REVIEW OF AVAILABLE SYNCHRONIZATION AND TIME DISTRIBUTION TECHNIQUES

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ABSTRACT

The methods of synchronizing precision clocks will be reviewed placing particular attention to the simpler techniques, their accuracies, and the approximate cost of equipment. The more exotic methods of synchronization will be discussed in lesser detail.

The synchronization techniques that will be covered will include satellite dissemination, communication and navigation transmissions via VLF, LF, HF, UHF and microwave as well as commercial and armed forces television. Portable clock trips will also be discussed.

Before we discuss methods of synchronization, we should briefly review who the users of Precise Time and Time Interval (PTTI) are, and why they need synchronization.

Celestial navigation has, probably, the most users of precise time: certainly more than 100,000. They have very modest requirements, time to about 100 milliseconds at best. However, they do put a requirement on the more precise users of time. That is, they force the DUT1 code on the time signal and force the leap seconds. Because most of these users are very unsophisticated as far as time is concerned, their time must be "on time" for their navigation requirements. Users of precise time must always be aware of leap seconds - which, at the present time, occur about once a year.

Geodesy has more precise requirements time to one millisecond or perhaps even 100 microseconds for position determinations on the Earth's surface.

There are two main users of synchronization. First are the communicators requiring synchronization to 25 microseconds or better due to the increasingly high data modulation rates, time division multiplexing, and the use of synchronized spread spectrum. Second are users of synchronization for positioning systems. We must remember that the speed of radio waves or of light is approximately 300 meters per microsecond or approximately 1000 feet per microsecond. For electronic navigation, particularly in the rho-rho navigation mode, distance from the transmitter must be known. To know position to 1000 feet, time must be known to better than one microsecond.

Time and frequency are also used for identification, as for example, in collision avoidance systems and Identification - Friend or Foe, etc.

Many of these systems do not necessarily require synchronization to time of day. However, in the interest of redundancy and economy, it is essential that all systems be externally synchronized to the same time scale. This allows backup in case of failures. For example, satellite systems can, in case of failure of their clocks, use a nearby Loran-C station to synchronize their clocks again. The time scale to which all systems should be synchronized in the Defense Department is that of the Naval Observatory. But since the Naval Observatory time scale is coordinated with that of the Bureau International de l'Heure, and the National Bureau of Standards, there are many sources of time that can be used for synchronization depending on the accuracy required. However, care must be taken as international synchronization or domestic synchronization is not absolute to one microsecond. Many of these sources, however, can be reduced to that accuracy after corrections are applied.

There are many methods to synchronize clocks. Which method to choose depends on several requirements. The first requirement is the precision of synchronization. One must be aware that if he wants one tenth of a microsecond precision he is not going to be able to do it by looking, for example, at a wall clock. The user has to know what precision of synchronization he wants before he can determine which of the many methods of synchronization to use. The second requirement is the frequency of access to synchronization. If the user can synchronize every five minutes, then he can obviously use a very poor oscillator. However, if he can only synchronize once a year, then he is very limited in terms of the number of oscillators he can use. A third requirement, related to the second, is the quality of the clocks used both in reliability and performance.

For economy of PTTI distribution, we impose PTTI on both navigation and communications stations. We use these transmissions because there is very little additional cost in order for them to be "on time". It simply means an interface with an external time system. For redundancy, we use many different systems. For obvious reasons, the organization of PTTI services is a hierarchy. The master clock or timing signal for DoD is located at the Naval Observatory. From the Naval Observatory we then use trunk line timing to the precise-time reference stations, many of which are at SATCOM terminals. From these we can monitor Loran-C transmissions. Thus Loran-C is the next step down. This process continues down to the user.

There are many methods of distributing PTTI information. High frequency radio time signals have an accuracy of approximately one millisecond. With an excellent operator this can be reduced somewhat. However, it is global in distribution if foreign radio time signals are also used. These signals are given in Series 1 of the Naval Observatory Time Service publications, in case such a list of stations is needed.

