'Time-telling' techniques

In the future, new systems such as satellites and microwave communication networks will carry time-dissemination services

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G. J. Whitrow, author of *Natural Philosophy of Time*, relates the story of the Russian poet, Samuel Marshak, who, when he was first in London and still did not know English well, went up to a man in the street and asked, "Please, what is time?" The man looked surprised and replied, "But that's a philosophical question. Why ask me?" In this article we plead the same excuse and deal only with some limited aspects of time and frequency—including radio propagation effects, precise time broadcasts, artificial satellites, television, and portable clocks.

Fortunately, then, we only have to deal with three types of time information: date, time interval, and synchronization.[1] *Date* refers to a point in time—for example, February 13, 1961, 10:21 A.M., Mountain Standard Time. *Time interval* is the elapsed time between two dates. And *synchronization* means that two or more clocks show the same time.

One characteristic is evident—that time-synchronization techniques and frequency-control techniques are essential to modern communication systems. In a digital communications network, for example, economies are realized by applying time-division techniques to permit many users to share equipment. One requirement for time-division multiplexing (TDM) is the synchronization of various digital sources.[2] The extensive use of multiplex transmission systems also places stringent requirements on the accuracy of the carrier frequencies.[3] And, as frequency standards improve, so does timekeeping ability—which means that actual time-dissemination needs are decreasing, in the sense that the information rate required for a given accuracy of synchronization is less because local timekeeping ability is greater. This situation has the makings of a dilemma. As the state of the art in time and frequency advances, the needed rate of time-dissemination information decreases, tending to eliminate the justification for specialized time and frequency systems. The trend, quite naturally, is to look for existing communication systems that have enough excess channel capacity to satisfy both time- and frequency-synchronization needs.

In newly developing systems such as communications satellites, time- and frequency-dissemination requirements have been recognized and are included in the design stages. This trend will certainly continue and is already important in digital communication systems that employ TDM, in which synchronization considerations are no longer separate matters but an intimate part of the communication channel itself. Further indications of this trend may be seen in computer usage and pooling, wired-city concepts for supplying greatly enhanced two-way communications capability to urban dwellers, aircraft collision avoidance systems, and vehicle location and control systems.

Astronomical time scales

Why was Isaac Newton born in 1642 and not in some other year such as 1829? The Mad Hatter, in *Alice in Wonderland*, was very near the answer when he said, "If you knew time as well as I do, you wouldn't talk about wasting *it*. It's *him* . . . . Now, if you'd only kept on good terms with him, he'd do almost anything you liked with the clock." And, indeed, we can do almost anything we like with the clock. The date of an event is merely a convention, but one on which we all agree. A particular convention for assigning dates to events is called a time scale. The most familiar time scale is the apparent motion of the sun in the sky. To use the sun as a time scale, we must count days—make a calendar—from some initially agreed upon beginning. For more precise needs we break a day into hours, minutes, seconds, and sometimes even into millionths of seconds. The time that is derived from the apparent position of the sun is called *mean solar time*.

Because the apparent motion of the sun is due primarily to the rotation of the earth about its axis, and the motion

Today, there exists a need for sources of frequency and time reference signals, not only as key ingredients in navigation systems, but in a multitude of other systems essential to modern life. This article takes a capsule look at some of the topics presented in the May issue of *Proceedings of the IEEE*, a special issue that explores time and frequency in detail, including their generation, dissemination, and applications.

of the earth about the sun, apparent solar time will only be uniform if these two motions are uniform. In point of fact, they aren't, because the earth's rotational axis wobbles, and the rotation rate speeds up in the spring and slows down in the autumn. Also, the earth moves around the sun in a noncircular orbit, slowest when it is farthest from the sun and fastest when it is nearest. If this weren't enough, there is another effect, which is due to the inclination of the earth's axis to the plane containing its orbit around the sun. If the last two effects are taken into account and used to correct apparent solar time, a new time scale, commonly called Universal Time, results.

Atomic time scales

Until 1955, time was related exclusively to astronomical observations. However, since then a new time

