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Time and Frequency Users Manual

George Kamas
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ABSTRACT

This book is for the person who needs information about making time and frequency measurements. It is written at a level that will satisfy those with a casual interest as well as laboratory engineers and technicians who use time and frequency every day. It includes a brief discussion of time scales, discusses the roles of the National Institute of Standards and Technology (NIST) and other national laboratories, and explains how time and frequency are internationally coordinated. It also describes the available time and frequency services and how to use them. It discusses the accuracies that can be achieved with the different services, and the pros and cons of using various calibration methods.

Key words: frequency calibration; high frequency; Loran-C; low frequency; oscillators; relative frequency; satellite broadcasts; standards; time calibration; time code; time interval.

PREFACE

This book is intended to assist users of time and frequency calibration services in the United States and throughout the world. The book deliberately avoids using complex derivations or mathematical analysis. Instead, simple explanations have been given in the hope that more people will find the material useful.

Since the topics in this book are not covered in great depth, this book is intended as an overview of time and frequency calibration methods, and not as a comprehensive reference work. If you need more detailed information about a calibration method described in this book, please contact NIST or a manufacturer of time and frequency equipment.

CONTENTS

Chapter 1 - AN INTRODUCTION TO TIME AND FREQUENCY

This book is about time and frequency. It describes time interval, time of day, and frequency calibrations. It explains the time and frequency broadcast services that are available in the United States and other countries, and how you can use them. Your requirements may be as modest as setting your watch, or as involved as calibrating precision oscillators. In either case, you should find something of interest in this book.

Without realizing it, we use time and frequency every day. Knowing the correct time allows us to function in an orderly manner. We need to know what time to meet a friend for lunch, or to arrive at school or work. It's all right to get to church early, but it's embarrassing to walk in during the sermon. And we'd all be disappointed if we missed our airplane after months of planning a Hawaiian vacation.

In these examples, knowing the correct time to within a few minutes is usually adequate. But even a few seconds can sometimes be quite important. For instance, every day hundreds of people drop nickels, dimes, and quarters into parking meters, coin-operated washers and dryers, and other machines that "keep" time. Businesses pay thousands of dollars for the use of a computer's time. We all pay telephone bills based on the time we spend using the telephone. These activities all require accurate time. Fifteen minutes on a parking meter should really be 15 minutes and not 14. An error in the meter's timer could mean a parking ticket. If we talk on the telephone for 7 minutes, we don't want to be billed for 9 or 10.

Frequency is just as important as time. Every timer has a frequency source inside. In fact, time as we know it (seconds, minutes, and so on) is simply the accumulation of other more frequent time pulses. Thus "time of day" is a label, a name tag given to just one of many possible pulses. But all of these pulses represent a frequency. One pulse per second (like a clock tick) has a frequency of 1 hertz. From this we can build up a "day" by counting 86 400-second ticks, or we can start with a much higher frequency of a million pulses per second and count these faster pulses a million at a time to get a pulse rate of once per second. These examples show that "frequency" describes the rate at which events occur, and that "time" is the name or label that we give to an interval. In fact, time interval is the

correct way to label a period of elapsed time. To measure frequency we will use time interval. In this book there will be many references to such procedures (counting, timing, and the calibration of devices) used to produce different pulse rates.

Accurate pulse rates or frequencies are used every day. TV stations must transmit on the exact frequencies assigned by the Federal Communications Commission (FCC). Power companies supply power to homes and offices at 60 Hz (cycles per second), so that electric clocks keep the correct time. A stereo turntable needs to spin a record at 33-1/3 rpm (revolutions per minute) instead of 32 or 34 rpm, so that the musical tones are reproduced accurately.

Our voices range in frequency from about 87 Hz (bass) to 1175 Hz (soprano). Our ears can detect sounds ranging from a telephone dial tone at about 400 Hz, a smoke alarm at 600 Hz, and a dentist's ultrasonic drill at 10 000 Hz. A piano has notes from 27.5 to 4186 Hz. "A" above middle "C" in the musical scale is 440 Hz, a frequency often used to tune musical instruments.

Unlike the other basic physical standards (length, mass, and temperature), frequency and time (or more properly, time interval) are relatively easy to measure with great precision. For example, a length measurement of 2.5 micrometers (0.0001 inch) is difficult to make. On the other hand, time measurements of 1 nanosecond (0.000000001 second) are commonplace in the world of science.

WHO NEEDS TIME AND FREQUENCY?

As we saw in the introduction, we all are involved with time and frequency to some extent. For most of us, knowing the time to within 1 minute or so is usually enough. However, some users need to know the exact second or even millionth of a second (microsecond). Let's look at some of the more sophisticated users of time and frequency:

CELESTIAL NAVIGATORS need time of day to determine their exact location. An error of 2 seconds could cause a ship to miss its destination by about 1 kilometer.

Other **SHIPPERS and BOATERS** need even more accurate time of day. When ships use sophisticated electronic navigation systems, an error of only 3 microseconds could cause unwanted errors.

POWER COMPANIES compare their generator frequency to control electric power flow at exactly 60 Hz. If they didn't, electric clocks wouldn't keep the correct time. They need precise time to monitor the power grid to help prevent "brownouts" and massive power failures. They also use time to help locate power outages and trouble on the lines. Time is also important for keeping track of power flow for billing purposes.

RADIO & TV STATIONS must broadcast signals exactly on their assigned radio frequencies. They also need accurate time of day so they can join their networks at the right instant.

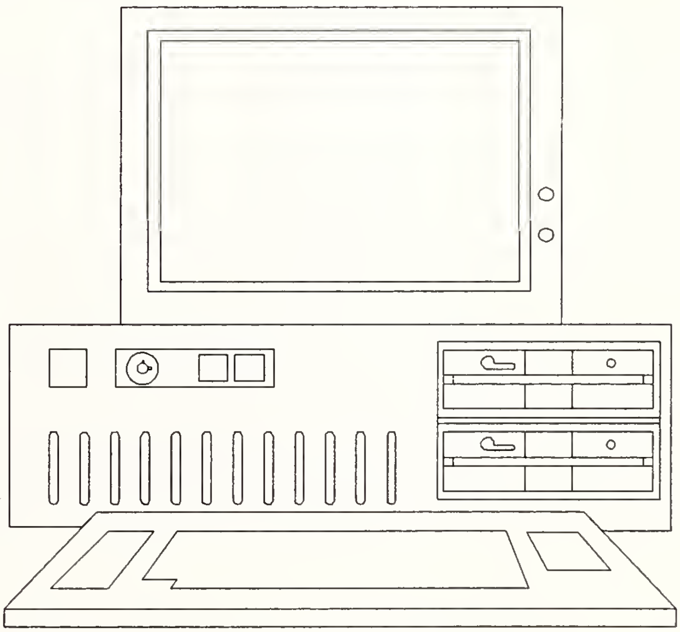
The **MEDICAL PROFESSION** uses time and frequency sources to calibrate medical test equipment, for date and time printouts in hospital care units, and for timing therapy and observational procedures used in daily health care.

The **OIL INDUSTRY** needs accurate timing to help automate oil well drilling, especially offshore.

JEWELERS & CLOCK/WATCH MANUFACTURERS need to set digital watches and clocks to the correct time of day and rate before they leave the factory.

RAILROADS use time-of-day radio signals to set watches and clock systems, so that trains arrive and depart on schedule.

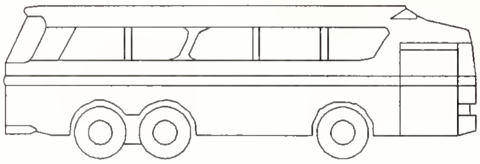
The **COMPUTER INDUSTRY** needs accurate time intervals for billing purposes and for synchronizing communication between systems many miles apart.



POLICEMEN need accurate time to check stopwatches and radar guns used to clock speeders. They use frequency sources to calibrate radar devices used for traffic control.

SURVEYORS use time signals to measure distance. For example, 3 microseconds translate into 1 kilometer in distance when using electronic instrumentation.

MANUFACTURERS need time and frequency signals and sources to calibrate counters, frequency meters, test equipment, timers used in electric appliances, and a variety of other equipment.



The **TRANSPORTATION INDUSTRY** needs accurate time sources to synchronize clocks used in public transportation systems, and for vehicle location, dispatching, and control.

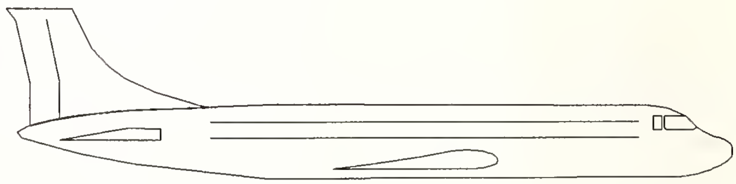
SPORTSMEN use elapsed time. Sports car rallies are timed to 0.01 second or less. So are many track and field events.

The **TELEPHONE INDUSTRY** needs accurate clock time for billing and telephone time-of-day services. They need accurate frequency signals so that long-distance phone calls don't become garbled during transmission.

The **COMMUNICATIONS INDUSTRY** depends on accurate frequency control for its ability to deliver messages to its users. Time is needed for labeling the time of occurrence of important messages.

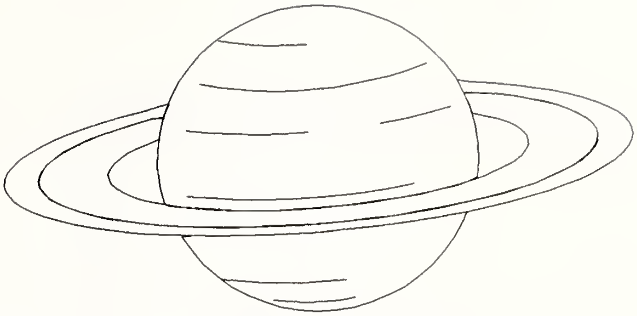
The **MUSIC INDUSTRY** uses frequency, obtained from tuning forks and crystal oscillators and radio services (the 440 Hz tone, for example) to tune pianos, organs, and other musical instruments.

The **TELECOMMUNICATIONS INDUSTRY** needs time intervals accurate to 1 microsecond to synchronize satellite and communications terminals spread over wide geographical areas.



The **AVIATION/AEROSPACE INDUSTRY** needs accurate time interval sources for aircraft traffic control systems and for synchronization at satellite and missile tracking stations. The Federal Aviation Administration (FAA) records accurate time of day on its audio tapes along with the air-to-ground communications from airplanes. Having an accurate record of when particular events occurred can help determine the cause of a plane crash or equipment failure.

ASTRONOMERS use time of day for observing astronomical events, such as lunar occultations and eclipses.



Accurate time setting is required for **MASTER CLOCK SYSTEMS** in large institutions, such as airports, hospitals, large factories, and office buildings, so that all clocks in the system read the same time.

The **MILITARY** uses accurate time of day to synchronize clocks on aircraft, ships, submarines, and land vehicles. They also use it to synchronize communications between bases, and for radio navigation.

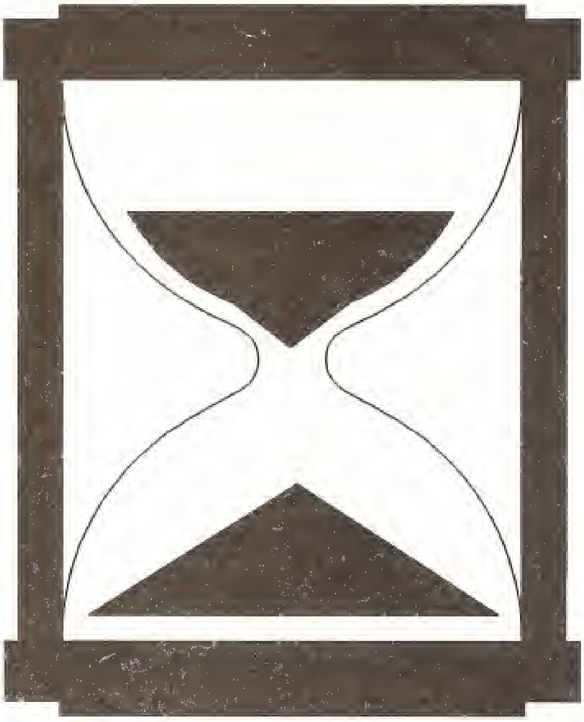
GEOPHYSICISTS/SEISMOLOGISTS studying lightning, earthquakes, weather, and other geophysical disturbances need accurate timing to obtain data synchronously and automatically over wide geographical areas. They use it for labeling geophysical events. Other **SCIENTISTS** use time sources for controlling the duration of physical and chemical processes.

WHAT ARE TIME AND FREQUENCY?

The introduction and examples show that time and frequency are closely related. Frequency is simply the rate at which things happen. For example, a human pulse beats at a rate of 60 to 100 times per minute. U.S. power companies vary the voltage at a rate of 60 times per second. Each of these rates is a frequency. The basic unit of frequency is the hertz (Hz). The hertz was named after Heinrich Hertz, an early radio scientist. If something happens once per second, we say that it occurs at a frequency of 1 Hz.

As you might have guessed, we use a frequency source to get time interval and time of day. For example, inside many wristwatches you will find a tiny quartz crystal a few millimeters in length. This sliver of quartz vibrates at a frequency of about 32 000 times a second (32 kilohertz, or 32 kHz). A mechanism inside the watch counts these vibrations. When 32 000 vibrations (or time intervals) have occurred, 1 second has elapsed. At this point, the watch will either update its digital display or move the "hands" of the clock.

In fact, the international definition of the second is based on counting a frequency. A second is a time interval, and it is defined in terms of the cesium atom. This is explained in some detail elsewhere in this book. For now, we can say that a second consists of counting 9 192 631 770 periods of a property associated with the cesium atom. In other words, the tiny time intervals of the oscillating cesium atom are totaled to get a new (longer) time interval we call the "second."



Since we used the cesium "vibrations" to get an interval of a second, we can, of course, use time interval to describe frequency. If you knew exactly when a second started and ended, you could count events in that second and define a frequency. For example, if you electronically counted 1000 cycles of a certain signal in 1 second, you would know that the frequency of that signal was 1000 Hz, or 1 kilohertz (1 kHz). The definition of frequency is based on properties associated with the cesium atom. The atom causes vibrations or oscillations. After some 9 billion of these have occurred, we give that interval the name "second," which is the time interval equal to over 9 billion smaller time intervals. This is then continued through minutes, hours, days, years, and so on. Time interval is a very important quantity. It defines time of day and duration, and is the basis for using the term "frequency."

WHAT IS A STANDARD?

When calibrations are made, a reference standard is needed. The calibration is then referenced to the standard. According to Webster, the definition of a legal standard is "something set up and established by authority, custom, or general consent as a model or example." In the United States, the National Institute of Standards and Technology (NIST) is legally responsible for maintaining and distributing all of the standards of physical measurement.

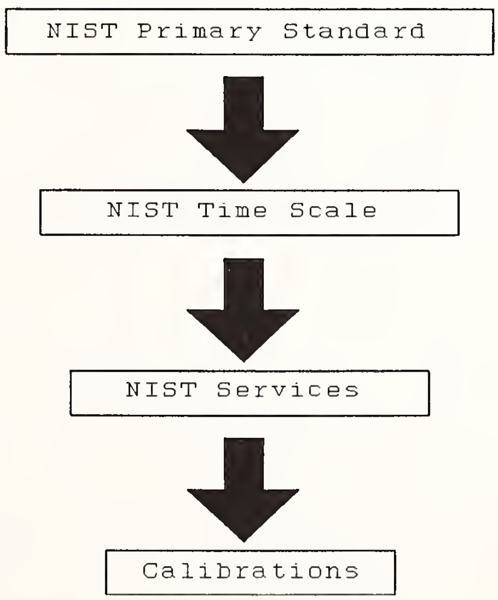
The four basic standards are length, mass, time interval (often just called time), and temperature. All other measurements can be derived from these four. As stated earlier, time and frequency can be controlled and measured with greater precision than the other basic standards. This is because the physical devices used (atomic and quartz crystal oscillators) are very stable, and the measurements performed depend on electronic parts that are capable of very fast changes in their on/off states.

THE NIST STANDARDS FOR TIME AND FREQUENCY

Time of day is not a "standard" in the same sense as a meter stick or a standard set of weights. The real standard is time interval, which is the length of time between two events. By agreement, a day is simply the accumulation of 86 400 seconds. By referencing to a standard time interval of 1 second, a number of organizations (including NIST) can maintain accurate time-of-day clocks. These clocks will always agree with each other, and the variations in time of day from country to country are extremely small.

Even though there is no physical "standard" for time of day, most countries keep a carefully controlled frequency source with suitable electronics set "on time." They do this by starting with the correct time interval (usually cesium derived) and then generating other intervals such as the second or minute. As a result, the time of day throughout the world is almost the same in every country. Once a standard is set equal to other such standards, their differences (if any) in the future depend on the time interval of the driving frequency source. In the same way that a watch depends on its balance wheel or quartz crystal, the national standards of the world depend on their cesium "balance wheels."

The NIST standard for frequency and time interval is located in Boulder, Colorado. It is the latest in a series of atomic oscillators built and maintained by NIST to provide the official reference for time interval or frequency in the United States. The current machine is referred to as the "master" or "primary" frequency source. It is used to calibrate other oscillators ("secondary" standards), which are used to operate a time scale (a time scale is a system of carefully operated oscillators), and then distributed to users through the NIST services:



The NIST time scale is adjusted to agree with similar time scales in other countries. The output of the time scale is distributed to users through the various frequency and time broadcast services described in this book.

The NIST time scale works the same way as a clock or watch. It has a frequency source, a means of counting the frequency source and keeping time of day, and a way of getting a useful output. In a clock or watch, the frequency source can be a 60-Hz power line, a balance wheel, tuning fork, or quartz crystal. The counter for totaling the cycles of frequency into seconds, minutes, and hours can be mechanical or electronic. The output can be displayed digitally or by the position of the "hands" of the clock.

Anyone wanting to calibrate their frequency source or to compare their own time-of-day pulses, uses the NIST time scale as a master clock. They then set their secondary clocks to agree with the master clock. A similar situation has existed since man started keeping time. For example, one of the first clocks used by man was the sundial. Sundials worked by measuring the Sun's angle. Someone may have "set" an hourglass by carrying it outdoors and reading the time on the sundial. Once they knew the correct time they could turn the hourglass over and return indoors. By doing so, they could keep fairly accurate time for the next hour. In this example, the sundial is the master clock, and the hourglass is a secondary clock referenced to the master clock.

HOW TIME AND FREQUENCY STANDARDS ARE DISTRIBUTED

NIST distributes frequency and time signals to the general public. Most time and frequency data are distributed by radio. Time of day, frequency, and time interval are broadcast from radio stations WWV, WWVH, WWVB, and from the GOES satellites. These services are controlled and operated by NIST. Precise time and frequency can also be obtained by radio from Loran-C, Omega, and Global Positioning System (GPS) broadcasts. These services are not operated by NIST, but they can provide an indirect reference to the NIST time scale. Many of the broadcasts mentioned above are explained in detail elsewhere in this book. NIST also distributes time and frequency data by telephone (both voice and data) and through printed material.

Once obtained by radio, time and frequency signals are often distributed by cables. For example, the standards laboratory of a manufacturing plant may provide signals for users throughout the plant area. The type of distribution system used depends on the plant layout and the level of accuracy needed. If you need to maintain the accuracy of an atomic oscillator throughout a large area, you need the very best equipment and cables, and even then you'll lose some accuracy. On the other hand, you can relax the specifications if all you need is a time-of-day signal accurate to within 1 second.

One of the main problems with distribution systems is that cables pick up noise along their path. This causes the signal at the end of the cable to be less useful than desired. Not all cables work on all frequencies. It would be tempting to use commercial telephone lines, but the highest practical frequency you can distribute in that way is 1 kHz. Any attempt to send pulses over a telephone line intended for voice communication, but it wouldn't work due to the limited bandwidth. Also, delays may be introduced because telephone companies often combine several signals on the same line. Delays are also introduced when calls are transmitted by satellite.

Designing a good distribution system may require a large investment in both time and money. As a result, some users with high accuracy requirements find that it isn't practical to maintain a local distribution system, and they simply re-establish time and/or frequency at each destination point.

Of course, it's difficult to say how much accuracy can be obtained with any distribution system. There is no simple formula for successful distribution of time and frequency signals, although the more effort you expend, the better your results will be.

FREQUENCY CALIBRATIONS

If you have access to a frequency standard, you can use that standard to calibrate other frequency sources. A calibration can take one of two forms:

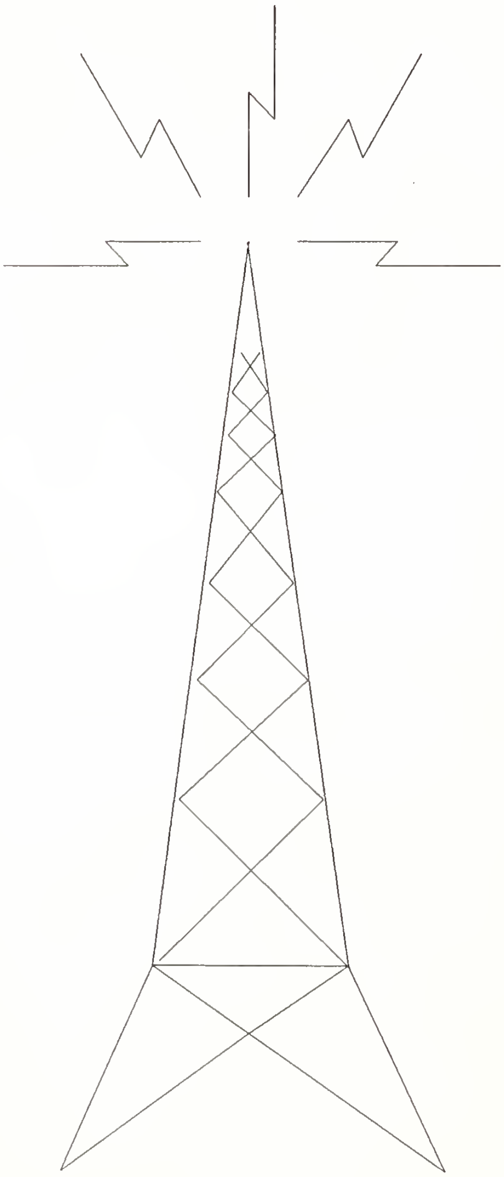
- *You can calibrate a frequency source by adjusting it to agree with the standard.*
- *If you are satisfied with the accuracy of the frequency source, you can simply measure its frequency offset by comparing it to the standard and noting the error when you make other calibrations using the source.*

Calibration laboratories can measure the error of frequency sources with resolutions ranging from a few parts per thousand to one part per trillion (1.00E-12). The resolution needed depends upon the organization's end product. Precise calibrations require paying more attention to detail but are not difficult to achieve.

Nearly all calibrations of time and frequency equipment are called frequency calibrations. This is because the frequency of the device's internal oscillator is what is actually being calibrated. For example, if your watch is 1 minute fast every day, you can put it back on time by moving the minute hand. However, moving the minute hand doesn't change the frequency at which the watch is running, and tomorrow it will be fast again.

To make the watch keep better time, you need to calibrate the internal oscillator by adjusting its frequency and also reset the "hands" as required.

Since all calibrations are made using a standard, we can say that they are traceable to that standard. If you make a calibration in the United States, it should be traceable to NIST. This requires using a reference frequency distributed by NIST. Traceability to NIST is always desirable and is the goal of many calibration laboratories.



To better illustrate traceability, let's look at an example. Suppose you set your watch from a time signal in your laboratory. The signal comes to you from your company's distribution system. If you trace the signal back through the system, you might find that it comes from an oscillator on the manufacturing plant grounds. If the oscillator is calibrated using NIST radio signals, it can claim a certain accuracy level compared to NIST. This accuracy is transferred to your laboratory perhaps only slightly reduced. Taking all these factors into account, the signal in your laboratory (and therefore your watch) is traceable to NIST.

Users who require legal evidence of traceability should keep a record or log of their calibration activities, even for something as simple as listening to a radio or telephone and setting time of day. Such a log book becomes evidence of the exact steps followed and the time they were performed. If more sophisticated means are used, then chart records or photographs can be kept on file for a reasonable time to demonstrate traceability.

What kind of accuracy is obtainable? As we said before, frequency and time can both be measured to very high accuracies with very great measurement resolution. As this book explains, there are many different ways to make calibrations. Your accuracy depends on the technique you choose and on the amount of error in your measurements. Typically, frequency calibration accuracies range from parts per million by high frequency radio signals to parts per trillion for satellite or Loran-C signals. A great deal depends on how much effort you are willing to spend on getting a good, accurate measurement.

Although some users take precise frequency measurement for granted, most time and frequency devices need periodic calibration. For example, if a quartz oscillator is supposed to produce a 5 MHz frequency, the frequency may still be in error by a significant amount. Age affects the frequency of all quartz oscillators, and they can fail. Users need to know their measurement requirements, and whether the method they choose meets those needs.

Once an oscillator is calibrated, it may not need to be calibrated again for a long time. Today's oscillators are of excellent quality, and they may meet your accuracy requirements for many weeks. Of course, nothing can be taken for granted. If you come into your laboratory on Monday morning hoping that everything stayed put over the weekend, you might be unpleasantly surprised. Digital dividers used to drive electronic clocks do jump occasionally, especially if the power supplies are not designed to protect against power glitches. It makes sense, therefore, to check both time and frequency periodically to insure that the frequency is right and the clock is on time. If they are not, you can then make an adjustment.

Many users find it convenient to maintain a continuous record of their oscillator's frequency. This record will show when an oscillator needs calibration, and the results of past calibrations. Normally, this record is a chart comparing the performance of the oscillator to a radio signal which is traceable to NIST.

TERMS USED

This section covers some of the terminology used throughout the rest of this book.

Mega, Milli, Parts per ..., and Percents

Throughout this book, we use terms such as kilohertz and megahertz, milliseconds and microseconds. We also talk about accuracies of parts in 1.00E-09 or 0.5%. The tables on the following pages explain the meaning of these terms, and should serve as a convenient reference for the reader.

PREFIX CONVERSION CHART		
Prefix	Definition	Example
Pico	1 trillionth	Picosecond - 1 trillionth of a second
Nano	1 billionth	Nanosecond - 1 billionth of a second
Micro	1 millionth	Microsecond - 1 millionth of a second
Milli	1 thousandth	Millisecond - 1 thousandth of a second
Kilo	1 thousand	Kilohertz - 1 thousand hertz
Mega	1 million	Megahertz - 1 million hertz
Giga	1 billion	Gigahertz - 1 billion hertz
Tera	1 trillion	Terahertz - 1 trillion hertz

CONVERSIONS FROM PARTS PER ... TO PERCENT			
PARTS PER			PERCENT
1 part per hundred	=	1.0E-02	1.0%
1 part per thousand	=	1.0E-03	0.1%
1 part per 100 thousand	=	1.0E-05	0.001%
1 part per million	=	1.0E-06	0.0001%
1 part per 100 million	=	1.0E-08	0.000001%
1 part per billion	=	1.0E-09	0.0000001%
1 part per 100 billion	=	1.0E-11	0.000000001%
1 part per trillion	=	1.0E-12	0.0000000001%
1 part per 10 trillion	=	1.0E-13	0.00000000001%

The unit used almost universally for frequency is the hertz, which means one cycle or one pulse or one event per second. A "cycle" can be generated in many different shapes. It can be a sine wave or a square, triangular, or sawtooth wave. Keep in mind as you read this book that not all of the waveforms being considered are sine waves.

Throughout this book, consideration is given to frequencies of all ranges from the 1 Hz clock tick to many billions of hertz in the microwave region. The table below lists the frequencies by bands. Most frequencies of interest are included in this table. The radio frequency band contains the often heard references to high frequency, very high frequency, low frequency, and so on.

RADIO FREQUENCY BANDS	
RF Bands	Frequency Range
VLF (Very Low Frequency)	3 - 30 kHz
LF (Low Frequency)	30 - 300 kHz
MF (Medium Frequency)	300 kHz - 3 MHz
HF (High Frequency)	3 - 30 MHz
VHF (Very High Frequency)	30 - 300 MHz
UHF (Ultra High Frequency)	300 MHz - 3 GHz

The difficulty of measuring frequency accurately is not directly related to the frequency range. Making precise measurements at low frequencies is just as difficult as making precise measurements at high frequencies.

In some places in this book, we refer to the wavelength rather than the frequency being used. Wavelength is especially convenient when calculating antenna lengths. In fact, a glance at an antique radio dial shows that the band was actually marked in wavelengths. For example, radio amateurs still refer to frequency allocations in terms of the 20-, 10-, or 2-meter bands.

The conversion of wavelengths to frequency can be made for most purposes by using the simple equation

$$\text{Wavelength in meters} = \frac{300\ 000\ 000}{f}$$

where 300 000 000 meters per second is approximate speed of light, and f is the frequency in hertz. From this, we can see that the frequency of the 10-meter band is approximately 30 MHz, and 1000 kHz on the broadcast band is 300 meters.

Precise calculations of wavelength have to take the medium into account. For example, signals travel slower inside a coaxial cable than they do through the atmosphere.

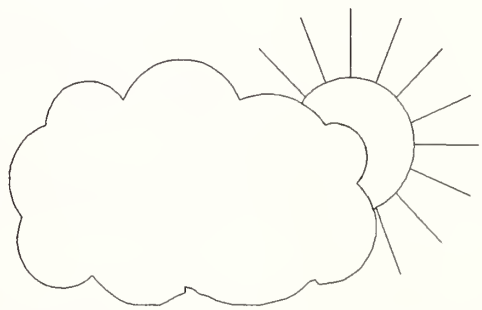
Chapter 2 - TIME SCALES

There are a number of different time scales. The astronomical time scale is based on the apparent motion of the Sun in the sky. The atomic time scale is based on the "swings" of atomic oscillators. Time scales work the same way as clocks. Of course, the pendulum in a time scale can be an atomic oscillator, and the "swings" are very rapid. For example, a 1 MHz oscillator "swings" one million times per second (the "swings" are electronic pulses). To keep track of these rapid swings we group the rapid pulses into slower ones. Thus one million microseconds become 1 second, which is something a human can deal with.

To see how the various time scales came about, let's take a brief look at the history of time.

SOLAR TIME

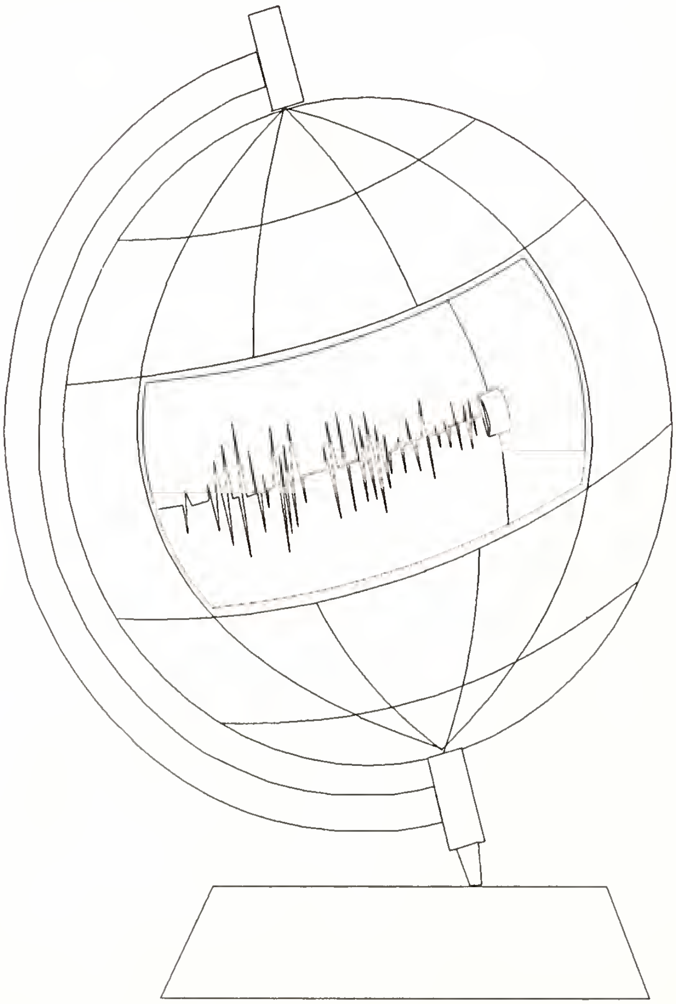
Consider a time system that uses the Sun and a sundial. The Earth rotates once every 24 hours, and we call this period 1 day. The shadow on the sundial can indicate fractions of cycles (time of day). As complete days elapse, calendars can be used to count the days and divide them into weeks and years.



However, clocks based on the Earth's rotation do not run at a constant rate. This is because the Earth's orbit around the Sun is not circular, and the Earth slows down and speeds up depending on its distance from the Sun. The early astronomers and mathematicians understood these laws of motion and were able to correct the "apparent solar time" to obtain a more uniform time called "mean solar time." This correction is called the Equation of Time and is often found engraved on sundials. Universal Time (UT0) is equal to mean solar time if you make the correction at the Greenwich meridian in England. This time scale was given the name UT0, the first in a series of time scale designations that have evolved through the years.

If you use a star that is farther away than the Sun, the fact that the Earth's orbit is not perfectly circular becomes less important. This system of timekeeping is named "sidereal time" and is similar to mean solar time since both are based on the Earth's spinning on its axis. The rate is different by 1 day per year, since the Earth circles the Sun once per year.

As better clocks were developed, astronomers began to notice a discrepancy in Universal Time measured at different locations. This difference was eventually identified as being caused by a wobble in the Earth's axis. The amount of wobble is about 15 meters (nearly 50 feet) at the pole. By careful measurements made at various observatories throughout the world, this wobble was corrected for, and a new time designation called UT1 was born. In its search for uniformity, the world community had now taken care of both the non-circular orbit (UT0) and the axis wobble of the Earth (UT1).



When better clocks were developed, it was found that UT1 displayed fluctuations whose origin was unknown. Due to the availability of stable electronic clocks, these fluctuations could be and were removed. This resulted in an even more uniform time scale called UT2.

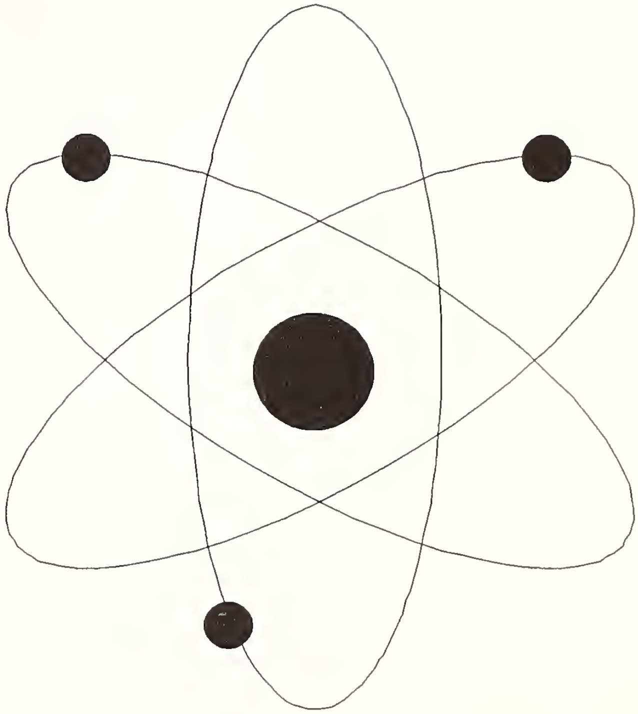
To review, UT1 is a true navigator's scale related to the Earth's angular position. UT2 is a smooth time and does not reflect the seasonal variations in the Earth's position. When the world's timekeepers went to UT2, they bypassed the navigators' real needs. A little later we'll describe the present-day system which fixes the problem.

Up until now we have talked about the Universal Time family. Let us now look at the other members of the time family. The first of these is "ephemeris time." An ephemeris is simply a table that predicts the positions of the Sun, Moon, and planets. Astronomers soon found that these predicted positions on the table did not agree with the observed positions, because the rotational rate of the Earth was not a constant. In response to this problem, the astronomers created what is called "ephemeris time." It is determined by the orbit of the Earth about the Sun, and not by the rotation of the Earth on its axis.

ATOMIC TIME

Another kind of time that can be generated and used is Atomic Time. Atomic Time is different from Universal Time, but the concept is similar. Universal Time is obtained by counting cycles of the Earth's rotation from some agreed-upon starting point. Atomic Time is obtained from counting cycles of a signal from an atomic frequency source.

In 1971, the General Conference of Weights and Measures officially recognized the Atomic Time Scale and endorsed an International Atomic Time Scale (TAI). Since January 1972, TAI has been used by most countries in the world.



Atomic time scales give us very accurate time of day because they use very stable atomic oscillators. Furthermore, they give us essentially constant intervals of time. In other words, atomic time scales are uniform timekeepers. Uniformity is desired when we are trying to make two events occur at the same time.

Let's review for a moment the several time scales we have discussed. First, the universal time family is dependent on the Earth's spin on its axis. Second, Ephemeris Time depends on the orbital motion of the Earth about the Sun. And finally, Atomic Time, which is very uniform and precise, depends on a fundamental property of atoms.

As shown in the table below, measurement uncertainties limit the stability of Ephemeris Time to about 0.05 second in a 9-year period. Universal Time can be determined to a few thousandths of a second or several milliseconds in 1 day. Atomic Time is stable to a few billionths of a second in a minute or less. From these numbers, it is easy to see why scientists have been leaning toward a time scale based on atomic clocks.

Universal Time (UT0,UT1,UT2)	3 milliseconds in 1 day
Ephemeris Time (ET)	50 milliseconds in 9 years
Atomic Time	<100 nanoseconds in 1 minute

COORDINATED UNIVERSAL TIME

Coordinated Universal Time (UTC) was adopted in 1971 and became effective in 1972. UTC is based on an Atomic Time Scale. As a result, a UTC clock gradually gets out of step with the Sun. This is the same situation that causes us to have leap years. Since the year is not an exact multiple of the day, we add a day every 4 years to keep our calendar in step with the seasons.

The same scheme was adopted to keep clocks in step with the Sun, and the "leap second" was born. To make adjustments in the clock, a particular minute would contain either 61 or 59 seconds instead of the conventional 60 seconds. You could, therefore, have either a positive or a negative leap second. It was expected and proved true that leap seconds would normally occur about once a year.

By international agreement, UTC is maintained within 0.9 second of the navigator's time scale UT1. By adding positive or negative leap seconds, a good clock can keep approximate step with the Sun. Since the rotation of the Earth is not uniform, we cannot predict exactly when leap seconds will be added or deleted, but this is usually done on June 30 or December 31.

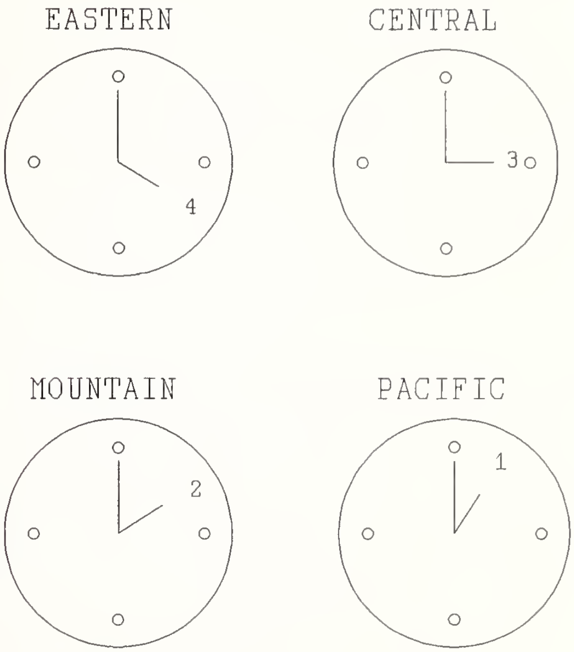
If you tune to a frequency and time broadcast (radio station WWV, for example), the announced time is often UTC. This time is uniform. It will never differ from UT1 by more than 0.9 second. Most users, such as radio and television stations and telephone time-of-day services, use UTC so they don't care how much it differs from UT1. Even most navigators don't need to know UT1 to better than 0.9 second, so UTC also meets their needs.

