HIGH PRECISION TIME TRANSFER METHODS

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ABSTRACT

This paper specifically addresses the problems encountered in making high precision (0.1 microsecond or less) time interval measurements as applied to precise time transfers. Included is a brief overview of what measurements are necessary, what uncertainties can be expected in the measurement, how the measurement can be applied to time transfer techniques in use today (portable clocks, SATCOM, TV, Loran-C), the pitfalls that can be encountered, the errors which result from being a victim of pitfalls, and an indication of the type of hardware available for measurements of this type. It is demonstrated that cumulative uncertainties can be reduced to less than 100 nanoseconds in even the more complex, long distance measurement situations if proper attention is paid to measurement techniques.

INTRODUCTION

The purpose of this paper is to present an investigation and analysis of the measurement errors encountered in making Precise Time and Time Interval (PTTI) measurements. With the advent of frequency standards having stabilities in parts in 10^{-12} to 10^{-14} and digital clocks with pulse jitter in the tens of picoseconds, measurement errors which previously could be ignored as second order have now become important. Since the majority of time transfers or synchronizations are realized by means of time interval measurements between two clocks, the investigation is limited to such measurements.

Errors can be classified as either residual or systematic. Residual errors are by definition those which remain after all known systematic errors have been eliminated and are therefore the limiting factors in regard to the accuracy which can be associated with the quantity measured. They are subject to reduction only by improving the measured system. Systematic errors on the other hand, are associated with the measuring system or techniques and are those which can be avoided, corrected or reduced. The major emphasis of the investigation was further limited to systematic errors. Systematic errors can be divided into three catagories:

1. Gross errors - These are mistakes or blunders attributable to the investigator and include misreading instruments, improper adjustment, using the wrong instrument, recording the wrong number, reading the wrong quantity, etc.

2. Instrument errors - These are inherent problems in the measuring system itself such as calibration, time base error, synchronous averaging, etc.

3. Measurement errors - These are caused by physical effects on the measured quantity such as distortion of the signal, improper impedance matching, transmission problems, etc.

Suggestions for reducing the category 1 errors and analyzing the category 2 and 3 errors are presented. A simple model of a general time interval measurement system is developed. A simple mathematical formula which can be used to combine estimates of error for relative system evaluations is presented. Examples of commonly used PTTI systems and equipment are examined and discussed.

GENERALIZED MEASURING SYSTEM

Figure 1 presents a diagram of a general PTTI system. Every PPTI system can be broken down into these segments for analsis. In the general case, the two clocks produce coherent output signals at repetition rates which have periodic times of coincidence. In the simplest case they are 1 pulse per second.

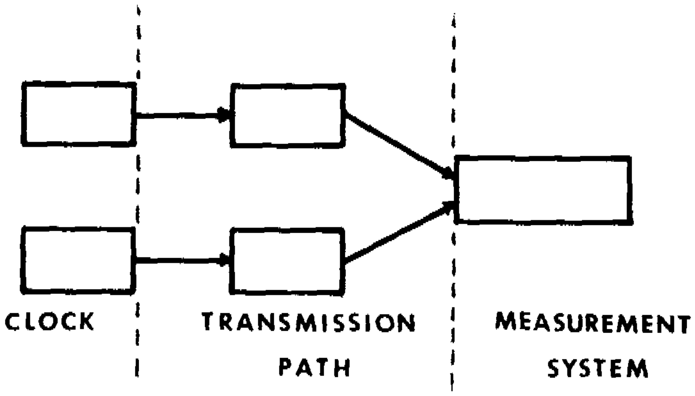

FIG. 1 GENERALIZED SYSTEM

These signals pass through transmission medium and set into motion a measurement process which results in a measurement of the relative position of two events in the time domain.

