HIGH PRECISION TIME TRANSFERS IN THE FIELD

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ABSTRACT

During May-July 1975, the Naval Observatory aided the Applied Physics Laboratory of the Johns Hopkins University in a program (under contract to the U. S. Air Force and Defense Advanced Research Projects Agency) to improve the accuracy and precision of the Loran-C navigation system. One phase of this program consisted in accurately measuring the path delay undergone by a Loran-C signal between ten pairs of points. Each pair of points consisted of a fixed site located on the grounds of the Naval Observatory and one of ten remote sites located within a radius of 800 miles of the Naval Observatory and also along a ray path to one of the following three East Coast Loran-C transmitters - Carolina Beach, Nantucket and Dana.

The Naval Observatory's function in the program was to perform time transfers between the fixed site and each of the ten remote sites when data were recorded at a remote site.

Eleven time transfers were performed during the time period. The average length of a portable clock trip was about eight hours. Analysis indicated that the probable error of any one time transfer was ± 27 ns for the remote sites and ± 11 ns for the fixed site. Thus, the two clocks could be synchronized with a probable error of ± 29 ns.

INTRODUCTION

During May-July, 1975, the Applied Physics Laboratory (APL) conducted a number of field measurements in conjunction with an experiment attempting to improve the navigation capability of the Loran-C system. One aspect of the field measurements was to accurately measure the path delay undergone by a Loran-C signal as it passed between two points.

The experiment involved two sets of identical precision measuring equipment. One set was located at the U. S. Naval Observatory (USNO). The other set was located in a mobile van and moved sequentially to ten different sites located on ray paths from Loran-C transmitters through USNO. The sites were within an 800 mile radius of the USNO. Precise geodetic coordinates for the ten sites were determined by the DMA Topographic Center using TRANSIT.

The USNO's function in the program was to perform time transfers (synchronize the clocks) between the fixed site (USNO) and each of the ten remote sites when data were being recorded at a remote site. Knowing the distance between each site and the propagation time as measured by the instant of reception of the same pulse at the fixed and remote sites, one could measure the difference between the predicted and the observed travel time of the signal.

In this paper, a simple and straightforward method of evaluating the precision of measurement of a clock difference is presented. The use of a more sophisticated method was obviated by the performance of the portable clock during the trips as will be discussed later.

It is believed that the results presented here reflect the precision with which time transfers in the field can presently be performed with state-of-the-art equipment, with little or no special care and/or preparation.

OPERATIONAL PROCEDURE

Three HP 5061 Cesium Beam Frequency Standards, all with option 004 (High Performance Cesium Beam Tube), were used for the experiment. They were designated as follows:

a. PC - Cesium Clock 787 used as the portable clock;
b. FIX - Cesium Clock 871 located at the fixed site on the grounds of USNO;
c. VAN - Cesium Clock 862 located in the mobile van.

In order to minimize the handling of PC during the field trips, it was decided to charter a small single engine plane (Piper Cherokee) out of Dulles International Airport for transport of the PC. The advantages of adopting such a procedure were:

1. Excessive handling of the PC at the air terminals at both ends of the trip was eliminated. One only

had to drive the car transporting the PC from USNO up to the plane and transfer the clock to the plane.

2. The transport of the PC through or close by airport surveillance devices was eliminated.
3. The possibility of having to transport the clock on commercial propellor driven aircraft on which there was no access to electrical power was avoided. The aircraft used in the experiment was wired to run the PC from its battery.
4. Flexibility in time of departure was gained, thus minimizing the duration of the trip.
5. Airports could be selected as close as possible to the remote site, thus minimizing the transportation of the clock from airport to remote site.

Eleven portable clock trips were made, the first site being visited twice. Table I lists the places and duration of the trips.

On each clock trip, the following procedures were performed. The PC was compared to the USNO Master Clock (MC) using a tick to tick measurement with an HP 5345A Electronic Counter. Next, the fixed site clock was compared against the PC, since it was located in a building which did not have access to the USNO MC. Because of the short duration between the comparison of PC with USNO MC and the comparison of PC with FIX, the fixed site clock could immediately be related to USNO MC. The PC was then transported to the remote site, and a comparison with VAN was made. After returning from the trip, the fixed site clock was again compared to the PC. Finally, the PC was compared to the USNO MC.

It should be pointed out that at the outset of each trip, the PC was not adjusted to agree with the USNO MC either in frequency or epoch. It, as well as all clocks in the experiment, was left free-running.

PROBABLE ERRORS OF TIME TRANSFERS

If one had no figure of merit other than the precision with which the measurements could be made, one could easily develope an erroneous picture of the precision with which one could say that the clock at the fixed site could be synchronized with the clock in the van.

