LONG-TERM EXPERIENCE WITH CESIUM BEAM FREQUENCY STANDARDS

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ABSTRACT

Since its introduction 8 years ago, the 5071A cesium frequency standard has been installed in many national and regional laboratories. Data from over 150 clocks currently reported to the BIPM is used to estimate overall frequency accuracy. USNO data taken on a daily basis defines overall life expectancy and daily performance variations.

Data from NIST gives a 1000-day string of frequency deviations on two clocks, and lesser time span for other clocks. The accumulated data gives insight into cesium frequency stability flicker floor and beam tube end-of-life behavior. In addition, a production database now includes over 1500 clocks.

A recent analysis of data from all sources has highlighted actual clock performance in a variety of environments. The details of the analysis and the results obtained form the core of this paper.

1. BIPM DATA

The Bureau International des Poids et Mesures (BIPM) publishes a monthly series of reports on the clocks that contribute to International Atomic Time (TAI). Currently, their respective laboratories report approximately 220 clocks to the BIPM. The data from these clocks forms the ensemble that is TAI. Of interest for this paper are the two reports, *w00.xx*, Relative Weights of the Clocks, and *r00.xx*, Monthly Rates of the Clocks.

The relative weight of a clock is a measure of its stability compared to the BIPM ensemble of clocks. The total weight of the clock ensemble is 1.0. No single clock can have a weight greater than 0.7 percent. Data extracted from *w00.02* is shown in Table I, sorted by total weight.

	NUMBER	*TOT. WEIGHT*
Agilent 5071A	157	81.8%
H Masers	42	14.9
Primary Cesium Std	3	2.1
Agilent 5061A/B	10	0.4
All Others	7	0.8

Table I. Number of clocks and total weight by clock type from BIPM Report *w00.02*

The monthly rate of a clock is a direct measure of the offset or intrinsic accuracy of the clock as compared to the BIPM ensemble. Data was obtained from BIPM Report *r00.02* for 20 standard clocks and 137 high performance clocks. The reduced data is shown in Figures 1 and 2. Figure 1 is for the standard clock. This shows that only one clock exceeded a frequency offset of 5 x 10^{-13} (its offset was 6.3 x 10^{-13}).

Figure 2 is the same data for high performance clocks. Of interest is that no high performance clock exceeded a frequency offset of 4.6 x 10^{-13}.

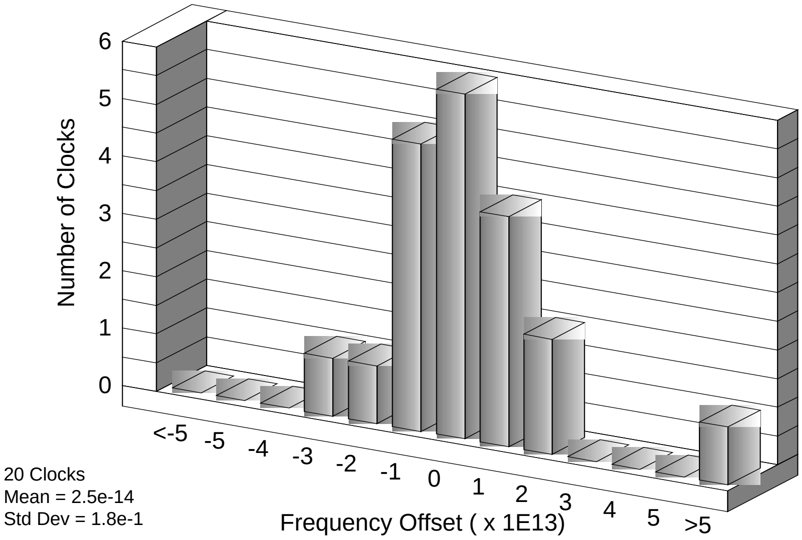

Figure 1. Frequency offset histogram for 5071A standard clocks. From BIPM Report *r00.02* – Data through 2/25/00