Portable clock trips accurate to about one-half microsecond, again global, are presently being conducted. In the Department of Defense, an Air Force request for portable clock trips can be made to the Newark Air Force Station, Newark, Ohio. Army or Navy requests for portable clock trips can be made to the Naval Electronic Systems Engineering Center, Washington, located on the Naval Observatory grounds. Stops at or for other agencies and international organizations can be arranged. The Naval Observatory still makes a limited number of clock trips.

VLF and OMEGA have from one to three microseconds accuracy in phase tracking. This is a relative measure. It does not give absolute time. Once a clock is "on time", these measures can be used to keep it "on time".

Other than portable clocks, Loran-C is still probably the best and most precise time-distribution system available at the present time. It, unfortunately, is not even available in all areas of the northern hemisphere. In the future, it will be available in the western part of the United States, which will then make Loran-C available to users throughout most of the northern hemisphere. The SATCOM or the defense communication satellite is used for trunk line timing with an accuracy of approximately one-tenth of a microsecond. Transit satellite, a Navy navigation satellite, can also be used for time and can provide about 10 microseconds accuracy, globally. The Navigational Technology satellites have an accuracy, or certainly will have, of approximately one-tenth of a microsecond on a global basis.

Television can be used both locally and at fairly long range (at least in the United States) with a local precision of approximately 20 nanoseconds, or even better. However, 20 nanosecond precision requires that the two synchronizing stations observe the same television station. For long range, the accuracy is perhaps one microsecond. Here, care must be taken that the same live network program be used. This is done between Boulder, Colorado, Newark, Ohio and Washington, D.C., and the results are published in Series 4 of the Naval Observatory Time Service publications.

Microwave can also be used to synchronize in line-of-sight. Optical devices can be used in line-of-sight, where the error of determination can, perhaps, be as little as one nanosecond. There are many others, such as very long baseline interferometry (VLBI), cables, power lines, pulsars, and moon bounce.

Before discussing these different systems, let us examine the general problem of synchronization (Figure 1). The transmitter is to be used as a marker, not necessarily "on time". At receiver A, clock A starts counter A and the marker stops it. Reading A is the time of clock A minus the time of the marker (which is unknown) plus the delays in the system. System delays include the delay in propagation from the transmitter to the receiver plus the delay in the receiver. Similarly at B, reading B is the time of clock B minus the time of the marker plus the delays from the marker to B. This is always true. It is always algebraically the start of the counter minus the stop of the counter. If it is done this way, one of the largest, most common errors made in synchronization may be avoided, namely, the sign of the difference in time of the two clocks. The difference of these two readings must be taken algebraically, thus the time of clock A minus the time of clock B is equal to the reading of counter A minus the reading of counter B minus the sum of TAU A minus TAU B, where TAU A and TAU B are the propagation delays from the transmitter to clock A and B respectively. It is easiest to determine TAU A and TAU B by means of a portable clock with which to calibrate the system. However, TAU A and TAU B can usually be determined with sufficient accuracy from theoretical calculations.

If the transmitter is "on time" or the correction to the transmitter is known, two stations are no longer required. It requires that the propagation time, TAU A, be calculated. The Naval Observatory will, upon request, calculate these progation delays for users if they do not have the capability. The request must include the location of the station and the transmitter that is being used. Once the propagation time and the receiver delays are known, then the reading at A is simply the time of clock A, which started counter A minus the time of the marker which stopped counter A plus the delays.

Let us go into more detail on PTTI signals from communication stations. High frequency time signals are useful signals, because very many of the very precise time signals have an ambiguity and require that the user be within a certain accuracy initially. The easiest and cheapest way to get to the required accuracy is to use a high frequency time signal. The Navy time signals have an accuracy of about one millisecond and receivers cost several hundred dollars. However, the time signals are broadcast only for five minutes at intervals of six hours. They can be heard anywhere in the world. The schedules are given in Series 1 of the Naval Observatory Time Service publications. The signal is on for 300 milliseconds, off for 700 milliseconds, and it transmits a code each minute indicating how many minutes are left before the hour. Probably, more useful signals to most everyone are the PTTI signals such as WWV, CHU, WWVH, etc. which are on continuously. They have an accuracy of a little better than one millisecond. The reason for this is that the propagation varies from time to time with this order of accuracy. HF timing receivers are very inexpensive.