However, a small number of users need UT1 time to less than 0.9 second. To meets the needs of these users, most standard frequency and time radio stations broadcast a correction which can be applied to UTC to obtain UT1. On WWV, for instance, the corrections, in units of 0.1 seconds, are encoded into the broadcasts by using double ticks or pulses after the start of each minute. The amount of correction is determined by counting the number of successive double ticks heard each minute, and the sign of the correction is given by the location of the double ticks within the minute (most frequency and time stations worldwide have some such scheme for UT1).

Keep in mind that UTC prevents you from simply subtracting the dates of the events to get the time difference between them. You must take into account any leap seconds that were added or deleted.

TIME ZONES

Standard frequency and time stations usually broadcast Coordinated Universal Time (UTC), which is referenced to the Greenwich meridian. However, many users want to display the local time used in their city. If the time is being decoded from a time code (as opposed to a voice time-of-day announcement), the problem can be solved by using clocks that can display time for any of the world time zones, even though they are receiving and decoding UTC. Each time zone differs from UTC by a specific number of hours. The map on the next page shows the time zones currently in use in the continental United States.



Contrary to popular opinion, NIST is not involved with determining time zones in the United States. This responsibility belongs to the Department of Transportation, because the need for time zones came about when railroads were first used for interstate commerce. Information about time zones can be obtained from the Department of Transportation, Washington, DC 20590.

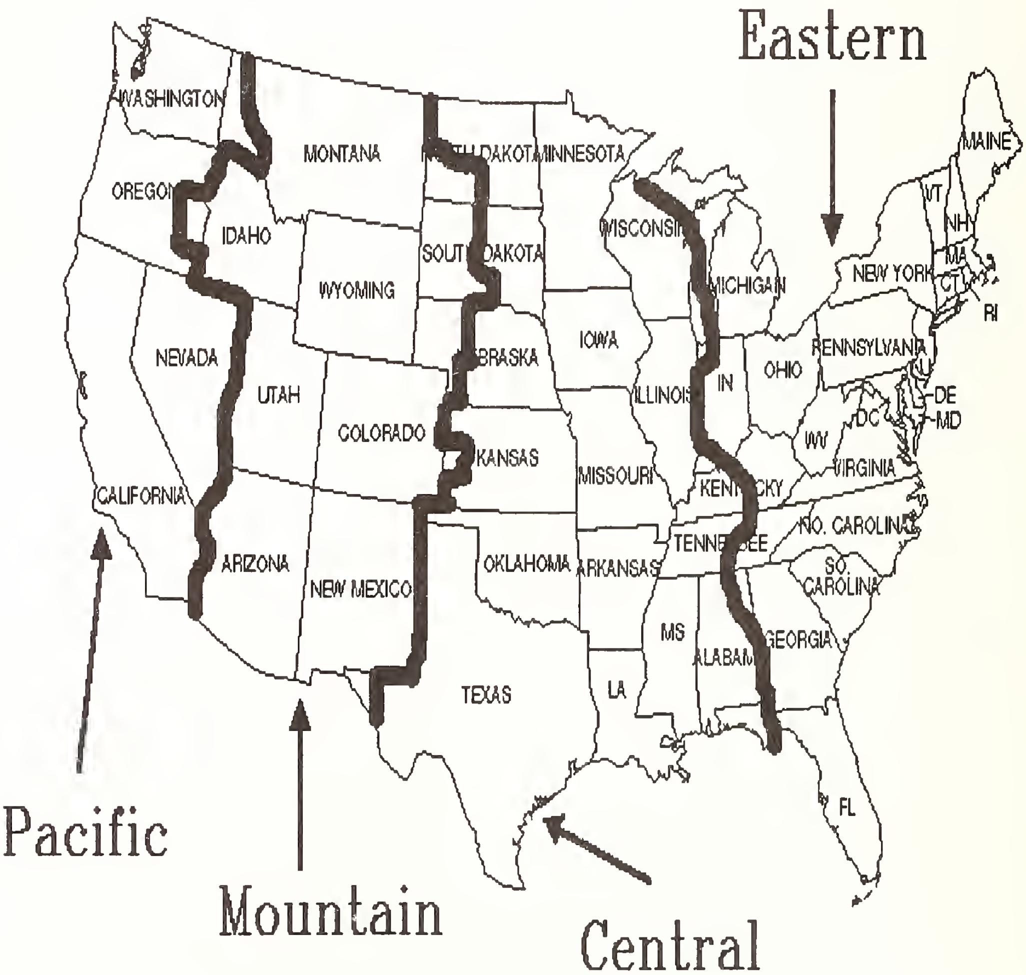
USING TIME SCALES FOR NAVIGATION AND ASTRONOMY

Although most users like the uniformity of Atomic Time, there is one application that needs the variability of Solar Time. This is in the area of celestial navigation where Earth rotation (even though it fluctuates) is used in finding out where you are on the Earth.

Navigators who find their positions from the stars are among the largest user group of standard time broadcasts. Since the Earth rotates once in 24 hours, a person can find his position (in longitude) if he knows his local time and the time difference between the Greenwich meridian and himself. As an example, a person trying to find his position uses an instrument like a sextant to measure the local solar time wherever he might be on the Earth. He then needs to know the time at the Greenwich meridian. This is the same problem that generated all the interest several hundred years ago in developing a good chronometer. Those clocks were used for many years until radio clocks were invented. Even today, most vessels do not leave home without a good chronometer.

Many countries operate high frequency radio stations to serve navigators and many other users. The United States operates WWV in Fort Collins, Colorado, and WWVH in Hawaii. Similar stations are operated by the Canadians and the Japanese and many countries in Europe and Asia. The U.S. Navy also broadcasts time signals from a number of radio stations.

Most large countries also maintain observatories to measure and record astronomical time. This is done using telescopes. The official U.S. observatory is operated by the Navy in Washington, DC. Astronomical time is difficult to measure accurately. Errors of a few milliseconds are realized even after a whole evening's sightings have been taken and averaged.



Standard Time Zones of the Continental United States

INTERNATIONAL COORDINATION OF FREQUENCY AND TIME ACTIVITIES

Unlike other physical standards, time interval or frequency can be obtained from many sources. Both Canada and the United States have primary frequency standards that also act as flywheels for accurate timekeeping. In addition, the U.S. Naval Observatory (USNO) makes astronomical observations for determining UT1 and keeps many frequency sources running for use by the Department of Defense. Many laboratories throughout the world maintain primary frequency standards for their countries.

The agency responsible for UT1 is the International Earth Rotation Service (IERS) located in Paris, France. The IERS determines when leap seconds are needed.

The agency responsible for atomic time (UTC and TAI) is the International Bureau of Weights and Measures (BIPM), also located in Paris, France. The BIPM determines the frequency (rate) of UTC and TAI by comparing the primary frequency standards located in several countries (including the United States, Canada, Japan, and Germany). The time for UTC is based on international time scale comparisons between hundreds of clocks located in many laboratories around the world. The time scale comparisons are currently made using the Global Positional System (GPS) or Loran-C. The BIPM evaluates the data from each time scale and corrects the data from each contributor. By international agreement, all UTC time scales must agree with the UTC time scale operated by the BIPM to within ± 1 millisecond. The result is a uniform world frequency (and time) system that differs from country to country by only a small amount. So, whether you get your frequency and time from CHU in Canada or the PTB in Germany, it will differ only slightly from the U.S. standard.

The Role of the National Institute of Standards and Technology (NIST)

NIST is in the U.S. Department of Commerce and has been authorized by Congress to undertake the following functions:

> *"The custody, maintenance, and development of the national standards of measurements and the provisions of means and methods for making measurements consistent with those standards, including the comparison of standards used in scientific investigations, engineering, manufacturing, commerce, and educational institutions, with the standards adopted or recognized by the Government."*

The Time and Frequency Division of NIST, located in Boulder, Colorado, carries out the above functions related to frequency or time interval and keeps time-of-day clocks running on its time scale system. The Time and Frequency Division has many responsibilities. The division operates the NIST standard of frequency and time interval, as well as several time scales based upon this standard. In addition to maintaining the standard, research efforts are carried out to improve it. This group also offers a direct service for calibration of oscillators and clocks.

The Time and Frequency Division also distributes the standards and continually finds new and improved methods of distribution. At this writing, the distribution services consist of high frequency radio stations WWV and WWVH, low frequency radio station WWVB, telephone time-of-day services (both voice and data), and several services based on radio signals from GOES and GPS satellites or Loran-C navigation signals. This division also produces literature and conducts seminars on how to use these services, and provides calibration and monitoring data to the general public. The services are used to provide national and international frequency and time coordination.

To summarize, NIST maintains services based upon the primary frequency standards. These services are constantly being improved and are designed to meet the needs of users at all levels of accuracy for frequency and time calibration. Training seminars are offered, and a number of publications are available to assist the public. For more information, contact:

Time and Frequency Division
National Institute of Standards and Technology
325 Broadway
Boulder, CO 80303

The Role of the U.S. Naval Observatory (USNO)

The U.S. Naval Observatory (USNO) is in the Department of Defense (DOD). Under a DOD directive, the USNO is responsible for:

> *"..... maintaining a reference standard (astronomical and atomic) for use by all DOD components, other agencies of the Federal Government, DOD contractors, and related scientific laboratories. This responsibility includes that of programming the necessary resources to maintain the reference standard and to disseminate precise time to DOD users."*

The USNO contributes (along with a number of other laboratories throughout the world) data to the International Earth Rotation Service (IERS) which combines the results into the final values of UT1. The USNO is the only organization in the United States that determines UT1 operationally.

The USNO serves as the main time and frequency reference for the DOD and its contractors. The DOD provides frequency and time services throughout the world. These include many different radio transmissions, satellite signals, and portable clocks.

The USNO accomplishes its global responsibilities with a system of cooperating worldwide stations that make measurements and keep very good frequency and time references. The USNO also publishes information about its services. For more information about these publications, contact:

U.S. Naval Observatory
Time Services Department
34th & Massachusetts Avenue, NW
Washington, DC 20392-5100

The three military services of the DOD have established focal points for matters dealing with frequency and time. These facilities coordinate DOD efforts and provide information to their organizations and contractors. The focal points are:

1. Aerospace Guidance and Metrology Center, Newark Air Force Station, OH 23055 (for the Air Force).

2. Navy Electronic Systems Command, Code 510, Washington, DC 20360 (for the Navy).

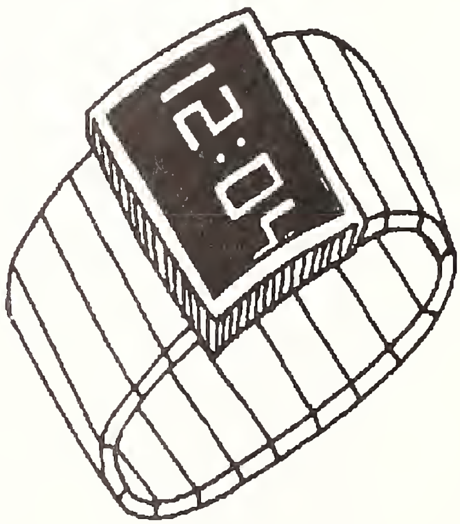
3. U.S. Army Material Development & Readiness Command, DRCQA-PC, Alexandria, VA 20315 (for the Army).

Chapter 3 - AN INTRODUCTION TO FREQUENCY SOURCES

This chapter is about electronic frequency oscillators, how they work, and how they can be used. It talks about some of the physical properties of frequency sources and includes a table comparing the different kinds of devices that are available.

FREQUENCY SOURCES AND CLOCKS

Most clocks (especially the very accurate and precise ones) are based on high-quality frequency sources. If we look at an event which occurs regularly (the sunrise, for example), we can state how many of these events occur in a given time period. This number is the frequency of this series of events. In our example, we could say that the frequency of sunrises is 7 events per week, or 365 events per year. "Events per week" or "events per year" would be the unit which we used for our frequency number. This number changes if we use different units. In our example, we assumed that we knew the definition of a week and a year, and the numbers change accordingly.



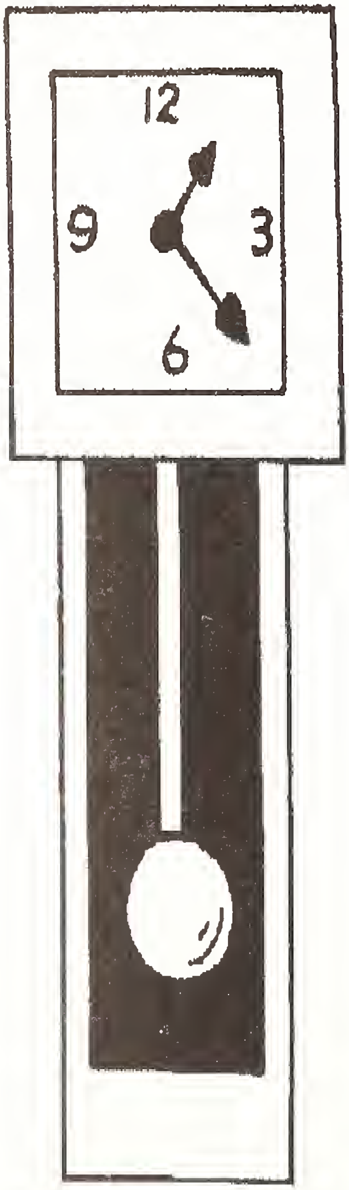
Now, what is the time interval between the events? The answers for our examples are simple: One sunrise follows the other after t = 1/7 week, or t = 1/365 year, where we used "week" and "year" as two possible choices for our unit of time.

We have learned two things. First, for periodic events, the time between the events is related to the frequency of their occurrence in the following simple way:

$$\text{Frequency} = \frac{1}{\text{Time Interval}}$$

Second, periodic events can be counted to define time. The frequency source becomes a clock when we add a counting mechanism for the events.

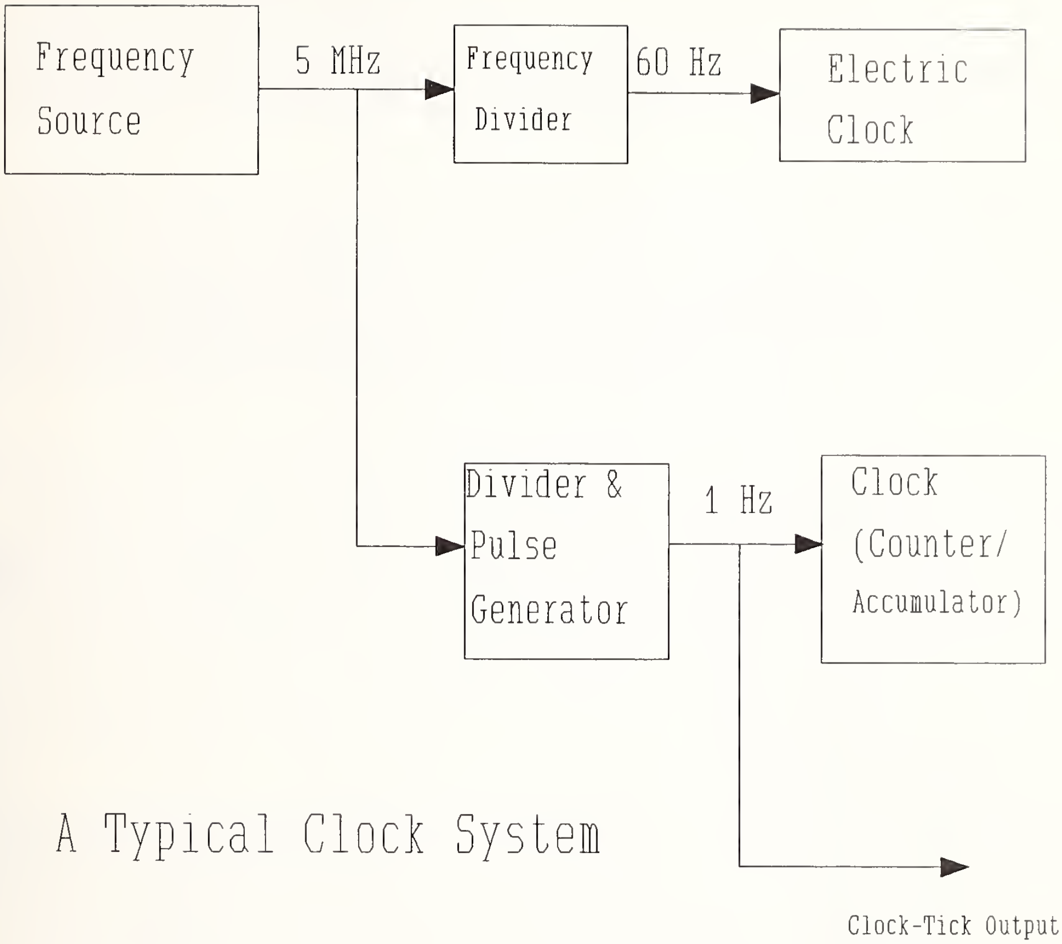
In this example, the frequency used is that of the rotating Earth. The time between recurring events is one day. The rotating Earth has served mankind for thousands of years and until recently was the source of the definition of time interval. The counting mechanism which made it a clock was the recording of days and years.



The need to get along for many days which might be cloudy, without sunlight, and to measure time intervals much shorter than a day, brought about the invention of clocks. The first "modern" clocks were based on the pendulum. Pendulum clocks were invented about 400 years ago and are still widely used today. The pendulum may be a suspended weight (gravitational pendulum) like in "grandfather" clocks, or the balance wheel (torsion pendulum) of modern mechanical wristwatches. A pendulum clock has all of the same features found in quartz crystal and atomic clocks.

In a pendulum clock, the pendulum has to be kept in motion by some type of energy source. In a wristwatch, this energy source is typically the winding spring or battery. The pendulum or spring produces small bursts of energy that drive the gears inside the clock. The moving pendulum is a frequency source. In order to have a clock, a read-out mechanism is necessary which counts and accumulates the ticks from the frequency source (more accurately, the time interval between the ticks) and displays the result. In our example of a wristwatch, this is accomplished by using a digital display or a set of gears that move the hands on the clock face.

We have just discussed how adding a counting mechanism to a frequency source creates a clock. This task can also be performed by an electronic frequency divider. For example, a signal from a 5-MHz oscillator can be divided to 60 Hz (see figure on next page). The 60-Hz voltage can then be used to drive an electrical clock motor similar to those driven by the 60-Hz power line frequency that we use at home and at work. Or, an additional electric pulse generator may be used that generates one very sharp electrical pulse per second. The time interval of 1 second between the pulses (corresponding to a frequency of 1 Hz) comes directly from our frequency source. These pulses can be used directly in time comparisons with those of other similar clocks, or they can drive gears or a digital display.



A Typical Clock System

The electric power line is a very good frequency source for many applications. A clock driven from the power line will keep excellent time. This is because the power system is carefully controlled to maintain its frequency within definite limits. Each power company is notified in advance to set its frequency to a particular value, so that the millions of clocks on the system (in homes and offices across the country) will gain or lose time as required to keep the clocks correct. The time corrections are usually done at night.

The basic unit of time is the second (symbol s). The second has been defined by using the property of a cesium atom. A second equals 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom. So, the frequency of a "cesium pendulum" is 9 192 631 770 events per second (the cesium atom is a very "fast" pendulum). The unit used for describing frequency is the hertz (Hz), which means one event per second.

THE PERFORMANCE OF FREQUENCY SOURCES

The performance of a frequency source is usually described in terms of its accuracy, reproducibility, and stability. These are defined as:

ACCURACY

How well does it relate to the definition? In the case of frequency, accuracy is a measure of how well the frequency source relates to the definition of a second (in terms of cesium) mentioned previously. The very high frequency of the cesium oscillator is divided to a lower easier-to-use value and compared.

REPRODUCIBILITY

If you built a number of frequency sources and adjusted them, how well would they agree in frequency? This term obviously applies to sources that are manufactured and then tested to see how they differ.

STABILITY

Once a frequency device is set to a given frequency, how well does it generate that value during some period of time? At any given moment, an oscillator generates an output signal whose frequency depends on a number of factors: temperature, time since turn-on, line voltage, vibration and shock, and so on. Some time later its frequency will change, again due to a number of causes. The difference between its frequency at one moment in time and another moment is called stability. The specification for stability is usually given for a number of time periods: 1 second, 10 seconds, minutes, hours, or even days, months, or years. Stability is an important factor in oscillator cost. More stable oscillators cost more.

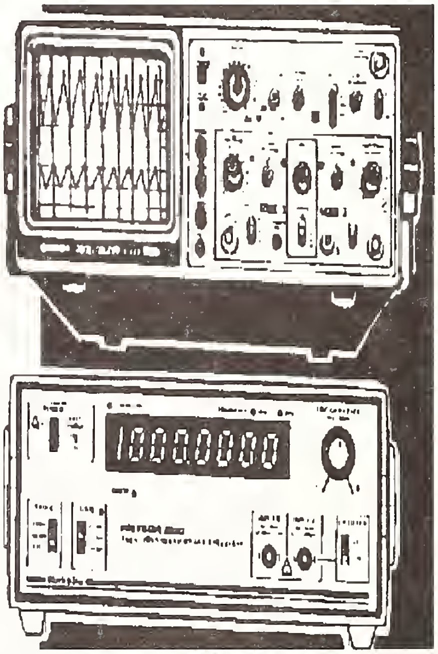
The three characteristics are all important. Accuracy is sought by those who evaluate and compare high-quality frequency sources. Reproducibility is important in applications when several frequency sources are expected to agree with each other. However, the stability of a frequency source is usually the most important characteristic for the average user.

The frequency stability of a frequency source depends on many things that might cause frequency changes. Frequency stability can be measured by taking a reasonably large number of successive readings on an electronic counter which counts the frequency of the device to be evaluated. Each counter reading (in hertz) is obtained by counting the output frequency for some specified time period. This sampling time can usually be chosen by simply adjusting a knob on the counter; for example, a sampling time of 0.1 second or 1 second may be chosen. The result will change as the sampling time changes.

Furthermore, variations in the readings of measured frequency might be expected to average out if observed long enough. This is not always so. The stability of the frequency source usually depends on the sampling time of the measurement and tends to get smaller with longer sampling times. But, again, there are many exceptions to this.

The frequency fluctuations at some later time may be partially due to the previous fluctuations. Then, the computed value depends on the particular way in which the many counter readings are averaged and evaluated. Another influence on measured stability depends on whether the counter starts counting again immediately after completion of the preceding count or if some time elapses ("dead-time") before counting starts again.

Finally, the electronic circuits used in measuring frequency stability have a finite response time. This means that they cannot follow frequency fluctuations faster than some given rate. For example, our eyes cannot register light fluctuations which occur faster than about every 1/10 of a second; we say that the eye has a frequency response (bandwidth) of 10 Hz, or that the eye cannot follow frequencies higher than 10 Hz.



In order to measure frequency stabilities for sampling times smaller than some value, our measurement equipment has to provide for an electronic frequency bandwidth which is large enough.

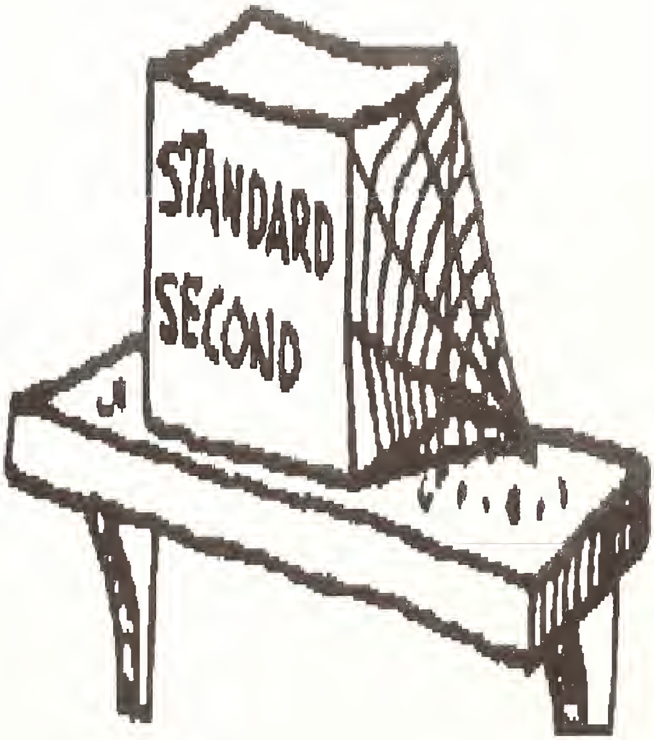
To summarize: A recommended way of properly measuring and describing frequency stability is the following: (a) make sure that the frequency bandwidth of the total measuring setup is large enough; (b) use a counter with a dead-time as small as possible (the dead-time should be less than the reciprocal bandwidth; if not, use the computation procedures that exist to allow for larger dead-times); (c) take enough readings at a given sampling time. The result is that you'll see how the frequency of a source will change if you watch it for 0.01 second, 0.1 second, 1 second, and so on. Such short observation times have applications in radar, communications, and other fields.

Often, results are expressed as a relative (sometimes called fractional) value. The value obtained for the frequency stability is divided by the nominal frequency to normalize it. This lets us "rate" the oscillator as being 1 in a million or 5 in 10 million, and so on.

There is a sound basis for using the relative frequency stability instead of using frequency stability directly. Relative frequency is a numeric and is independent of the actual operating frequency of the oscillator being discussed. This makes it possible to compare the stability of a 10-MHz oscillator to a 10-kHz oscillator.

In fact, many high-quality oscillators have 1-, 5-, and 10-MHz outputs. However, calibrating these sources might require the generation of a different frequency, for example, a signal divided to 1 Hz. If the original source had a relative frequency stability of one part per million (1.00E-06), then the 1-Hz signal would have the same relative frequency stability. This assumes, of course, that the generation of new frequencies does not change the stability. This assumption is true for most applications.

PRIMARY AND SECONDARY STANDARDS



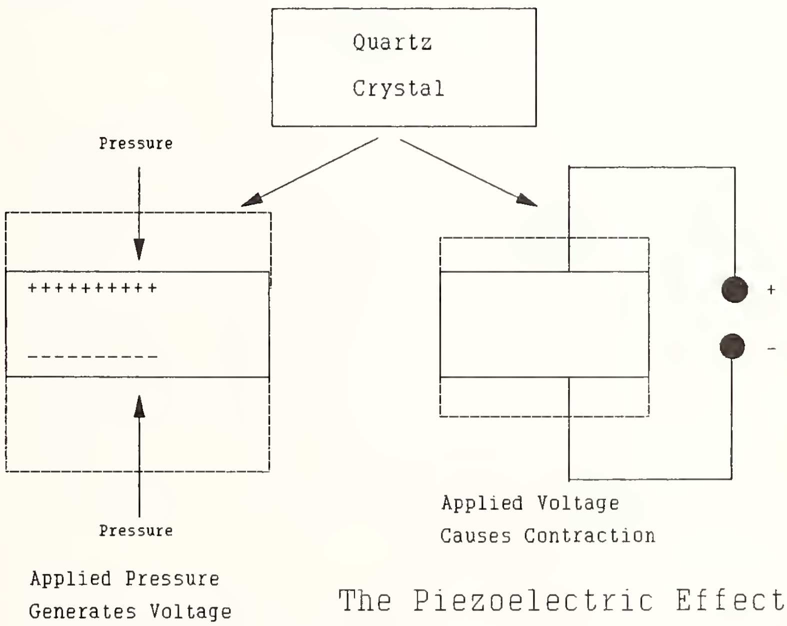
At this point, we should briefly discuss the terms "primary frequency standard" and "secondary frequency standard." These terms refer to how oscillators are used. Any frequency source, regardless of its accuracy or stability, can be a primary frequency standard if it is used as the sole calibration reference for other frequency sources. A secondary frequency standard is a device that is calibrated against a primary frequency standard, and then used to calibrate other frequency sources.

The machines used for primary standards, like the one at NIST and those in other countries, are in a class by themselves. Because of the way they have been built and operated, they can be evaluated. This means that experimental data are taken and used to calculate the errors in their output frequency due to all known causes. It is because of this careful evaluation that their accuracy can be stated without having to check these machines against others. This concept will be discussed in more detail in the section on cesium beam oscillators.

QUARTZ OSCILLATORS

Quartz oscillators (sometimes called crystal oscillators) are widely used. They range from the tiny units found in wristwatches to elaborate instruments found in laboratories. Quartz oscillators provide good performance at a reasonable price and dominate the field of frequency sources.

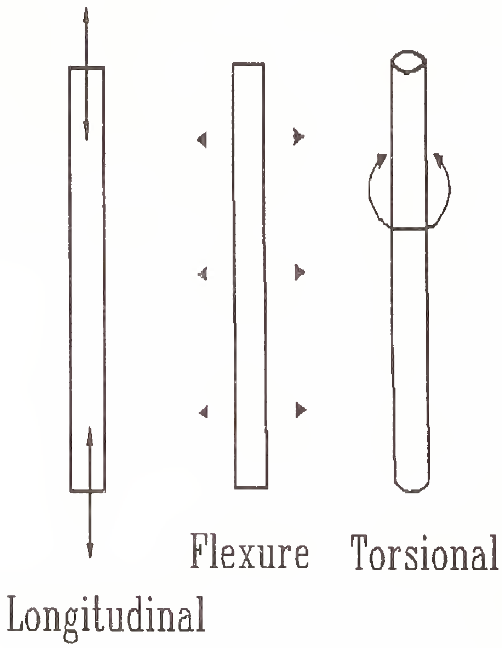
The quartz crystal in the oscillator is a mechanical resonator. The resonator's oscillations have to be excited and sensed. This is done by taking advantage of the piezoelectric effect in the quartz crystal; that is, mechanical compression of the crystal generates a voltage across the crystal. Conversely, the application of an external voltage across the crystal causes the crystal to expand or contract depending on the polarity of the voltage.



The Piezoelectric Effect

A crystal is not a homogeneous medium but has a certain preferred direction; thus, the piezoelectric effect has a directional dependence with respect to the orientation of the crystal. In order to take advantage of the piezoelectric effect, the crystal block must be cut in a well-defined way with respect to the crystallographic directions. The raw material used today is natural or synthetic quartz. A block is cut out of the raw crystal material in the desired orientation with the aid of optical techniques which allow the determination of the crystallographic axes. The high-precision, final orientation of the cut and the tuning to the desired frequency are then done by grinding and etching, controlled by x-ray methods.

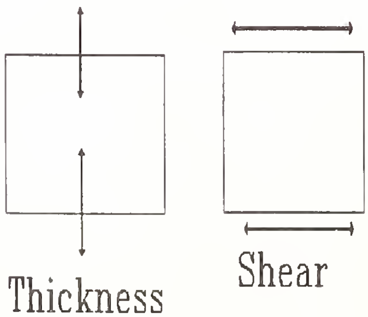
The quartz crystal can be cut and electrically excited in a variety of ways (as shown below). The most common types of vibrations (modes) are the longitudinal and thickness modes, the flexure (bending) mode, the torsional mode, and the shear mode. In order to use the piezoelectric effect, metal electrodes have to be attached to the crystal surfaces so that the desired mode is excited.



The electrodes are typically created as extremely thin metallic coating by vacuum evaporation of metals. Electric leads are attached to the electrodes by soldering. They also serve as the mounting support, thus freely suspending the quartz crystal. In order to least upset the mechanical vibrations of the crystal, the electrode-support leads are attached at points where no vibrational motion occurs (nodes). The crystal is then packaged, and the case is either filled with a protective gas or else evacuated.

Using the crystal, an oscillator can be built by adding an electronic amplifier feedback and a power supply. The oscillator's output frequency is determined by the quartz crystal resonator. The resonating frequency of the crystal is determined by the physical dimensions of the crystal and the type of crystal used. For example, the resonance frequency for a longitudinal mode of vibration is approximately

$$v_0 = 2.7 \times 10^3 \times \frac{1}{L}$$

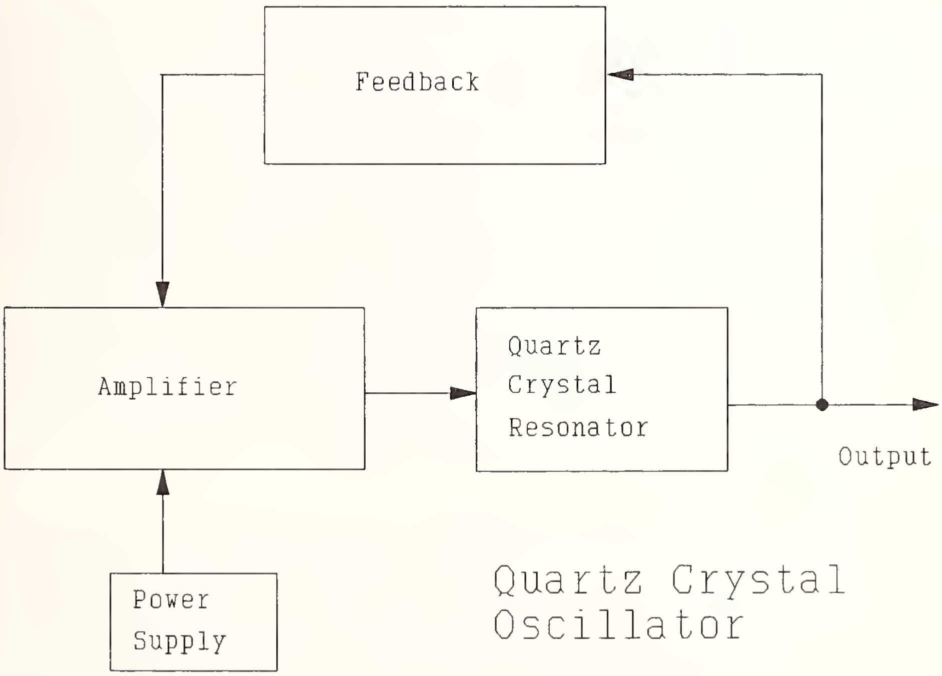


where L is the length of the crystal. If L is in meters, the resonance frequency v_0 will be in hertz. The equation allows us to estimate the size of the crystals. For example, a 100-kHz crystal is just a few centimeters long. Making quartz crystals with resonance frequencies above 10 MHz is hardly possible. However, we can excite resonators not only in their fundamental mode (previously discussed), but also at multiples (overtones) of this fundamental resonance frequency. For example, a violin string can vibrate at frequencies which are multiples of its fundamental. Quartz crystals designed for excitation at multiples of their fundamental resonance frequency are called overtone crystals.

Temperature and Aging of Crystals

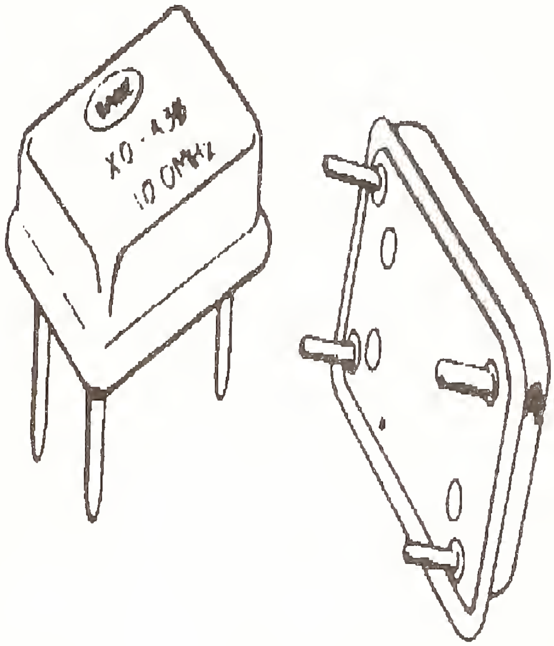
Temperature and aging are two factors that influence quartz oscillator performance. There is a temperature dependence of the quartz crystal that affects its resonance frequency, and there is also a drift of the resonance frequency due to aging.

The temperature dependence is caused by a slight change in the elastic properties of the crystal. Certain cuts (crystallographic orientations of the crystal) minimize this effect over a rather wide range of temperatures, most notably the "AT" and "GT" cuts. Temperature coefficients of less than one part in 100 million per kelvin (or degrees celsius) are possible. In other words, the fractional frequency change will be less than 1.00E-08 with 1 degree of temperature change. Crystal oscillators must be carefully designed if very high frequency stabilities are desired. If large environmental temperature fluctuations are to be tolerated, the crystals themselves are enclosed in electronically regulated ovens which maintain a constant temperature. In some crystal oscillators this is done to better than 1/1000 of a degree.



An alternate solution to the temperature problem is the so-called temperature-compensated crystal oscillator or TCXO. An additional frequency-determining element in the oscillator, which can be just a small capacitor, allows us to tune the oscillator over a limited range. If a temperature sensor is added to cause a change in this capacitor, the change in resonance frequency of the crystal resonator can be cancelled. Capacitors whose values change with an applied voltage (varactors) are used. The applied voltage is derived from a temperature-sensing circuit.

The TCXO does not necessarily require further temperature control by an oven. However, there is a drawback to this approach. By adding another frequency-determining element, the crystal resonator loses a corresponding part of its control on the output frequency of the whole oscillator. The long-term stability (days) of TCXO's is therefore below that of crystals with a good oven control. TCXO's are used in small, usually portable units of relatively lower performance. They are used where frequency stabilities from day to day and frequency changes (over tens of degrees of temperature) of not better than 1.00E-09 are needed.



Small quartz oscillators used in electronic circuits

Aging is a common trait of all quartz oscillators. It is a nearly linear (uniform) change in resonance frequency with time. Drift often is negative, meaning that the resonance frequency decreases. A frequency decrease could indicate an increase in the crystal size. There are many possible causes: contamination (depositing of foreign material) on the surfaces; changes in the electrodes or the metallic plating; reforming of loose (from grinding and etching) surface material, or changes in the internal crystal structure. All of these are possibly caused or enhanced by the vibrating motion of the oscillating crystal. Recent crystal-holder design improvements, combined with clean vacuum enclosures, have led to a reduction of aging to about 1.00E-11 per day. For a 5-MHz crystal with a thickness of a little less than a millimeter, this aging corresponds to an absolute thickness change of only 1.00E-11 of a millimeter, or less than 0.1% of the diameter of an atom.

When a quartz oscillator is first turned on, it will not usually oscillate at its original frequency. It will go through a "warm-up" period while the temperature of the crystal resonator and its oven stabilizes. The warm-up period may last several days or more. During this time, a large but diminishing drift occurs until the oscillator reaches its normal operating temperature.

Quartz Oscillator Performance

Quartz oscillators are very stable. The best available oscillators have stabilities of a few parts in 1.00E-13 for sampling times from 1 second to 1 day. The limitations in stability are mainly due to noise from electronic components in the oscillator circuits. This noise can be reduced by selection of low-noise components and by special circuit designs. Thus, there is a fair chance that crystal oscillator stability can reach values of less than 1.00E-13 for sampling times of seconds to hours. For times shorter than one second, stability is often determined by additive noise in the output amplifiers. This can be reduced by a crystal filter in the output. The long-term stability beyond several hours sampling time is determined by aging and by external factors like line voltage variations, temperature fluctuations, and so on.

It is apparent, therefore, that crystal oscillators require calibration at least once a year. They may need it more often depending on the application. Frequency adjustments are made with a small added capacitor in much the same way as was discussed in connection with the TCXO.

The most stable crystal oscillators, with the lowest aging rate, may cost several thousand dollars or more. They have a volume of a few thousand cubic centimeters and require input power of about 10 watts. They have an elaborate crystal oven for temperature control, well-designed electronics, and usually several output frequencies which are derived from the oscillator with frequency dividers and multipliers. These high-performance devices may use 2.5- or 5-MHz crystal resonators and have a relative frequency of 1.00E-11 per day.

Cheaper and smaller crystal oscillators are available in a variety of designs. As price goes down, the performance also goes down. Costs can go down to below $100, sizes to a few cubic centimeters, and power requirements to less than 0.1 watt. Relative frequency can be as much as 1.00E-06.

