Using LORAN-C Broadcasts for Automated Frequency Calibrations

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ABSTRACT
The LORAN-C (LOng RAnge Navigation) system is a radio navigation system maintained by the United States Coast Guard. LORAN-C signals are widely used as a navigation aid. Since the signals are extremely stable, they can also serve as an excellent reference for frequency calibrations. Any quartz, rubidium, or cesium oscillator can be calibrated with LORAN-C.

This paper tells how to use LORAN-C signals for frequency calibrations. It describes the LORAN-C system, lists the equipment that you need, shows the data you can obtain, and discusses the accuracy you can expect. It also discusses the NIST Frequency Measurement System, an automated calibration system that uses LORAN-C signals.

INTRODUCTION
Like all calibrations, a frequency calibration is simply a comparison. You compare the device being calibrated to a reference whose performance is known. The device being calibrated is usually a quartz, rubidium, or cesium oscillator. The reference is usually another oscillator (of higher performance) or a frequency signal received by radio.

There are several advantages to using radio signals for calibrations. First of all, nearly all radio calibration signals have a cesium oscillator at their source. A cesium oscillator is a nearly perfect source of frequency. Its relative frequency (frequency error) is about 1×10^{-13} per day. This means that a clock referenced to a cesium oscillator could potentially keep time within a few nanoseconds (billionths of a second) per day. Cesium oscillators are quite expensive both to buy ($30,000 - $80,000) and maintain, and not all calibration laboratories can afford them. It is usually far less expensive to buy a radio receiver and essentially "share" a cesium with many other users. Second, even if a calibration lab does have a cesium, they still need to check its performance. The only practical way to do this is by comparing the cesium's output to a radio signal.

Of course, some compromises are made when you use a radio signal for calibrations. The frequency source may be nearly perfect at its origin, but it loses accuracy due to variations that change the length of the radio path. For example, HF radio signals have large path variations. The frequency you can obtain from an HF station (like NIST stations WWV and WWVH) is only accurate to within about 1×10^{-7} per day. You can do much better (up to 1×10^{-11}) with LF and VLF radio stations (like NIST radio station WWVB) because the path variations are much smaller. LORAN-C can do even better. As we will discuss in this paper, LORAN-C is capable of producing frequency accurate to 1×10^{-12} per day, or good enough to meet the requirements of nearly any calibration laboratory.

LORAN-C is the best ground based calibration signal currently available. In fact, it compares favorably with some satellite systems currently in use. Satellite based systems have an advantage over ground based systems, however, because there is a clear path between the receiver and transmitter and nearly all path variations are due to satellite motion. Because of this, all future calibration signals will probably originate from satellites.

HOW LORAN-C WORKS

The LORAN-C navigation system consists of nearly 20 synchronized "chains" or networks of stations. These chains provide coverage for 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 two to four slave stations (designated as W, X, Y, and Z). The master station 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 pulses.

In order to navigate with LORAN-C, you must receive signals from three separate transmitters (the master and at least two slaves). However, you only need to receive one station for frequency calibrations. 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.

All LORAN-C stations broadcast on the same carrier frequency (100 kHz). Because of this, the receiver has to distinguish between signals broadcast from a number of different stations. Each 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) each 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 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 chain is 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 3 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. Figure 1 illustrates the way Loran-C pulses are transmitted.

The signal from each LORAN-C transmitter radiates in all directions. Part of the signal travels parallel to the surface of the Earth. This is called the groundwave. The rest of the signal travels upward and is reflected off of the ionosphere. This part of signal is called the skywave. Receiving the skywave is less desirable than receiving the groundwave, because the skywave signal "moves" around and produces a less stable frequency. This movement is caused by the motion of the ionosphere due to the rise and fall of the Sun. If you use the skywave for frequency calibrations, your accuracy may be less than 1×10^{-10} per day.

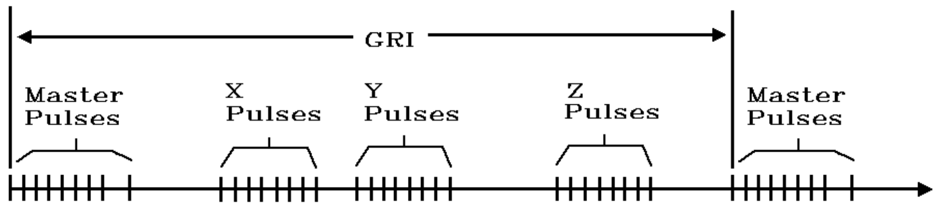

Figure 1. The Transmission Sequence of LORAN-C Pulses.

The groundwave is usually easy to receive in most populated areas in the Northern Hemisphere. You will usually receive the skywave only if the groundwave signal has traveled a long distance and is too weak and noisy for the receiver to track. If this happens, the receiver will lock to the skywave signal. If your receiver is within about 2400 kilometers (1500 miles) of a LORAN-C transmitter, you should be able to receive the groundwave.