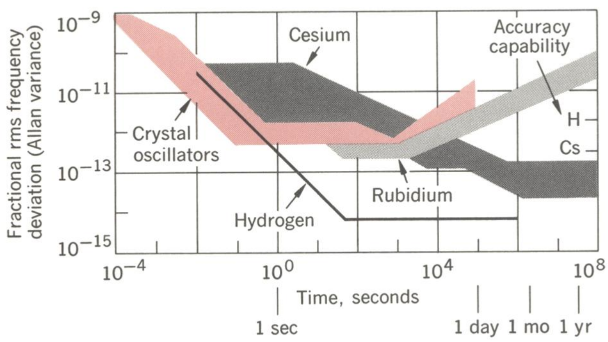
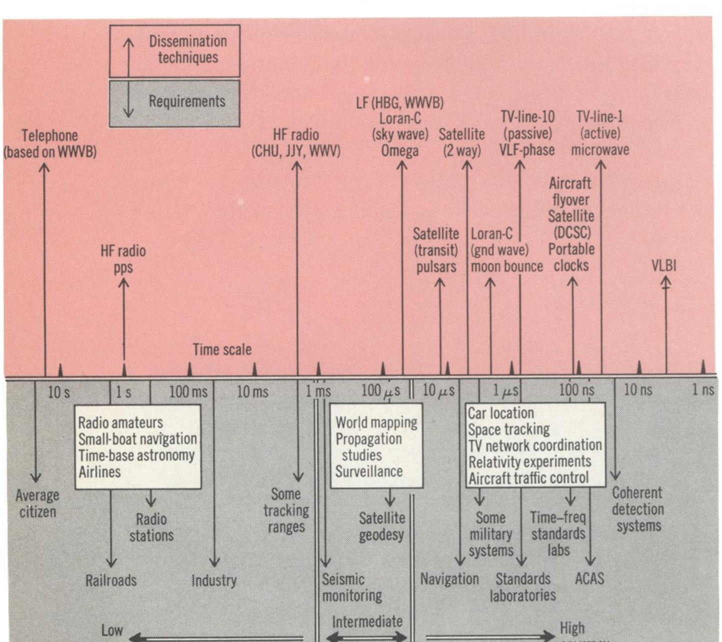


FIGURE 1. Accuracy and stability capability of crystal, rubidium, cesium, and hydrogen oscillators. The width of the stability curves for all but the hydrogen oscillator reflects the range between manufacturer specifications and typical performance. In all cases, the typical performance is better than the manufacturer's specifications. Hydrogen devices are not commerically available.

FIGURE 2. The time-accuracy requirements of various users. In the low-accuracy region, users require the date; at higher accuracies, synchronization is more important.



scale has evolved: atomic time, based upon the cycles of a signal in resonance with cesium atoms. Today, the definition of a second is no longer associated with an astronomical observation, but is defined as the "duration of 9 192 631 770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium atom 133."[4]

The scale that we commonly use today, called Coordinated Universal Time,[5] came into effect in the late 1950s and was modified this year. This scale is a mixture of both astronomical measurements and the atomic definition of the second. Using the atomic second raises a problem that was not present with astronomical time. The astronomical second was defined so that there were exactly 86 400 seconds in the day. Now that the second is independent of variations in the earth's rotational rate, there won't, except for an accident of nature, be an even number of seconds in a day. In exactly the same way that we now add an extra day to the year on leap years, we will now add or delete a second, called the leap second, as required to keep astronomical and atomic times within 0.7 second of each other. If possible, the leap seconds will only be at the beginning or end of the year.

Frequency standards

The first successful atomic frequency standard was put into operation at the National Bureau of Standards (NBS) during the latter part of 1948, and in 1955 a cesium beam frequency standard became operational at the National Physical Laboratory, England. Today, the leading high-performance frequency references are cesium beam resonators, hydrogen masers, rubidium vapor cells, and quartz crystal oscillators.

Two important characteristics of any frequency standard are accuracy and stability: how clcse the device comes to achieving the atomic definition of the second, and how much the frequency of the device wanders about. A device that is not very accurate can be very stable—in the same way a train always leaves exactly 8 minutes after the scheduled time. The cesium beam is the most accurate, whereas the hydrogen maser is the most stable for periods of time ranging from about 10 seconds to one day. Outside of this time range, other devices are more suitable than the hydrogen maser. From a practical point of view, other important considerations are reliability, initial cost, production experience, and support required after initial installation. Figure 1 summarizes the accuracy capabilities of the various devices, as well as the frequency stability as a function of observation time.[6]

Dissemination methods

In our everyday lives we depend upon many sources for time information: the telephone time service, the bank clock, one's wristwatch, time announcements on local radio and television stations, and so forth. Generally speaking, these sources of time are accurate to a minute or less and are more than adequate for everyday needs.

For more sophisticated users standard time and frequency radiobroadcasts in the band between 2.5 and 25 MHz are commonly used. Although there is no accurate way to estimate the total number of users of this type of broadcast, limited statistics are available. When NBS commenced a standard time and frequency broadcast from a new facility at Fort Collins, Colo., it received over

10 000 requests for QSL cards. When NBS was considering changes in the format of the broadcasts, it received more than 6000 responses to a questionnaire.

