In the continental U.S., frequency standard comparisons to an accuracy of a part in 10^{10} can be approached in an 8 hour period. A 30 day period may give accuracies of parts in 10^{12}. The local standard being calibrated must, of course, be of a quality commensurate with the realization of such high accuracies. NBS station WWVB, at Ft. Collins, Colorado, is kept to within a tolerance limit of 1 part in 10^{11}.

The receiver and comparator system phase track a voltage-controlled oscillator with the transmitted signal. The local frequency standard is then compared to the phase tracking oscillator. The comparator's strip chart recorder makes a continuous recording of the phase differences, measured in μs.

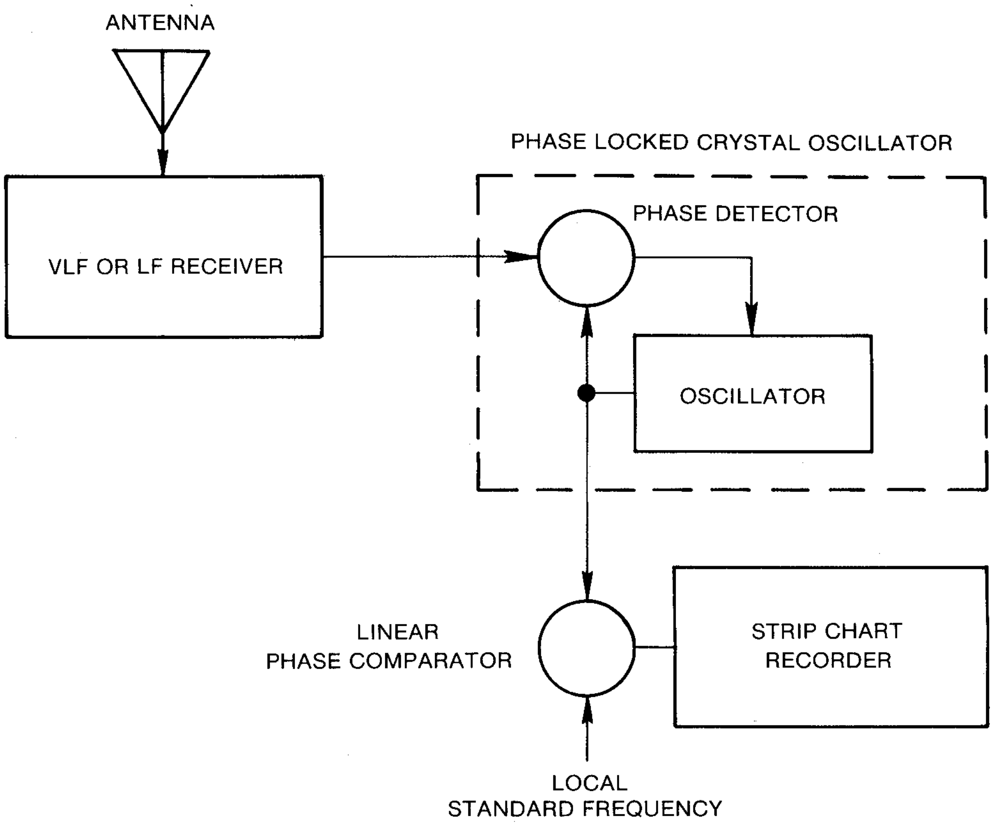

Figure 4-3. LF or VLF Frequency Determination

In operating the receiver-comparator, the user should always consider the system as a whole:

1) Transmitted signal;
2) Transmission path;
3) Receiver-comparator system;
4) Local standard.

The first two parts of the system are not under the user's control, so he must choose his observation time when a frequency standard signal is being transmitted and when transmission conditions are optimum. He should keep up to date on the NBS or other low frequency services by requesting to be placed on the appropriate mailing list of the transmitting agency (see AN 52-1).

Antenna location and orientation are important. Best location is on the roof of a building on the side facing the transmitter. The antenna should clear by 3 feet or more any metal structure, roof, etc.

The receiver-comparator plots the phase difference of a locally generated signal vs. that of the received carrier by means of a strip chart recorder.

It is possible to make frequency comparisons by measuring changes in phase, over a period of time, between a locally generated signal (from a quartz crystal oscillator, counter time base, etc.) and the received carrier. The fractional frequency offset of the local signal with respect to the received signal is equivalent to the change in the phase measured over a time interval. The receiver-comparator plots this phase difference as a function of time with, under laboratory conditions, a resolution better than 1 μs of phase difference.

The slope of the trace made by the strip chart recorder is, at a given instant, proportional to the frequency offset between the local standard and the received signal $d\phi/dt$. It is possible to interpret the chart trace by selecting two points on the trace some distance apart in chart time and to read off the change. If N is the difference in μs of two readings three hours apart, then N can be said to be the average frequency offset of the local oscillator in parts in 10^{10}. This is apparent from the following:

$$\frac{N \text{ microseconds}}{3 \text{ hours}} = \frac{N}{3(3600)10^6} = \frac{N}{10^{10}}$$

The fractional time error corresponds to the fractional frequency error:

$$\left|\frac{\Delta f}{f}\right| = \left|\frac{\Delta t}{t}\right| = \pm N \times 10^{-10}$$

OTHER LF/VLF SINGLE FREQUENCY TECHNIQUES—While no other LF or VLF comparison method offers the convenience and simplicity afforded by use of the receiver-comparator just described, there are a number of equipment arrangements which can be used.

Two methods are discussed here. One involves the use of an electronic counter in its time interval mode for the comparison and the other uses an oscilloscope display.

The system that employs a simple LF/VLF receiver, a time interval counter and other equipment, shown in Figure 4-4, could serve to determine the drift of a local standard such as a quartz crystal oscillator.

