A NEW CESIUM BEAM FREQUENCY STANDARD PERFORMANCE DATA

John A. Kusters
James L. Johnson

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

Introduction

Recent papers have discussed the principles of a new architecture for cesium beam frequency standards.[1-4] The design goal of the new architecture was to develop an atomic frequency standard that is essentially independent of environmental effects. Reduction in Ramsey pulling due to cesium beam tube design effects was discussed in 1991[1,2]. With the addition of electronics that address power shift, C-field effects, and Rabi pulling, the new cesium standard shows the expected reduction in overall instabilities due to environmental factors and electronics errors. This paper reports actual performance data obtained from a number of standards designed incorporating the new architecture as measured by various measurement laboratories. The data substantiates the design theories, plans, and goals to produce a frequency standard whose sensitivity to environmental factors is greatly reduced when compared to existing standards.

Background

Previous cesium beam frequency standards generally exhibit a substantial response to environmental influences, such as temperature, pressure, humidity, and external magnetic fields[5-9]. An example of this is shown in Figure 1 where data collected over a year shows that frequency changes measured in several frequency standards maintained in a constant temperature environment, show a strong correlation with measured humidity.

Responses to environmental effects have become the major limitation on overall accuracy and on long-term stability in atomic frequency standards. This in turn requires metrology laboratories using these devices to design elaborate physical facilities to house the instruments in an attempt to minimize the environmental effects.

In addition, warm-up of a cesium frequency standard requires 24-36 hours of stabilization time to achieve final stability. This is a consequence of the typical cesium beam tube design, which conventionally consists of a copper Ramsey cavity weighing more than 1 kg. with a cesium oven at one end operating at 90-130ºC, and a hot-wire ionizer at the other end operating in excess of 900ºC. Typical thermal response times of a cesium tube are on the order of 6-10 hours, resulting in overall thermal equilibrium times of at least 24 hours.

Primarily through an expanded understanding of the underlying causes of the cesium standard's sensitivity to outside environmental factors, and extensive computer modeling of the atomic physics and of the electronic architecture, we became convinced that with the proper design, environmental factors could be greatly reduced. At the same time this should result in a more useful instrument that requires no special operating environment, and that should be fully operational meeting all specifications within 30 minutes of power-up. The latter condition is especially desirable for field transportable, fast set-up metrology and calibration facilities.

Consequently, a multi-facility, multi-year program was undertaken to develop a cesium standard based on the new architecture.

Environmental Testing

As a part of the investigation of the new architecture and as a qualification process for instruments developed during the project, the response of the new cesium beam frequency standards to external effects had to be accurately determined.

Reference Standard

The fundamental requirement for determining the response of any standard to an outside influence is to have an appropriate reference standard against which to measure. Given the expected thermal response time of the cesium beam tube and other components in the standard, full temperature equilibrium takes about 18 hours to achieve. This dictated that temperature changes in the environmental chamber should occur no more often than once every 24 hours. This in turn requires that the reference standard have sufficient stability over extended time periods to be able to measure the environmental effects. Early in the testing program, we determined that our house frequency standard, composed of several HP5061 cesium standards, did not have the needed accuracy or stability to be used as a reference standard. Given its sensitivity to temperature and humidity, the expected stability of the house standard over several days of measurement was on the order of a part in 10^{13}. During the first temperature run, no change in frequency of the new standard was observed within the allowable measurement errors of the house standard.

The first challenge was to create a reference standard that was sufficiently stable and had sufficient intrinsic accuracy to be used as a reference. As a result, three of the new standards were constructed and connected as an active ensemble as shown in Figure 2. In this configuration, the controller drives the three standards to operate at exactly the same frequency and phase, producing a frequency that is the mean frequency of the three standards, and where the absolute sum of the corrections applied to the individual standards are at a minimum. Operating in this manner, for identical standards, the overall accuracy and stability improve as the square root of the number of units in the ensemble, while the phase noise spectral density (in dB) improves as 10 log(number of units). This results in a reference standard whose expected accuracy and stability is a factor of 1.7 greater than that of a single unit.

Testing at facilities outside of Hewlett-Packard was done using various models of hydrogen masers. Up to sampling times in the vicinity of 10^5 seconds, this proved adequate. Beyond this, corrections had to be made to the data to account for the drift of the maser used as the reference frequency standard.