On low frequency, there is WWVB at 60 kilohertz, which can be used for phase tracking in order to determine standard frequencies.

All Navy VLF stations will be on Frequency Shift Keying (FSK). The assigned frequency is the "mark". The "space" is the frequency that is 50 hertz away. The mark, while not continuous, sounds exactly like the high frequency signals. Receivers for VLF cost from $1000 to $5000. Time signals are on only five minutes before the hour on certain stations. The code stream from VLF stations is timed so that the time difference between the middle of the rise time of each pulse (frequency shift) and the middle of each decay time is exactly a multiple of 20 milliseconds. This can be used as a timing signal with an ambiguity of 20 milliseconds. VLF stations are used primarily for phase tracking. The frequency of the VLF stations is good to a few parts in 10^{12} per day, therefore with phase tracking and corrections published in Series 4 of the Naval Observatory Time Service publications, the user can maintain an oscillator relative to the Naval Observatory oscillator with an accuracy in time of one to five microseconds. There are several problems, however, in phase tracking VLF stations. There is a diurnal shift each day, so the user must be careful and only use the portion where daylight is continuous between the receiver and the transmitter. There are also sudden ionospheric disturbances (SID) that occur occasionally. Usually, these are quite apparent and after a little practice users learn to recognize that an SID is occurring and ignore that period. Times of SID's are given in the Series 4 or in the teletype Series 5 of the Naval Observatory Time Service publications. There are also polar cap absorptions which are a little more difficult to identify because they last longer, on the order of several days.

We use the Television Line 10, odd, horizontal sync pulses as a marker for time comparisons. A receiver can cost as little as $400 and can give time comparisons as accurate as 10 nanoseconds. In the Washington area, we have placed the transmitter of Channel 5 "on time" and corrections are given in Series 4 of the Naval Observatory Time Service publications. It can be used as a time signal. For long distance, a live program must be used. The delays change quite often.

PTTI information is also transmitted over electronic navigation systems. Navigation VLF stations that can be used for standard frequency are the OMEGA signals. For them also, the SID, polar cap absorptions, and diurnal shifts have to be taken into account. They can be used exactly as the communication stations; however, they have lower power and a commutator is necessary because they time share the navigation signals. They do have some unique frequencies such that time sharing is not necessary, and a commutator would not be necessary.

Loran-C and Loran-D are probably the most important synchronization signals at the present time. There are now eight chains in operation. All have cesium oscillators operating so they all have very good frequency. Time can be obtained at distances of 1500 miles from these stations to an precision of 1/10 of a microsecond with corrections from Series 4 of the Naval Observatory Time Service publications, and absolute time to better than several microseconds. The Western Pacific, North Atlantic, East Coast, Norwegian Sea and Mediterranean chain times are usually kept to better than 5 microseconds. In the future, additional chains will be added; 3 on the east coast, 2 in the Gulf of Mexico and 7 on the west coast of the United States. This should cover the coastal regions of North America. However, all of them may not be timed. Automatic receivers cost about $4000 to $5000. Very competent operators may obtain high precision using low cost receivers ($1500).

How do we keep these chains "on time"? The East Coast chain is measured directly at the Naval Observatory so that the quantities that are in Series 4 of the Naval Observatory Time Service publications are direct measures. The Norwegian Sea chain and the Mediterranean chain are tied to the U. S. Naval Observatory through the North Atlantic via the U. S. Coast Guard (daily messages) and a monitoring station in Northern Scotland. This allows us to have 2 measures across the North Atlantic. We can also measure the North Atlantic chain directly with respect to the East Coast chain at the Naval Observatory. The Northwestern Pacific chain is tied to the Naval Observatory via portable clock trips (approximately every 6 months), SATCOM terminals in Okinawa and Guam, and by the rate correlation method. There are approximately 14 cesium clocks monitoring Loran-C in the Western Pacific. The rate correlation method simply means that if one clock changes in frequency, it should be reflected in any difference measured with respect to that clock. If you take differences A minus B and A minus C and clock A changes by one part in 10^{13}, both of these differences should change by one part in 10^{13}, whereas, the difference between B and C should not change at all. It works very well in the Pacific and the last clock trip indicated about a half a microsecond deviation over the previous six months. The Central Pacific chain is tied to the Naval Observatory via the SATCOM in Hawaii and portable clock trips.