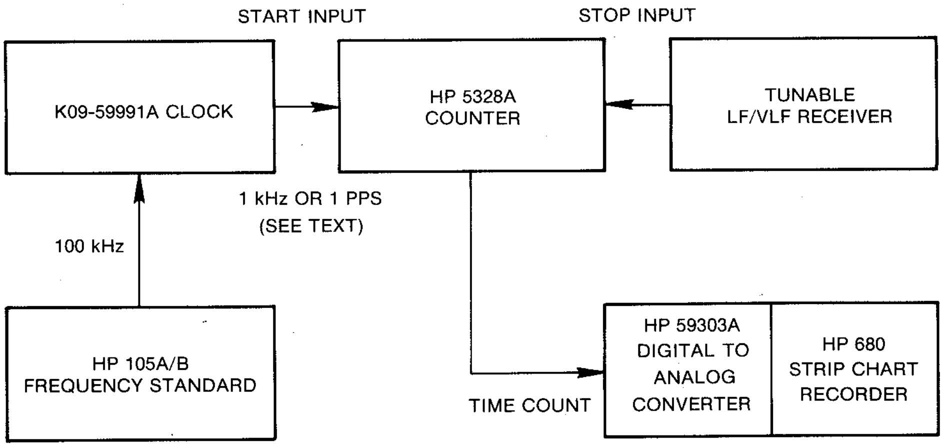

Figure 4-4. LF/VLF Comparison System Using a Counter

For example, suppose the 60 kHz signal from NBS station WWVB is to be the reference. The Model 105A/B Quartz Oscillator output drives the K09-59991A clock. The clock's 1 PPS output is used to start the interval count and the received 60 kHz carrier is used to stop it. The Model 5328A Counter's trigger level and slope controls permit the selection of precisely repeatable points on the start and stop waveforms. The Model 59303A Digital-Analog Converter and the Model 680 Recorder make, from the time interval counter's measurements, a continuous record from which the relative time-drift of the local oscillator can easily be determined.

A short calculation indicates that this method makes possible a comparison accuracy of a part in 10^9 or better in an hour. Since there are approximately 4 x 10^9 microseconds in 1 hour, a frequency difference of 1 part in 10^9 between the received signal and that from the local standard would result in a time drift of about 4 microseconds over a 1 hour measurement. This value is found to be well within the resolution of the equipment.

Calculation of the frequency error of the local standard can be made as described in Section III and is based upon the time drift of the average time interval readings.

A comparison method that, using an oscilloscope, makes possible a visual comparison of a local oscillator against LF/VLF signals and can be set up as shown in Figure 4-5.

The signal is received and amplified and is displayed on the oscilloscope (vertical axis), which is synchronized externally by a signal from the local standard being compared.

Comparison measurements are made by positioning the zero crossing of the waveform to some reference point on the oscilloscope and observing the amount and direction of drift over a period of time. A drift toward the right of the screen indicates that the frequency of the local standard is high, whereas a drift to the left indicates that the frequency is low. Average frequency error may be calculated from the following relationship:

$$\left|\frac{\Delta f}{f}\right| = \left|\frac{\Delta t}{t}\right|$$

where

$\frac{\Delta f}{f}$ = average frequency error

Δt = amount of drift during period T

t = comparison period

Comparison accuracy of this technique is determined by oscilloscope trigger stability, sweep calibration accuracy, and the user's ability to integrate and resolve Δt. It is not recommended that frequency standards with accuracy requirements better than several parts in 10^9 be calibrated by this method.

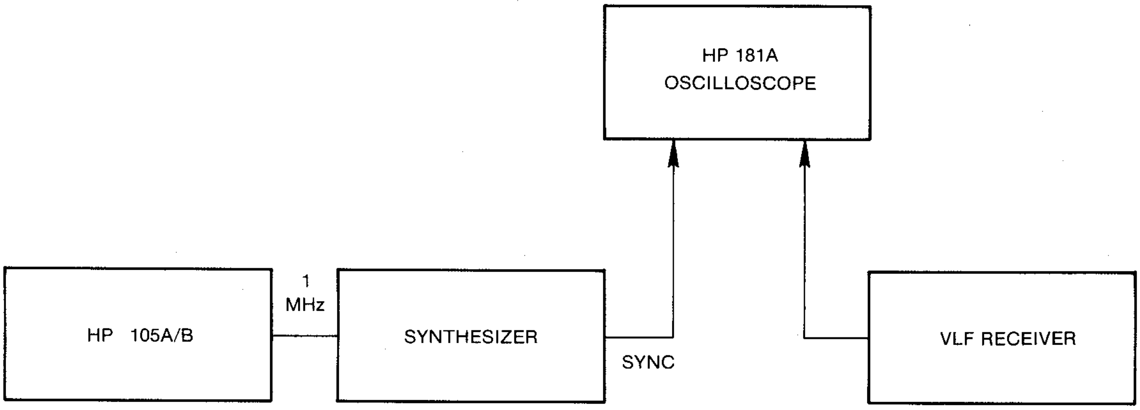

Figure 4-5. VLF/LF Comparison Using an Oscilloscope

LORAN C NAVIGATION SYSTEM

Loran-C (LOng RAnge Navigation) is a navigation system, currently available in some parts of the Northern Hemisphere, designed to provide precise position for ships, submarines, and aircraft. Early in the 1960's NBS examined the Loran C navigation System to determine its usefulness in time and frequency distribution. Since then, the Loran-C transmitters have been cesium stabilized and today the system is one of the most accurate time transfer medium available via radio waves.

The Loran-C navigation system is operated by the U.S. Coast Guard. The carrier frequency is 100 kHz, with a 20 kHz bandwidth, and the transmission format uses pulsed transmission. There are currently 30 transmitting stations organized into seven chains, around the world. Expansion of coverage to new areas is underway, with Western U.S. coverage due in 1977. Each chain consists of one master station and two or more slave stations. Table 4-2 contains a listing of the seven Loran-C chains.

Table 4-2. Loran-C Stations

CHAIN	RATE	STATIONS	
U.S. East Coast	9930	M	Carolina Beach, NC
		W	Jupiter, FL
		X	Cape Race, NF
		Y	Nantucket Is., MA
		Z	Dana, IN
Mediterranean	7990	M	Simeri Crichi, Italy
		X	Lampedusa, Italy
		Y	Kargabarun, Turkey
		Z	Estartit, Spain
Norwegian Sea	7970	M	Ejde, Faroe Is.
		W	Sylt, Germany
		X	Bo, Norway
		Y	Sandur, Iceland
		Z	Jan Mayen, Norway
North Atlantic	7930	M	Angissoq, Greenland
		W	Sandur, Iceland
		X	Ejde, Faroe Is.
		Z	Cape Race, NF
North Pacific	5930	M	St. Paul, Pribiloff Is.
		X	Attu, AK
		Y	Port Clarence, AK
		Z	Sitkinak, AK
Central Pacific	4990	M	Johnston Is.
		X	Upolo Pt., HI
		Y	Kure, Midway Islands
Northwest Pacific	9970	M	Iwo Jima, Bonin Islands
		W	Marcus Island
		X	Hokkaido, Japan
		Y	Gesashi, Okinawa
		Z	Yap, Caroline Islands

**Approximate value*

The repetition rates used in the Loran-C pulse code format provide three basic benefits:

1. The chains and the individual stations can be separated and identified.
2. Coherent stray interference is eliminated.
3. The signal to noise ratio is optimized for a given geographical location.

