TRACEABILITY IN ATOMIC FREQUENCY STANDARDS

John A. Kusters
Charles P. Little

Hewlett-Packard Co.
Santa Clara Division
Santa Clara, California 95052-8059

Abstract

In the manufacturing of cesium-based primary frequency standards, the cesium standard's normal operating frequency must be verified to be within the basic accuracy specifications set for that standard.

HP Santa Clara is the west coast reference station for the U.S. Naval Observatory. Daily comparison of time between HP and UTC(USNO) are made using common view GPS techniques. The data obtained permits continuous tracking of a bank of cesium standards. The bank of standards is used internally as a house reference standard. The production area is located several hundred meters from the house standard. In the production area, an active "real time" ensemble composed of three of the new HP5071A Primary Frequency Standards is used as a local reference. Continuous measurement of the house standard and up to 31 units under test are made relative to the local reference. This permits easy determination of the relative difference between UTC and the standards under test.

Introduction

Planning for the production of the HP5071A Primary Frequency Standard began about four years ago. At that time we realized, because of the accuracy and stability [1] of this new product, we would have to make a major upgrade to the house frequency standard system. The goal for the new system was to provide a clean, stable, accurate working reference, physically close to the test units in the production area. The job was complicated by the fact that the production line was located over 200 meters from the existing HP house standard, and the cables carrying the standard frequency signal passed through several environments in different parts of the factory causing unpredictable phase shifts in the standard frequency signal.

Because of budget constraints the new system had to use as much of the original configuration as possible. In addition, as part of a major upgrading of our production test facilities, an automated final test system for the new cesium standard was included in the plan.

In this paper we will discuss each of the elements in the measurement chain between our GPS reference receiver and the frequency standard units under test. Figure 1 shows a block diagram of the frequency reference chain and production test system.

HP Santa Clara Reference Standard

The house time and frequency reference standard is located in the Santa Clara Division Measurement Standards Lab. This lab is an official reference station for the U.S. Naval Observatory. The time and frequency reference standard is a "paper clock" ensemble consisting of four HP5061A/B cesium beam frequency standards. A block diagram of the system is shown in Figure 2. The most stable unit is selected as the master clock, and is continuously compared against each of the other ensemble units to monitor its stability and accuracy. From time-to-time the frequency of the master clock may be adjusted slightly to bring it into closer agreement with UTC. The master clock provides the ensemble's working output.

A long term reference to UTC is maintained by use of a Global Positioning System (GPS) timing receiver. The receiver has an internal clock which operates from the 5 MHz output of the ensemble master clock. Time is compared through common view GPS to UTC(USNO) once per day by monitoring satellite PRN13 for a period while the satellite is at its highest point above the horizon. The link between the corrected UTC time and the ensemble master clock is provided by a time interval counter controlled by an automatic data logging system. On a daily basis, the system measures the time difference between the ensemble master clock and the updated clock in the GPS timing receiver. The resulting data is stored and processed to precisely determine the frequency difference between UTC and the ensemble master clock. A typical sample of this data is plotted in Figure 3. The plot shows a frequency difference of 9 parts in 10^{14} between UTC and the ensemble master clock for the month of September 1992.

A secondary source of timing information comes from Loran-C navigation system broadcasts. Timing data from four different Loran-C stations is compared against GPS time through the ensemble master clock. This data is used for two purposes: (1) it is collected by the USNO on a daily basis as a check on the monitored Loran-C stations, and (2), it is saved to provide the measurement standards lab with backup to the GPS data.

Real-Time Ensemble

Figure 4 shows a block diagram of the real-time ensemble. The term "Real-time" refers to the fact that the ensemble controller makes continuous, real time adjustments to the three frequency standards included in the ensemble. A key point is that the internal cesium loop operates unsteered, at its natural frequency. The output of each of the three frequency standards is precisely steerable in steps of 6.3 parts in 10^{15} by use of an internal high-resolution direct digital frequency synthesizer [4].

In the real-time ensemble, the output signal from each frequency standard is phase-compared with the ensemble output signal. This signal is derived from a power summer which combines the outputs of the three frequency standards [5]. The result of these comparisons is sent to the ensemble controller. The ensemble controller determines a frequency offset for each frequency standard output which will bring it in phase with the ensemble output. In order to produce a true average of the three undisturbed frequencies, the controller selects the minimum set of offsets which sum to zero. The three outputs are driven to operate in phase, and at the average frequency of the three standards in the ensemble.