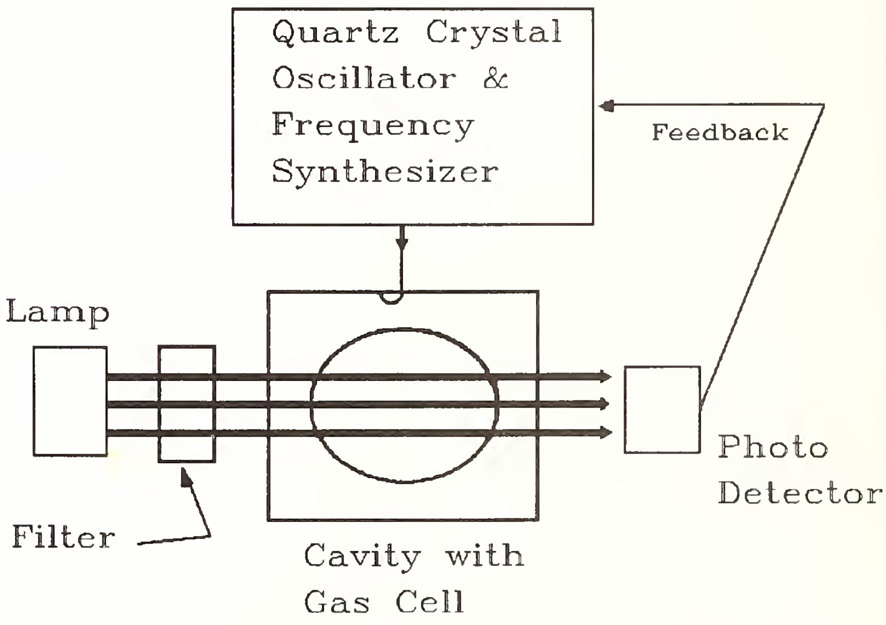
For information on measuring the performance of quartz oscillators, please see chapter 4.

ATOMIC OSCILLATORS

This section discusses the design and performance of the three types of atomic oscillators which are currently in use.

Rubidium Gas Cell Oscillators

Rubidium atomic resonance is at 6 834 682 608 Hz. Rubidium oscillators use a gas cell containing rubidium gas. In order to reduce the effect of collisions among the rubidium atoms, argon, an inert buffer gas, is introduced into the cell at about 1/1000 of atmospheric pressure. This allows lifetimes of the rubidium atom oscillations of about 1/100 second. The oscillation lifetime is still limited by atom collisions. Atomic collisions, as well as the simultaneous action of the light and the microwave signals on the same atom, cause frequency shifts of the order of 1.00E-09. These frequency shifts depend strongly on the composition, temperature, and pressure of the buffer gas and on the intensity of the light. As a result, rubidium gas cells vary in their resonance frequency by as much as 1.00E-09, depending on the particular setting of the frequency shifting parameters when the oscillator is manufactured.



Rubidium Gas Cell Oscillator

Since rubidium oscillators do change frequency, they need initial calibration and also recalibration just like quartz oscillators. The stability performance of rubidium oscillators is still quite spectacular. At 1-second sampling times, they display a stability less than 1.00E-11 and perform near 1.00E-13 for sampling times up to 1 day. For longer averaging times, the frequency stability is affected by the frequency drift, which is typically 1.00E-11 per month. This is much better than a quartz oscillator. As with quartz oscillators, the performance of a rubidium oscillator generally goes down as the price goes down.

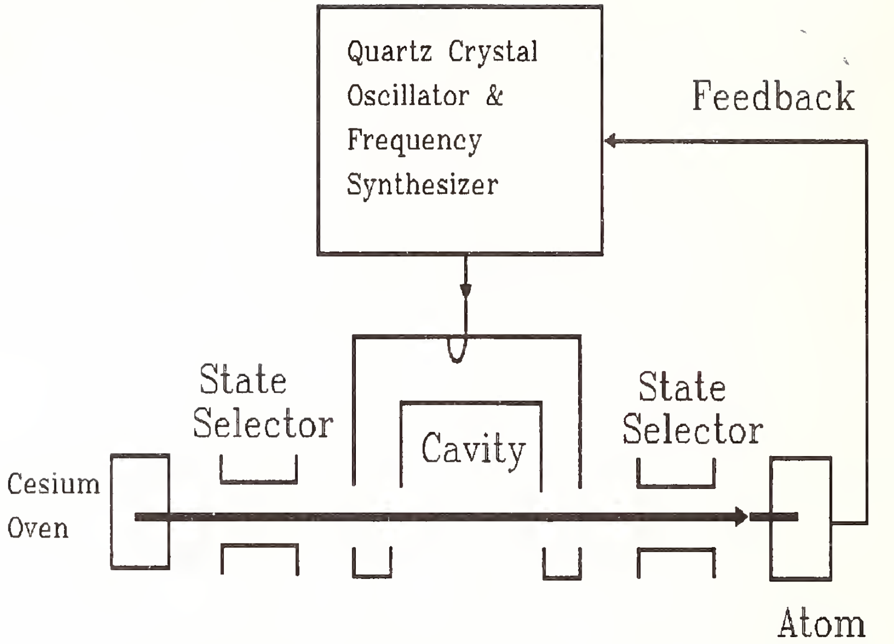
Rubidium oscillators are used when excellent medium-term stability (a few minutes to a day) is needed. They are smaller and less expensive than cesium beam oscillators and work well in situations where a quartz oscillator (with its need for more frequent calibration and its greater environmental sensitivity) would not suffice. Since rubidium oscillators are more stable, they give better results with fewer adjustments than quartz oscillators.

Cesium Beam Oscillators

For a cesium oscillator, atomic resonance is at 9 192 631 770 Hz. An oven contains the cesium metal. If heated to about 100 degrees celsius, enough cesium gas will be produced to form an atomic beam, which leaves the oven through one or many channels into a vacuum chamber. The beam traverses first the state-selecting magnet, then the microwave cavity. Typically, a cavity with separated interrogation regions is used. In the cavity, an external microwave signal acts on the beam. The beam finally reaches the atom detector after passing another state-selecting magnet. The atom detector is simply a tungsten wire which is heated to about 900 degrees celsius by passing an electric current through it. This wire is biased with a few volts dc, and cesium atoms which hit it become electrically charged or ionized and can be collected on an auxiliary electrode. The stream of electrically charged atoms at this electrode represents an electric current which is amplified, detected, and used in the feedback network.

Atoms move through the cavity at speeds of about 100 meters per second. In commercially available cesiums (which have to be reasonably small), the cavity is only about 0.2 meter long. The corresponding interaction time is two-thousandths of a second. In laboratory devices (like the NIST primary standard), the cavity may be 4 meters long, or even longer.

The fractional frequency stability of laboratory and commercial cesium standards can reach 1.00E-14 at sampling times of less than 1 hour to days. The short-term frequency stability is limited by fluctuations in the atomic beam intensity, "shot noise," which is basic and unavoidable. These fluctuations affect the frequency stability less as more intense atomic beams are used. This approach, which is becoming available in both commercial and laboratory cesium standards, improves the stability. Laboratory cesium standards allow a more complete and easier evaluation of all effects on the frequency than commercial standards.



Cesium Beam Oscillator

Cesium oscillators are used extensively where high reproducibility and long-term stability are needed for sampling times of more than a day. They are the workhorses in most of today's accurate frequency and time distribution services. By definition, cesium oscillators are a primary frequency source. This means that (when operated correctly) a cesium oscillator will be very close to its correct frequency without any calibration. However, since the expected level of performance is so high, checking the performance is a very important part of operating a cesium oscillator.

Hydrogen Masers

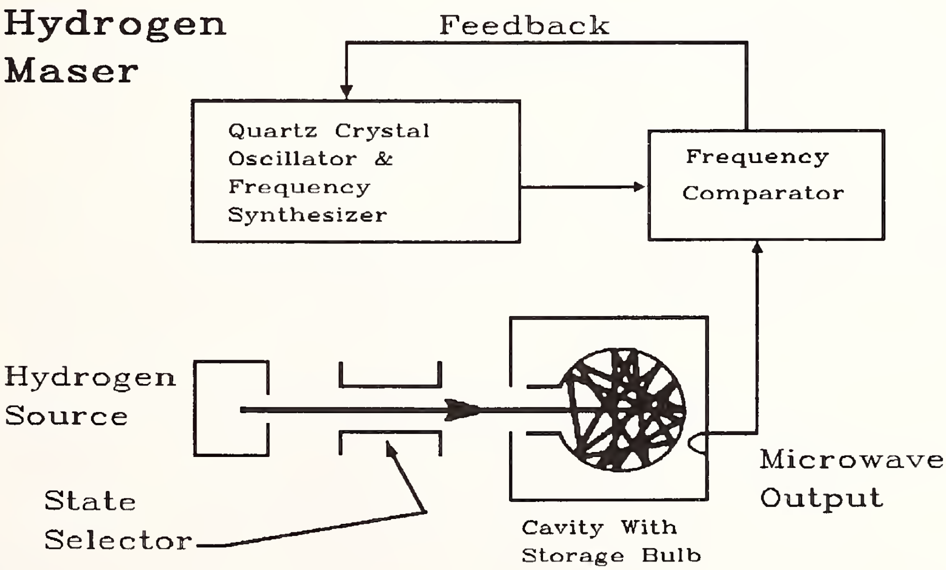
Maser is an acronym meaning "microwave amplification by stimulated emission of radiation." The atomic resonance frequency is at 1 420 405 752 Hz. While not in widespread use, hydrogen masers represent the state of the art in commercially available oscillators for averaging times of 1 second to 1 day.

Hydrogen masers work like this: All natural hydrogen gas is composed of hydrogen molecules. Each hydrogen molecule is formed by chemical bonding of two hydrogen atoms. The beam source is a radio frequency gas discharge in molecular hydrogen. This discharge produces atomic hydrogen with high efficiency. The atomic hydrogen beam leaves the source through one or many channels into a vacuum chamber. The beam then traverses a state-selecting magnet and enters a storage bulb in the microwave cavity.

The storage bulb is made from quartz glass which has low electric losses. Its inner walls are lined with Teflon. This coating allows many collisions of the hydrogen atoms with the walls without significantly disturbing the oscillations of the atoms. The underlying physical mechanisms are not yet fully understood. The storage bulb is typically 0.15 meter in diameter and dimensioned in such a way as to hold hydrogen atoms for about 1 second. After about 1 second, the atoms leave the bulb and thus also leave the microwave cavity. If the intensity of the hydrogen beam, which consists only of upper state atoms (emitting atoms), is sufficiently large and if the cavity losses are sufficiently low, self-oscillation will start in the cavity. The maser itself will generate a microwave signal. We then have a maser-oscillator with an output frequency directly derived from the atomic resonance. A quartz oscillator can be locked to this frequency by frequency comparison techniques.

The hydrogen maser is not quite as accurate as a cesium oscillator. This is because of experimental difficulties in the evaluation of the frequency shift due to the collisions of the hydrogen atoms with the Teflon surface of the storage bulb. This limits the long-term stability over periods longer than several days. Values of long-term stability are not better than those of cesium oscillators. However, for periods of a few seconds to a day, the hydrogen maser has the best stability of all existing oscillators. Its application is limited to uses where these stabilities are critical and where a rather bulky device is not a handicap. Unlike cesium and rubidium oscillators, hydrogen masers have not yet been evaluated under adverse environmental conditions. The number of hydrogen masers in use is very small compared to the numbers of cesium beams and rubidium devices, and the cost of a maser is still very high.

The table on the next page summarizes the oscillators discussed in this chapter.



COMPARISON OF FREQUENCY SOURCES				
Feature	Type of Oscillator			
	Quartz	Rubidium Gas Cell	Cesium	Hydrogen Maser
Output Frequencies (typical)	10 kHz to 100 MHz	1, 5, or 10 MHz	1, 5, or 10 MHz	1, 5, or 10 MHz
Relative Frequency (1 second)	1.00E-06 to 1.00E-12	2.00E-11 to 5.00E-12	5.00E-11 to 5.00E-13	5.00E-13
Relative Frequency (1 day)	1.00E-06 to 1.00E-12	5.00E-12 to 3.00E-13	1.00E-13 to 1.00E-14	1.00E-13 to 1.00E-14
Causes of Long-Term Instability	Aging of Crystal & Electronic Components	Aging of gas cell, filter, & light	Aging of Electronic Components	Cavity Pulling
Time for clock to be off 1 microsecond	1 second to 10 days	1 day to 10 days	1 week to 1 month	1 week to 1 month
Start-Up after being off	seconds to hours	10 minutes to 1 hour	30 minutes to 1 hour	several hours
Resonator Life-Span	many years	more than 3 years	3 years	no data
Weight in kilograms (pounds)	0.1 to 10 (2 oz to 20 lbs)	1 to 20 (3 to 45 lbs)	16 to 400 (35 to 70 lbs)	over 100 kilograms
Power consumed (watts)	0.1 to 15	12 to 35	30 to 200	40 to 100
Estimated Cost	$5 to $10 000	$5 000 to $20 000	$30 000 to $50 000	over $200 000

Chapter 4 - MEASURING FREQUENCY

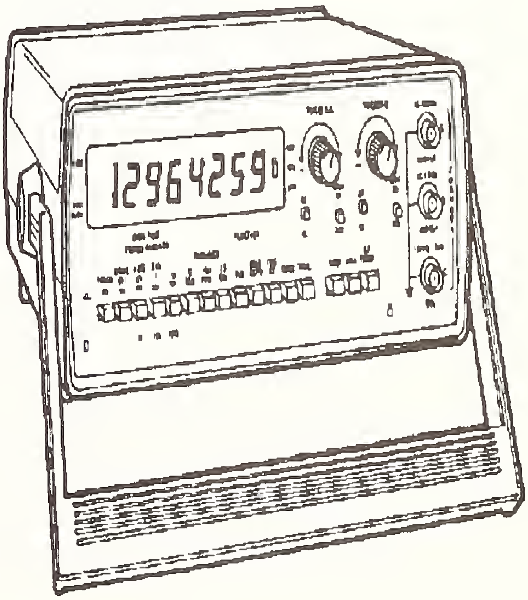
In the last chapter, we discussed the different types of frequency sources (oscillators) that are available. This chapter discusses how to measure an oscillator's performance. It covers the equipment needed to make time and frequency measurements, what the equipment is used for, how it is used, and the kind of results that you can expect.

Determining the frequency of an electrical signal involves counting the number of cycles or pulses that occur over a given time interval. For example, a digital clock may change its display at a rate of 1 Hz (once per second). This rate has been given the name of a famous German inventor, Heinrich Hertz. One Hz equals one event per second.

This chapter uses scientific notation when discussing the accuracy of an oscillator. For example, a relative frequency of 1 part in 10 to the 11th is written as 1.00E-11.

THE THEORY OF FREQUENCY MEASUREMENTS

Frequency and time interval can be measured with greater precision than any other physical quantities. Frequency measurements are made by comparing signals from two frequency sources. This is true in music, for example, where the orchestra tunes its instruments to the oboe. In the same way, oscillators are measured, adjusted, and calibrated by comparing their output with the output from a higher quality frequency source. The higher quality frequency source can be a radio signal or another oscillator.



A simple and direct way to measure frequency is to use a frequency counter. The problem with this method is the time it takes to make measurements of very high resolution. The resolution of an ordinary counter is increased by increasing the gate time. For example, a 1-second count of a 1-MHz signal might give a resolution of 1 Hz. The resolution improves to 0.1 Hz after 10 seconds. This resolution was obtained by waiting longer. It would take many hours to reach the resolution of a precision oscillator. Even if the time were available, this method is not recommended because it allows only a few readings per day, and the chances for error become great. A system that must run continuously for hours to get one reading is susceptible to errors due to power outages and other causes.

A better approach is to measure time interval instead of frequency. This method takes advantage of modern circuit chips and is faster. For example, if two oscillators with 1-Hz outputs are compared using a time interval counter, a high resolution reading can be obtained every second. A typical counter might have a 100-MHz time base. This means the measurement resolution obtained is the period of the 100-MHz signal (10 nanoseconds). Therefore, changing from frequency to time interval measurements results in a dramatic increase in resolution.

Time Interval Measurements

The technique of measuring time interval to determine frequency is commonly used for precise calibrations. Time interval measurements are made using an electronic device called a time interval counter (TIC). To use a TIC, you connect signals from two different frequency sources. One signal serves as a start pulse, and the other serves as a stop pulse. The TIC measures the interval between the occurrence of the two pulses.

Time interval counters differ widely in specification and design details, but they all share several basic parts. These are: the time base, the main gate, and the decade counting assembly (DCA).

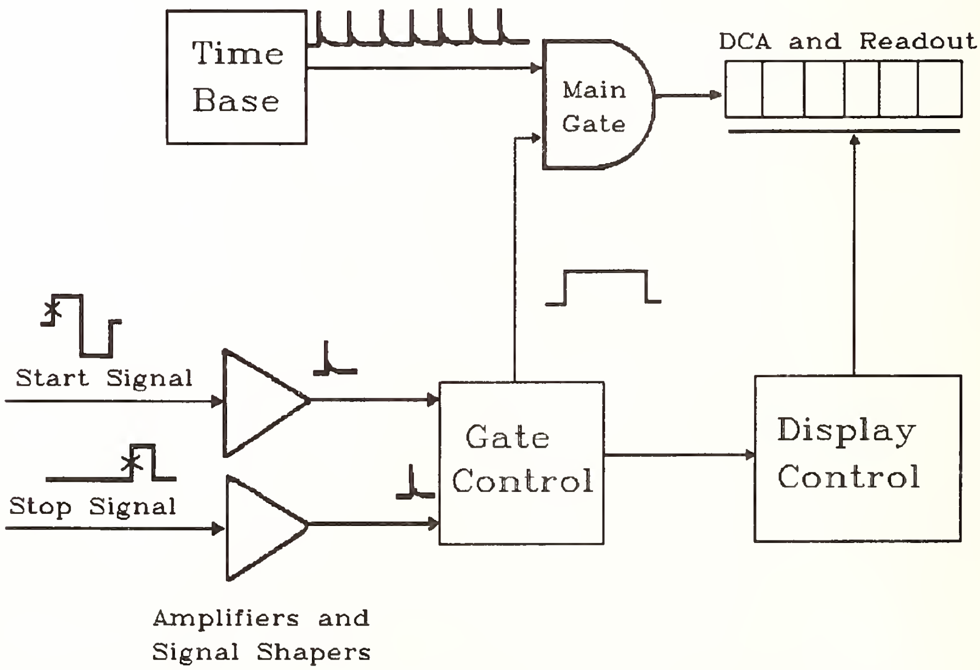
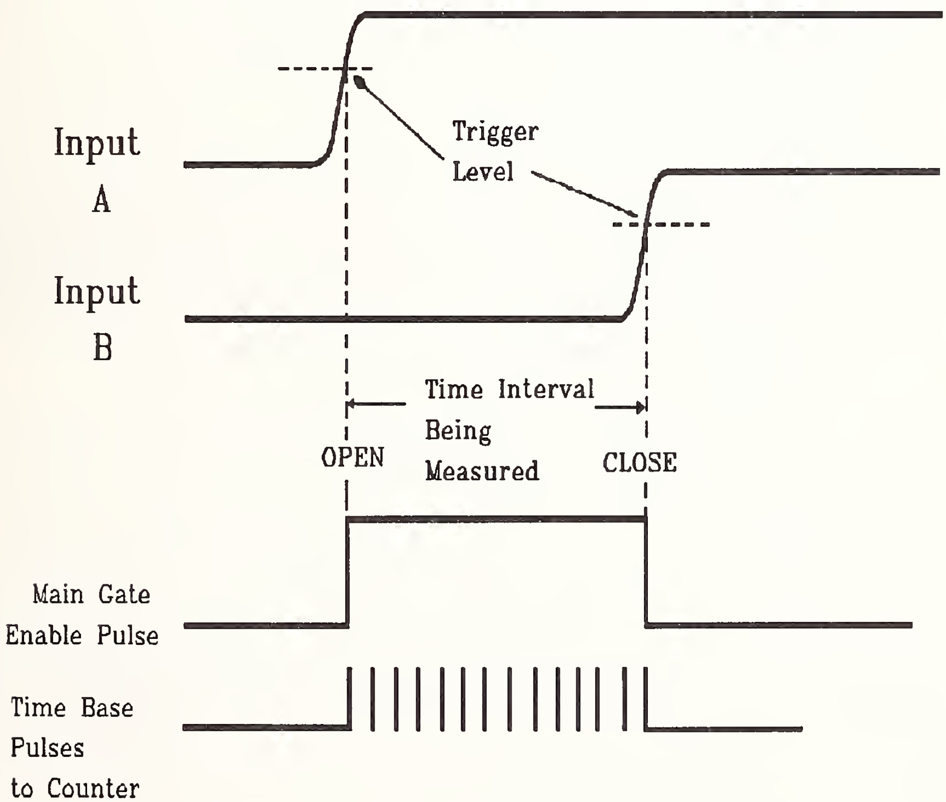


Diagram of Time Interval Counter

The time base provides uniformly spaced pulses for counting and control of the TIC's circuitry. The time base must be stable because time base errors will directly affect the measurements. Most counters use an internal quartz oscillator for a time base.

The oscillator may be followed by decade dividers to allow the user a choice of several different gate signals. Adding more dividers to the chain makes it possible to obtain longer measurement intervals. Increasing the frequency of the time base makes it possible to count shorter time increments (higher resolution).

The main gate controls the time at which the count begins and ends. The gate may be actuated automatically by pulses from the time base or manually by means of a switch on the control panel. Pulses which pass through the gate are routed at the decade counting assembly where they are displayed on the counter's digital readout. After a preset display period, the counter resets itself and starts another count.



Measuring the time interval between two input signals

Other counter sections include amplifiers, pulse shapers, power supplies, and control circuits. The input channels are usually provided with level controls and attenuators to set the exact amplitude limits at which the counter responds to input signals. Proper setting of the level controls helps reject noise or other unwanted signals.

A counter in its "frequency measurement" mode will display the result as a frequency (Hz, MHz, and so on). On the other hand, readings produced by a time interval counter are in time units. The readings measure the length of the interval (in time units) between the signals being calibrated. If the two signals have exactly the same frequency, the time interval will not change. If the two frequencies differ, the time interval will change, although usually very slowly. It is exactly as if each signal were a clock, and the readings tell whether one clock gained or lost time relative to the other clock.

It takes two readings to get one data point. A single reading of the time interval between two clocks is not useful. It is the second reading, subtracted from the first, that tells whether time is gained or lost. This gain or loss of time is a measure of the frequency difference between the two frequency sources.

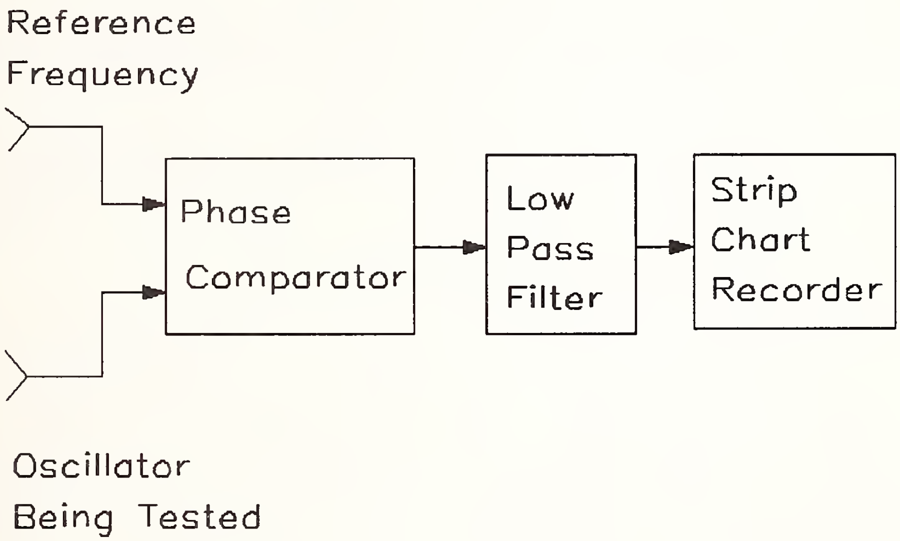
Using a Measurement System

A typical standards laboratory has a primary oscillator which it uses as a frequency reference. In many cases, the standards lab has made a considerable investment in this oscillator. Quartz oscillators (based on 1990 prices) range from $500 to $10 000; rubidium oscillators from $5 000 to $20 000; and cesium oscillators from $30 000 to $50 000.

The primary oscillator is used to calibrate equipment that is now in the lab or that is expected soon. It too must be periodically calibrated so that its accuracy is known. Calibrating the primary oscillator must be done on-site. Since oscillators are sensitive to shipment, it is not practical to send them to another laboratory for calibration. Being turned on and off can cause their frequency to change.

The ideal situation for a laboratory is to backup its primary oscillator with batteries, keep it running all the time, and continuously measure its performance using a measurement system. A good measurement system allows even small laboratories to perform calibrations at a relative frequency of 1.00E-12. To get an idea of what this relative frequency (or frequency offset) means, if such an oscillator were used to drive a time-of-day clock it would gain or lose only one ten-millionth of a second a day!

Calibration labs can use several types of frequency measurement systems. Manufacturers offer VLF, LF, and Loran-C receivers that make measurements and record the data on chart paper or via computer data logging. This equipment often uses the primary oscillator as a receiver input. The receiver then makes the comparison and draws the chart. Front panel indicators assist in operating the system. Receiver options include different types of antennas, some distribution capability, and even a way to discipline the primary oscillator to make it agree in frequency with the radio signal. A block diagram of this type of system is shown below.



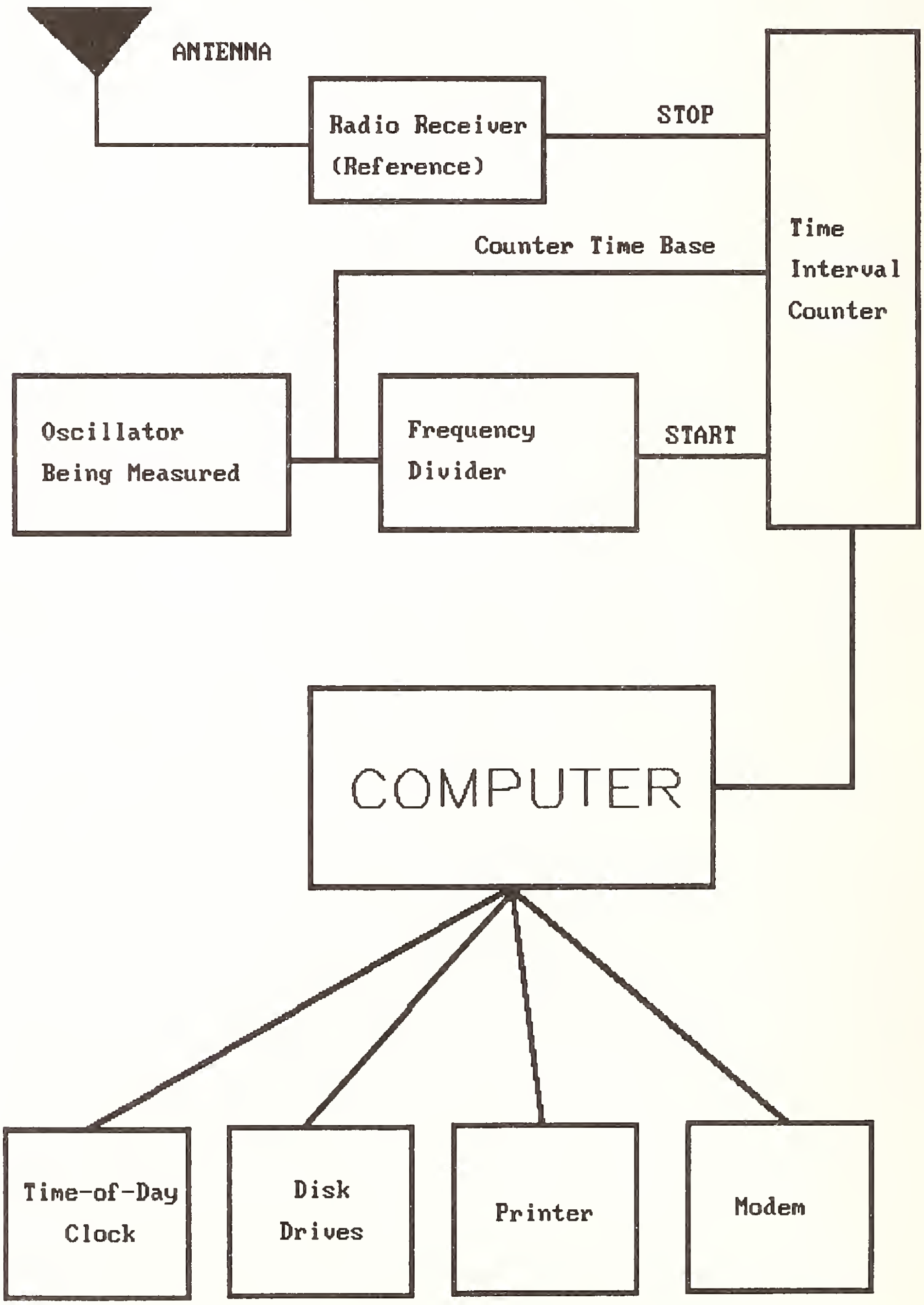
A Typical Commercially-Available Frequency Measurement System

All measurement systems work basically the same way: they make comparisons between two signals. One signal is a reference frequency, and the other signal is the signal being measured. The reference is assumed to be more accurate than the signal being measured and is most often a radio signal traceable to the NIST time scale (traceability is discussed later in this chapter). The different radio signals you can use as reference frequencies are described in chapters 5-7. The signal being measured is from an oscillator like those discussed in chapter 3.

The data from the system must be recorded in some way. The readings can be manually recorded in a logbook, or continuously recorded by a chart recorder. However, modern measurement systems often use a computer. A computer-controlled measurement system is described in the next section.

A COMPUTER-CONTROLLED MEASUREMENT SYSTEM

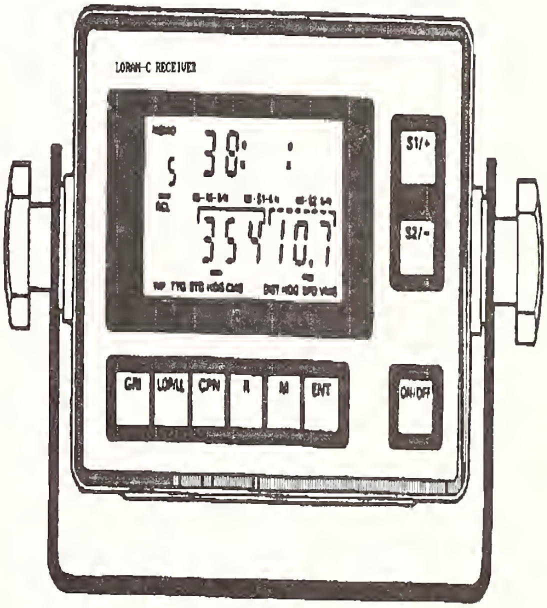
This section describes the design and operation of a typical computer-controlled measurement system. Each part of the system is discussed in the following paragraphs. A block diagram of the entire system is shown below.



The Reference Frequency

The designer of a computer-controlled measurement system needs to decide which radio signal should be used as a reference frequency. The different radio signals you can use are discussed in chapters 5-7. Help is also available from the manufacturers of time and frequency equipment and also from the national laboratories that control the radio signals. NIST assists users in this area with publications, phone consultation, and training seminars.

The decision should be based on the accuracy required by the system. If the required accuracy is very high, or if it can be expected to increase in coming years, then consider only those radio signals which support that accuracy. For example, WWV can be used to calibrate an oscillator of modest performance, but a high-performance oscillator may require using signals from WWVB or Loran-C. Loran-C is a radio navigation system maintained by the U.S. Coast Guard (Loran stands for LOng RAnge Navigation).



The choice of radio signal is also limited by the location of the laboratory, reception problems with certain radio signals, available equipment, and past experience. Another factor is whether the radio signal lends itself well to automation. It may be better to use a signal that is easy to automate by computer, even if the initial cost of the equipment is higher. If low-cost equipment is purchased, it may require a lot of attention. In these instances, the labor costs could soon exceed the amount of money that was originally saved.

Since a radio signal is used, you also need to consider the type of antenna required. The antenna needs to be on the roof, and the receiver may need to be grounded. Several antenna types are currently offered. VLF and Loran-C receivers generally operate with short vertical whips or loops, but HF services like WWV need long wires for good, noise-free reception. The antenna should be mounted in an area free from obstructions and interference.

The system described here uses Loran-C radio signals as a reference frequency. It includes a radio that receives a signal from a Loran-C station. Loran-C is described in more detail in chapter 6.

Loran-C signals make an excellent reference frequency for a number of reasons. They are extremely accurate, with a relative frequency of about 1.00E-12 per day. This is good enough to check the performance of cesium, rubidium, or quartz oscillators. The continued accuracy of Loran-C is insured since the stations are controlled by cesium standards monitored by the U.S. Coast Guard and the U.S. Naval Observatory, in addition to NIST. Loran signals are also traceable to NIST. Traceability is described in more detail later in this chapter.

A second benefit is that some Loran-C receivers are inexpensive and automatic. Finally, each Loran-C station has an effective range of over 1000 miles (1600 kilometers). Since numerous Loran-C transmitters are in operation, this means that Loran can be received in just about any location in the Northern Hemisphere (including all 50 States).

The Frequency Divider

The signals connected to a time interval counter for comparison must have the same (or a related) frequency. For example, in order to compare a 5-MHz signal to a 1-MHz signal, both signals must first be divided to a lower frequency (usually 1 Hz). The system includes a frequency divider for this purpose.

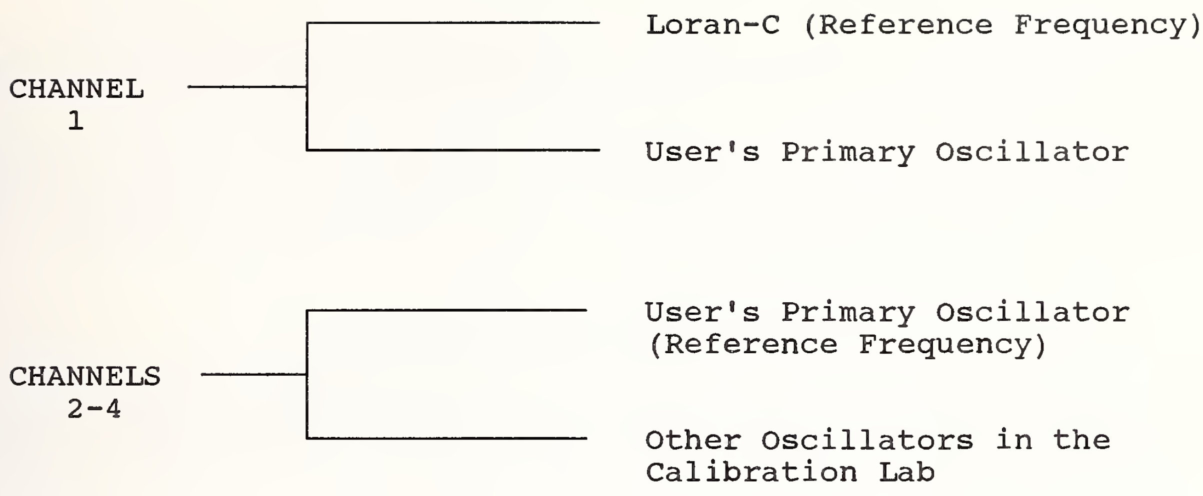
The frequency accepts input frequencies of 1, 5, or 10 MHz and divides them to 1 Hz for comparison. It also produces a signal that matches the frequency (about 10 Hz) of the output pulse from the Loran-C receiver.

The frequency divider accepts signals from one to four oscillators. This allows the primary oscillator to be compared to Loran-C (the reference frequency), and the other three oscillators to be compared to the primary oscillator.

The Time Interval Counter

The system's time interval counter can measure up to four channels simultaneously. It has no knobs or controls and therefore reduces measurement errors due to knob settings. The counter's time base frequency is obtained from the primary oscillator. The time base frequency can be 1, 5, or 10 MHz. A light indicates whether a time base signal is present.

Channel 1 of the counter is dedicated to the calibration of the primary oscillator in the laboratory. The primary oscillator is compared to the Loran-C reference frequency. Channels 2, 3, and 4 can be used to compare other oscillators to the primary oscillator (see the figure on the next page).

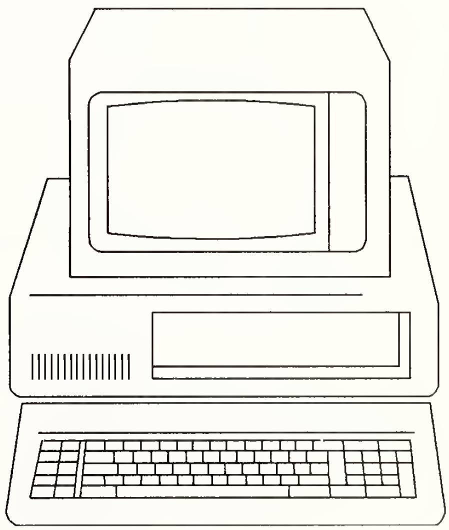


Calibration Procedure Using a Typical Measurement System

The Computer

Just about any computer can be used to control a measurement system. This NIST system is controlled by a low-cost microcomputer with two disk drives, a monitor, and a printer.

The computer averages time interval readings and stores the data and the time the data were taken on disk. The time is obtained from a clock inside the microcomputer. The computer runs 24 hours a day and restarts automatically after power outages.



Every 24 hours, the computer stops taking data and plots the data recorded in the last 24 hours. It then prints a copy of this plot on the printer. The information contained on the plots is described in the next section. The plotting is done automatically, without user interaction.

After the system plots, it starts taking readings for the next day. The process continues in this way: recording, plotting, recording, plotting, and so on. The only operator attention required is to occasionally add paper to the printer.

The computer software used by the system is "transparent." It requires little attention and makes users feel that they are using a completely integrated system.

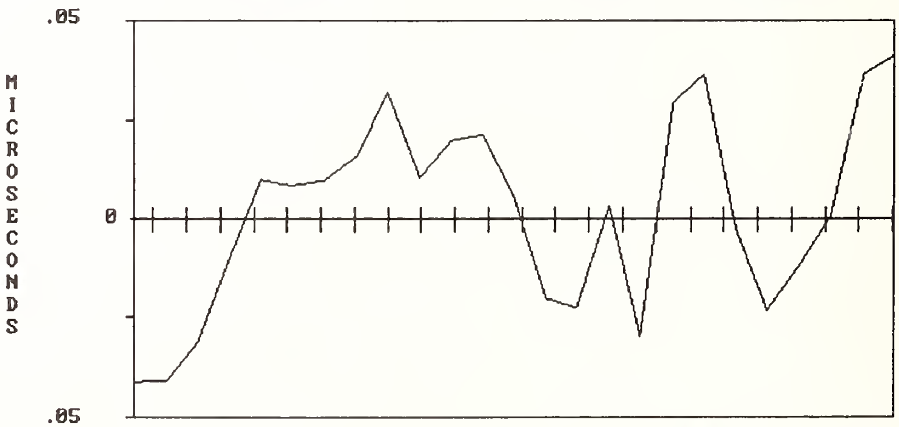
Output of the Measurement System

As mentioned, the system stops taking data once every 24 hours and produces a plot of the performance of each oscillator being measured. Since one to four oscillators can be measured, from one to four plots are printed each day.

Since radio signals are affected by events along their path (like bad weather and electrical interference), data from a radio signal must be averaged when compared to a primary oscillator (which may have a relative frequency of less than 1.00E-11 per day). A 24-hour measurement is sufficiently long and still provides the user with a daily report of each oscillator's performance.

A sample phase plot is shown below. Each plot shows the number of microseconds that were gained or lost in the 24-hour interval of the measurement. The unit for the vertical axis is microseconds. The unit for the horizontal axis is time of day (hours).