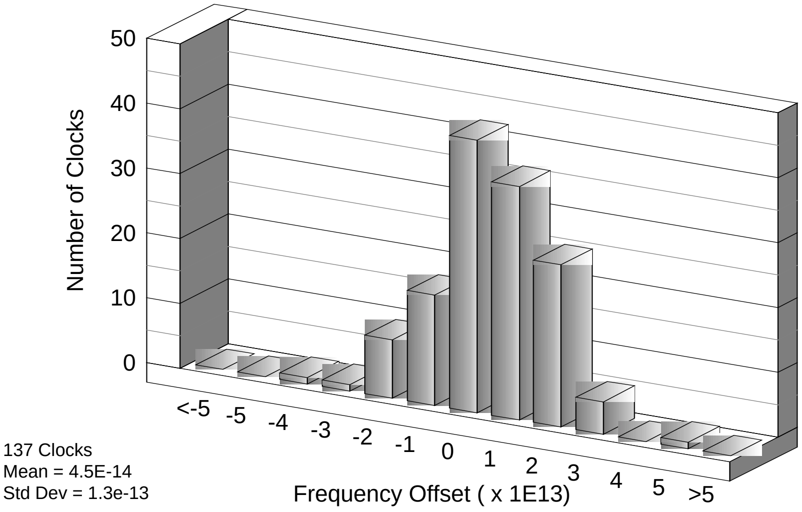

Figure 2. Frequency offset histogram for 5071A high performance clocks. From BIPM Report *r00.02* – Data through 2/25/00

2. USNO/NRL DATA

The United States Naval Observatory (USNO) and the Naval Research Laboratory (NRL) have retrieved data routinely on all clocks located either at NRL or USNO. Currently, in excess of 40 clocks are at USNO. For most of these we have data starting from the initial installation of the clock through most of its entire lifetime. Most of the data is retrieved by querying the clock through its ":SYST:PRIN?" command and storing the output.

Data is taken every hour. Over the past 8 years, roughly 60,000 records have been stored for each of many clocks. Cesium beam tube data is also contained in the record. Reported are the tube serial number, ion pump current, electron multiplier voltage to maintain 100 nA beam current, and information about various rf and tube output signal levels.

2.1 Cesium Beam Tube Lifetime

Beam tube lifetime is determined by several factors. These are:

1. Contamination
2. Hot-wire Ionizer
3. Ion Pump
4. Electron Multiplier
5. Cesium Supply

Of these, process and/or design control the first three. Most end-of-life conditions are due to either the electron multiplier or the cesium supply. Electron multipliers are essentially coulombic devices. Lifetime is determined ultimately by the total electron flux through the device. Extensive accelerated lifetime studies show that the expected lifetime of the multiplier when operating with 100 nA from its final dynode is approximately 25 years.

Cesium supply is also governed by design. The amount of cesium is limited by oven capacity. The tubes contain 5.6 grams of cesium. This is sufficient for at least 75 years operation at the standard tube oven temperature of 90°C.

The high performance tube operates at a nominal 130°C. and consumes cesium at a rate that is an order of magnitude higher than the standard tube.

2.2 Birth and Death of a Cesium Beam Tube

The major advantage of the database that exists for these clocks is that we can track a number of clocks throughout their lifetime. Figure 3 shows the early electron multiplier voltage readouts from clock number 148. Typical electron multiplier voltages range from 1500 to 2350 volts when the units are shipped from the factory.

