Characterization and Concepts of Time-Frequency Dissemination

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Abstract—Fundamental considerations that arise in designing a time or frequency dissemination system, are discussed and some dissemination methods are surveyed. A section on "Signal design for time and frequency dissemination" briefly summarizes radio propagation characteristics, discusses time signal format design, and considers how noise affects time and frequency signals.

We point out fundamental techniques of time and frequency dissemination and describe similarities between systems for time dissemination and navigation. The use of synchronous satellite transponders and commercial television systems for time dissemination is emphasized because of their great promise. No attempt is made to cover every existing dissemination system; some systems are treated elsewhere in this *Special Issue on Time Frequency*. The concluding section gives three categories of users according to their required accuracy and shows typical systems which can provide desired accuracies. Various dissemination techniques are charted and evaluated in terms of salient characteristics such as accuracy, geographical coverage, cost factors, and others. To alleviate an existing frequency spectrum problem, we suggest that designers of communication and navigation systems consider opportunities for including time and frequency dissemination in their systems.

I. Introduction

THE TIME AND FREQUENCY dissemination (TF/D) community has witnessed some startling developments in recent years. There was a time when the instabilities in oscillators were so great as to mask the instabilities in HF standards broadcasts. In those days the limiting factor in the error budget for a time dissemination link was the clock instability, not the uncertainty in the arrival time of the time mark.

The development of better clocks changed the situation. The accuracy of today's dedicated dissemination services cannot compare to the capabilities of today's time standards, and improvements in time standards are continuing. Dedicated time broadcasts through the earth's atmosphere already do not fully serve high-accuracy users. We believe that satellite systems and microwave communication networks will carry most of tomorrow's time dissemination services.

This paper takes note of some systems with requirements for time dissemination that exceed the capabilities of today's services. It discusses the fundamental considerations that arise in designing a time or frequency dissemination system, and it surveys some dissemination methods.

Section II describes terms and concepts that are used throughout the paper. The concepts are elementary but important. Lack of agreement in terminology has led to much confusion in recent years.

Section III begins with a brief summary of radio propagation considerations. In the discussion of formats, we introduce various concepts of arrival time and ambiguity. The effect of noise on time and frequency signals is considered.

Fundamental design considerations as well as descriptions of typical methods for TF/D are presented in Section IV. We emphasize TV and satellite techniques because of their great promise. No attempt is made to treat every existing dissemination system. Some important systems are described by other authors in this *Special Issue on Time and Frequency*. The concept of a "transfer standard" is developed and the similarities between time dissemination systems and ranging systems are explored.

The concluding section categorizes users according to their required accuracy, and compares salient features of important time dissemination methods. In the light of the congested frequency spectrum, we suggest that communication and navigation systems designers consider the advantages of including time and frequency dissemination in their systems.

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II. Fundamental Concepts

The purpose of this section is to consider some concepts and to establish some terminology that will be used later in the discussion of time and frequency dissemination.

A. Clocks

The fundamental component of timekeeping is a clock. A clock consists of a frequency standard, a scheme for counting oscillations and keeping track of the count, and a readout device for displaying the count. An interpolation device may be added for use between counts. A clock is a device which accumulates the cycles of an oscillator and presents the result in some convenient form.

The oldest clock of all uses the rotating earth. Man counts sunrises and keeps track of the count with a calendar. The characteristic unit of this clock is one day. A sundial or a wall clock may be used to interpolate between successive sunrises. A more recent clock makes use of the cesium-atom resonance in controlling the slaved oscillator, and uses digital electronic circuitry to keep track of oscillations and to display the count [1].

The cesium clock is much more stable than the earth clock; that is, the length of one atomic second is very nearly the same as the length of any other atomic second. The length of the day may vary considerably, however. The atomic clock is more stable than the earth clock, and they get out of step. It is possible to alter the atomic time scale so that it will stay more or less in step with the earth time scale, but in so doing a hard choice must be made. If the atomic time scale were to have the same number of seconds every year, then the length of the second would have to be changed periodically, i.e., a "rubber second" would be used. Since the length of the atomic second is held constant, then the number of atomic seconds in one year is not an invariant. (Recently the International Radio Consultative Committee (CCIR) has adopted the usage of occasional "leap seconds.") A discussion of the recent implementation of the latter alternative appears elsewhere in this issue [2].

Three of some basic concepts encountered in the discussion of time and frequency are 1) date, 2) frequency (dimensionally, the reciprocal of time interval), and 3) time/frequency synchronization.

B. Date[1]

The date refers to the name of a specific instant on an ordered scale, e.g., 1972, July 12, 12 h, 24 min, 43.01200 . . . s. In other words, the date is the time of an event reckoned from some arbitrary origin. This concept of time has usually been related to the location of the sun but that relationship is complicated.

C. Frequency

Frequency and time interval are related inversely (dimensionally). To measure the frequency of occurrence of some phenomenon one counts the number of occurrences during a measured interval of time. Time interval refers to duration. A time interval of 1 h can be measured correctly by a clock that is not on time but is running at the correct rate.

D. Synchronization

For a system to be time synchronized the clocks in the system must read the same time as each other, but not necessarily the same as any formal time scale. For example, the World War II movies always depicted the fighter pilots synchronizing their watches to the squadron leader's watch, not to WWV.

The resynchronization interval of a communication system could be regarded as its characteristic unit of time. It may bear little resemblance to the time unit of formal time scales. A coherent communication system may pass messages lasting only a few tens of microseconds. If the person to whom the message is addressed is not synchronized in time with the sender he may very well miss the message.

It is not necessary in principle for synchronized systems to align their oscillators or time scales with those of the organized time and frequency community, but there are sometimes benefits to the system or to others external to the system if alignment is allowed for in system design. The system benefits to the extent that redundant resynchronization capabilities may exist in the form of standard time and frequency broadcasts or other accessible communication or navigation systems which are aligned. Correspondingly, other time and frequency users may derive benefit if a designer aligns his system.

The options for timekeeping are many. The cost and complexity of alternative methods are related to the required accuracy, the location of the user, and the required resynchronization interval. A man sailing a boat in the Pacific Ocean requires time for navigation. He needs a clock whose accumulated errors during the voyage will be very small. He may choose an expensive clock which he sets just before he leaves port. He may prefer a less expensive clock which he sets every day with a radio receiver tuned to a standard time broadcast signal such as WWVH or JJY.

Most careful users can obtain 1-ms time accuracy using a receiver tuned to a high-frequency standard time broadcast; some can do better. Since the time tick is on time when it leaves the transmitter, corrections must be made for the travel time of the radio wave. It takes about 3 μs for a radio wave to travel 1 km (propagation delay). Therefore, the time tick will arrive 3 ms late at the antenna of a user 1000-km distance from the transmitter. An additional allowance must be made for the signal to pass through the receiver (receiver delay). The 1-ms error mentioned above is related to the uncertainty associated with the measurement of the signal arrival time. Other problems related to radiowave propagation will be discussed later.

Standard time and frequency broadcasts such as WWV, WWVH, CHU, and JJY are more than adequate for everyday needs. The launching of earth satellites during the late 1950's, however, required worldwide tracking networks to be accurately synchronized. The availability of portable atomic frequency standards stimulated planning for new navigation and communication systems requiring microsecond synchronization.

A basic requirement of some systems is that all clocks show the same time. If synchronization is lost because of a power failure or other cause, the clocks must be reset. One method is to carry a portable clock from a time reference station to reset the clock which has stopped. This and other methods will be considered later.

E. Users of Time

Time is a basic dimension in the physical world. It is the dimension of which man is most often conscious in his activities. Many years ago man rose with the sun. The visible sun was all the clock he needed. As his activities increased in sophistication he began to require interpolation devices to subdivide the day into smaller increments. The shadow on a sundial was a daytime indicator; the notches on a burning candle could serve at night. (The latter did not comprise a clock as we have defined it since no frequency standard was involved.) Today we use the wrist watch or wall clock to meet our casual needs and the crystal or atomic standard for our exacting needs.

The second of time today is based upon the atomic second, but astronomers, navigators, and others are served best by a time scale which permits them to relate the time displayed by their clocks to the earth's rotation angle. For the convenience of such users the UT1 time scale is provided. This scale is generated by the rotating earth with corrections made even for the earth's polar motion.

Today, many people depend on the electric wall clock whose frequency standard is the power companies' generator. In the United States the power utilities generally synchronize their generators to the National Bureau of Standards' low-frequency broadcast, WWVB [3]. Hence most electric clocks run at the same rate. Such clocks are normally set on time by referring to radio time announcements or by dialing the time on the telephone. Radio time signals can be used either to perform a clock function or to set clocks.

Many systems exist which are able to disseminate standard frequencies and standard time signals with sufficient convenience and accuracy for most users in metrology. These same systems may be used to disseminate other standard units of measurement, including those for electromotive force (volt), length (meter), and attenuation (decibel), among others. These dissemination systems, together with the inherently high precision of frequency standards and of frequency/time metrology, may help to establish

[1] See key word index for definitive discussion of epoch (date).

a unified standard for measurement. The progress and feasibility for a unified standard is discussed by Halford *et al.* [4].

III. Signal Design for Time and Frequency Dissemination

In its transit from reference station to user, a time signal must pass through some transmission medium. This medium alters the signal and will contain extraneous radiations which will affect it. The radio propagation medium and the effects of noise are considered in this section.

A. Radio Propagation Effects

With the exception of portable clock methods, all techniques discussed in this paper utilize radio waves to carry time and frequency information from a reference transmitter to a distant user. The words of NBS scientists 40 years ago still hold true: "Radio waves of which the frequency is carefully controlled and accurately known furnish a standard of frequency which is simultaneously available everywhere that the waves can be received" [5].

Radio has offered attractive means of transferring standard time and frequency signals since the early 1900's. In 1932 the frequency stability of the WWV primary standard, and hence of the transmitted signal, was about 1×10^{-5}. The full accuracy could be recovered from the signal received by a user. Today the accuracy of the transmitted signal has been improved by about 7 orders of magnitude, but the accuracy of the signal as received has not improved nearly as much.

In a low noise, outer space environment, radio signals suffer little degradation. In the earth's atmosphere, however, there are effects which limit the accuracy and stability of radio time and frequency signals.

Time and frequency broadcasts can be classified in a number of ways. One useful distinction is between those with carrier frequencies low enough to be reflected by the ionosphere (below 30 MHz) and those sufficiently high to penetrate the ionosphere (above 30 MHz). Signals from the former may be observed at great distances from the transmitter, but they suffer from ionospheric propagation anomalies that limit accuracy; the latter are restricted to line-of-sight applications: they show little or no signal deterioration caused by propagation anomalies. The most accurate systems are those which use the higher line-of-sight frequencies. Broadcasts using lower carrier frequencies serve the largest number of users.

Descriptions and mathematical models of the propagation medium that are useful in designing time dissemination systems are in the literature [6]–[8]. A summary description of bands 4 through 10 is given in Appendix I.

B. Format Considerations

Consider a timing signal consisting of some waveform repeated at uniform intervals of time T (see Fig. 1). Knowing the time requires knowledge of the number of units and fractional units ΔT that have elapsed from the starting point T_E. The path delay t_d is the elapsed time between the broadcast and the reception of the signal. Determination of the path delay is not a trivial problem but we will assume that it has been done in this example.

In the design of signals for time dissemination, it is important to know whether the user is primarily interested in obtaining T_E, ΔT, or both, from the timing signal. Is the requirement for date? for frequency? or for both? Measurements must be made in the presence of noise which can cause the signal arrival time to jitter δ_t (illustrated by the double arrow in Fig. 1). There is a wide

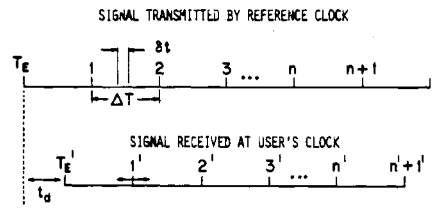

Fig. 1. A time dissemination link.

variety of noise which may be encountered, but we will assume an additive noise power with a uniform spectral density N_0 (gives rise to white phase noise).

Arrival Time/Frequency Tradeoff: Optimization of a signal for time is done at the expense of its usefulness for frequency. Consider a time signal which consists of a single pulse of duration q of a carrier wave of frequency f. It is desired to designate a certain moment in time (the date) with respect to T_E. Assume that the pulsewidth can be adjusted but that the energy contained in the pulse is to be held constant. The standard deviation σ_t in the time of arrival of the leading edge of this signal is [9]

$$\sigma_t = \frac{t_r}{(2\,\mathrm{SNR})^{1/2}} \tag{1}$$

where t_r is the pulse risetime and SNR is the pulse signal-to-noise power ratio. The bandwidth occupied by the signal is given approximately by $1/t_r$. If q, the pulse duration, is decreased while the energy in the pulse is held constant, then the SNR will be increased and the arrival time can be measured more accurately. Since the signal consists of a single pulse, the best way to obtain frequency (i.e., interval information, ΔT) is to measure the carrier frequency f of the pulse. The standard deviation of the carrier frequency measurement σ_f is a function of the reciprocal of the duration q of the pulse. Thus the measurements of arrival time and of frequency are related in this example. Optimization of the signal for precise time measurement reduces its usefulness as a source of frequency.

Arrival Time/Frequency Optimization: Assume now that the single pulse of energy lasts for q seconds, and that the frequency of the carrier can be measured to the precision required by the user. Is there any way to improve the time of arrival measurement without sacrificing the frequency measurement?

The arrival time measurement depends on the SNR at the leading edge of the pulse and not upon the duration of the pulse. This suggests that the arrival time measurements could be improved by increasing the number of leading edges.

