THE LONG-TERM STABILITY OF THE U.S. NAVAL OBSERVATORY'S MASERS

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Abstract

The U. S. Naval Observatory (USNO) currently maintains 20 cavity-tuned hydrogen maser frequency standards at its Washington, DC (USNO-DC) and Alternate Master Clock (USNO-AMC) facilities, of which 13 have been in use for at least 7 years. This paper analyzes and characterizes the long-term frequency behavior of these masers, as observed.

INTRODUCTION

The U.S. Naval Observatory (USNO) uses a combination of cavity-tuned hydrogen maser frequency standards and commercial cesium standards to create its timescale. This paper concentrates on the observed long-term performance of the hydrogen masers in an operational setting. The USNO received its first five cavity-tuned hydrogen masers in 1989 and 1990, and five more masers were delivered in 1992 through 1994. These masers, coupled with the acquisition of cesium-beam standards and improved time transfer techniques, led to significant improvements in the stability of the USNO Master Clock.

The reader is cautioned that the data presented here were gathered for operational purposes, and therefore controlled experiments were not conducted. While some allowance has been made in the analysis for environmental effects, there is no way to rule out the possibility that some of the variations are due to unmonitored or misunderstood environmental changes. In addition, although all the masers whose data are reported herein were constructed by the Symmetricom or the companies it has acquired, the design and construction details of the individual masers have changed over time.

METHODOLOGY: DATA AND ANALYSIS

The USNO has on file a full set of hourly clock differences recorded by our data acquisition system (DAS) since 14 August 1989 (MJD 47752); they are measured with a precision of 50 ps by a switch and counter system, in the form of timing differences between each clock and the Master Clock **[1]**. For this and other reasons, statistical measures based upon hydrogen maser data taken with the switch system are not utilized for averaging times less than 2 days. For short sampling intervals, we use data taken with a low-noise measurement system (herein designated TSC), which has a measured precision of 2 ps.

For this analysis, two reference standards internal to the USNO are employed, along with the 2004 realization of Terrestrial Time, TT (BIPM04) **[2,3]**, which in some of the figures is abbreviated as TT04. For data previous to 14 July 1995 (MJD 49912), the only USNO internal timescale available is A.1 **[4,5]**, which for this analysis can be considered to be an average of the USNO cesiums. Beginning on MJD 49912, there were enough available hydrogen masers to justify an internal USNO timescale using purely maser data. Although this timescale is termed the maser mean (MM), its long-term frequency behavior mimics the USNO's cesium-only mean (CM), because the MM is generated by removing from each maser's data the results of a long-term frequency-fit to the USNO cesium mean. The differences between TT (BIPM04), the A.1, and the MM stayed consistent to within 5 ns/day (Figure 1) or 10^{-21}/s (Figure 2), except for a short time before MJD 47869, and in all cases the frequency difference between the standards was significantly less than the observed range of individual maser frequency variations.

Although the agreement between internal and external references is quite close on scales of 100 days or more, time transfer noise and other factors lead to significant disagreements between the internal USNO and the external timescales for averaging times that are less, particularly in data taken before GPS was utilized. Figure 3 shows how the correspondence has improved over time.

Humidity controls of the USNO-DC masers NAV01, NAV03, NAV04, NAV05, NAV08, NAV15, and NAV18 were disabled between MJD 52996 and 53050, and therefore the data from those masers during that period are ignored. With one possible exception (NAV01, which was exposed to the elements by Hurricane Andrew in 1992), the magnitudes of the inferred dependencies of frequency on relative humidity were roughly consistent with those from systematic and controlled studies conducted at the National Institute of Standards and Technology (NIST) **[6]**.

For the statistical analysis in part IV, data from three masers (NAV13, NAV14, and NAV16) located at the USNO-AMC are not presented because time transfer noise limits the ability to measure their stability. Similarly, analysis of data from the maser NAV09 is not presented because of an intermittent problem limiting its stability, which most likely involves its heater circuits.

In this paper, all frequencies will be expressed as fractional frequencies $(f-f_0)/f_0$, from the nominal frequency, f_0. This fractional frequency will be expressed in ns/day; 1 ns/day is 1.16×10^{-14} in dimensionless units. Drifts in the fractional frequency are given in units of inverse seconds; a frequency drift of 1 ns/day every day corresponds to $1.34\ 10^{-19}$/sec

