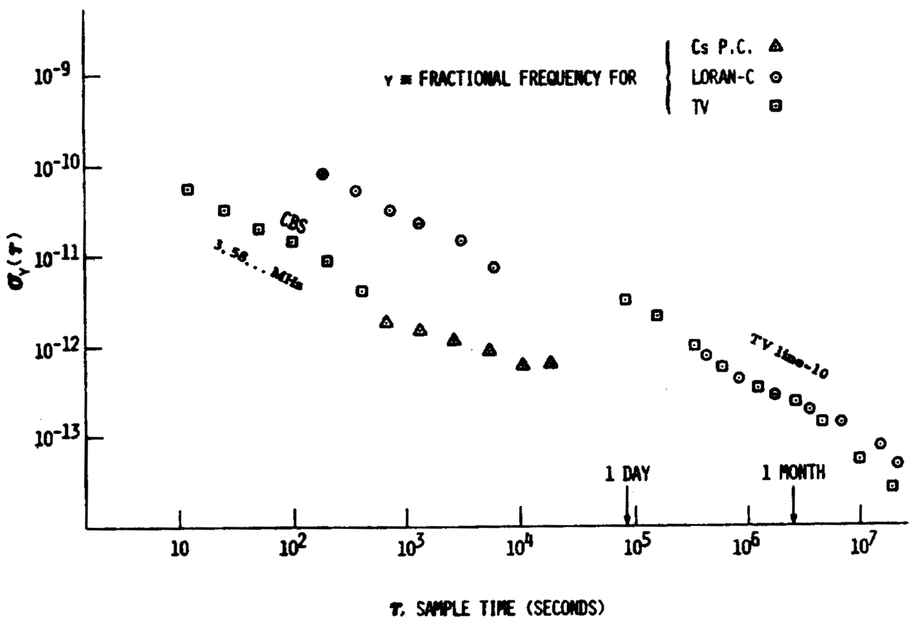


Fig. 13 - Relative fractional frequency stability versus sample time for Loran-C, 3-network TV line-10, CBS TV color subcarrier, and cesium portable clock.