Radio propagation effects. Near the transmitter antenna, a direct signal, generally called the ground wave, is strongest. At greater distances the ground wave becomes too weak to receive, and the sky wave, a signal reflected from the ionosphere, predominates. Whether a sky wave is received depends upon the frequency of the radio signal, the angle at which the signal impinges upon the ionosphere, the time of day, the season, the progress of the sunspot cycle and other, more subtle effects. As a rule of thumb, frequencies below 30 MHz will be returned to the earth, and those above will penetrate the ionosphere and pass into space. For this reason, all of the standard bands allocated for time and frequency broadcasts are at frequencies below 30 MHz, with one notable exception, which will be mentioned in connection with satellite time dissemination.

For a given frequency, the chance of the signal being returned decreases as the angle of incidence decreases. The signal that just penetrates the ionosphere at vertical incidence is called the critical frequency (f_c). All signals at vertical incidence above the critical frequency penetrate the ionosphere, and those below reflect from it. The critical frequency varies considerably as a function of time of day and latitude, among other things. The region where the ground wave is too weak to receive and where there is yet no sky wave is called the skip zone. The extent of this zone depends upon the degree to which the signal frequency, f, exceeds f_c. Because of these factors many time and frequency broadcasts from a single location are transmitted at several different radio frequencies in the expectation that at least one signal will be available to the user.

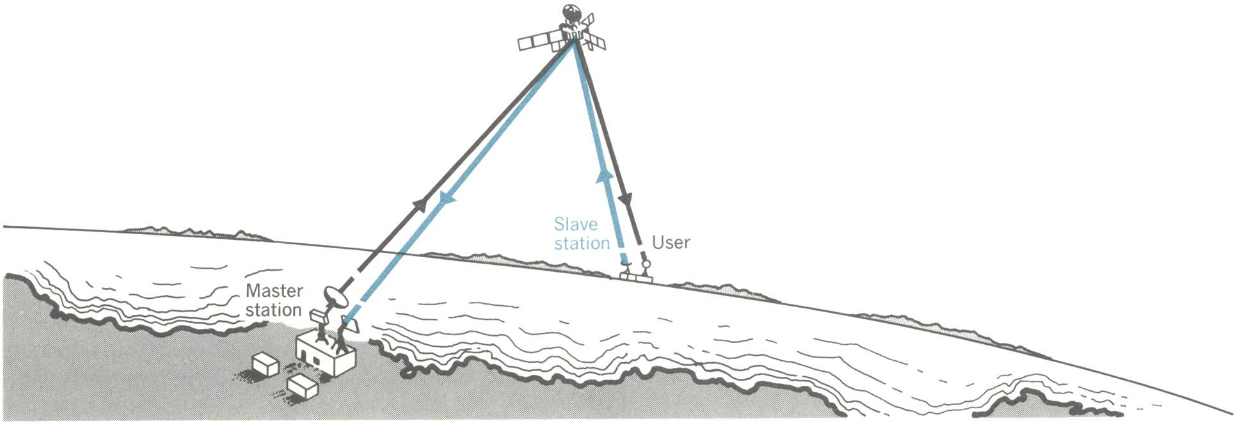
Precise time broadcasts. Most of today's radiobroadcasts devoted primarily to time and frequency information are in the 2.5- to 25-MHz range. From these broadcasts most users are not able to obtain timing accuracies better than about 1 ms, unless they are fortunate enough to be within the ground wave of one of the broadcasts. Yet, there are many applications, a few of which are shown in Fig. 2, that require accuracies of 1 ms or better. These new requirements have led to an international frequency allocation of 20 kHz for time and frequency dissemination. Both experiment and theory indicate that there should be considerable improvement in time accuracy because of the stable propagation paths at VLF (very low frequencies: 3–30 kHz). At VLF it is not possible to transmit information such as a voice broadcast because of the limited bandwidth at low carrier frequencies. Some VLF time broadcasts have been incorporated on a limited basis into existing communication facilities by the U.S. military, but it is expensive to establish new transmission facilities in this frequency range. As a result, there has been a tendency to incorporate time and frequency information into existing VLF facilities.

Navigation systems for time dissemination. One of the most fruitful classes of radio systems for time dissemination is hyperbolic navigation—the most important being Loran-C. Loran-C does not contain time information (voice announcements, etc.) in the sense of a broadcast such as that of the U.S. station, WWV, or the Canadian station, CHU. Nevertheless, a number of characteristics of the system are ideal for accurate dissemination of time. First, the signals are referenced to atomic frequency standards, and consist of repetitive sequences of short-rise-time pulses, which permit accurate time-of-arrival measurements. Perhaps the most interesting feature, which is also of great importance to navigation, is that it is possible at some locations to separate the ground wave from the sky wave.