Cesium Oscillator Vs Loran-C 9940 (Fallon, Nevada)



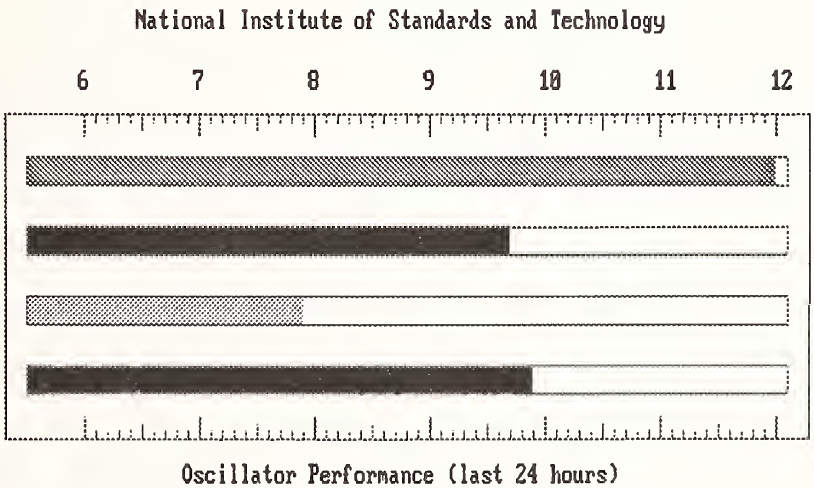
07/04/89 (MJD 47711)   Channel 1   (MJD 47712) 07/05/89
16:27   [tic marks = 1 hour]   15:03
Data points= 25   Relative Frequency: +3.72E-13   r=+0.38

The plots also show the computed relative frequency of the oscillator. The relative frequency is printed below the plot. Relative frequency is calculated by fitting a linear least-squares line to the data and taking the slope of the line. The system can show relative frequency offsets ranging from 1.00E-06 to 1.00E-12. This allows the system to measure the full range of oscillators, from low-quality quartz oscillators to high-quality atomic oscillators.

Day to Day Operation of the System

The computer-controlled system was designed to make daily operation easy. The automatic plotting and relative frequency features make the lab technician's job easier, make the calibrations less confusing, and reduce the amount of operator attention. However, the frequency measurement system should be checked daily to make sure that everything is working. The manuals included with the equipment explain which front panel lights and meters are important for daily system checks. Once a lab technician becomes familiar with the equipment, the daily check should take only a few minutes.

Part of the check requires looking at the system's computer screen. A picture of the screen is shown below. The screen was designed so that the operator can check the status of the system with just a quick glance.



07-09-89 1740 UTC	Press <CONTROL-X> to exit Press <CONTROL-P> to plot	Change in Time (µs)	Counter Reading (µs)
	Cesium vs Loran-C 9940 (Fallon, Nevada)	-0.01	45.56
	Brand X Quartz vs Cesium	-0.02	53.07
	Brand Y Quartz vs Cesium	→ +0.03	60.51
	Rubidium vs Cesium	-0.00	68.08

The measurement screen is divided into two parts. The bottom part of the screen contains a box with information about the signals being measured. The left side of this box shows the present time (UTC) and date. Below the date and time are the titles given to each measurement channel. On our sample screen (on the previous page) the title for Channel 1 is: Cesium vs Loran-C 9940 (Fallon)

This title tells us that a cesium oscillator is connected to Channel 1 and is being compared to a Loran-C signal. Loran-C is the reference frequency, and the cesium oscillator is the oscillator being measured. The cesium oscillator is the reference frequency on Channels 2, 3, and 4. By looking at the titles for those channels, you can see that quartz oscillators are being measured on Channels 2 and 3, and that a rubidium oscillator is being measured on Channel 4.

The right side of the box has two columns. The rightmost column is labeled *Counter Reading*. This shows the last actual reading obtained from the counter. This number is the time interval (in microseconds) between the signal from the reference frequency and the signal being measured (see page 43). The leftmost column is labeled *Change in Time*. This shows the difference (in microseconds) between the last two counter readings. For example, if this number is 0.01, it means that the oscillator being measured has moved 0.01 microsecond (10 nanoseconds) since the last counter reading was taken. The system measured the performance of the oscillator by accumulating these time differences.

The top part of the measurement screen contains a bar graph. This graph shows the performance of each oscillator being measured over the last 24 hours. Each bar is a different color. The color of the bar matches the color of the title for the channel.

The numbers at the top of the bar are a measure of oscillator performance. For example, 6 represents a relative frequency of 1.00E-06, 9 represents a relative frequency of 1.00E-09, and so on. The longer the bar, the better the performance of the oscillator. If the bar is all the way to the right, the relative frequency of the oscillator is 1.00E-12 or better. This means that the oscillator is drifting less than 0.1 microsecond (100 nanoseconds) in 24 hours. If the bar is all the way to the left, the relative frequency of the oscillator is 1.00E-06 or worse. This means the oscillator has drifted more than 0.1 seconds (100 milliseconds) in 24 hours.

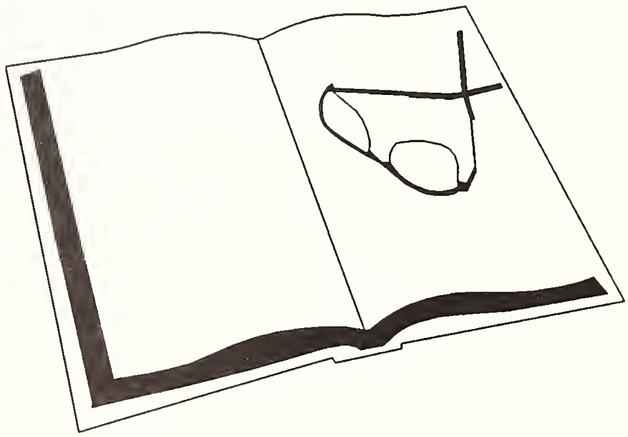
The exact performance of the oscillator is shown on the daily phase plots (page 50). The bar graph gives the operator a quick indicator of each oscillator's performance. By looking at the bar graph, the operator can tell if there were any losses of the signals being measured; for example, if the Loran-C receiver tracked properly for the last 24 hours. The operator will also soon get a feel for how well each oscillator is expected to perform and will quickly be able to notice if an oscillator is not performing properly.

Keep in mind that the quantity being measured is a very small number. This means that even a small error at any time during the daily measurement run will affect the data. For this reason the equipment should be left on; sudden temperature changes should be avoided, and electrical interference (from cleaning equipment, power devices, generators, etc.) should be minimized.

Recordkeeping

Users of a measurement system should keep enough records to satisfy the needs of the laboratory. For example, users of the system described above could keep the daily plots in a notebook for future reference and diagnostic purposes. They can also keep the data on computer disk and record the daily relative frequency values.

Users of an integral radio-oscillator-recorder (page 45) can keep the chart records provided to support claims of traceable calibrations. If data from the signal being received are listed in a NIST or USNO publication, those documents should also be kept.



All calibration labs that use a measurement system should draw up a system block diagram showing how signals are generated, distributed, and calibrated. When changes are made, they can be noted on copies of the diagram. This block diagram keeps the lab manager aware of any changes and possible problem areas.

TRACEABILITY FOR FREQUENCY MEASUREMENTS

Traceability means that a measurement can be traced back to the national frequency standard (in the United States, that standard is the NIST time scale). The NIST primary frequency standard is physically located in Boulder, Colorado. Access to the NIST frequency standard is by radio methods. Measurements made using the radio signals discussed in chapters 5-7 are traceable to NIST.

The rule for traceability is simple: The radio signal used must either be directly controlled by NIST, or monitored by NIST. Signals controlled by NIST include WWV, WWVB, WWVH, and GOES. The signals monitored (directly and indirectly) by NIST include Loran-C, GPS, the Navy VLF signals, the Omega navigation signals, and Canadian and European broadcast signals. All of these signals are useful because they are referenced to atomic oscillators. Since they are carefully controlled, monitored, and intercompared between national laboratories, traceability to NIST is assured. For example, users of the signals from radio station CHU in Canada can be assured that these signals can be traced to NIST, since the relationship between the Canadian and U.S. national standards is known.

The accuracy of the traceability is limited, however, by the number of steps in the traceability path. Users should investigate the limitations so that no confusion exists over what can or cannot be accomplished with a given signal.

We can illustrate traceability using Loran-C as an example. Loran-C is traceable to NIST because its signals are monitored by NIST. The received signals from Loran-C are continuously compared to the nation's frequency standard. Through this monitoring, NIST is able to measure the accuracy of the Loran-C signals relative to the NIST time scale. NIST (and the USNO) publish Loran-C data and make it available to Loran-C users. A sample is shown below. By looking at this data, users can see that the day-to-day variations between Loran-C and the NIST time scale are very small, a fraction of a microsecond every 24 hours.

September 1989	Modified Julian Date	Loran-C (Dana 8970)	Loran-C (Fallon 9940)
15	47784	-0.16	-0.10
16	47785	-0.23	-0.25
17	47786	+0.30	+0.20
18	47787	+0.21	-0.10
19	47788	+0.06	+0.06
20	47789	+0.06	-0.21
21	47790	-0.16	+0.01
22	47791	-0.16	-0.20
23	47792	-0.16	+0.01
24	47793	+0.12	-0.20
25	47794	-0.11	+0.01
26	47795	+0.31	+0.46
27	47796	-0.04	-0.11
28	47797	+0.17	+0.26
29	47798	-0.34	-0.58
30	47799	+0.05	+0.13

The measurement system we just described used Loran-C as a reference frequency. Users of the system measure the performance of their oscillator by comparing it to Loran-C. The data in the figure were obtained by using the NIST time scale as a reference frequency and using it to measure the performance of Loran-C.

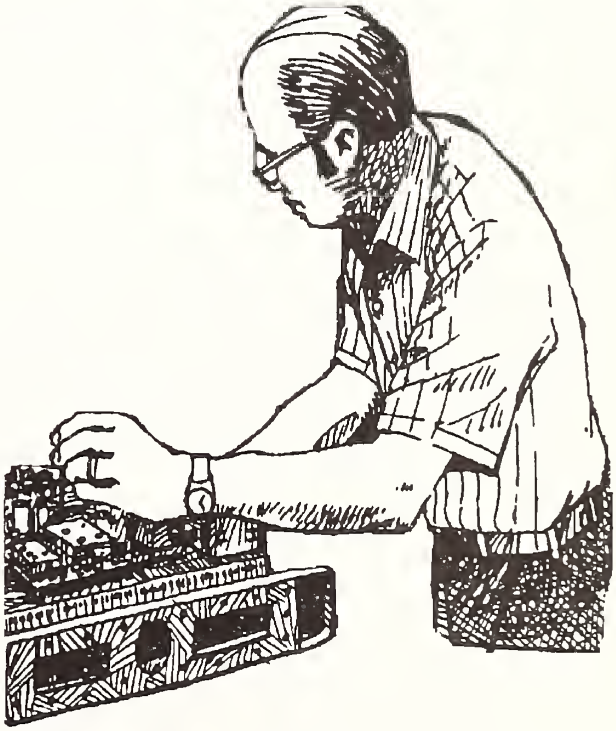
The small variations in Loran-C do not concern most users. For example, the relative frequency of Loran-C is about 1.00E-12 over a 24-hour period when compared to the NIST time scale. If the user is calibrating an oscillator to within 1.00E-09 of Loran-C, the small errors in the Loran-C phase will not cause any problems. In this instance, the performance of the reference frequency greatly exceeds the accuracy requirements of the laboratory. This makes it fairly easy to establish traceability. From the user's viewpoint, using Loran-C to make the calibration works just as well as using the NIST time scale. Traceable radio signals like Loran-C make it possible for even the smallest lab to make state of the art calibrations.

WHAT A FREQUENCY CALIBRATION MEASURES

Frequency calibrations measure the relative frequency of the oscillator. The time interval over which measurements are performed is important. For the purposes of this book, a time period of 1 day (24 hours) has been chosen.

From this starting point, two things need to be considered: the mathematics of calibrations, and the names and symbols to be used. This section follows the international practices of the frequency and time industry and the major calibration laboratories.

A measurement becomes a calibration if it compares the oscillator's long-term frequency to UTC(NIST), which means Coordinated Universal Time at NIST. Traceability to NIST means that the oscillator was compared to UTC(NIST) over a traceable path (using WWVB, Loran-C, and so on). The oscillator then becomes a traceable frequency source. The normal length of a calibration is 24 hours (1 day). There are cases, however, when this time period can be shortened.



The desired result of a calibration is to obtain the relative frequency of the oscillator with respect to UTC(NIST). The international symbol for relative frequency is F. Relative frequency is defined by the following equation:

$$F = \left[\frac{f(\text{actual}) - f(\text{nameplate})}{f(\text{nameplate})} \right]$$

The Definition of Relative Frequency

The nameplate frequency (usually 1, 5, or 10 MHz) is what the frequency of the oscillator should be. If an oscillator operated exactly at its nameplate frequency, it would be a perfect frequency source. In the real world, however, there is always some frequency error, or a difference between the actual frequency and the nameplate frequency. This frequency error is what a calibration measures. It is usually a very small number. In much of the literature, the frequency error is referred to as delta-f (delta means a small difference).

The equation finds the size of the frequency error. Dividing delta-f by the nameplate value normalizes the equation. This lets the operator ignore the actual oscillator frequency and concentrate on the frequency error.

To illustrate what we have covered so far, let's look at the numbers that calibration technicians use to report their results. These are the same kinds of numbers used by manufacturers when they quote specifications for their oscillator or frequency source. This notation is also used internationally by many different countries.

For example, consider a 1-MHz oscillator that is high in frequency by 1 Hz. The numbers needed to compute the relative frequency of the oscillator are shown below. All numbers have been converted to Hz so that we have a common unit to work with.

f(nameplate) = 1 000 000 Hz (1 MHz)

f(actual) = 1 000 001 Hz (1.000 001 MHz)

delta-f = 1 000 001 Hz - 1 000 000 Hz = 1 Hz

The quantity delta-f by itself is very useful. It shows us that we have a frequency error of 1 Hz. But our use of mathematical notation will be more useful if we take one more step. That step is called normalization and consists of dividing the frequency error by the nominal frequency like this and labeling it as relative frequency (using the equation we looked at earlier):

$$F = \frac{1\ 000\ 001 - 1\ 000\ 000}{1\ 000\ 000} = 0.000\ 001 = 1.00\text{E-}06$$

This tells us that our source has a frequency error of 1 Hz (the numerator) but that it is only 1 Hz out of a million (the denominator). Using powers of ten for ease of writing, we have 1.00E-06. The usefulness of this notation is obvious. We can describe this oscillator as having a 1-Hz error in one million, a one part per million error, or we can say that its relative frequency is 1.00E-06.

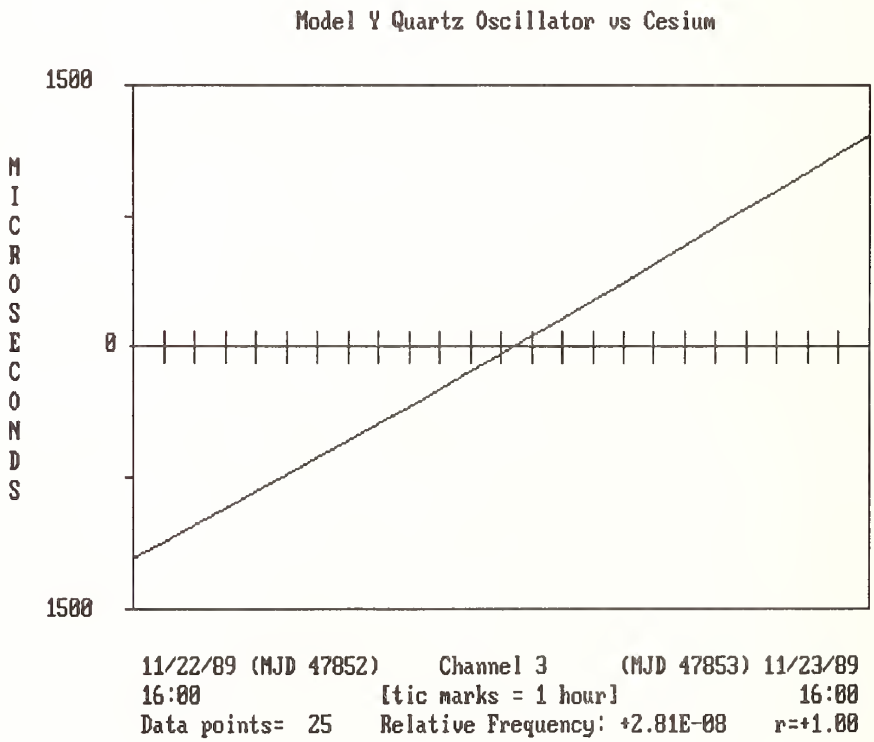
This form of notation is useful for the very small numbers that occur in the measurement and calibration of high quality oscillators. Also, the notation gives us the "feel" we need to make judgments about the devices we are using. The same 1-Hz error for a 10-MHz oscillator is a smaller part of the nominal frequency and gives us a smaller relative frequency. By dividing the delta frequency or frequency error by the nominal frequency, we no longer have to worry about whether the nameplate frequency is 1 MHz, 10 MHz, or 3.5875 MHz. The relative frequency value (F) serves as a sort of report card for oscillators. It lets us compare the performance of oscillators, regardless of their nameplate frequency.

Another benefit of this notation is that it doesn't make any difference if we use the oscillator output directly or if we use a divided version of the oscillator. For example, we can divide the 1-MHz output of an oscillator to 1 Hz without changing the results. This means that we can deal with sources of any frequency by using dividers to make the measurement problems more manageable. It is much easier to deal with lower frequencies, and the final results are the same.

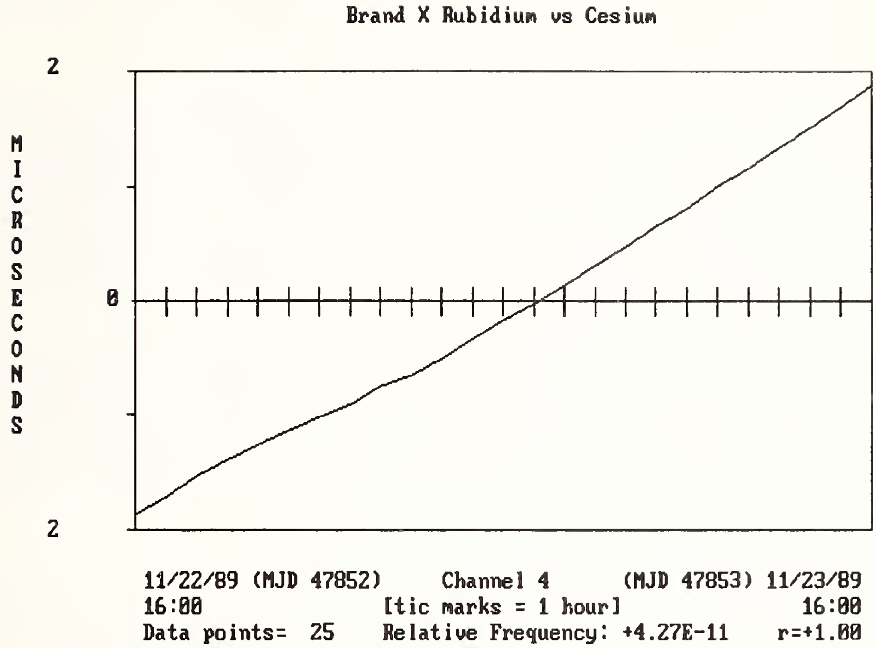
The sign of F changes from + to - if the oscillator output is lower than the nameplate. This follows international convention and is the practice followed by many manufacturers. F is a number and has no dimensions like hertz or percent. F does not depend on the oscillator frequency. For example, if a 10-MHz oscillator had an actual frequency output of 10 000 010 Hz, it would also have an F of 1.00E-06.

The graphs below show the frequency performance of a quartz, rubidium, and a cesium oscillator. All three are graphs of actual data recorded at NIST and are typical of the type of performance you can expect from each type of oscillator.

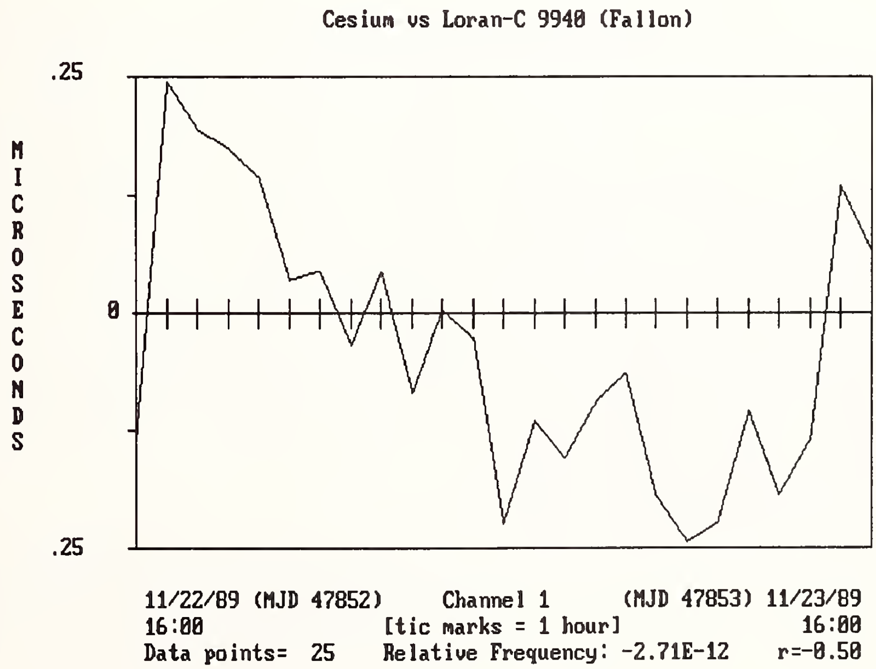
The first graph is of a low-cost quartz oscillator. This oscillator is typical of the oscillators used as timebases in counters and other electronic test equipment. Its relative frequency is 2.81E-08 (shown below the plot). The amount of oscillator drift over the 24-hour period is nearly 3 000 microseconds.



The next graph (shown at the top of the next page) shows the performance of a rubidium oscillator. Over the 24-hour period, the amount of oscillator drift is only about 4 microseconds. The relative frequency of the rubidium is 4.27E-11.



And finally, the plot below shows the performance of a cesium oscillator when compared directly to Loran-C. Because a radio signal is being used, this plot is not as smooth as the other plots. However, notice that the two signals never differed by more than 0.5 microsecond (500 nanoseconds) over the 24-hour period.



SUMMARY

Time interval measurements are the method of choice when making accurate frequency calibrations. You can buy or build many types of measurement systems based on the time interval method, but all should run 24 hours a day and use a reference frequency that is traceable to NIST. We encourage users to discuss their needs with manufacturers of time and frequency equipment and to read the available literature.

Relative frequency, or F, is a way to talk about an oscillator's performance in a way that is easy to understand; the oscillator is either higher or lower in frequency than it is supposed to be. Measuring relative frequency requires dealing with very small quantities, since the difference between the actual frequency and the nameplate frequency is usually very small.

The next three chapters discuss radio signals that can be used as the reference frequency for a measurement system. All of these signals are traceable to NIST. They include high and low frequency broadcasts and signals broadcast from satellites. Obviously, you will not want (or need) to use all of the services. Your accuracy requirements, available manpower, and budget are all contributing factors in choosing a service that best meets your needs.

Chapter 5 - CALIBRATIONS USING HF RADIO BROADCASTS

High frequency (HF) shortwave radio broadcasts are a popular source of time and frequency information. HF signals from stations such as WWV (Ft. Collins, Colorado), WWVH (Kauai, Hawaii), and CHU (Ottawa, Canada) are readily available and provide essentially worldwide coverage. A number of foreign countries operate services in these frequency bands, and the signals can be received with relatively low-cost receivers.

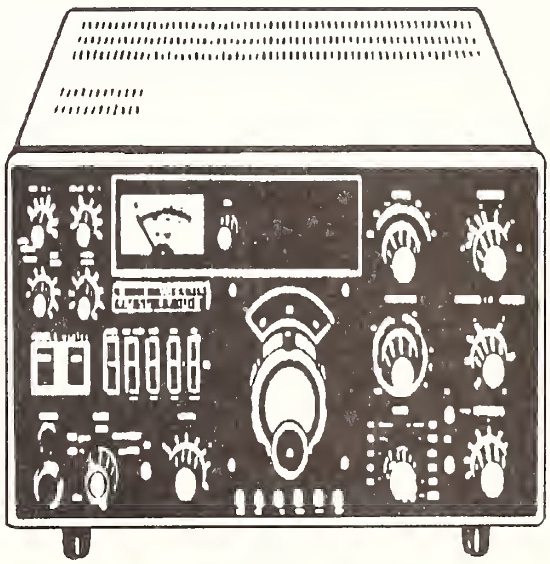
In addition to the simpler, low-cost receivers, several manufacturers now provide more elaborate receiving equipment. These receivers pick the best signal automatically by re-tuning from one frequency band to another. Also, you can now buy receivers with a built-in computer interface, making it possible to obtain a time code to reset a computer clock. Of course, any shortwave radio receiver from the simplest to the most elaborate can be used.

BROADCAST FORMATS

Many HF radio stations worldwide can be used for time and frequency measurements. Many of these stations are listed in the table on pages 64-65. The following paragraphs discuss the stations located in the United States and Canada.

WWV/WWVH

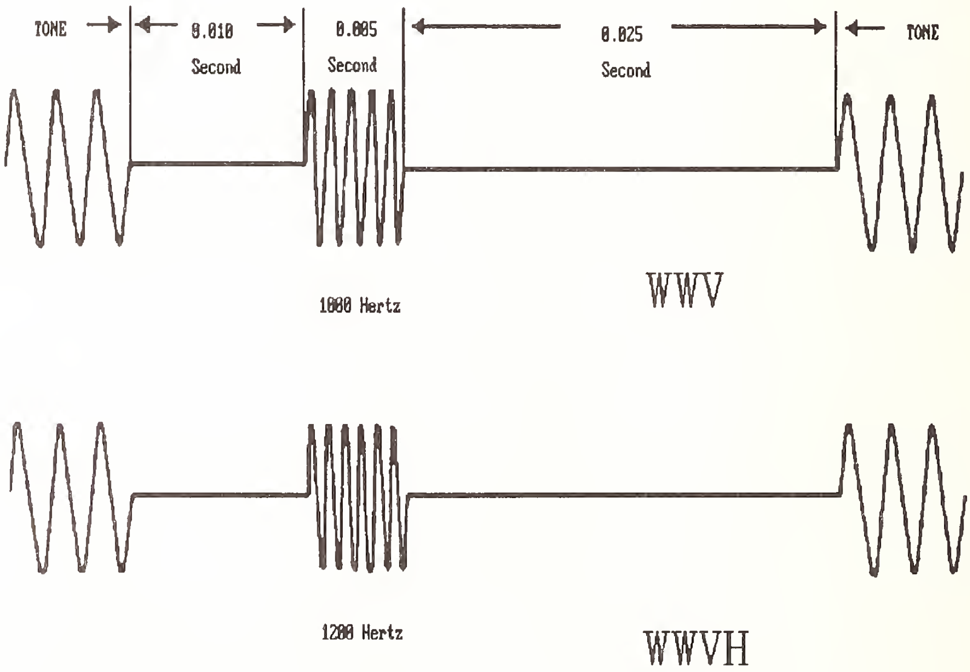
Standard time and frequency stations WWV and WWVH are operated by the National Institute of Standards and Technology (NIST). WWV is in Ft. Collins, Colorado, and WWVH is in Kauai, Hawaii. Both stations broadcast continuous time and frequency signals on 2.5, 5, 10, and 15 MHz. WWV also broadcasts on 20 MHz. All frequencies carry the same program, and at least one frequency should be usable at all times. As a general rule, frequencies above 10 MHz work best in the daytime, and the lower frequencies work best at night.



The stations get their signals from a cesium beam frequency source. They each use three "atomic clocks" to provide the time of day, audio tones, and carrier frequencies.

The rates or frequencies of the cesium oscillators at the stations are controlled to be within 1.00E-12 of the NIST frequency standard located in Boulder, Colorado. Time at the stations is kept within a few microseconds of the NIST atomic time scale, UTC(NIST).

The seconds pulses or "ticks" transmitted by WWV and WWVH are obtained from the same frequency source that controls the carrier frequencies. They are produced by a double sideband, 100 percent modulated signal on each RF carrier. The first pulse of every hour is an 800-millisecond pulse of 1500 Hz. The first pulse of every minute is an 800-millisecond pulse of 1000 Hz at WWV and 1200 Hz at WWVH. The remaining seconds pulses are brief audio bursts (5-millisecond pulses of 1000 Hz at WWV and 1200 Hz at WWVH) that sound like the ticking of a clock. All pulses occur at the beginning of each second. The 29th and 59th seconds pulses are omitted.



Each tick is preceded by 10 milliseconds of silence and followed by 25 milliseconds of silence to avoid interference from other time stations and to make it easier to hear the tick. The total 40-millisecond protected zone around each seconds pulse is illustrated in the figure. This means that the voice announcements are also interrupted for 40 milliseconds each second. This causes only a small audio distortion. The ticks have priority and must be received clearly.

The complete broadcast format for WWV and WWVH, showing exactly what is broadcast during each minute of the hour, is listed on pages 78-80.

CHU

Canada has many frequency and time services similar to those in the United States. The Canadian HF broadcast station CHU is located near Ottawa. Its signals can be heard over much of the United States and are a valuable alternative to the WWV signals. It has the same propagation characteristics, and the same receiving techniques are used.

The CHU signals differ from those of the U.S. stations in two ways. They are not in the standard frequency bands, and they use a different format. The format is principally voice and ticks. At CHU, cesium frequency sources are used to generate the carriers and the seconds pulses. Two systems are used to complement each other in cases of maintenance or failure. The output from the cesium oscillator is fed to a frequency synthesizer which produces the 3330-, 7335-, and 14670-kHz carrier signals for the transmitters.

A 100-kHz signal is fed into one of two digital clocks, where it is divided into seconds pulses of 100-Hz tone. The clock gates out the 51st to 59th second pulses of each minute to permit the voice announcements to be inserted, and also gates out the 29th pulse to identify the half-minute point.

The same 100-kHz signal is fed into two "talking clocks." One announces the station identification and time in English, and repeats the time in French. The other announces the station identification and time in French, and repeats the time in English.

In 1975, CHU converted its operation to single sideband. It now broadcasts upper sideband with full carrier. This is called the 3A3H mode. Users can still get the carrier as a frequency standard, and an ordinary AM radio will allow reception of the audio signals.

A time code appears in the 31st to the 39th seconds pulses of each minute. The modulation is the commercial 300 baud FSK (frequency shift keying) at frequencies of 2025 and 2225 Hz. The code is a modified ASCII code in which each 11-bit character contains two BCD digits, with one start bit and two stop bits. The first digit is the number 6 for identification, which should be verified in the receiving clock; the remaining 9 digits give the day, hour, minute, and second of UTC. The entire message is then repeated so that the receiving clock can check for identical messages before updating. The code ends, and update occurs at 0.5 second. This half-second must be added, along with the time zone hour, to give the correct time. The same code is also available by telephone. Details can be obtained by writing to the Time and Frequency Section, National Research Council, Ottawa, Ontario, Canada.

The table on the following pages contains information about other HF Time and Frequency Stations.

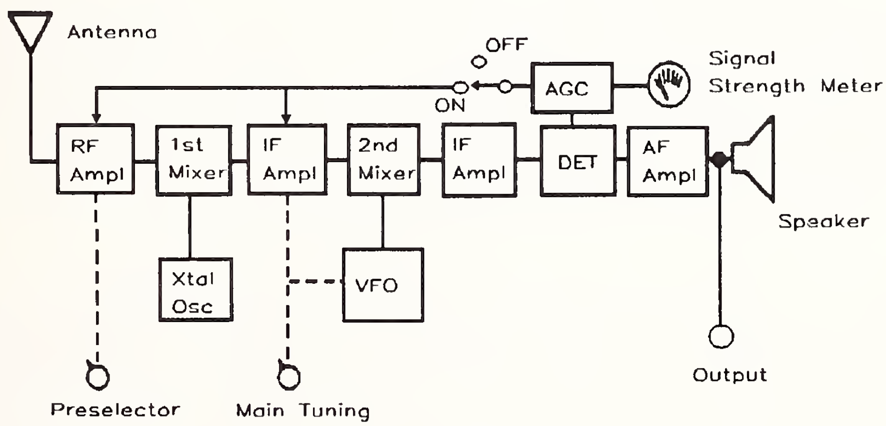
HF STANDARD FREQUENCY AND TIME SIGNAL BROADCASTS					
Name	Country	Carrier Power (kW)	Broadcast Frequency (MHz)	Days/ Week	Hours/ Day
ATA	India	8	5, 10, 15	7	24
BPM	China	10-20	2.5, 5, 10, 15	7	24
CHU	Canada	3-10	3.330, 7.335, and 14.670	7	24
HLA	Republic of Korea	2	5	5	7
IAM	Italy	1	5	6	2
IBF	Italy	5	5	7	2.75
JJY	Japan	2	2.5, 5, 8, 10, 15	7	24
LOL	Argentina	2	5, 10, 15	7	5
OMA	Czecho-slovakia	1	2.5	7	24
RCH	USSR	1	2.5, 5, 10	7	21
RID	USSR	1	5.004, 10.004, 15.004	7	24
RIM	USSR	1	5, 10	7	20.5
RTA	USSR	5	10, 15	7	20.5
RWM	USSR	5-8	4.996, 9.996, 14.996	7	24
VNG	Australia	10	5, 10, 15	7	24
WWV	United States	2.5-10	2.5, 5, 10, 15, 20	7	24
WWVH	United States	5-10	2.5, 5, 10, 15	7	24

HF STANDARD FREQUENCY AND TIME SIGNAL BROADCASTS (continued)					
Name	Country	Carrier Power (kW)	Broadcast Frequency (MHz)	Days/ Week	Hours/ Day
ZLFS	New Zealand	0.3	2.5	1	3
ZUO	South Africa	4	2.5, 5	7	24

RECEIVER SELECTION

This and the following sections discuss the use of HF broadcasts for time and frequency calibrations. For convenience, we will refer mainly to WWV; however, the discussions also apply to other HF broadcasts.

Almost any shortwave receiver can be used to receive HF signals for time and frequency calibrations. However, for accurate time and frequency calibrations, it is important to have a good antenna-ground system and a receiver with optimum sensitivity, selectivity, image rejection, and frequency or phase stability. A block diagram of a typical high-performance receiver is shown below.



Block Diagram of a High–Performanance

HF Receiver

The first requirement of a good receiver is sensitivity. Therefore, a tuned RF amplifier is desirable because it increases sensitivity. The next requirement is selectivity. This is the ability of a receiver to reject interference. Often, either crystal or mechanical filters are used.

The third feature of a good receiver is the ability to reject interference from an undesired signal at what is called the image frequency. Since the IF signal is the difference between the local oscillator frequency and the incoming signal, there are always two different incoming signals that can produce the same IF signal. One is above and the other below the oscillator frequency. Refer to radio texts for further explanations.

A local crystal oscillator can be used in these receivers to provide tuning stability. Other information regarding well-designed receivers can be found in such reference material as the *Radio Amateur's Handbook*.

Several receivers will automatically tune themselves to WWV. If timing is a special problem in your home or business, of course check the receiver very carefully before you purchase it. The single best option to look for in a receiver is the provision for an external antenna. This may be just a short wire or an elaborate rooftop installation. Fancy knobs and adjustments won't help much if you can't get a good signal.

ANTENNA SELECTION

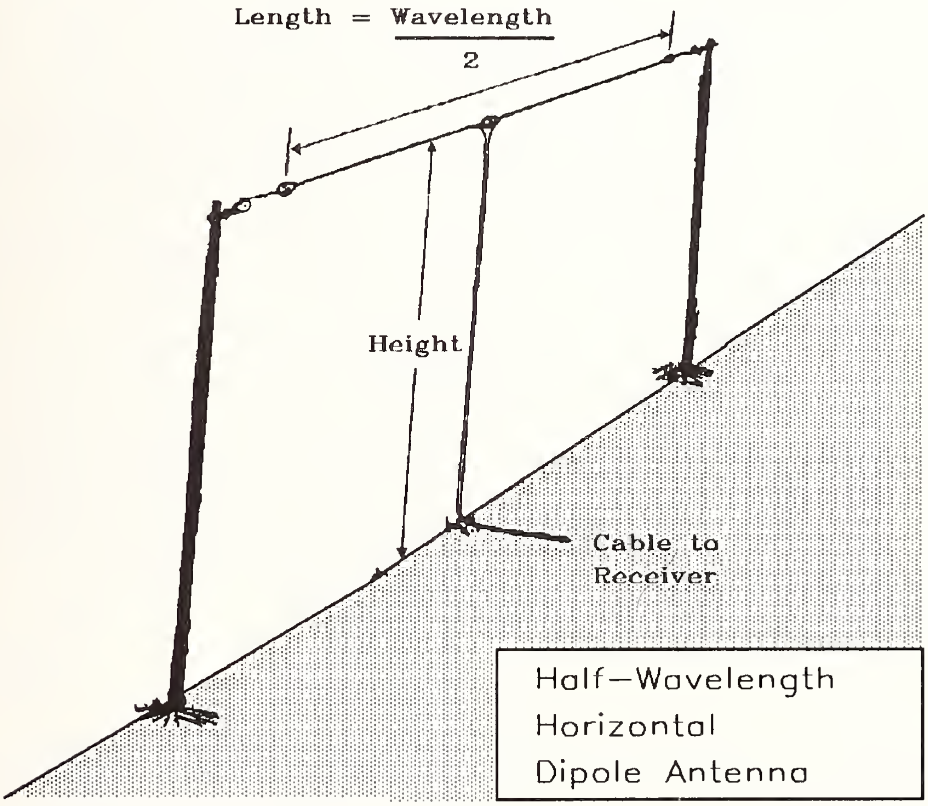
Some HF stations transmit on more than one frequency. Because of changes in ionospheric conditions, most receivers are not able to pick up the signals on all frequencies at all times in all locations. However, unless there are severe magnetic disturbances (which make radio transmissions almost impossible), users should be able to receive the signal on at least one of the broadcast frequencies. As a general rule, frequencies above 10 MHz provide the best daytime reception, while the lower frequencies are best for nighttime reception.

All-band antennas capable of covering the entire HF band are commercially available. These are used for around-the-clock communication, where the entire HF band must be used for maximum reliability. Depending on location, an antenna and a receiver capable of receiving two or more frequencies may be required. Any of the different WWV frequencies transmitted may be received depending upon distance, time of day, month, season, and sunspot cycle. This section discusses the type of antenna best suited to each frequency. For more information, refer to antenna manuals such as those published by the American Radio Relay League.

Antennas for the 2.5- to 4-MHz Range

In order to use these frequencies during the daytime, your receiver should be located within 320 kilometers (200 miles) of the transmitter. This is because the ground wave from the transmitter will travel only a short distance. These frequencies become more useful at night, however, especially during the winter season in the higher latitudes, where longer nights prevail. Reception is then possible over distances of several thousand miles.

There are two types of antennas which work in the 2.5- to 4-MHz range. The vertical monopole quarter-wavelength antenna is very effective in receiving long distance skywave signals normally arriving at angles of 20 degrees or less. It is also useful for receiving weak groundwave signals.



For nighttime reception on paths up to several thousand miles, the skywave is predominant, and a horizontal dipole half-wavelength antenna is recommended. The antenna should be located a quarter-wavelength or higher above ground. Choose an area free from obstructions and interference.

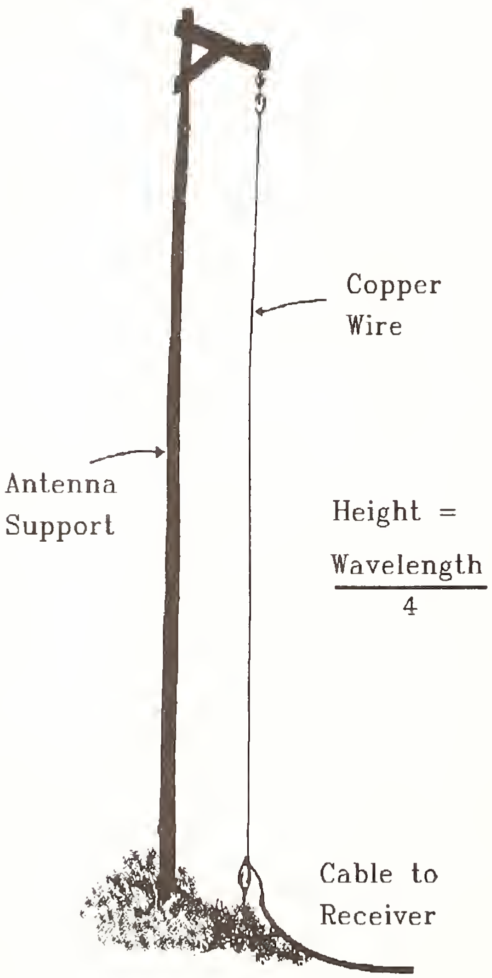
Antennas for the 4- to 5-MHz Range

These frequencies can be received at greater distances than the 2.5-MHz frequency throughout the day or night, especially during the minimum of the sunspot cycle. Reception is possible up to 1600 kilometers (1000 miles) under ideal conditions, but the range is usually less than that during the day.

