EXPERIENCE AT THE CENAM WITH TIME AND FREQUENCY STANDARDS SIGNALS RECEIVED BY THE GLOBAL POSITIONING SYSTEM (GPS)

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Abstract

The Time and Frequency Division of the Centro Nacional de Metrologia (CENAM) in Mexico has been working along two years with two high-stability signals reception systems: GPS and LORAN-C. We have determined the frequency stability of these systems using a cesium standard as the national reference. In Mexico this kind of research had not been done until now.

In this paper a general review about advantages and disadvantages of different frequency and time dissemination systems is given. Then we expose the results of experimental research on frequency stability of GPS and LORAN-C for an averaging time of from 1 s to 1 day for different observation days. Finally we present the results of experimental research on electromagnetic interference around GPS receiver antenna, delay, and attenuation introduced by the transmission line. A time difference measurement system developed by staff of CENAM at the National Research Council (NRC) in Canada is used in order to calculate the frequency stability. Time domain measurements to calculate frequency stability for GPS and LORAN-C systems are employed.

1 INTRODUCTION

In recent times high-precision and high-stability oscillators, combined with modern techniques of communications systems, make possible the generation of common time and frequency reference signals and their dissemination via radio frequencies (RF). This is the responsibility for any time and frequency primary lab, which has two main activities. The first one is the generation and maintenance of the frequency and time national standards and the second one is the dissemination of these national standards to all potential users. Time and frequency metrology has a great importance in a multitude of essential services like high-speed communications systems, navigation systems, digital telecommunication networks, telephone, TV, and broadcast services. Also, it is of concern to the efficient use of the electromagnetic spectrum to warn about possible interference conditions, e.g. in geophysics, geodesy, radioastronomy, spacetracking, etc. Specifically the fundamental roles of high-stability time and frequency signals in our country are actually in the communications field. But in general the number of very demanding users in these and others fields in all of the world increase continuously. In this sense accuracy and precise means for dissemination of time and frequency standard signals traceable to national and international standards have assumed great importance recently.[1]

We can distinguish three general methods to disseminate frequency and time standard signals: (1) using portable clocks, (2) using some communication systems which employ a physical medium as the transmission medium, and maybe the most important dissemination method (3) using any communication system which employs free space as the transmission medium.

The third general method can be sub-classified according to the electromagnetic spectrum division realized by the ITU. Each band in the electromagnetic spectrum is identified by its name and its number. The bands dedicated to broadcast frequency and time services have been numbered from 4 to 9. But some other signals intended for some established systems like navigation can be included in this classification. So we have the following broad subdivisions:

1. High Frequency, HF (band 7: 3 MHz - 30 MHz), standard time and frequency broadcast services. The typically gotten frequency stability in this band is 1×10^{-7} per day. This is mainly due to several factors such as ionospheric reflections from E, F1, or F2 layers, depending on distance, frequency, time of day, and conditions of the ionosphere.[1]

2. Low Frequency, LF (band 5: 30 kHz - 300 kHz), standard frequency broadcast services and the Long Range Navigation, LORAN-C system. LF signals propagate between the bounds of the ionospheric D layers and earth and are, thus, guided around the curvature of the earth to great distances with low attenuation and excellent stability. But several factors such as propagation over water or dry land, solar activity, atmospheric disturbances, and daily ionospheric height changes, besides other factors, considerably limit the attainable accuracy of time transfer and frequency stability, except in the case of groundwave propagation for short distances from the transmitter where the ionosphere is not involved; in this case typical frequency stability is 1×10^{-11} per day.

In this classification we also consider LORAN-C system, which is an accurate navigation system that is maintained by the U.S. Coast Guard in the U.S. A receiver that measures the arrival times of the signal from three LORAN stations can determine its position with an accuracy of about 100 feet at a range over 1,000 miles. Because of the desire for good long-range position accuracy, the frequency and transmission time of each LORAN transmitter is controlled by a set of cesium clocks or hydrogen masers whose frequency accuracy is maintained by the U.S. Naval Observatory. Because the timing characteristics of the LORAN transmission are so tightly controlled, a receiver measuring the signal from a single LORAN station can produce a very accurate frequency output that is traceable to the U.S. Naval Observatory and NIST. LORAN-C stations transmit a pulsed signal at a carrier frequency of 100 kHz. Transmissions of the various stations are differentiated by the timing of their pulses. The LORAN transmitters in a specific geographical region are arranged in groups of at least three to at most six stations called chains, which are differentiated by the repetition rate of the pulses transmitted by the stations in the chain. This rate is called the Group Repetition Interval or GRI. For example, the South Central USA chain has a GRI of 96,100 microseconds and each station in that chain (six stations in total) will transmit its signal once every 96,100 microseconds. If the receiver synchronizes its timing with the desired GRI, only stations in that GRI will produce a stable signal.[7]