The Loran-C carrier is at 100 kHz, where there is still considerable ground-wave signal, even at 1000 km from the transmitter. A single pulse leaving the transmitter arrives at the user's location via two paths—the ground-wave and sky-wave paths. Because the ground-wave path is shorter, the ground pulse arrives at least some 30 μs ahead of the sky-wave pulse, thus allowing undisturbed measurement of the ground pulse. Experiments indicate that accuracies of 2 μs can be achieved in areas with good ground-wave coverage.[7] At lower frequencies this cannot be done easily because the carrier frequencies will not allow the transmission of short-rise-time pulses. At higher frequencies the ground wave is too weak, except near the transmitter.

The Omega VLF navigation system, which is in the

FIGURE 3. The one-way satellite user needs only a receiver, but must obtain a one-way path delay. The two-way satellite user (indicated in color) needs both receiver and transmitter. Path delay drops out.



implementation stage, is receiving considerable attention as a means of time and frequency dissemination.[8] Since it is not feasible to separate the ground and sky waves in this frequency range, the best results are obtained from signal sources so distant that no ground wave is present. At closer distances there is a complicated interference pattern, produced by the ground and sky waves, which makes the signals unsuitable for accurate time dissemination. At great distances, however, the sky wave is very stable with a potential time-dissemination capability of a few microseconds if great care is taken. On the other hand, accuracy in the 100-μs region should be easily obtained. The other great virtue of this system is that relatively few stations could provide reliable worldwide coverage—something that is sorely needed and not available with any operational system. At the present time, scientific or other programs that require time-coordinated measurements on a worldwide basis must reference measurements in different parts of the world to different systems. This is not only a nuisance but is expensive if many different types of timing equipment are required. Perhaps even more important, there is always the question of the relative accuracies provided by the various systems and the degree to which the time signals from these various sources are coordinated with each other.

The design of the Omega system permits a further timing feature of potential usefulness.[9] Enough unused communication capability exists to allow a slow-speed, digital time code to be added. This code could give hour, minute, and second information such as that provided by a conventional clock, as well as the day of the year.

Satellite dissemination. Another means of time dissemination that could potentially provide a high-accuracy, reliable, worldwide system is the transmission of radio time signals from satellites. There are a number of possible configurations to consider. The geostationary or low-altitude satellite has the advantage that one satellite can provide continuous coverage to nearly one third of the earth's surface, except near the poles, with little variation in signal path delay. A high-inclination low-altitude satellite can provide worldwide coverage, but only on an intermittent basis. An additional disadvantage is that the range changes substantially and continuously during a time transferal.

It is easier to maintain a clock on the ground than in the satellite, but the satellite must contain a transponder that relays a timing signal from the master station to the user, as shown in Fig. 3. From a practical point of view, it is not reasonable to use this approach with a low-altitude orbiting satellite, since a worldwide network of ground stations would be required to provide a time signal continuously to the satellite for relay. Thus, an onboard clock appears more suited for low-altitude satellites.

In a *one-way broadcast*, the user receives a signal from the satellite, much as he receives a signal from a standard HF broadcast. The propagation delay is usually obtained from a set of orbital elements. Experience indicates that path delay can be determined to about 10 μs.[10]

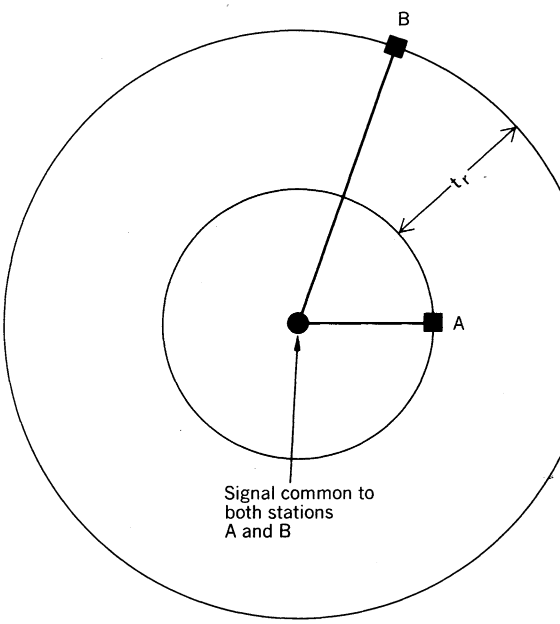
With the *two-way system*, no orbital elements are required, and, in fact, it is not even necessary to know the locations of the master and user stations. This method requires the exchange of signals between the master and slave stations (Fig. 3), which allows the master station to determine the round-trip path delay from master to satellite to slave and return. At the frequencies commonly employed the atmospheric effects are small, so that the one-way path delay equals half the round-trip delay. Experiments in the VHF and UHF bands indicate that with inexpensive equipment, accuracies of a few microseconds can be achieved, and with more sophisticated equipment, 0.1 μs. Even better results have been achieved with military satellites containing microwave transponders.[11] In these experiments the time information has been included in ongoing communications so that it is not readily available to nonmilitary users. Also, the necessary equipment is relatively expensive and complex. Nevertheless, the experiments indicate the potential of two-way satellite time dissemination in the microwave region.