To establish a basis for comparison of various systems, a simple means of determining a relative value of uncertainty is necessary. If we examine Figure 1 and assign an uncertainty X_{ij} to each system component in the start and stop channel and X_k to the common measuring equipment (as shown in Figure 2) the entire system relative uncertainty can be expressed as

$$\sigma = \sqrt{\Sigma X_{ij}^2 + X_k^2}$$

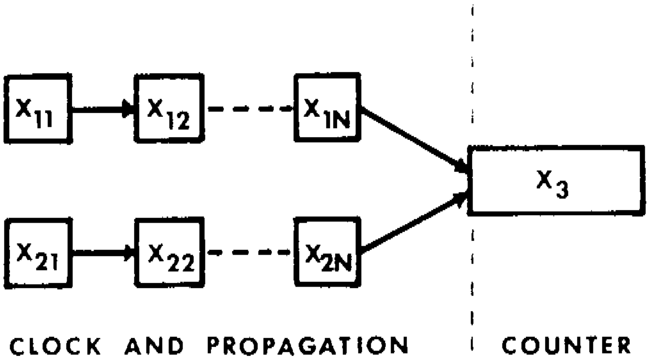

FIG. 2 GENERALIZED UNCERTAINTIES

It can be shown [1] that if we combine two or more measurements, using a clock as a transfer standard to determine the relative position in time of two other clocks, the total relative uncertainty can be expressed as

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \dots + \sigma_n^2}$$

Before applying this to some typical measurement situations, we should examine briefly the components of the generalized measuring system.

Clocks

For the purposes of this paper, we shall define a clock as a device generating a one pulse per second (IPPS) signal. Although the purpose of this clock is to maintain a precise time scale over long periods of time, the clock characteristic of concern in this paper is how the clock behaves over the short interval of time necessary to make time interval measurements. The behavior of a number of clocks is presented in Appendix A, Table 2. In summary, this shows that the best clocks available have an uncertainty (jitter) of ± 0.05 nanoseconds, while older clocks may have up to ± 2 microseconds of jitter. This uncertainty falls into the residual category since it is inherent to the clock system and subject to reduction only by improving the clock system. In most cases, one has little control over the circumstances which determine the residual uncertainties of the clocks being measured and the estimates of uncertainty due to clock performance must be accepted and dealt with accordingly.

Transmission Path

When the signal leaves the clock, degeneration immediately sets in. All classes of systematic uncertainties begin to accumulate along with the residuals. In the simplest case, the transmission path is a short piece of coaxial cable; in its most complex form, the path may include long cable runs, microwave links, radio transmitters, satellites, and receivers. Here the possibility of a gross uncertainty appears and the possibility of other systematic errors increases in proportion to the complexity of the path. Uncertainties introduced by short coaxial lines are usually insignificant. They become significant when they exceed a few meters in length and the delay caused by their introduction is neglected. Uncertainties introduced by complex transmission paths can amount to hundreds of nanoseconds in fixed propagation path configurations and microseconds in variable path configurations. In all cases, the total uncertainty is the accumulation of uncertainties in each segment of the propagation or transmission path. The majority of the measurement uncertainties develop in this area and it is also a likely location for gross uncertainties to appear. Table 3 of Appendix A gives estimates of systematic uncertainties due to transmission path for typical transmission media. Many of these uncertainties can be reduced and propagation delays determined with detailed investigation into the transmission processes involved, but initial or one time measurements are subject to these errors and the uncertainties must be accounted for in any systems measurement.

Measuring Instrument

The point is finally reached where the clock pulse is to be measured. It may be the same pulse virtually undistorted, it may be the same pulse distorted or it may be a new pulse reconstituted from the transmitted information. The problem becomes one of making a well defined, repeatable measurement with a minimum of measurement and instrument errors and no gross errors. The measurement error is reduced by attention to proper termination of the transmission line to prevent reflections and distortion due to discontinuties and impedance mismatch. Instrument error is reduced by optimizing measurement conditions and giving attention to the details of operation and idiosyncrasies of the instrument being used. Gross errors are eliminated only by experience and careful attention to each measurement situation.

In general, uncertainties in the measuring system fall into four areas: the ± 1 count error, the internal trigger error, time base error, and error due to minimum measurable intervals. Since these subjects are covered in detail quite well elsewhere [2, 3] only the basic general concepts and their contribution to the uncertainty will be discussed.