Temperature Sensitivity

During early temperature measurements, analysis of the data using correlation techniques showed that there was a frequency change response that occurred every 24 hours, the same period as the temperature cycling. The correlation also showed peaks with time periods less than 24 hours, indicating that some other process was occurring. Given that at this time we were looking for effects on the order of parts in 10^{14}, after a difficult and time-consuming process the phase detector used to measure the phase difference between the unit under test and the reference standard was found to be temperature sensitive and varying with the room air conditioning. After also environmentally controlling the phase detector, the upper bound of the temperature sensitivity of the standard was determined to be 1 x 10^{-15}/ºC.

Further testing at JPL was performed to refine the data. This facility was used because of the excellent environmental chambers used, the existence of several hydrogen masers as reference standards, and the outstanding work done by this group in evaluating and understanding the environmental effects seen in our older standards[8,9]. Figure 3 is a plot of the Root Allan Variance of the standard under test. This is a conventional method of expressing oscillator stability as a function of averaging time[10]. In this test, temperature was cycled between 15º and 35ºC. once per day. If there had been a significant response to temperature, this would have shown as a peak in the stability curve at a period corresponding to 24 hours. Given that there is none, the upper bound of the temperature sensitivity over the 20ºC temperature range was determined to be less than 1 x 10^{-14}, or correspondingly, less than 5 x 10^{-16}/ºC.

Humidity Sensitivity

Early testing for humidity effects was performed in our facility with no detectable results. An extended run was done using NRL facilities. Figure 4 is a plot of the relative humidity and observed frequency. During this run, the temperature was also being cycled from -17º to 57ºC. exceeding the design specification at both ends. Figure 5 is a plot of the correlation function between relative humidity and frequency. Two peaks are shown, but they arc too weak to draw any conclusion. NRL data indicates that both temperature and humidity effects are bounded by the measurement uncertainty of 1 x 10^{-14}.

Pressure Sensitivity

No sensitivities to changes in ambient pressure were seen within the limits of the reference standard. Tests were run over pressure ranges equivalent to 0 - 12,000 m. altitude. An interesting sidelight is that although most frequency standards are specified in terms of altitude change, the new unit is sufficiently stable that relativistic effects dominate all other effects in a change in altitude.

Magnetic Field

No frequency shifts within the limits imposed by the reference standard (in this case, a hydrogen maser) were seen in a ±2 gauss field- Data was taken in both DC and 55 Hz magnetic fields in all three axes[11].

Further Characterization

Time Domain Stability

Figure 6 is a plot of the time domain stability in the range of 0.01 to 20 seconds. Figure 3 is a similar plot extending the sampling time out to 10^6 seconds. Of interest here is that at roughly 10^5 seconds, the cesium standard uncertainty crosses the locus for the hydrogen maser used as the reference standard. Freedom from environmental effects results in a flicker-floor substantially below that of conventional cesium frequency standards.

Warm-up Time

Figure 7 is a plot of warm-up time and frequency offset from a hydrogen maser as measured by NIST. From this plot, measured on an instrument that was flown from Santa Clara to Denver, driven to NIST Boulder, then plugged in with no stabilization time, the warm-up time to meet specifications was 10 minutes, 16 seconds.

Phase Noise

Characteristics of the new standard in the frequency domain is shown in the phase noise plot in Figure 8. Apparent here is the improvement in phase noise especially in regions closer to the carrier, from 1 Hz to 1000 Hz offset.

Other Effects

Tests for all other effects, including EMI and radiated and conducted susceptibilities were conducted with no observable results within the measurement uncertainty of the reference standard. Tests also included verification to conformance to MIL-STD-461C, EC-92, and MIL-T-28800D.

Conclusions

The experimental data indicates that it is possible to design and construct frequency standards that are environmentally insensitive, at least to the level of 1 part in 10^{14}. A sound understanding of the physics of processes involved also leads to a rapid warm-up of the cesium instrument.