Several one-way experiments have been conducted with low-altitude satellites containing onboard clocks. When accurate orbital elements are available, it has been possible to achieve accuracies in the 10- to 50-μs region.[12,13]

As a means of upgrading existing standard time and frequency broadcasts, the one-way broadcast from a geostationary satellite is probably the best compromise. The great majority of civilian users do not need the high accuracy provided by two-way systems with the attendant complication to both receive and transmit from each site. The one-way system provides large geographical coverage with greater reliability and considerably better accuracies than standard HF time and frequency broadcasts. Although no such broadcast presently exists, international allocations have been assigned at 400.01 $\pm$ 0.05 MHz and 4272 $\pm$ 2 MHz for downlinks and 6427 $\pm$ 2 MHz for an uplink.

An interesting variation on satellite time dissemination has been developed by the Jet Propulsion Laboratory. A radar signal at 7150 MHz, directed toward the moon, is reflected back to earth and is recorded by one of several existing ground stations to be synchronized. The one-way path delay is computed from the position of the moon and ground stations. With this method accuracies of $\pm$20 μs have been achieved.[14]

FIGURE 4. A transfer standard link. Differential time between stations = t_r = r/signal velocity.



Transfer standard technique

The signals described so far are specifically designed for time and frequency dissemination or are suitable for dissemination because of the inherent stabilities and repetitive nature of the signals. Another means of time transferal uses signals that neither are designed for time dissemination nor even are necessarily repetitive or referenced to a stable clock. In fact, the method doesn't even require cooperation from those responsible for the signal.

Figure 4 shows a radio station that occasionally emits a pulse of radiation, perhaps on a random basis. This random pulse may be used to synchronize the clocks at A and B as follows: If the clocks at A and B are already synchronized, then the arrival time difference at A and B is simply the time t_r it takes the pulse to travel the differential distance r. If t_r is known and is constant with time, then any clock error will be apparent, since the measured clock difference will no longer equal t_r, the additional difference being the amount of the clock error.

In 1965 this technique was applied to television synchronization pulses over a microwave network linking Prague, Czechoslovakia, to Pottsdam, Germany.[15] Since that time the method has gained wide acceptance, and recent measurements in the United States have achieved accuracies of better than 1 μs with an rms day-to-day stability of about 30 ns.[16]

Another part of the television signal has proved useful for frequency information. Each television sync pulse ends with a few cycles of signal at a frequency of 3.57954 . . . MHz, which is used as a phase reference in implementing color television. The three major networks stabilize the color subcarrier with rubidium oscillators. Measurements on the color subcarriers indicate that a precision of about one part in 10^{11} can be obtained in about 15 minutes.[17] These measurements can be meaningfully related to standard frequency since the NBS publishes the frequency offsets of the three networks.[18]

Television time code

The great stability of the television transfer standard technique for time dissemination has led NBS to investigate extensively the possibility of incorporating an unobtrusive time code into the television format. This has been accomplished by inserting, at the television studio, a time code into one line of the television signal format.[19] This code is referred to a cesium clock, also at the studio. The line used occurs during the vertical blanking interval, which appears as the horizontal bar that rolls across the television screen when the vertical hold is maladjusted. Special equipment can remove the time code and display the time information. Two options are available: a digital display of hours, minutes, and seconds on the television screen, or, where more precise time is needed, a display of the time difference between the television time "tick" and the user's local clock to a resolution of 1 ns. Because of path instabilities, the accuracy of the system is about 100 ns if the user is within the local service area of the television station and about 1 μs at remote locations where the signal reaches the user primarily by microwave. In both cases the path delay must be calibrated and must be accounted for.

Portable clocks

An obvious way to synchronize is to transport a clock between the clocks that require setting. This method is used extensively today, especially by the military, to synchronize clocks at locations that do not have access to radio time broadcasts or for which such broadcasts do not provide the necessary accuracy. Typically, portable cesium clocks are used, and a typical closing error after a trip of about ten days is 1.0 μs. The degree of accuracy that can be achieved is enhanced if the clock can be transported quickly. Techniques have been developed to facilitate this. The portable clock is flown over the remote location, and the time is transferred via radio signals between the aircraft and ground station. The path delay either can be calculated from the known positions of the aircraft and ground station or measured directly via a two-way radio exchange. Experiments indicate that the path delay measurement with a two-way exchange is accurate to 30 ns or better.[20] In general, drift of the portable clock time will contribute the predominant error for flight times in excess of a few hours.