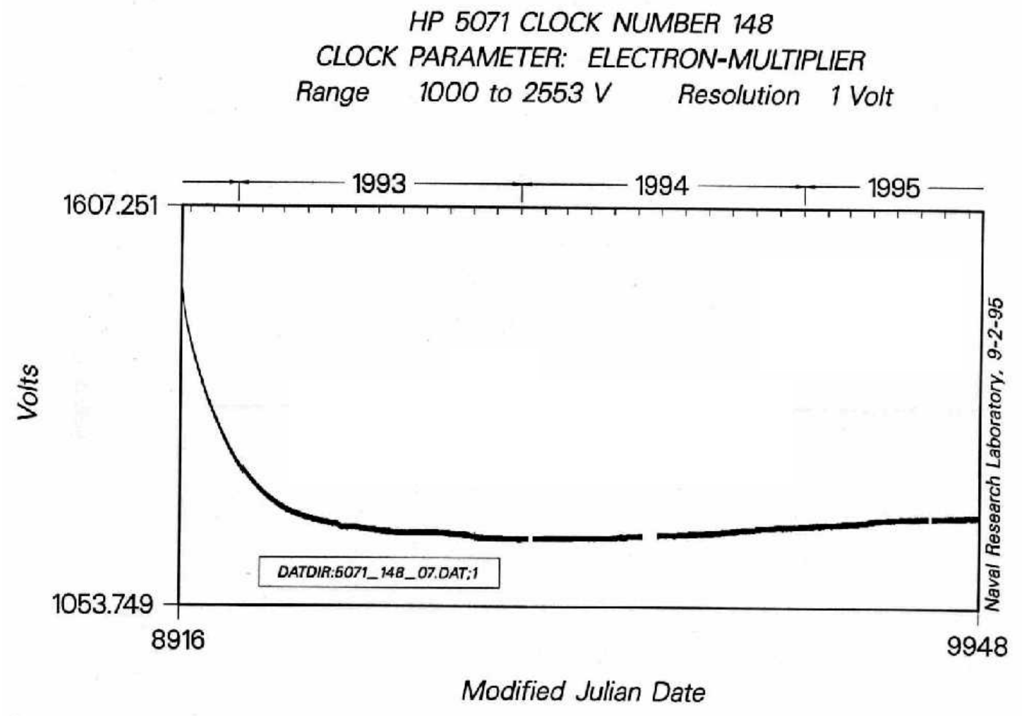

Figure 3. Electron multiplier voltage for the first 2 3/4 years of operation.

This plot illustrates a common feature seen in many beam tubes. The clock keeps a constant 100 nA beam current out of the tube by changing the electron multiplier voltage. Over the first 6-9 months, the electron multiplier voltage drops. On some clocks the decrease exceeds 400 volts. A drop in voltage implies that either the cesium flux from the oven or the electron multiplier gain is increasing. Of the two, increased electron multiplier gain is, by far, the most likely.

Some early clocks exhibited a problem with decreasing electron multiplier voltage. In some cases, the voltage could drop below 1000 volts, a fatal error as far as the electronics are concerned. Since this was an otherwise excellent tube, changes were made in the design of the multiplier voltage divider string to 'cure' the observed problem.

Near end-of-life of this tube, the electron multiplier voltage is shown in Figure 4. Plots of electron multiplier voltage and AC amplifier gain are shown. Under normal circumstances, the clock controls the electron multiplier voltage to maintain 100 nA output. When the electron multiplier voltage reaches its ceiling of 2553 volts, the system issues a warning message. At this point, to maintain an adequate signal output level, the AC amplifier gain starts increasing from its nominal 14.4% to ultimately 100%. This constitutes a fatal error. The tube is out of cesium.

This clock was installed on MJD 48916, and ultimately ran out of cesium around MJD 50950. Total lifetime was 5.56 years.

After an initial decrease in voltage, the constancy of electron multiplier gain over the life of the tube has been shown to be quite good. For this cesium beam tube, as seen in Figures 3 and 4, the voltage slowly changed from about 1160 volts at its minimum to about 1300 volts over a five-year period, then rose abruptly to its maximum value as the cesium supply was depleted.