At night, 5 MHz becomes a very useful frequency for long-range reception except during maximum sunspot cycle. It is excellent during early dawn and early evening in the winter months. Horizontal dipole antennas are a good choice for this band. You can also consider using a multiband antenna.

Antennas for the 7- to 10-MHz Range

At these frequencies, reception over great distances is possible during the day or night, but they are still dependent upon the sunspot cycle. During the minimum sunspot cycle, great distances can be covered using 7-10 MHz in the daytime when higher frequencies cannot be received. And during the maximum sunspot cycle, these are probably the best frequencies to use at night when the lower frequencies cannot be heard. However, during the maximum sunspot cycle, reception is limited to short distances during the day with limitations comparable to those noted for 5 MHz. The 7-10 MHz range can also provide daytime reception at fairly close range, and can be used when 5-MHz reception is poor. The half-wavelength horizontal dipole antenna should be selected for short distances. A quarter-wavelength vertical monopole antenna is suitable at greater distances.



Quarter–Wavelength Vertical

Monopole Antenna

Antennas for the 14- to 15-MHz Range

These frequencies are best suited for long-range reception during the day. They are not usable for short-range reception except during periods of maximum sunspot activity. However, for long-range reception, they are the most favored frequencies during both sunspot cycle conditions. Under average conditions, the maximum wave angle is limited to 30 degrees or less.

During maximum sunspot cycle, reception may even be possible during the night in some locations. During minimum sunspot cycle, they are useful only during the daylight hours and dawn and dusk periods. Both horizontal and vertical antennas work well in this range.

ANTENNA DIMENSIONS FOR 2.5, 5, AND 10 MHz			
Frequency	Quarter-WaveLength Vertical Antenna	Half-WaveLength Horizontal Dipole Antenna	
(MHz)	Height	Length	Height
2.5	28.37 m 94' - 7"	56.1 m 187'	15 to 30 m 50' to 100'
5.0	14.05 m 46' - 10"	28.07 m 93' - 7"	9 to 15 m 30' to 50'
10.0	7.05 m 23' - 6"	14.05 m 46' - 10"	7.5 to 15 m 25' to 50'

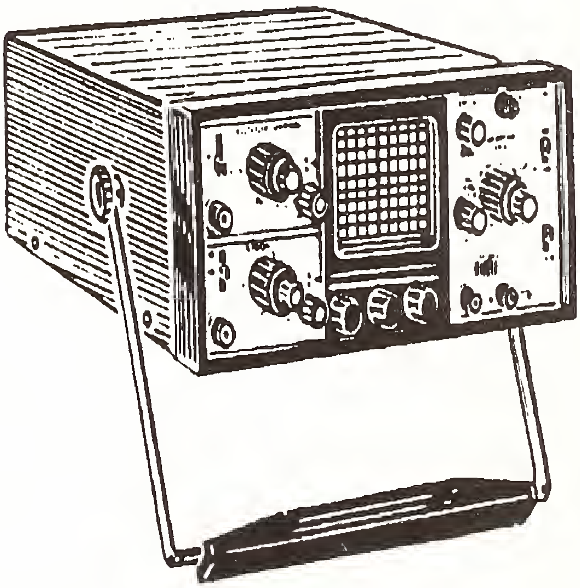
Antennas for 20 MHz

Normally, 20 MHz is the best frequency to use for daytime reception and will be optimum at either noon or a few hours past noon. Signals at this frequency arrive at very low wave angles and are useful only for long distance reception. During the minimum of the sunspot cycle, reception is poor but improves during the winter. During the maximum of the sunspot cycle, the reception is excellent at night and during the day. The vertical monopole that favors low wave angle radiation has been used at this frequency with favorable results.

USING HF BROADCASTS FOR TIME CALIBRATIONS

Time of day is available from many sources in the United States and Canada. Radio and television stations mention the time frequently and, in fact, use the time of day to schedule their own operations. Telephone companies offer time-of-day services in many locations.

Most time-of-day services in the United States start at NIST. A NIST telephone service is available by calling (303) 499-7111. In addition, WWV and WWVH broadcast voice time-of-day once each minute. This is also the case for CHU, where the time is given alternately in French and English. Using the WWV voice announcement and the tone following the words, "At the tone, XXXX hours XXXX minutes Coordinated Universal Time," a person can check a wall clock or wristwatch to within a fraction of a second. The UTC time that is announced can be converted to local time by using a time zone map.



Recovering time at higher accuracies requires using electronic equipment. For example, if an oscilloscope is used to see the seconds ticks, the user can set clocks with much greater accuracy than is possible by only listening to the ticks.

The following sections describe several methods of recovering time of day with resolutions better than 1 millisecond (1000 microseconds) by using an oscilloscope. Under very favorable conditions, it is possible to recover time to within 100 microseconds. In each case, path and equipment time delay corrections are necessary for accurate results.

For best results using any of these methods, the following guidelines are recommended:

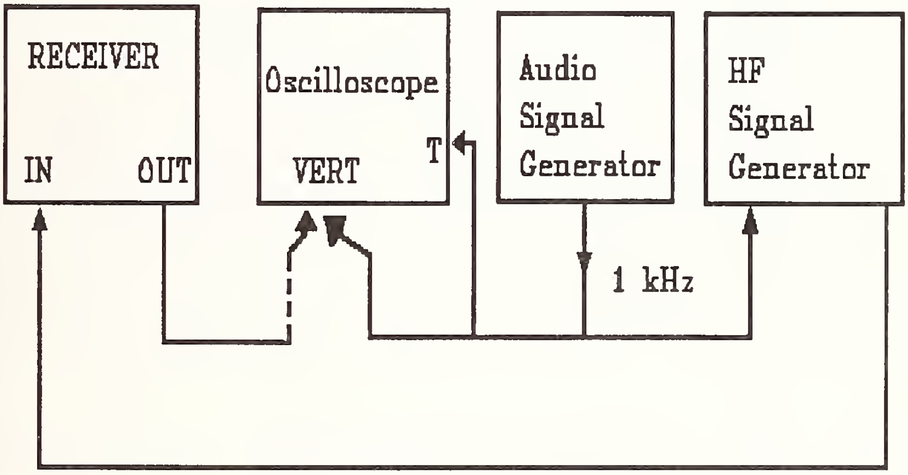
- *Make measurements at the same time every day.*
- *Avoid twilight hours, when the ionosphere is the least stable.*
- *Use the highest frequency that has good reception.*
- *Look at the received signals on the oscilloscope for a few minutes to judge the stability of propagation conditions.*

Measuring the Receiver Time Delay

For accuracy in time-setting, the receiver delay must be known. Typical delays in receiver circuits are usually less than a millisecond. However, they should be known to the user who wants the very best timing accuracy. The actual delay in the receiver will vary with tuning and knob settings.

To measure the receiver time delay, the following equipment is required (connected as shown in the diagram):

- *an oscilloscope with a calibrated, externally triggered time base*
- *an HF signal generator*
- *an audio signal generator*

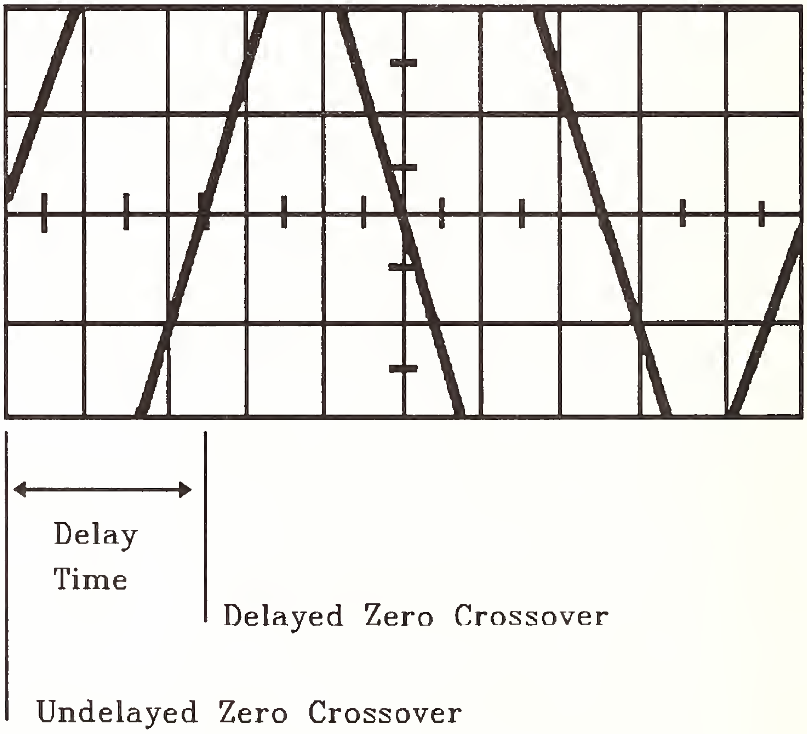


Equipment Setup for Receiver Time–Delay Measurements

The receiver should be tuned to receive WWV/WWVH signals. This is because the receiver delay time varies with slightly different receiver dial positions. Therefore, the receiver tuning should be set and marked where the maximum signal is received. The frequency of the HF signal generator is then adjusted for peak receiver output.

The audio signal generator is set to a 1-kHz output frequency. An accurate 1-kHz signal is not required. The HF generator is externally modulated by the 1-kHz signal. The oscilloscope sweep rate is set to 100 microseconds per division with positive external triggering from the 1-kHz signal. The vertical amplifier gain is set high for a large vertical deflection. The vertical position control is adjusted for zero baseline with no input signal.

Initially, the 1-kHz signal generator is connected to the vertical input of the oscilloscope. The trigger level is adjusted so that the trace crosses or touches the horizontal center line at the left. The horizontal position can be adjusted so that the signal crosses the first division on the left as shown below. The crossover point of the undelayed signal will serve as the zero delay reference point.



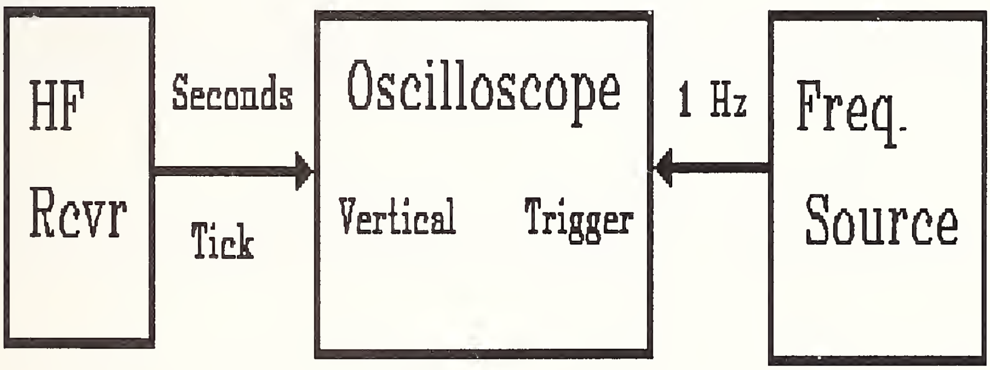
Without touching any of the oscilloscope controls, disconnect the 1-kHz signal from the vertical input and replace it with the delayed 1-kHz signal from the receiver output. Since a receiver delay is almost always less than 1 millisecond (1 cycle of a 1-kHz signal), there is little chance of ambiguity on which cycle to measure. The delay is equal to the sweep time from the reference undelayed crossover to the first delayed crossover point.

If the delayed signal's phase is the opposite of the reference 1-kHz signal, the receiver has an inverted output signal. However, the receiver delay time remains unchanged, and the only difference will be that the output seconds pulse will be inverted with a negative leading edge. For receiver delays of less than 500 microseconds, the sweep rate can be 50 microseconds per division.

This technique produces a local signal that approximates the timing signal. It uses the same frequency on the dial and uses the same tone frequency. If you have a two-channel scope, you can display the tone before it enters the RF signal generator and after it comes out of the receiver.

Using an Adjustable Frequency Source to Trigger the Oscilloscope

This method (sometimes called the direct trigger method) requires an oscilloscope with an external sweep trigger and accurately calibrated time base, and a receiver with electronic audio output. The frequency source (clock) must be adjustable so its 1-pps output can be advanced or retarded. Connect the equipment as shown:



A 1-Hz pulse from the frequency source is used to trigger the oscilloscope sweep. At some time interval later during the sweep, the seconds tick appears on the oscilloscope display. The time interval from the start of the sweep to the point where the tick appears is the total time difference between the local clock and the transmitting station. By subtracting the path and receiver time delays from the measured value, the local clock time error can be determined (path delays are discussed on page 85). The equation to determine time error at a receiving location is shown on the next page.

TIME ERROR = TR - TT = TD - (PPD + RTD)

where: *TR* = *time at receiving station*

TT = *time at transmitting station (WWV, WWVH)*

TD = *total time difference (measured using oscilloscope)*

PPD = *propagation path time delay (computed)*

RTD = *receiver time delay (measured)*

Note: The units (usually milliseconds) should be the same for all terms.

Tune the receiver to the station and set the oscilloscope sweep rate to 0.1 second per division. You can listen to the broadcast to check the quality of reception. The tick will then appear on the oscilloscope display. If the tick is one division or more from the left side of the scope display, adjust the time of the local clock until the tick falls within the first division from the left side. If the local time tick is late, the received tick will be heard before the sweep starts. If this is the case, adjust the local clock until the tick appears.

After the local seconds pulse has been properly adjusted and appears within the first division (0.1 second in time), increase the sweep rate. Then adjust the clock again until the leading edge of the received pulse starts at a time equal to the propagation delay time plus the receiver delay time after the trigger.

The sweep rate should be increased to the highest rate possible. However, the total sweep time should not exceed the combined propagation and receiver delay time minus 5 milliseconds (to allow for the length of the received seconds pulse).

With a sweep rate of 1 millisecond per division, for example, greater resolution can be realized by measuring the second zero crossover point of the 5 millisecond received ticks. Although the leading edge of the seconds pulse as broadcast from these stations is "on time," it is difficult to measure due to the slow rise time at the beginning of the burst and distortion due to propagation. For this reason, the second zero crossover should be used. The second zero crossover of the WWV or CHU pulse is delayed exactly 1000 microseconds, and the WWVH crossover is delayed 833 microseconds. The delay is called the cycle correction.

At a sweep rate of 1 millisecond per division, any changes in arrival time (jitter) are readily apparent. After watching the pulses for a period of a minute or two, select a cycle that is undistorted and relatively large in amplitude. In determining the time at a receiving location, include the delay of the chosen zero crossover point, then add the cycle correction to the propagation and equipment delay using the following equation:

TIME ERROR = TR - TT

= TD - (PPD + RTD + cycle correction)

where: *TR* = *time at receiving station*

TT = *time at transmitting station (WWV, WWVH)*

TD = *total time difference (measured using oscilloscope)*

PPD = *propagation path time delay (computed)*

RTD = *receiver time delay (measured)*

Cycle correction = *1000 microseconds per cycle (WWV or CHU)*
= *833 microseconds per cycle (WWVH)*

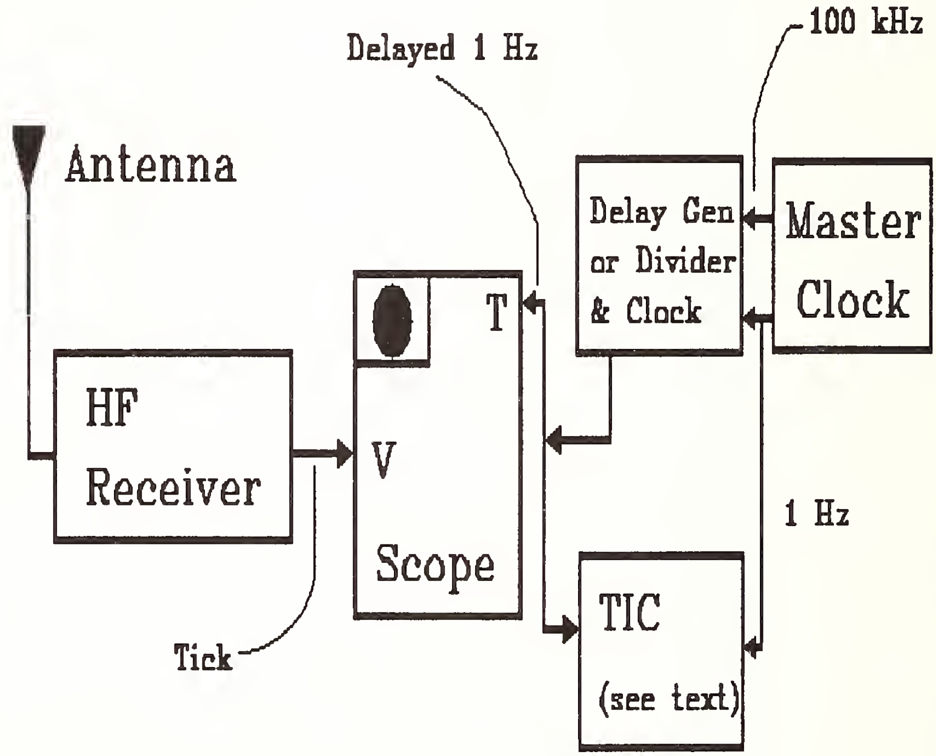
Delayed Triggering: An Alternate Method That Doesn't Change the Clock Output

To improve the resolution of measurement, the oscilloscope sweep must be operated as fast as possible. You can sweep the scope faster by generating a trigger pulse independent of your clock and then positioning the pulse for maximum sweep speed. However, you then must measure the difference between the clock and the trigger pulse. This can be accomplished by using an oscilloscope with a delayed sweep circuit built in or with an outboard trigger generator. The latter method is discussed here, but an oscilloscope with a delayed sweep could also be used. Refer to the instrument manual for assistance.

On a typical digital delay generator, a delay dial indicates the delay between the input local clock tick and the output trigger pulse. If the user already has a variable rate divider to produce delayed pulses, a time interval counter can be used instead of the delay generator. In either case, the trigger delay must be accounted for in measuring the time delay (TD) of the received tick with respect to the local master clock.

Measurements should be made at the same time every day (within 10 minutes) for consistent results. Choose the time of day when it is approximately noon midway between the transmitting station and the receiver's location. For night measurements, choose a time when the midpoint is near midnight. Do not make measurements near twilight.

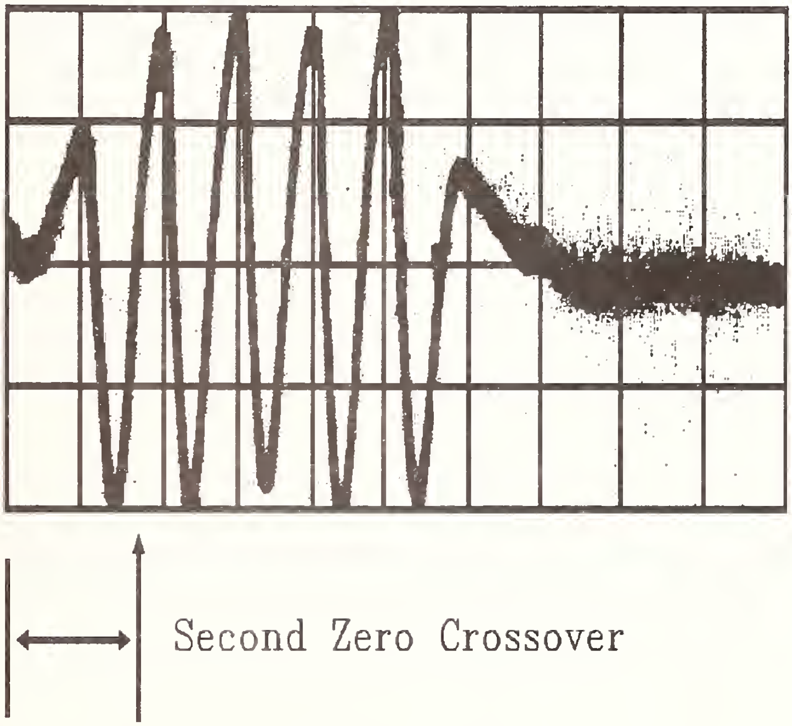
Connect the equipment as shown below. A commercially available frequency divider and clock can be used in place of the controlled delay generator. A time interval counter is then used to measure the output of the delayed clock to the master clock. The output of the delayed clock is used to trigger the oscilloscope. The procedures described previously also apply to this method.



With the oscilloscope sweep adjusted to 1 millisecond per division, the trigger pulse should be delayed by an amount equal to the propagation delay in milliseconds. Don't worry about fractional milliseconds in the delay. The sweep should be adjusted so that it begins exactly at the left end of the horizontal graticule and is vertically centered.

The second zero crossover point of the tick (see figure on next page) should be observed and carefully measured. With the sweep at 1 millisecond per division, the delay of the second zero crossover on the oscilloscope is measured to the nearest one-tenth of a millisecond and added to the trigger delay, resulting in an approximate total time delay.

If the local clock 1-pps time is exactly coincident with the UTC(NIST) seconds pulse, the total measured time delay will be approximately equal to the sum of the propagation delay time, the receiver delay time (typically 200 to 500 microseconds), and the cycle correction (1000 microseconds for WWV or CHU and 833 microseconds for WWVH).



To further increase the resolution of delay measurement, increase the oscilloscope sweep rate to 100 microseconds per division and adjust the trigger pulse from the generator to be approximately 500 microseconds less than the total delay time previously measured. At these settings, the second zero crossover of the tick will be somewhere near the middle of the oscilloscope face.

The vertical centering of the sweep should be rechecked and centered if necessary. The tick is measured to the nearest 10 microseconds. The result should be within ± 100 microseconds of the result obtained at the 1 millisecond per division sweep rate. If the result of this measurement falls outside this tolerance, then the procedure should be repeated by measuring the time delay at a sweep rate of 1 millisecond per division. Use the equations on pages 74-75 to obtain the time.

Using Oscilloscope Photography for Greater Measurement Accuracy

By photographing five or more overlapping exposures of the WWV/WWVH tick, you can estimate an average of the tick arrival time with more accuracy. The exposures are made when consistently strong and undistorted ticks appear on the oscilloscope. To determine the time, the average of the second zero crossover point of the tick is measured using the procedure described previously.

To make measurements using this technique, you need an oscilloscope camera that uses self-developing film. Place the camera shutter in the time exposure position so that it can be opened and closed manually. The lens opening of the camera, the oscilloscope trace intensity, and the scale illumination must be determined by experiment. Refer to your camera manual.

One of the previously described procedures is followed to obtain the seconds tick. At a sweep rate of 1 millisecond per division, the shutter is opened before the sweep starts and closed after the sweep ends. This is repeated each second until five overlapping exposures are completed. The pictures should be taken when the ticks begin to arrive with the least distortion and maximum amplitude.

This procedure can also be used at a faster sweep rate of 100 microseconds per division with the second zero crossover point appearing in the middle of the trace (one complete cycle of the tick should be visible). By taking overlapping exposures of the ticks, you can obtain an average reading from the photograph.

USING THE WWV/WWVH TIME CODE

The broadcasts from WWV and WWVH include a time code. The time code signal is 100 Hz away from the main carrier and is called a subcarrier. The code pulses are sent out once per second. With a good signal from a fairly high-quality receiver, you can hear the time code as a low rumble in the audio. HF receivers that receive and decode this signal can automatically display the time of day. The next section describes the time code format.

Time Code Format

The WWV and WWVH time code is continuously broadcast in binary coded decimal (BCD) format on a 100-Hz subcarrier. The time code is a modified version of the IRIG-H code. The code is transmitted serially on a 100-Hz subcarrier at a rate of one pulse per second.

The time code is in binary coded decimal (BCD) format. Groups of binary digits (bits) are used to represent decimal numbers. The binary-to-decimal weighting scheme is 1-2-4-8. The least significant bit is always sent first. The table below shows the BCD groups and the equivalent decimal number:

BINARY GROUP Weight: 1 2 4 8	DECIMAL EQUIVALENT
0 0 0 0	0
1 0 0 0	1
0 1 0 0	2
1 1 0 0	3
0 0 1 0	4
1 0 1 0	5
0 1 1 0	6
1 1 1 0	7
0 0 0 1	8
1 0 0 1	9

The decimal number is obtained by multiplying each bit in the binary group by the weight of its respective column and then adding the four products together. For example, the table shows that the binary group 1010 is equal to 5. This is derived by:

$$(1 \times 1) + (0 \times 2) + (1 \times 4) + (0 \times 8) = 1 + 0 + 4 + 0 = 5$$

In the standard IRIG-H code, a 0 bit consists of exactly 20 cycles of 100-Hz amplitude modulation (200 milliseconds duration), and a 1 bit consists of 50 cycles of 100 Hz (500 milliseconds duration). The WWV/WWVH code differs from IRIG-H because all tones are suppressed briefly while the seconds pulses are transmitted.

Tone suppression also deletes the first 30 milliseconds of each binary pulse in the time code. This makes the WWV/WWVH bits 30 milliseconds shorter than the IRIG-H bits. Therefore, 170 millisecond pulses are recognized as 0 bits, and 470 millisecond pulses are recognized as 1 bits. The leading edge of each pulse coincides with the positive-going crossing of the 100-Hz subcarrier; but due to the tone suppression, it occurs 30 milliseconds after the start of the second.

Within 1 minute, enough bits are sent to express the minute, hour, and day of year, the UT1 correction, and a Daylight Saving Time (DST) indicator. The coded time information refers to the time at the start of the 1-minute frame. Seconds are determined by counting pulses within the frame. Two BCD groups are needed to express the hour (00 to 23) and minute (00 to 59); and three groups are needed to express the day of year (001 to 366). Some bits in the BCD groups are unused, but may provide additional information in the future. To represent units, tens, or hundreds, the basic 1-2-4-8 weights are multiplied by 1, 10, or 100, as appropriate.

Each frame begins with a unique spacing of pulses that mark the start of a new minute. During the first second of the minute, no pulse is transmitted. This creates a 1-second (1000-millisecond) hole. Since the pulses are already delayed 30 milliseconds by the tone suppression, the UTC minute actually begins 1030 milliseconds (1.03 seconds) earlier than the first pulse in the frame. For synchronization purposes, a position identifier pulse is transmitted every 10 seconds. The position identifier pulse lasts for 770 milliseconds (77 cycles of 100 Hz).

UT1 corrections are sent during the final 10 seconds of each frame. These corrections are to the nearest 0.1 second. The UT1 correction is expressed with bits called control functions. Control function #1 occurs at 50 seconds and tells whether the UT1 correction is negative or positive. If a 0 bit is sent, the correction is negative; if a 1 bit is sent, the correction is positive. Control functions #7, #8, and #9 tell the amount of the UT1 correction. They occur at 56, 57, and 58 seconds, respectively. Since the UT1 corrections are in tenths of seconds, the binary-to-decimal weights are multiplied by 0.1.

DST information is sent by control function #6, at 55 seconds. If DST is in effect, a 1 bit is sent. If Standard Time is in effect, a 0 is sent. The setting of this bit is changed a few hours prior to 0000 UTC on the date of change. This schedule notifies users in the continental United States of the time change several hours before it occurs locally (usually at 2:00 a.m.). Receivers that display local time can read control function #6 and make the 1-hour adjustment automatically when time changes occur.

Additional changes to the WWV/WWVH time code formats are planned for implementation during early 1991. These involve addition of two digits of the current year, a leap second warning indicator, and improved indicators of Daylight Saving Time. Contact NIST for current status information regarding these changes.

USING HF BROADCASTS FOR FREQUENCY CALIBRATIONS

In addition to the widely used time service of WWV and WWVH, standard frequencies are also available to the broadcast listener. Both stations provide a calibrating frequency that is readily available for comparison and measurement.

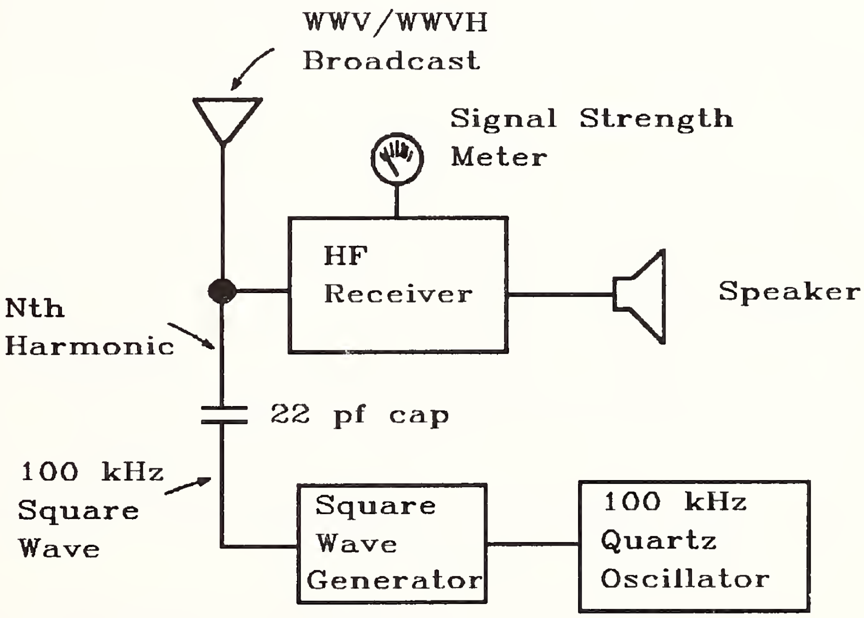
There are two ways to use WWV (or WWVH) as a standard frequency. You can measure your own frequency source against WWV and write the difference down for reference, or you can adjust your frequency source to make it agree with WWV.

In this section, several calibration methods are discussed. These methods use WWV-type signals to calibrate lower accuracy quartz oscillators. Under good conditions, relative frequencies of 1.00E-07 are possible. Direct frequency comparison or measurement with WWV can usually be accomplished to about 1.00E-06. This resolution can be improved by long-term (many weeks) time comparison of clocks operated from a frequency source rather than direct frequency comparison. Three methods of calibrating frequency sources using the broadcasts of WWV/WWVH are discussed: (1) beat frequency method; (2) oscilloscope pattern drift method; and (3) frequency calibrations by time comparisons.

Beat Frequency Method

The beat frequency or heterodyne method is a simple technique commonly used by radio operators to calibrate transmitters and tune receivers. A frequency offset of about 1.00E-06 can be accurately determined. This means that this method can be used to calibrate a 1-MHz signal to within 1 Hz.

The figure below shows an arrangement for calibrating a 100-kHz oscillator. A 100-kHz signal containing harmonics is coupled to the receiver input along with the WWV signal from the antenna.



Equipment Setup for
Beat Frequency Method

The beat frequency method works by heterodyning or mixing a known and accurate frequency (like a WWV RF signal) with the output of an oscillator. The mixing is accomplished by the converter circuit in any superheterodyne receiver. The difference frequency of the two RF signals can be amplified and detected. The result is an audio output signal called the beat frequency or beat note.

The frequency of the beat note is the difference of the two input frequencies. When the two frequencies are made equal, their difference decreases to zero and is called "zero beat." When zero beat is reached, the oscillator is equal in frequency to the WWV frequency.

To calibrate a frequency source or quartz oscillator with an output frequency lower than that broadcast by WWV, the correct harmonic equal to the WWV signal is required. For example, if a 100-kHz signal is to be calibrated with the WWV 5-MHz carrier frequency, then it must also contain a harmonic 50 times itself. This means that the signal to be calibrated has to be a submultiple of the WWV carrier frequency.

Theoretically, a sine wave does not contain any harmonics. In practice, though, all sine wave signals contain enough harmonics to produce a beat note. A square wave signal, on the other hand, is very rich in harmonic content and is ideal for generating harmonics to calibrate receivers and transmitters in the HF and VHF band. A simple method of generating a square wave from a sine wave is by clipping the signal with a diode clipping circuit. To obtain a strong harmonic signal for beat notes requires a large amplitude signal to produce heavy clipping. A better method is to digitally condition the 100-kHz signal to produce square waves.

If the receiver input impedance is low (50 to 100 ohms), a 10- to 20-picofarad (pF) capacitor can be used to couple the high frequency harmonic to the receiver input and to reduce the level of the lower fundamental frequency. If the receiver has a high input impedance with unshielded lead-in wire from the antenna, the harmonic signal can be loosely coupled to the receiver input by wrapping a few turns of an insulated wire around the antenna lead-in and connecting it directly to the output of the oscillator. For receivers with built-in or whip antennas, you must experiment to find a way to inject the oscillator signal.

The relationship between the oscillator error and the beat note that is measured during the calibration looks like this:

```
f(actual) = f(nameplate) + delta-f
```

The actual oscillator output is designated as f(actual). This is made up of two parts, the correct frequency f(nameplate), plus an error that we can designate as delta-f.

When we make our measurement, a harmonic of f(actual) is beat against the carrier frequency, f(carrier). The resulting beat note f(beat) is the difference between the two and is written as:

$$f(\text{beat}) = f(\text{carrier}) - \text{harmonic of } f(\text{actual})$$

A negative sign in the answer is ignored, so the answer is always a positive number. To find the frequency error, delta-f, we divide f(beat) by the number of the harmonic (N):

$$\text{delta-f} = \frac{f(\text{beat})}{N}$$

For example, if a beat frequency of 100 Hz is measured between the WWV 5-MHz carrier frequency and the 50th harmonic of a 100-kHz oscillator signal, the frequency error of the 100-kHz signal is:

$$\text{delta-f} = \frac{100 \text{ Hz}}{50} = 2 \text{ Hz}$$

The oscillator frequency is in error by 2 Hz. The relative frequency of the oscillator is 2 parts in 100 000 or 2.00E-05. To determine whether the oscillator is high or low in frequency, the oscillator frequency must be changed to note which way the beat frequency decreases. If increasing the oscillator frequency decreases the beat note, it indicates that the oscillator frequency is lower than the WWV/WWVH frequency.

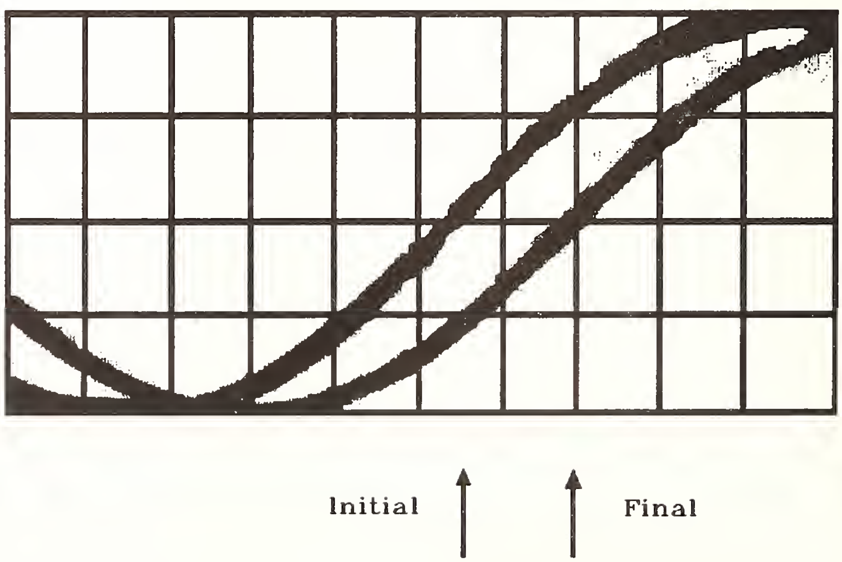
If the beat note is above 50 Hz, headphones, a speaker, or a counter can be used. Below that frequency, a dc oscilloscope can be connected to the receiver detector. A signal strength meter can be used and the beats counted visually. The automatic gain control (AGC) should be disabled, if possible, for the meter fluctuations to be more noticeable. The manual RF gain can be adjusted to compensate for loss of the AGC.

To correct the oscillator frequency, turn the adjustment knob in the direction that lowers the frequency of the beat note. Between 50 Hz and about 1 Hz, the beat note cannot be heard, and the signal strength meter will begin to respond to the beat note as it approaches 1 Hz. As zero beat is approached, a very slow rise and fall of the background noise or the WWV audio tone can also be heard on the speaker. The meter effect is much easier to follow. As it approaches zero beat, the very slow rise and fall of the signal strength may sometimes become difficult to distinguish from signal fading due to propagation effects.

Oscilloscope Pattern Drift Method

The oscilloscope pattern drift method is good for comparing two frequencies if you have an oscilloscope with external triggering. The method requires an oscilloscope with an accurately calibrated sweep time base. External triggering is obtained from the signal to be calibrated. This signal can be any integer submultiple of the tone being received from WWV/WWVH. The receiver (tuned to WWV or WWVH) has its audio output connected to the vertical input of the oscilloscope. With the sweep rate set at 1 millisecond per division, the trigger level is adjusted so that a zero crossover of the corresponding 600- or 500-Hz signal is near midscale on the scope.

By measuring the phase drift during a given time interval, the frequency error is determined. If the zero crossover from the oscillator being measured moves to the right, the oscillator is higher in frequency than the WWV signal, and if it moves to the left, the oscillator is lower in frequency (see figure below). Under ideal conditions, a relative frequency of 1.00E-06 can be determined by increasing the observation time.



Frequency Calibrations by Time Comparisons

If you are already making daily time calibrations using WWV or WWVH, you can use the data you obtain to make frequency calibrations of the oscillator driving your clock. You can do this by recording the daily time differences and then calculating the frequency rate. The operation is similar to telling your jeweler that your watch gains or loses so many seconds a day. He then adjusts the rate to compensate.

The operation proceeds something like this. Each day, note the amount the clock output differs from WWV. Then keep an accurate record of the history of the oscillator in terms of the time gained or lost with respect to WWV ticks. This change in time can then be converted to the relative frequency of your oscillator. See chapter 4 for more information on the mathematics involved.

In summary, frequency calibrations can be made by recording only the time error produced by an oscillator. This technique is recommended for lower quality oscillators and for situations when you are already making time calibrations.