Very-long-baseline interferometry techniques

One of the most promising techniques, where extremely high accuracy is required, involves an adaptation of procedures developed by radio astronomers for long-baseline interferometry. In a curious way this technique has led us back to where we started—the observation of a star. Observations are made of a star at two locations, A and B (Fig. 5). If A is the master-clock location, and the clock at B requires synchronization, the time τ, can be calculated from the known direction of the star and the locations of

Keeping up with the times

In 1658 the King of Spain offered 60 000 ducats to "the discoverer of longitude." One hundred and twenty-five years later the problem had still not been solved, so the British government came forward with an offer of its own: 20 000 pounds. Although scientists of that period realized the key to determining longitude involved a combination of astronomical observations and time measurements, no clock was capable of keeping good time on the high seas. Then, in 1735, John Harrison, an Englishman, presented a working model of his temperature-compensated pendulum clock to the Board of Longitude. After many trial demonstrations and several models later, Harrison received the full reward.

Harrison's clock kept time to about III seconds a day. Since then there have been significant advances in timekeeping technology, culminating with today's devices based on atomic phenomena. Navigators using Harrison's clock were soon to discover that different locations on the earth yielded different Universal Time values—a result of the then unknown wobbling of the earth on its axis. A second correction was made in 1935, when seasonal changes in the earth's rotational rate were discovered. Consequently, when one talks of Universal Time, he should specify the UT scale: UTO, John Harrison's time scale; UTI, a scale that takes into account the earth's wobble; UT2, a scale that corrects for variations in the earth's rotation; or UTC, the new Coordinated Universal Time System.

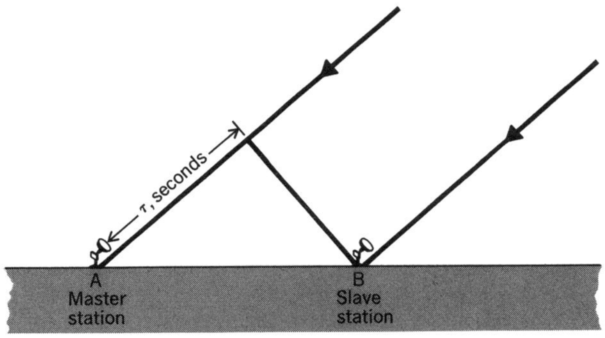


FIGURE 5. Clock synchronization using adaption of long-baseline interferometry. In this example, the signal from the star will arrive at B τ seconds before it arrives at A. τ can be calculated from the known direction of the star and the locations of A and B.

A and *B*. If a cross check of the clocks at *A* and *B* indicates a time difference other than τ, the discrepancy is the amount that the clocks are out of synchronization. This technique could provide 1-ns synchronization over continental distances.[21]

Comparison of dissemination systems

Many factors must be considered before the best system, or combination of systems, can be selected for a particular application. Figure 2 shows some typical time requirements by various categories of users and indicates systems that could meet the requirements. Nevertheless, this illustration only refers to accuracy, which is only one dimension of what is really a multidimensioned problem.

Table I compares some of the systems discussed in this article in terms of several important characteristics of dissemination systems. The ratings of good, fair, and deficient are both arbitrary and broad. In the context of this discussion, they may be helpful for purposes of comparison and evalution.

Accuracy of frequency synchronization refers to that accuracy with which frequency standards can be made to agree within some frame of reference. As with time transfer, the three basic ratings are in terms of the classes of accuracy users shown in Fig. 2.

Accuracy of date transfer refers to that accuracy with which time can be relayed to a given location. The numbers given are believed to be realistic for most users; it must be recognized that these numbers must be adjusted for either extremely favorable or unfavorable conditions and locations. The ratings of good, fair, and deficient are referenced to the needs of high-, medium-, and low-accuracy users, as shown in Fig. 2.

Ambiguity applies to that interval of time to which a given system or technique can provide identification with certainty. The larger this interval, the more information the system must supply, and the less ambiguous it is. In some cases two values are shown: One is the basic period of a given carrier frequency, sequence, or audible tone; the other, by means of time code, provides date information for periods up to a year. For instance, a time system consisting of pulses at 1-minute intervals has an ambiguity of 1 minute for all who don't know the time to ±0.5 minute or better. The NBS television system, using the coded data displays, has 24-hour ambiguity.

Coverage refers to the region in which the dissemination technique can be used to obtain the stated accuracy. In many cases special considerations such as ground wave versus sky wave, propagation over land or water, and availability of television line networks may affect the coverage of a specific signal.

Percent of time available describes the operating time of a service—that is, continuous (good), a certain portion of a day (usually specified fair), or only occasionally, irregularly, or by special arrangement (deficient). Interruptions caused by propagation conditions such as sudden ionospheric disturbances, VLF diurnal phase shifts, or HF ionospheric disturbances are not considered.