3. Very Low Frequency, VLF (band 4: 3 kHz - 30 kHz), communication transmissions and the OMEGA system. VLF propagation is similar to that of LF signals which propagate between the bounds of the ionospheric D layer and earth. Typical frequency stability in this band is 1×10^{-11} per day or better.[1]

4. Ultra High Frequency, UHF (band 9: 300 MHz - 3 GHz), communication transmissions and the Global Positioning System (GPS).[1] UHF signals are very stable. Most of the limitations described above for the HF, VLF, and LF bands are overcome by satellite-based dissemination. The atmospheric radio noise in the UHF band is almost negligible so the signal-to-noise ratio is dictated by the receiver thermal noise, although multipath distortion and fading may be present. Relatively low power of transmission is required for hemispheric coverage of satellite signals with excellent stability. Directional antennas are advisable; both antenna and equipment complexity tend to increase, especially at the higher frequencies. The obtained precision is comparable or better than that gotten by using ground-based dissemination systems.

The users which use satellite-based dissemination can operate in one-way and two-way modes. In the first case the user operates in a passive mode, simply receiving the time information directly from the satellite. There are currently five regularly operational satellite broadcasts that can be considered as one-way satellite time dissemination systems; these are briefly described in [3]. The Global Positioning System is considered as being in the one-way category. A complete description of this system can be reviewed in [5].

2 FREQUENCY STABILITY OF STANDARD FREQUENCY SIGNALS

Frequency stability is a term used to characterize the variations in frequency exhibited by high-stability frequency signals and it is also employed when two oscillators are compared. In the IEEE standard (No. 1139-1988) for *"Standard Terminology for Fundamental Frequency and Time Metrology"* are defined the Allan variance (AVAR) and the modified Allan variance (MVAR) as the time-domain stability measures. AVAR is a useful means of characterizing a clock's frequency stability and MVAR is an accepted measure of the performance of time and frequency transmission systems and telecommunication networks.[6] The Allan variance for overlapping samples is defined as[9]:

$$\sigma_y^2(\tau) = \frac{1}{2\tau^2(N-2m)} \sum_{i=1}^{N-2m} (\chi_{i+2m} - 2\chi_{i+m} + \chi_i)^2 \qquad (1)$$

where χ represents phase measured in time units[10], N is the total number of phase measurements or time interval difference spaced by a sampling time, τ_0, and there is no dead time between measurements. The averaging time, τ, is given by $m\tau_o$, where m is the number of measurements that will be considered. Analogously, the modified Allan variance is defined as follows:

$$mod\ \sigma_y^2(\tau) = \frac{1}{2\tau^2 m^2(N-3m+1)} \sum_{j=1}^{N-3m+1} \left[\sum_{i=j}^{m+j-1} (\chi_{i+2m} - 2\chi_{i+m} + \chi_i)^2 \right] \qquad (2)$$

There are several methods by which to measure frequency stability for frequency standards and their signals received from a radio dissemination system. One of them is the so-called Dual Mixer Time Difference System (DMTD).[8] And this is the measurement technique used in this experimental research. DMTD was constructed by staff of CENAM at the NRC in Canada; it has 32 channels for 5 MHz high-stability signals compatible with generated signals by cesium or rubidium frequency standards and GPS or LORAN-C receiver outputs. The DMTD is used with a 4.9995 MHz offset oscillator to have a 500 Hz beat frequency and get a resolution improving factor of 1×10^4 with respect to direct measurements taken with a time interval counter. The noise level is as low as 1×10^{-13} for an averaging time of 1 s and the bandwidth is 500 Hz; acquisition is continuous and automatic with an RS-232 communication interface. No dead time between measurements is present.

3 FREQUENCY STABILITY OF STANDARD FREQUENCY SIGNALS RECEIVED BY GPS AND LORAN-C SYSTEM AT THE CENAM

In the GPS the carrier phase and pseudorange are affected by Selective Availability (SA), ionospheric and tropospheric effects, frequency instability in satellites' clocks, frequency instability in receiver clocks, relativistic effects, multipath, potential interference conditions, and random phase noise, and in general there are aging, drifts, and frequency instabilities in all oscillators, amplifiers, and electronic devices used in any communication system, for example frequency up/down converters.

On the other hand, instabilities in frequency standards signals from LORAN-C are linked to subionospheric radio propagation and interference conditions between sky wave and ground wave, and in general there are aging, drifts, and frequency instabilities in all oscillators, amplifiers and others electronic devices involved in any radio dissemination system.