Accuracy. The Loran-C system provides the capability of obtaining submicrosecond synchronization by use of the groundwave. Skywave users can obtain ±10-50μs accuracy. As in any timekeeping system using radio waves, the accuracy depends upon the variations in the system. First, the propagation delay and propagation path variations must be known. Second, the delays through the equipment must be determined and last the operator must have some skill in cycle selection for accurate time transfer. All of these constants can be determined by means of a portable clock.

Advantages and Limitations. Loran-C has a number of tremendous advantages to the timekeeping system user.

1. The transmitters are controlled by redundant cesium standards and are referenced to UTC (USNO). The USNO publishes weekly phase corrections for the chains.
2. Propagation effects of the groundwave signals allow accuracy of time transfer to about ± 0.3 microsecond. Skywave signals can provide ± 10-50 μs synchronizations depending upon the number of hops.
3. The time of coincidence, (TOC) explained in later paragraphs, for time coordinated chains is provided in advance by USNO.
4. Equipment costs are reasonable, however, they increase as the user's requirements become more stringent.

In contrast, the limitations are:

1. The time transfer accuracy is limited to the accuracy to which the delays (equipment and propagation) are determined. Terrain effects and mixed sea and land paths limit the obtainable accuracy.
2. Local clock time must be known to better than half the chain repetition period to eliminate Group Repetition Period (GRP) ambiguity (typically ~10 milliseconds).
3. Cycle selection is difficult and requires highly skilled operators.
4. Coverage is not global.

Time and Frequency Determination. The Loran-C system does not broadcast a time code signal. Therefore, it is important to know the time-of-coincidence (TOC) of a Loran-C signal relative to a UTC second. Each chain transmits in a particular format, as shown in the example of Figure 4-6. Within the Group Repetition Period, GRP, (a different GRP is assigned to each chain), the master station transmits exactly spaced groups of nine pulses. Each of the slave stations transmits, in turn, eight pulses within the GRP.

There is only one GRP that will provide a TOC every second. The period between a pulse coinciding with one UTC second and another pulse-UTC-second TOC, depends upon the repetition rate of the chain. Each chain is assigned a different repetition period. The available rates are shown in Table 4-3 as well as the period of time between UTC seconds and Loran-C rate coincidence. The TOC varies for the different rates; for example, a repetition period of 59,400 μs gives a coincidence interval of 297 seconds, whereas a rate of 79,500 μs repeats every 159 seconds. The USNO publishes the periodic coincidence from an arbitrary origin in null ephemeris tables for each calendar year in Series 9 of the Time Service Announcements. The initial date (epoch) for all Loran-C master stations has been arbitrarily set at $00^h00^m00^s$, 1 January 1958. If coincidence measurements are to be made using slave stations, the user must account for the corresponding emission delays.