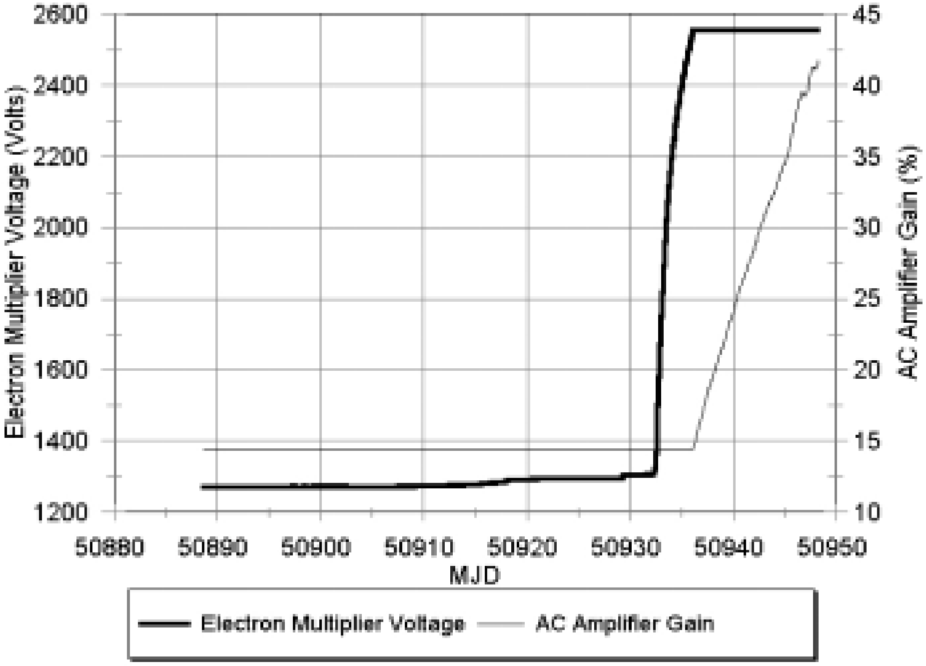

Figure 4. Electron multiplier and
AC amplifier gain showing tube
end-of-life for clock number 148

2.3 Cesium Beam Tube Lifetime Statistics

The knowledge of the complete history of a representative sample of cesium clocks has given a reasonably accurate estimation of the lifetime statistics of the high performance beam tube.

Of the units on which data is available to the authors and contributors, a total of 98 high performance units have run out of cesium. The first units were shipped in April 1992. Life times for units have ranged from 4.7 years, to 7.6 years, with several of the earlier units still running. At present, the mean-time-to-failure for the beam tubes that have failed is 6.34 years, with a standard deviation of 0.55 years. The data to date reflects the leading edge of the end-of-life curve.

As the remaining early tubes reach their end-of-life, the mean tube lifetime should increase.

The data also indicates that the decrease in electron multiplier voltage as seen in Figure 3 was most likely not due to increased cesium beam flux as we observe lifetimes consistent with our earlier calculations.

3. NIST DATA

At the U.S. National Institute of Standards and Technology (NIST), frequency data is taken every 2 hours for each clock. Several clocks have continuous records exceeding 1500 days.

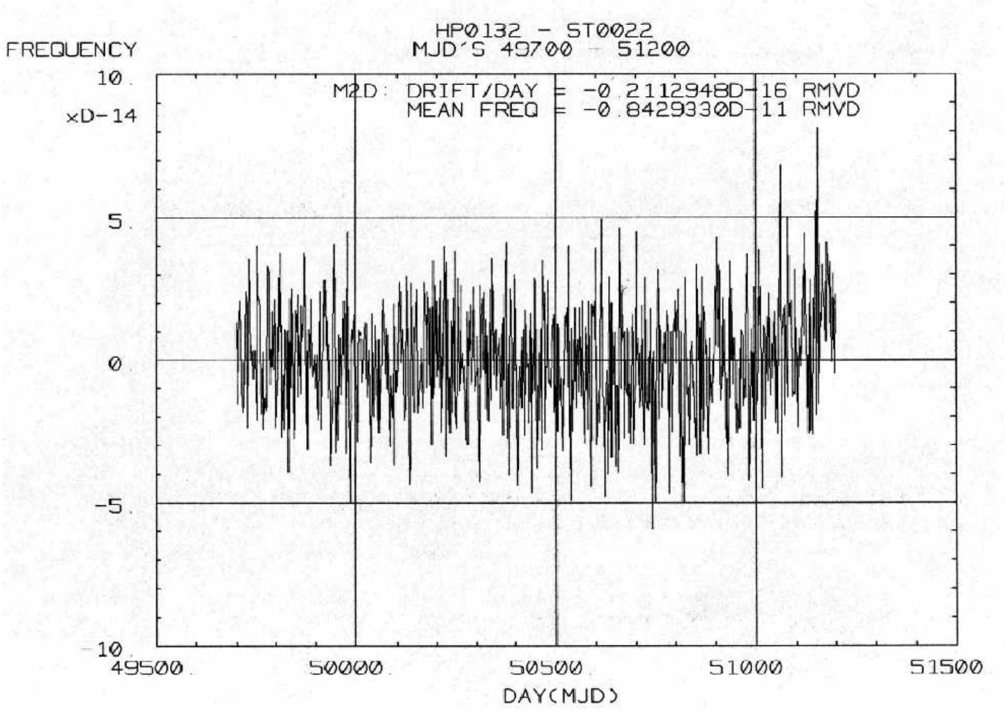

Figure 5. Frequency history of clock 132
1500 days of data

3.1 End-of-Life Experience

Recently, clock serial number 132 ran out of cesium. Figure 5 is a plot of the frequency of clock 132 as measured against a NIST maser. Of interest here is the last 200 days prior to running out of cesium. The frequency shows a definite aging characteristic. At least two USNO clocks showed similar positive aging slopes in the last 300-500 days before end-of-life. A number of other USNO clocks did not. The data is too sparse at present to draw any conclusions.