The ± 1 count error is inherent in all digital systems relying on direct counting of the output cycles of a time base gated by the measured signals. Thus a counter with a 10 mHz time base can have an error of ± 0.1 μsec.

Trigger error is due to both the internal noise developed in the start and stop channels and the precision attainable in repeated setting of the trigger level controls. Internal trigger error is generally insignificant, but that due to the settability of the level controls can be quite large and contribute significant amounts to the measurement uncertainty.

Time base errors are generally insignificant since the internal oscillators of high quality counters are stable in the range from 1×10^{-7} to 1×10^{-9}, measurement times are general less than one second, and a highly stable external time base is usually available.

Error due to the smallest measurable time interval becomes a problem when the instrument has a very high resolution, but cannot distinguish between closely spaced input pulses. For example, if an instrument has a resolution of .01 microsecond, but cannot make a reliable measurement when input pulses are spaced closer than 0.1 microsecond, the error can be as large as the measured value when measuring short intervals. This generally is not a problem in newer counters utilizing highspeed digital logic and improved counting techniques.

PTTI MEASUREMENT TECHNIQUES

Every effort must be made to reduce the likelihood of gross errors in PTTI measurements. Operator errors are much more likely if measurements are made by personnel with minimal training and understanding of what is being measured and what the measurement process actually is. Fatigue after long, involved itinararies and the attendant lack of attention to necessary details in procedures also contribute to gross errors when measurements are made in the field. For this reason, standard measurement and reporting procedures must be established and followed. Personnel must understand the measurement if gross errors are to be minimized.

All measurements in any series of measurements should be made using the same equipment, particularly the time interval counter. For example, if for any reason a long cable must be used to measure a clock at a remote site, then the same cable should be used in making all the other measurements. Prior to making a measurement, the following must be accomplished:

1. The measurement criteria must be defined. At what polarity, level and slope is the measurement to be taken? What is the proper termination impedance?

2. The measured quantity should be examined and compared to prior data, if available, to ascertain that the measurement criteria and the measured quantity are consistent. A record (photo or sketch) of the measured pulse should be made and annotated with pertinent data such as amplitude, width, rise time, etc. Any distortion should be noted and a determination made of how this might affect the measurement.

The time interval counter is then prepared for the measurement:

1. The best available source of frequency is selected for a time base.

2. The counter is tested or calibrated using internal

and/or external signals to test for proper operation and counting.

3. Input levels, slopes and slope polarities are set.

4. Input lines are checked for proper termination.

Once this has been done, the measurement can be made in the following manner:

> The two clocks are connected to the time interval counter such that the smaller of the two possible numbers is displayed. The result is recorded as
>
> Start Clock - Stop Clock = Reading.

This procedure has several advantages. The result is always the smaller of two possible answers, it is recorded as a positive number, it has less digits to record, the start-stop convention is logical and easily remembered, arithmetic is involved and the shorter interval results in reduced time base error. Having taken these steps to reduced gross uncertainties, we can proceed with the analysis of other systematic errors.

TYPICAL SYSTEMS

Using the analysis and measurement techniques so far presented we can look at several typical measurement situations encountered in PTTI.

Portable Clocks

The most straightforward and often encountered high precision time transfer is that involving portable clock operations. A portable clock is measured against a reference, taken to a remote clock against which another measurement is made, and returned to the reference clock for a final measurement to close the loop (closure). A straight line fit is assumed between the initial and final measurements so that any difference between the two is apportioned linearly over the time elapsed between the two measurements. The validity of this technique may be open to question; however, one is free to assign his own estimate of this closure error using any criteria desired. Since for the purposes of this paper this uncertainty is residual, we need only examine the sources of systematic uncertainties. Assuming we are synchronizing (measuring) a portable, high performance cesium clock to the USNO Master Clock, using short coaxial cables and a high resolution time interval counter driven from the portable clock, an estimate of the contribution of each component in the system can be determined from the tables in the appendix.