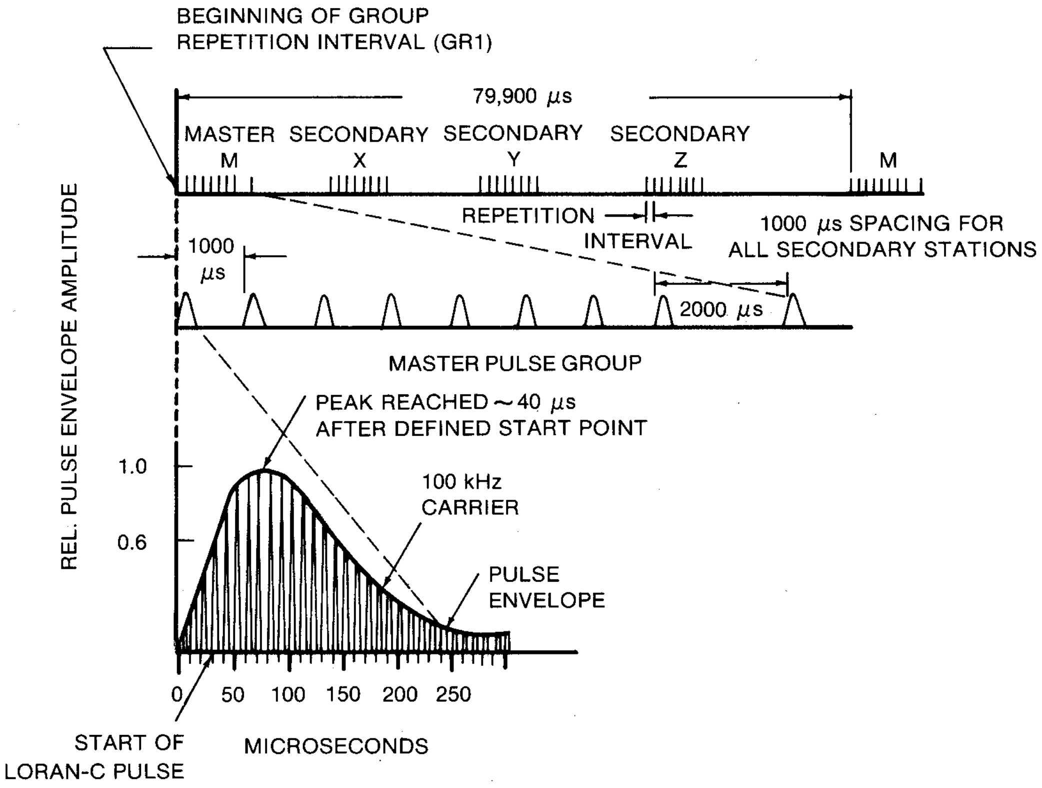

Figure 4-6. Loran-C Pulse Group Format

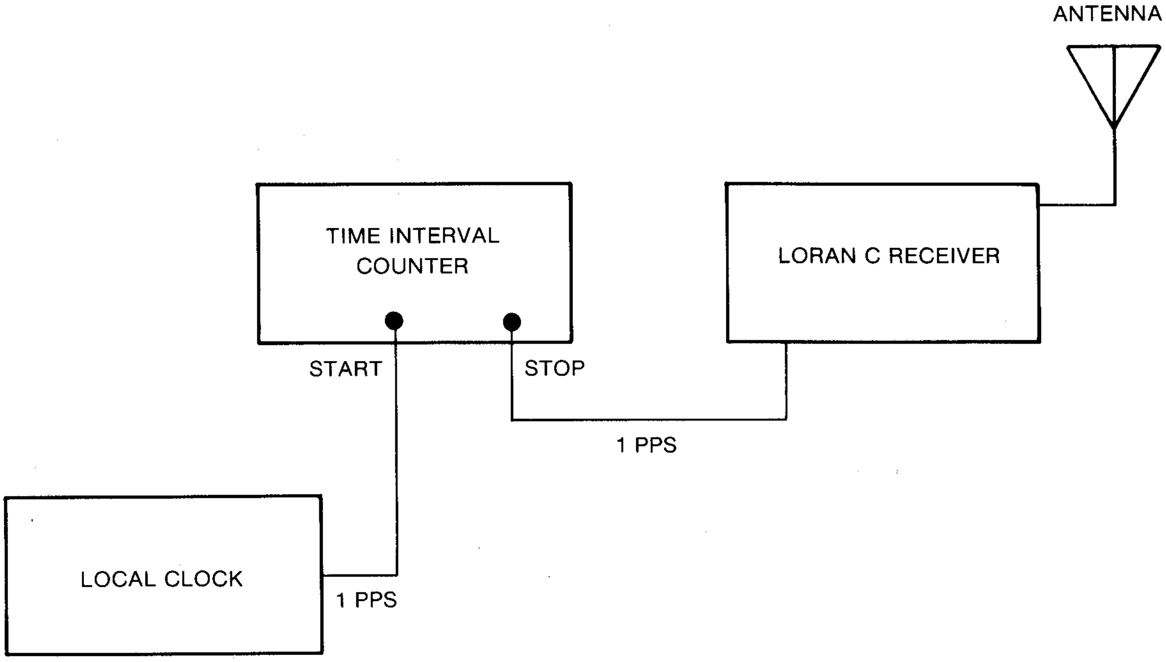

Figure 4-7. Loran-C Timekeeping System

Now that we have an idea of the type of pulses transmitted by the Loran-C network, let us examine how we can make use of this navigation system for time transfer and timekeeping.

Figure 4-7 shows one equipment configuration, out of several, for receiving and utilizing Loran-C transmissions for time transfer. In this particular equipment configuration, the local clock's 1 PPS is used to start a time interval counter and the output of the Loran-C receiver is used to stop the counter. The output of the Loran-C receiver is a 1 PPS phase-locked to the received signal and synchronized to agree with the TOC. Using the count on the Time Interval Counter and published USNO data we can determine the difference between UTC (USNO) and the local clock.

Table 4-3. Loran-C Group Repetition Periods

GROUP REPETITION PERIOD - μs	PERIOD OF TIME BETWEEN UTS* AND LORAN RATE COINCIDENCES (SECONDS)
50,000	1
49,900	499
49,800	249
49,700	497
49,600	31
49,500	99
49,400	247
49,300	493
60,000	3
59,900	599
59,800	299
59,700	597
59,600	149
59,500	119
59,400	297
59,300	593
80,000	2
79,900	799
79,800	399
79,700	797
79,600	199
79,500	159
79,400	397
79,300	793
100,000	1
99,900	999
99,800	499
99,700	997
99,600	249
99,500	199
99,400	497
99,300	993

**UTS* = Universal Time Second or UTC Second.

$$\text{UTC (USNO)-UTC (local)} = t_d + t_s - t_m$$

where

t_d = propagation path delay as computed or measured by portable clock trip

t_s = Loran-C transmitter station error as published in USNO Publication Series 4: Daily Phase Values and Time Differences

t_m = measured time difference between received Loran-C pulse and local clock.

Example: At the Hewlett-Packard plant in Santa Clara, California on 10 September 1975, the local clock (a HP 5061A) was compared against the Loran-D (similar format to Loran-C) West Coast station (4930).

t_d = 2198.8 μs

t_s = 11.4μs (from Series 4 dated 11 September 1975, copy contained in Appendix E)

t_m = 2209.8μs (measured with an HP 5345A Electronic Counter)

therefore;

$$\begin{aligned}\text{UTC (USNO)-UTC (HP)} &= t_d + t_s - t_m\\ &= 2198.8 + 11.4 - 2209.8\\ \text{UTC (USNO)-UTC (HP)} &= +0.4\mu s\end{aligned}$$

which means that the HP local clock was 400 nanoseconds behind UTC (USNO) on 10 September 1975.

TELEVISION SIGNALS

There are several ways television signals can be used to disseminate time and frequency depending on required accuracy, available television accuracy, determination of propagation delays, etc. There are two basic techniques possible with television signals; passive and active. In passive techniques, the TV signal simply acts as a transfer standard for either time or frequency or both. Active techniques involve the unused TV spectrum being used to carry time information. The techniques described in this section pertain to all TV systems, but the discussion centers around the National Television Systems Committee (NTSC) system in use in the U.S.

One passive time transfer technique involves two or more clock locations receiving the same TV transmitter signals. This technique places no restrictions on the individual transmitter. It does require that the clocks to be located within the viewing area of the transmitter. A second passive technique involves two or more clocks receiving the same network broadcast originating from the same studio but relayed to and transmitted by two or more stations in different viewing areas. In this type of technique the system delays must be known as well as the propagation path delays for each individual transmitter and receiver when doing time synchronization. The unknown delays do not affect frequency calibration accuracy.

In one particular experimental time transfer system using passive TV techniques, the USNO obtained the cooperation of a local Washington, D.C. TV station. The color subcarrier frequency, 3.5795 454 . . . MHz, is stabilized with a cesium beam frequency standard and phase shifted so that sync pulses in the vertical interval coincide with 1 PPS signals referenced to the USNO master clock. Specifically, the line-10 pulse marker (odd field) is compared against a one-second pulse of the USNO master clock. A time of coincidence (TOC) between the two pulses occurs every 1001 seconds (16 min 41 sec) due to the repetition rate of the TV frame (33.366 667 ms per frame).