There are other navigational signals that can be used for synchronization. The TRANSIT satellite is good to about 10 microseconds (Laidet, L. M., Proc. IEEE, 60, p 630, 1972).

Timation navigational technology satellite, and the GPS can provide timing accuracy of approximately 1/10 of a microsecond.

A portable clock is still probably the most accurate method to transfer time over long distances. Portable clocks have an accuracy of half a microsecond. The costs are simply the costs of three airplane tickets plus per diem plus two strong backs.

Some stations are built primarily for PTTI information. These are the standard time and frequency stations throughout the world such as WWV, WWVH, CHU, JJY and a great number in Europe. In fact, the problem really is that there are too many of them and the user has difficulty knowing which one he is receiving unless he is well aware of the various characteristics of these stations. The list of these stations is given in Series 1 of the Naval Observatory Time Service publications. The National Bureau of Standards also has a satellite time service, the ATS satellite, which is good to approximately 50 microseconds. It is a stationary satellite useful in the United States.

There are many other methods of synchronization. One method is to use shielded cables. The user must remember that it does take the signal time to go through the cable and he does have to measure these delays if the cable is very long. Also, if the cable is very long, he has to worry about temperature effects. The changes in 10,000 feet of test cable at the Naval Observatory varied from 10 to 20 nanoseconds each day due to the diurnal changes in temperature. Microwave links can be used for synchronization to better than 10 nanoseconds. There are optical means to synchronize, such as optical fibers or a flashing light. One can use calculations to keep a clock in synchronization, such as the rate correlation method. This method requires at least 3 oscillators, and the more oscillators there are, the more accurate the method becomes. Not all the oscillators need to be in the users own laboratory. For example, if the user has a Loran-C receiver, the cesium oscillator at the Loran-C station can be used as one oscillator.