LORAN-C transmits pulses so that the receiver can distinguish between groundwave and skywave signals. Most receivers are designed to track the third cycle of the pulse. A picture of a Loran-C pulse with the third cycle identified is shown in Figure 2. The third cycle is a good cycle to track for two reasons. First, it arrives early in the pulse so we know that it is groundwave. Second, it has considerably more amplitude than the first and second cycles in the pulse. This makes it easier for the receiver to track.

LORAN-C receivers don't need to track the third cycle in order to be a good frequency reference. Another groundwave cycle can be tracked, as long as the receiver stays locked to the same cycle. If the receiver loses the signal, it will normally move deeper into the pulse in order to find a stronger signal to track. Each time the receiver jumps cycles, a 10 microsecond step will show up in your calibration data (10 microseconds is the period of the 100-kHz carrier). If you have a good antenna and receiving system and are within 1500 miles of the transmitter, these cycle jumps are fairly rare.

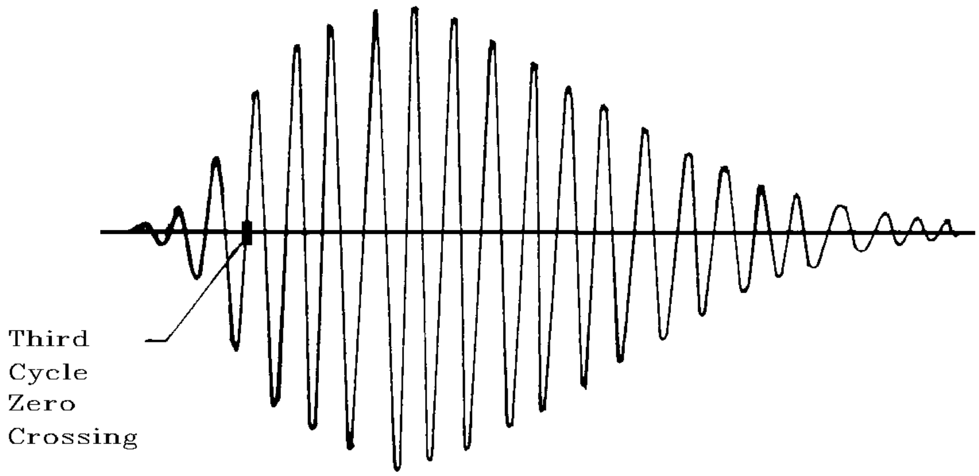

Figure 2. A LORAN-C Pulse with the Third Cycle Identified.

It should be noted that most modern LORAN-C receiver designs automatically handle the process of station selection and cycle selection. Therefore, knowing about these topics is not a prerequisite to operating a LORAN-C receiver. It is helpful, however, when you review your calibration data.

LORAN-C RECEIVING EQUIPMENT

There are two types of commercially-available LORAN-C receivers: timing receivers and navigation receivers. Timing receivers are made specifically for time and frequency calibrations. Since the market is fairly small, only a few companies manufacture these receivers. They range in price from about $3000 to $8000. Timing receivers have a multitude of features. They provide you with several different frequency outputs (usually 10 MHz and the GRI pulse are provided), and they are often capable of directly measuring the performance of an oscillator without purchasing any additional equipment. Some models have a computer interface, so that the data can be sent to a computer and stored.

LORAN-C navigation receivers are quite different. They are mass produced for the marine market and are very inexpensive (some cost as little as $200). However, navigation receivers were designed for navigation only. They were not designed for frequency calibrations and do not provide frequency outputs. Before you can use them for calibrations, they must be modified so that they output the GRI pulse. NIST has made this modification to several different navigation receivers, although it may not be possible on all models.

Unlike timing receivers, navigation receivers cannot be used as a complete calibration system. You must design a system around a navigation receiver before calibrations can be made. However, once a system is in place, navigation receivers seem to work just as well as timing receivers when used as a reference frequency.

In most parts of the Northern Hemisphere, LORAN-C signals are strong and easy to receive. An eight-foot vertical whip antenna is usually adequate for either type of LORAN-C receiver. The antenna should be mounted on a rooftop location, free from obstructions.

Nearly all LORAN-C receivers are now microprocessor controlled and very easy to use compared to earlier models. As mentioned earlier, these new receivers are automatic, whereas the old models were manually operated. In most cases, you simply type in the GRI from the front panel and the microprocessor does the rest. It distinguishes between signals from many different stations and picks out the station that you want to receive. It also locates and tracks a specific cycle in the pulse (usually the third cycle). Most receivers do all this in just a few seconds. And as an added bonus, the new receivers are smaller and less expensive than the older units.

USING THE GRI PULSE AS A REFERENCE FREQUENCY

To make frequency calibrations, you need to compare the LORAN-C reference frequency to the frequency output of the oscillator being calibrated. The method discussed here uses the Group Repetition Interval (GRI) pulse of the LORAN-C receiver as the reference frequency. This GRI pulse can be obtained from either a timing or navigation type receiver. The frequency output of the oscillator is usually either a 1, 5, or 10 MHz signal.