X_{11} - HP 5061A CS OPT 004 = 5 x 10^{-12} = .005 nsec

X_{12} - TSI Nanoclock = 0.05 nsec

X_{13} - Coax Cable = 0

X_{21} - HP 5061A CS OPT 004 = 5 x 10^{-12} = 0.005 nsec

X_{22} - HP 5061A Clock = 1.0 nsec

X_{23} - Coax Cable = 0

X_3 - HP 5345L Counter

Time Base = .005 nsec

Trigger Error = .02 nsec

Count Error = 2 nsec

(In each case X represents the uncertainty contributed by each segment of the measuring system in Figures 1 and 2.)

$$\sigma_1 = \sqrt{\Sigma X_{ij}^2 + \Sigma X_k^2} = 2.2 \times 10^{-9} \text{ sec.}$$

If we now perform a typical portable clock operation (See Figure 3.)

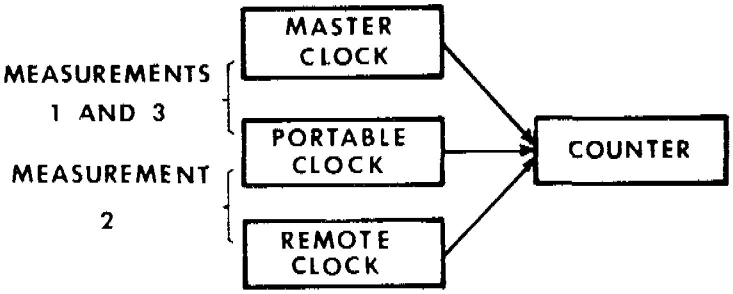

FIG. 3 PORTABLE CLOCK TIME TRANSFER

using the portable clock as a transfer standard and measuring another clock having the same specifications as the portable clock, we determine that the second measurement uncertainty is

$$\sigma_2 = 2.5 \times 10^{-9} \text{ sec.}$$

Returning and making a measurement against the Master Clock (assuming zero closure), we find a third uncertainty of

$$\sigma_3 = 2.2 \times 10^{-9} \text{ sec.}$$

Combining these using

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2}$$

we find a total uncertainty for a portable clock (pc) measurement of

$$\sigma_{pc} = 4 \times 10^{-9} \text{ sec.}$$

For a 1965 vintage system (HP 5060 cesium with 115 BR clocks and a 5245L counter) we find

$$\sigma_{pc} = 2.5 \times 10^{-6} \text{ sec.}$$

Loran-C

High precision time transfers utilizing Loran-C (Figure 4) can be examined by considering the simple case, for example, of determing the difference between the USNO Master Clock and another clock within groundwave range of the East Coast Chain Master Station at Cape Fear, North Carolina. This case is analogous to a two measurement portable clock situation with the addition of uncertainties in the transmission path, X_{23}, which includes the transmitter, antennas, receivers, and complex oversea and overland propagation paths.

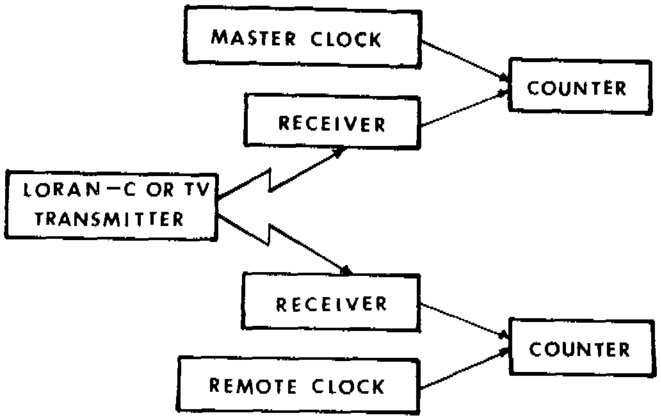

FIG. 4 LORAN—C OR TV TIME TRANSFER

An analysis of uncertainties, including estimates of those of interest has been published by Pakos [4]. This combined with uncertainties from Appendix A for loran receivers yields an estimate for X_{23} of

$$X_{23} = \sqrt{X_{pa}^2 + X_{pe}^2 + X_{lc}^2 + X_r^2}$$

where

X_{pa} = propagation anomaly = 0.2 μsec

X_{pe} = propagation path prediction = 0.1 μsec

X_{lc} = transmitted signal uncertainty = 0.02 μsec

X_r = receiving system delay uncertainty = 0.01 μsec

$$X_{23} = 0.23 \times 10^{-6} \text{ sec.}$$

Substituting this value in the previous calculation and assuming the same instrumentation at both sites yields

$$\sigma_1 = \sigma_2 = .23 \times 10^{-6} \text{ sec}$$

and

$$\sigma_{1c} = \sqrt{\sigma_1^2 + \sigma_2^2} = .33 \times 10^{-6} \text{ sec.}$$