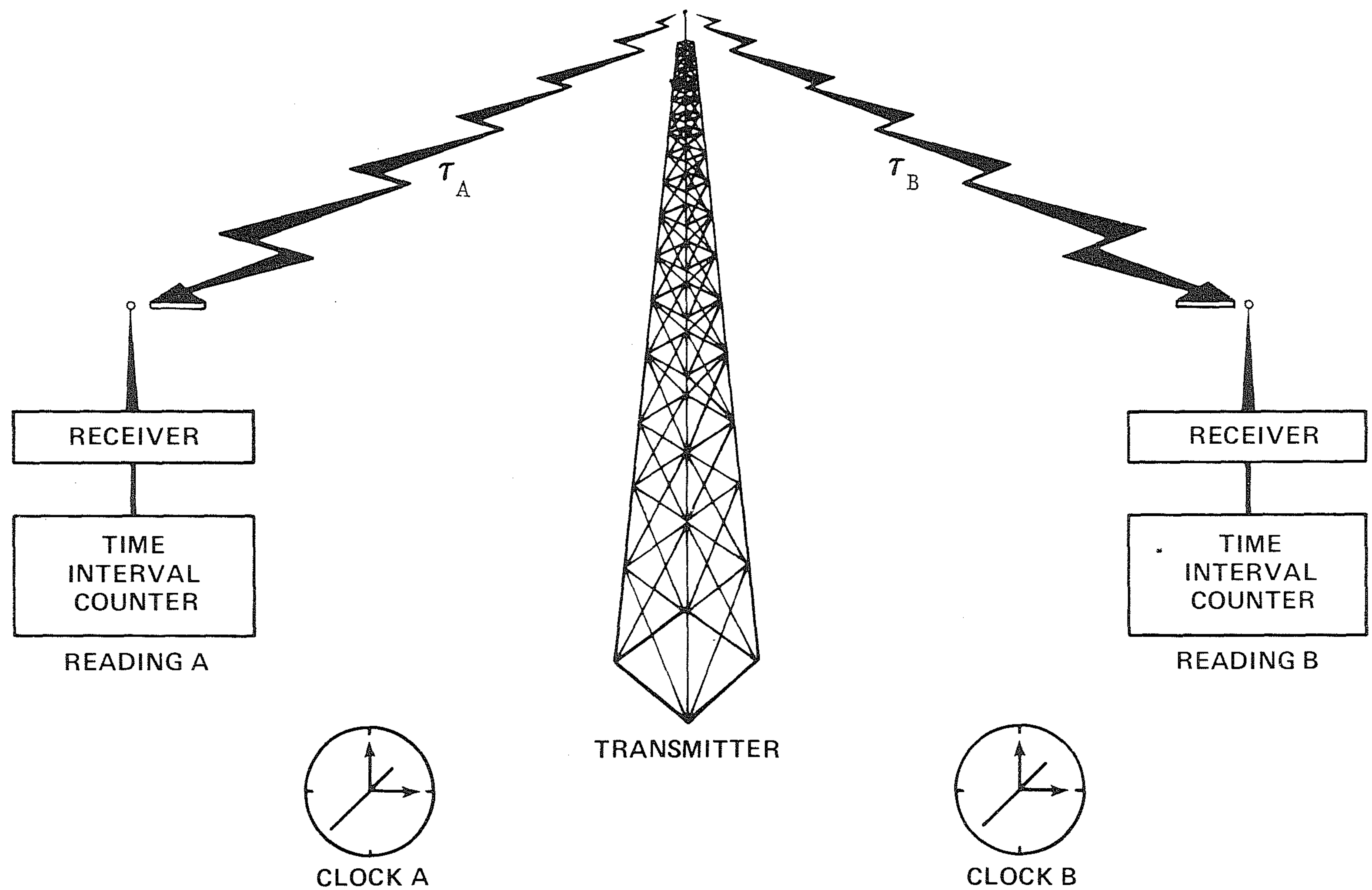
One must also remember that quite frequently one can get synchronization from a neighbor. Hopefully, this meeting will identify the stations with precise time. If the stations who have precise time would share with their neighbors, this would help a great deal.

There are several exotic methods of synchronization, such as VLBI and pulsars. It is very expensive, of course, to set up unless a receiver is already available. Also, there are pulsars, one of which now seems to be constant enough to be used as a marker for synchronization.

In this matter of synchronization, there is a very good chapter in the NBS Monograph 140, the NBS Time and Frequency book (edited by Byron Blair). It discusses a great number of these systems in detail. Another general review is in Volume 60 of the Proceedings of the IEEE of May 1972.

In the future, we can look forward to the Global Positioning System, which should give us very accurate time in the global sense.

"PASSIVE" SYSTEM FOR DIFFERENTIAL TIME TRANSFER



[CLOCK A - CLOCK B] = [READING A - READING B] - [τ_A - τ_B]

Figure 1.

QUESTION AND ANSWER PERIOD

MR. TEWKSBURY:

Dave Tewksbury, Smithsonian

Geodesy requirements in epoch (UTC) time for laser data reduction for the Smithsonian Astrophysical Observatory ask $\pm 25\ \mu s$ maximum. This precision is necessary to accurately determine intercontinental distances to $\pm 10 \rightarrow 40$ cm. To measure continental drift and/or plate movement will require even more precise epoch time.

DR. HALL:

I think your requirements come about because rotational time doesn't enter in the reduction. It is hopeless to get UT1 to an accuracy of 25 microseconds. If you are using UTC for synchronization or distance measures that is not really what I referred to as geodesy relative to the star system.