The preferred way of comparison is to plug both signals into a device called a *time interval counter* (TIC). A TIC measures the time interval between the two signals. One signal serves as a start pulse to the TIC, and the other serves as a stop pulse. The TIC starts measuring the time interval when the start pulse arrives, and stops measuring when the stop pulse arrives.

The GRI pulse is an excellent reference frequency, but it can be difficult to use. As we discussed earlier, possible GRI values range from 40,000 to 99,990 microseconds. For example, the United States Gulf of Mexico chain has a GRI of 79,800 microseconds. This means that the pulse is transmitted at a non-standard frequency of about 12.53 Hz. In order to use the GRI, a frequency divider is required.

NIST has designed calibration systems using two types of frequency dividers. The first type uses an odd-rate divider that divides the oscillator frequency until it is the same frequency as the GRI. The odd-rate divider is set using switches on the front panel and can produce any possible GRI frequency. For example, you could plug a 5 MHz oscillator into one of these dividers and produce a frequency with a period of 79,800 microseconds to match the GRI of the 7980 chain. These two signals can then be plugged into a TIC and compared. If you use this method, the largest possible TIC measurement will be equal to the period of the GRI.

The latest method employed by NIST is to use a TIC with built-in frequency dividers. This unit accepts the GRI as the start pulse and uses the oscillator output as the stop pulse. The oscillator output is automatically divided to 10 kHz. This works, because the period of 10 kHz is 100 microseconds, and the GRI pulses are always an even multiple of 100 microseconds. If you use this method, the largest possible TIC measurement is 100 microseconds.

After you get the TIC measurements, they must be recorded. The preferred way of doing this is to have a computer read the TIC and display, process, and store each measurement. A series of 5 measurements might look like this:

45.67
45.68
45.69
45.70
45.71

Each number in the above series represents one time interval measurement from a counter with 10-nanosecond resolution. The unit is microseconds. For example, at the time of the first measurement the two signals were 45.67 microseconds apart. The 45.67 has no particular significance. It's just an arbitrary number used as an example. What is significant is the way the numbers change from measurement to measurement. For example, the difference between the first number in the series (45.67) and the last number (45.71) is 0.04 microseconds (40 nanoseconds). This difference means that one signal is moving or drifting relative to the other signal. This drift must be measured in order to make a calibration.

You can measure the amount of oscillator drift by taking the difference between each pair of measurements, and then adding the differences together. The sum of the differences is the oscillator drift. The measurement period is the length of time over which measurements were made. For example, if measurements were made for 24 hours, the measurement period is 24 hours. The relative frequency (frequency error of the oscillator being calibrated) is calculated as follows:

$$\mathbf{RF} = \frac{\textbf{Oscillator Drift}}{\textbf{Measurement Period}}$$

To illustrate, let's say that the oscillator drifts 1 microsecond over a 24-hour period. The measurement period is 24 hours, but must be converted to the same unit as the oscillator drift (microseconds). There are more than 86 billion microseconds in 24 hours, so the equation becomes:

$$\mathbf{RF} = \frac{\mathbf{1}}{\mathbf{86{,}400{,}000{,}000}}$$

As you can see, as the drift gets smaller, the number used to state relative frequency gets smaller. In other words, the smaller the relative frequency number, the better the oscillator. Since the relative frequency is such a small number, it is usually converted to scientific notation:

$$\mathbf{1.16 \times 10^{-11}}$$

The relative frequency states the oscillator's performance. As we mentioned earlier, LORAN-C is accurate enough to calibrate oscillators with a relative frequency as high as 1×10^{-12}.

AN AUTOMATED FREQUENCY CALIBRATION SYSTEM USING LORAN-C

You can assemble an automated frequency calibration system if you have the proper hardware and software. Some of the required hardware has already been discussed: the LORAN-C receiver and antenna, a time interval counter, and a frequency divider. You also need a computer system to interface to the time interval counter, and a printer so you can print out the results of your calibrations. With the appropriate software, this type of system can make unattended calibrations, 24 hours a day, 7 days a week and provide you with a continuous record of the performance of your frequency standard.

An automated LORAN-C system can provide a complete solution to nearly all frequency measurement and calibration problems. These systems are easy to set up and use, they run without operator attention, and they provide high accuracy frequency calibrations that are traceable to NIST.

NIST has designed an automated frequency calibration system using the techniques described in the previous sections. This system is leased to users of the NIST Frequency Measurement Service. NIST provides complete support for this system, and immediately replaces any parts that fail. For more information about this service, you can call NIST at (303) 497-3378 or (303) 497-3212, or write to: Michael Lombardi, NIST, Division 847, 325 Broadway, Boulder, CO 80303.