We can have very slow and/or fast phase variations present in GPS and LORAN-C frequency standard signals. The effect of each factor that degrades the high frequency stability present in the origin station can be considered as one of the five types of noise present in a frequency standard signal.[10]

Prior to measuring the frequency stability of the frequency standard signal with GPS and LORAN-C, measurements were made of delay and attenuation in the transmission line which was used with the receiver equipment. So the electromagnetic environment surrounding the GPS receiver antenna was characterized using the ground magnetic North as reference to stand the antenna. Several antennas were used in different frequency ranges: From 200 MHz to 1300 MHz both a conical log spiral antenna and log periodic dipole antenna were used; from 1000 MHz to 1500 MHz a double-ridged guide horn antenna was used. The implemented system is showed in Figure 1 and in the worst case the obtained level at the input of the antenna was lower than -50 dBm.

Day-by-day reception of frequency standards signals from GPS at CENAM has been excellent. So it has been possible to calculate the frequency stability for these signals for an averaging time of from 1 s to 1 day using a Dual Mixer Time Difference System. But LORAN-C reception was interrupted every day; better reception was obtained usually at nights, after 20:00 hrs, and seldom in the mornings. The GRI programmed was 96,100 microseconds and the frequently received station was Raymondville, Texas. So we have no time interval difference or phase shifts measurements for continuous days; it was possible to calculate only frequency stability for averaging times less than one day. The system shown in Figure 2 was implemented to measure frequency stability for GPS and LORAN-C.

Typical GPS frequency standard signals are shown in Figures 3-5 for several elapsed times. And typical LORAN-C frequency standard signals are shown in Figures 6-8 for the same elapsed times taken into account for GPS, but on different days. These graphs show the reconstructed phase signals from the original data files obtained from DMTD. After reconstructing the phase signals we applied algorithms to calculate AVAR and MVAR for several averaging times. The obtained results for an averaging time of from 1 s to less than 1 day are shown in Table 1. And the results of frequency stability for GPS for an averaging time of from 1 day to 8 days are illustrated in Figure 9. In this figure ranges of several days are shown: the graph titled "A" means frequency stability from MJD 50365 to MJD 50394 and the graph titled "B" is from MJD 50289 to MJD 50313.

Table 1. Frequency stability for GPS and LORAN-C for an averaging time of from 1 s to 170 minutes.

Averaging Time [s]	LORAN-C		GPS	
	AVAR	MVAR	AVAR	MVAR
1	1.52×10^{-11}	1.52×10^{-11}	8.52×10^{-11}	8.52×10^{-11}
2	2.18×10^{-11}	2.04×10^{-11}	1.01×10^{-10}	8.67×10^{-11}
4	3.24×10^{-11}	2.97×10^{-11}	1.15×10^{-10}	9.46×10^{-11}
8	4.62×10^{-11}	4.09×10^{-11}	1.45×10^{-10}	1.23×10^{-10}
16	6.11×10^{-11}	5.24×10^{-11}	2.10×10^{-10}	1.66×10^{-10}
32	6.92×10^{-11}	5.87×10^{-11}	2.63×10^{-10}	1.95×10^{-10}
64	9.10×10^{-11}	8.33×10^{-11}	3.12×10^{-10}	2.58×10^{-10}
128	1.35×10^{-10}	1.23×10^{-10}	3.97×10^{-10}	2.78×10^{-10}
256	1.50×10^{-10}	1.14×10^{-10}	2.35×10^{-10}	7.93×10^{-11}
512	9.90×10^{-11}	5.39×10^{-11}	1.37×10^{-10}	5.23×10^{-11}
640	7.81×10^{-11}	5.89×10^{-11}	7.39×10^{-11}	4.11×10^{-11}
1280	5.45×10^{-11}	3.93×10^{-11}	4.08×10^{-11}	1.85×10^{-11}
2560	3.40×10^{-11}	2.15×10^{-11}	1.92×10^{-11}	6.99×10^{-12}
5120	1.81×10^{-11}	1.17×10^{-11}	1.04×10^{-11}	3.32×10^{-12}
10240	1.26×10^{-11}	7.27×10^{-12}	5.20×10^{-12}	8.44×10^{-13}

4 CONCLUSIONS

There was no condition of important interference with the GPS standard signals, so we can obtain high-stability frequency and time standards. And we have gotten phase shifts measurements for several consecutive days, so we have determined the frequency stability for one day. But the nearest and frequently locked stations of LORAN-C system at CENAM, Queretaro, Qro. were Raymondville, Texas, and Gillette, Wyoming, both in GRI 96,100 microseconds. And we obtain better performance when we lock the signal transmitted by Raymondville; usually this happens only at nights and seldom in the mornings. We think that distance (more than 1,500 km) was a critical factor to this situation. The results obtained are important because this is a preliminary work necessary for future research on simultaneous reception. We are planning to begin a coordinated comparison, common view by co-located receivers and by receivers separated by several thousand kilometers, like those at the primary labs NIST and NRC.