Acknowledgments

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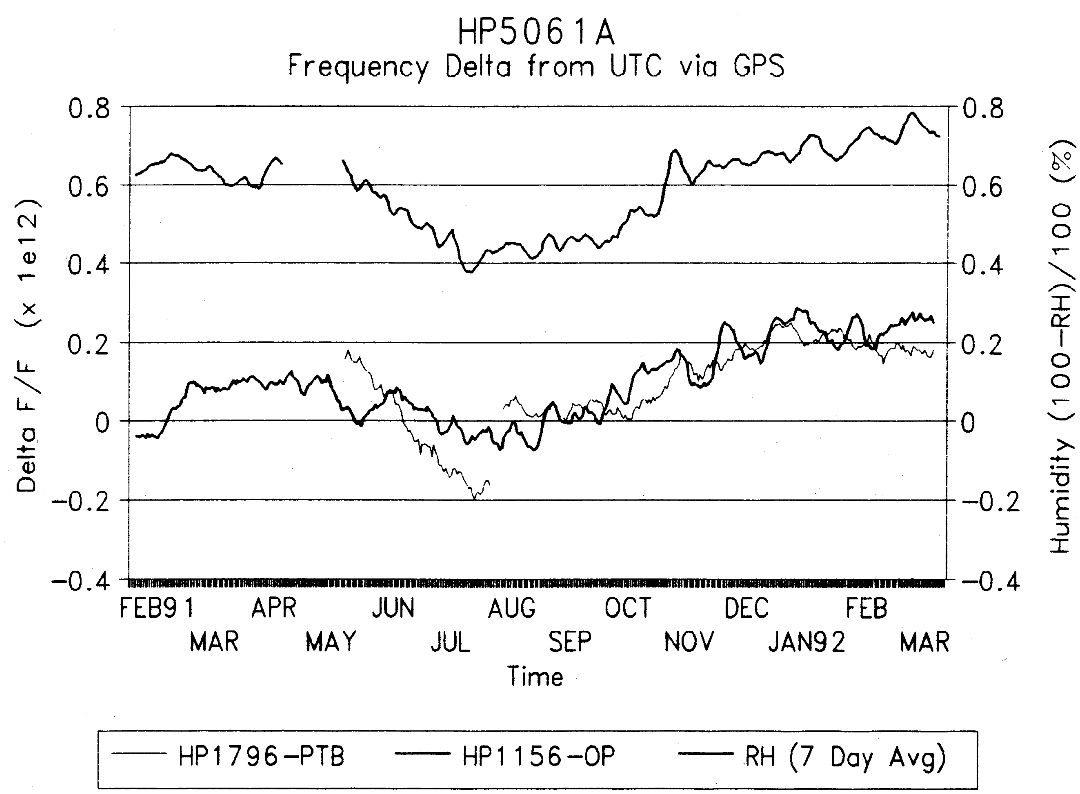

Figure 1: Upper trace - scaled relative humidity. Lower traces, - offset from UTC for two cesium standards as determined by common view GPS. (Data courtesy of HP Geneva Time & Frequency Laboratory)

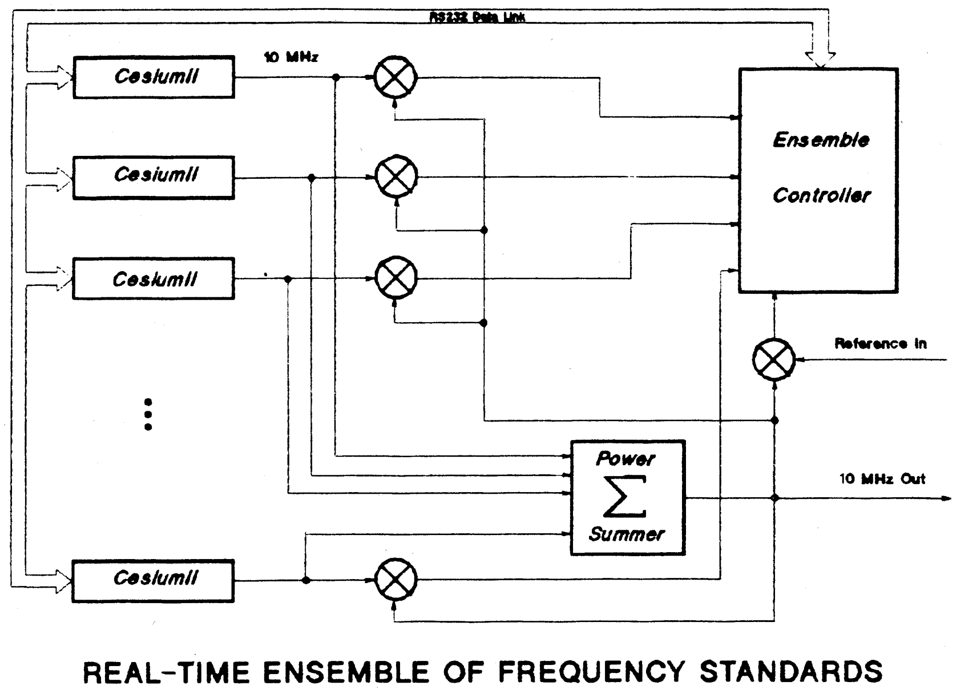

Figure 2: Block Diagram, real-time ensemble of cesium standards.