Let us divide the single pulse, of duration q and signal level S, into m pulses, each of duration q/m, with the same signal level S. The total signal will consist of m pulses, but the aggregate duration of these m pulses will still be q. The precision of the frequency measurement will not be deteriorated. Since there will be m leading edges to measure, the standard deviation of the arrival time measurement will be decreased by a factor $(m)^{-1/2}$, provided that the m measurements are independent. This requires that the time between successive pulses be at least $1/B_{bw}$ seconds, where B_{bw} is bandwidth; otherwise, the noise fluctuations on successive pulses will not be independent.

Ambiguity and Waiting Time: The time of arrival measurement has been improved without degradation of the frequency measurement, but another problem has been introduced. Unless additional information is available, it is no longer possible to determine which one of the m pulses represents the time. Thus the cost of improving the arrival time measurement, while maintaining the same frequency error, is the introduction of ambiguity. An additional benefit is derived once the ambiguity is resolved, however. The user can obtain time information more often.

Consider the price of eliminating the ambiguity. In a timing system which consists of 1 pulse per second (pps), no user has to wait more than 1 s for a "seconds marker." For those users who do not already know the time to the nearest second, however, the system is ambiguous. The system could be made unambiguous for such users by going to a lower pulse rate. But, then the users who already know the time to the nearest second would have to wait longer for a timing mark.

Identification and Ambiguity: If it is desired to maintain the time markers at the 1 per second rate and still satisfy the users who do not know the time to the nearest second, then additional information must be provided to resolve the ambiguity. WWV uses such a system: the basic pulse train is supplemented by voice announcements.

If a fixed quantity of energy is available per unit time, allocating energy for identification (to reduce the signal ambiguity) will result in reduced knowledge of the time of arrival of the pulses. This is attributable to the lowered SNR. Thus reduced ambiguity is obtained at the cost of reduced measurement precision.

One user of a 1 per second timing signal may desire that certain pulses be omitted (easier identification). A second user may desire that all pulses be retained so that he may improve his measurement precision. Thus a signal can be too precise (ambiguous) for one user and overidentified for another.

Arrival Time and Ambiguity: Is it possible to design a signal which is optimum for both arrival time measurements and elimination of ambiguity? Consider a signal consisting of a group of coded pulses, each of which is coherent with the time tick. One of the pulses in the group could be designated as the time mark. It would appear that both arrival time and ambiguity needs have been satisfied optimally. It can be shown, however, that optimum determination of the time of arrival of the signal requires a prior knowledge of the signal shape. That is, one must not only have complete information about the code format but he must know which component of the code will arrive next. But, if he already has all that information then the only new information he can receive from the code is related to arrival time. Thus he cannot simultaneously identify optimally and determine arrival time optimally. If he does not know which component of the code will arrive next he could accelerate his identification process by using a number of parallel decoders optimized for each of the possible signals.

There does not appear to be any general method for designing signals which will simultaneously satisfy the requirements of ambiguity, time of arrival, and interval (or frequency) measurement. In the pulse code example above, the reduction of ambiguity requires a signal with frequency components spread throughout the available bandwidth. High precision in time of arrival measurement requires that frequency components should be concentrated near the edges of the available bandwidth (fast rise pulse).

C. Noise Considerations

The previous discussion has treated the effects of noise on a single pulse. It is possible that a signal may reach a user's location by a number of parallel paths. Some of the paths may be subjected to Doppler effects imposed by the motion of the ionosphere. Therefore, a pulse received by a user is actually a composite of a number of pulses that came by parallel and somewhat different paths. A complete analysis of the resulting composite pulse would require a detailed path delay calculation.

In a multiple-tone VLF time system the accuracy with which a user can obtain time cannot exceed the accuracy of his path delay prediction. His ability to predict path delay is limited by his knowledge of the reference transmitter and user locations and by his knowledge of the propagation medium.

Additive and Multiplicative Noise: Noise affecting time dissemination systems falls into two categories. The first is usually called additive noise and refers to noise energy added to the spectral region occupied by the signal. Examples are ignition noise, noise generated by the receiver, atmospheric noise, and cosmic noise. The effects of additive noise can be made as small as desired by increasing the strength of the signal.

The second category, multiplicative noise, is produced, for example, when the propagation medium distorts or modulates the signal. It cannot be diminished by increasing the signal strength.

Diversity Techniques: Diversity techniques have been developed to offset multiplicative noise for communication channels. They have not generally been applied to time dissemination. The technique involves obtaining a large number of independent measurements of the signal for a given amount of signal energy. In principle, if the noise in the measurements always adds incoherently and if the signals add coherently, the lack of measurement precision due to the multiplicative propagation noise can be made arbitrarily small, provided the available energy is divided into enough diversity elements. Eventually the additive noise will dominate over the multiplicative noise and will represent the fundamental limitation.

With some kinds of diversity it is not necessary to divide the available energy into packets in order to reduce the signal energy per packet. An example is space diversity. Here the signal is observed simultaneously at points on the ground sufficiently far apart for the noise fading to be uncorrelated. Other examples are polarization and angle of arrival diversity. (For further discussion, see [10], [11].)

Multiplicative Noise and Path Delay Calibration at VLF: It has been demonstrated theoretically [12] and experimentally [13] that the velocity of 10-kHz to 20-kHz radio signals is nearly constant, at least at great distances from the transmitter. Near the transmitter, however, the average VLF signal velocity between the user and the transmitter changes in an irregular way as a function of distance [14]. (Above 20 kHz there is some evidence that even at great distances from a transmitter the signal velocity as measured at a receiver continues to be irregular [15].) In general, below 20 kHz the transition from regular to irregular occurs at a distance of about 10 000 km from the transmitter.

There is a seeming paradox associated with VLF. A VLF signal is more useful as a source of time to a user at a great distance from the transmitter than it is to a nearby user. But the SNR is highest near the transmitter. If better methods of predicting the behavior of VLF signals in this irregular region could be developed, then receiver designers could take advantage of the high SNR and serve the needs of a vastly increased number of users.

Because of the great importance of the irregular region, it will be considered in more detail. Consider a simple two-frequency timing system with two closely spaced CW signals at frequencies f_1 and f_2. In this system, the beat frequency, $\Delta f = f_2 - f_1$, is used as a coarse time marker to identify a specific cycle of either carrier frequency. This removes ambiguities, and a more precise time of arrival measurement is made at the higher carrier frequency. The difference frequency signal will travel from transmitter to receiver with a group velocity which depends upon the phase velocity versus frequency characteristic of the propagation medium. Specifically, the group velocity V_g is related to phase velocity V_p by the expression

$$V_g = \left[\frac{d(\omega/V_p)}{d\omega}\right]^{-1} \qquad (2)$$

where ω is the angular frequency. The concept of group velocity breaks down if the derivative $[d(\omega/V_p)]/d\omega$ is not well behaved. In a dispersive medium, such as exists at VLF, V_p is a function of ω; so the group delay t_d over a path r is given by the expression [16]

$$t_d = \left[\frac{r}{V_p}\right]\left[1 - \frac{\omega}{V_p}\frac{dV_p}{d\omega}\right]. \qquad (3)$$

At VLF the phase velocity versus frequency dependence cannot be expressed as a simple function of the properties of the propagation medium, except perhaps at great distances from the transmitter. The most accurate results are obtained from numerical solutions of Maxwell's equations with some realistic model of the ionosphere [17], [18]. Since the difference frequency may travel with a group velocity that is different from the phase velocity of either one of the two carrier frequencies [19], the difference frequency signal may slip in phase with respect to either one of the carrier frequencies as a function of distance from the transmitter. This could lead to incorrect cycle identification of the carrier frequency unless the difference in velocities is known.

It has been demonstrated that at great distances from the transmitter one can correctly identify a cycle by using different group and phase velocities [20], [21]. Unfortunately, the concept of group velocity applies only at great distances from the transmitter, where the phase velocity versus frequency characteristics are well behaved, i.e., $[d(\omega/V_p)]/d\omega$ is well behaved.

Near the transmitter a different approach must be used as illustrated by considering the propagation of a VLF pulse.

There are two distinct effects which must be considered. First, the average propagation velocity of the pulse (group velocity) may be equal to or less than the velocity of light. Second, the pulse may be changing its shape as it propagates through the medium. If a particular point on the pulse has been tagged as the time reference point at the transmitter, it is necessary to determine how this "tag" point is mapped into its new position as the pulse distorts during its propagation away from the transmitter. If this is unknown it will not be clear to the user which point on the received pulse represents the reference point as transmitted.

Having correctly identified the tagged point, one must recognize that the average pulse velocity may be less than the velocity of light. A multifrequency VLF system is somewhat similar to the propagation of a pulse in the following sense. A short pulse of length t_s consists of a group of Fourier frequencies, i.e., a number of Fourier components which occupy a spectral region approximately equal to $1/t_s$. In a dispersive medium such as the ionosphere, each one of these Fourier components will travel with a different phase velocity [16]. In a sense then, when a VLF tone system is used, the Fourier components are sent one at a time. If the user could store the received tones, he could add them together to produce something looking like a pulse.

This composite waveform would have some well-defined shape as it left the transmitter. Because of the dispersive properties of the propagation medium, this composite waveform will change in shape with increasing distance until it has reached the region where the phase velocity is well behaved. Beyond that point the composite waveform will not change further with increasing distance.

To use the time system for accurate transfer it is necessary to know in detail the structure of this composite waveform as a function of distance from the transmitter. Similarly, use of the VLF multitone system for accurate time transfer requires detailed knowledge of the phase versus frequency and distance characteristics of the signals.

IV. Time and Frequency Dissemination Techniques

A. *Dissemination System Design Considerations*

A time/frequency dissemination system can be characterized by its accuracy, ambiguity, repeatability, ease of use, cost to the user, and number of users served. These concepts will be introduced by reference to a hypothetical dissemination system.

Consider a very simple system consisting of an unmodulated 10-kHz signal as shown in Fig. 2. A positive going zero-crossing of this signal, leaving the transmitter at 0000 UT, will reach the receiver at a later time equivalent to the propagation delay t_d. The *accuracy* of the user's measurement of time can be no better than the accuracy with which this delay can be predicted. Since all cycles of the signal are identical, the signal is *ambiguous* and the user must somehow decide which cycle is the "on time" cycle. This means, in the case of our hypothetical 10-kHz signal, that the user must already know the time to $\pm 50\ \mu s$ (half the period of the signal). Assume that the user is not in a position to compute the propagation delay but that the delay is very nearly the same from day to day, i.e., it has good *repeatability*. If a portable clock can be carried to the user once, he can "calibrate" the propagation delay and accurately set his clock in the future.

Some users, geophysicists for example, are interested in making time coordinated measurements over large geographic areas. They want all measurements to be referred to a single time source. Therefore, they would like all measurement stations to be able to hear the same time broadcast, i.e., the *coverage* of a system is important. Another important characteristic of a timing system is the *percent of time the service is available*. The man on the street who has to keep an appointment needs to know the time only to a minute or so. Although he requires only coarse time information he wants it on demand so he carries a wrist watch that provides the time to him 24 h a day. On the other hand, a user who needs time to a few microseconds normally has a very good clock which he updates only once or twice a day.

Another characteristic of a dissemination system is its *reliability*, the likelihood that a time signal will be available when it is supposed to be. At times one cannot receive an HF timing signal because of propagation fadeouts.

Some important *economic considerations* are the cost to establish and maintain the system, the number of users that will be served by the system, and the cost to the user in terms of operator skill and equipment investment. If a service is to offer a number of accuracy levels, economic factors include receiver cost for a stated accuracy, operator skill for stated accuracy, and the number of users served at a stated accuracy. It seems reasonable to design a dissemination service so that the cost to the user for a

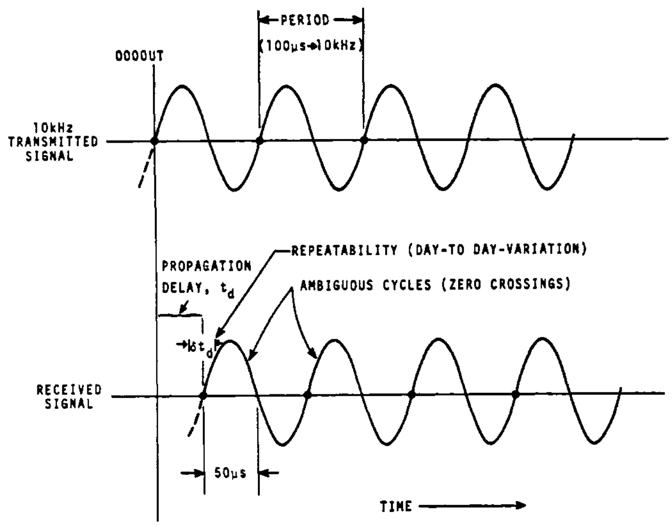

Fig. 2. A single-tone dissemination scheme.

particular time service should be directly related to the accuracy he requires.

B. Frequency from Time Measurements

Dimensionally, frequency is the reciprocal of time interval. It is no surprise, then, that a frequency dissemination service can be useful for timekeeping and that frequency information can be obtained from a time broadcast.

Any "time dissemination" service can be used as a source of frequency. If the time difference between a user's clock and the reference clock increases between measurements, the user knows that the oscillator in his clock is running faster than that in the reference clock, and he can compute his frequency offsets.