The results for the frequency stability of the GPS and LORAN-C systems obtained were those expected by theory. So this means that the Time and Frequency Division of CENAM has reliable high-stability signal reception and measurement systems. Accordingly, currently CENAM is a contributor to UTC. And we confirmed the usefulness of GPS due its great advantages with respect to the other radio dissemination techniques, because even with SA, the most important features of GPS include its high positional accuracy in three dimensions, global coverage, all-weather capability, continuous availability to an unlimited number of users, accurate timing capability, and ability to meet the needs of a broad spectrum of users.

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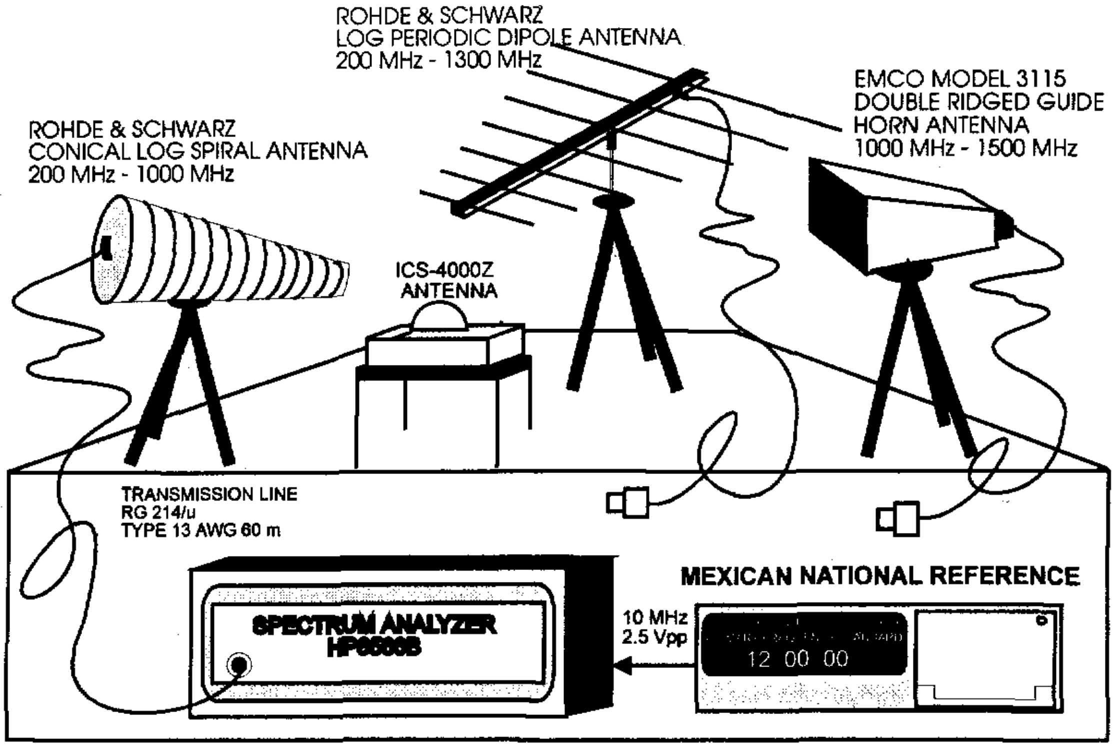

Figure 1. Implemented system to characterize the electromagnetic environment surrounding the GPS receiving antenna.