The largest contributor to the total uncertainty is that associated with the transmission path. It should be emphasized that this is the uncertainty associated with a single measurement using conservative values for propagation uncertainties. In most cases these can be reduced an order of magnitude by portable clock synchronization to verify projected propagation delays, by observing the behavior of the received signal over a period of time and by tuning the system to reduced the effect of propagation anomalies. If X_{pa} and X_{pe} are reduced by a factor of ten then

$$X_{23} = 0.03 \times 10^{-6} \text{ sec}$$

$$\sigma_1 = \sigma_2 = 30 \times 10^{-9} \text{ sec}$$

$$\sigma_{1c} = 42 \times 10^{-9} \text{ sec.}$$

Television

The concept of high precision time transfers employing TV is exactly analogous to Loran-C. The loran clock is replaced by a TV clock in Figure 4. If we consider a simple case involving, for example, the USNO and WTTG Channel 5 in Washington, we can determine the measurement uncertainties very easily. The transmission path uncertainties are

$$X_{pa} = 0.005 \ \mu\text{sec}$$

$$X_{pe} = 0.05 \ \mu\text{sec}$$

$$X_{tv} = 0.02 \ \mu\text{sec}$$

$$X_r = 0.01 \ \mu\text{sec}$$

$$X_{23} = .055 \times 10^{-6} \text{ sec}$$

$$\sigma_1 = \sigma_2 = .055 \times 10^{-6} \text{ sec}$$

and

$$\sigma_{tv} = \sqrt{\sigma_1^2 + \sigma_2^2} = 80 \times 10^{-9} \text{ sec.}$$

Satellite

Time transfers between two SATCOM satellite terminals are somewhat different in comparison to the measurement techniques previously covered. Since this mode of making high precision transfers involves a simultaneous two way transmission of the time data at high frequencies through a synchronous satellite, the uncertainties due to propagation anomalies and path predictions are reduced. The nature of the transmitted information and the high data rates possible require that the transmitters and receivers be highly stable. The readout of the time transfer data has a ± 1 count error at present, which amounts to 0.1 microsecond. This limits the system to an uncertainty of

$$\sigma = 0.14 \times 10^{-6} \text{ sec.}$$

Improvement in this case is dependent on improvement of the measuring equipment. Increasing the resolution to 0.01 microsecond in future systems should result in the uncertainty being reduced to less than

$$\sigma s = 20 \times 10^{-9} \text{ sec.}$$

Composite System

If we examine a typical operational system, we should be able to arrive at a meaningful estimate of uncertainty in the the measurement chain. For example, The Naval Observatory has a Precise Time Reference Station in Hawaii which monitors Loran-C and determines the difference between the Master Clock and the Central Pacific Loran-C Chain (4990). What uncertainty exists in this value that can be attributed to the measurement systems? The total system consists of the following links and transfer methods:

USNO to SATCOM (Brandywine, MD) - Portable Clock

SATCOM (Brandywine) to SATCOM (Hawaii) - Satellite

SATCOM (Hawaii) to Reference Station - TV

Reference Station to Loran-C Transmitter -Loran-C.

Combining the values previously determined for these links (as they presently exist) we find, under ideal conditions,

$$\sigma_{NO-4990} = \sqrt{\sigma_{pc}^2 + \sigma_s^2 + \sigma_{tv}^2 + \sigma_{lc}^2}$$

$$= 2 \times 10^{-7} \text{ sec.}$$

CONCLUSION

This paper has presented a discussion of high precision time transfer techniques and the uncertainties one can expect in making relative measurements between clocks using these techniques. It must be emphasized that these results are what can be expected from a competent investigator using state-of-the-art equipment under relatively good operating conditions. Generally, total uncertainties are greater due to operation under less than ideal circumstances and the existence of residual errors not amenable to easy analysis and reduction.