C. Portable Clock Carrying

There have always been and presumably will be applications for time synchronization that exceed the capabilities of dedicated time dissemination services for coverage or accuracy. Portable clocks can be employed to meet requirements which are hard to satisfy by other techniques. Basically, a portable clock consists of a stable oscillator whose output is integrated or counted by a clock mechanism to indicate time. The portable clock method consists of establishing the time of the portable unit (which may be a quartz crystal or atomic clock) in terms of the reference time scale prior to a clock synchronization trip. Usually, the clock is flown to a general area where the measurements are to be made, with intermediate transportation by auto. Self-contained batteries can maintain power for periods of hours. Time synchronization consists of bringing designated time pulses into coincidence or to fixed delay relationships. Frequency comparison can be made through phase intercomparison for a given time interval. At the conclusion of a trip the portable clock is again compared with the original time scale reference, and the time closure difference is distributed backwards as the deviation within which the portable clock measurements fall.

The forerunner of this method dates back to 1923 when W. G. Cady carried portable piezo resonators to compare frequency standards in Italy, France, England, and the U. S., and showed agreement to about 1 part in 10^3 [22]. Since the 1920's great strides have been made, and in the early 1960's Reder and Winkler transported atomic clocks over intercontinental distances and synchronized clocks to several microseconds [24]. A series of "flying clock" measurements, using portable atomic frequency standards, were made at laboratories located worldwide from 1964 to 1967 [23]. An average time change of about 5 µs in 16 months indicated an agreement of several national time scales to about 2 parts in 10^{12}. Also, in 1967 Swiss portable atomic clocks (cesium) were flown to various time centers in the U. S., Canada, and the Far East for time comparisons. At the conclusion of these tests, one of the clocks showed a time closure of 26.7 µs over a 255-day period (about 1 part in 10^{12}) when compared with the laboratory standard at the Cantonal Observatory [25].

The success of portable atomic clocks to bridge distance gaps between a master standard and user led the U. S. Naval Observatory (USNO) to establish, in 1968, a master clock location and six worldwide reference stations around the world [26]. Reference atomic clocks at each of the time stations are available for precise time measurements which can be referred to the USNO master clocks in Washington, D. C. These stations are coordinated by portable clock visits every few months. Time closures for a representative portable clock trip is about 1.1 µs [28]. As the USNO and NBS UTC scales are mutually coordinated to within $\sim\pm 5$ µs of each other [27], clock synchronizations at the USNO time reference stations can also be related to the NBS time scale within this tolerance (or even better *post facto*).

A major advantage of the portable clock method is that it is the principal means of microsecond clock setting and frequency synchronization without a dependent link to a master source. The clocks are transportable self-contained units requiring a minimum of comparison instrumentation. Limitations include the high cost of the clocks coupled with transportation expense. The clocks are usually hand carried and a (small) possibility always exists of clock failure during transit. Fortunately, the best clock for a particular application is not necessarily the most expensive or accurate one. Also, it is sometimes difficult to transport portable clocks to remote locations. (The U. S. Geological Survey required clock synchronization at Pitcairn Island in connection with their satellite triangulation program a few years ago. A clock was flown to the closest commercial airline terminal in the Pacific, where it was transferred to a ship. A longboat carried it through the breakers to the landing at Pitcairn.) Specific need, environmental conditions, budgets, and other considerations may all interface to dictate the optimum choice and/or compromise for a given portable clock measurement. The cost of portable clock comparisons may decrease in the near future with the availability of a new and smaller cesium-beam portable clock [29].

D. Aircraft Flyover Time Synchronization

Another method of time synchronization is a refinement of the portable clock technique. In aircraft flyover, planes carry an atomic clock and transmit a coherent time signal to synchronize a time scale at a receiving site. The method dispenses with cross-country and local transportation, reduces the time required to synchronize many remote locations, and affords the opportunity to synchronize inaccessible sites such as mountain or island stations, ships, other aircraft, etc.

Some aspects of this method were considered in connection with early aircraft collision avoidance studies. The method was first reported by Markowitz [30] and was recently refined by Besson [31].

The basic method of aircraft flyover synchronization is illustrated in Fig. 3. The *S*-band transmissions are amplitude modulated at a peak power of about 50 W. The passband is 10 MHz.

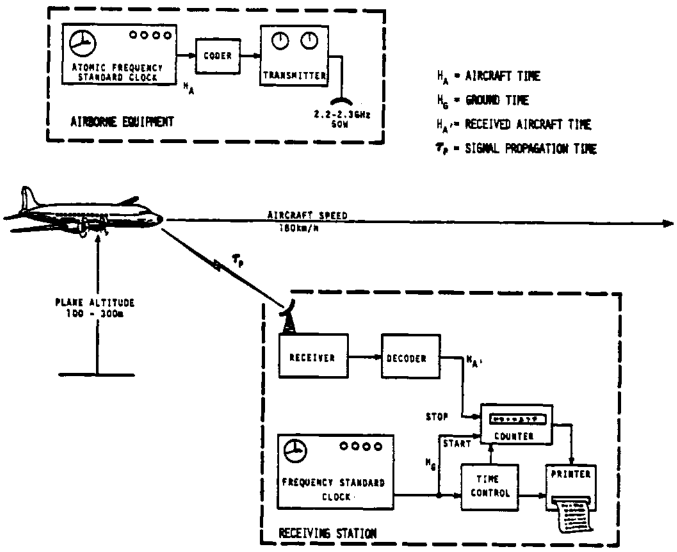

Fig. 3. Basic method of aircraft flyover synchronization.

The time scale is coded and sent at a 10-Hz rate permitting 10 time scale measurements per second. The receiving site uses a counter with 10-μs resolution and a readout which prints the deviations between the radio-received time scale and the local time scale 5 to 10 times per second.

Aircraft flyover determines the clock difference between the ground station time H_G and aircraft time H_A which is shown to be [31]

$$H_G - H_A = (H_G - H_{A'}) - (\tau_{TR} + \tau_P) \tag{4}$$

where

$H_{A'}$ received aircraft time at ground station; $= H_A - (\tau_{TR} - \tau_P)$;

τ_{TR} time delay of transmitter–receiver equipment (nearly constant);

τ_P time delay for aircraft signal to reach receiver, dependent upon aircraft location relative to receiver.

The evaluation of τ_{TR} and τ_P should resolve the time scale deviations, $(H_G - H_A)$. Two methods have been proposed.

Method 1: A one-way transmission from aircraft to user is employed in this technique. The aircraft passes over the site to be synchronized at low altitude (100–300 m) at a flight speed of about 50 m/s. The observed time scale difference $H_G - H_{A'}$ approaches a minimum as the aircraft reaches the point directly over the receiver and then increases as flyover continues. The minimum reading corresponds to the vertical radial distance between the aircraft and receiver and is the true altitude recorded by the aircraft instruments. This critical distance point should not exceed 10° from perpendicularity. Besson indicates that with a transmission rate of 10 sync pulses per second and a 3-percent altitude error, the propagation time standard deviation $\Delta\tau_P$ is 30 ns or less. The instrumentation delay standard deviation $\Delta\tau_{TR}$ is reported as 10 ns or less [31].

Method 2: This technique involves simultaneous transmission by both the user and the aircraft, so the propagation time delay τ_P drops out of the equation for clock time difference. The aircraft does not have to fly directly over the receiver at a fixed altitude.

Limitations in the two-way system include the degree of accuracy to which the time scale deviations between the aircraft and ground station clocks can be measured in the short time available and the difficulty of measuring the equipment delays at both time sources.

In September 1970 the French group (Office National d'Etudes et de Recherches) cooperated with several intercontinental time centers and made an international comparison of atomic clock scales through aircraft overflight. The experiment plan included both one- and two-way type of comparisons with three or four overflights of each time center. A nonstop one-way flight was expected to take about 18 h. The experiment, named Synchran (North Atlantic Synchronization), was performed during the period September 9–15, 1970. Corrections included propagation delays, instrument factors, clock drifts, and relativity effects. The results indicate accuracies of about 40 ns [32].

E. Clock Synchronization Using the "Transfer Standard" Technique

Identification, *synchronization*, and *delay calibration* are three operations that are common to all time dissemination schemes. In a standard time broadcast an event such as the transition from the zero to the one state in a binary system, or the beginning of a tone or a particular zero crossing of a continuous tone in an analog system, is chosen to represent the time mark. This event must be *identified* unambiguously at the time reference transmitting station, and *synchronized* with the reference clock. The equipment delay is calibrated and the transmitted time adjusted accordingly. In order to recover the time from the received signal, a user must unambiguously *identify* the time mark in the signal format and *synchronize* his clock to it after *calibrating* the propagation path delay.

Thus identification, synchronization, and calibration operations must be performed at both the master and the user time stations. In the case of a standard time broadcast service these operations are being performed simultaneously by many users, while they are being performed only once at the reference station.

The dissemination "system" should be construed to include the equipment of all users as well as that of the reference station. The costs of the standard time broadcast service "system" are allocated such that the investment in user equipment at a single user station is vastly less than the investment in equipment at the reference station. Thus a standard time broadcast service is designed along the lines of a public utility, where a great many customers require similar services to be available all the time.

It is convenient but not necessary in principle for time or frequency information to be transferred from the reference station to the user station by a radio broadcast originating at the reference station.

Refer to Fig. 4. Assume that the reference station A and the user station B both have receivers tuned to monitor some electromagnetic event that is going to occur at a remote location TS. The coordinates of locations A, B, and TS are not known but are fixed. Both A and B have monitoring devices that will record the time displayed by their clocks when the electromagnetic disturbance associated with the event is received. Finally, assume that clocks A and B are on time with each other. t_A seconds after the event occurs the time T_A displayed in clock A will be recorded, where t_A is the propagation delay from TS to A. t_B seconds after the event occurs the time T_B displayed in clock B will be recorded. Since the time at which the event occurred is not known, and since the distances of A and B from TS are not known, t_A and t_B are not predictable. But if the time readings T_A and T_B are compared, one

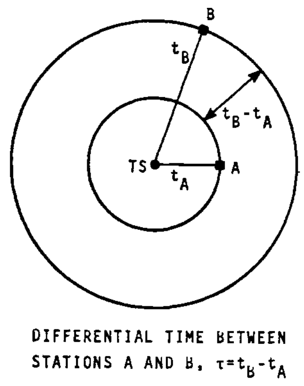

Fig. 4. A transfer standard link.

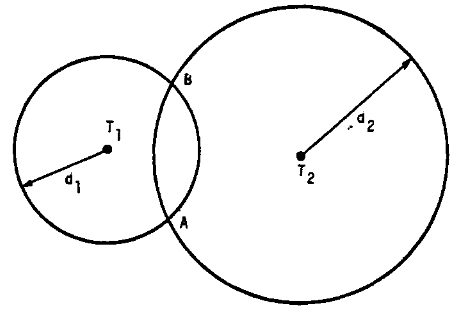

Fig. 5. Range-range navigation.

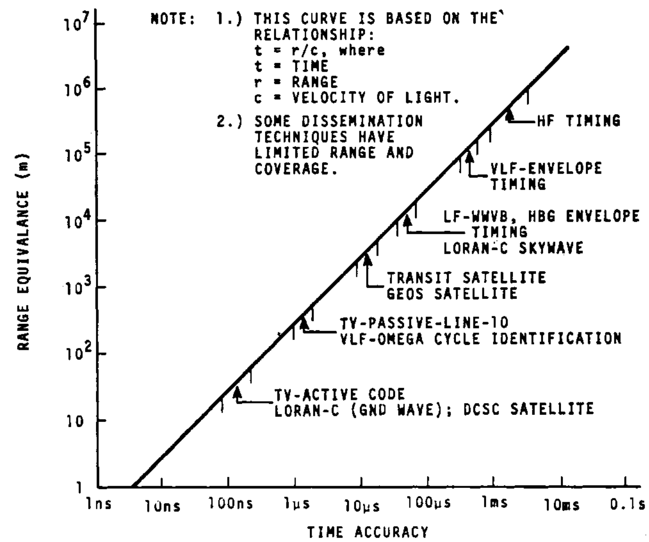

Fig. 6. The relationship between navigation or ranging accuracy and clock or timing accuracy.

can learn the *difference* τ in the propagation delay times along the two fixed paths.

If a second event is monitored at some later time the new readings, T_A and T_B, recorded at A and B will obviously be different from the first set. But the time *difference* τ will be the same as before, provided that the clocks are still synchronized.

A change in τ could only be explained by a loss of coordination or change in path delay between clocks A and B. If clock B is adjusted by an amount equal to the *change* in τ then it will once again be synchronized with clock A. If no further loss of synchronization occurs, τ computed for yet another event will be the same as it was originally.

Thus the time difference between a reference clock and a user's clock can be determined by comparing each in turn to an independent "tick" available to both, and then differencing the comparisons. It is like making comparisons with a portable standard known to be operating at the correct rate but not necessarily on time. The time is "transferred" by a standard which is not, itself, on time; hence the term "transfer standard" technique.

The example used was chosen to emphasize the following aspects of the transfer standard technique:

1) The coordinates of the reference station, the user station, and the transfer standard need not be known although they must not change.

2) The "event" monitored contains no time information, and the time of its occurrence need not be known; it must only be unambiguously identifiable.

3) If the "transfer standard" is a radio broadcast, as it normally is, the transmitting station plays no active part in the process and need not even be aware that it is being so used.

The requirement that the event must be unambiguously identifiable implies that the time separation between "events" must be greater than the uncertainty associated with the knowledge of the user's clock time, and with the knowledge of the propagation delays. If other means are employed to maintain gross clock coordination and the "transfer" technique is being used to keep track of short-term drifts, then the time separation of events need only be greater than the peak-to-peak drifts involved. Vertical sync pulses from commercial television transmitters serve nicely for this purpose; Loran-C is also commonly used.

If a user wishes to begin using this technique to transfer time to a location having a clock not known to be on time, he may begin making comparisons and bring in a portable clock to "calibrate" the link at his convenience. He can then reconstruct the time history of his clock prior to the portable clock visit.