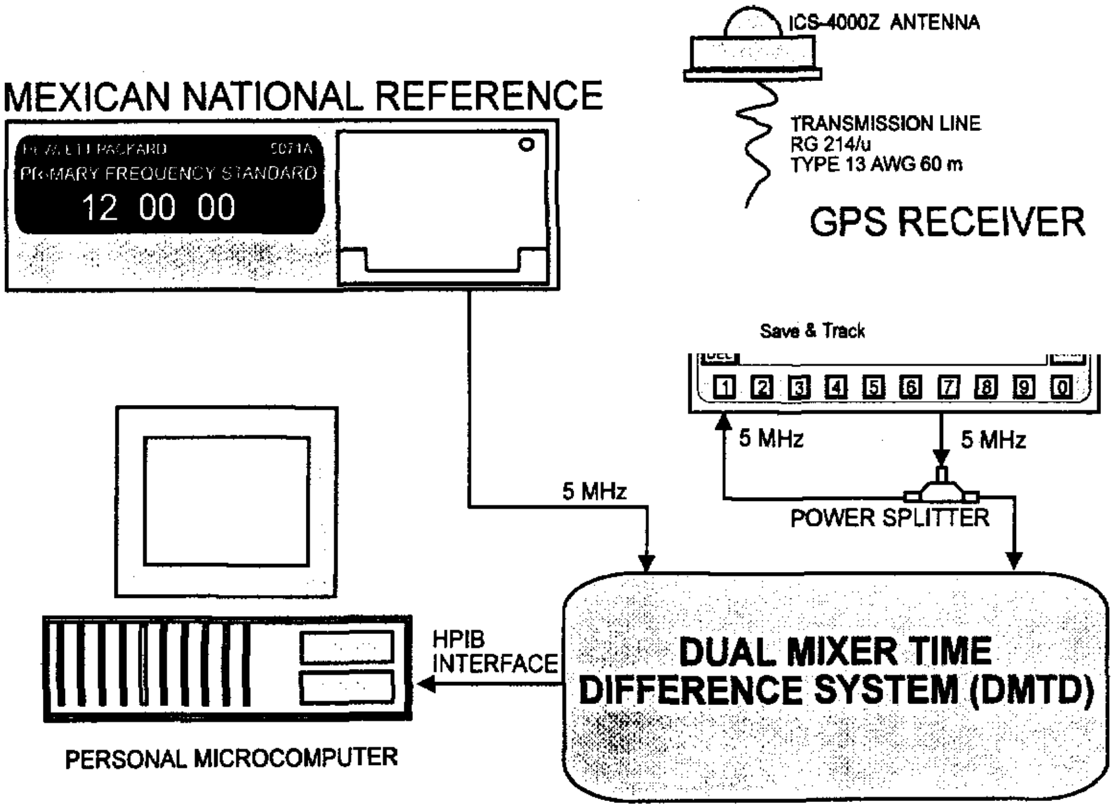

Figure 2. Implemented system to measure frequency stability for GPS and LORAN-C system.

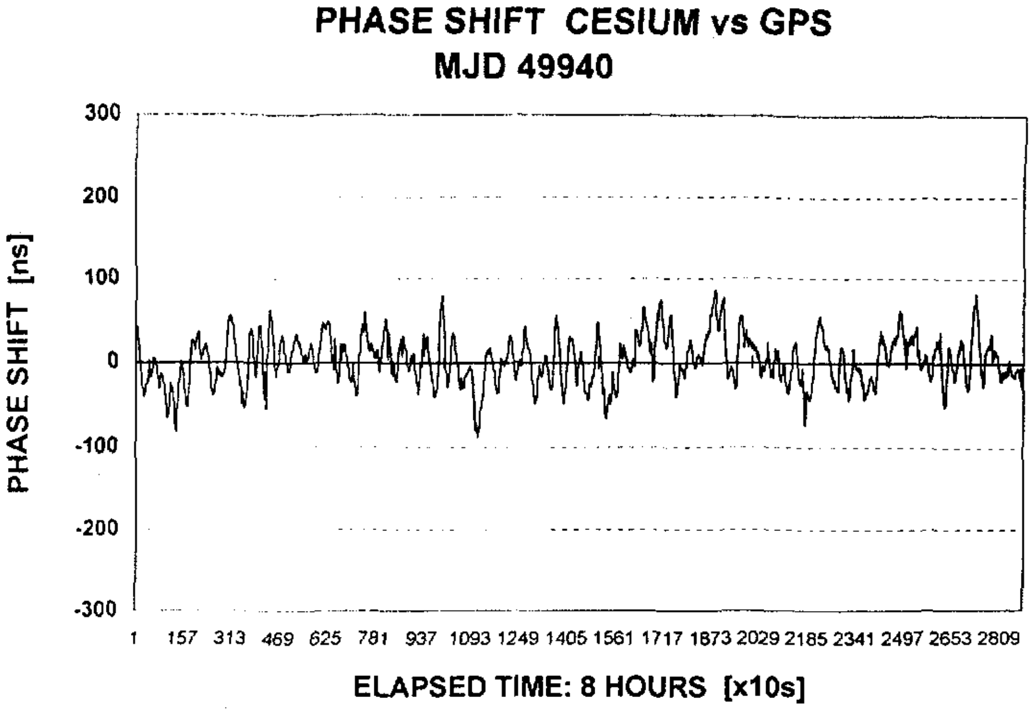

Figure 3. Typical standard frequency signal from GPS (elapsed time: 8 hours).