ACKNOWLEDGMENT

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[2] Hewlett-Packard Company, Time Interval Averaging, Application Note 162-1.

[3] Hewlett-Packard Company, Application Note 52-3.

[4] Pakos, Paul E., "Use of the Loran-C System for Time and Frequency Dissemination", Frequency Technology, Vol 7, pp. 13-18, 1969.

QUESTION AND ANSWER PERIOD

SGT. OSTROWSKI:

Sgt. Ostrowski, Newark Air Force Station.

Ken, in your remarks to get to the microsecond and the nanosecond, I understand it is unavoidable, but we forgot the hour-minute and second and if the clocks are not within a half-second of one another, the microsecond is unrelatable.

MR. PUTKOVICH:

True.

I have had that happen to me a number of times.

MR. LUCK:

John Luck, National Mapping.

When you returned from your round the world clock trips, what interpolation technique do you actually use when you publish your final results and what time period do you use to get your interpolations?

MR. PUTKOVICH:

We use strictly a straight line interpolation unless we have some indication that we have had a phase jump and can pin it down quite well. It is usually just a straight line interpolation from the beginning of the trip to the end of the trip and aportion the difference over the trip, in a straight line interpolation between the two points, beginning of the trip and the end of the trip.

MR. LUCK:

In other words, you don't use the history, say for 20 days before you set out and for 20 days after you return?

MR. PUTKOVICH:

We try to take the clocks out, the portable clocks particularly, we try and have them set with essentially a zero offset to the master clock. This helps.

MR. BABITCH:

Dan Babitch, Hewlett Packard.

Early in the talk you gave an unwitting, but very vivid demonstration of one other error source when you subtracted 7 from 14 microseconds and got 8.

MR. PUTKOVICH:

That ruined my whole amazing demonstration, by the way. I didn't know what to do when that happened.

MR. NeSMITH:

Bill NeSmith, Hawaii Stadn.

I notice you had a problem on the 5 microsecond due to the antenna reversal. We had a similar situation in Hawaii. We received two antennas about two years apart. The first antenna, we had the same type of problem you have. We contacted the manufacturer and found out the arrow was painted on backwards.

MR. PUTKOVICH.

That is what the error usually is. You take them at face value as having been checked out and they are not.

DR. WINKLER:

Maybe one should suggest here, as a standard routine, if you exchange LORAN equipment, to test it against your previous setup. If you have a new receiver, leave everything else the same, just change the antenna lead into the new receiver, and establish a differential delay and use your old propagation constants as a reference. One can go very far in doing that, by using arbitrarily the first receiver as a set of reference because there you have the longest history with portable clock calibrations.

This must be done routinely. If you insert a multifilter, for instance, or a multi-coupler, it will add delays on the order of a microsecond or so and you determine that in the field. If you change the tuning of the slot filter it will change the delay of the multi-filter and you determine the effect compared to your previous setting. With just one receiver one can determine all these relative changes and provide continuity in recordings and measurements.

LCDR. POTTS:

Potts, Coast Guard.

Actually, there is a superior method, I think, Ken, to the 5-microsound ambiguity and that is to use a whip antenna.

MR. FULLERTON:

Les Fullerton, U. S. Coast Guard.

Do you utilize a tick-to-phase measurement before and after making clock trips?

Mr. Putkovich:

Yes, we do. The tick-to-phase was an outgrowth of using 115 BR plots in the early days of vertical clock measurements when we had quite a bit of possibility of having a change in the tick-to-phase measurement, when what you wanted to do was ascertain that the clock was still in step with the oscillator.

We still do it, but I don't know whether it is necessary. It is just a carryover from early times. I like to use it because it gives you a little bit of additional information on the trip in the event that you do have some sort of a failure. There is a slight possibility that you are going to have a jump in your divider chain driving the clock, something like that. So, it is a little bit of extra data.