F. The Use of Radio Navigation Systems for Time Dissemination

Radio navigation systems and standard time broadcast stations have much in common. Both depend on the constancy of the speed of light for their concept of operation, and both utilize periodic formats. To emphasize this point it will be shown how standard time broadcasts can be used for navigation.

Refer to Fig. 5. Assume that a time signal radiated from transmitter T_1 is received by a ship at location A. If the ship's navigator knows the coordinates of the transmitter, and if he has an on-time clock, then he can measure directly the propagation delay of the received signal. He can then compute his distance d_1 from T_1 by multiplying the measured propagation delay by the speed of light. Thus he knows that he is somewhere on the circle of radius d_1. If he can receive a second time signal from T_2, whose coordinates are also known, he can place himself on the circle of radius d_2. He now knows that he must be either at A or B. This is the range–range or rho–rho navigation scheme. The navigator can resolve the position ambiguity by a coarse knowledge of his position or by listening to the time signal from a third transmitter.

The corollary to this example is that navigation systems can be used for time dissemination if the signal format generator is stabilized and some recognizable character within the format is aligned in some fashion with the time tick. The range accuracy and timing accuracy capabilities of some systems are indicated in Fig. 6.

Loran-C is a navigation system whose time dissemination capabilities have been exploited extensively [33]. Time can be obtained from the ground wave with a reported accuracy of about 1 μs. It has a much higher accuracy as a "transfer standard."

Appendix II lists characteristics of frequency stabilized navigation systems.

G. Time and Frequency Dissemination Using Television

Four categories of dissemination using television (TV) have been investigated:

1) Time dissemination. TV transmissions can be utilized as a "transfer standard" for clock coordination [34], [35].

2) Frequency dissemination. Frequencies contained in the TV transmission can be stabilized, providing accurate frequency information directly, or they can be used in a "transfer standard" application [36].

3) Time and frequency dissemination. Time and frequency information can be injected into unused portions of the TV format for dissemination [37].

4) Time and frequency dissemination. Sync pulse trains can be stabilized in frequency, then aligned in some fashion with a time scale [38].

1) *Sync Pulse "Transfer Standard" Clock Coordination:* The method was first demonstrated in 1965 when synchronization via TV microwave links was accomplished between Prague, Czechoslovakia, and Potsdam, Germany [34]. The method has since gained wide acceptance. In 1968, NBS began using TV sync pulses to synchronize the time broadcasts from Fort Collins, Colo., to the UTC (NBS) Time Scale at NBS, Boulder, Colo. [39]. The accuracy of such measurements is better than 1 μs with an rms day-to-day deviation of about 30 ns.

NBS line-10 "transfer standard" time dissemination: Following the work of Tolman [34] NBS developed the TV line-10 system (line 10 pulse of the odd field in the 525-line system *M*) as a "transfer standard" method of comparing remotely located clocks. Clock stations nearly anywhere in the United States, able to receive a given TV broadcast simultaneously, can maintain clock coordination for periods of months to within a few microseconds once the initial coordination has been achieved by other means [40]. The ambiguity of the technique is 33 ms.

Since a "transfer standard" technique is used, the conscious participation of the transmitting station is not required. Equipment required at a user station includes a TV receiver, a line-10 synchronized pulse generator, a digital counter-printer, and a precision clock. Clock comparison occurs through differential measurements of TV line-10 data. These are taken simultaneously at comparing clock stations and remain constant within a few microseconds from day to day, except when rerouting occurs. Both NBS and the USNO publish line-10 data regularly in their periodic bulletins [41], [42].

2) *Stabilization of Color Subcarrier:* Frequency stability measurements of the color subcarriers of the three major U. S. networks (originating in New York) have been made at NBS, Boulder [43]. The received subcarrier is compared in frequency to the NBS standard, and the networks are advised of their frequency offset so that they can adjust their oscillators. The networks have been able to hold their atomic oscillators on nominal frequency very accurately. A determination of frequency difference with an uncertainty of about 1 part of 10^{11} in 17 min is normal. NBS has designed instrumentation to synthesize the output of a 1-MHz or 5-MHz local frequency standard to 3.57 . . . MHz and to compare phases of the local synthesized signal to the received subcarrier frequency. The frequencies of the atomic oscillators at each of the three originating networks in New York City are measured at Boulder in terms of the rate of the NBS Atomic Time Scale, AT (NBS). The precision of measurement is about $\pm 1 \times 10^{-11}$ for each of the three network standards. NBS publishes such average weekly data [41]; representative data are given in Table I. (Note: TV color subcarrier frequencies are still offset from nominal by about -300 parts in 10^{10}.)

TABLE I
TELEVISION NETWORK ATOMIC STANDARD FREQUENCIES IN TERMS OF AT(NBS)

Dates of Measurement Period 1971	Average Fractional Frequency Offset (parts in 10^{10})		
	ABC	CBS	NBC
30 May– 4 June	−301.40	−295.77	−300.42
7 June–11 June	−301.51	−295.78	−300.44
14 June–18 June	−301.57	−295.79	−300.48
21 June–25 June	−301.63	−295.83	−300.59
28 June– 2 July	−301.60	−295.81	−300.59

3) *Injection of Time and Frequency Information into TV Format:* Techniques for transmitting time and frequency information within the broadcast TV format have been developed at NBS. Initial tests were made at Denver, Colo., using lines 15 to 17 [36]. In January 1971, Koide and Vignone tested the technique on a 45-km path in California and found the synchronization accuracy to be better than 100 ns [44].

The favorable results experienced in the early tests led to nationwide tests of a refined technique. These tests, still in progress, utilize line 1.

The line-1 "NBS TV Time System": The line-1 technique called the "NBS TV Time System," can be employed for nationwide network distribution, or it can be used for local distribution [37]. This is a proposed time and frequency dissemination system now being tested. The technique is shown schematically in Fig. 7. Time information is encoded in a binary coded decimal (BCD) format. A 1-MHz sine wave provides frequency and precise time information.

The user station is equipped with a TV receiver, a decoder, an alphanumeric character generator, and optional auxiliary equipment for automatically measuring the time difference between the received time signal and the user's clock. Several modes of operation are available to the user.

1) Coarse time (hours, minutes, and seconds) can be displayed on demand on the user's TV screen in alphanumeric characters.

2) The time difference between the received time and the user's clock time can be displayed on the TV screen with nanosecond resolution.

3) The received 1-MHz sine wave can be used for direct frequency comparison.

Digital time dissemination: A reference time standard and a time code generator are installed at the point of program origin (network or local studio). Both the code and its complement are sent for redundancy. The code carries hour-minute-second (HMS) information derived from the reference time standard. The system does not measure propagation delay time; this delay is treated as clock error, which is insignificant for coarse timing. The user must make a calibration of the path delay between the clock at the code injection point and the clock at the receiver if accurate time is desired.

At the user's clock station a decoder is required. Optional comparison instrumentation is available if desired. The line-1

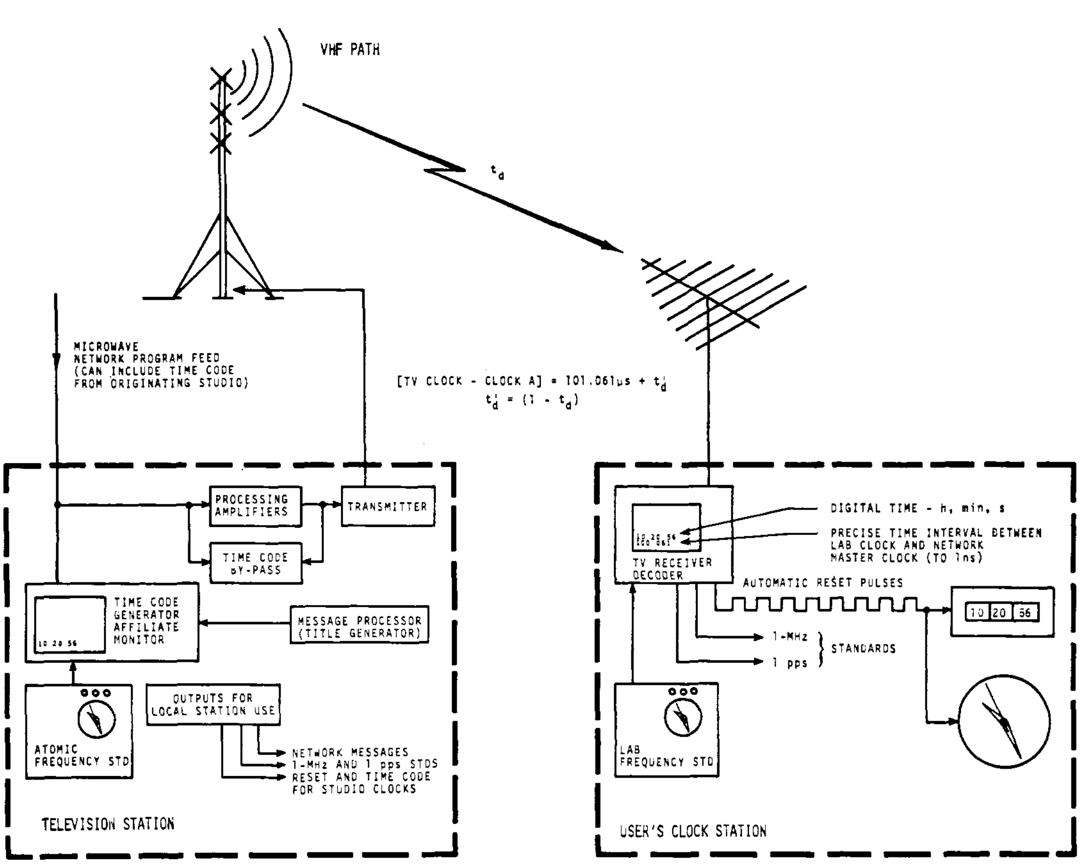

Fig. 7. Line-1 TvTime System.

system provides an HMS readout on a modified commercial TV receiver, which includes a built-in digital clock regulated by the time code. In the event no code is received, the digital clock reverts to internal control.

1-MHz frequency dissemination: The line-1 system also provides a precise frequency standard. A stable 1-MHz carrier is transmitted during the interval between the first and second equalizing pulses of lines 1 and $262\frac{1}{2}$. At the decoder, a phase-locked oscillator recovers this signal using an approach similar to the detection of the color subcarrier in a color TV receiver. Results at NBS indicate that such a received standard frequency permits calibration of a local standard to 1 part in 10^{11} in less than $\frac{1}{2}$ h.

The line-1 system can provide time and frequency to nearly everyone in the United States at a small increase in receiver cost; the transmission of data has no effect on network programs or viewing reception and is without cost to the user; data can be obtained from three networks, providing redundancy. The system can provide very accurate synchronization throughout the continental United States.

Although interstate microwave routings are sometimes altered, the probability that four networks would be disturbed simultaneously is remote. In recent years, rerouting has been infrequent.

The NBS TV Time System has provision for automatic synchronization. Thus the West Coast divider chain can be locked to the East and any station can synchronize its local clock by comparison to network feed.

In the case of taped shows, the local station equipment removes the old time code and reinserts correct local time. The same equipment has a time scale changer to correct the code for both time zone and daylight savings time. It is estimated that 70 percent of the United States population could be reached by installing synchronized coders at the network centers in New York and by distributing the code over existing microwave links. Since the means of distribution already exists, implementation of the system would be relatively inexpensive. As the UTC scales at both NBS and USNO are mutually coordinated to within ± 5 μs of each other, users of the line-1 system would have effective access to both scales.

H. Satellite Time-Frequency Dissemination Techniques

This section describes various concepts of satellite TF/D and documents initial tests. It is meant to complement the papers by Easton [45] and Ehrlich [46] as well as several letters in this issue. It concludes with some experimental results NBS has obtained using relatively inexpensive equipment and simplified techniques.

The major problem confronting the user of TF/D techniques by terrestrial ionospherically reflected radio signals is the difficulty of predicting the radio delay path which results from the complexities in the ionospheric-atmospheric propagation. Artificial satellites, in combination with VHF radio signals, show several advantages over conventional radio dissemination methods. Propagation delays can be calculated to high accuracy (≤ 100 μs); the refractive index for most satellite-to-earth radio paths is near the free space value since the ionosphere and troposphere effects constitute a small fraction of the total path; and multipath effects are negligible for all but the highest accuracy systems using receivers at low elevation angles.

Questions of concern in the design of an artificial satellite TF/D system are: does one use a geostationary or low-altitude moving satellite; should the satellite be used as a retransmitter of a time signal eminating from the ground or as an active emitter with on-board clock; and does the design require a one-way or two-way mode of signal transmission?

One geostationary satellite can provide 24-h service to approximately $\frac{1}{3}$ of the earth's surface. On the other hand, a moving low-altitude satellite can provide service to the whole earth within a given time period but for only short measurement periods of ~10 to 15 min. Operation of a satellite with an on-board clock complicates clock maintenance and necessitates periodic adjustments although no continuous RF transmission is required from the ground. Use of a satellite relay or transponder permits the clock to be maintained on the ground and allows use of a general purpose communication satellite, perhaps on a time shared basis. A one-way satellite system is one which users operate in a listen or receive-only mode. A two-way satellite system involves bilateral communications between a reference clock and receiver clocks relayed by the satellite transponder.