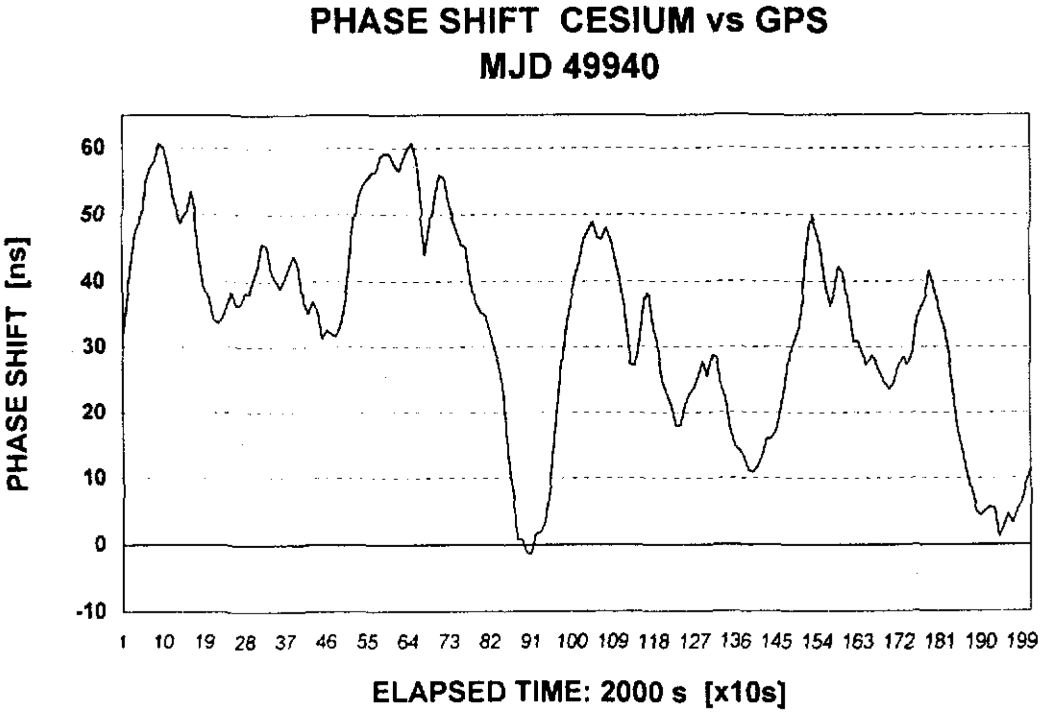

Figure 4. Typical standard frequency signal from GPS (elapsed time: 2,000 s).

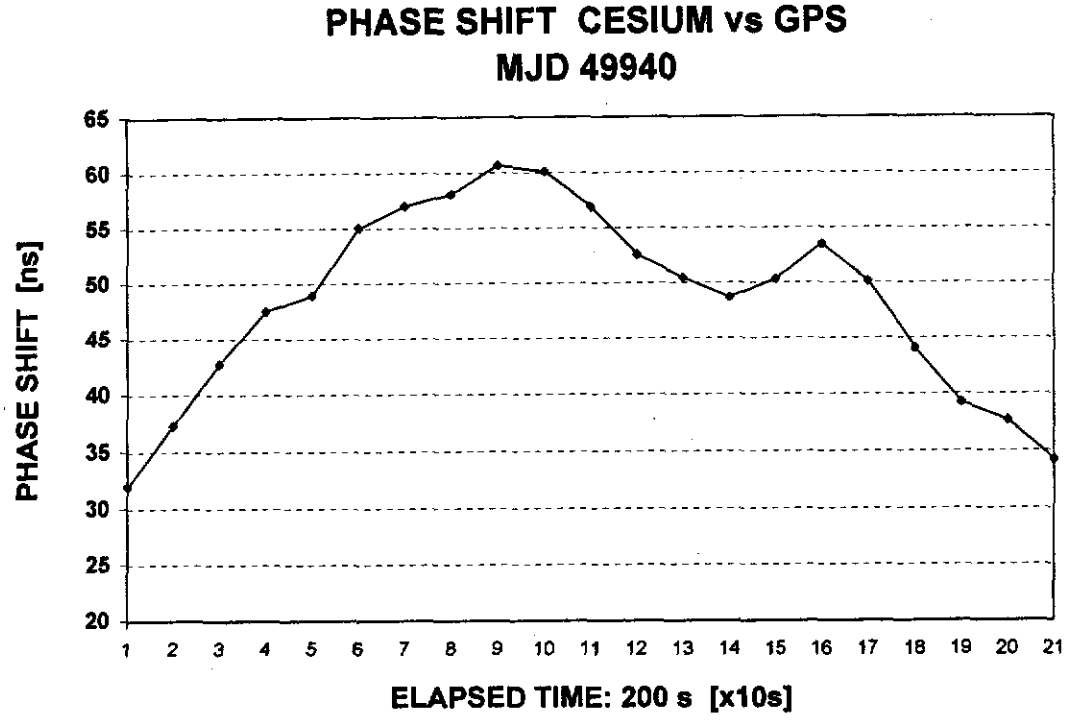

Figure 5. Typical standard frequency signal from GPS (elapsed time: 200 s).