A further advantage of power summing is that output frequency stability (Allan Variance) and phase noise are reduced by the square root of N and 10 log N (dB) respectively (where N is the number of sources in the ensemble). Finally, data kept by the ensemble controller allows a "three-cornered hat" measurement of the stability of each source. This data is continuously examined for instability and stored for future reference.

Even though the ensemble provides the working reference for production frequency measurements, it is not kept in a controlled environment. Extensive testing of the HP5071A by independent labs shows virtually no change in frequency due to environmental changes [2]. This environmental insensitivity reduces the cost of the test system because neither the ensemble nor the test units need to be environmentally controlled, even though the final test runs for a minimum of five consecutive days.

The output signal from the real-time ensemble is sent to the measurement system where it provides the reference for accuracy and stability measurements on the newly produced frequency standards.

Long-Term Stability Measurement System

The measurement system, shown in Figure 5, uses a time interval phase measurement technique to compare the frequency of the test units to that of the ensemble [3]. The time interval counter is used to measure the phase difference between the 5 MHz output from the ensemble and the unit under test.

Each unit under test is sampled every 12.5 seconds. Each sample represents the average of 1000 measurements of the time difference between the local reference and the unit under test. Data reduction from 80 consecutive samples produces an effective time difference for that 100 second period. Data is acquired on each unit for a total of 6 days, or 518 time difference measurements.

The data thus obtained yields a plot similar to Figures 6 and 7. The data in Figure 6 was derived from an HP5071A which contains a high-performance cesium beam tube; Figure 7 data came from a standard cesium tube unit.

To precisely determine the relative output frequency of each test unit, a least-squares-fit line is computed from the time-difference data. The frequency offset of the test unit (with respect to the ensemble) is computed from the slope of that line.

In addition to the production frequency standards under test, the system also measures the signal from the HP house standard. This data is reduced in the same manner described above, and stored giving a continuous record of the frequency difference between the ensemble and the HP house standard. An automatic alarm in the measurement system warns the operator if there is a significant frequency change or jump between the frequency of the ensemble and that of the HP house reference standard.

Results

The data produced thus far must be further reduced to give frequency measurements traceable to UTC(USNO). Corrections for the offset between the ensemble and the HP house standard are computed from the data obtained by measuring the house standard on the measurement system. The frequency difference between the HP house standard and the ensemble is plotted in Figure 8. Also plotted is the offset data obtained via common view GPS showing the offset measured between the house reference standard and UTC(USNO). The figure shows the ensemble to be between 2.3 and 2.6 parts in 10^{13} low with respect to the HP house standard. Figure 8 also indicates clearly the problems with transmitting high precision frequency signals over coaxial cable, thorough several distribution amplifiers, and at least 4 different micro-climates. The environmentally-induced phase changes cause a significant spread in the measured frequency offset on the order of 1 part in 10^{13}. Frequency changes seen in the data were caused by switching master units in the House Standard, then making C-field corrections to syntonize it with UTC.

After all corrections are applied, the scattergram shown in Figure 9 was obtained. A histogram of the same data is shown in Figure 10. The data shown has a mean of 1.3 parts in 10^{14} and a standard deviation of 2.3 parts in 10^{13}. Also shown is that the maximum deviation seen on all units produced is less than $\pm 6 \times 10^{-13}$.

Accuracy

We have shown how production frequency measurements have a traceability chain from UTC to the measurement of new cesium beam frequency standards on the production line. The remaining issue is the accuracy with which the production units can be measured.

Sources of uncertainty in this measurement are the frequency determination from GPS, frequency transfer from the HP standards lab to the production area, real time ensemble frequency, and the production measurement system. Our best estimates of these uncertainties are as follows.

GPS

Monitoring one GPS satellite for long periods while using the master clock as a "flywheel" yields fairly good results. Over a four week period we are able to determine UTC with an uncertainty of around 100 ns. This translates to a frequency uncertainty of about 4 parts in 10^{14}.

Line Noise

The signal line from the from the HP house standard picks up noise and phase shifts as it passes through the factory to the cesium standard production area. These factors give this signal an uncertainty of about 7 parts in 10^{14}.

Measurement System

A system very similar to the production test system is described and characterized in [3]. Based on this data, and measurements of our production test system, we estimate its measurement uncertainty to be close to 3 parts in 10^{14}.