Figure 6 is a plot of the last 100 days of a recent failure on Clock 182. Although the clock appears to operate correctly, the increased frequency variation seen during the last forty days has caused this clock to become unusable.

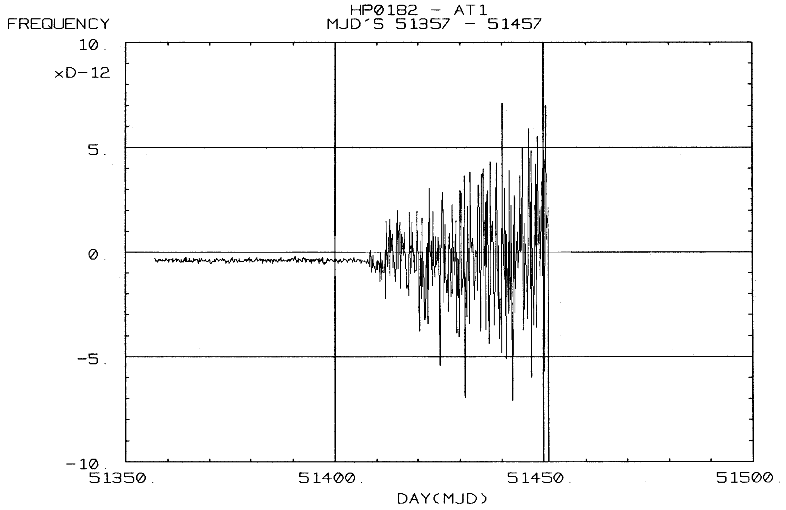

Figure 6. Last 100 days of clock 182 showing increase in instability during the last 40 days of operation

The timing is consistent with USNO experience as shown in Figure 4. When the cesium source is depleted, there is a sharp rise in electron multiplier voltage that takes 1 to 10 days to reach its range limit.

At that point, the AC amplifier gain starts to increase reaching its limit somewhere between 3 and 10 days. While the clock appears to be still functional, the NIST data shows that frequency instability during the final days may become so severe that the clock is not usable. The cause is probably decreased signal/noise ratio because of decreased beam flux. Figure 7 shows data from the Jet Propulsion Lab (JPL) for two 5071A units. Data on the end-of-life unit was taken 2 days after the signal degradation was first noticed.