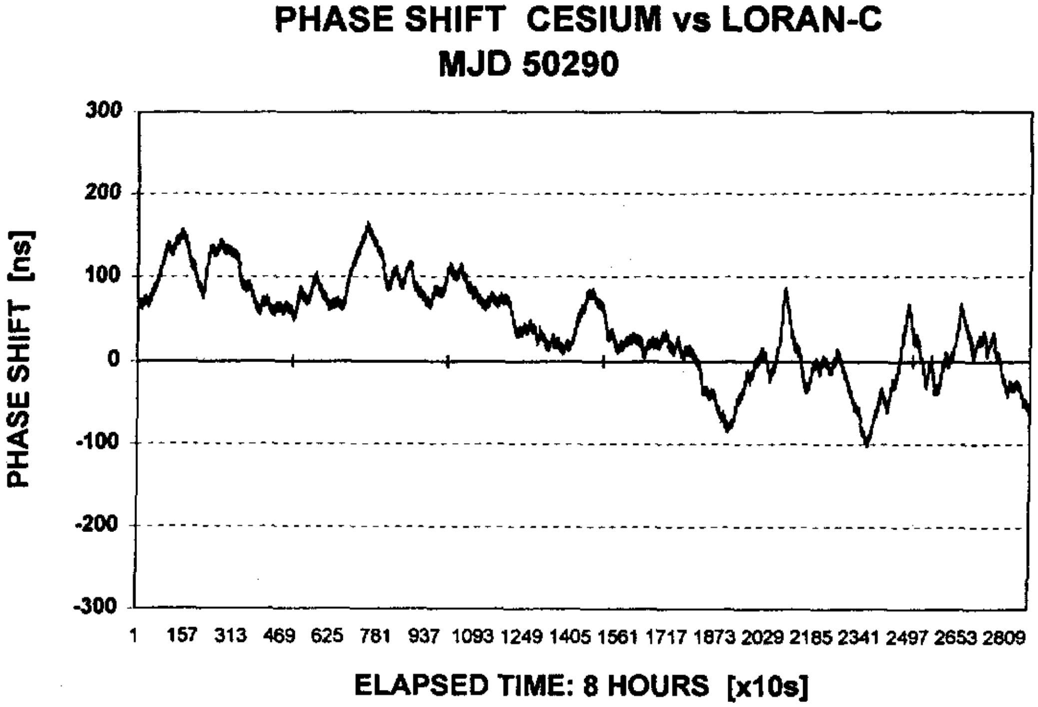

Figure 6. Typical standard frequency signal from LORAN-C (elapsed time: 8 hours).

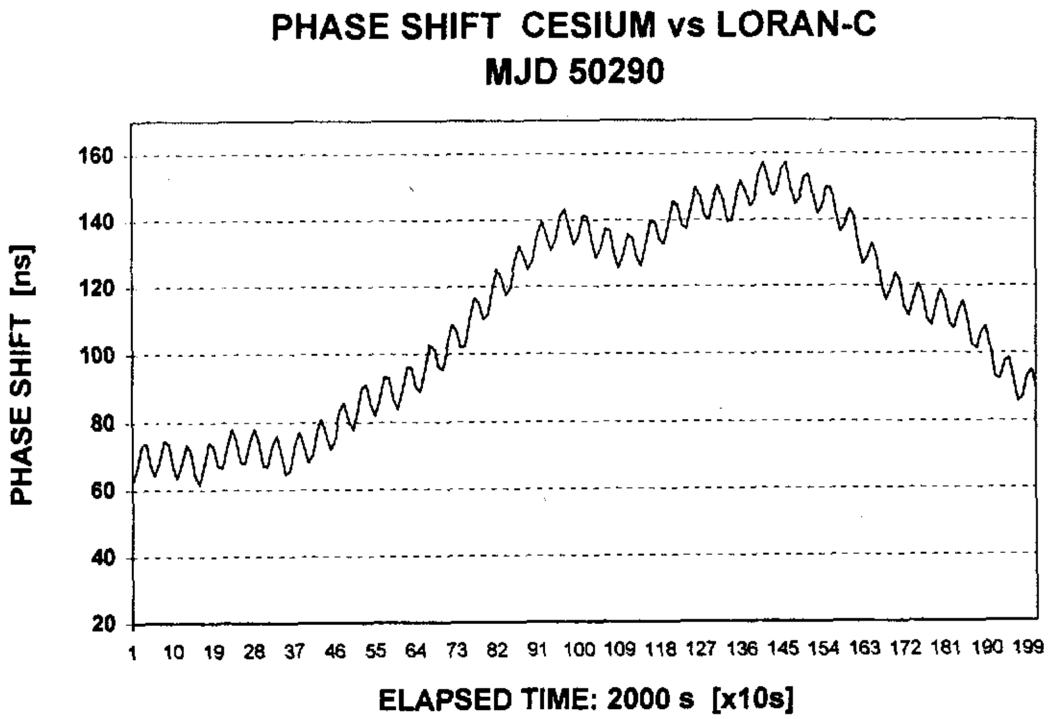

Figure 7. Typical standard frequency signal from LORAN-C (elapsed time: 2,000 s).