Local Reference

Finally, the uncertainty contribution of the real time ensemble, as described above, is the square root of 3 better than an individual ensemble unit. For a 5 day averaging time (the duration of the frequency measurement) the ensemble contributes an uncertainty of less than 1.5 parts in 10^{14}.

Using a square-root-of-the-sum-of-the-squares method the total system error is estimated at less than1 part in 10^{13}. This level of accuracy is sustainable because of the number of cesium standards in the system, and the continuous cross checking between the system elements. As presently configured the system provides more than sufficient accuracy to guarantee our present specifications.

Conclusion

The data shown indicates that we can indeed measure the long-term accuracy of all units produced with sufficient precision to guarantee that all units meet a published accuracy specification of $\pm 1 \times 10^{-12}$, and that this accuracy level can be maintained in a normal production environment.

Acknowledgments

The authors thankfully acknowledge discussions with Robert Pitcock, manager of HP's Standards Lab, for details on how the house reference system is maintained, and for the data relating the house reference system to UTC(USNO).

References

[1] Hewlett-Packard model 5071A Primary Frequency Standard technical data sheet.

[2] Johnson, James L. and Kusters, John A., "A New Cesium Beam Frequency Standard Performance Data," Proceedings of the 1992 IEEE Frequency Control Symposium, page 143, IEEE catalog number 92CH3083-3.

[3] Kusters, John A., "Determination of the Aging Rates of High Stability Rubidium Frequency Standards," April 1989 Proceedings of the Second International Conference on Frequency Control and Synthesis.

[4] Giffard, Robin P. and Cutler, Leonard S., "A Low-Frequency, High Resolution Digital Synthesizer", Proceedings of the 1992 IEEE Frequency Control Symposium, page 188, IEEE Catalog number 92CH3083-3.

[5] Stem, A., "About Sum of Signals and Possible use in Time and Frequency Systems," Proceedings of the Forty-Fifth Annual Symposium on Frequency Control, pp 659-666, IEEE Catalog number 91CH2965-2.