The first satellite time experiments were conducted in August 1962 with the communication satellite Telstar [47]. These experiments related to the USNO (Washington, D. C.) clock to the Royal Greenwich Observatory (RGO) clock in England to about 1 μs. Signals were relayed via a satellite microwave transponder between the two locations in the two-way mode. If the paths are reciprocal and the satellite motion negligible during the transmissions, the one-way path delay is one-half the round trip delay. The two-way exchange has the advantage that knowledge of the satellite location and ground stations is not required. Its disadvantages are that both ends of the path must have both a transmitter–receiver capability and only one user may be synchronized during the radio exchange of data. The U. S.–Great Britain experiments used SHF signals (microwave) with wide bandwidths. The high accuracy of wide bandwidth at microwave frequencies is at the expense of costly equipment which is beyond the range of many users. This high cost of equipment prompted NBS to a somewhat different approach in an attempt to realize the potential of accurate time and frequency dissemination via satellites. NBS has worked only with geostationary satellites, and initially conducted two-way experiments using the NASA ATS-1 satellites containing a VHF transponder at about 150 MHz [48]. With inexpensive receivers and transmitters, accuracies of about 5 μs were reported for those studies. Basic ionspheric effects appeared not to limit these results.

A one-way transmission mode involves a different category of satellite experiments. Gatterer *et al.* [49] studied the one-way mode and determined the accuracy of the technique to be ~10 μs by using path delay calculations based on satellite tracking during the measurements. In this method, users compare the received time signal with their local clock time, and correct for path delay. Information about the path delay may be obtained from orbital elements which may be relayed by the satellite. Path delays are determined from orbital elements. (Orbital elements describe the satellite's orbit and its position in that orbit at a given date.) They are obtained from observations of the satellite motion over a period of time. Such information usually is issued approximately monthly by the agencies responsible for their operation.

NBS has also performed one-way transmission tests with communication satellites such as LES-6 (Lincoln Laboratories) and TACSAT [50], [51], as well as the NASA satellites ATS-1 and ATS-3. These satellites operated in the VHF and UHF bands in the range of 150 to 300 MHz. At these frequencies and with the power of transmission involved, one is able to use small inexpensive antennas, with an SNR more than adequate for the measurements. A pictorial view of the master station and five receiving stations in the North and South American continent used for comparing the path delays from measurement and calculation is shown in Fig. 8. When one of the receiver clocks was synchronized to the master clock, orbital elements provided for TACSAT permitted 75-μs accuracy and similar elements for LES-6, about 25 μs [50]. The so-called "side tone ranging" method employed by tracking ranges was used as an experimental method for evaluating low-cost techniques at minimum cost.

NBS is pursuing geostationary satellite dissemination studies with ATS-3 in a one-way mode and a WWV-type format including voice [52]. The objective is to provide a reliable accurate service, without the propagation deficiencies of WWV, at low cost to many users. Other types of satellites such as active (with onboard clocks), polar orbiting, navigation, etc., also show great potential for time and frequency dissemination [45], [46].

Advantages of satellite timing (using geostationary satellites in a one-way mode) include: an inexpensive means of setting clocks to 100 μs or better, and frequency comparisons from day-to-day time interval measurements to several parts in 10^{10}; the satellite gives wide geographic coverage; the VHF or UHF signals show little fade except at high latitudes and equatorial regions; and daily measurements can be made in short time periods (within several minutes) with relatively inexpensive equipment and antennas. Limitations could include the difficulty in determining the satellite's exact position and effecting an accurate signal path delay; three geostationary satellites are necessary for worldwide coverage except for the poles; satellites can fail, be destroyed, or their orbits changed. Overall, satellites offer potential of meeting the timing needs of many classes of users at various accuracy levels.

I. Standard Time and Frequency Broadcasts

The World Administrative Radio Council (WARC) has allocated certain frequencies in five bands for standard frequency and time signal emission as shown in Table II. For standard frequency transmissions, the CCIR recommends that carrier frequencies be maintained so that the average daily fractional frequency deviations from the internationally designated standard for measurement of time interval should not exceed $\pm 1 \times 10^{-10}$. Appendix III gives characteristics of standard frequency and time signals that are broadcast in the allocated bands, as reported by the CCIR. Appendix IV gives characteristics of stabilized frequency and time signals that are broadcast outside the allocated frequencies which can, however, provide useful time and frequency information.

V. Summary

A. Categorization of Time Users by Required Accuracy

It is convenient to classify users of time into three categories: low accuracy (more coarse than 1 ms); intermediate (1 ms to about 50 μs); and high accuracy (more stringent than 50 μs). Fig. 9 illustrates the time accuracy requirements of some users and the normal capabilities of representative time dissemination techniques and services. The accuracy obtainable, using a given technique, varies considerably with the location and skill of the user.

The low-accuracy group contains the largest number of users; their needs are generally met by telephone time of day service,

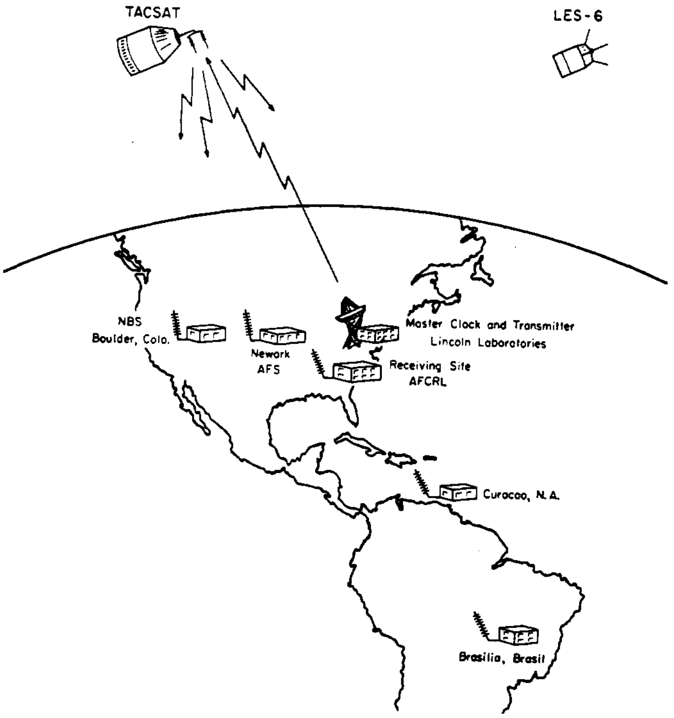

Fig. 8. Typical network for experimental satellite time relay.

TABLE II
STANDARD TIME AND FREQUENCY ASSIGNMENTS

Band Number	Designation	Frequency Range
4	VLF	20.0 kHz ±50 Hz
6	MF	2.5 MHz± 5 kHz
7	HF	5.0 MHz± 5 kHz 10.0 MHz± 5 kHz 15.0 MHz±10 kHz 20.0 MHz±10 kHz 25.0 MHz±10 kHz
9	UHF	400.1 MHz±25 kHz (satellite)
10	SHF	4.202 GHz±2 MHz (satellite-space to earth) 6.427 GHz±2 MHz (satellite-earth to space)

telephone access to WWV, commercial radio time announcements, and standard time broadcasts (WWV, CHU, JJY, etc.).

The intermediate group is fast growing. Organizations engaged in satellite geodesy, seismic monitoring, and satellite tracking require time in the intermediate accuracy range. The basic characteristics of reliability, geographical coverage, availability of signals, accurate propagation predictions, and equipment costs relevant to needed accuracy have been explored largely in response to this group's needs.

High accuracy is required by coherent detection communication systems, long baseline interferometry facilities, and organizations engaged in precision ranging. Submicrosecond accuracy is generally sought by laboratories with clocks capable of maintaining time at that level. The proposed aircraft collision avoidance system requires widespread dissemination of time with submicrosecond accuracy [53]. Reliability, percentage of time available, and worldwide coverage are of paramount importance to ACAS system designers.

At present, there is no implemented time dissemination system that permits comparison at will, anywhere in the world, of a user's clock to a primary standard, at an accuracy level that fully exploits the capability of atomic standards. Satellites appear to be capable of meeting the challenge but no worldwide satellite time dissemination has been implemented.

Although the number of time users who have present requirements for submicrosecond accuracy is relatively small, these are not negligible. One technique that can satisfy such users to some degree involves the physical transportation of battery-operated portable atomic clocks.

B. Comparison of Time-Frequency Dissemination Techniques

Fig. 10 compares some TF/D techniques. Such an evaluation is subjective, and some classifications are borderline. It is an attempt, though, to show a realistic picture of present or proposed dissemination systems in terms of their capabilities and potentials. Accuracy figures are documented by applicable references. The ratings of good, fair, and poor are both arbitrary and broad. In the context of this presentation they may be helpful for purposes of comparison and evaluation. Further explanatory comments concerning the scope and intent of the various characteristics identified in Fig. 10 follow.

1) *Accuracy of date transfer* refers to that accuracy (degree of conformity with some specified value) to which time of day can be established at 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, locations, etc. The ratings of good, fair, and poor are referenced to the needs of high-, medium-, and low-accuracy users as shown in Fig. 9.

2) *Accuracy of frequency synchronization* refers to that accuracy to which frequency standards can be synchronized within some frame of reference. As with date transfer the three basic ratings are in terms of the classes of accuracy users shown in Fig. 9.

3) *Ambiguity* applies to that interval of time which a given system or technique can provide with certainty. 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, the period of a TV frame, 33 ms, is the ambiguity of the TV line-10 technique. The line-1 TV system, using the coded data displays, has 24-h ambiguity.

4) *Coverage* refers to the geographical 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, availability of TV line networks, etc., may affect the coverage of a specific signal.

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

6) *Reliability* estimates the degree of confidence in the operation of a system and considers such factors as propagation condi-

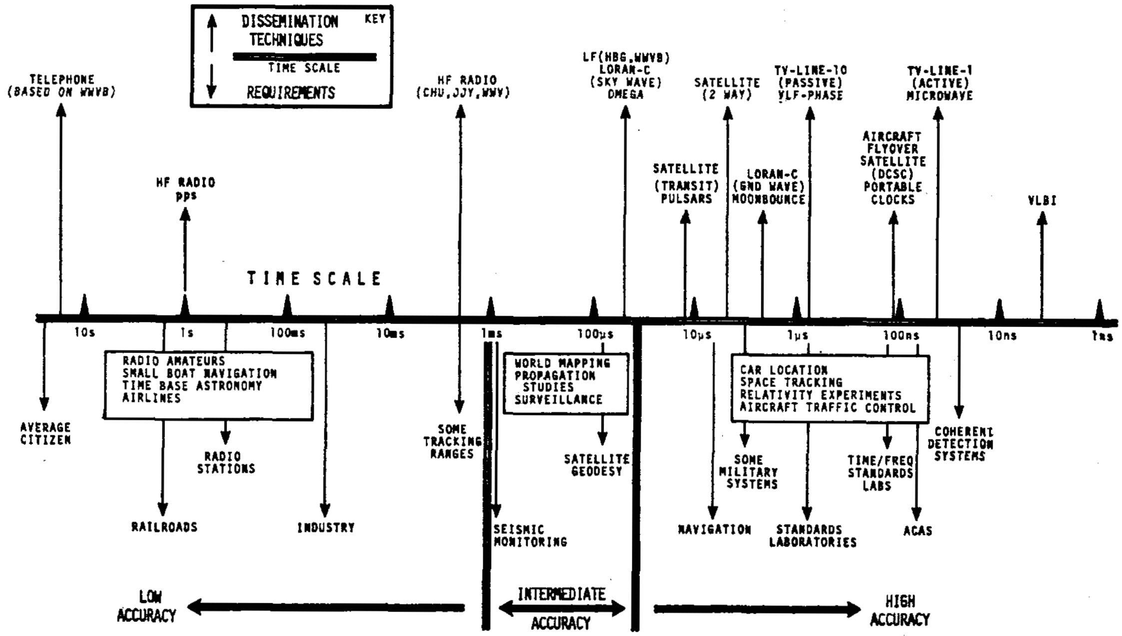

Fig. 9. Time accuracy requirements.

	DISSEMINATION TECHNIQUES	STATUS (1)	ACCURACY-FREQUENCY SYNCHRONIZATION	ACCURACY FOR DATE TRANSFER	AMBIGUITY (4)	COVERAGE FOR STATED ACCURACY	% 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	REFERENCES
HF/MF RADIO	STANDARD FREQ. BROADCASTS(WWV)	O			1 DAY / 0.5MIN	HEMISPHERE		[illegible]					[54,55]
	NAVIGATION SYSTEM LORAN-A	O	[illegible] (2)	2-5μs NOT UTC		[illegible]		[illegible]					[56]
LF RADIO	STANDARD FREQ. BROADCASTS(WWVB)	O	(3) 1×10^{-11} (PHASE-24h)	[illegible]	1 YR	[illegible]			[illegible]		[illegible]		[57,58]
	NAVIGATION SYSTEM LORAN-C	O	1×10^{-12} GND(3)	∿1μs(GND) 50μs (SKY)	50ms / PHASE 10μs	[illegible]					[illegible]		[33,59]
VLF RADIO	COMMUNICATION/SFB GBR, NBA, WWVL	O	1×10^{-11} (3)	[illegible]	PHASE ∿50μs	GLOBAL							[60,61,62]
	NAVIGATION SYSTEM OMEGA	O/P	$<1\times10^{-11}$ (3)	≤10μs■	[illegible] / PHASE ∿100μs	GLOBAL							[63,64,65]
SATELLITES (VHF/UHF RADIO)	STATIONARY SATELLITES ONE WAY	E/O	[illegible]	[illegible]	DEPENDS ON FORMAT	HEMISPHERE	STATIONARY						[49,50,52]
	STATIONARY SATELLITES TWO WAY	E/O	1×10^{-12} (24h)	∿100ns	DEPENDS ON FORMAT	HEMISPHERE							[48,66]
	ON-BOARD CLOCK (ACTIVE) ONE WAY - LOW ALTITUDE	O	[illegible]	0.5-50μs	DEPENDS ON FORMAT	WORLD	[illegible]	[illegible]					[45,67,68]
PORTABLE CLOCKS	PHYSICAL TRANSFER	O	1×10^{-12}	100ns*	1 DAY	LIMITED BY TRANSPORTATION	AS NEEDED		NONE				[23,28]
	AIRCRAFT FLYOVER 2-WAY	E	1×10^{-12}	≤100ns	DEPENDS ON FORMAT	LIMITED BY TRANSPORTATION	AS NEEDED						[30,31]
TELEVISION (VHF/SHF RADIO)	PASSIVE -LINE-10	O	1×10^{-11} (24h)	∿1μs	1 DAY / ∿33ms	[illegible]	[illegible]				USA FOR EXAMPLE		[34,40,69]
	ACTIVE-LINE-1(NBS TV TIME SYSTEM)	E	1×10^{-11} (<30 MIN)	<100ns●	1 DAY / ∿33ms	[illegible]					USA FOR EXAMPLE		[37]
SHF RADIO	MICROWAVE	E/O	$\sim1\times10^{-13}$ (PER WEEK)	≤100ns	PHASE COMPARISON								[70]
	VLBI	P	5×10^{-14}	∿1ns	DEPENDS ON FORMAT	HEMISPHERE	AS NEEDED						[71]

GOOD FAIR POOR

Fig. 10. A comparison of some dissemination techniques. *Notes:* (1) Status of technique indicated as follows: O—operational; P—proposed; E/O—experimental operational. (2) Estimates of day-to-day measurements within 2000 km (1250 mi) of Loran-A stations. These emissions not coordinated with UTC and manually operated crystal clocks drift. (3) From day-to-day phase measurements, e.g., ∼1 μs per day phase change approximates 1 pt. in 10^{11} in frequency difference. (4) Left-hand designation gives the shortest time interval that cannot be resolved; right-hand number gives basic ambiguity. †, by ground wave 1600 km; by sky wave thousands of kilometers depending upon conditions. ■, with proposed time code. ★, closure after 1 day. ●, within local service area of TV transmitter and path delay known.

tions, system components in satellite environment, rerouting of TV network programs, etc.