MEASURING RADIO PATH DELAY

Measuring radio path delay involves two things. First, the great circle (curved) distance must be found between the transmitter and receiver. A simple computer program to accomplish this (written in BASIC) is listed below. This program calculates the great circle distance between any two points on the earth.

```
' Great Circle Distance Program (written in BASIC)

' function to convert radians to degrees
def fnRadToDegrees(x) = x/57.2957795131
' function to calculate the arccosine of a number
def fnArcCos(x) = ((-atn(x/sqr(-x*x+1)) + 1.5707633)*57.2957795131)

cls                         ' clear the screen
dim pointa(6)               ' array for point A coordinates
dim pointb(6)               ' array for point B coordinates

print "This program calculates the distance and the path delay between"
print "points A and B.  You must enter the coordinates for both points."
print
print "Enter Coordinates for Point A"
print
input "Is the Latitude in Degrees North (Y or N, Default is Y): ", q1$
input "Is the Longitude in Degrees West (Y or N, Default is N): ", q2$
if q1$<>"n" and q1$<>"N" then NorthA=-1 else NorthA=0
```

```
print
input "Latitude Degrees:  ", pointa(1)
input "Latitude Minutes:  ", pointa(2)
input "Latitude Seconds:  ", pointa(3)
input "Longitude Degrees: ", pointa(4)
input "Longitude Minutes: ", pointa(5)
input "Longitude Seconds: ", pointa(6)

' reduce latitude and longitude of Point A to two floating point numbers
y1=pointa(1)+(pointa(2)*60+pointa(3))/3600
y2=pointa(4)+(pointa(5)*60+pointa(6))/3600
y1=fnRadtoDegrees(y1)                              ' Point A latitude
y2=fnRadtoDegrees(y2)                              ' Point A longitude
if q2$="N" or q2$="n" then y2=fnRadtoDegrees(360)-y2    ' adjust longitude if in eastern hemisphere

print
print "Enter Coordinates for Point B"
print
input "Is the Latitude in Degrees North (Y or N, Default is Y): ", q1$
input "Is the Longitude in Degrees West (Y or N, Default is N): ", q2$
if q1$<>"n" and q1$<>"N" then NorthB=-1 else NorthB=0
print
input "Latitude Degrees:  ", pointb(1)
input "Latitude Minutes:  ", pointb(2)
input "Latitude Seconds:  ", pointb(3)
input "Longitude Degrees: ", pointb(4)
input "Longitude Minutes: ", pointb(5)
input "Longitude Seconds: ", pointb(6)

' reduce latitude and longitude of Point B to two floating point numbers
z1=pointb(1)+(pointb(2)*60+pointb(3))/3600
z2=pointb(4)+(pointb(5)*60+pointb(6))/3600
z1=fnRadtoDegrees(z1)                              ' Point B latitude
z2=fnRadtoDegrees(z2)                              ' Point B longitude
if q2$="N" or q2$="n" then z2=fnRadtoDegrees(360)-z2    ' adjust longitude if in eastern hemisphere

p=cos(abs(y2-z2))              ' cosine of difference in longitude between points A and B
y3=sin(y1)                     ' sine of   Point A latitude
y4=cos(y1)                     ' cosine of Point A latitude
z3=sin(z1)                     ' sine of   Point B latitude
z4=cos(z1)                     ' cosine of Point B latitude

if NorthA<>NorthB then         ' points are on opposite sides of equator
    c=y4*z4*p-y3*z3
else
    c=y4*z4*p+y3*z3            ' points are on same side of equator
end if

c=fnArcCos(c)                  ' distance in nautical miles
miles=c*60*1.151               ' distance in miles
kilos=c*60*1.8522              ' distance in kilometers
pathdelay=miles*5.376344086    ' path delay in microseconds
print
print
print "Distance in Miles:             ";miles
print "Distance in Kilometers:        ";kilos
print "Path Delay in Microseconds:  ";pathdelay
end
```

The second thing we need to know is the number of times the signal bounces from the ionosphere to the Earth (hops). This factor is part of the propagation delay that the signal experiences along its path. The computer program we just looked at estimates the path delay, but does not take propagation delay into account. For groundwave signals transmitted at low frequencies (like those discussed in chapter 6), this estimate is probably very accurate. However, for HF signals it probably isn't. The reason for this is that at any particular time, the path delay may not be at its average value. Since the path is constantly changing by small amounts, it cannot be estimated with great accuracy.

Knowing the exact number of hops between the Earth and ionosphere is important; otherwise, estimates of path delay can be off by 500 to 1000 microseconds (0.5 to 1 millisecond). If you are trying to make time calibrations to within 1 millisecond, you need more accurate estimates of the path delay.

The ionosphere is made up of a number of layers whose actual height varies both daily and seasonally. This changes the path delay a lot if the receiver and transmitter are close to each other. Since the Earth is round, there is a maximum ground distance a single hop can span. This is about 4000 kilometers or 2200 miles. For greater distances, the radio waves must obviously be reflected a number of times. Any error in the wave path computation for one hop must be multiplied by the total numbers of hops.

To reduce the error in estimating the path delay, the frequency used for reception should be selected for the least number of hops. This should also result in a stronger signal. Some frequencies will penetrate the ionosphere and not reflect. Other frequencies will skip over your receiving site, so a lower frequency must be selected. Use of the maximum frequency that is receivable assures the least number of hops. This maximum usable frequency is called the MUF. A frequency about 10 percent below the MUF provides the best reception.

For distances under 1600 kilometers (1000 miles), the single-hop mode of transmission dominates. For short distances, the height must be estimated carefully. For distances of less than 1600 kilometers, where only a single-hop mode of transmission occurs, a much wider range of error in the height can be tolerated.

Errors can be reduced by estimating height according to time of day, season, latitude, and sunspot cycle. An average height of 250 kilometers is reasonable for the winter months when propagation conditions are good at 10 MHz and above. In summer, the average height can be increased to 350 kilometers. In the fall, the estimated height can be decreased again. Using this method can reduce the error.

For distances of 1600 to 3200 kilometers (1000 to 2000 miles) where multiple-hop transmission occurs, the height must be determined with greater accuracy. Heights for a particular latitude, longitude, and time of day are available from the World Data Center, NOAA, Department of Commerce, Boulder, CO 80303.

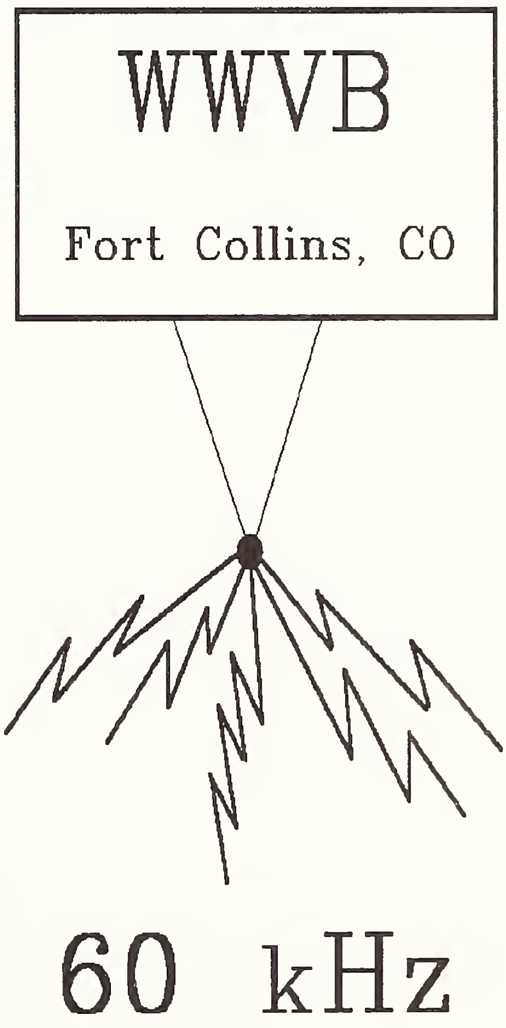
SUMMARY

High Frequency (HF) radio broadcasts are commonly used for time and frequency calibrations. Accuracies ranging from 1 millisecond for time calibrations to 1.00E-07 for frequency calibrations can be obtained. If your accuracy requirements are higher, you should use one of the radio broadcasts discussed in the next two chapters.

Chapter 6 - CALIBRATIONS USING LF AND VLF RADIO BROADCASTS

Along with the widely used high frequency broadcasts discussed in chapter 5, NIST also operates a frequency and time service on WWVB, a low frequency (LF) radio station. WWVB is on the WWV site in Ft. Collins, Colorado. WWVB continuously broadcasts time and frequency signals at 60 kHz for the continental United States.

WWVB operates at 60 kHz to take advantage of the stable radio paths in that frequency range. Both frequency and time signals are provided, but no voice transmissions are made due to the narrow bandwidth of the transmitter/antenna combination. Many countries have services in this band, which ranges from 30 to 300 kHz, as well as in the VLF (very low frequency) band from 3 to 30 kHz. In addition to discussing the use of WWVB, this chapter also covers other LF and VLF stations, including the 100-kHz Loran-C broadcasts.



It may seem unusual to send signals in a frequency band that is almost in the audio range, and these signals pose some special problems for the transmitter and receiver design engineers. However, low frequencies such as the 60-kHz signal of WWVB are used because of their remarkable stability. Radio waves at low frequencies use the Earth and the ionosphere as a waveguide and follow the Earth's curvature for long distances. Accuracies of 1.00E-11 or better for frequency and 500 microseconds for time can be achieved by using LF or VLF broadcasts. Users can do even better with Loran-C.

GENERAL INFORMATION ABOUT LF AND VLF STATIONS

The following sections contain some general information about LF and VLF time and frequency broadcasts.

LF and VLF Antennas

Using a quarter-wavelength antenna to receive LF and VLF signals is obviously impossible; at 60 kHz, this antenna would have to be about 2 miles long! As a compromise, antennas that are electrically "short" are used with tuning boxes and special couplers. On vertical antennas, top loading is often used. This consists of radial wires extending from the top of the antenna to the ground. Of course, as with any antenna system, a good ground is essential.

The physical location of LF and VLF antennas is important. The location affects signal strength and noise. Keep the antenna away from metal objects. Long-wire antennas should be at least 15 to 20 feet above ground. Several commercial antennas use preamplifiers so the connecting coaxial cable supplies power to the amplifier. In those cases, care must be taken to avoid shorting the cable.

Manufacturers of VLF-LF radio receivers offer a variety of antenna types. Long-wire antennas up to several hundred feet are available. Whip antennas 8 to 10 feet long are used where space is a problem. On the other hand, air loop antennas are able to reject interference but do not have as much gain as whips. Ferrite loop antennas are often smaller than the air loops.

All of these antennas benefit from having couplers and/or amplifiers incorporated into the antenna structure to allow a match to be made with the shielded antenna cable. For more information about LF and VLF antennas, consult an engineering handbook or an antenna manual.

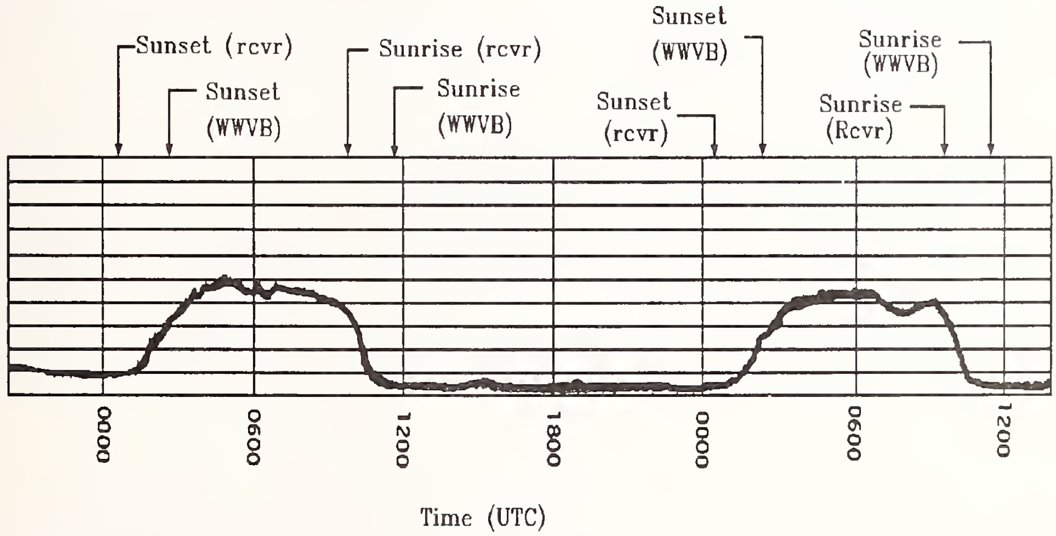
Signal Formats

WWVB transmits a carrier for frequency information and changes the level (-10 decibels (dB)) of that carrier to transmit a binary time code. The Omega Navigation System sends only the carrier. The Loran-C navigation system transmits pulses. Receivers for all of these signals usually "lock" onto the carrier and thus recover frequency information. In addition, some means are provided to hear the station. This is usually just a tone output. For example, if you were to listen to WWVB, you would hear the 1-second code segments as a tone that changes from loud to soft. There are no voice signals on any of the LF or VLF stations. The bandwidth used cannot transmit voice signals.

Propagation Characteristics and Other Phase Changes

Phase records made of VLF and LF stations show phase shifts caused by the daily and seasonal changes along the radio path. These phase shifts occur when sunrise or sunset occur on the path from the transmitter to receiver. For instance, as the path is changing from all darkness to all daylight, the ionosphere lowers. This shortens the path from transmitter to receiver. This shortened path causes the received phase to advance. This phase advance continues until the entire path is in sunlight. The phase then stabilizes until either the transmitter or receiver enters darkness. When this happens, the ionosphere begins to rise, causing a phase retardation.

A strip chart recording of the phase of WWVB is shown below. The chart shows the signal from WWVB being compared to a very stable oscillator, so the phase shifts can be attributed to WWVB and not the oscillator. The phase shifts that take place at sunrise and sunset can be easily seen. The magnitude of the change is a function of the path length, and the rate of the change is a function of the path direction.



Phase of WWVB as received in the eastern United States (chart is 50 microseconds wide)

A phase recording from a stable VLF or LF radio station contains a great deal of information. The user's job is to sort out this information so that he can understand what is happening to the frequency source that is being calibrated. Most stations operate with a nearly perfect record, but mistakes can happen. This happens just often enough so that the user needs additional information. This information consists of monthly or weekly notices of the actual phase of the signal (measured in microseconds). NIST publishes data for WWVB, and the U.S. Naval Observatory (USNO) publishes data for a number of LF and VLF stations. This information is free upon request.

Do not rush through LF or VLF calibrations. Certain practices are highly recommended. Be careful when you adjust the receiver. Once it is working properly, do not change knob settings or cabling. Always operate the equipment continuously, if possible. This gives you a continuous chart record so that you know when to expect sunrise/sunset phase shifts. You can also detect local interference and noise conditions. If your receiver has a mechanical phase counter, jot down the readings on the chart. This is a great help in trying to reconstruct events that happen on weekends or at night.

A typical occurrence for a tracking receiver is the cycle phase shift. Since the receiver is faithfully following a zero crossing of the received phase, it doesn't know which of the thousands of crossings it is locked to. If the receiver loses lock, it will simply go to the next crossing that comes along. On a phase chart this will show up as a phase shift equal to one cycle of the carrier.

For the 60-kHz WWVB signal, one cycle of phase equals 16.167 microseconds. If the chart recorder/receiver combination is producing a chart that is 50 microseconds wide (see the chart on the previous page), the pen will move about one-third of the way across the chart for each cycle change. You need to identify and ignore these phase shifts when making calibrations. Keep in mind that phase charts are ambiguous by an amount equal to the period of one cycle of the carrier frequency.

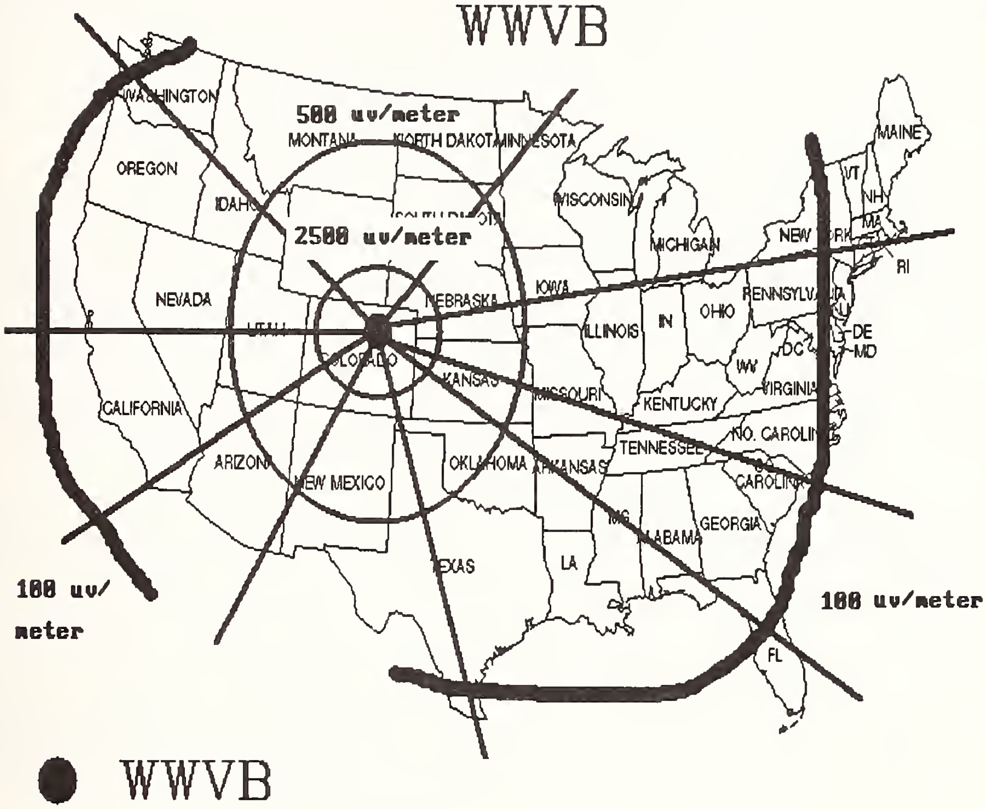
How can you tell whether the recorded phase difference indicates a change in your oscillator, the path, or the transmitted signal? The answer is that you must know from experience. If you plan to use VLF or LF signals for frequency calibrations, you must become very familiar with the characteristics of the signals you are using. Battery backup for receivers is highly desirable, in fact, almost necessary if you plan to calibrate precise oscillators over a period of many days. All of this may sound difficult, but it really isn't. The results are worth the effort when you consider that you can perform calibrations up to 1.00E-11 in 24 hours.

Field Strengths of LF and VLF Stations

The field strength of the WWVB signal has been measured along nine radial paths from the station. These measurements are summarized on the field contour map shown on the next page. The map does not show the nonlinear field gradient between the 500- and 100-microvolt per meter contour.

Destructive interference occurs between the first hop skywave and the groundwave at approximately 1200 kilometers (750 miles) from the station. On some radial paths, this dip in field intensity is quite severe and will cause signal loss at certain times. The distance between the station and this null varies from day to night. It is also seasonal. The sharpness of the null is much less pronounced in the winter. In general, the signal should be stronger during the winter months.

Measured Field Strength of WWVB



Monitoring Station Availability

No matter which station is chosen as a basis for calibration, WWVB, Omega, or VLF, you should be on a mailing list to receive notices of changes in operation schedule. WWVB currently operates 24 hours a day, every day. No changes in operating format are made without advance notification. The Omega stations do schedule maintenance outages and other changes in operation. Announcements regarding the status of the various Omega stations in the Omega Navigation System are given hourly on both WWV and WWVH.

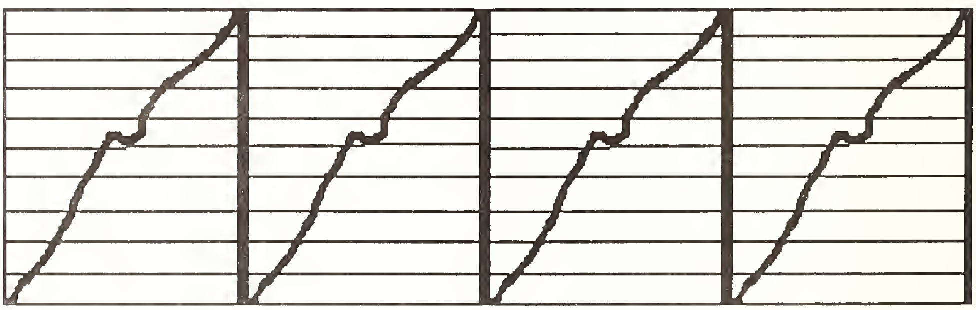
Currently, NIST and the USNO are monitoring and reporting the phase differences of some of the U.S. Loran-C stations. In addition, NIST monitors and reports phase differences for WWVB, and the USNO offers data on the VLF and Omega stations. These data are available to interested users by contacting the Time and Frequency Division of NIST or the USNO.

FREQUENCY CALIBRATIONS USING WWVB

Commercially available WWVB receivers are often used to compare a local oscillator with the received WWVB signals. These receivers are often complete frequency measurement systems like the one shown on page 45. WWVB serves as the reference frequency for these systems. They may include a built-in chart recorder that shows the phase change of the oscillator being measured relative to the WWVB signal. This type of system is discussed in this section. If it meets your needs, WWVB can also be used as the reference frequency in a computer-controlled measurement system like the one shown on page 46.

The phase change depends on the relative difference between your oscillator and the cesium oscillator controlling the WWVB signal at the transmitter. If a precision oscillator (like a rubidium or cesium) is being used, most of the phase changes are caused by WWVB. For example, in the chart shown on page 91, the phase shifts are due to the diurnal effect, or the rise and fall of the Sun along the radio path between the transmitter and the receiver. During the daytime and nighttime, WWVB serves as a very stable reference frequency with a relative frequency of about 1.00E-11.

If you use a WWVB receiver to compare a lower quality oscillator, the diurnal phase shifts will be less noticeable. For example, if your oscillator is performing at a relative frequency of 1.00E-08, it is drifting about 1000 microseconds (1 millisecond) per day. With this much drift, the diurnal phase shifts may not be noticeable at all. However, the chart recording may be difficult to interpret. If you are using a chart record that is 50 microseconds wide, the chart will "overflow" nearly once an hour. This means that the pen on the chart recorder will drop from the top of the chart back to the bottom and start over. The result will be a jagged record like the one shown below:



On low-quality oscillators you may want to increase the chart width as much as possible (to 100 microseconds, for example). On higher quality oscillators you may want to decrease the chart width to show more resolution. You can also vary the speed of the chart recorder. You need to study the manuals for the receiver and chart recorder so that you can produce charts that are easy to interpret and that suit your calibration needs.

When you use WWVB for frequency calibrations, remember that the signal started out at the transmitter as a nearly perfect frequency source. By the time it arrives as your receiver, it has been altered by diurnal phase shifts, and noise along the radio path. If you know what to look for, you can interpret the chart recordings obtained from your receiver and measure the performance of your oscillator at accuracies as high as 1.00E-11.

Computing Relative Frequency from a WWVB Chart Recording

There are two ways to compute relative frequency from a VLF or LF plot. You can take the slope of the daytime portion of the plot (the straight portion), or you can take the time difference between two discrete points 1 day apart. This second method is easier to use. For example, after comparing your oscillator to your WWVB receiver for over 24 hours, you can select one point on the chart that was recorded during the daytime (to avoid diurnal phase shifts). You can then take the difference between this point and a point recorded 24 hours later. For the purposes of our example, let's say that this difference is 25 microseconds, or one-half the width of a typical chart.

Since WWVB is the reference frequency, the 25-microsecond phase shift is attributed to the oscillator being tested. The number of microseconds in a 24-hour period is shown below:

86 400 000 000

Since the oscillator moved 25 microseconds, we can say that its relative frequency is equal to 25 parts in 86 400 000 000 parts, or:

$$\frac{25}{86\,400\,000\,000}$$

This number represents the relative frequency of the oscillator under test. Since the number is so small, we use scientific notation:

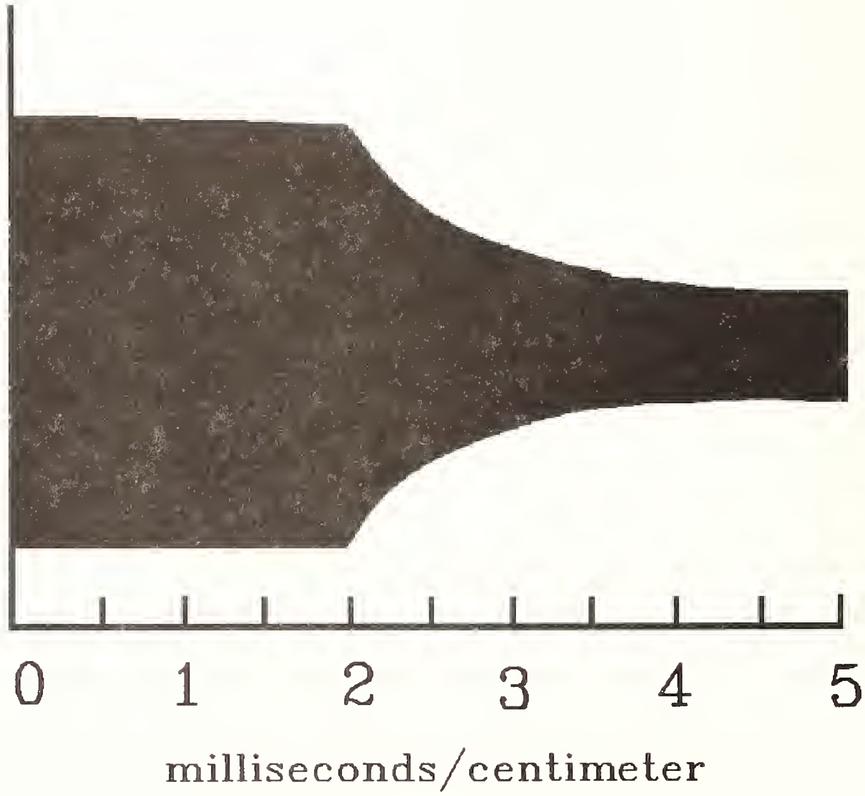
2.89E-10

If you use the slope of the daytime phase to compute relative frequency, you need to account for cycle jumps and transmitter phase shifts. On days when the radio propagation is poor or the signal is noisy, it may not be possible to get an accurate relative frequency reading for that day. For more information on relative frequency and what it means, see chapter 4.

TIME CALIBRATIONS USING WWVB

Like the high frequency stations WWV and WWVH, WWVB also broadcasts a time code. There are three ways to use the time code. The first (and most expensive) way is to use a WWVB receiver that automatically decodes and displays the time. There are a number of manufacturers that produce this type of equipment. A second way is to use a receiver with internal logic circuits that provide a level shift code output. This code may be applied directly to a strip chart or to an oscilloscope for manual use. And finally, the simplest way is to observe the amplified signal using a tuned radio frequency receiver and an oscilloscope.

The illustration below shows the signal envelope as seen on an oscilloscope at the transmitter with a scale of 5 milliseconds per centimeter. The on-time point is easily seen. With the horizontal scale of the oscilloscope expanded to 200 microseconds per centimeter, the on-time point can be determined to within about ±2 cycles of the 60-kHz carrier. Of course, the farther the receiving site is from the transmitter, the more the signal-to-noise ratio degrades until some averaging techniques must be employed. Since the WWVB data rate is only one bit per second, visual integration is very difficult, especially when the horizontal scale is expanded to allow greater time resolution. Averaging or signal integration using a signal averager or an oscilloscope camera works quite well at remote receiving locations.



The actual process of time recovery consists of viewing the signal envelope on an oscilloscope that is being triggered by a local clock at the receiving site. Having previously determined the path delay, its value can be subtracted from the total observed delay on the oscilloscope to obtain the local clock error.

In very noisy locations, where the on-time point is difficult to identify, a photograph of the waveform can be helpful. Sometimes it is advantageous to allow a number of oscilloscope traces to be exposed on the same piece of film. This has an averaging effect that simplifies the location of the on-time point. However, a single exposure can be used. Take the photo and draw one horizontal line through the average of the waveform amplitude and another line along the average slope of the dropout. The intersection of these lines is the on-time point.

Receiving sites that are long distances from the transmitter have an added problem when high resolution timing is desired. If the delay to the receiver site is, say, 15 milliseconds and the sweep speed is set to 1 millisecond per centimeter, the on-time point of the envelope will be off the oscilloscope face.

This problem can be solved if a second clock is available. The second clock can be adjusted late so that when used for the oscilloscope trigger source, the on-time point will be near the beginning of the trace. The sweepspeed can now be increased to obtain the desired resolution. The time intervals to be accounted for are the time between the beginning of the trace and the on-time point, and the interval between the local clock and the second clock. The local clock error is:

Local Clock Error = D - delta(tc) - delta(to)

where: D is the propagation delay

delta(tc) is the interval between the two clocks

delta(to) is the trace delay on the oscilloscope

If the local clock error is positive, then the local clock pulse occurs after the transmitted time pulse. If the local clock error is negative, then the local clock pulse occurs before the transmitted time pulse.

Format of the WWVB Time Code

WWVB transmits a special time code that provides time information. This service is used by seismologists, standards labs, commercial power companies, and others interested in synchronization with accuracies of the order of 500 microseconds. The code provides year, day, hour, and minute information. Seconds are resolved by counting bits. A correction, applied to the transmitted time to obtain Earth time, UT1, is also provided for use by some astronomers and navigators. Other code bits provide information about Daylight Saving Time, leap years, and leap seconds.

Unlike a code that is designed primarily for machine decoding, the WWVB code was originally designed to be manually decoded from strip chart recordings or tapes. To simplify this process for a human decoder, the most significant bit occurs first in each code word. The actual bit, whether a binary zero, binary one, or position identifier, is determined by the duration of the power reduction of the transmitter carrier.

The WWVB time code is synchronized with the 60-kHz carrier and is broadcast continuously at a rate of one pulse per second. The time code is sent in binary coded decimal (BCD) format. Bits are sent by shifting the power of the 60-kHz carrier. The carrier power is reduced 10 dB at the start of each second. If full power is restored 200 milliseconds later, it represents a 0 bit. If full power is restored 500 milliseconds later, it represents a 1 bit. Reference markers and position identifiers are sent by restoring full power 800 milliseconds later.

The time code is in binary coded decimal (BCD) format. Groups of binary digits (bits) are used to represent decimal numbers. The binary-to-decimal weighting scheme is 8-4-2-1. The most significant bit is always sent first. This is the reverse of the WWV/WWVH time code. The table below shows the BCD groups and their decimal equivalent:

BINARY GROUP Weight: 8 4 2 1	DECIMAL EQUIVALENT
0 0 0 0	0
0 0 0 1	1
0 0 1 0	2
0 0 1 1	3
0 1 0 0	4
0 1 0 1	5
0 1 1 0	6
0 1 1 1	7
1 0 0 0	8
1 0 0 1	9

The decimal number is obtained by multiplying each bit in the binary group by the weight of its respective column and then adding the four products together. For example, the table shows that the binary group 0101 is equal to 5. This is derived by:

$$(0 \times 8) + (1 \times 4) + (0 \times 2) + (1 \times 1) = 0 + 4 + 0 + 1 = 5$$

Every minute, the WWVB time code sends the current minute, hour, day of year, and year; a UT1 correction, and Daylight Saving Time (DST), leap second, and leap year indicators. Two BCD groups are needed to express the hour (00 to 23) and minute (00 to 59); and three groups are needed to express the day of year (001 to 366). To represent units, tens, or hundreds, the basic 8-4-2-1 weights are simply multiplied by 1, 10, or 100 as appropriate. The coded information refers to the time at the start of the one-minute frame. Seconds are determined by counting pulses within the frame.

Each minute begins with a frame reference pulse lasting for 0.8 second. A position identifier pulse lasting for 0.8 second is transmitted every 10 seconds.

UT1 corrections are broadcast at seconds 36 through 44 of each frame. These corrections are to the nearest 0.1 second. The bits transmitted at 36, 37, and 38 seconds show whether UT1 is positive or negative with respect to UTC. If 1 bits are sent at seconds 36 and 38, the UT1 correction is positive. If a 1 bit is sent at second 37, the UT1 correction is negative. The amount of the UT1 correction is sent in a 4-bit BCD group at 40, 41, 42, and 43 seconds. The binary-to-decimal weights are multiplied by 0.1, because the UT1 corrections are expressed in tenths of seconds. Information about tens of year is sent in seconds 45 through 48, and units of year information are sent in seconds 50 through 53.

The WWVB time code also contains information about leap years, leap seconds, and DST. The leap year bit is transmitted at 55 seconds. If it is set to 1, then the current year is a leap year. The bit is set to 1 during each leap year sometime after January 1 but before February 29. It is set back to 0 shortly after January 1 of the year following the leap year. Receivers that read this bit can automatically adjust themselves during leap years. Receivers can also automatically adjust themselves for leap seconds, by reading the leap second warning bit transmitted at 56 seconds into the frame.

Two DST bits are sent at 57 and 58 seconds. Using two bits allows a receiver that is turned on during a time change day to set its time correctly. Bit 57 changes from 0 to 1 at 0000 UTC on the day of the change from standard time to DST. Exactly 24 hours later, bit 58 also changes from 0 to 1. On the day of change back to standard time, bit 57 will go from 1 to 0 at 0000 UTC, followed exactly 24 hours later by bit 58. During all other days both bits will be 0 or 1, depending on whether standard time or DST is in effect.

FREQUENCY CALIBRATIONS USING THE OMEGA NAVIGATION SYSTEM

The Omega Navigation System consists of eight VLF radio stations operating in the 10- to 14-kHz range. The eight stations are listed below:

Omega Navigation System Stations					
Call Sign	Location	Power (kW)	Carrier (kHz)	Days/ Week	Hours/ Day
Omega A	Alda, Norway	10	11.05 - F 10.20 - A 11.33 - C 13.60 - B	7	24
Omega B	Monrovia, Liberia	10	11.05 - G 10.20 - B 11.33 - D 13.60 - C	7	24
Omega C	Haiku, Oahu, Hawaii	10	11.05 - H 10.20 - C 11.33 - E 13.60 - D	7	24
Omega D	La Moure, North Dakota	10	11.05 - A 10.20 - D 11.33 - F 13.60 - E	7	24
Omega E	La Reunion	10	11.05 - B 10.20 - E 11.33 - G 13.60 - F	7	24
Omega F	Golfo Nuevo, Argentina	10	11.05 - C 10.20 - F 11.33 - H 13.60 - G	7	24
Omega G	Woodside, Victoria, Australia	10	11.05 - D 10.20 - G 11.33 - A 13.60 - H	7	24
Omega H	Tsushima Islands, Japan	10	11.05 - E 10.20 - H 11.33 - B 13.60 - A	7	24

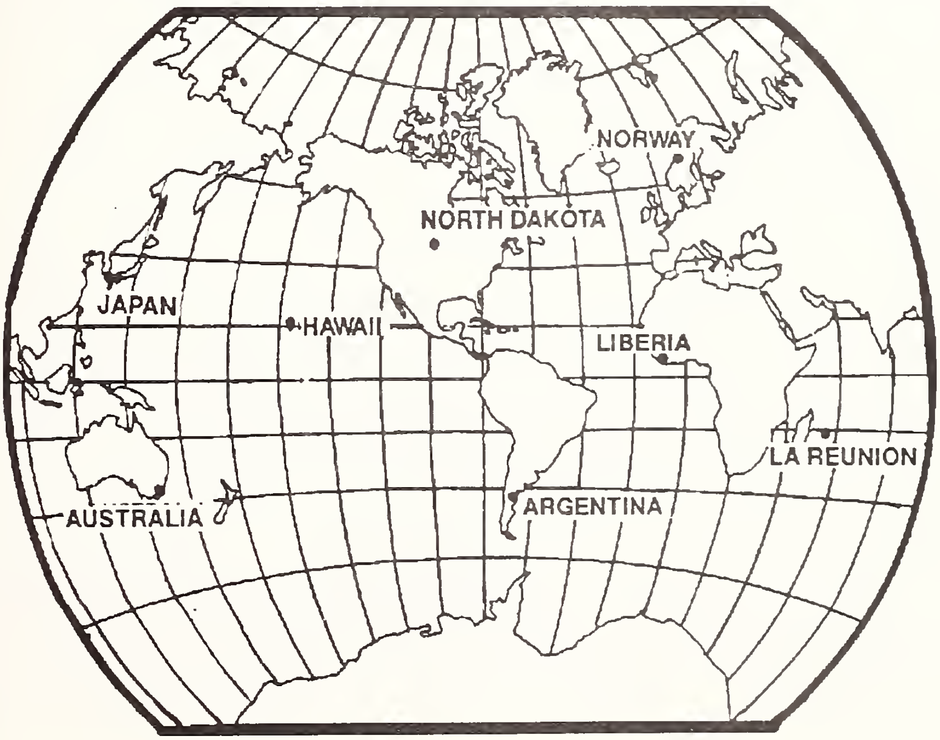
If you decide to use an Omega signal for frequency calibrations, a phase-tracking receiver is recommended. If one of the navigation frequencies is to be used, then an Omega commutator must also be used. This is a device that turns the phase-tracking receiver on and off at the proper times to receive only the desired Omega station.

The frequencies and the format segments of the Omega stations are referenced to cesium beam oscillators, so the transmissions are very stable. The USNO monitors and reports the daily phase values for each Omega station. NIST radio stations WWV and WWVH (see chapter 5) each broadcast a 40-second message describing the current status of the Omega Navigation System. This message is broadcast at 16 minutes after the hour on WWV and at 47 minutes after the hour on WWVH.

Operating Characteristics of Omega

The eight Omega stations transmit in the internationally allocated VLF navigational band between 10 and 14 kHz. Since the Omega stations transmit at a very low frequency and at a high power (10 kilowatts), it is possible to receive at least one Omega station just about anywhere in the world. In some remote locations, Omega might be the only signal available for frequency calibrations. The map below shows the location of the eight Omega stations.

Location of Omega Stations



Each Omega station transmits on four common navigational frequencies (10.2, 11.05, 11.33, and 13.6 kHz) and one unique frequency (from 11.8 to 13.1 kHz) using an omnidirectional antenna. In order to prevent interference, transmissions from each station are time-sequenced in an eight-segment frame as shown in the figure below. Each station uses one channel of the frame for each of the four common frequencies, and four segments for its unique frequency. The unique frequencies for each station are marked with an asterisk. The unique frequency is normally used for frequency calibrations.

Station	Segments with Frequencies in kHz							
	1	2	3	4	5	6	7	8
Norway	10.02	13.60	11.33	12.1*	12.1*	11.05	12.1*	12.1*
Liberia	12.0*	10.20	13.60	11.33	12.0*	12.0*	11.05	12.0*
Hawaii	11.8*	11.8*	10.20	13.60	11.33	11.8*	11.8*	11.05
North Dakota	11.05	13.1*	13.1*	10.20	13.60	11.33	13.1*	13.1*
La Reunion	12.3*	11.05	12.3*	12.3*	10.20	13.60	11.33	12.3*
Argentina	12.9*	12.9*	11.05	12.9*	12.9*	10.20	13.60	11.33
Australia	11.33	13.0*	13.0*	11.05	13.0*	13.0*	10.20	13.60
Japan	13.60	11.33	12.8*	12.8*	11.05	12.8*	12.8*	10.20

* unique frequency

The Omega signal pattern is arranged so that only four stations transmit on the navigational frequencies during each segment. Since no stations broadcast on the same frequency at the same time, each individual station can be identified. The length of each segment varies from 0.9 to 1.2 seconds, and there is a 0.2-second silent interval between segments. The entire signal pattern repeats itself every 10 seconds.

All Omega transmitting stations are synchronized by means of very stable cesium beam frequency standards. The synchronization of all transmissions is tightly controlled, and the phase relationships between all signals are maintained to within a fraction of a cycle. Although the signals are highly stable as transmitted, you need to be aware of the propagation characteristics of Omega before you use the signals for frequency calibrations. These characteristics are discussed in the next section.

Propagation Characteristics of Omega

The same characteristics that allow Omega signals to be received at great distances also limit their accuracy. Since Omega signals are propagated between the Earth and the ionosphere, the propagation parameters change as a result of changes in the Earth or ionosphere. If you use Omega for frequency calibrations, you need to be aware of several types of phase shifts that might show up in your data.

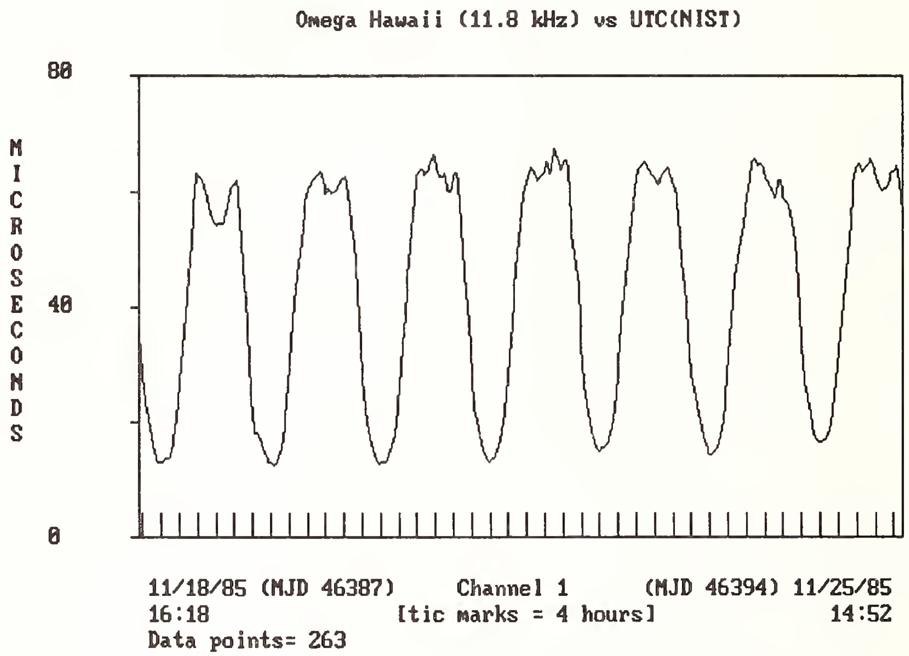
The most common type of Omega phase shift is due to the diurnal effect. Like WWVB signals (page 91), Omega signals are subject to diurnal phase shifts due to the rise and fall of the Sun along the radio path. However, since these diurnal phase shifts are highly repeatable, it is possible to predict when they will occur and to correct for them during calibrations.