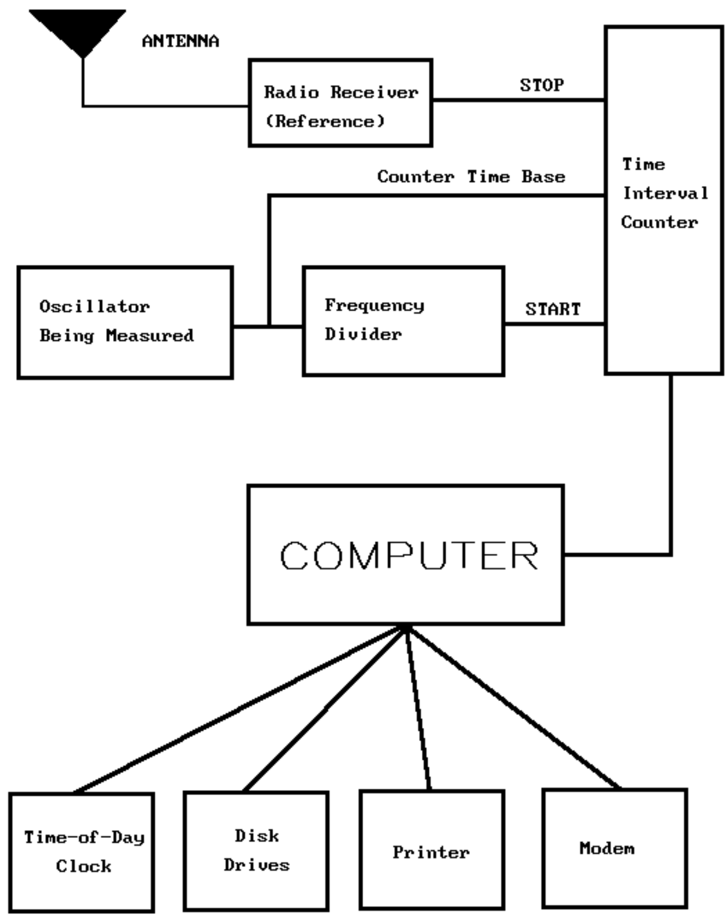

Figure 3. Block Diagram of the NIST Frequency Measurement System.

Figure 3 is a block diagram of the hardware used in the NIST system. NIST also provides software that records, stores, and graphs the data automatically. The results of any previous calibrations can be retrieved at any time. All calibration data is presented using full-color, easy to understand graphics displays.

The NIST system uses a 4-channel time interval counter, so up to 4 oscillators can be calibrated at one time. And as part of the measurement service, each system is connected to NIST by modem. Each subscriber to the service has their data verified by NIST and receives a monthly report that certifies traceability.

In the next section, we'll look at some LORAN-C data recorded and graphed with the NIST Frequency Measurement System.

LORAN-C PERFORMANCE

This section contains a number of graphs showing the type of performance you can typically expect from LORAN-C. Most users in the United States should be able to achieve results as good or better than those shown here. As listed in the table below, there are 7 LORAN-C master stations in the continental United States. Six of the 7 (5930 is the exception) are within 2400 kilometers (1500 miles) of Boulder, Colorado and are monitored daily by NIST.

5930	Caribou, Maine
7980	Malone, Florida
8290	Havre, Montana
8970	Dana, Indiana
9610	Boise City, Oklahoma
9940	Fallon, Nevada
9960	Seneca, New York

Table 1. LORAN-C Master Stations in the Continental United States.

As the graphs will illustrate, LORAN-C is almost unequaled as a frequency calibration source. You can think of LORAN-C as a cesium oscillator that is being delivered to your site by radio. In fact, in the long run LORAN-C is better than a single cesium, because each transmitter site has 3 cesium oscillators that are constantly being "steered" to produce the most accurate frequency possible.

Of course, LORAN-C isn't perfect. Like all radio calibration signals, its accuracy is reduced by variations in the radio path. Even the LORAN-C groundwave is subject to small variations in the amount of time required for a GRI pulse to get from the transmitter to your receiver. The size of these variations depends upon the signal strength, the weather and atmospheric conditions, and the quality of your receiver and antenna.

Figure 4 shows the type of path variations you can typically expect. It shows a comparison between the LORAN-C 9940 chain as received in Boulder, Colorado, and the NIST national frequency standard. The 9940 broadcast is from the master station in Fallon, Nevada. This station is about 1152 kilometers (720 miles) from Boulder.