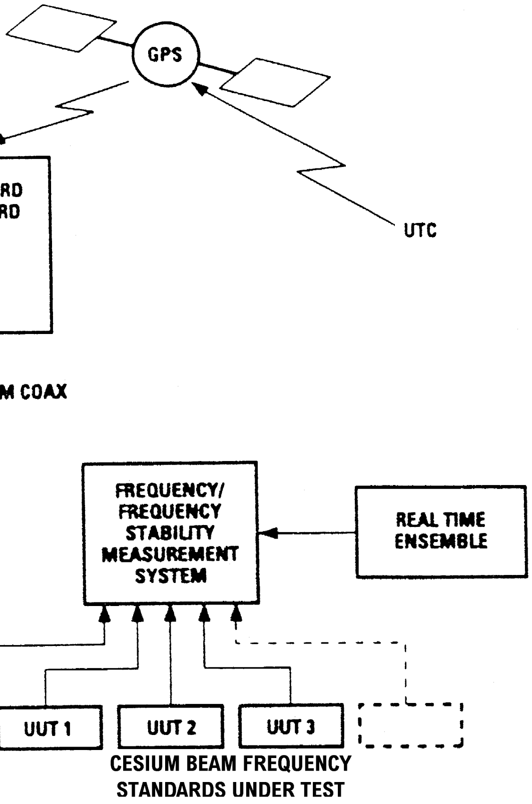

Figure 1. Block Diagram of Hewlett-Packard Frequency Standard/Measurement System

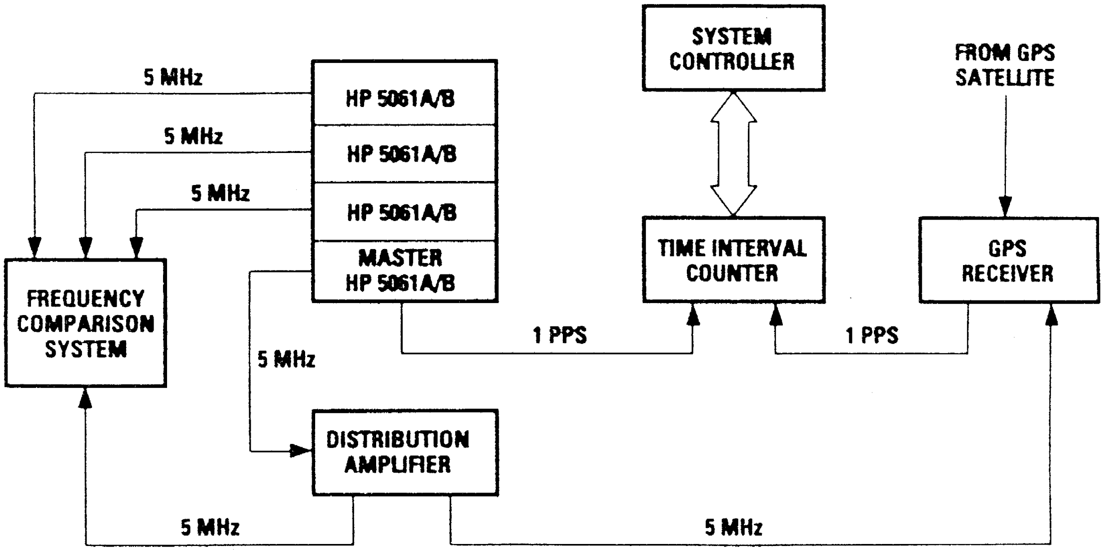

Figure 2. Hewlett-Packard Time and Frequency Reference Standard