7) *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. Equipment such as oscilloscopes, digital counters, etc., is not included. A poor rating implies a cost greater than several thousand dollars; fair refers to a cost in the 1000–2000-dollar range; and good indicates a cost less than 1000 dollars.

8) *Cost per calibration* considers factors such as the cost of required instrumentation to make the calibration and the probable frequency of calibration.

9) *The 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 TV technique is considered to have more potential users than the WWVB broadcasts, even though both cover the continental United States. Relevant factors include the low cost of TV receivers and random propagation disturbances associated with WWVB reception.

10) *Operation skill required for stated accuracy* describes the degree of difficulty in making a time/frequency measurement to the 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 poor rating indicates that complex procedures and special skills are required for a given technique. The use of the Omega system for time, for example, requires envelope recognition followed by cycle identification.

Some shorthand notation is used in Fig. 10 in connection with the satellite techniques. *Passive* describes a satellite which 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 while an *orbiting* satellite is one with a period of revolution other than 24 h.

It must be emphasized that the ratings are relative and arbitrary. Indeed, a system with a poor rating may be the best choice for many users. A severe limitation on the usefulness of Fig. 10 is that it reflects judgments of all parameters of a given system assuming 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 excluded, with the result that *coverage* is rated poor.

A system designer will probably be forced to make 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*.

Note that most techniques that rate good in accuracy are shown as fair or poor in other important categories. No one technique shows all favorable ratings, but HF broadcasts, stationary satellite relays (passive), and the proposed NBS TV Time System stand out with only one poor rating each.

C. *Opportunities for the Future*

An increasingly large number of systems independently generate and disseminate their own frequency and time information. The radio spectrum devoted to that purpose is impressive. To the extent that it might be possible for systems to share time and frequency information, the needs of spectrum conservation could be served.

Workers involved in the design of communication and navigation systems now in the conceptual stage may have opportunities to provide valuable time and frequency dissemination services. It may be possible for them to design their synchronization pulse formats to be more convenient for time dissemination without compromising their own system operation. Correspondingly, a system designer conscious of the opportunities to disseminate frequency information may be able to better accommodate that function by referencing his system frequencies to recognized frequency standards and by choosing more convenient subsystem frequencies where possible.

On the other hand, it may be that the organized time and frequency community has not fully recognized what its role could be in providing dissemination services. Should there be a "time and frequency utility" that would distribute very accurate time and frequency information much more widely than is presently being considered? Assume that such a service were available to every home, office, and factory in the United States. To what use might communications designers put such a resource?

One interesting possibility is related to privacy in communication. If a pseudo-noise code is used over a stable link, secure communication is an easy matter. The parties merely start their code word at some prearranged instant. A third party monitoring their communication cannot easily recognize when intelligence is being communicated, much less understand what the information is. This sort of privacy would be of great value to a computer communications industry that is sensitive to suggestions that unauthorized parties might gain access to their computer banks.

Individuals might similarly profit by such privacy in banking and other transactions conducted at a keyboard in the home. Anyone interested in the "wired city" concept should find the prospects interesting.

The spectrum conservation implications of a "time and frequency utility" are enormous. Opportunities exist for the time sharing of communication channels and reducing bandwidth allocations. The need to transmit time and frequency information to meet communications by subsystem requirements would be lessened. About 15 to 20 percent of the bandwidth of a television signal is devoted to keeping television receiver oscillators running at the correct rate and to maintaining synchronization. These operations are performed independently on every channel. Would it be possible to reduce the bandwidth of television signals (and perhaps to use a simple receiver) if viewers had accurate time and frequency in their homes?

Designers of mobile communication systems could capitalize on the availability of accurate time to moving vehicles. They could time share scarce mobile channels, and they could provide privacy to those using the channels. Vehicle location systems could operate more efficiently if the vehicle had accurate time. The location system could be designed to update clocks in vehicles.

The capability for keeping accurate time has outstripped the capabilities for disseminating it in the last two decades. The challenge of the future is to exploit the opportunities for disseminating time, and for putting well-disseminated time to good use.

APPENDIX I

CHARACTERISTICS OF RADIO FREQUENCY BANDS

Frequency Band	Frequency Ranges	Wave Length Range	Typical Stability	Typical Uses	Factors Affecting Propagation	General Description of Frequency Band Transmission
VLF (Very Low Frequency) Band 4	3-30 kHz Omega (10.2 to 13.6 kHz) Communications (16 to ~26 kHz) Time/Frequency (20 kHz)	10^5-10^4 m	pts in 10^{11} per day or better (10-30 kHz)	Navigation; Time/Frequency Disseminations; Communications	Time of day; propagation over land or water; ground conductivity; direction of propagation; noise; solar activity; atmospheric disturbances; polar cap and varied latitude paths; daily variation in height of ionosphere causes diurnal shifts at sunrise and sunset. At long distances from a transmitter (>10,000 km), the long path signal can interfere with the short path signal. Night time propagation shows increased variation over daytime propagation. Dispersion effects (phase velocity of radio signal varies as a function of its frequency) cause phase and group velocities to differ and must be evaluated in timing systems using multi-frequency techniques. Mode interference at sunrise and sunset can cause cycle "slips", especially at high frequencies in band.	VLF signals propagate between the bounds of the ionospheric D layer and earth and are thus guided around the curvature of the earth to great distances with low attenuation and excellent stability. Diurnal changes are very abrupt when transmitter and receiver are near or at the same longitude; the amount of the diurnal change varies with the distance of path travel and carrier frequency, and the diurnal phase shift is predictable to several microseconds [72, 73]. VLF propagation has been extensively studied and reported [74,75,76] and models have been developed for predicting phase delay and signal strength at varying distances and transmitter power. It has been found both experimentally and theoretically that the phase variation with distance tends to become more regular in the 10-20 kHz region as the distance from the transmitter increases. The high Q of VLF antennas precludes a rapid pulse rise which limits envelope timing to about 1 ms. VLF signals are broadcast from worldwide transmitters radiating about 1 kW to 1 MW of power. Stable VLF signal reception during daylight hours, with totally sunlite path, permits day-to-day phase comparisons accurate to one or two μs [60, 61, 77]. (See paper by Swanson and Kugel (this issue [63]) which describes both the Omega and other VLF signals.)
LF (Low Frequency) Band 5	30-300 kHz Time/Frequency (40 to ~100 kHz) Loran-C (100 kHz) Stabilized Carrier Broadcast Stations (~90 to 200 kHz) mainly European stations	10^4-10^3 m	pts in 10^{11} per day (60-200 kHz dependent on propagation path and distance) pts in 10^{13} per day for ground wave signals	Navigation; Time/Frequency Disseminations; Ionospheric Studies; Communications; Commercial Broadcasts	Propagation over water and land paths shows variation; time of day; ground conductivity; solar activity; atmospheric disturbances; interactions of modes during sunrise and sunset cause cycle "slips"; daily ionospheric height changes cause diurnal changes at sunrise and sunset. Appreciable dispersion occurs in ground wave propagation. LF, in contrast to VLF, allows pulsed systems because lower Q antennas can be used. Pulsed transmissions allow separation of ground wave from sky wave signals, so that only ground conductivity and irregular terrain effects need be considered.	LF continuous wave (CW) propagation is similar to that of VLF signals. The higher frequency broadcasts are most stable within ground wave distance of the transmitter (about 500 km). LF signals generally show greater attenuation with distance than VLF signals. A wider bandwidth permits pulsed signals at 100 kHz. This allows separation of the stable ground wave pulse from the variable sky wave pulse up to 1500 km and overseas ranges to more than 2000 km. LF signals are broadcast from North America, Europe and Japan with transmitted radiated powers of 5 to 400 kW. Stable CW LF signal reception during daylight hours with a totally sunlite path can give phase comparisons to several μs for paths greater than 5000 km [78]. LF envelope time measurements are good to about 40-50 μs [58] while LF ground wave signals provide precisions of nanoseconds and accuracies of about a μs. LF propagation characteristics have been described by Johler, Berry, and Belrose [79, 80, 81]. (See paper by Potts and Wieder (this issue [33]) which describes the Loran-C navigation system and its use for time dissemination).
MF (Medium Frequency) Band 6	300 kHz-3 MHz Commercial Station Broadcasts (535-1605 kHz) Loran-A (1.85-1.95 MHz)	10^3-10^2 m	pts in 10^7 (Loran-A can provide better stability in some cases.)	Commercial Broadcasts; Maritime Services; Navigation (Loran-A); Standard Frequency Broadcasts	During day time, absorption in the D layer eliminates the sky wave. At night, reflections occur from E and F layers resulting in reception of sky waves at distant points. Moving layers and interaction of modes can cause severe distortion. Atmospheric noise varies greatly, being especially high during summer nights. In urban areas, man-made noise can dominate.	The MF band is most useful within ground wave distance (less than 150 km in the day, perhaps half of that at night). It will support signals with a sufficient bandwidth for time pulses, especially at the high end. Coarse time signals are accurate to about 500 μs. Time comparison accuracies of ±30 μs are expected from JJY broadcasts at reception distances of 1000 km using 2.5 MHz signals [82]. A commercial broadcast station in Tennessee, U. S. A. (650 kHz) is phase stabilized to several μs/day of the NBS WWVB broadcasts [83], providing a local relay standard frequency service. Standard frequency and time broadcasts are transmitted at radiated powers ranging from less than 1 kW to about 5 kW.
HF (High Frequency) Band 7	3.0-30 MHz	10^2-10 m	pts in 10^7	Standard Frequency Broadcasts; Communications; Short Wave Broadcasts	Ionospheric reflections from E, F1, or F2 layers, depending on distance, frequency, time of day, and conditions of the ionosphere (quiet or disturbed). Distant reception may be through multiple hops (ionosphere-ground reflections). Movement of reflection points in the ionosphere and interference between hop modes may cause severe distortion. Other factors include the 11-year sunspot cycle, seasonal and diurnal variations, global location, solar flares, ionospheric storms, magnetic storms, sporadic E, etc. Atmospheric noise varies widely, being highest during summer nights. Man-made noise may predominate.	This is the so-called short wave band. The ionosphere absorbs little energy, resulting in worldwide reception. Movement of reflection points can introduce Doppler shifts and fluctuations in amplitude and phase, degrading accuracy to pts. in 10^7. For more accurate reception, one is limited to the ground wave at distances less than 160 km during the day, perhaps half that at night. A 30 MHz frequency is the approximate upper limit for usual sky wave propagation. Sufficient bandwidth is available to enable time pulse transmission in this frequency band. Many studies of HF band have been made [84, 85]. Computer programs can predict maximum usable frequencies (MUF), optimum frequencies (FOT), and critical frequency with given circuit reliability and service [86] for different locations, directions of propagation, time of day, season, sunspot activity, etc. Winkler [87] notes that WWV signals received at the USNO, Washington, D. C. (2400 km land path) showed day-to-day variations of ~ 200 μs if the measurement is duplicated at the same time every day on the same frequency. Receiving equipment and antennas are simple and inexpensive. Standard frequency and time are transmitted at radiated powers that range from 0.5 to 20 kW.
VHF (Very High Frequency) Band 8	30-300 MHz	10-1 m	pts in 10^{12} (Line-of-sight)	Television; FM Commercial Broadcasts; Satellite Experimental Time Broadcasts; Communication Satellites	Influenced principally by terrain; it is difficult to propagate signals over hills because of diffraction effects. Signals can also reflect from tall buildings, mountains, etc., causing multipath distortion and fading. Other influencing factors include atmospheric inhomogeneities; turbulence, ducts, Sporadic E. In earth-satellite links, the ionosphere also introduces Faraday rotation, scintillation, and dispersion. Propagation path for satellite signals essentially reciprocal. Angle of signal transmission will determine, to some extent, accuracy obtainable from satellite signals because of the length of ionospheric path. Man-made and galactic noise are both fairly low.	Signals in this band are generally limited to line-of-sight and near line-of-sight (usually < 150 km); however, ionospheric scatter (1000 km or more) and tropospheric scatter (<1000 km) systems exist. Signals penetrate the ionosphere with low loss of stability (at least at mid-latitudes). Satellite transmitter power is relatively low (40-100 w), and can transfer signals to nearly a whole hemisphere [50]. TV transmissions show potential for precise time broadcasts in a local service area [36,38,44]. Propagation characteristics have been described by Bullington; Lawrence, et al.; Aarons, et al. [88, 89, 90]. For low power applications, the cost of antenna and receiving equipment is fairly low. Directional antennas, capable of responding to varied polarizations, give optimum response to VHF satellite signals.
UHF (Ultrahigh Frequency) Band 9	300 MHz-3.0 GHz	1-0.1 m	pts in 10^{12} (Line-of-sight)	Television; Communications; Time/Frequency Comparisons; Radar	Diffraction can cause serious attenuation. Otherwise, the major effects are due to atmospheric inhomogeneities. The index of refraction is a function of water vapor content, temperature, and pressure, and varies from point to point and instant to instant. Phase scintillations show RMS jitter directly proportional to frequency. In earth-satellite links, refraction through the atmosphere takes place primarily in the lower 20 km, and most effects on satellite timing are at low elevation angles. Ionospheric effects are almost negligible. The band is characterized by low noise density (man-made noise predominates); receiver thermal noise and galactic noise may also be important.	Most of the troposcatter systems are found in this band. These are high powered, point-to-point communication links from 100 to almost 1000 km long. Otherwise, signals are limited to line-of-sight (usually less than 100 km). Such signals are very stable, although multipath distortion and fading may be present. Propagation characteristics are described by Reed and Russell; Bean and Dutton [91, 92]. Many of the environmental satellites and most of the broadcast satellites are expected to operate in this band. UHF TV is available and can be used in ways similar to TV at VHF. Relatively low power of transmission is required for hemispheric coverage of satellite signals with excellent stability. Directional antennas are advisable; both antenna and equipment complexity tend to increase, especially at the higher frequencies.
SHF (Super High Frequency) Band 10	3.0-30 GHz	10-1 cm	pts in 10^{12} (Line-of-sight)	Telecommunications Networks; Time/Frequency Comparisons; Navigation Satellites; Communication Satellites; Radar	Diffraction causes serious attenuation. Multipath phenomena become factors of concern to users of this frequency band. Atmospheric variations give rise to subrefractive and super-refractive conditions, ground based and elevated ducts, all of which may lead to anomalous propagation. At the higher end of the band, rainfall attenuation and scatter may be limiting factors, and molecular absorption by oxygen and water vapor begins to be significant. Noise density is very low; man-made noise is comparable to receiver thermal noise; at 10 GHz, the sky brightness temperature begins to dominate, particularly at low elevation angles. Ionosphere appears transparent to these frequencies and effects are nearly non-existent.	This is the so-called microwave or centimeter wave band. Signals are limited to line of sight, and the microwave relay systems are composed of many short (40-60 km) hops or links. The long haul lines of the common carriers usually use such systems. They seem to show long range stabilities of several μs [40,69]. Microwave links are also used to relay time signals from a source to a remote broadcast terminal. A 32 km link at the USNO uses signals in the 7 GHz region (radiated power 7 W) and shows phase resolution less than 10 ns and a time setting capability better than 100 ns [70]. Antennas are usually highly directive; they and the system equipment tend to be both expensive and complex. At the higher end, where molecular absorption is present, there are nevertheless "windows" which enable stable signals to be transmitted between earth and space with little signal degradation. Propagation characteristics are described by Dougherty and Thompson [93, 94].