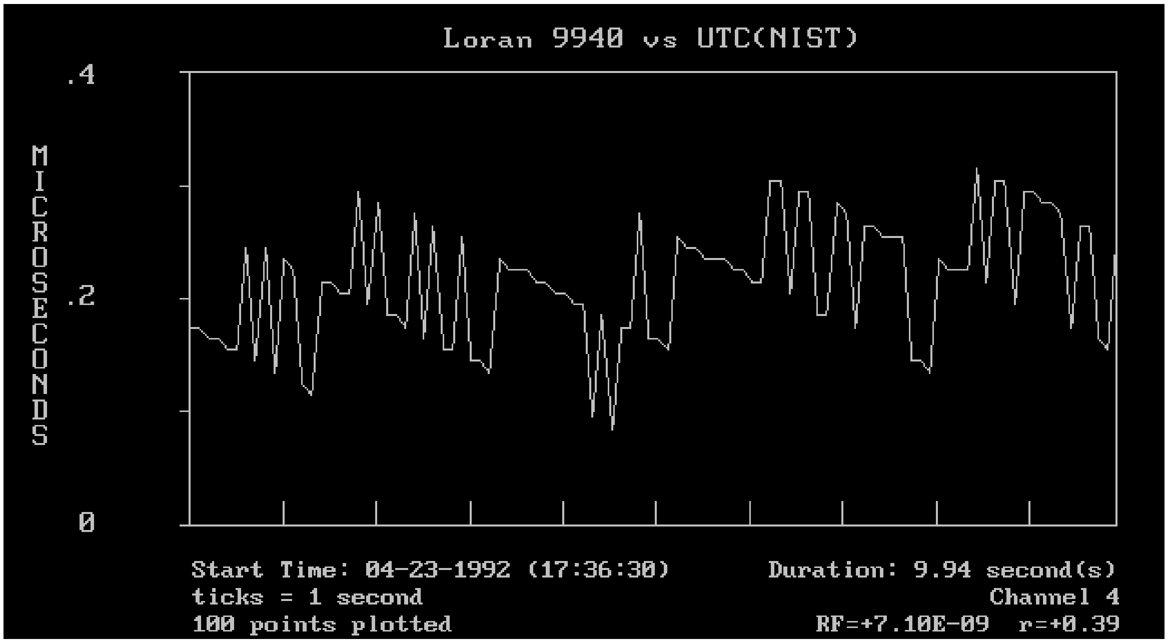

Figure 4. LORAN-C path variations over a 10-second period.

The graph in Figure 4 was created by comparing 100 consecutive GRI pulses from the 9940 chain to the NIST national frequency standard. The measurement period was 9.94 seconds (100 x 99,400 microseconds). During this short period, the drift between the NIST frequency standard and the cesium oscillators at the LORAN-C transmitter is negligible. Therefore, the data on the graph is simply the LORAN-C path noise, or the difference in the arrival times of the GRI pulses due to path variations. As you can see from the graph, the range of the path noise is about 200 nanoseconds. In some cases, the difference in the arrival times of 2 consecutive GRI pulses exceeds 100 nanoseconds.

The path noise repeats itself and can be averaged out over longer time periods. To illustrate this, Figure 5 shows a comparison where the measurement period is 10 times longer (1000 GRI measurements instead of 100). As you can see, the range of the data is about the same as it was in Figure 4.

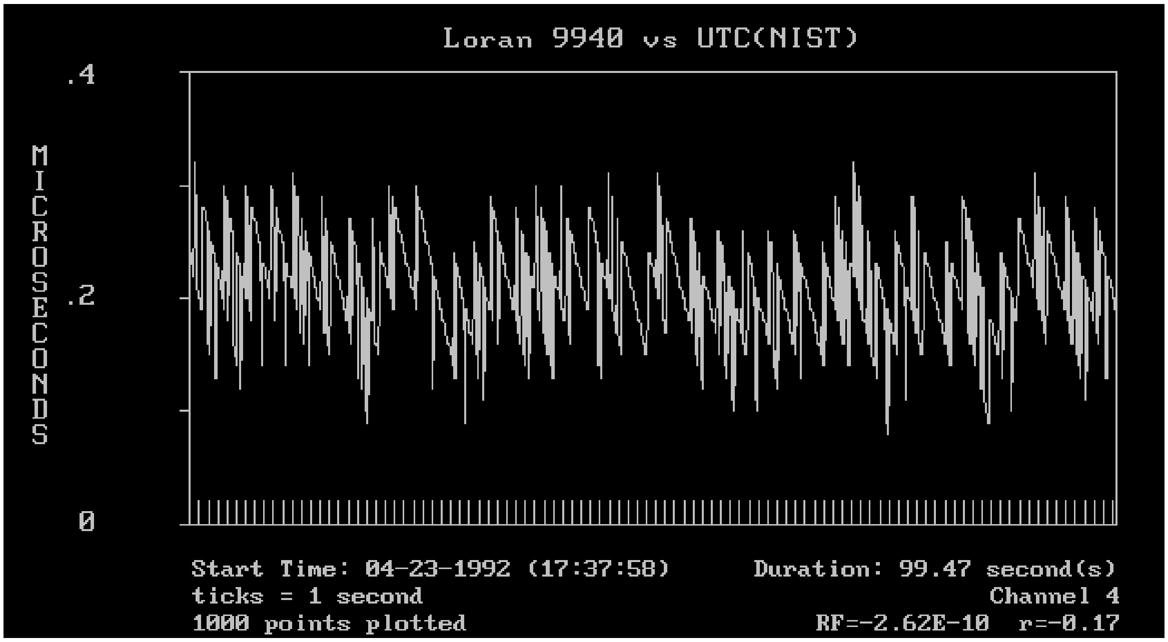

Figure 5. LORAN-C path variations over a 100-second period.