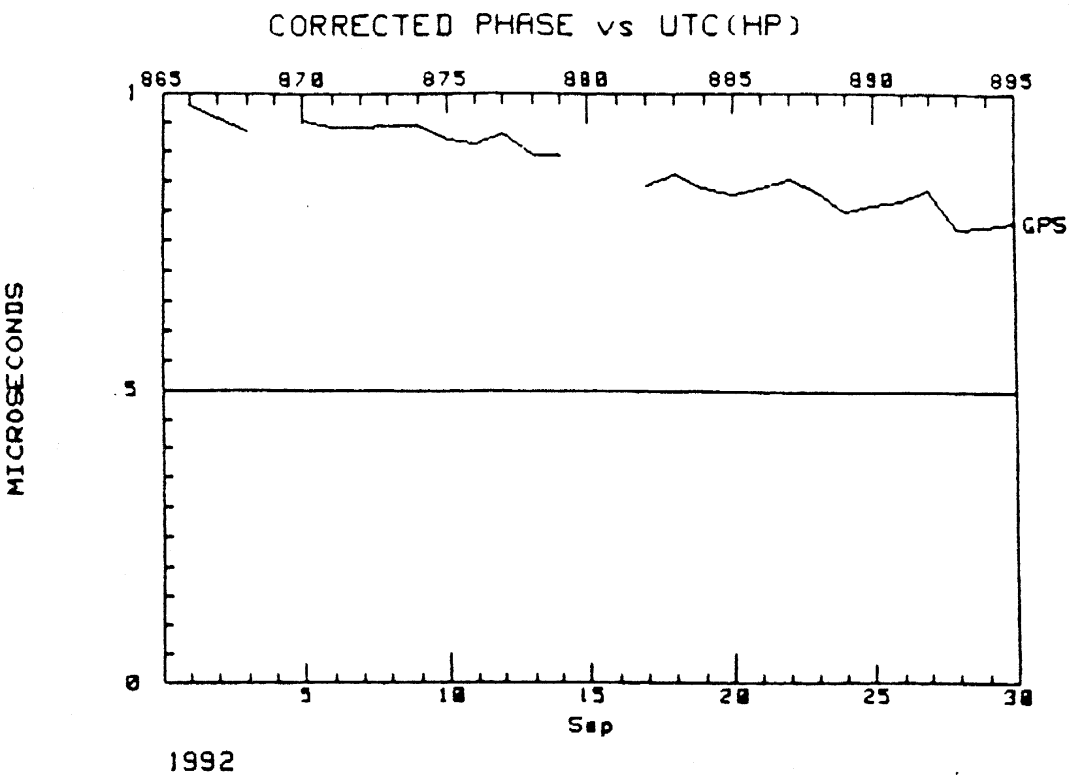

Figure 3. Ensemble master clock vs. UTC

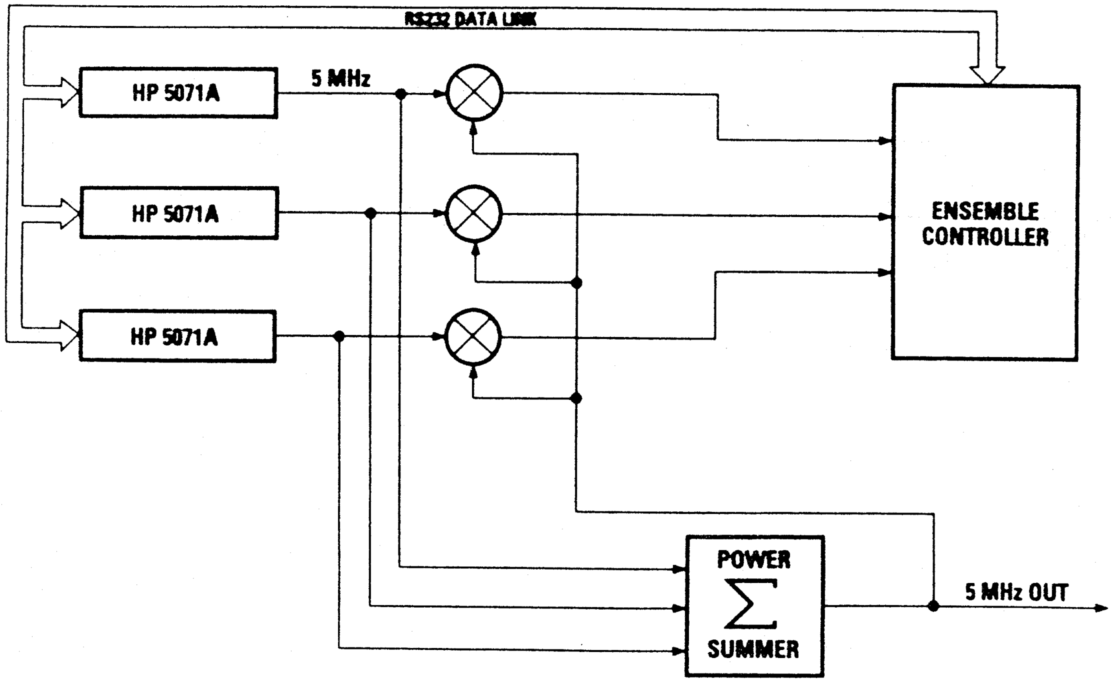

Figure 4. Block Diagram of Production Real-Time Ensemble

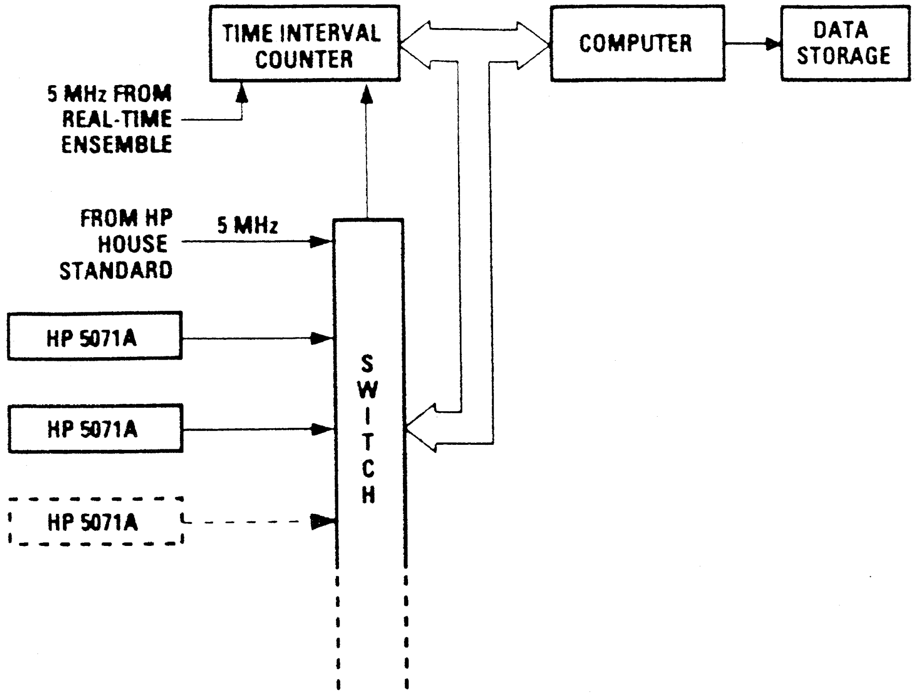