Accuracy. The accuracy obtained using television depends on:

1) The particular method being used;
2) The degree to which the television signal is related to UTC time scale (in some methods);
3) The calculation accuracy for propagation path delays.

It is possible to obtain time accuracy of a few microseconds using a passive line 10 technique from stabilized network programs in the U.S. Using the passive technique previously described for local service areas, time transfer can be made with an accuracy of better than 100 nanoseconds. Using the technique proposed by the USNO, clocks can be synchronized within the local TV service area to within a few nanoseconds of the referenced clock.

Advantages and Limitations. Table 4-4 lists the advantages and limitations of the various TV time and frequency transfer techniques.

Table 4-4. Advantages and Limitations of TV Time and Frequency Transfer

Television Technique	Advantages	Limitations
Transfer standard (differential) using a TV sync pulse received in a TV transmitter local service area.	1. Precise clock comparisons can be made to better than 100 ns. 2. Comparisons can be made at any time during transmission without modification or influence on network programming. 3. Method is independent of microwave network routing. 4. Comparison equipment at a receiving station is relatively inexpensive. 5. Measurement methods are simple. 6. Simultaneous clock measurements can be made at an unlimited number of stations within a local service area.	1. Clock readings must be taken simultaneously by timing centers requiring synchronization. 2. Data must be exchanged between participating stations after the fact of measurement. 3. Technique gives only comparative clock differences. Calibrated path delays between stations is required for absolute time comparison. 4. Coverage limited to line of sight VHF or UHF signals which may be subject to multipath interference within a local TV service area.
Transfer standard (differential) using received TV line-10 throughout continental U.S.	1. Precise clock comparisons can be made to about several microseconds nearly anywhere throughout continental U.S. 2. Three television networks with atomic clock references (Rb) provide redundancy and enable cross synchronization; system has no effect on network programming. 3. One-a-day measurements are adequate for precise frequency standards. 4. Users can compare TV line-10 measurements with published NBS and USNO values and relate time scales if propagation path is calibrated. 5. Modular frame intervals can permit advance predicted TV delays.	1. Microwave paths can be interrupted or networks rerouted without notice. 2. Clock readings must be made simultaneously by all stations requiring synchronization. 3. Measurements require simultaneous viewing of "live" broadcasts originating from New York City studios for near-continental coverage; present network distribution system uses a delay tie-in with West Coast transmission lines which limits coverage of West Coast area; also there is limited availability of simultaneous viewing of nationwide network programs. 4. System will not work with tape delays. 5. NBS and USNO measurements are not made on weekends and reference data at these times are unavailable. 6. Line-10 TV system ambiguity is ~33 ms. 7. Propagation anomalies may limit system's usefulness in some areas of the continental U.S.
Real time transfer from time-scale-related transmissions (line-10 in local TV service area).	1. System can set or synchronize clocks within the local TV service area to a few nanoseconds of a reference clock. 2. The stabilized modular frame intervals permit prediction of TOC between 1 pps of an atomic time scale and emitted line-10 odd pulses, months in advance. This allows construction of TOC charts and independent clock synchronizations. 3. System will operate with existing line-10 TV receivers. 4. Operation is without interference or effect on regular programming. 5. Measurement methods are simple.	1. Requires installation of atomic cesium clock and phase shifting synthesizer at local TV transmitter. 2. Absolute clock calibrations require knowledge of delay between the transmitter atomic standard and local standard at TV receiving site. 3. Clock time must be known to half the system ambiguity or ~16 ms. 4. Coverage limited to line of sight VHF or UHF signals which may be subject to multipath interference within a local TV service area.

Time and Frequency Determination. The equipment setup for the passive line-10 techniques is shown in Figure 4-8. For the two methods described previously using line-10, differences occur in the techniques involved rather than the equipment required.

As shown in Figure 4-8, the equipment required is:

1) A TV receiver;
2) A line-10 pulse generator;
3) The local standard;
4) A time interval counter;
5) An optional digital recorder (printer).

The basic measurement between two or more locations involves each observer starting a time interval counter with a 1 PPS tick at an agreed upon time. The counter is then stopped with the next TV line-10 sync pulse. The observers at each location must communicate with each other and calculate the difference in their respective time interval readings. In the case of the network system, reference time interval readings are published by NBS and USNO at specific times of day. The NBS publications include data on the West Coast networks as supplied by the Hewlett-Packard Company. The difference in the readings is the sum of the clock errors and the difference in total path delays.

If time is to be transferred from one location to another via a single TV transmitter, the distance from the TV transmitter location to each of the receivers can be computed. In addition the propagation delay calculated as described in Appendix A for millisecond accuracies or for microsecond accuracy a portable clock type would be required.