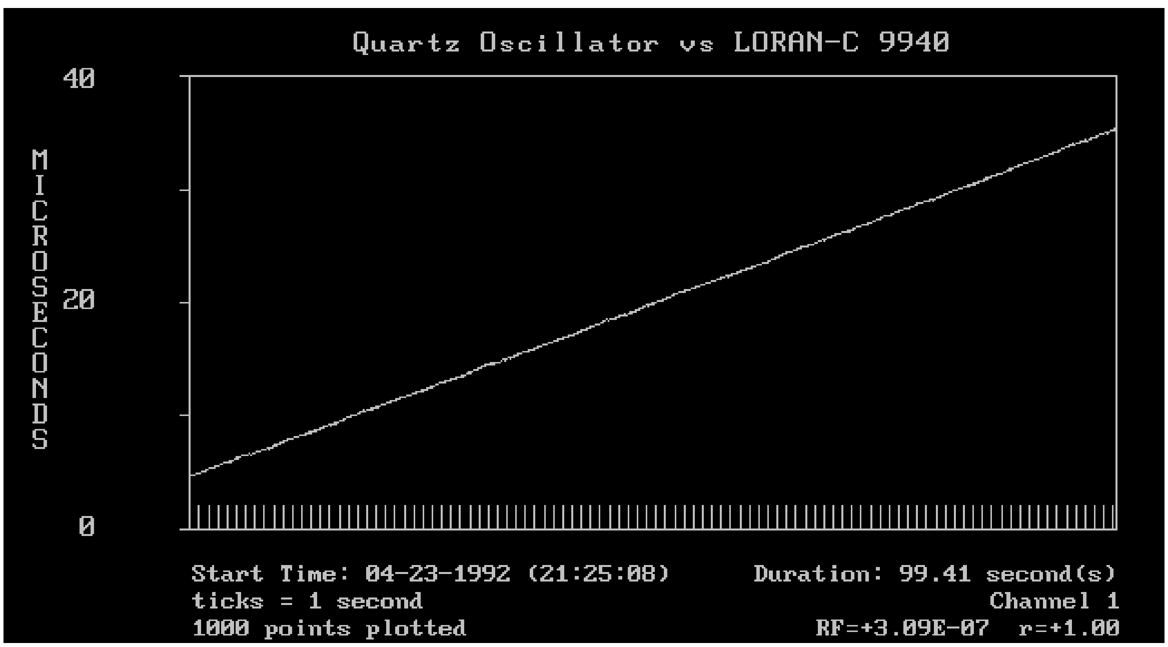

Figure 6. Quick Calibration of a low-quality Quartz Oscillator.

Although the path noise does average out, it still influences the time required to make a calibration. The better the oscillator, the longer it takes to calibrate. For example, a rubidium oscillator may only drift about 1 microsecond in 24 hours. Since oscillator drift is linear, you can calculate that it will drift just slightly more than 1 nanosecond in a 100-second measurement period. Can you calibrate a rubidium using LORAN-C in 100 seconds? No. The 200 plus nanoseconds of path noise will hide the 1 nanosecond of oscillator drift. You need to wait much longer before you can separate the oscillator drift from the path noise.

If you have a fast drifting oscillator, however, you can use LORAN-C to make a quick calibration. Figure 6 shows the performance of an oscillator that is high in frequency by about 3×10^{-7}. This type of oscillator is commonly found in test equipment like signal generators and counters. Notice that Figure 6 has the same measurement period as Figure 5 (100 seconds). However, none of the path noise present in Figure 5 is visible in Figure 6. The path noise is hidden by the oscillator drift.

The NIST Frequency Measurement System uses a 24-hour measurement period for calibrations. When a 24-hour measurement period is used, the path noise is not a problem when calibrating quartz or rubidium oscillators. This is because the LORAN-C signal is more accurate than the oscillator output. For example, Figure 7 shows a precision quartz oscillator with a relative frequency of 1×10^{-10} compared to LORAN-C. The data is very smooth, and the path noise is not noticeable. For this type of calibration, using LORAN-C works just as well as using the NIST national frequency standard.