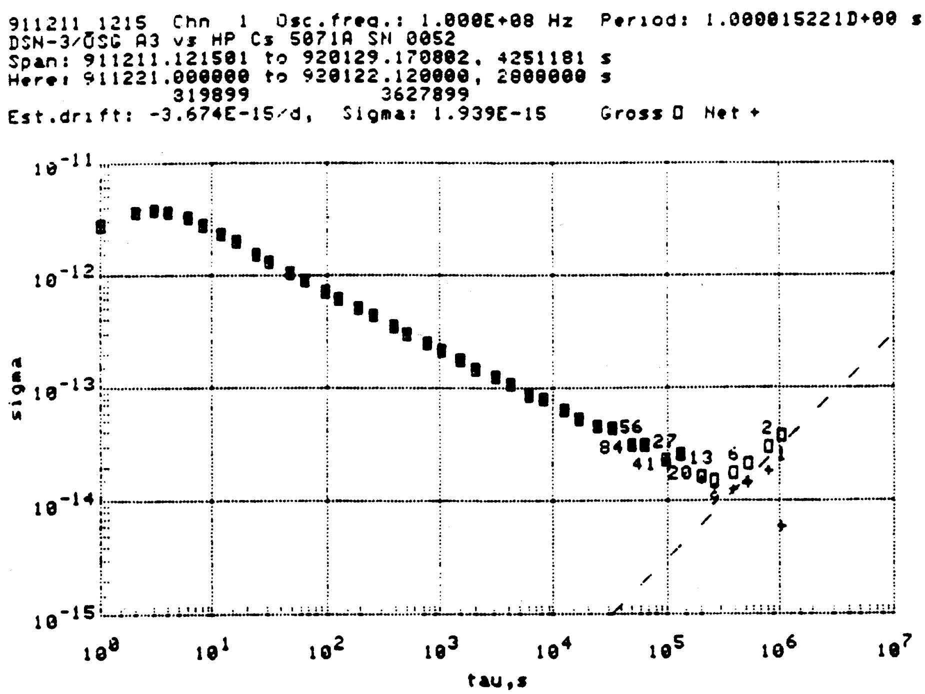

Figure 3: Root Allan Variance as determined by comparison to a hydrogen maser. Dashed line in lower right corner indicates expected instability in the hydrogen maser. (Data courtesy of Jet Propulsion Lab, California Institute of Technology)

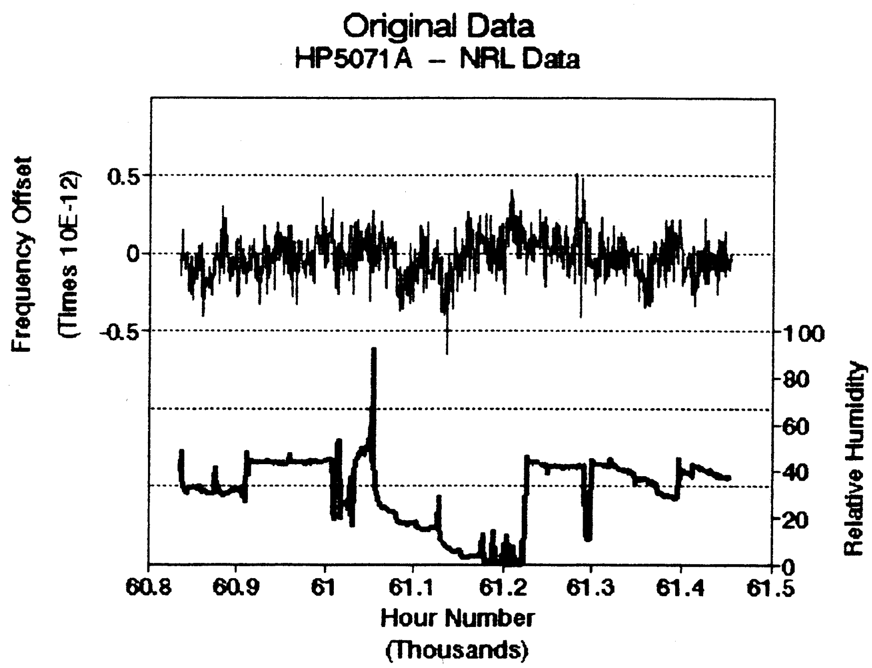

Figure 4: Upper trace - frequency offset from UTC.
Lower trace - measured relative humidity.
(Data courtesy of Naval Research Laboratory)