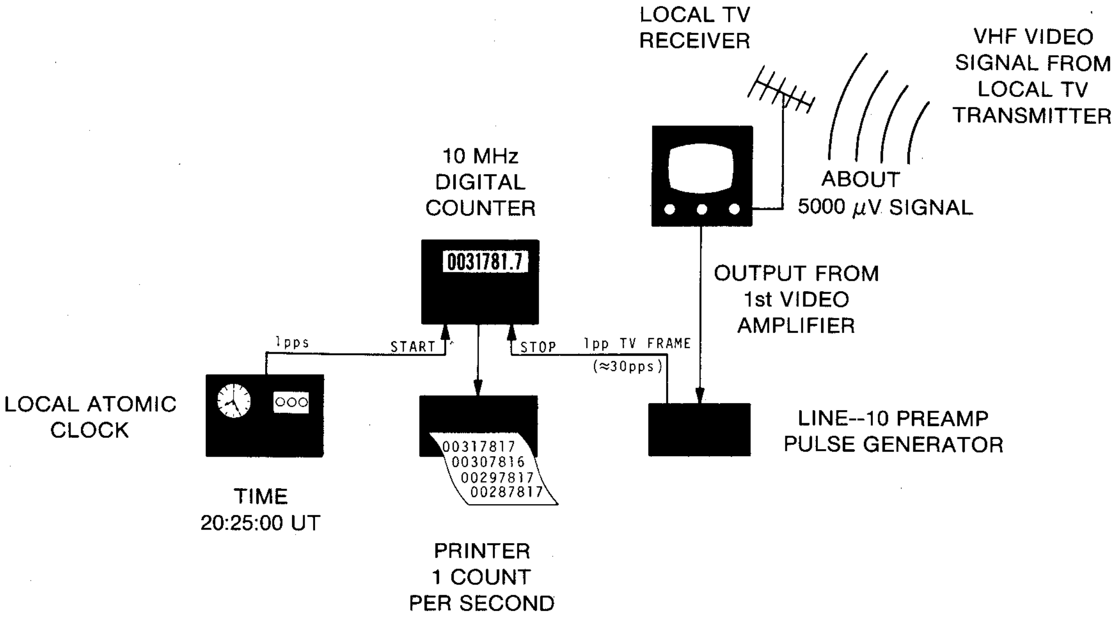

Figure 4-8. Typical Line-10 TV Receiver Equipment Configuration

Example:
It is mutually agreed that two stations, with identical equipment, equidistant from Channel 5 located nearby will compare their clocks each day at $12^{h}10^{m}00^{s}$ each day. In the month of August they obtain the following results:

TIME INTERVAL MEASUREMENT (μsec)

Date	**Receiver 1**	**Receiver 2**	**Difference**
9	2973.7	2637.6	336.1
10	2437.5	2100.3	337.2
11	2556.5	2218.1	338.4
12	2097.3	1757.8	339.5
13	1976.5	1635.8	340.7

The data gives a $\Delta t = 1.1\mu$sec/day with no apparent aging or drift effects (measurement over a longer time would provide a better comparison of aging or frequency drift between the two clocks). The frequency offset for the two clocks can be computed by:

$$\frac{\Delta f}{f} = \frac{\Delta t}{t} = \frac{1.1\mu\text{sec}}{24\text{ hours}} = 1.27\text{x}10^{-11}$$ frequency offset (difference) between the two clocks.

It should be noted that for this particular example, the equipment was the same in both receivers and hence the difference in system delays was negligible (this should be verified in an actual situation). Secondly, the receivers were equidistant from the transmitter and therefore the propagation path delay difference was negligible.

Of course the system and path delays are only important for time transfer (such as the USNO system) and not frequency comparison since frequency comparison is dependent only upon the relative rate difference of the two clocks. The initialization of the two clocks can be accomplished via a portable clock or if a portable clock is not available, the clock which is to be designated the remote site could be transported to the master clock location, synchronized, and then returned to its own location. Unfortunately, for this particular time and frequency transfer technique, the two clocks must be within 33 ms of each other to remove ambiguity of framing pulses. The use of a flying clock could also provide a means of calibrating the propagation path delays. In the table of measurements, the actual time interval measurement changed from day-to-day although the difference was fairly constant. The randomness is due to the fact that the TV frequency differs from UTC by about -300×10^{-10} and the frame rate is not coincident with 1 PPS. The stability of the TV transmitter is unimportant in this case. What is important is that the two clocks measure time from the same pulse.

NETWORK TV USAGE—The equipment setup is the same for this technique as shown in Figure 4-8. All three of the major U.S.A. networks (ABC, NBC, CBS) stabilize their color subcarrier (3.579 . . . MHz) using Rubidium frequency standards. The frequency, however, is offset by about $-300\text{x}10^{-10}$ due to the fact that the Rubidium standards were installed during the time when the UTC was offset $-300\text{x}10^{-10}$ relative to atomic time, AT (the official offset is currently zero).

All three of the networks are monitored in frequency relative to the NBS and USNO and data are published to indicate the performance of the network frequencies. The fact that the networks' frequencies are available to a large number of users and the receiving equipment is relatively inexpensive makes it very attractive as a time and frequency transfer medium. Information regarding the use of a low cost comparator for direct frequency comparison against the TV color subcarrier frequency (3.579 ... MHz) is available from NBS, Time and Frequency Services Section, Boulder, Colorado, 80302.

There are three major problems in using network TV signals in the U.S. First, the propagation path can change due to changes in the routing of the TV signal over microwave networks, etc.

Second, the show being used must be a broadcast originating from the network studio. This separates the West Coast from the East Coast and Midwest portions of the U.S. due to the fact that almost all programs from the East Coast are retransmitted on the West Coast at a later time. Data on the West Coast transmissions are now being published by NBS. Third, to use the networks as a frequency standard requires that the user take his measurements and then wait for the NBS and USNO to publish data on the network performance or call either agency before he can verify his own performance. This delay creates a lag in being able to correct his own frequency. However, with reasonable reliability one can extrapolate the NBS and USNO frequency data since the network Rubidium clocks are seldom changed.

TIME AND FREQUENCY TRANSFER USING NETWORK TV—The broadcasts over network TV can be used to transfer time and frequency from one location to another. The technique is the same as if the same transmitter were used except that now the same program source is used., i.e., the network studio. However, the delay from the studio to each location must be determined for time transfer and the same network program must be used. The delay can be calibrated using a portable clock.

EXPERIMENTAL TV TECHNIQUES—The cesium stabilized line-10 system developed by the USNO is currently an experimental system. The potential for this system to become operational appears to be in the distant future due to the costs involved.

PORTABLE CLOCKS

The most accurate and reliable method for transferring time from one location to another involves physically transporting a clock from one site to the other. This technique is by no means a new one. International comparisons were made by carrying piezo resonators to seven laboratories in Italy, France, England and the United States in 1923. Primary frequency standards were shown to be in agreement to within 1 part in 10^3. Several portable clock trips were conducted between 1923 and 1964 using quartz oscillators and early cesium standards. The accuracies obtained during these trips varied between 3 parts in 10^5 to several parts in 10^{10}.

In 1964 Hewlett-Packard initiated a series of experimental flying clock trips. The last of the series was conducted in 1967. In the last trip, which took 41 days, 53 locations in 18 countries were visited. The clocks were transported over 100,000 km with time correlations accurate to about $0.1\mu s$. The time closure between the reference clock and the two portable clocks was $3.5\mu s$ corresponding to frequency differences of 5 and 10 parts in 10^{13} between the portable standards and the reference.