Reliability estimates the degree of influence on the operation of a system of such factors as propagation conditions, system components in satellite environment, and rerouting of television network programs.

Receiver cost for stated accuracy refers to the relative cost of an appropriate receiver and antenna system for obtaining the stated accuracy of a given technique. Auxiliary equipment such as oscilloscopes and digital counters is not included. A deficient rating implies a cost greater than several thousand dollars, fair refers to a cost in the $1000 to $2000 range, and good indicates a cost less than $1000.

Cost per calibration considers factors such as the cost of required instrumentation to calibrate the path delay.

Number of users that can be served refers to the probable number of users for a given dissemination technique, assuming regular availability of the service and considering the equipment costs involved. For example, the television technique is considered to have more potential users than the WWV broadcasts, even though both cover the continental United States, because most homes have television receivers that could have the time display feature at little extra cost.

Operator skill required for stated accuracy describes the degree of difficulty in making a time/frequency measurement to a stated accuracy. A good rating is shown if the time information can be obtained simply from an oscilloscope display or a counter reading. A fair category indicates that the user must process the data to obtain the required information, make multiple measurements or select particular cycles of a radio signal, and/or use specialized receiving techniques. A deficient rating indicates that complex procedures and special skills are required for a given technique.

Some shorthand notation is used in Table I in connection with the satellite techniques. Passive describes a satellite that relays time signals from a ground reference station to users. Active describes a satellite with an onboard clock. A stationary satellite is earth-synchronous or geostationary, and an orbiting satellite is one with a period of revolution other than 24 hours.

These ratings are relative and somewhat arbitrary. Indeed, a system with a deficient rating may be the best choice for many users. A severe limitation on the usefulness of Table I is that it reflects judgments of all parameters of a given system and assumes that a user desires the highest accuracy normally available from the system. In the case of Loran-C, for example, use of the sky wave is reduced, with the result that coverage is rated deficient.

A system designer probably will be forced to make

I. Comparison of dissemination systems

	Dissemination techniques	Status (1)	Accuracy-frequency synchronization	Accuracy for date transfer	Ambiguity (4)	Coverage for stated accuracy	Percent of time available	Reliability	Receiver cost for stated accuracy	Cost per calibration	Number of users that can be served	Operator skill required for stated accuracy
HF/MF radio	Standard freq. broadcasts (WWV)	O	1×10^{-7} (Poor)	1000 µs (Poor)	1 day / 0.5 min	Hemisphere		Depends on conditions (Fair)				
	Navigation system Loran-A	O	5×10^{-11} (2) (Fair)	2–5 µs not UTC	(Poor)	Limited areas (Fair)		Depends on conditions (Fair)	(Poor)		Special areas (Poor)	(Fair)
LF radio	Standard freq. broadcasts (WWVB)	O	(3) 1×10^{-11} (Phase, 24 h)	Envelope ~50 µs (Fair)	1 yr /	Use (WWVB) limited (Fair)			Moderate (Fair)	(Fair)	U.S.A. (WWVB) Europe Others (Fair)	
	Navigation System Loran-C	O	1×10^{-12} gnd (3)	~1 µs (gnd) 50 µs (sky)	50 ms / Phase 10 µs	Special areas † (Fair)			(Poor)		Special areas (Fair)	(Fair)
VLF radio	Communication/SFB GBR, NBA, WWVL	O	1×10^{-11} (3)	Envelope 500 µs (Fair)	/ Phase ~50 µs	Global			(Fair)			
	Navigation system Omega	O/P	$< 1 \times 10^{-11}$ (3)	≤ 10 µs ■	Proposed code—1 yr. / Phase ~100 µs	Global			Moderate (Poor)	(Poor)		Time code (Poor)
Satellites (VHF/UHF radio)	Stationary satellites one-way	E/O	1×10^{-10} (24 h) (Fair)	10-50 µs (Fair)	Depends on format	Hemisphere	Stationary					
	Stationary satellites two-way	E/O	1×10^{-12} (24 h)	~100 ns	Depends on format	Hemisphere	(Poor)		(Poor)	Moderate (Poor)	(Poor)	(Fair)
	On-board clock (active) one way—low altitude	O	$\sim 1 \times 10^{-10}$ (24 h) (Fair)	0.5–50 µs	Depends on format	World	10–15 min per pass 2–4 per day (Fair)	Clock needs adjustment (Fair)	(Fair)	(Fair)		(Fair)
Portable clocks	Physical transfer	O	1×10^{-12}	100 ns*	1 day	Limited by transportation (Fair)	As needed		None	(Poor)	(Poor)	
	Aircraft flyover two-way	E	1×10^{-12}	≤ 100 ns	Depends on format	Limited by transportation (Fair)	As needed (Fair)		(Fair)	(Poor)	(Fair)	(Fair)
Television (VHF/SHF radio)	Passive—Line 10	O	1×10^{-11} (24 h)	~1 µs	1 day / ~33 ms	Network coverage (Fair)	"Live" programs	(Fair)			U.S.A. for example	
	Active—Line-1 (NBS TV time system)	E	1×10^{-11} (< 30 min)	< 100 ns ●	1 day / ~33 ms	Network coverage (Fair)		(Fair)			U.S.A. for example	
SHF radio	Microwave	E/O	$\sim 1 \times 10^{-13}$ (per week)	≤ 100 ns	Phase comparison	Local links (Poor)			(Fair)		(Poor)	(Fair)
	VLBI	P	5×10^{-14}	~1 ns	Depends on format	Hemisphere	As needed (Fair)		(Poor)	(Fair)	(Poor)	(Fair)