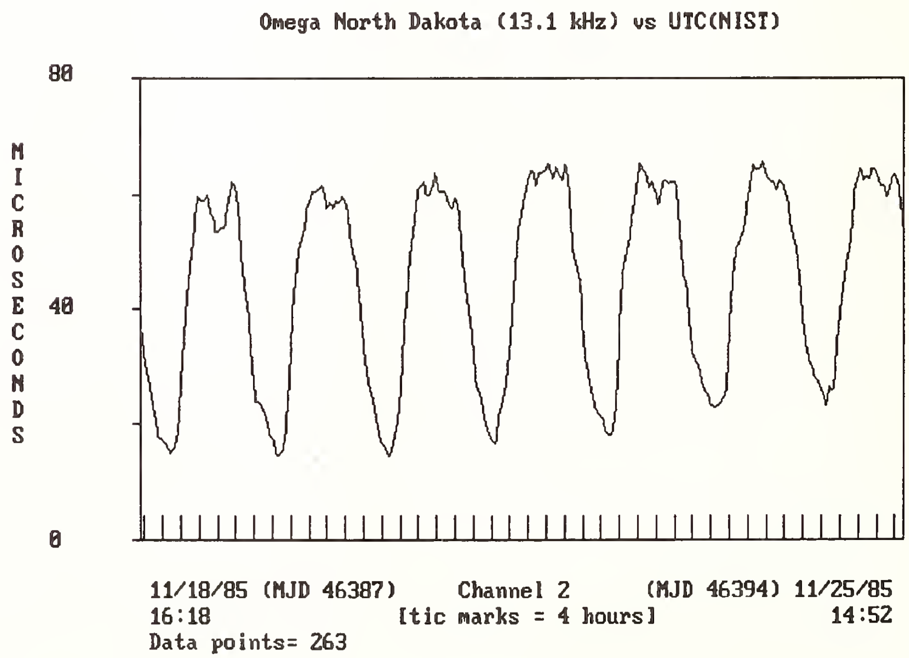
Unpredictable short-term variations may also occur. Ninety-five percent of the time, these are small variations related to random propagational variations which will not degrade the signal's accuracy. Occasionally, however, large disturbances can occur as a result of solar emission of ray or particle bursts. The emission of rays from the Sun occasionally causes a short-term disruption of Omega signals; this is called a Sudden Phase Anomaly (SPA). The duration of a SPA is generally not greater than 1 hour, but it can cause a large phase shift. A SPA can occur as often as 7-10 times per month. It usually affects signals from only a few stations at a time since rays from the Sun usually enter only part of the illuminated portion of the Earth's surface.

The Omega phase can also be shifted by a Polar Cap Disturbance (PCD). A PCD occurs when a large quantity of protons are released from the Sun. Although an infrequent occurrence, a PCD might shift the phase of an Omega signal for a period of several days. However, a PCD only affects those transmissions involving arctic propagation paths. Because of their possible long duration, PCD notices are broadcast as navigational warning messages on WWV and WWVH (see page 101).

Modal interference is another form of signal interference. It occurs when the Omega signal propagates in different ways over the radio path, and the various propagation modes interfere with each other (the groundwave interferes with the skywave, for example). Under ideal conditions, one mode would be dominant at all times, and the received phase from Omega would be regular. However, in practice, the competing modes do not completely disappear. The worst thing that can happen with modal interference is a situation where the modal dominance changes. An example of this is a situation where one mode is dominant during the day and a second mode is dominant at night. During the transitional period between day and night, the two modes are equal, and abnormal transitions may occur in which cycles are "slipped" or lost.

The plots below show the phase of Omega as received at NIST in Boulder, Colorado, and compared to the national frequency standard over a 1-week period (7 days). The first plot shows the 11.8-kHz signal from Hawaii, and the second plot shows the 13.1-kHz signal from North Dakota. The plots show that the Omega signals are stable and the diurnal phase shifts are predictable. The plot of the Hawaii signal demonstrates that Omega signals are usable over a very long radio path (several thousand miles).





OTHER LF AND VLF TIME AND FREQUENCY STATIONS

There are a number of other LF and VLF time and frequency stations located around the world. Information about many of these stations is listed in the table below and on the next page.

LF and VLF Time and Frequency Stations					
Call Sign	Location	Power (kW)	Carrier (kHz)	Days/ Week	Hours/ Day
DCF77	Mainflingen, Germany	20	77.50	7	24
GBR	Rugby, United Kingdom	60	15.95 16.00	7	22
HBG	Prangins, Switzerland	20	75.00	7	24
JJF-2 JG2AS	Sanwa, Sashima, Ibaraki, Japan	10	40.00	7	24
MSF	Rugby, United Kingdom	25	60.00	7	24
NAA	Cutler, Maine United States	1000	24.00	7	24
NCA	Aguada, Puerto Rico	100	28.50	7	24
NTD	Yoshima, Japan	50	17.40	7	24
NLK	Jim Creek, Washington, United States	125	24.80	7	24
NPM	Lualualei, Hawaii, United States	600	23.40	7	24
NSS	Annapolis, Maryland, United States	400	21.40	7	24

LF and VLF Time and Frequency Stations					
Call Sign	Location	Power (kW)	Carrier (kHz)	Days/ Week	Hours/ Day
NWC	NW Cape, Australia	1000	22.30	7	24
OMA	Liblice, Czechoslovakia	5	50.00	7	24
RBU	Moskva, USSR	10	66.67	7	24
RTZ	Irkutsk, USSR	10	50.00	7	23
RW-166	Irkutsk, USSR	40	200.00	7	23
RW-76	Novosibirsk, USSR	150	272.00	7	22
UNW3	Molodechno, USSR	---	25.50, 25.10 25.00, 23.00 20.50	7	2
UPD8	Arkhangelsk, USSR	---	25.50, 25.10 25.00, 23.00 20.50	7	2
UQC3	Khabarovsk, USSR	300	25.50, 25.10 25.00, 23.00 20.50	7	2
USB2	Frunze, USSR	---	25.50, 25.10 25.00, 23.00 20.50	7	3
UTR3	Gorky, USSR	300	25.50, 25.10 25.00, 23.00 20.50	7	2

TIME AND FREQUENCY CALIBRATIONS USING LORAN-C

As we discussed in chapter 4, radio signals from Loran-C can make an excellent reference frequency for calibrations. The success of Loran-C signals is due to a number of things. Each station broadcasts 24 hours a day, 7 days a week. Each station is controlled by cesium standards, and the signals are carefully monitored and controlled by the U.S. Coast Guard, NIST, and the U.S. Naval Observatory (USNO). Loran-C groundwave signals provide state-of-the-art frequency and time calibrations. Even the skywave signals, though slightly less accurate, can become the basis of excellent high-quality calibrations. And since many Loran-C transmitters exist, the signals are usable just about anywhere in the northern hemisphere.

Like Omega, Loran-C is a radio navigation system (Loran is an acronym for LOng RAnge Navigation). All Loran-C stations broadcast on a frequency of 100 kHz, using a bandwidth from 90 to 110 kHz. At this low frequency, the radio waves follow the Earth's curvature and are not subjected to the large diurnal phase shifts that occur with signals from WWVB or Omega.

The Loran-C navigation system consists of many synchronized "chains" or networks of stations. These chains provide groundwave coverage of most of the United States, Canada, Europe, the North Atlantic, the islands of the Central and West Pacific, the Philippines, and Japan. Each chain has one master station (designated as M), and from two to four slave stations (designated as W, X, Y, and Z). Information about each Loran-C chain is listed below and on the next two pages. This information lists all of the chains being monitored by the USNO at the time of this writing, but new stations are continually being added. For the exact status of the Loran-C system, please contact the U.S. Coast Guard.

Loran-C Time and Frequency Stations

Chain	Stations		Power (kW)
4990	Johnston Island, Hawaii, USA	M	275
	Upolu Point, Hawaii, USA	X	275
	Kure Island, Hawaii, USA	Y	275
5930	Caribou, Maine, USA	M	350
	Nantucket Island, Mass., USA	X	275
	Cape Race, Newfoundland, Canada	Y	1500
	Fox Harbour, Labrador, Canada	Z	800
5990	Williams Lake, BC, Canada	M	400
	Shoal Cove, Alaska, USA	X	540
	George, Washington, USA	Y	1600
	Port Hardy, BC, Canada	Z	400

Loran-C Time and Frequency Stations			
Chain	Stations		Power (kW)
7930	Fox Harbour, Labrador, Canada	M	800
	Cape Race, Newfoundland, Canada	W	1500
	Angissoq, Greenland	X	760
7960	Tok, Alaska, USA	M	540
	Narrow Cape, Alaska, USA	X	400
	Shoal Cove, Alaska, USA	Y	540
7970	Ejde, Faeroe Islands, Denmark	M	325
	Sylt, Germany	W	325
	Boe, Norway	X	165
	Sandur, Iceland	Y	1500
	Jan Mayen, Norway	Z	165
7980	Malone, Florida, USA	M	800
	Grangeville, Louisiana, USA	W	800
	Raymondville, Texas, USA	X	400
	Jupiter, Florida, USA	Y	275
	Carolina Beach, N. Carolina, USA	Z	550
7990	Sellia Marina, Italy	M	165
	Lampedusa, Italy	X	325
	Kargabarun, Turkey	Y	165
	Estartit, Spain	Z	165
8970	Dana, Indiana, USA	M	400
	Malone, Florida, USA	W	800
	Seneca, New York, USA	X	800
	Baudette, Minnesota, USA	Y	800
9940	Fallon, Nevada, USA	M	400
	George, Washington, USA	W	1600
	Middleton, California, USA	X	400
	Searchlight, Nevada, USA	Y	540
9960	Seneca, New York, USA	M	800
	Caribou, Maine, USA	W	350
	Nantucket Island, Mass., USA	X	275
	Carolina Beach, N. Carolina, USA	Y	550
	Dana, Indiana, USA	Z	400

Loran-C Time and Frequency Stations			
Chain	Stations		Power (kW)
9970	Iwo Jima, Japan	M	1800
	Marcus Island, Japan	W	1800
	Hokkaido, Japan	X	1000
	Gesashi, Japan	Y	1000
	Yap, Caroline Island	Z	1000
9980	Sandur, Iceland	M	1500
	Angissoq, Greenland	W	760
	Ejde, Faeroe Island, Denmark	X	325
9990	St. Paul, Alaska, USA	M	275
	Attu, Alaska, USA	X	275
	Point Clarence, Alaska, USA	Y	1000
	Narrow Cape, Alaska, USA	Z	400

The master station in a Loran-C chain transmits groups of pulses that are received by the slave stations. The slave stations receive the master pulse groups, and then transmit similar groups of synchronized pulses.

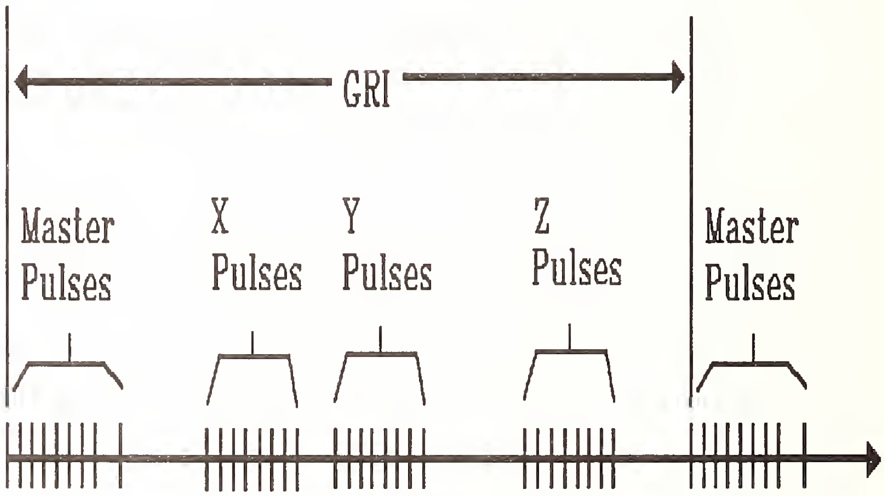
When Loran-C is used to navigate, the constant time differences between the reception of the master pulses and the slave pulses are used to determine a line of position (LOP). Determining an LOP requires receiving signals from three separate Loran-C transmitters (the master and at least two slaves). However, for frequency and time applications, you only need to receive one Loran-C station. This station can be either a master or a slave, although some receivers require the master station to be received before the slaves can be identified.

Format of Loran-C Broadcasts

All Loran-C stations broadcast on the same carrier frequency (100 kHz). Because of this, a Loran-C receiver has to distinguish between signals broadcast from a number of different transmitters.

Each Loran-C chain is identified by a unique Group Repetition Interval (GRI). The length of the GRI is fixed, and each chain is named according to its GRI (divided by 10). For example, the 7980 chain has a GRI of 79 800 microseconds. This means that every 79 800 microseconds (or about 12 times per second) every station in the chain transmits a group of pulses. The GRI must be long enough for each station in the chain to transmit its pulses and to accommodate for spacing between the pulses. Enough time must be included between the pulses so that signals from two or more stations cannot overlap in time anywhere in the coverage area. Therefore, the minimum GRI is determined by the number of stations in the chain, and by the distance between the stations. Possible GRI values range from 40 000 microseconds to 99 990 microseconds.

Once a Loran-C chain has been identified, the stations within the chain can also be identified by looking at the pulses. The master station sends its pulses first. The master transmits 8 pulses separated by a 1000-microsecond delay. Then 2000 microseconds after the 8th pulse, a 9th pulse is sent. The 9th pulse is used to identify the master station. The slave stations then send their pulses in turn. For example, if a chain has three slave stations (X, Y, and Z), they send their pulses in order. X goes first, then Y, then Z. Each slave station transmits 8 pulses separated by a 1000-microsecond delay. The figure below illustrates the way Loran-C pulses are transmitted.



Loran station identification is also aided by separately phase-coding the master and slave pulses. Each group of pulses is coded by a phase reversal process which enables the receiver to eliminate certain types of interference. All these subtle differences in transmission pulse rates make Loran-C receivers fairly complex. If you have a manual Loran-C receiver, you need to know many of the details of the broadcast format before you can acquire and track a Loran-C signal. However, some Loran-C receivers are now completely automatic. If you key in the GRI, these receivers will acquire and track the desired stations in just a few seconds.

Loran-C Reception

Radio energy from each Loran-C transmitter radiates in all directions. A portion of the energy travels out from each transmitting station parallel to the surface of the Earth. This is the groundwave.

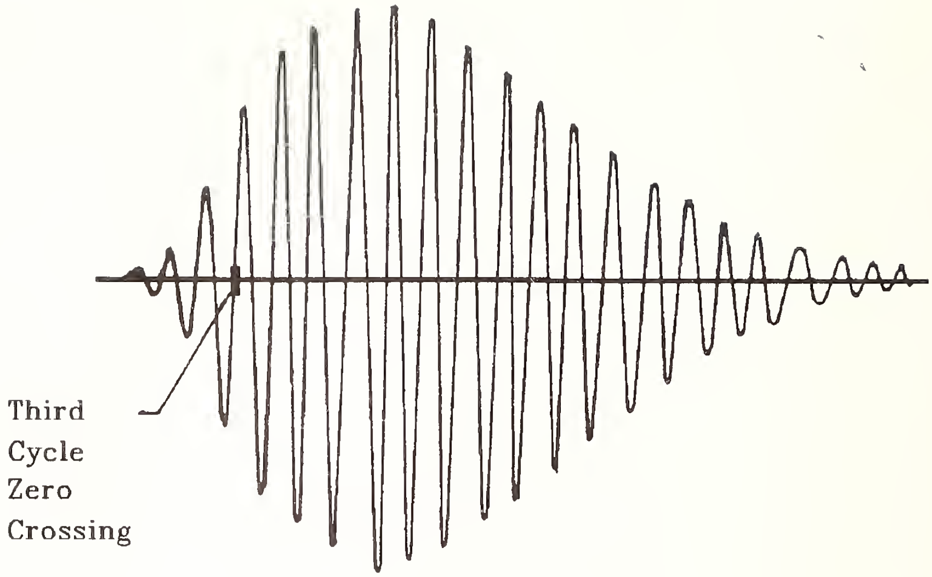
Useful Loran-C groundwave coverage extends from approximately 2400 to 3200 kilometers (1500 to 2000 miles). During periods of good reception, this range may be greater; and during periods of high noise and interference, it may be less. However, with typical noise and interference levels, 2400 kilometers (1500 miles) is a good estimate of the *reliable* groundwave range of Loran-C signals from a station transmitting 300 kilowatts.

Part of the Loran radio signal radiates upward from the transmitting antenna and is reflected from the electrified layer of the atmosphere known as the ionosphere. This signal is called the skywave. If the groundwave signal has traveled a long distance, it will be reduced in amplitude and weakened. The receiver will pick up both the groundwave and the skywave signals. The receiver cannot easily lock to the groundwave because it is weak and noisy, so it will lock to the skywave signal.

Receiving the skywave is less desirable than receiving the groundwave. This is because the skywave signal "moves" around, since it is reflected off the ionosphere. This movement is caused by the motion of the ionosphere due to the rise and fall of the Sun. If you are receiving skywave signals from Loran-C, you may see diurnal phase shifts in your data, similar to those (although smaller in magnitude) from WWVB (page 91) or Omega (page 104).

Receiving the skywave signals isn't all bad, however. Because the skywave signals are stronger than groundwave signals at great distances, skywave lock-on is possible at distances beyond where the groundwave signals can be received. And although the skywave moves around, it does so in a predictable way. With good recordkeeping, the Loran-C skywaves can yield very good time and frequency data.

Part of the reason that Loran-C transmits pulses is so that the receiver can distinguish between groundwave and skywave signals. The accuracy of the system is based on the fact that the early part of the pulse (the part that leaves the transmitter first) will travel along the ground and arrive before the less stable skywave pulse that bounces off the ionosphere. By determining what cycle of the pulse is being tracked, you can tell if you are tracking a skywave or a groundwave. Many receivers track the third cycle of the pulse. The third cycle arrives early enough to be groundwave but has enough amplitude for the signal to be strong. A picture of a Loran-C pulse with the third cycle identified is shown on the next page. The shape of the pulse makes it possible for a receiver to identify one particular cycle of a 100-kHz carrier, and to stay locked to that cycle.



Getting Time From Loran-C

Loran-C pulses are very stable and can be used as the frequency source for a very accurate clock. Loran-C does not have a time code, and the clock must originally be set to the correct time (UTC), using a time signal from WWV (chapter 5) or some other source. However, once the clock is set, the Loran-C pulses should keep the clock accurate to within 10 microseconds or better.

If you use Loran-C pulses to drive a clock, you must remember that the interval between pulses (the GRI) is not an even multiple of 1 second. For example, the stations in the Loran 7980 chain transmit their pulses every 79 800 microseconds, or a little more than 12 times per second. In order to get time from Loran-C, you need to know the time of coincidence (TOC) when the Loran pulse coincides with a 1 second pulse. Depending on the GRI, a TOC may occur as infrequently as every 16 minutes. You can obtain TOC tables for all Loran-C chains by writing to the U.S. Naval Observatory, Time Services Department, Washington, DC, 20392-5100.

Some Loran-C receivers have a TOC button. If the receiver is locked to the incoming signal, you can press this button when a TOC occurs to synchronize a 1 pulse-per-second (1 pps) timing signal to the Loran pulses. If you do not lose power, and the receiver does not lose lock, the timing pulses will stay on time. It is important to keep a battery supply connected to the receiver to prevent loss of synchronization in case of power outages.

As mentioned previously, a clock driven by Loran-C pulses can keep time to within 10 microseconds. Of course, keeping time at this accuracy requires taking path and equipment delays into account. In addition, you need to know the sample point where the receiver is locked on the signal. Since Loran-C operates at 100 kHz, the zero crossings of the pulses are separated by the 10-microsecond period. Whenever your receiver moves from one cycle to the next, the time jumps by 10 microseconds. Some Loran-C timing receivers have oscilloscope and chart recorder outputs so you can see the exact position of the sample point.

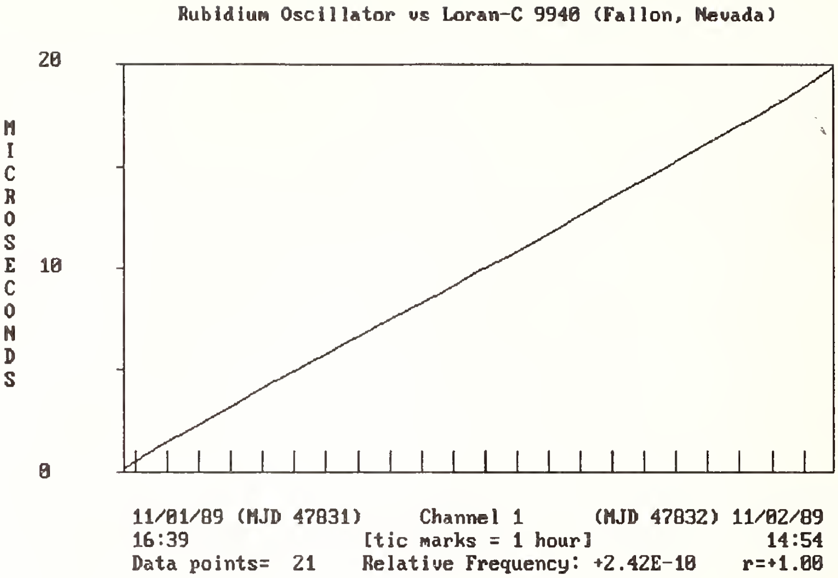
Frequency Calibrations Using Loran-C

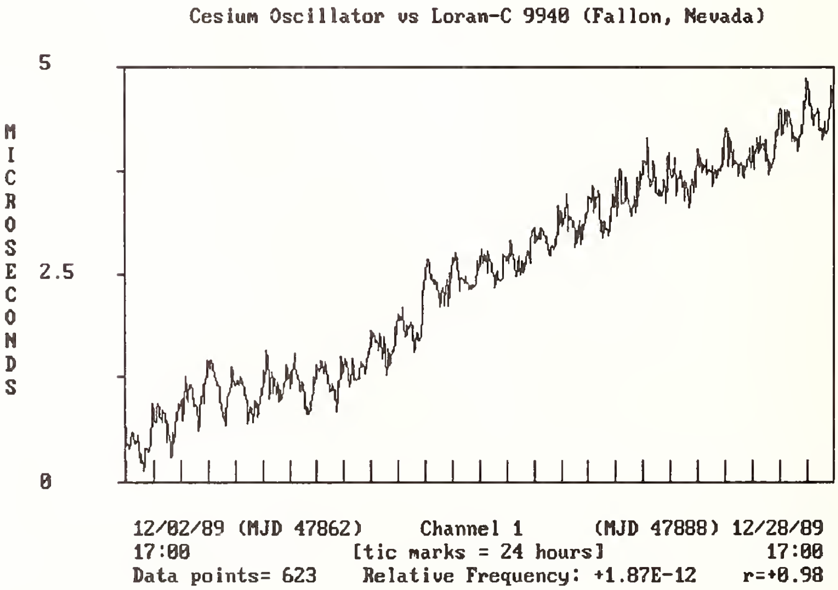
When using Loran-C for frequency calibrations, time interval measurements are the method of choice. For details about making frequency calibrations using the time interval method, please read chapter 4. That chapter discusses a computer-controlled frequency measurement system based on the time interval method that uses Loran-C as a reference frequency (page 46). This system uses a time interval counter to measure and record the time interval between the Loran-C signal and the signal from the oscillator being calibrated. Using a system like the one described in chapter 4 allows even the smallest laboratory to make state-of-the-art frequency calibrations.

Loran-C is almost unequaled as a frequency calibration source. Loran-C signals are good enough to calibrate quartz, rubidium, or cesium oscillators. One reason for this is that the Loran-C groundwave (unlike other VLF or LF broadcasts) is not subjected to large diurnal phase shifts. Of course, Loran-C signals change phase due to propagation noise along the radio path. However, these phase shifts are quite small and average out over a 24-hour period. For example, the relative frequency of Loran-C is about 1.00E-12 over a 24-hour period when compared to the NIST time scale. This means that the amount of Loran-C phase shift over a 24-hour period is only about 0.1 microsecond (100 nanoseconds).

The small errors in Loran-C phase generally do not cause problems when making frequency calibrations. This is because the Loran-C signals are far more accurate than the frequency output of most oscillators. For example, assume that Loran-C is being used to calibrate an oscillator with a calibration requirement of 1.00E-10. Since Loran signals are accurate to about 1.00E-12 over a 24-hour period, this means they are 100 times more accurate than the calibration requirement for the oscillator. If the performance of the oscillator relative to Loran-C is plotted, the small errors in the Loran-C phase are not even visible. A plot which illustrates this is on the next page. For this type of calibration, using Loran works just as well as using the NIST time scale.

The second plot on the next page shows a cesium oscillator compared to Loran-C over a period of nearly 4 weeks. This data is plotted on a much smaller scale than the previous plot, and the data is not as smooth because the small errors in the Loran-C phase are now visible. However, the plot still shows us that the cesium oscillator is high in frequency (although only by 1.87E-12), relative to Loran-C.





SUMMARY

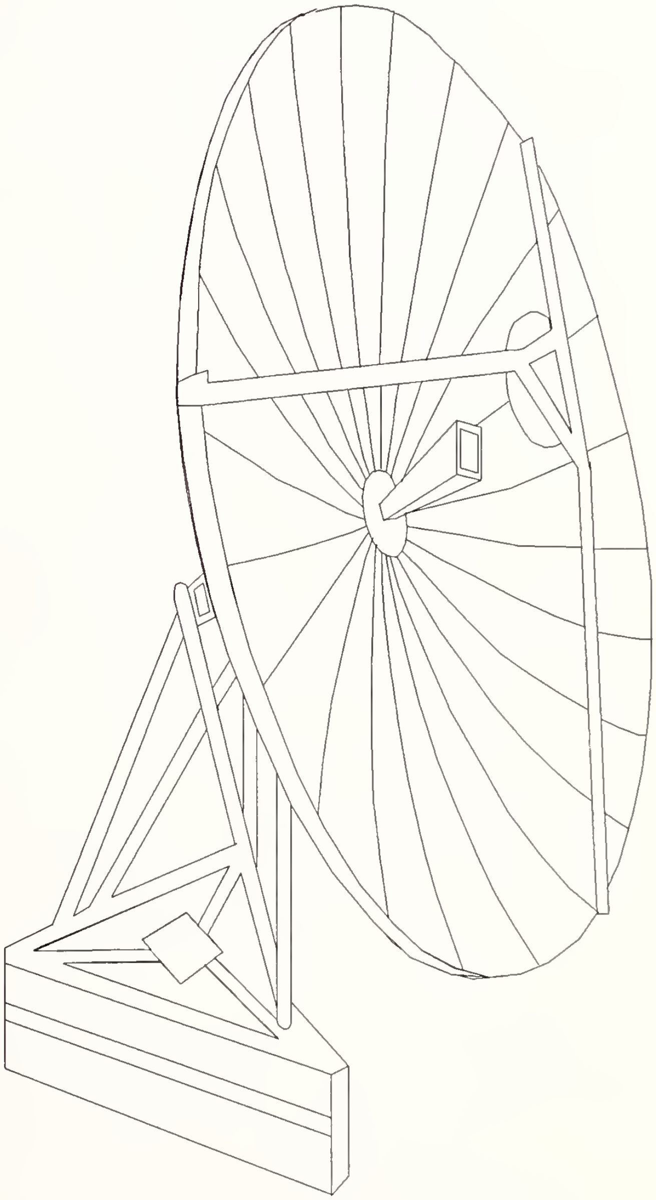
Signals broadcast from LF and VLF radio stations are an excellent choice for time and frequency calibrations. These signals provide more accuracy than the HF signals discussed in chapter 5. However, using LF and VLF signals might require more time, money, and effort than using HF signals.

The next chapter of this book discusses yet another alternative: time and frequency signals broadcast by satellite.

Chapter 7 - CALIBRATIONS USING SATELLITE BROADCASTS

Several satellite signals are available for time and frequency calibrations. An earth-orbiting satellite is a nearly ideal vehicle for broadcasting time and frequency radio signals. This is because the path between the satellite and the receiver is clear, and not influenced by earth-bound noise sources.

NIST provides a continuous time code through the GOES (Geostationary Operational Environmental Satellite) satellites. These satellites are operated by the National Oceanic and Atmospheric Administration (NOAA). The time code is referenced to UTC(NIST) and is broadcast continuously to the entire Western Hemisphere from two satellites (GOES/East and GOES/West). This cooperative arrangement between NIST and NOAA was made by formal agreement. The current agreement extends until 1997.



The U.S. Navy operates the TRANSIT series of navigation satellites, with major participation by the Applied Physics Laboratory of the Johns Hopkins University and the U.S. Naval Observatory. The operation of this system is also discussed in this chapter.

In addition to GOES and TRANSIT, the Global Positioning Satellite System (GPS) is also covered in this chapter. GPS offers users several advantages. Its frequency band, signal strength, and the use of atomic oscillators on board each satellite allow high-accuracy calibrations. Also, its popularity should make equipment available that is versatile and easy to use.

USING THE GOES SATELLITE BROADCASTS

A satellite signal is no different than any other radio signal as far as the user is concerned. You should not be discouraged by the difference in frequency or the operating techniques needed for frequency and time calibrations using GOES. In fact, tests have shown that GOES is one of the easiest services to use and can be used in areas where other signals are nearly impossible to receive. The equipment provided by manufacturers is usually quite sophisticated and nearly automatic in its operation.

The GOES satellites are in geostationary orbit 36 000 kilometers above the equator and travel at a speed of about 11 000 kilometers per hour. Geostationary means that the satellites stay above the same spot on the Earth's surface. Because they are geostationary, the path delay for the time code remains relatively constant at all times.

Geostationary satellites for time broadcasting are almost always in view and provide a source of continuous synchronization. Non-geostationary satellites, on the other hand, offer exposure to the user for only short periods of time at intervals ranging from about 1 hour to many hours or even days. Thus, non-geostationary satellite systems usually have a number of satellites in orbit.

GOES can be used for frequency calibrations. You could use GOES signals as the reference frequency for a frequency measurement system like the one shown on page 46. However, GOES has a time-code output (perhaps its major application is for its time code), and most commercially available GOES receivers were designed for time recovery. Frequency calibrations obtained using GOES time data fall into the accuracy range from 1.00E-06 to 1.00E-09 (for a 1-day measurement) with respect to NIST, depending on the sophistication of the equipment used.

The path from the receiver to a geostationary satellite is free from obstructions and allows using high carrier frequencies that are largely unaffected by the ionosphere and troposphere. This eliminates the fading and path length variations which are characteristic of terrestrial HF signals. The clear path also means that the path delay can be computed with greater accuracy than with HF signals.

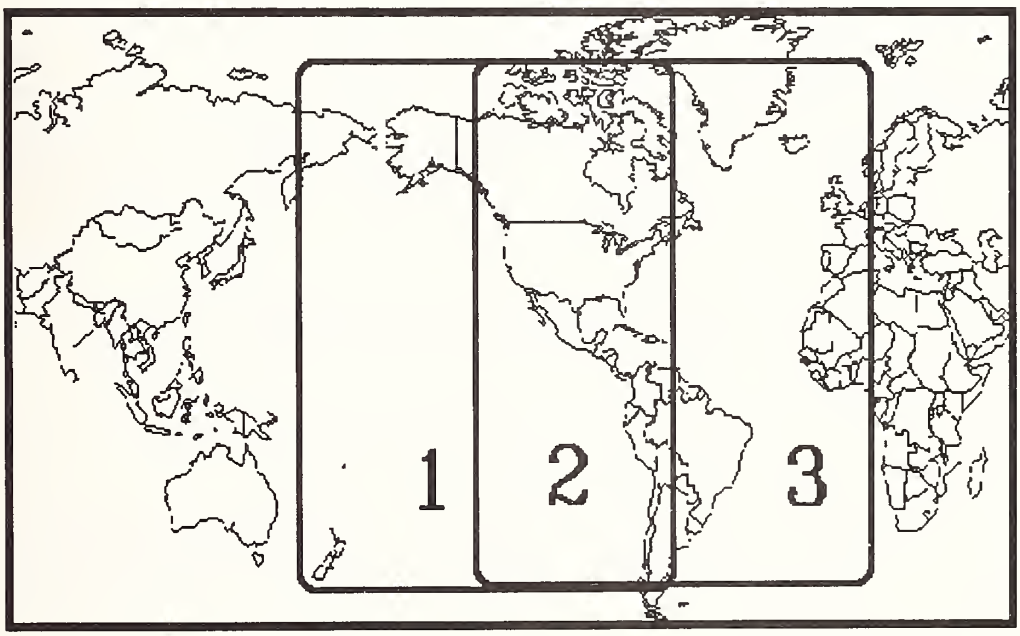
The NIST master clock is located on the ground rather than in the satellite itself. The satellite is only a transponder used to relay signals. This allows for easy control and maintenance of the system, thus guaranteeing better performance and reliability.

Because of these advantages, the GOES satellite can provide a continuous time message to receivers in its view. It can control the frequency rate of the slaved ground clock to eliminate the need for high-quality oscillators and can also provide position data to correct for propagation delays.

GOES COVERAGE

There are usually three GOES satellites in orbit, two in operation and a third serving as an in-orbit spare (this situation can change due to failure of one or more satellites). The two operational satellites are normally located at 135 degrees and 75 degrees West Longitude, and the spare is at 105 degrees West Longitude, however, this may change at times depending upon the current operational status of the available satellites. The western GOES operates on 468.825 MHz; the eastern on 468.8375 MHz. The approximate coverage of the two operational satellites is shown on the map below. As you can see from the map, much of the Western Hemisphere is covered by at least one satellite. The continental United States is covered by both satellites.

It is relatively simple to point an antenna to either satellite. If the path to the satellite is clear, pointing in the general direction of the satellite is usually sufficient, particularly for relatively low gain antennas (<10 dB). Satellite positions may change with time. Users should check the monthly NIST Time and Frequency Bulletin for the latest information.



1 – GOES/West

2 – Both Satellites

3 – GOES/East

GOES SIGNAL CHARACTERISTICS

As mentioned earlier, there are three GOES satellites in orbit, two in operational status with a third serving as an in-orbit spare. The signal characteristics of the two operational satellites are summarized in the table below:

	GOES/West	GOES/East
Frequency	468.8250 MHz	468.8375 MHz
Polarization	RHCP*	RHCP*
Modulation	CPSK (±60)**	CPSK (±60)**
Data Rate	100 BPS	100 BPS
Satellite Location	135 West	75 East
Signal Strength (output from isotropic antenna)	-131 dBm	-131 dBm
Coding	Manchester	Manchester
Bandwidth	400 Hz	400 Hz

* right hand circularly polarized
** coherent phase shift keying

GOES TIME CODE FORMAT

The GOES time code is generated and sent to the satellite from NOAA's facility at Wallops Island, Virginia. The frequency standards at Wallops Island provide a stable and accurate reference for the time code. They are compared to UTC(NIST) with Loran-C and GPS. The transmitted accuracy from Wallops Island is kept within at least 10 microseconds of UTC(NIST).

The GOES time code includes the current year, complete time-of-year information, the UT1 correction, satellite position information, accuracy indicators, Daylight Saving Time and leap second indicators, and system status information.

The time code is interlaced with interrogation messages that do not contain time and frequency information. The interrogation messages are used by NOAA to communicate with systems gathering weather data. The interrogation messages are broadcast at a rate of 100 bits per second. They are one-half second, or 50 bits in length. The first 4 bits form a BCD time code word. The remaining 46 bits do not contain timing information.

A time code frame consists of 60 BCD time code words. It takes 60 interrogation messages, or 30 seconds, to complete a time code frame. The completed time code frame contains a synchronization word, time code accuracy indicators, Daylight Saving Time (DST) and leap second indicators, system status information, a time-of-year word (UTC day of year, hour, minute, and second), the last two digits of the current year, the UT1 correction, and the satellite's position. The position information is updated every minute. It includes the satellite's latitude, longitude, and height above the Earth's surface.

GOES TIME CODE PERFORMANCE

The GOES time code can be used at three performance levels: uncorrected for path delay, corrected for mean path delay only, and fully corrected.

Uncorrected: The total path delay from Wallops Island, Virginia (where the time code originates), to the satellite and then back to Earth is about 260 milliseconds. To compensate for this path delay, the signals are advanced by 260 milliseconds before transmission from Wallops Island. The uncorrected signal arrives back on Earth nearly on time (within 16 milliseconds), depending upon the receiver's location.

Corrected for Mean Path Delay: If the appropriate mean path delay correction is made, the signal arrival time is usually accurate to within ±0.5 milliseconds. (Occasionally, however, NOAA uses satellites that produce delay variations of several milliseconds during a 24-hour period.) For example, the mean path delay from San Francisco through GOES/East is 255 milliseconds. The mean path delay consists of 130.5 milliseconds from satellite to Earth, and 124.5 milliseconds from Earth to satellite. Since the time is advanced by 260 milliseconds before leaving Wallops Island, it arrives at San Francisco 5 milliseconds early. You can correct for mean path delay in San Francisco by subtracting 5 milliseconds from the time signal.

Fully Corrected: The satellite's orbit is not perfectly circular and not in the plane of the equator. Therefore, the path delay at a fixed location typically varies by a few hundred microseconds throughout the day. Also, the satellites are sometimes moved to keep their orbital position within assigned limits. This movement causes irregular changes in the path delay. Obtaining a fully corrected time signal requires correcting for these position changes. Since satellite position data are included in the time code, users (and automatic receivers) can make these corrections. A fully corrected time signal is usually accurate to within ±100 microseconds. The ultimate accuracy depends on equipment delays and noise levels in addition to the path delay.

GOES EQUIPMENT

GOES time code receivers are commercially available. Some of them are accurate to within 100 microseconds over averaging periods of hours, months, or years. Other versions are accurate to within 1-2 milliseconds over the same periods. For a list of manufacturers, contact the Time and Frequency Services Group, 576.00, NIST, 325 Broadway, Boulder, CO 80303.

The manufacturers of GOES receivers also sell several different types of antennas. The best performance has been obtained using a right hand, circularly polarized helical antenna with about 10 dB gain. Excellent results have been obtained with the microstrip antenna, also shown. Dipoles and loops have also worked at lower levels of performance. All of these antennas had gains in the range of 3 to 10 dB. As a general rule, GOES antennas are small and easy to use and install. They often work well indoors. This makes it easier to receive GOES than many other time and frequency signals.

TIME CALIBRATIONS USING GOES

To use the GOES signals to calibrate or set another clock, you need to determine the relationship of the satellite-controlled clock's 1 pps output relative to UTC(NIST) and to the clock being calibrated. This relationship is usually determined by use of a time interval counter. For example, the clock to be calibrated may start the counter; then the satellite controlled clock stops it. The relationship between UTC(NIST) and the clock being calibrated is then known by combining this measured result with the computed difference between the satellite clock and UTC(NIST).

An example of the clock calibration procedure is given below. The clock to be calibrated is located in Boulder, Colorado, where the GOES satellite signals are being received. The calibration procedure is listed here for informational purposes. Keep in mind that few, if any, users would actually need to work through this example. Most GOES receivers perform these calculations automatically.