APPENDIX II

CHARACTERISTICS OF FREQUENCY STABILIZED NAVIGATION SYSTEMS USEFUL FOR TIME/FREQUENCY COMPARISONS(1)

STATION				TRANSMITTER		CARRIER (2)				TIME SIGNALS (2)		PERIOD OF OPERATION	
CALL SIGN	CHAIN DESIGNATION (3)	APPROXIMATE LOCATION	LONGITUDE LATITUDE	ANTENNA TYPE	CARRIER POWER $kW_{(4)}$	STABILIZED FREQUENCIES kHz	GROUP REPETITION PERIODS (GRP) µs	ACCURACY PTS IN 10^{10}	TIME PULSES pps	DURATION	METHOD OF ADJUSTMENT	DAYS PER WEEK	HOURS PER DAY
LORAN-C SS7-M		Carolina Beach, N.C. U. S. A.	+34°03'46"N +77°54'46"W	OMNI-DIRECTIONAL	800	100		±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SS7-W		Jupiter, FLORIDA U. S. A.	+27°01'59"N +80°06'53"W	OMNI-DIRECTIONAL	400	100		±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SS7-X	EAST COAST U. S. A.	Cape Race, NEWFOUNDLAND	+46°46'32"N +53°10'29"W	OMNI-DIRECTIONAL	3000	100	99,300	±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SS7-Y		Nantucket Island U. S. A.	+41°15'12"N +69°58'39"W	OMNI-DIRECTIONAL	400	100		±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SS7-Z		Dana, INDIANA U. S. A.	+39°51'08"N +87°29'11"W	OMNI-DIRECTIONAL	400	100		±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SL3-M		Ejde, Faroe Is.	+62°17'57"N + 7°04'15"W	OMNI-DIRECTIONAL	400	100		±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SL3-W		Sylt, GERMANY	+54°48'29"N - 8°17'41"E	OMNI-DIRECTIONAL	300	100		±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SL3-X	NORWEGIAN SEA	Bo, NORWAY	+68°38'05"N -14°27'54"E	OMNI-DIRECTIONAL	200	100	79,700	±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SL3-Y		Sandur, ICELAND	+64°54'31"N +23°55'08"W	OMNI-DIRECTIONAL	3000	100		±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SL3-Z		Jan Mayen, NORWAY	+70°54'56"N + 8°43'59"W	OMNI-DIRECTIONAL	200	100		±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SH4-M		Johnston Is.	+ 16°44'44"N +169°30'32"W	OMNI-DIRECTIONAL	300	100		±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SH4-X	CENTRAL PACIFIC	Upolo Pt., HAWAII	+ 20°14'50"N +155°53'09"W	OMNI-DIRECTIONAL	300	100	59,600	±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SH4-Y		Kure, MIDWAY IS.	+ 28°23'41"N +178°17'30"W	OMNI-DIRECTIONAL	300	100		±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SS3-M		Iwo Jima, JAPAN	+ 24°48'04"N -141°19'29"E	OMNI-DIRECTIONAL	4000	100		±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SS3-W		Marcus Is.	+ 24°17'08"N -153°58'51"E	OMNI-DIRECTIONAL	4000	100		±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SS3-X	NW PACIFIC	Hokkaido, JAPAN	+ 42°44'33"N -143°43'05"E	OMNI-DIRECTIONAL	400	100	99,700	±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SS3-Y		Gesashi, OKINAWA	+ 26°36'21"N -128°08'54"E	OMNI-DIRECTIONAL	400	100		±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
LORAN-C SS3-Z		Yap CAROLINE IS.	+ 9°32'46"N -138°09'55"E	OMNI-DIRECTIONAL	4000	100		±0.05	YES	CONTINUOUS	1 µs STEPS	7	24
OMEGA Ω/N (5)	NIL	Aldra, NORWAY	+66°25'N -13°09'E	TOP-LOADED FJORD SPAN	4(ERP) (5)	10.2-A 11-1/3-C 12.3(u) 13.6-B(6)	NIL	±0.5	$NIL_{(7)}$	CONTINUOUS (8)	(2)	7	24
OMEGA Ω/ND (REPLACES ΩN.Y.)	NIL	La Moure, N.D.,U.S.A.	+46°22'N +98°20'W	TOP-LOADED VERTICAL UMBRELLA	10(ERP)	10.2-D 11-1/3-F 13.6-E 12.85 } 13.1 } (u)	NIL	±0.5	$NIL_{(7)}$	CONTINUOUS (8)	(2)	7 (ABOUT APRIL 1972)	24
OMEGA Ω/T	NIL	Trinidad, WEST INDIES	+10°42'N +31°38'W	TOP-LOADED VALLEY-SPAN	1(ERP)	10.2-B 11-1/3-D 12.0(u) 13.6-C	NIL	±0.5	$NIL_{(7)}$	CONTINUOUS (8)	(2)	7	24
OMEGA Ω/H	NIL	Haiku, HAWAII U. S. A.	+ 21°24'N +157°50'W	TOP-LOADED VALLEY-SPAN	2(ERP)	10.2-C 11-1/3-E 12.2(u) 13.6-D	NIL	±0.5	$NIL_{(7)}$	CONTINUOUS (8)	(2)	7	24

Notes: (1) Principal information extracted from *CCIR Proc. XIIth Plenary Assembly* (New Delhi, India, 1970), vol. III [95], and the *BIH Annual Report* for 1971 [96]. The reader is referred to these documents for additional notes on variations of some broadcasts, as well as transmission formats.

(2) These broadcasts will be transmitted with zero offset after Jan. 1, 1972; Omega system will not make leap second adjustments.

(3) These Loran-C chains are time synchronized and phase controlled within ±15 µs of UTC (USNO). *M* designation indicates master; *W*, *X*, *Y*, *Z* indicate slave stations. Four additional chains are used for Loran-C navigation and employ Cs standards for frequency control, but are not maintained within ±15 µs of UTC. Of these, the Mediterranean and North Atlantic are time-monitored and corrections in terms of UTC (USNO) are published weekly; the North Pacific (Alaska) and Southeast Asia are unsynchronized and are not related to UTC. These latter four chains are subject to time jumps and equipment failures. Synchronization of stations within a chain is held usually within ±0.2 µs.

(4) Peak power except as noted estimated radiated power (ERP).

(5) Eight worldwide Omega navigation stations are planned for full implementation in the 1970's. Global coverage is anticipated with each station radiating 10 kW of power at stabilized frequencies between 10.2 and 13.6 kHz. Four interim stations are now in operation and are in process of being upgraded. Additional Omega stations will be constructed in Japan, Australia–New Zealand area, La Reunion (Indian Ocean), and Argentina.

(6) Letters refer to segments of Omega format except *u* which indicates unique assigned frequency to given station.

(7) Day, h, min, low-bit rate time code proposed for future inclusion in Omega format.

(8) Omega format is time multiplexed.

Appendix III

Characteristics of Standard Frequency and Time Signals in Allocated Bands(1)

STATION			TRANSMITTER			CARRIER (2)				TIME SIGNALS (2)		PERIOD OF OPERATION	
CALL SIGN	APPROXIMATE LOCATION	LONGITUDE LATITUDE	ANTENNA TYPE	RADIATED CARRIER POWER kW	NUMBER OF SIMULTANEOUS TRANSMISSIONS	STANDARD FREQUENCIES MHz	MODULATION Hz	ACCURACY PTS IN 10^{10}	TIME PULSES pps	DURATION MIN	TIME SIGNAL ADJUSTMENT	DAYS PER WEEK	HOURS PER DAY
ATA	New Delhi, INDIA	+28°34'N -77°19'E	HORIZONTAL DIPOLE	2	1	10	1;1000	±200	YES	CONTINUOUS	VLF STEERING PORTABLE CLOCK	5	5
FFH	Paris, FRANCE	+48°32'N -02°27'E	RADIATING MAST	5	1	2.5	1;1000	±2	YES	30/h	UTC	5(M-F)	8.5
IAM	Rome, ITALY	+41°52'N -12°27'E	VERTICAL λ/4	1	1	5	1;1000	±0.5	YES	10/15	UTC	6	2
IBF	Torino, ITALY	+45°02'N -07°46'E	VERTICAL λ/4	5	1	5	1;1000	±0.5	YES	CONTINUOUS	UTC	7	2.75
JG2AR	Tokyo, JAPAN	+35°42'N -139°31'E	OMNI-DIRECTIONAL	3	1	0.02	1	±1		CONTINUOUS	NON-OFFSET CARRIER	5(M-F)	2 (0530-0730 UT
JJY	Tokyo, JAPAN	+35°42'N -139°31'E	VERTICAL λ/2 DIPOLES; (λ/2 DIPOLE, TOP-LOADED FOR 2.5 MHz)	2		2.5;5 10;15	1;600; 1000;1600	±0.5	YES	CONTINUOUS	UTC	7	24 (9 MIN INTER-RUPTION PER h)
LOL	Buenos Aires, ARGENTINA	-34°37'S +58°21'W	HORIZONTAL 3-WIRE FOLD-ED DIPOLE	2	3	5;10;15	1;440; 1000	±0.2	YES	CONTINUOUS	UTC	7	5
MSF	Rugby, UNITED KINGDOM	+52°22'N +01°11'W	HORIZONTAL QUADRANT DIPOLES; (VERTICAL MONOPOLE, 2.5 MHz)	0.5	3	2.5;5;10	1;1000	±1	YES	5/10	UTC	7	24
OMA	Praha, CZECHOSLOVAK S.R.	+50°07'N -14°35'E	T	1	1	2.5	1;1000	±10		15/30	UTC	7	24
RWM/RES	Moskva, U.S.S.R.	+55°45'N -37°18'E		20	1	5;10;15	1;1000	±50	YES	10/2 h	UTC (UT1-UTC TO 10 ms)	7	19
WWV (3)	Fort Collins, COLORADO U.S.A.	+40°41'N +105°02'W	VERTICAL λ/2 DIPOLES	2.5-10 (VARIES WITH CARRIER FREQ)	6	2.5;5;10 15;20;25	1;100;440; 500;600; 1000;1500	±0.1	YES	CONTINUOUS	UTC	7	24
WWVH (3)	Kauai, HAWAII U.S.A.	+ 21°59'N +159°46'W	PHASED VERTICAL λ/2 DIPOLE ARRAYS (VERTICAL λ/2 FOR 2.5 MHz)	2.5-10 (VARIES WITH CARRIER FREQ)	5	2.5;5;10 15;20	1;100;440; 500;600; 1200;1500	±0.1	YES	CONTINUOUS	UTC	7	24
WWVL (4)	Fort Collins, COLORADO U.S.A.	+40°41'N +105°03'W	TOP-LOADED VERTICAL	1.8	1	0.02	NIL	±0.1	NIL	NIL	NON-OFFSET CARRIER	7	24
ZLFS	Lower Hutt, NEW ZEALAND	-41°14'S -174°55'E		0.3	1	2.5	NIL	±500	NIL	NIL		1	3
ZUO	Olifantsfontein, REPUBLIC OF SOUTH AFRICA	-25°58'S -28°14'E	VERTICAL MONOPOLE	4	1	5	1;1000	±0.5	YES	CONTINUOUS	UTC	7	24
ZUO	Johannesburg, REPUBLIC OF SOUTH AFRICA	-26°11'S -28°04'E	HORIZONTAL DIPOLE	0.25	1	10	1;1000	±0.5	YES	CONTINUOUS	UTC	7	24

Notes: (1) Information obtained as in Appendix II.