Good (white) Fair (pink) Poor (grey)

See text for an explanation of characteristics.
(1) Status of technique: O—operational, P—proposed, E/O—experimental operational.
(2) Estimates of day-to-day measurements within ~2000 km of Loran-A stations. These emissions are not coordinated with UTC and manually operated local crystal clocks drift. UTC—universal time, coordinated.
(3) From day-to-day phase measurements; for example, 1-µs-per-day phase change approximates one point in 10^{11} in frequency difference.
(4) Left-hand designation gives the shortest time interval that cannot be resolved. Right-hand number gives the basic ambiguity.
† By ground wave, 1600 km; by sky wave, thousands of kilometers depending on conditions.
■ With proposed time code.
* Closure after one day.
● Within local service area of television transmitter; path delay known.

compromises in choosing a dissemination service. He may have to trade receiver cost for reliability or accept a low percent of time available for high accuracy and good coverage.

The future

An underlying, unifying theme runs through most of the applications of time and frequency technology; namely, it provides a convenient basis for many different types of "pigeonholing" systems, ranging from scheduling one's daily activities to the functioning of modern communication and navigation systems. To a large degree the accuracy of time information required is related to the "reaction time" of the system in question. It doesn't make sense to meet a friend for lunch at 3 µs past noon. But with high-rate communication systems, accurate time is essential because a message may only last a few microseconds. Time and frequency are key ingredients in the efficient use of the radio spectrum. In fact, the initial purpose of early standard radio-frequency broadcasts was to provide a reference so that broadcast stations could stay on their assigned frequencies.

Advances in the state of the art of time and frequency now permit many of the older needs to be met. But, as in many fields, improvements lead to new applications. For instance, workers will no longer remain as specialized as they once were, but will become much more involved in the areas to which their techniques are applied. An example of this may be found in the new field of vehicle location. Until recently, vehicle location systems were intended only to aid the navigator of a ship or airplane. Accuracy of a kilometer or so is ordinarily quite adequate for such purposes. Nevertheless, to achieve this accuracy, radio determination systems such as Loran-C or Omega employ time or phase comparisons in the microsecond range. Frequencies transmitted are low to achieve coverage of large areas of the world.

New requirements for vehicle location are, however, somewhat different. In the case of a bus, taxi, or police car, it is the dispatcher, not the driver, who wants to know the vehicle location. Further, to free the driver for other functions, the system should operate without the driver's assistance. Increased accuracies are needed: 150 meters or better.

A system for meeting these requirements—automatic vehicle location (AVL)—can create complex problems. Higher-frequency bands may be required to permit higher position accuracies. Exploration of bands as high as UHF is already taking place. Problems are severe: Densely spaced, metal high-rise buildings cause extreme multipath effects, and noisy city environments greatly increase interference effects. The location system must be integrated with a communication system to report vehicle location to the dispatcher on command—with consideration for efficient spectrum utilization. This already complex system must then be integrated into a command and control system for an entire fleet of vehicles, which may include Teletype systems, hard-copy capability, data bank access, and two-way voice communication systems. And, as if the problem were not formidable enough, the squeeze on the availability of money means that economics becomes an important factor. On-board vehicle equipment costing more than the car is hard to justify, and existing facilities, such as commercial television or FM radio broadcasts, will need to be viewed critically. In effect, the time and frequency aspects of such a system must be compatible with many other requirements. And the time and frequency designer must become familiar with an increasing variety of problems outside his traditional field.

On the other hand, the great utility of time and frequency technology to numerous systems tends to encourage the generation and dissemination of specialized time scales in each system. Can we continue indefinitely in this direction? Clearly, the answer is no, because the electromagnetic spectrum is a limited resource. We no longer can afford to design a system based on expediency or an immediate sense of urgency. We must carefully consider our existing resources, and we must make sure that new systems serve a multiplicity of users on the broadest possible scale.

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