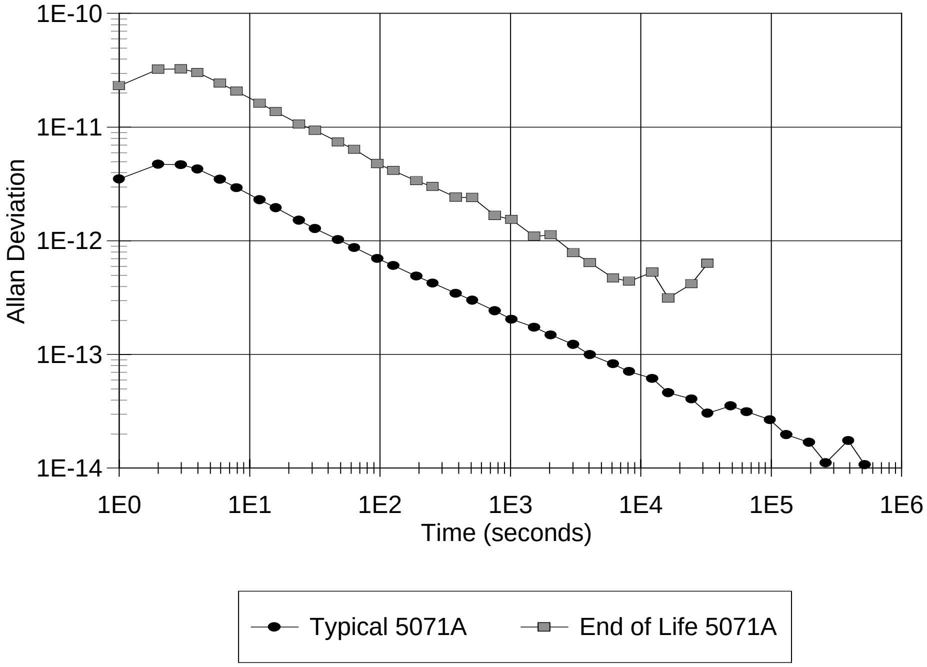

Figure 7. Allan Deviation of a typical clock and one approaching end of life

3.2 Long-term Stability

Long-term data collected on the NIST clocks provides excellent information on the long-term stability of these clocks as expressed in their Allan Deviation.

The original specification for the time domain stability floor was set at 2 x 10^{-14}. Data from NIST shows that this was very conservative.

Figure 8 is a plot of the Allan Deviation for NIST clock 1074 after accumulating 900 days of measurements.

Data taken on NIST clocks indicates the time domain stability flicker floor is about 5 x 10^{-15}, that this floor is usually achieved for averaging times less than 10^{7} seconds, and that the drift of a typical clock is on the order of ± 2-4 x 10^{-17} per day. This is consistent with USNO data we recently obtained.

4. AGILENT DATA

All production cesium clocks are tested in a variety of automatic test systems. Data is either saved on the local LAN, or as paper copies.

The database contains information on over 1500 cesium clocks and cesium beam tubes. A logical exercise was to compare data from all sources to the original specifications set by the 5071A design team.

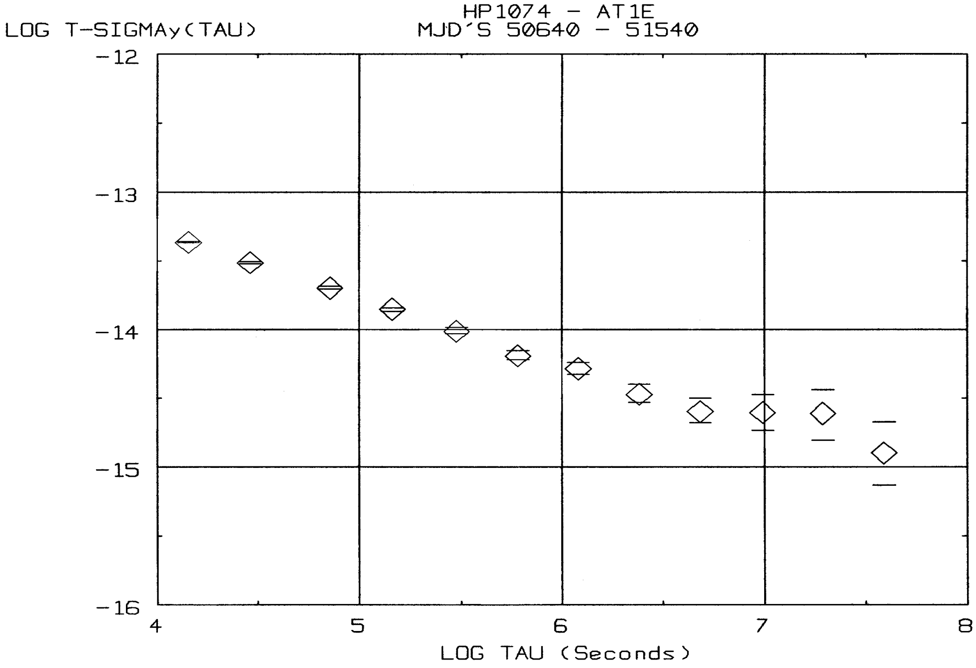

Figure 8. Allan Deviation of clock 1074

5. DATA ASSESSMENT

The policy chosen to set specifications for this clock is to use worst-case-sum methodology. This has an advantage over more typical root-sum-square methods in that it is more conservative and eliminates corner cases where a particular combination of effects causes the clock to fail its specifications. This method has a disadvantage in that we must ensure that all possible combinations are tested. Effects have been seen in previous atomic clocks that are not linear, but indeed involve strong cross coupling between several effects.

As a result, matrices were devised outlining actual measured performance and comparison to specification. Emphasis was placed on frequency accuracy, time domain stability, and environmental data.