One figure of merit which could be used to evaluate a clock's performance after a field trip is the closure value, i.e., the difference between the comparison of the portable clock with the reference clock at the beginning and end of the trip. However, this value, in itself, has no real significance unless we know or assume that the portable clock had a rate identical to the reference clock at the start of the trip. What would be of greater statistical interest is the difference between the observed closure and that which we would expect based on our past knowledge of the performance of the clocks involved.

Any difference between the observed and predicted closure means that during the trip either a change in frequency or a jump in clock time occurred in one or both of the clocks concerned. When this event occurred or to which clock, we do not know. Therefore, the value for the difference between the two involved clocks interpolated to some instant between the beginning and end of the trip could be in error by the full amount of this difference depending on the kind of event and when it occurred. (In fact, the error could even be larger!)

During the course of the clock trips, it became evident that the clock selected for the PC had troubles with its divider circuitry. Testing in the laboratory showed that sudden accelerations could cause a jump of one nanosecond in time. This meant that throughout the duration of the clock trip, we could expect the accumulation of these random jumps in time to be significant. Phase comparison tracings of the PC with that of the USNO MC immediately before and after the trips indicated that no significant rate changes occurred during most trips. This indicated that most of the difference between the observed and predicted closure was entirely due to the random jumps in time caused by handling of the clock during the trip. Nevertheless, the difference between the observed and predicted closures is the only statistical information we have. It is the only information we can use to assess the precision of our ability to synchronize two clocks.

Table II summarizes the data for the difference between USNO MC and the fixed site clock. The first column gives the Modified Julian Date (MJD) on which the clock trip started. The second column gives the values of the observed closures for each of the trips. The next column lists the predicted closures based on a linear extrapolation of the rate difference between the USNO MC and FIX. The interval of time on which the extrapolated rate difference was based varied as a function of the duration between trips. The last column contains the difference between the observed and predicted closures.

Assuming that these differences reflect our errors in determining (USNO MC - FIX), we can compute the probable error of a single determination. This turns out to be ± 11 ns. The probable error of a single determination is determined from

$$\varepsilon = 0.6745 \sqrt{\frac{\Sigma r_i^{\,2}}{n}}$$

where ε is the probable error of a single determination, r_i is the difference between the observed and predicted closure of the ith measurement, and n is the number of determinations. It will be assumed that this is the precision with which we can determine an interpolated value for the (USNO MC - FIX).

The precision with which we can compute the difference between the remote clock and USNO MC will reflect the precision with which we can interpolate the difference (USNO MC - PC) because it is through the portable clock that we relate the remote clock (VAN) to USNO MC.

An analysis indentical to the one given earlier can be done again to obtain the precision with which one can determine an interpolated value of (USNO MC - PC). Table III lists for the various trips the differences between the observed and predicted closures for (USNO MC - PC). It should be noted that the (O-P)s exhibit a systematic trend which can be explained by the accumulation of the aforementioned jumps in the portable clock divider circuitry. Again, assuming these differences to be the errors in our determinations, we compute the probable error of a single determination to be ± 27 ns. It will be assumed that this is the precision with which we can determine the interpolated value for (USNO MC - PC).

The value (PC - VAN) is an observed value having associated with it the precision with which we can make our readings (± 2 ns). Therefore, the precision with which we can determine (USNO MC - VAN) is simply the square root of the sum of the squares of the respective probable errors, i.e., ± 27 ns.

DISCUSSION

The analysis seems to have been complicated by the fact that it was decided to reference all measures to the USNO MC. The remote and fixed site clocks could have been related through the portable clock alone. The introduction of the USNO MC had the advantage of referring the fixed site clock to a reference clock which was in a rigidly controlled environment and therefore, hopefully, less susceptable to changes in frequency or jumps in clock time. As a result, it was hoped that the differences between the observed and predicted closures would be minimized because the values would be reflecting changes in only one of the two clocks. If the analysis had been performed without referring the measures to the USNO MC, but only by referring all measures to the portable clock, the probable error associated with differences between the fixed and remote site clocks would have been ± 38 ns, a degradation of 30% of the results cited earlier.

Plots of the differences (USNO MC - VAN) and (USNO MC - FIX) indicated no unusual behavior and indicate reasonable confidence in the results.

It should be noted that no corrections for relativity, special or general, were applied. The duration of trips and the speeds and altitudes at which the plane flew did not warrant them.