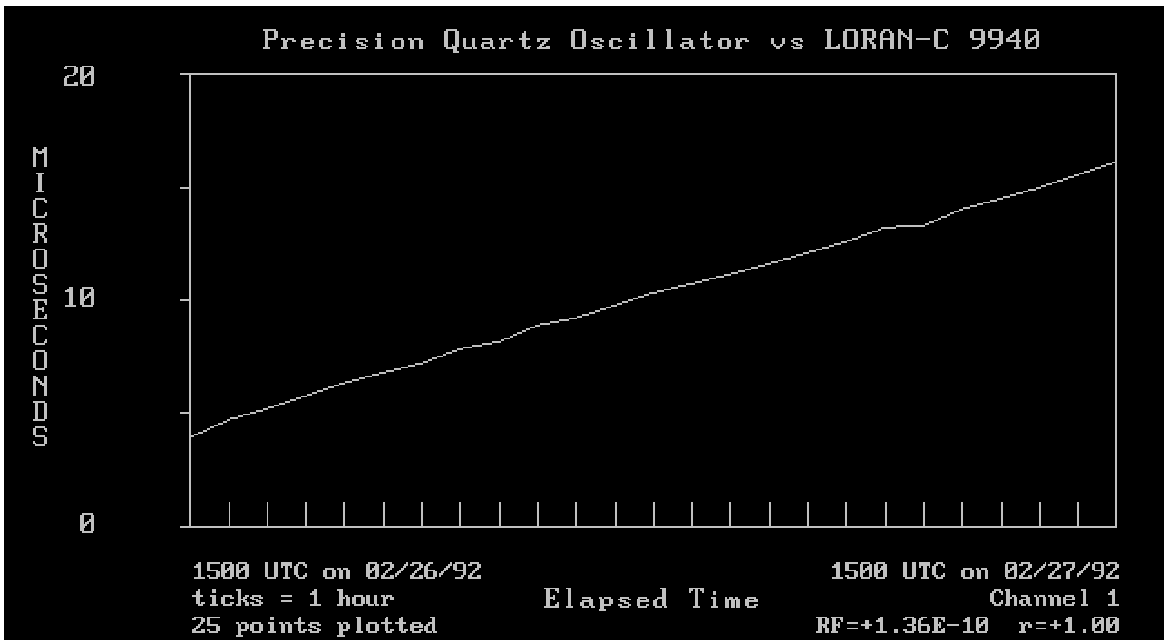

Figure 7. A 24-hour comparison of a Quartz Oscillator to LORAN-C.

When calibrating rubidium oscillators, the path noise is slightly more noticeable over a 24-hour period, but still does not change the results. Figure 8 shows the results of a comparison between a rubidium and the 9610 chain. The rubidium frequency is high by about 2×10^{-11}. The thick line on the graph is an estimate of the actual oscillator performance. This line varies from actual data by a small amount due to the path noise, but the results of the calibration are not changed.

When calibrating cesium oscillators, 24 hours may not be long enough. Figure 9 shows the results of a 24-hour comparison between a cesium and the 9940 chain. The thick line is an estimate of the oscillator drift. However, since the path noise is so pronounced, it is difficult to know if this estimate is valid.

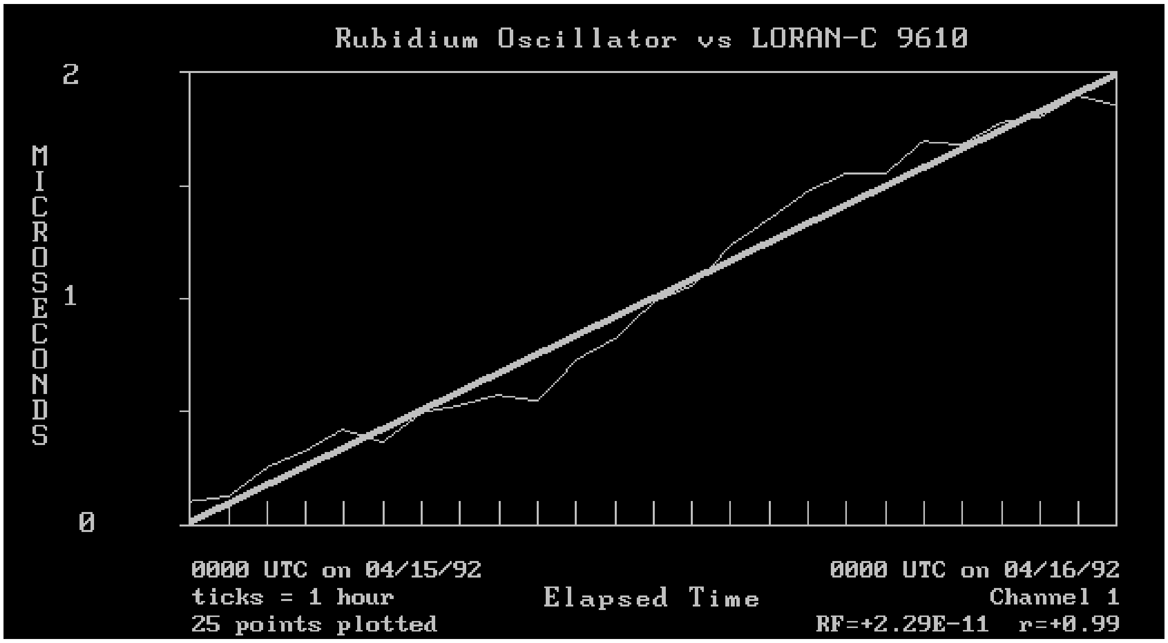

Figure 8. A 24-hour comparison of a Rubidium Oscillator to LORAN-C.