5.1 High Performance Clock Specifications

Based on BIPM data, the specified accuracy of the high performance clock was tightened to 5 x 10^{-13}.

Based on USNO, NIST, and Agilent data, the long-term stability flicker floor specification was tightened to a guaranteed value of 1.0 x 10^{-14}, with a typical value of 5 x 10^{-15}.

Time-domain stability limits due to environmental effects were removed. To date, no changes of frequency that are a function of environmental changes have been observed.

No other changes were needed.

5.2 Standard Clock Specifications

Based on BIPM data, the specified accuracy of the standard clock was tightened to 1 x 10^{-12}.

The long-term stability flicker floor specification was tightened to a guaranteed value of 5 x 10^{-14} with a typical value of <1.5 x 10^{-14} based on design similarity with the high performance clock.

As in the high performance clock, limits on time-domain stability due to environmental effects were removed.

Based on USNO, NIST, and Agilent data, we believe that our model for cesium consumption and tube life is essentially correct, justifying an increase in the standard cesium beam tube warranty to 10 years.

The largest discrepancy between performance and specification was found in comparing long-term stability measurements with specification. The data and the original specification are shown in Figure 9. Product specifications have been modified to provide a better correlation with actual performance.

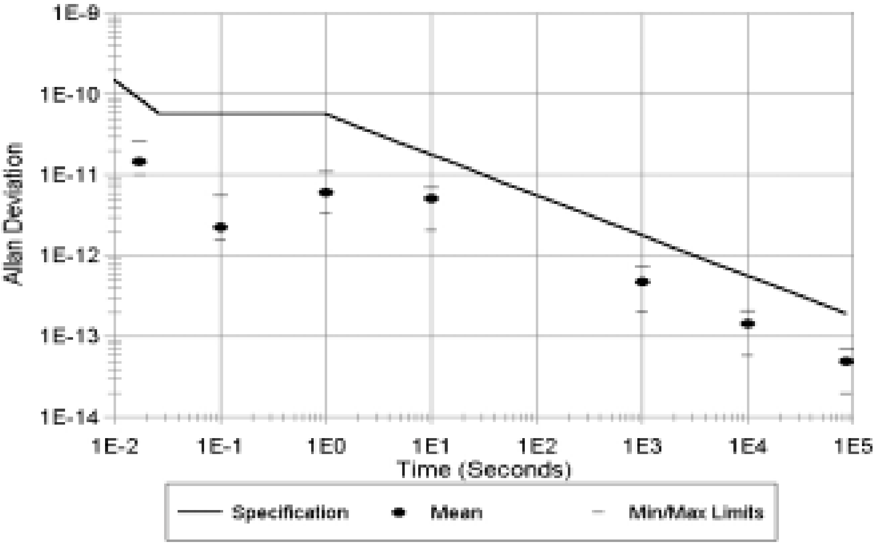

Figure 9. Short and intermediate time-domain stability based on a sample of 50 standard clocks.

5.3 Electronic Reliability

During the seven years since its introduction, the clock has averaged an annual failure rate of 10%, or an MTBF of 10 years, not including beam tube end-of-life failures. Recent improvements in clock firmware have resulted in a continuing reduction in the fail rate.

6. SUMMARY

Data from various external sources cited in this paper confirms the performance specifications of the clock. The data also provides the opportunity to continue to improve both actual performance and product specifications. For critical applications, closer monitoring of actual unit performance is essential to minimize the effect of increased frequency instability observed in near end-of-life beam tubes.

7. ACKNOWLEDGEMENTS

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8. DISCLAIMER

The U.S. Naval Observatory, the National Institute of Standards and Technology, the Naval Research Laboratory, and the Jet Propulsion Laboratories as a matter of policy do not endorse any commercial product, nor can it confirm any conclusions in this paper that are based upon information or work at other institutions.

9. REFERENCES

This paper is based upon, and is an extension of an invited paper given by the speaker at the 1999 Joint Meeting of the European Frequency and Time Forum and the IEEE International Frequency Control Symposium, in Besançon, France, 13-16 April, 1999.

Kusters, J.A. et al, *Proceedings of the 1999 Joint Meeting of the European Frequency and Time Forum and the IEEE International Frequency Control Symposium*, “Long-Term Experience with Cesium Beam Frequency Standards,” IEEE Publication 99CH36313, pp. 159-163, April, 1999.