Since the first availability of the HP 5060A and its successor, the HP 5061A Cesium Beam Frequency Standards, numerous government and commercial agencies and organizations have conducted portable clock time transfers with excellent success.

Accuracy. As mentioned before, the portable clock technique for transferring time is the most accurate of the commonly used practices. Time transfer can be accomplished within 100 ns and frequency can be transferred with an accuracy of 1 part in 10^{-12} for one trip and parts in 10^{-14} for multiple trips using cesium clocks. Other clocks such as rubidium and quartz can be used but with lesser accuracy.

Advantages and Limitations. The advantages of the portable clock technique include:

1. Microsecond time synchronization of remote clocks can be obtained without a dependent radio link and the corresponding delays and propagation errors.
2. Manpower needs are minimal and equipment normally can be found in a standards laboratory.

3. The portable clocks are relatively lightweight, rugged and can operate from either internal standby batteries or external AC/DC sources.
4. The portable clocks are easily transported by commercial airlines and automobiles.
5. Newer portable cesium standards are relatively insensitive to shock and vibration, smaller in size and lighter in weight.

Limitations are:

1. The most accurate portable clocks are expensive, and the technique requires physical transportation of the clocks which in itself can be expensive. The accuracy obtainable is directly related to the cost of the clock.
2. The clocks are usually handcarried and, although experience has indicated high reliability, there is the possibility of the clocks stopping or changing rate enroute due to power outages, excessive vibration, or environmental changes of temperature, humidity or air pressure.
3. It is difficult or impossible to make side-by-side comparisons at some locations due to inaccessibility such as certain islands, mountain stations, etc. In these cases, an aircraft fly-over technique can be used, but the cost of the operation increases significantly. The aircraft fly-over technique is described in detail in NBS Monograph 140.

Time and Frequency Transfer. Accomplishing a time and frequency transfer using a portable clock is a relatively simple task. Figure 4-9 shows a typical equipment configuration at the master clock location. If we wish to initially set a remote clock,there are basically two methods which can be used depending upon the initial accuracy desired. The most accurate technique requires that the transfer clock (portable clock) be initially compared and set both in frequency and time as closely as possible with the master clock.

The procedure is as follows:

> Using a linear phase-comparator (such as K05-5060A or K19-5061A) and a strip chart recorder, compare the relative phase drift of the 5 MHz signal from the two standards long enough to achieve the level of measurement accuracy desired.

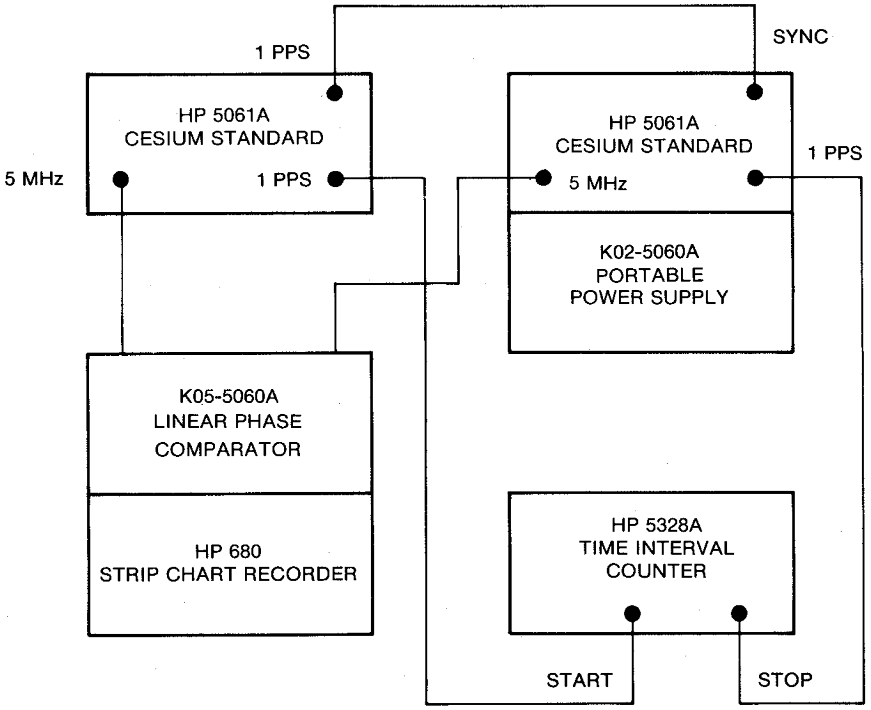

Figure 4-9. Typical Portable Clock Equipment Setup (at Master Station)

Example:
The accuracy desired is that obtainable with the High Performance Cesium Beam Frequency Standards, HP 5061A with Option 004. Assume that all three standards (master, portable, and remote) are High Performance Units. The settability of the HP 5061A Option 004 is 1×10^{-13} (using the HP 10638A Degausser).

At 5 MHz each minor division on the HP 680A Strip Chart Recorder corresponds to 4 ns of phase. If we watch the phase chart and detect 4ns phase change in 67 minutes (4000 secs) then the frequency offset is

$$\left|\frac{\Delta f}{f}\right| = \left|\frac{\Delta t}{t}\right| = \frac{4 \times 10^{-9}}{4 \times 10^{3}} = 1 \times 10^{-12}$$

This measured frequency offset tells us that we have to correct the frequency of the portable clock by 10×10^{-13}. The direction of the phase change will tell us which direction it must be corrected. By adjusting the portable clock oscillators fine frequency control knob from 250 to 200 in OPEN LOOP, we can note the direction of the phase change. The portable clock frequency is now low and will lose time. Reset to 250 and close the loop.

NOTE: Also make a notation as to the inputs to the K05-5060A. In future setups noting the connections to the inputs will determine which unit is fast or slow relative to other.

Using the C-field knob we can adjust the portable clock frequency by 10×10^{-13}. Each minor division of the C-field knob corresponds to 5×10^{-14} (increasing numbers will increase frequency), therefore the number of minor divisions is

$$\frac{10 \times 10^{-13}}{5 \times 10^{-14}} = 20$$

Once again, measure the frequency difference using the linear phase comparator. If the adjustment has been properly made, the time required to measure a 4ns phase change should be greater than 11.1 hours (40,000 s), assuming the adjustment is better than the settability spec, 1×10^{-13}.