Signals received in Boulder (105.26 degrees West Longitude and 40.00 degrees North Latitude) showed the satellite location to be:

134.92 degrees West Longitude
0.38 degrees South Latitude
+46 microseconds distance

The total path delay from NOAA's Wallops Island to the GOES receiver in Boulder, Colorado, is 266 351 microseconds. This delay can be broken into three parts:

WALLOPS ISLAND TO SATELLITE	133 606 microseconds
SATELLITE TO BOULDER	127 533 microseconds
MEASURED EQUIPMENT DELAY	5 192 microseconds

TOTAL DELAY	266 351 microseconds

Since the GOES signal is late with respect to the clock at Wallops Island, we can write our equation as follows:

GOES SIGNAL - WALLOPS ISLAND CLOCK = -266 351 microseconds

To compensate for the path delay between Wallops Island and the GOES receiver, the Wallops Island clock is set 260 000 microseconds early with respect to UTC(NIST). This means that a GOES signal received anywhere inside the coverage area will always be within 16 000 microseconds of UTC(NIST). In the case of our receiver in Boulder, the time difference is only -6 351 microseconds (260 000 - 266 351):

GOES SIGNAL - UTC(NIST) = -6 351 microseconds

The measured time interval between the clock being calibrated and the GOES signal is stated as:

CLOCK BEING CALIBRATED - GOES SIGNAL = +6,548 microseconds

Then, by adding the last two equations:

CLOCK BEING CALIBRATED - UTC(NIST) = +197 microseconds

This means that the clock being calibrated is within 197 microseconds of UTC(NIST). From this example, you can see that GOES serves as an excellent reference for time calibrations.

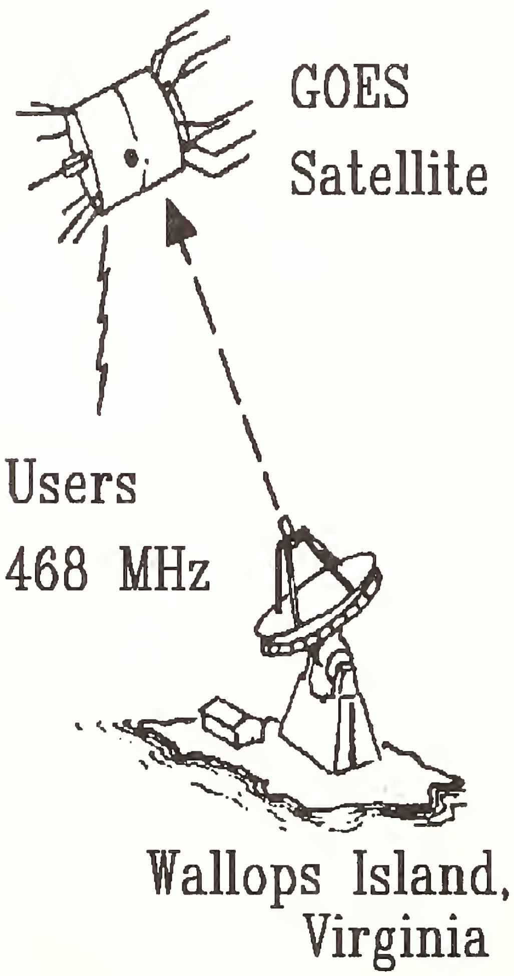
PRECAUTIONS FOR GOES USERS

The following paragraphs describe some conditions you should be aware of while receiving GOES signals.

Interference From Land-Mobile Radio Services

The land-mobile radio services can interfere with the GOES time code, since they use the same frequencies (468.8250 and 468.8375 MHz). This interference occurs mainly in urban areas with high land-mobile activity. Since the land-mobile frequency allocations have priority over the GOES allocations, complaints to the FCC do not help.

Because of the specific frequencies involved, the land-mobile services affect GOES/West more than GOES/East. Therefore, users in urban areas should use GOES/East if land-mobile interference is a problem.



Larger-than-Normal Time Code Deviations

The GOES time code is as accurate as stated more than 99 percent of the time. However, some situations can cause larger-than-normal time code deviations. One such situation occurs when NOAA uses a GOES/East and/or GOES/West satellite with larger-than-normal orbit inclinations. In this instance, users in "uncorrected" mode may receive time with variations of several milliseconds.

A more common problem (though of much shorter duration) occurs when stationkeeping maneuvers are performed on the satellites. These maneuvers are performed every 1 or 2 months to keep the satellites in their assigned orbit locations. Receivers that use the position data can compensate for these maneuvers; however, the position data are not updated until 0000 UTC on the day after the maneuver. This means that for up to 24 hours following a maneuver, the time code may be off by more than the normal 100 microseconds. NIST changes the accuracy-indicator bit in the time code to indicate when this condition occurs.

Continuity

NIST cannot guarantee the long-term continuance of the GOES time code, since the satellites belong to NOAA. However, NIST and NOAA have agreed to include the time code in the GOES satellite transmissions as long as possible. The current agreement extends to 1997.

THE TRANSIT NAVIGATION SYSTEM

These Navy navigation satellites have been operational since 1964. Known as the TRANSIT satellites, their design, power, and coverage provide an excellent source of time and frequency signals for calibration purposes. The signal format used on the system lends itself well to time recovery from which frequency calibrations can be derived using the techniques previously described in this book.

TRANSIT, being an orbiting system, experiences a much larger Doppler shift of its radio signal than GOES. This is no real problem for the user since the overall system design takes this into account and provides enough information to the users so that accurate time recovery can be achieved. The biggest difference between GOES and TRANSIT is that the TRANSIT system can be used only during several brief periods each day when a satellite is in view of the receiver.

This system is a good candidate for users who have a worldwide requirement. TRANSIT will work anywhere in the world. GOES is limited to the Western Hemisphere and its oceans.

The satellites broadcast at about 400 MHz. Their message contains information that allows position fixing and time recovery. As with the GOES system, TRANSIT allows a user to recover time signals that can be used as a clock or to steer an oscillator's frequency. Unlike GOES, however, the TRANSIT time signal format does not include day-of-the-year information. Accuracy of the overall system is slightly better than GOES. As with the GOES system, the satellite message is designed to allow the receiver to synchronize itself, locate the required bits in the data stream and produce a time mark. At this writing, the TRANSIT system permits time recovery to within 10-50 microseconds.

Although TRANSIT is primarily a navigation satellite system, the U.S. Navy provides support for its frequency and time function. Users planning to obtain equipment to use TRANSIT, especially at remote locations, should contact the U.S. Naval Observatory (page 23) for the latest information. The manufacturers of TRANSIT equipment are another good source of information.

At this writing, the TRANSIT system is supported by five orbiting satellites. These are in a circular polar orbit at an altitude of about 1100 kilometers. Thus, a user on the Earth will see a satellite every 90 minutes or so. In contrast to a GOES-type of transponder, TRANSIT has an accurate clock onboard each of its satellites. These are monitored from earth-control stations, and corrections are sent to the satellites periodically to keep them on time. In addition to position information, the satellites send a time mark every 2 minutes. By monitoring the signals from four ground-monitor stations, the Navy is able to steer the on-board clocks by special commands and to carefully control the accuracy of the TRANSIT signals.

Equipment costs are higher for TRANSIT than for GOES, but still not unreasonable considering the few alternatives. Antennas are small, vertical, omnidirectional, and simple to install. Some TRANSIT receivers are computer-controlled and allow nearly hands-off operation. However, TRANSIT receivers typically require that you obtain the time of day (from another source) to within 15 minutes in order to resolve the time ambiguity of TRANSIT. For some applications, it may also be necessary to key your longitude and latitude into the receiver.

GLOBAL POSITIONING SYSTEM (GPS)

The Global Positioning System (GPS) is a worldwide satellite-based radio navigation system developed by the U.S. Department of Defense (DOD). The system allows users to obtain highly accurate time. GPS also transmits navigation information that permits positioning accuracy at two levels. The higher accuracy is obtained from the precision positioning service (PPS). Reduced accuracy is available from the standard positioning service (SPS).

The PPS signal is not available for use by the general public. However, the SPS signal is available to any properly equipped user. There are no fees associated with the use of SPS.

GPS should be fully implemented by the mid-1990's. The finished system will include 24 satellites (21 primary satellites and 3 in-orbit spares). The spares will usually be active and available to users. Each satellite will carry two rubidium and two cesium atomic standards. The 24 satellites will be located in 6 equally spaced orbital planes (4 satellites per plane) inclined at 55 degrees with respect to the equator. The altitude of each satellite is about 10 900 nautical miles.

GPS is being implemented in phases. The first GPS satellites (called Block I) were launched beginning in February 1978. A total of 11 Block I satellites were launched. As of this writing, seven are still operating and six are still usable for precise time transfer.

However, the Block I satellites were preliminary test units and will not be part of the 24 satellites included in the finished system. The satellites that will be included in the finished system are called Block II satellites. The first Block II satellite was launched in 1989, and the launches will continue at a rate of about 5 per year until all 24 satellites are in orbit. After that time, about 3 additional launches per year may be needed to provide GPS with the necessary in-orbit spares.

Once all 24 satellites are in orbit, the probability is greater than 99.6% that a user (at a random time and place on the Earth) will have coverage within the given threshold for PDOP (position dilution of precision). A value of PDOP < 10 and an elevation angle greater than 5 degrees are considered necessary to meet this condition.

Each GPS satellite broadcasts two carrier frequencies, called L1 and L2 (where L1 = 1575.42 MHz and L2 = 1227.6 MHz). Specified minimum signal strengths are -163 dBW and -160 dBW, respectively. Two spread spectrum waveforms (PRN) are in use:

(1) *a coarse acquisition code (C/A), with a 1.023-MHz chip rate and a period of 1 millisecond*

(2) *a precision code (P), with a 10-MHz chip rate*

The C/A code is associated with the Standard Positioning Service and the P code with the Precision Positioning Service. The C/A code is intentionally degraded in accuracy. The L1 frequency from each satellite is modulated with both the C/A and P codes, while the L2 frequency is only modulated with the restricted P code. Although all GPS satellites transmit on the L1 and L2 frequencies, the interference between satellites is minimal. This is because each satellite is given an individual code assignment to prevent interference.

Both the L1 and L2 carrier frequencies are continuously modulated with a 50 bit per second navigation message. This message contains the following information:

(1) *The current status of each satellite, allowing you to reject satellites that may be having problems.*

(2) *A "Handover Word (HOW)" needed in the acquisition of the P code from the C/A code.*

(3) *Satellite clock corrections, providing differences between the particular satellite clock and GPS system time and between*

GPS system time and UTC(USNO). GPS system time is normally kept within 1 microsecond of UTC(USNO), except that leap seconds are ignored by GPS system time. Users who apply all time corrections contained in the GPS data message can relate their clocks to UTC(USNO) with a precision of 100 nanoseconds and an accuracy of better than 1 microsecond.

(4) *Satellite position information.*

(5) *Information about ionospheric delay effects.*

(6) *Information about all GPS satellites. This allows you to acquire all satellites once the first one has been acquired.*

The GPS space segment is supported by a network. This network includes a master control station in Colorado Springs, Colorado, and multiple monitoring and upload stations located around the world. Each monitoring station transmits the data they receive to the master control station. This information is then sent to the GPS upload stations and uploaded into the satellites, so that the navigation messages can be updated.

GPS system time is produced by the reference clock at one of the monitoring station sites. This role of system reference clock can be switched from clock to clock and from station to station if necessary, without making significant changes to the GPS system time.

As mentioned earlier, users of the Standard Positioning Service (SPS) are restricted to signals with intentionally degraded accuracy. Since SPS is available to anyone, the DOD adds errors to the data in the interest of national security. Currently, SPS users can expect timing errors of about 300 nanoseconds, but DOD reserves the right to reduce the accuracy even more.

Even with the reduced accuracy of SPS, GPS is still an excellent time and frequency source. Most users should find it more than adequate. However, if you do need more precise time, you have several options:

(1) *You can receive signals from the Block I satellites. The current Block I satellites provide unrestricted, full-accuracy timing signals. Some of these satellites are expected to remain usable for several more years.*

(2) *You can use GPS in the "common-view" mode (described in the next section). The common-view mode does not totally eliminate the reduced accuracy of SPS, but it does minimize the effects.*

(3) *Since the data errors are random, you can improve the data by averaging.*

(4) *You can apply corrections to the received data.*

For more information about GPS, contact the Time Service Department of the U.S. Naval Observatory, 34th and Massachusetts Ave., NW, Washington, DC 20392. Their Automated Data Service contains a number of files accessible to civilian timing users of GPS that provide both current and past GPS data, as well as current information on the GPS system.

Using GPS

A variety of GPS receivers are available. These include sophisticated multi-frequency versions, small handheld units, and specialized timing receivers used for civilian timing applications. A single-frequency, SPS timing receiver can be purchased from a number of commercial suppliers at prices ranging from $15 000-$25 000 (1990 prices). These receivers are often completely automatic and require only a small omnidirectional antenna.

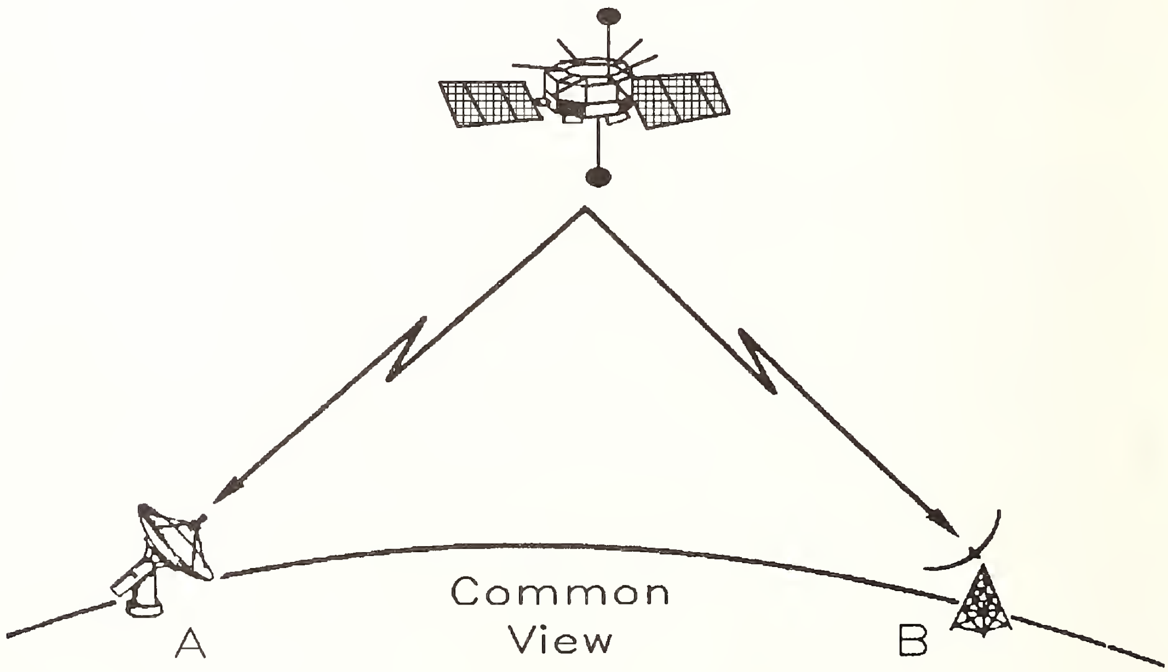
A typical GPS timing receiver can automatically acquire the signal from each desired GPS satellite, extract the timing information from the received signal, and apply corrections to the received time to determine either GPS system time or UTC(USNO). The receiver's coordinates must be known and entered into the receiver. This can be done either manually (if the precise location of the site is known), or automatically by the receiver, through performing a navigation solution from the GPS signals from multiple satellites. Ideally, the position should be known within 1 meter or better.

To derive UTC at your location, several corrections need to be determined and applied to the received satellite signal. First, the path delay from satellite to receiver must be computed by the receiver. This is possible because the precise positions of the satellite and receiver are known. The satellite position information is included in the navigation message, and the receiver's position was entered during receiver initialization. Next, the resulting path delay is further corrected for ionospheric and tropospheric delay effects, again making use of data supplied in the navigation message. At this point the time delivered to your site can be related to the time kept by the satellite's onboard clock.

In order to refer the received time to GPS system time or to UTC, further corrections are necessary. To relate to GPS system time, a correction must be applied for the amount of time offset between the satellite clock and GPS system time. This information is available to the receiver from the navigation message. Finally, you may apply a correction for the current difference between GPS system time and UTC(USNO). This information is available from continuous monitoring of the received GPS signals by the U.S. Naval Observatory. You can obtain the USNO data in various forms from the USNO's Automated Data Service by using a computer and a modem. Contact the USNO for a list of available GPS files and for instructions for accessing the computer database.

There are two principal methods for using GPS time. The first is the "time distribution" mode. In this mode the user receives the direct GPS timing signals and uses them as the local equivalents of GPS or UTC time (depending on which correction was applied). Some receivers provide standard time and frequency outputs that are phase locked to UTC(GPS) or UTC(USNO). The time distribution mode is capable of providing time to within 100 nanoseconds, but will be less accurate when using SPS.

The second method is the "common-view" mode. This mode is used to synchronize or compare time standards or time scales at two or more locations. For example, common-view is often used to make time scale comparisons between international laboratories. A diagram of the common-view mode is shown below:



Users at the two sites, A and B, make simultaneous measurements of the same GPS timing signal when the satellite is visible to each site with reasonable elevation angles. Each site measures the difference between its local clock and the received signal. Typically, repeated 6-second measurements are made during a satellite pass lasting for 10-15 minutes. The individual measurements at each site are then averaged to produce estimates of (Clock A - GPS satellite clock) and (Clock B - GPS satellite clock). If these results are then subtracted, the satellite clock drops out and an estimate of Clock A - Clock B remains.

One advantage of the common-view technique is that the errors associated with the satellite clock are common to both sites and are thus eliminated in the comparison. This means that satellite clock errors introduced by the SPS service should not affect the accuracy of common-view time comparisons. The common-view method also reduces the effect of satellite position errors. Since these errors are not totally common to the two paths they will still have some impact on the time difference results. If a comparison is being made between two widely separated locations (like the United States and Japan), this effect can produce uncertainties as large as several tens of nanoseconds.

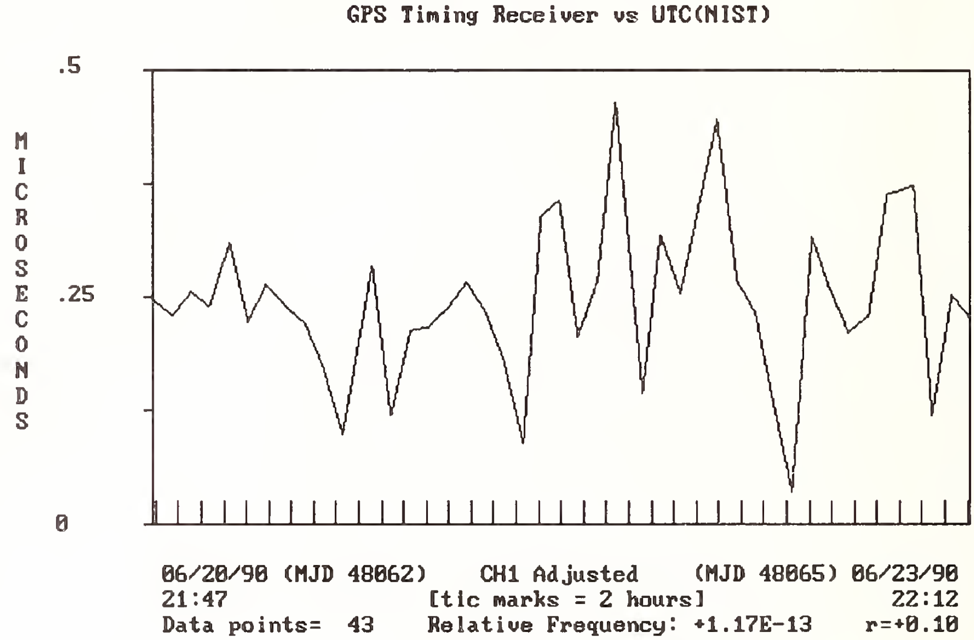
In order to use the common-view technique, the sites being compared must be close enough to each other to receive signals from the same satellite. However, the acceptable distance is larger than might be expected. For example, it is possible for common-view time comparisons to be made between the western United States and India.

The common-view method provides the basis for the NIST Global Time Service. This service allows users to procure a turn-key GPS receiving system from NIST and allows traceability to UTC(NIST) at accuracy levels of less than 100 nanoseconds. Also, BIPM publishes tracking schedules for common-view links between various regions of the world. Users wishing to compare time with other laboratories can consult these schedules to determine which satellites and time periods are available for common-view measurements. These comparisons can provide accuracies over intercontinental distances to within 10 nanoseconds.

To further improve the usefulness of GPS, other more specialized techniques are also being developed. One example is a codeless, ionospheric calibration receiver being developed by several laboratories. Since errors in predicting the ionospheric delay are a major source of time comparison uncertainties, this new receiver could significantly improve the results. The ionospheric calibration receivers make use of the fact that the two carrier frequencies (L1 and L2) are affected differently as they traverse the ionospheric region. By measuring this different behavior, you can predict the actual path delay more accurately. These new receivers can perform this calibration using the dual GPS frequencies without having access to the restricted P code transmissions. Another possible development is a receiver that can receive signals from both the GPS satellites and signals from the GLONASS system under development by the USSR.

GPS Performance

Although not all of the GPS satellites have been launched, the system's time transfer capabilities are available now, since only one satellite is needed to transfer time. The plot below shows GPS performance over a 3-day period when compared to UTC(NIST):



The plot shows data obtained with a commercially available GPS timing receiver. These receivers are readily available, and their cost has gone down over the past few years. The receiver was using the (C/A) code with intentionally degraded accuracy. Even so, the range of the data is less than 0.5 microsecond (500 nanoseconds) over the 3-day period.

The plot shows that GPS is an excellent source for precise time transfer. However, users outside the DOD should realize that the precision of GPS timing has been reduced and may be reduced further in the future. If you need time at the highest possible accuracy you should monitor future GPS developments very closely.

SUMMARY

Satellite signals are an excellent reference for time calibrations and may also be used for frequency calibrations. Commercially available satellite receivers are sophisticated, easy to use and install, and allow you to obtain time to within 100 microseconds or better.

The next chapter of this book discusses two NIST services that allow you to recover time by telephone.

Chapter 8 - CALIBRATIONS BY TELEPHONE

If your accuracy requirements are low, you may be able to get a perfectly acceptable time signal by telephone. This chapter describes two telephone services offered by NIST.

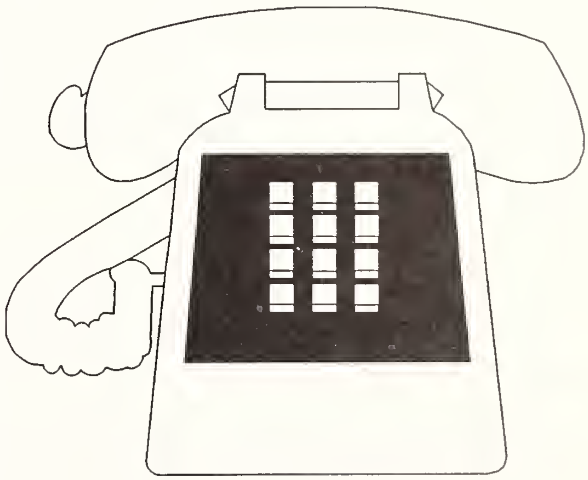
THE NIST (VOICE) TELEPHONE TIME-OF-DAY SERVICE

The audio portions of the WWV and WWVH broadcasts (chapter 5) can also be heard by telephone. The actual time you hear on the telephone will differ by a few milliseconds from that heard by radio. This is because of the delay in the telephone lines. In addition, if you are calling from any great distance, the way that the telephone company handles your call may limit the accuracy of the tones to a few hertz. This means that if you are making a calibration at 1000 Hz, you could have an error as great as 3 Hz. This accuracy is not as good as the accuracy obtained using radio signals, but may be perfectly acceptable.

To hear these broadcasts, dial (303) 499-7111 for WWV, and (808) 335-4363 for WWVH. Callers are disconnected after 3 minutes. These are not toll-free numbers, and callers outside the local calling area are charged for the call.

THE AUTOMATED COMPUTER TIME SERVICE (ACTS)

In 1988, NIST began the Automated Computer Time Service (ACTS). This service provides computers with telephone access to NIST time at accuracies approaching one millisecond. Since the time code uses the standard ASCII character set, it works with nearly all computer systems and modems. Simple hardware can also be built to set non-computer clock systems.



The phone number for ACTS is (303) 494-4774. ACTS operates at 300 or 1200 baud, with 8 data bits, 1 stop bit, and no parity. In addition to the UTC hours, minutes, and seconds, the time code includes the date, the Modified Julian Date (MJD), Daylight Saving Time and leap second indicators, a leap second flag, a UT1 correction, and other information. Users at 1200 baud receive the full time code each second, while 300-baud users require 2 seconds to receive the complete time code.

The ACTS Time Code Format

The time code for ACTS is sent in ASCII at either 300 or 1200 baud. Both baud rates require 8 data bits, 1 stop bit, and no parity. The 1200-baud format is shown below:

```
? = HELP
National Institute of Standards and Technology
Telephone Time Service


     (1 second pause here)
                              D  L D
 MJD  YR MO DA H  M  S  ST S UT1 msADV          OTM
47222 88-03-02 21:39:15 83 0 +.3 045.0 UTC(NIST) *
47222 88-03-02 21:39:16 83 0 +.3 045.0 UTC(NIST) *
47222 88-03-02 21:39:17 83 0 +.3 045.0 UTC(NIST) *
47222 88-03-02 21:39:18 83 0 +.3 045.0 UTC(NIST) *
47222 88-03-02 21:39:19 83 0 +.3 037.6 UTC(NIST) #
47222 88-03-02 21:39:20 83 0 +.3 037.6 UTC(NIST) #
etc...etc...etc....
```

The first part of the time code contains the Modified Julian Date (MJD), the date (year, month, day), and the time (UTC hours, minutes, seconds). This information is followed by the Daylight Saving Time (DST) information. The DST code is always a two-digit number (00 to 99). This code is normally 00 when Standard Time (ST) is in effect, or 50 when DST is in effect. About 48 days prior to a time change, however, this code starts counting the days until the change. When ST is in effect, the DST code counts down from 99 to 51 in the 48 days prior to the time change. When DST is in effect, the DST code counts down from 49 to 01 in the 48 days prior to the time change. In both cases, the code is updated at 0000 UTC.

The leap second (LS) flag is always "0," "1," or "2." If no leap second is scheduled at the end of the current month, it is "0." It is "1" if a leap second is scheduled to be added on the last day of the current month. The LS flag remains on for the entire month before the leap second is added. Once the leap second is added, the LS flag is reset to "0". The leap second flag is a "2" only if a leap second is to be deleted on the last day of the current month. So far, a negative leap second has never been needed.

The UT1 correction is shown as either a positive or negative number in steps of 0.1 second. The remainder of the time code shows the millisecond advance (msADV) and the on-time marker (OTM). The displayed time is valid at the OTM. The OTM is either an

"*" or a "#" character. When you first connect, the "*" OTM is displayed. This marker is transmitted 45 milliseconds early with respect to UTC(NIST). The 45 milliseconds accounts for the 8 milliseconds required to send a character at 1200 baud, an additional 7 milliseconds to compensate for delay from NIST to the user, plus a 30 millisecond "scrambler" delay. The "scrambler" delay approximately compensates for the internal delay found in 1200-baud modems.

If you echo all characters, NIST measures the round trip delay and advances the OTM so that the midpoint of the stop bit arrives at your computer on time. When this happens, the msADV shows the actual required advance in milliseconds and the OTM becomes "#." Four consecutive stable measurements are needed before the OTM switches from "*" to "#." If your 1200-baud modem has the same internal delay used by NIST (30 milliseconds), then the "#" OTM should arrive at your computer within ±2 ms of the correct time. Different brands of 1200-baud modems have different internal delays, and the actual offset of the "#" OTM may be as large as ±10 ms. This should still be more than adequate, however, since many computer clocks can only be set within 20-50 milliseconds.

The 300-baud time code is potentially more accurate than the 1200-baud code. Due to a simpler modulation scheme used at 300 baud, the OTM should arrive at your computer within 1 millisecond of the correct time.

Users are allowed 55 seconds on ACTS unless all lines are busy. In that case, the first call that reaches 15 seconds is terminated.

Performance of ACTS

With appropriate software, ACTS can set or check computer time-of-day clocks in one of two different modes:

Fixed Delay Mode - In this mode, the user receives the time code and an on-time marker character. The marker character has been advanced in time by a fixed amount to compensate for typical modem and telephone line delays. Unless the connection is routed through a satellite, the accuracy in this mode should be better than 0.1 second.

Measured Delay Mode - In this mode, the user's computer echoes all characters back to NIST and the round trip line delay is measured. The on-time marker character is then advanced to compensate for the line delay. The accuracy in this mode should be better than 10 milliseconds using a 1200-baud modem, or about 1 millisecond using a 300-baud modem. Accuracy at 1200 baud is limited by the internal delays in 1200-baud modems. Repeatability at both 300 and 1200 baud is about 1 millisecond.

The accuracies cited above assume that the telephone connection is reciprocal, that is, that the connections follow the same path, so the path delay is the same in both directions. Most phone connections are of this type.

NIST offers software which lets users use ACTS on several popular personal computers. The documentation for this software includes more information about the features of the service and a simple circuit diagram that can be used to obtain an on-time pulse. This material costs $35.00 (subject to change without notice). To order, contact: NIST Office of Standard Reference Materials, Room 205, Building 202, NIST, Gaithersburg, MD 20899, telephone (301) 975-6776. Ask for the Automated Computer Time Service Software, #RM8101. If you have questions or comments about ACTS, write to: NIST-ACTS, Time and Frequency Division, 576.00, 325 Broadway, Boulder, CO 80303.

APPENDIX - SUMMARY OF TIME AND FREQUENCY RADIO CALIBRATION SOURCES

The table below serves as a quick reference to the time and frequency radio calibration sources described in this book. When using the table, please keep in mind that the accuracies stated are relative to UTC(NIST) and are possible only within the coverage area of the signal. Some signals may not be usable in your area. For more specific information about each calibration source, please refer to the chapter listed in the table.

Name of Source and carrier frequency	Accuracy		Topic Covered In:
	Frequency (24 hours)	Time (microseconds)	
HF Signals (2.5 to 25 MHz)	1.00E-07	1000	Chapter 5
GOES Satellite (468 MHz)	1.00E-09	100	Chapter 7
Omega and VLF (10 to 15 kHz)	1.00E-10	1000	Chapter 6
WWVB and LF (30 to 300 kHz)	1.00E-11	1000	Chapter 6
Loran-C (100 kHz)	1.00E-12	< 10	Chapter 6
GPS (1575 MHz)	1.00E-13	< 1	Chapter 7

GLOSSARY

The following definitions are offered as an aid to the reader. The definitions relate to the way the terms appear in this book and may differ from the definitions listed in other references.

ACCURACY - the degree of conformity of a measured value to its definition.

AGING - the systematic change in frequency with time due to internal changes in the oscillator. For example, a 100-kHz quartz oscillator may age until its frequency becomes 100.01 kHz.

AMBIGUITY - having more than one possible value. For example, if a 24-hour clock displays a time of 3 hours and 5 minutes, it is ambiguous as to the day. If we add a number to the clock display to show that it is day 17, the time is still ambiguous as to the month. If we add another number showing it is month 3, the time is still ambiguous as to the year.

ATOMIC TIME (TA) - the time obtained by counting cycles of an atomic frequency source as opposed to time based on the Earth's rotation. Atomic time is extremely uniform.

AUTOMATIC GAIN CONTROL (AGC) - a circuit used in some radio receivers (including HF receivers) so that both weak and strong signals can be heard at similar volume.

CALIBRATION - a measurement that determines the frequency or time offset of an oscillator relative to the national standard, UTC(NIST). Calibrations are usually made by comparing the output of an oscillator to a reference signal known to be traceable to UTC(NIST). The reference signal is usually obtained by radio. Calibrations can also be made by making a direct comparison between two oscillators. In this case, one oscillator is assumed to be the better of the two and is used as the reference.

CESIUM OSCILLATOR (Cs) - any oscillator that uses cesium to obtain atomic resonance. Cesium oscillators are often used as a laboratory's primary frequency standard.

DECADE COUNTING ASSEMBLY (DCA) - a circuit used in counters that counts from 0 to 9 before it overflows. This enables the counter to display units of tens, hundreds, and so on.

DIURNAL PHASE SHIFT - the phase shift (diurnal means daily) associated with sunrise and sunset on low frequency radio paths.

DOPPLER EFFECT - an apparent change in frequency caused by movement of either the transmitter or receiver. In the case of radio waves, the Doppler effect occurs when the ionosphere changes its position.

DRIFT (FREQUENCY DRIFT) - the systematic change in frequency with time of an oscillator. Drift is due to aging plus changes in the environment and other factors external to the oscillator (see Aging).

DUT1 - the approximate time difference between UT1 and UTC, expressed to the nearest 0.1 second. The value of DUT1 is sometimes included in time codes (WWV, for example) so that listeners can correct the time as heard to make it agree with UT1 to within 0.1 second.

EPHEMERIS TIME (ET) - an astronomical time scale based on the orbital motion of the Earth.

FREQUENCY - if T is the period of a repetitive event, then the frequency (f) is equal to 1/T. Frequency is normally expressed in hertz, with 1 Hz meaning that an event occurs once per second.

FREQUENCY-SHIFT KEYING (FSK) - a means of modulating a radio carrier by changing its frequency by a small amount.

GREENWICH MEAN TIME (GMT) - a 24-hour time system based on the time at Greenwich, England. Greenwich Mean Time can be considered equivalent to Coordinated Universal Time (UTC), which is broadcast from all standard time and frequency radio stations. However, several international organizations have recommended that UTC be used rather than GMT in all applications.

GROUP REPETITION INTERVAL (GRI) - the rate of recurrence of specified groups of pulses. In the case of Loran-C, the GRI is altered between different groups of stations to avoid interference.

IONOSPHERE - the outer part of the Earth's atmosphere. The ionosphere consists of a series of constantly changing layers of ionized molecules. Many radio waves reflect back to Earth from the ionosphere.

JITTER - usually used to describe the small changes in a signal over time. Phase jitter causes a counter to be triggered either early or late.

JULIAN DAY (JD) - the Julian Day is obtained by counting days with a starting point of noon on January 1, 4713 B.C. (Julian Day zero). This is one way of telling what day it is with the least possible ambiguity.

LEADING EDGE - the first occurring change in a pulse. The leading edge can be either negative- or positive-going.

LEAP SECOND - an intentional increment of 1 second used to adjust UTC to ensure approximate agreement with UT1. An inserted second is called a positive leap second and an omitted second is called a negative leap second. A leap second is needed about once per year.

LONG-TERM STABILITY - describes the frequency change of an oscillator that occurs over periods greater than 1 second.

MAXIMUM USABLE FREQUENCY (MUF) - the highest frequency that can be used for radio transmissions without having the signal escape through the ionosphere. Signals below the maximum usable frequency will reflect off the ionosphere.

MEAN SOLAR TIME - time based on a mean solar day, which is the average length of all solar days in a solar year. The mean solar second is 1/86 400 of a mean solar day.

MIXER - an electrical circuit that mixes two signals and produces a new signal that is usually either the sum or the difference of the two inputs.

MODIFIED JULIAN DAY (MJD) - this is equal to the Julian day, shifted so its origin occurs at midnight on November 17, 1858. The MJD differs from the Julian Day by exactly 2 400 000.5 days.

NIST - abbreviation for The National Institute of Standards and Technology (formerly the National Bureau of Standards).

OMEGA NAVIGATION SYSTEM - a low frequency (10 to 15 kHz) navigation system also used for time and frequency calibrations.

PATH DELAY - the amount of time it takes for a radio signal to travel from the transmitter to the receiver.

PHASE JUMP - a sudden phase change in a signal.

PHASE LOCK - a servo mechanism technique for causing one signal to follow another. The signals can be (but do not have to be) at the same frequency. Phase locking in terms of frequency sources is analogous to a mechanical servo, where one shaft or wheel follows another.

PHASE SIGNATURE - a deliberate phase offset to identify a signal. WWVB as broadcast is deliberately phase shifted at 10 minutes after the hour. This tells you that are tracking WWVB and not some other signal.

POWER LINE FREQUENCY - in the United States, the power lines are held to a frequency of 60 Hz. This frequency is often used to drive electric clocks.

PRECISION - the degree of mutual agreement among a series of individual measurements. Precision is often (but not necessarily) expressed by the standard deviation of the measurements.

RECEIVER DELAY - the delay experienced by the signal going from the receiving antenna to the detector or output device, speaker, or oscilloscope terminal. A delay of several milliseconds is typical in high frequency radio receivers.

REPRODUCIBILITY - the ability of a single device (or a set of devices) to produce the same value when they are put into operation repeatedly without adjustment.

RESOLUTION - the degree to which a measurement can be determined is called the resolution of the measurement. For example, a measurement made with a time interval counter might have a resolution of 10 nanoseconds.

RUBIDIUM OSCILLATOR (Rb) - a precision atomic oscillator based on a resonance of rubidium gas.

SELECTIVITY - the characteristic of a radio receiver that allows it to separate one signal from another.

SENSITIVITY - the characteristic of a radio receiver that allows it to detect weak signals.

SHORT-TERM STABILITY - a description of the frequency fluctuations caused by random noise in an oscillator. To properly state the short-term stability, the number of samples, averaging time, repetition time, and system bandwidth must be specified.

SIDEREAL TIME - time based on observations of stars rather than the Sun. Sidereal time is used by astronomers and a sidereal day is equal to about 23 hours, 56 minutes, and 4 seconds of solar time. Because it is based on observations of stars, it is more accurately determined than solar time.

SIGNAL-TO-NOISE RATIO (SNR) - the ratio of the strength of a radio signal to that of the noise. This is a more useful term than signal strength.

STANDARD - a universally accepted reference. The NIST frequency standard is a cesium oscillator located at the National Institute of Standards and Technology in Boulder, Colorado. Many frequencies generated and used in the United States are referenced to this standard.

STANDARD FREQUENCY BAND - radio bands allocated expressly for the purpose of distributing standard frequency and time signals. For example, all of the transmissions of WWV occur in standard frequency bands centered on 2.5, 5, 10, 15, and 20 MHz.

SYNCHRONIZATION - in the context of timing, synchronization means to bring two clocks or data streams into phase so they agree. They need not be on time.

TCXO (TEMPERATURE COMPENSATED CRYSTAL OSCILLATOR) - a crystal oscillator that contains special components to minimize the effect of temperature on the crystal frequency.

TIME BASE - in a frequency counter the oscillator that provides the timing signals for measurement and control. The accuracy of the counter is directly related to the time base.

TIME INTERVAL COUNTER - a counter designed to measure the time interval between two input signals. Time interval counters are often used to measure the performance of an oscillator.

TIME OF COINCIDENCE (LORAN) - the time when the GRI pulse from a Loran-C station is coincident with an exact second of Coordinated Universal Time. These times of coincidence occur at regular intervals of 16 minutes or less, depending on the GRI.

TIME SCALE - a system of unambiguous ordering of events.

TRANSFER STANDARDS - the name given to a signal that is used to perform a calibration when it can be referenced to a standard. For example, since WWVB is referenced to the NIST frequency standard, it can be used as a standard to calibrate other oscillators at remote locations.

TRIGGER ERROR - the error associated with false triggering caused by phase noise or jitter on a signal.

UNIVERSAL TIME (UT) FAMILY - Universal Time (UT) is the name given to time scales based on the rotation of the Earth. UT is given in several ways. Apparent solar time is first corrected by the equation of time to mean solar time, UTO. It is then again corrected for migration of the Earth's poles to obtain UT1. This is further corrected by removing fluctuations of unknown origin to obtain UT2.

ZERO BEAT - the condition between two signals when no beat is heard or seen between the signals (when the frequencies are equal).

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This book is for the person who needs information about making time and frequency measurements. It is written at a level that will satisfy those with a casual interest as well as laboratory engineers and technicians who use time and frequency every day. It includes a brief discussion of time scales, discusses the roles of the National Institute of Standards and Technology (NIST) and other national laboratories, and explains how time and frequency are internationally coordinated. It also describes the available time and frequency services and how to use them. It discusses the accuracies that can be achieved with the different services, and the pros and cons of using various calibration methods.

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