Figure 5. Frequency/Frequency Stability Measurement System

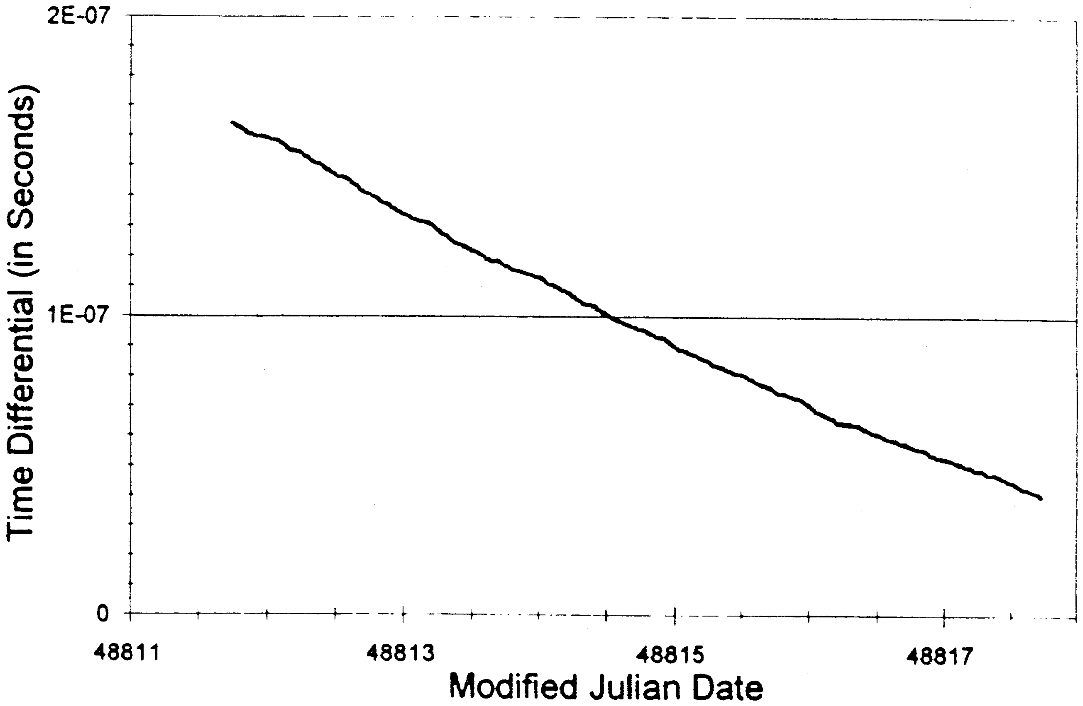

Figure 6. Continuous phase plot: HP 5071A with high performance cesium beam tube - 100 second data vs. Local Reference