Now that the frequency has been set, we can set the time in the portable clock. To do this first requires that the clock display be adjusted to correspond within 1 sec of the master clock. This is easily accomplished using the pushbuttons on the clock. Once the time is set to the nearest second, a cable is connected from the 1 PPS output of the master clock to the SYNC input of the portable clock and the SYNC button is pressed. The portable clock is now synchronized to within $10 \pm 1\mu s$ delay of the master clock. Now connect the master clock 1 PPS to the START input of a time interval counter and the portable clock 1 PPS to the STOP input of the counter. Measure the time interval between the two pulses. The two pulses can be manually adjusted to within ±50ns of each other using the thumbwheel TIME DELAY switches and the 0-1μsec TIME DELAY control.

The time difference, frequency offset, and time of measurement should be noted.
Move the portable clock to the remote site and perform steps 1 through 6 again, only this time the portable clock is the master and the remote clock is adjusted relative to the portable clock. Return the portable clock to the master clock site and again measure the time interval between the two clocks.

Example:

1. In transferring time from one location to another we use a portable clock. In setting the portable clock we note a time difference (measured) of 45 ns (behind the master clock) at the measurement time of $12^{h}15^{m}00^{s}$ 12 April 1974. The frequency offset at this time was 1×10^{-13} as we previously adjusted.
2. At the remote site we set the remote clock and measured a time difference of 50 ns with the portable clock behind the remote clock. We adjusted the remote clock to within

1×10^{-13} of the portable clocks frequency. The time of measurement for the time interval reading was $12^h15^m00^s$ 18 April 1974.

3. Returning the portable clock to the master clock site and making another time interval measurement (closure of the loop) we find a time difference of 776nsec ahead of the master clock. We attempted to make the two portions of the trip as equal as possible to simplify the error apportionment, therefore, when we returned the measurement was made at $12^h15^m00^s$ 24 April 1974.

Date	Measurement Number		
12 April 74	1	Master-portable =	45ns
18 April 74	2	Remote-portable =	50ns
24 April 74	3	Master-portable =	-776ns

Subtracting reading 1 from reading 3 we get

$$\Delta t_{total} = \Delta t_3 - \Delta t_1$$
$$\Delta t_{total} = -776\text{ns} - (45)\text{ns} = -821\text{ns}$$

Therefore on 18 April 1974, the remote clock was set relative to the master clock as calculated below:

$$\text{Master-portable} = 45 + \left(-\frac{821}{2}\right) = -365.5\text{ns}$$

and subtracting reading 2

$$\begin{array}{ll} \text{master-portable} & = -365.5\text{ns} \\ -(\text{remote-portable}) & = -\ 50.\ \text{ns} \\ \hline \text{master-remote} & = -415.5\text{ns} \end{array}$$

We might note here that we are unconcerned about readjusting the frequency offsets as measured. The only purpose in adjusting the frequencies for an initial clock setting is to try to bring the clocks closer together in frequency so that they might keep close relative time for a longer period. The frequency adjustment or measurement could have been eliminated if we were unconcerned about their relative frequencies. The relative frequencies might not be important to us at this time if we know the instruments are operating properly and within the manufacturer's specifications. The accuracy of the HP 5061A Option 004 High Performance Cesium Standard is $\pm 7 \times 10^{-12}$. Therefore, the maximum two units could be apart is 1.4×10^{-11}. If this frequency offset is within the timekeeping system requirements there is little gained in making the frequency adjustment in an initial time synchronization. However, the frequency measurement might still be made just to assure us that the instruments are operating properly.

The maintenance of a timekeeping system using portable clocks is not difficult. Periodic trips are made back to the remote sites and time measurements and adjustments made. For example, let us continue the previous example:

Date	Measurement Number	Measurement	Remarks
12 Oct 74	1	Master-portable = 45ns	
18 Oct 74	2	Remote-portable = 8471.5ns	Before reset
18 Oct 74	3	Remote-portable = 45ns	After Resynchronization
24 Oct 74	4	Master-portable = +445ns	

$$\Delta t_{total} = \Delta t_3 - \Delta t_1$$
$$= 455\text{ns} - 45\text{ns} = 410\text{ns}$$

Therefore, on 18 October 1974

$$\text{master-portable (adjusted)} = 45 + \frac{410}{2} = 250\text{ns}$$

$$\begin{array}{ll} \text{master-portable} & = 250 \text{ ns} \\ \underline{-(\text{remote-portable})} & \underline{= -8471.5\text{ns}} \\ \text{master-remote} & = -8221.5\text{ns (on 18 October 1974)} \end{array}$$

which indicates the remote clock is fast relative to the master.

From this information we can now calculate the average frequency offset between the master and remote clocks during the six month period.

$$\frac{\Delta f}{f} = -\frac{\Delta t}{t}$$

where $\Delta t = (\text{master-remote})_{18\ \text{Oct}} - (\text{master-remote})_{18\ \text{Apr}}$
$= -8221.5\text{ns} - (-415.5\text{ns}) = -7806$ ns
and $t = 183$ days

$$\frac{\Delta f}{f} = -\frac{\Delta t}{t} = \frac{7806 \times 10^{-9} \text{ second}}{183 \text{ days} \times 86400 \ \frac{\text{sec}}{\text{day}}} = +4.94\text{x}10^{-13}$$

Thus, the remote clock can be either adjusted or the frequency offset just noted, depending on whether the performance is within the established system tolerances.

The calculation of the resynchronized time setting error is:

$$\begin{array}{ll} \text{master-portable} & = 250\text{ns} \\ \underline{-(\text{remote-portable})} & \underline{= -45\text{ns}} \\ \text{master-remote} & = 205\text{ns} \end{array}$$

If more than one remote clock is involved in the system and compared on the same portable clock trip, the closure error can be allocated to each clock listed in proportion to the time of measurement to total trip time.

OTHER TIME AND FREQUENCY TRANSFER METHODS

In this section we have examined several of the more popular techniques of time and frequency transfer. There are several other techniques using a variety of radio waves. The techniques are basically the same as those already discussed. Each technique requires a good receiver to receive a stable signal and appropriate processing equipment as required. NBS Monograph 140 describes several techniques using satellites (including Transit and Timation) microwave links, Omega, very long baseline interferometry (VLBI), pulsars, and the ac power line.