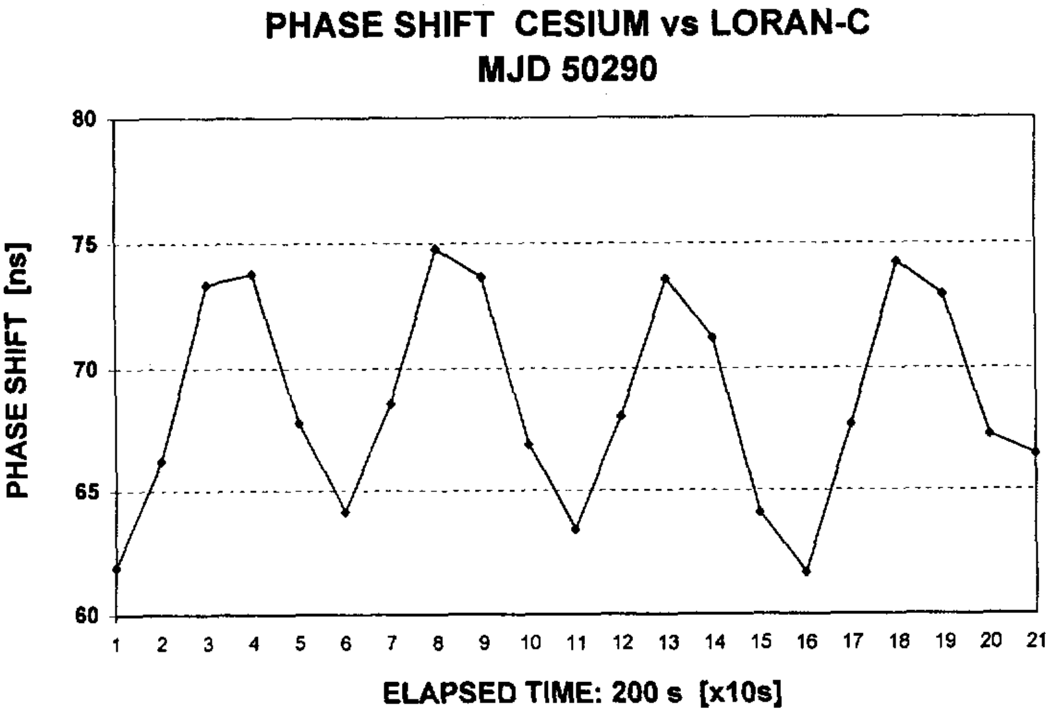

Figure 8. Typical standard frequency signal from LORAN-C (elapsed time: 200 s).

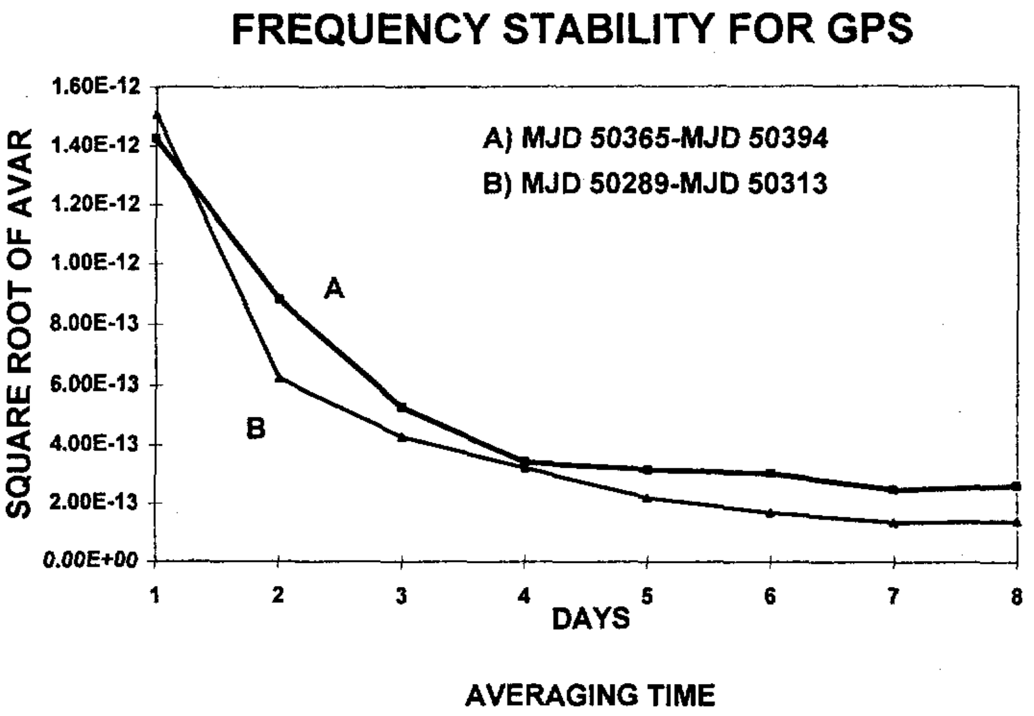

Figure 9. Frequency stability results for GPS for an averaging time of from 1 day to 8 days. (A) is from MJD 50365 to MJD 50394 and (B) is from MJD 50289 to MJD 50313.