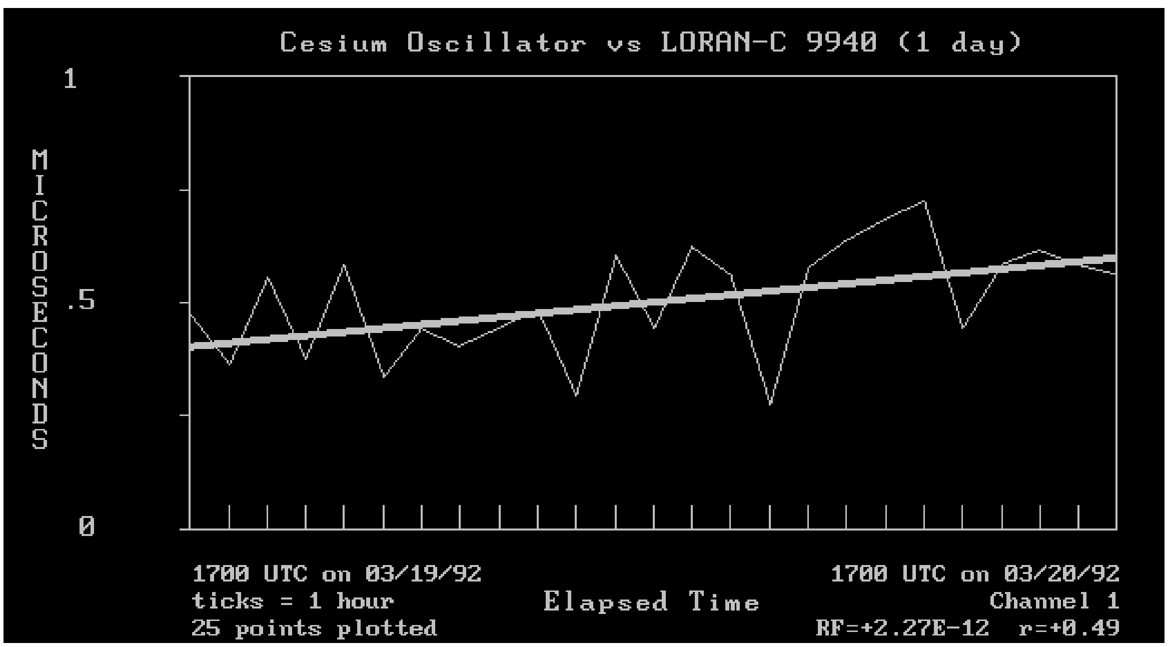

Figure 9. A 24-hour comparison of a Cesium Oscillator to LORAN-C.

When we add 72 more hours of data to the graph in Figure 9, we can clearly see that the cesium is drifting relative to LORAN-C. This graph is shown in Figure 10. Because of the path noise, this graph is not as smooth as the ones shown earlier in Figures 7 and 8. However, we can clearly see that the cesium frequency is high relative to LORAN-C by about 2×10^{-12}.

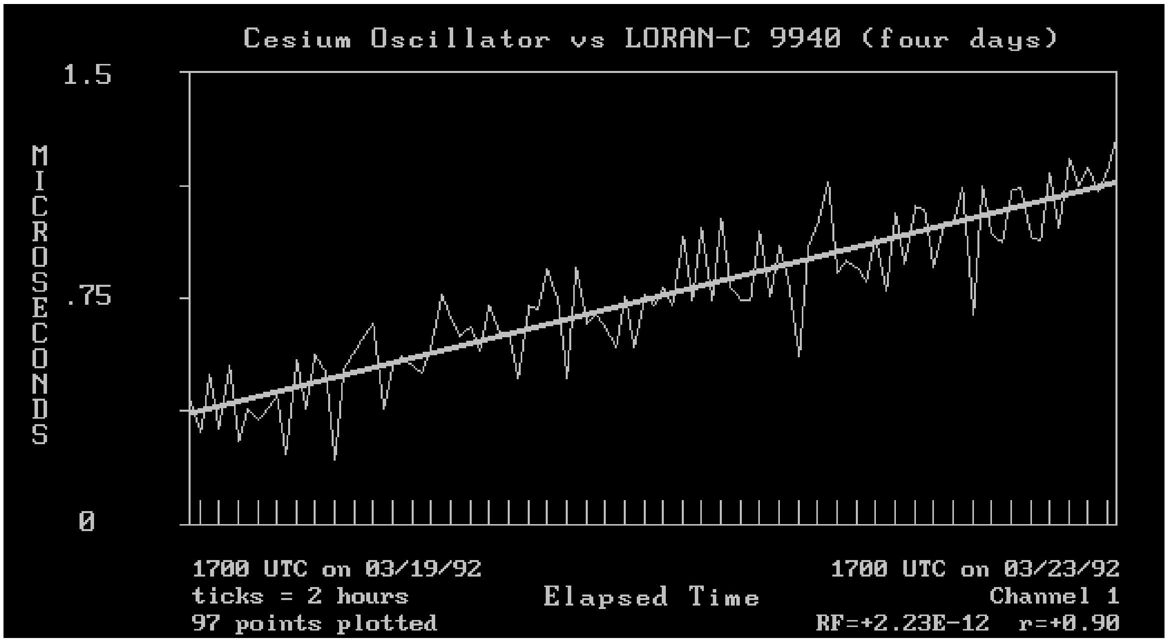

Figure 10. A 96-Hour comparison of a Cesium Oscillator to LORAN-C.

SUMMARY
A LORAN-C based frequency calibration system can provide a complete solution to nearly all frequency measurement and calibration problems. The stable LORAN-C pulses are an excellent, low cost reference frequency with enough accuracy to calibrate any type of oscillator.