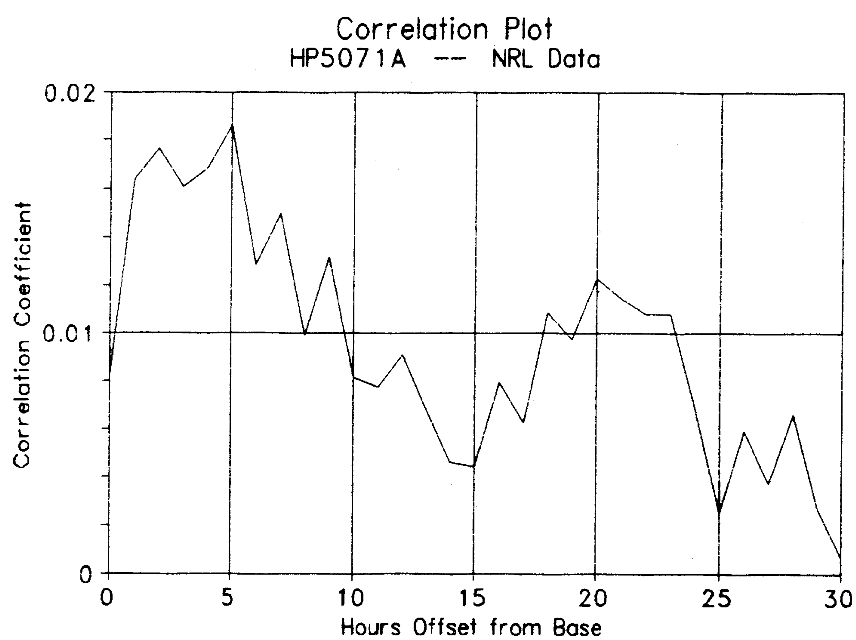

Figure 5: Correlation of data in Figure 4. Extremely weak peaks are observed at 5 and 20 hours offset.

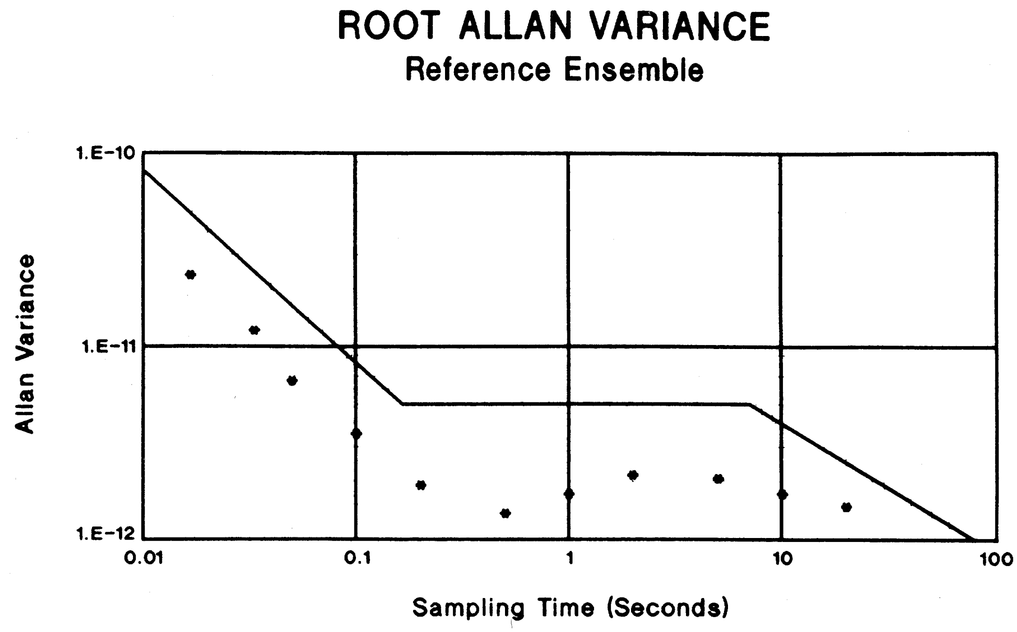

Figure 6: Root Allan Variance data for short sampling times.