(2) UTC time adjustment and zero offset of carrier frequencies (atomic frequency) commenced Jan. 1, 1972. Step adjustments of 1s (leap seconds) will be made when necessary (1-year intervals) to prevent UT1 differing from UTC by more than ±0.7 s. A special code is disseminated with time signals to give difference UT1 − UTC to 100 ms. The USSR broadcasts also will give difference to 10 ms. Time signals of all standard frequency broadcasts are to be maintained within ±1 ms of UTC.

(3) An IRIG-H (modified) BCD timing code is transmitted continuously. This code is produced at a 1-pps rate and carried on a 100-Hz subcarrier, at a complete time frame of 1 min. The code gives UTC in s, min, h, and day of year and contains 60/min locking rate, 6/min position identification markers, and a 1/min reference marker. The 100 Hz is synchronous with the code pulses, providing 10-ms resolution.

(4) WWVL can be used for synchronization; it is an experimental broadcast only and is on an intermittent transmission schedule.

APPENDIX IV

CHARACTERISTICS OF STABILIZED FREQUENCY AND TIME-SIGNAL EMISSIONS OUTSIDE ALLOCATED FREQUENCY ASSIGNMENTS(1)

STATION			TRANSMITTER			CARRIER (2)				TIME SIGNALS (2)		PERIOD OF OPERATION	
CALL SIGN	APPROXIMATE LOCATION	LONGITUDE LATITUDE	ANTENNA TYPE	RADIATED CARRIER POWER kW	# OF SIMUL-TANEOUS BROADCASTS	STABILIZED FREQUENCIES kHz	MODULATION Hz	ACCURACY PTS IN 10^{10}	TIME PULSES pps	DURATION MIN	TIME SIGNAL ADJUSTMENT	DAYS PER WEEK	HOURS PER DAY
	Allouis, FRANCE	+47°10'N -02°12'E	OMNI-DIRECTIONAL	500	1	163.84	NIL	±0.5	NIL	NIL	ZERO OFFSET CARRIER	7	24
CHU	Ottawa, CANADA	+45°18'N +75°45'W	FOLDED DIPOLES & RHOMBIC	3; 5	3	3330;7335; 14670	1;1000	±0.2	YES	CONTINUOUS	UTC	7	24
	Donebach, F.R. of GERMANY	+49°34'N -09°11'E	OMNI-DIRECTIONAL	70	1	151	NIL	±0.3	NIL	NIL	ZERO OFFSET CARRIER	7	24
DCF77	Mainflingen, F.R. of GERMANY	+50°01'N -09°00'E	OMNI-DIRECTIONAL	12	1	77.5	1;440	±0.2	YES	CONTINUOUS	ZERO OFFSET CARRIER	7	24
	Droitwich, UNITED KINGDOM	+52°16'N +02°09'W	T	400	1	200	NIL	±0.2	NIL	NIL	ZERO OFFSET CARRIER	7	22
GBR	Rugby, UNITED KINGDOM	+52°22'N +01°11'W	OMNI-DIRECTIONAL	60(EST.)	1	15.95 16.00	1	±0.2	A1 TYPE	4 x 5 PER DAY	UTC	7	22 (OFF 1300-1430 UT DAILY
HBG	Prangins, SWITZERLAND	+46°24'N -06°15'E	OMNI-DIRECTIONAL	20	1	75	1	±0.2	CARRIER INTERRUPTION	CONTINUOUS	UTC	7	24
JJF-2 JG2AS	Kemigawa, Chiba C JAPAN	+ 35°38'N -140°04'E	OMNI-DIRECTIONAL	10	1	40	NIL	±0.5	NIL	NIL	UTC	7	24
MSF	Rugby, U.K.	+52°22'N +01°11'W	OMNI-DIRECTIONAL	50	1	60	1	±0.2	CARRIER INTERRUPTION	CONTINUOUS	UTC	7	24
NAA(4)	Cutler, MAINE U. S. A.	+44°39'N +67°17'W	OMNI-DIRECTIONAL	1000 (EST.)	1	17.8	NIL	±0.5	NIL	NIL	UTC	7	24
NBA(4)	Balboa, Panama, Canal Zone U. S. A.	+09°04'N +79°39'W	OMNI-DIRECTIONAL	150 (EST.)	1	24	1	±0.5	CW TIME PULSES	5 EVERY EVEN h EXCEPT 2400	UTC	7	24
NPG/ NLK(4)	Jim Creek, WASHINGTON U. S. A.	+48°12'N +121°55'W	OMNI-DIRECTIONAL	250 (EST.)	1	18.6	NIL	±0.5	NIL	NIL	UTC	7	24
NPM(4)	Lualualei, HAWAII U. S. A.	+ 21°25'N +158°09'W	OMNI-DIRECTIONAL	140 (EST.)	1	23.4	NIL	±0.5	NIL	NIL	UTC	7	24
NSS(4)	Annapolis, MARYLAND U. S. A.	+38°59'N +76°27'W	OMNI-DIRECTIONAL	100 (EST.)	1	21.4	1	±0.5	CW TIME PULSES	5 EVERY h	UTC	7	24
NWC(4)	North West Cape, AUSTRALIA	- 21°49'S -114°10'E	OMNI-DIRECTIONAL	1000 (EST.)	1	22.3	1	±0.5	FSK PULSES	2 BEFORE 0430,1630 (EXPERIMENTAL)	UTC	7	24
OMA	Podebrady, CZEC-OSLOVAK S.R.	+50°08'N -15°08'E	T	5	1	50	1	±10	CARRIER INTERRUPTION A1 TYPE	23 h PER DAY	UTC	7	24
RWM-RES	Moskva, U.S.S.R.	+55°45'N -37°18'E		20	1	100	1	±50	A1 TYPE	5 EVERY h EXCEPT 2000	UTC	7	21
SAZ	Enköping, SWEDEN	+59°35'N -17°08'E	YAGI (12 db)	0.1 (EST.)	1	10^5	NIL	±50	NIL	NIL	ZERO OFFSET CARRIER	7	24
SAJ	Stockholm, SWEDEN	+59°20'N -18°03'E	OMNI-DIRECTIONAL	0.1 (EST.)	1	1.5 x 10^5	NIL	±1	NIL	NIL	ZERO OFFSET CARRIER	1 (FRIDAY)	2 (0930-1130 UT)
VE9GBS (3)	Ottawa, CANADA	+45°22'N +75°53'W	TOP-LOADED VERTICAL	0.006-1.4 (DEPENDENT ON FREQ.)	1	16.9, 23-200	NIL	±0.3	NIL	NIL	UTC	7	24
VNG	Lyndhurst, VICTORIA AUSTRALIA	- 38°03'S -145°16'E	OMNI-DIRECTIONAL	10	2	4500;7500 12000	1;1000	±1	YES	CONTINUOUS EXCEPT FOR SILENT PERIODS	UTC	7	24 (VARIES BY FREQUENCY)
WWVB	Fort Collins, COLORADO U. S. A.	+ 40°40'N +105°03'W	TOP-LOADED VERTICAL	16	1	60	1	±0.1	TIME CODE	CONTINUOUS	UTC	7	24
ZUO	Johannesburg, REPUBLIC OF SOITH AFRICA	-26°11'S -28°04'E	OMNI-DIRECTIONAL	0.05	1	10^5	1	±0.5		CONTINUOUS	UTC	7	24(SILENT 15-25 MIN PAST h)

Notes: (1) Information obtained as in Appendix II.

(2) As Note (2) in Appendix II.

(3) Experimental LF station used primarily for propagation studies. For schedule of frequencies broadcast, contact Dr. J. Belrose, Department of Communications, Shirley Bay, Ont., Canada.

(4) These stations are used primarily for communication. Transmissions are referenced to Cs frequency standards and are useful for frequency synchronization. Station characteristics are subject to change; however, changes are announced in advance to interested users by USNO, Washington, D. C.

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DISSEMINATION TECHNIQUES		STATUS (1)	ACCURACY-FREQUENCY SYNCHRONIZATION	ACCURACY FOR DATE TRANSFER	AMBIGUITY (4)	COVERAGE FOR STATED ACCURACY	% 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	REFERENCES
HF/MF RADIO	STANDARD FREQ. BROADCASTS(WWV)	O	1×10^{-7}	1000μs	1 DAY / 0.5MIN	HEMISPHERE		DEPENDS ON CONDITIONS					[54,55]
	NAVIGATION SYSTEM LORAN-A	O	5×10^{-11} (2)	2-5μs NOT UTC		LIMITED AREAS		DEPENDS ON CONDITIONS			SPECIAL AREAS		[56]
LF RADIO	STANDARD FREQ. BROADCASTS(WWVB)	O	(3) 1×10^{-11} (PHASE-24h)	ENVELOPE ~50μs	1 YR	USA(WWVB) LIMITED			MODERATE		USA(WWVB) EUROPE OTHERS		[57,58]
	NAVIGATION SYSTEM LORAN-C	O	1×10^{-12} GND(3)	~1μs(GND) 50μs (SKY)	50ms / PHASE 10μs	SPECIAL† AREAS					SPECIAL AREAS		[33,59]
VLF RADIO	COMMUNICATION/SFB GBR, NBA, WWVL	O	1×10^{-11} (3)	ENVELOPE 500μs	PHASE ~50μs	GLOBAL							[60,61,62]
	NAVIGATION SYSTEM OMEGA	O/P	$<1\times10^{-11}$ (3)	≤10μs■	PROPOSED CODE - 1YR / PHASE ~100μs	GLOBAL			MODERATE			TIME CODE	[63,64,65]
SATELLITES (VHF/UHF RADIO)	STATIONARY SATELLITES ONE WAY	E/O	1×10^{-10} (24h)	10-50μs	DEPENDS ON FORMAT	HEMISPHERE	STATIONARY						[49,50,52]
	STATIONARY SATELLITES TWO WAY	E/O	1×10^{-12} (24h)	~100ns	DEPENDS ON FORMAT	HEMISPHERE				MODERATE			[48,66]
	ON-BOARD CLOCK (ACTIVE) ONE WAY - LOW ALTITUDE	O	$\sim1\times10^{-10}$ (24h)	0.5-50μs	DEPENDS ON FORMAT	WORLD	10-15 MIN PER PASS 2-4 PER DAY	CLOCK NEEDS ADJUSTMENT					[45,67,68]
PORTABLE CLOCKS	PHYSICAL TRANSFER	O	1×10^{-12}	100ns★	1 DAY	LIMITED BY TRANSPORTATION	AS NEEDED		NONE				[23,28]
	AIRCRAFT FLYOVER 2-WAY	E	1×10^{-12}	≤100ns	DEPENDS ON FORMAT	LIMITED BY TRANSPORTATION	AS NEEDED						[30,31]
TELEVISION (VHF/SHF RADIO)	PASSIVE -LINE-10	O	1×10^{-11} (24h)	~1μs	1 DAY / ~33ms	NETWORK COVERAGE	"LIVE" PROGRAMS				USA FOR EXAMPLE		[34,40,69]
	ACTIVE-LINE-1(NBS TV TIME SYSTEM)	E	1×10^{-11} (<30 MIN)	<100ns●	1 DAY / ~33ms	NETWORK COVERAGE					USA FOR EXAMPLE		[37]
SHF RADIO	MICROWAVE	E/O	$\sim1\times10^{-13}$ (PER WEEK)	≤100ns	PHASE COMPARISON	LOCAL LINKS							[70]
	VLBI	P	5×10^{-14}	~1ns	DEPENDS ON FORMAT	HEMISPHERE	AS NEEDED						[71]

GOOD FAIR POOR

Fig. 10. A comparison of some dissemination techniques. *Notes:* (1) Status of technique indicated as follows: O—operational; P—proposed; E/O—experimental operational. (2) Estimates of day-to-day measurements within 2000 km (1250 mi) of Loran-A stations. These emissions not coordinated with UTC and manually operated crystal clocks drift. (3) From day-to-day phase measurements, e.g., ~1 μs per day phase change approximates 1 pt. in 10^{11} in frequency difference. (4) Left-hand designation gives the shortest time interval that cannot be resolved; right-hand number gives basic ambiguity. †, by ground wave 1600 km; by sky wave thousands of kilometers depending upon conditions. ■, with proposed time code. ★, closure after 1 day. ●, within local service area of TV transmitter and path delay known.