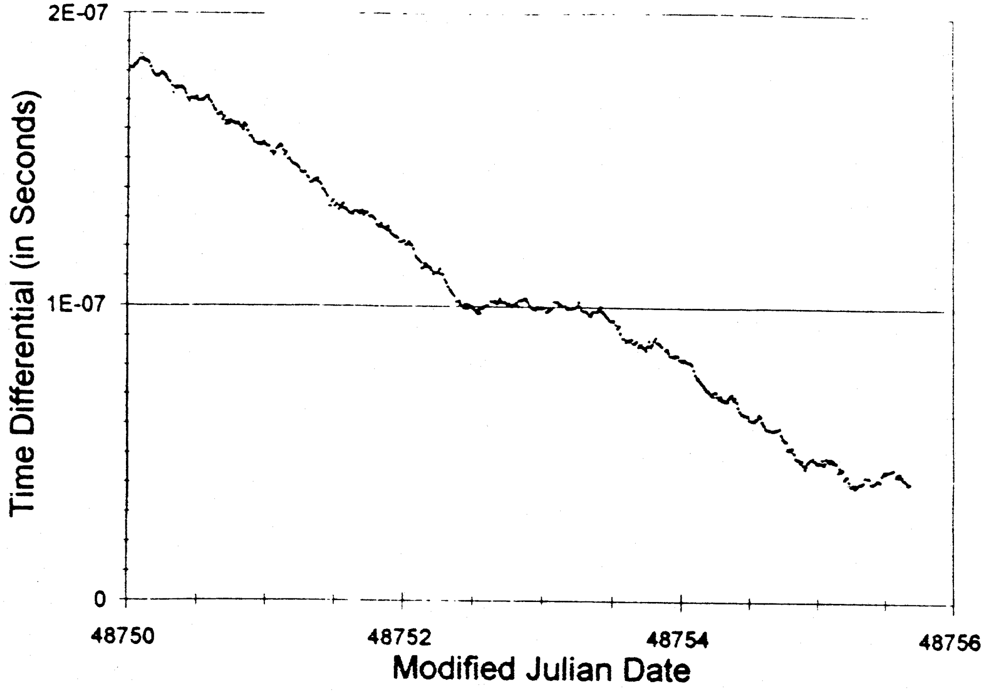

Figure 7. Continous phase plot: HP 5071A with standard cesium beam tube - 100 second data vs. Local Reference

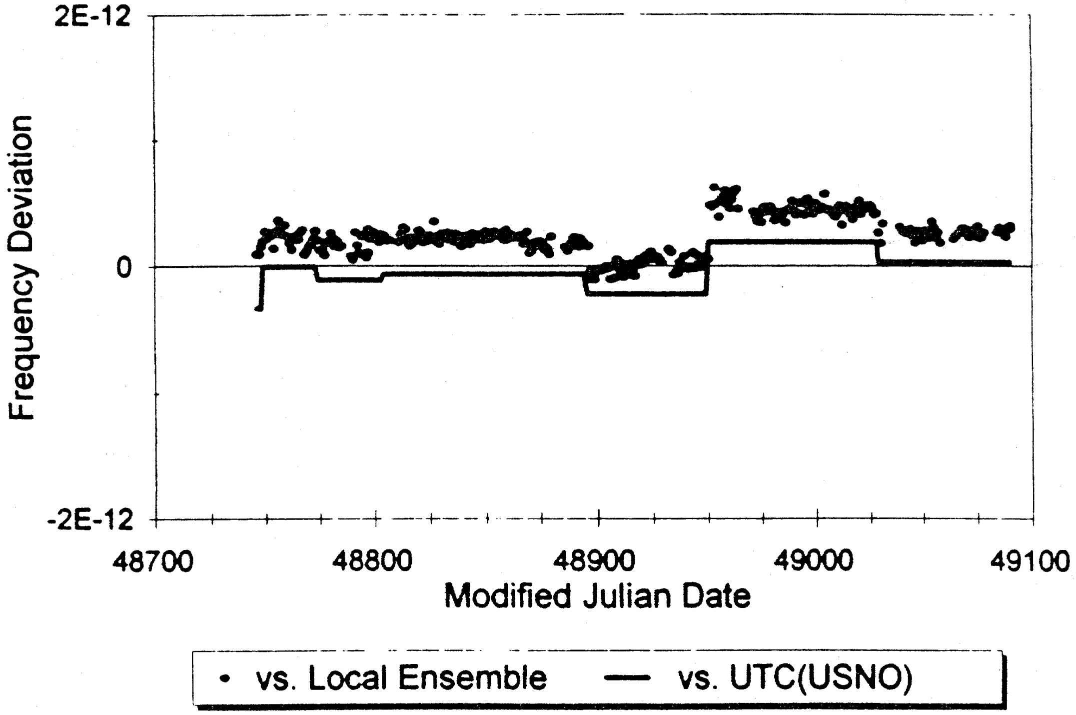

Figure 8. Frequency difference: HP house standard measurements Daily averages vs. Local Reference and UTC(USNO) via GPS