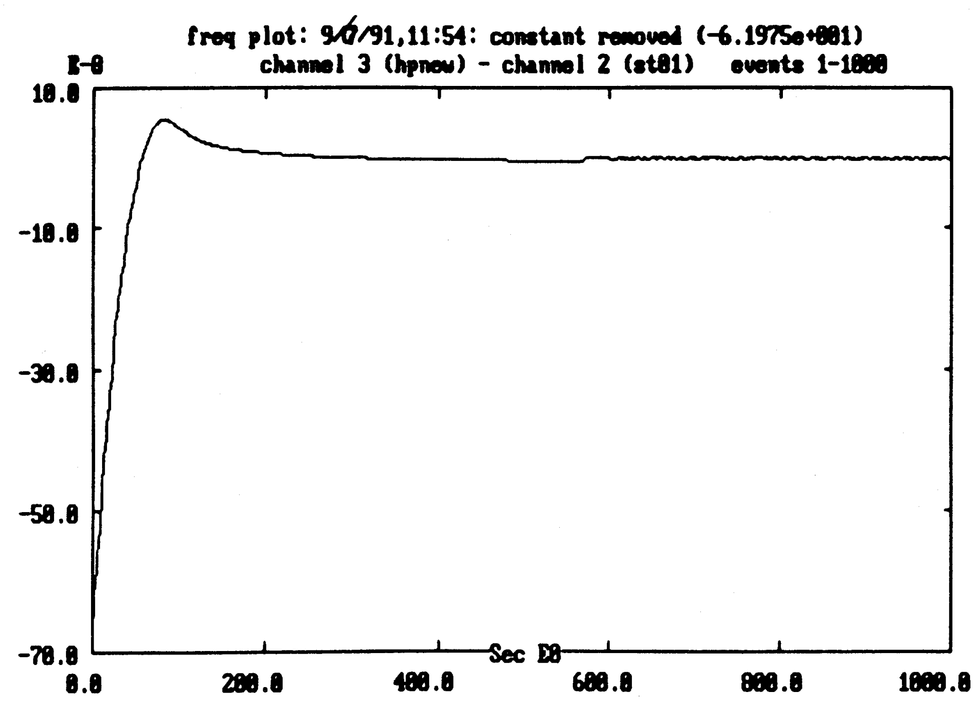

Figure 7: Measured frequency offset - from turn-on at NIST to 1000 seconds. Data indicates that frequency was stable at 616 seconds.

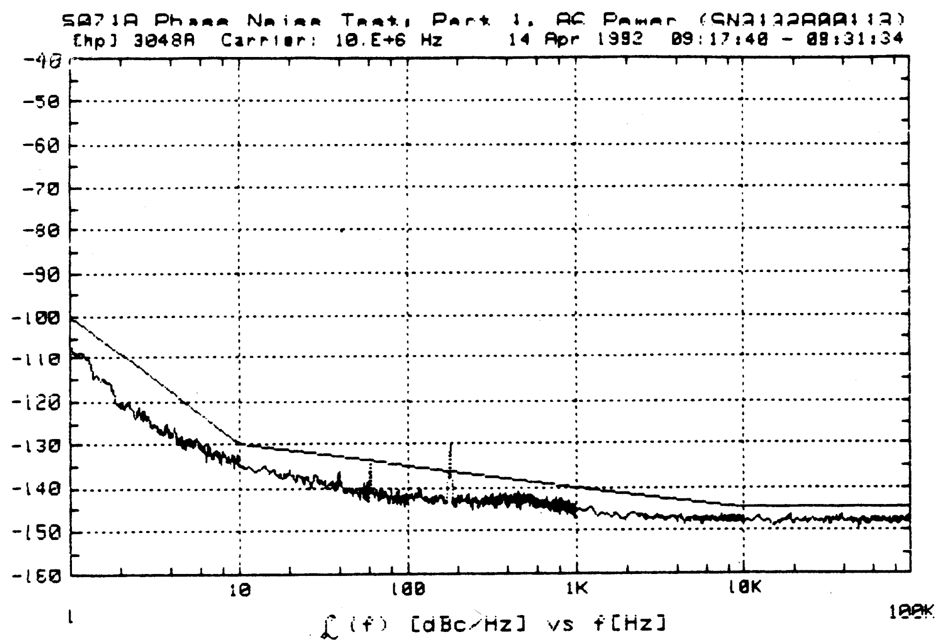

Figure 8: Phase Noise as measured on an HP3048A system