ACKNOWLEDGEMENTS

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Date	MJD	Length	Place
(1975)			
29 May	42 561	7^h 57^m	Toms River, NJ
30 May	42 562	7 26	Toms River, NJ
5 Jun	42 568	6 34	Georgetown, DE
10 Jun	42 573	8 05	Marietta, OH
12 Jun	42 575	12 56	Danville, IN
17 Jun	42 580	8 14	Bluefield, WV
19 Jun	42 582	5 39	Grottos, VA
24 Jun	42 587	6 26	Emporia, VA
26 Jun	42 589	11 09	Wilmington, NC
30 Jun	42 593	9 29	Dexter, NY
2 Jul	42 595	7 18	Towanda, PA

Table I - History of Clock Trips

MJD	Observed Closure	Predicted Closure	Difference (O-P) Closure
42 561	-6ns	11ns	-17ns
42 562	2	7	- 5
42 568	8	12	- 4
42 573	-6	5	-11
42 575	7	3	4
42 580	-6	23	-29
42 582	-1	21	-22
42 587	7	22	-15
42 589	18	40	-22
42 593	-1	7	- 8
42 595	7	17	-10

Probable Error of Single Determination = ±11ns

Table II - Data for (USNO MC - FIX)

MJD	Difference (O-P) Closure
42 561	83ns
42 562	38
42 568	22
42 573	- 3
42 575	44
42 580	37
42 582	-53
42 587	- 4
42 589	33
42 593	19
42 595	34

Probable Error of Single Determination = ±29ns

Table III - Data for (USNO MC - PC)

QUESTION AND ANSWER PERIOD

DR. WINKLER:

It is obvious that the more sophisticated you are in your data reduction, the poorer the results become and I have a wondering about that. It seems to be just another part of Murphy's law, that any corrections which you can think of, when applied make your results worse.

MR. ALLEN:

Perhaps you could tell me what prediction routine you use to predict the closure?

DR. KLEPCZYNSKI:

Just simple linear extrapolation of the rate. Looking at their prior rates, the samplings we had of the clocks, just extend that rate forward right before the clock trip started.

MR. ALLAN:

How long?

DR. KLEPCZYNSKI:

Usually there was about at least one day's worth of data or two days. The clock trips, when we started going, were occurring about every other day. When the clock was at the observatory, we could measure two or three points during the day, to base our extrapolation on.

The plots were not changing frequency that often.

MR. ALLAN:

Okay, so if I understand right, the prediction time, then, was based on about a previous 24-hour period?

DR. KLEPCZYNSKI:

That is correct.

MR. ALLAN:

That is quite a bit of error because you are still basically in the white noise region of the clock if, you know, if the clock doesn't have any abnormal perturbations otherwise. It may, in portable clock usage, but one could do quite a bit better than that, I think.

I have a question on the first slide which showed degradation as you applied your corrections.

It is the master clock where you have the predicted versus closure time and the addition of the two to give the total error. You can obviously see what may be an apparent bias.

DR. KLEPCZYNSKI:

Yes, there is.

MR. ALLAN:

And one wonders if, perhaps, that is due to a systematic in the prediction.

DR. KLEPCZYNSKI:

I would think so. But, I think as a reasonable number, the probable error then even becomes more real, that this is really what we would expect the results to show.

MR. ALLAN:

You are very conservative.

DR. KLEPCZYNSKI:

That is what I am trying to do, right?

DR. VESSOT:

I think the prediction algorithms are fine if you can use them, but I really believe that the portable clock under the conditions of its existence, while it is traveling around, is probably beyond any statistical rescue. If you are going to make such a statistic you have got to take the clock and look at the drift that it encounters under fairly controlled transportation conditions. I don't believe that the statistics one obtains in the lab can apply to the behavior of the clock while it is being environmentally gyrated in a small plane and moved about in the earth's magnetic field. I don't think that statistics are going to help there.

DR. WINKLER:

I would like to make a comment to that. I think you are beyond statistics in one specific sense and that is that I am firmly convinced, and I think you may hear about that later this afternoon, that for such clock trips the main effect is the change in the temperature that is producing a systematic bias because all of these clock trips were executed during the same part of the year, in summer. The clock, when moved outside the laboratory, was always exposed to a higher temperature, and it did not have time to settle down. I believe a substantial part of these biases are due to temperature phase shifts in the output circuits.

Of course, the data has not been collected, for these short trips, has not been sufficient to warrant, I think, anything more sophisticated. What has been done almost simultaneously, however, and this explains why we didn't have particularly high performing clocks available for that purpose. I think better results could be had if you tested these clocks carefully for temperature behavior and account for that.

I think more interesting results can be gotten if you sent clock sets onto a trip where some of these are as perfectly protected against environmental changes and others are not. Then you can evaluate what really happens. That is part of the experiment which will be reported on, I hope, by Carroll Alley this afternoon, and the effect is profound on their portable clock if it is not protected.