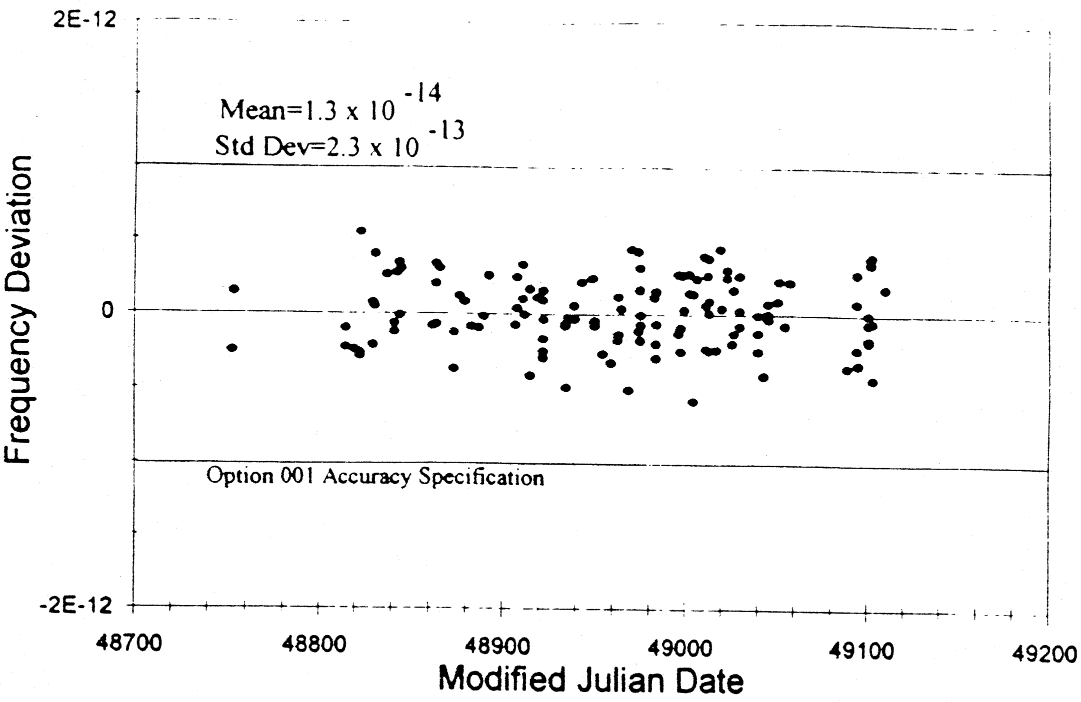

Figure 9. Test units vs. UTC(USNO) - 5 day averages

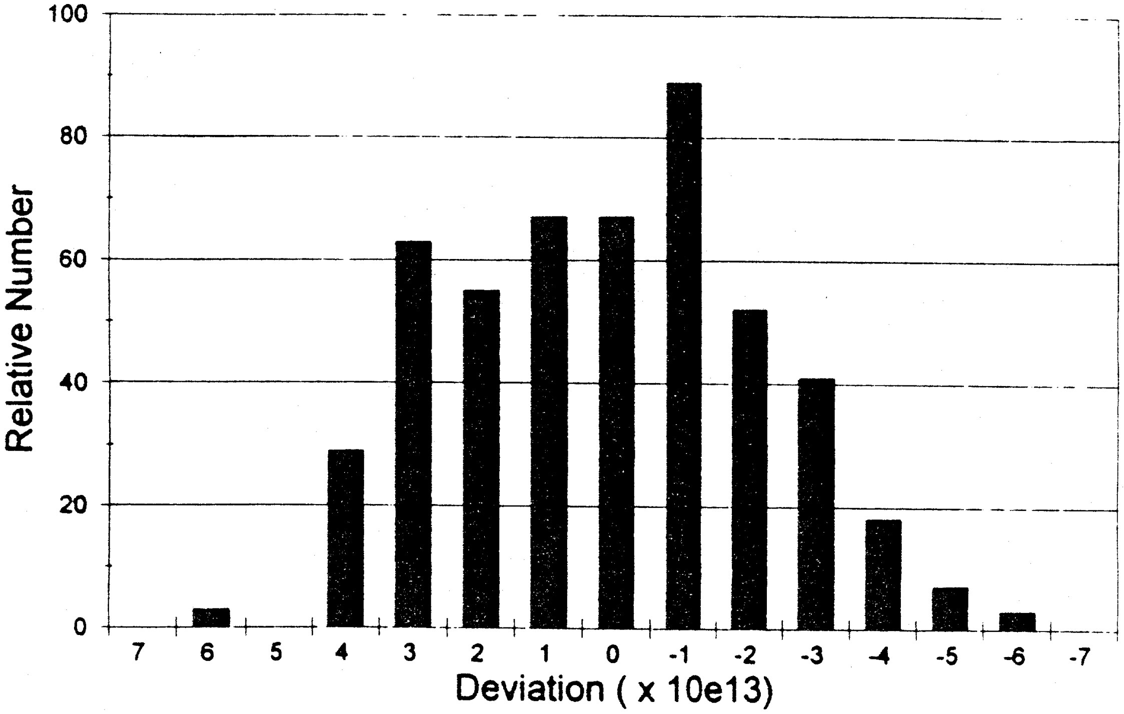

Figure 10. Histogram of test units vs. UTC(USNO) - 5 day averages