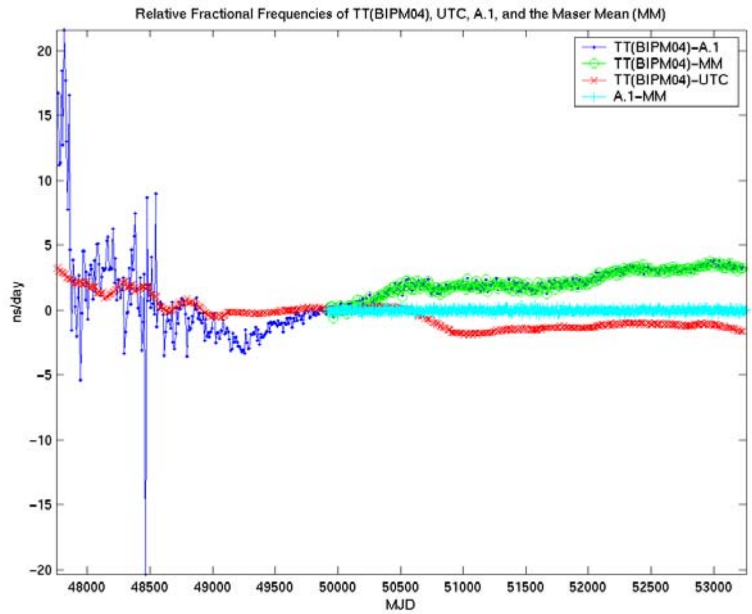

Figure 1. Fractional frequency differences between references used in this work. In all cases, the differences are less than the difference between individual masers and any one reference. The large variations before MJD 49000 (January 1993) reflect the significantly smaller number and higher instability of the existing cesium clocks (not shown), as well as the higher noise of pre-GPS time transfer.

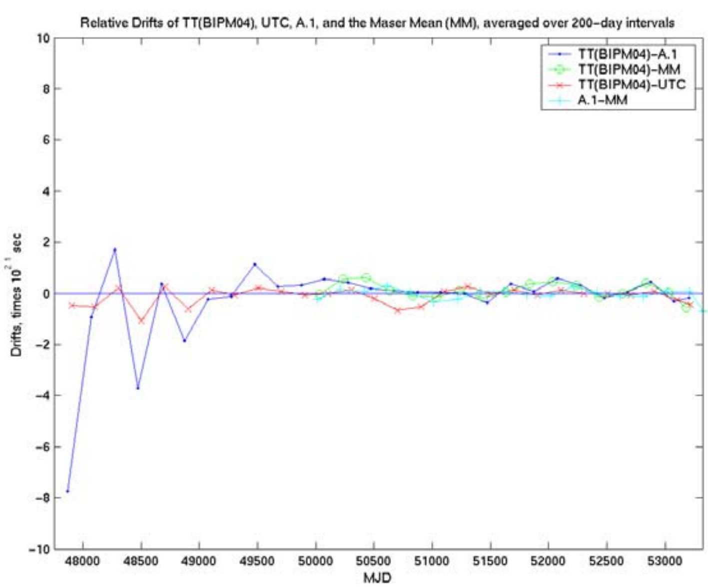

Figure 2. Frequency drifts between available timescale references. For display, the drifts have been multiplied by 10^{21} sec.

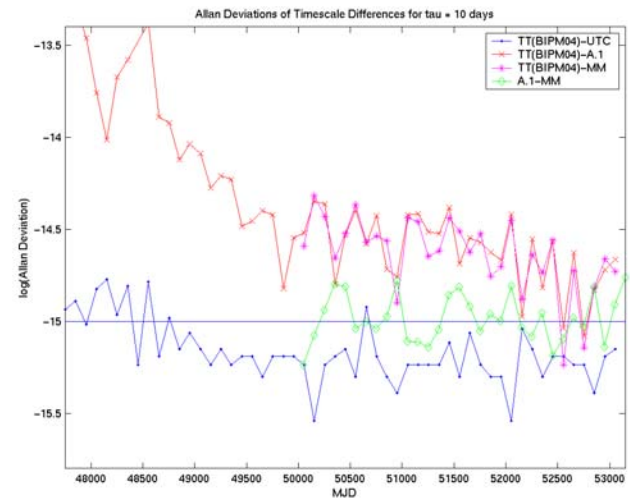

Figure 3. Allan deviation of differences between external and internal timescales, for tau of 10 days. The greater stability of the more recent data is due to several improvements in timekeeping. The Hadamard deviations are numerically similar to the Allan deviations for such short averaging times.

LONG-TERM FREQUENCY AND FREQUENCY DRIFT OF USNO HYDROGEN MASERS AS A TIME SERIES

In this section, frequency and frequency drift data from USNO masers are shown in slightly processed form, wherein obviously bad data were removed, and the ad-hoc frequency adjustments (shown in Table 1) were added to several individual masers. The removed data were in general unpresentable due to failures or adjustments in the environmental controls, the measurement systems, or the maser hardware. Some of the frequency adjustments were made to compensate for major changes in the maser's environment, such as being moved to a different building, and others were made to adjust for a frequency switch that occurred after a repair, adjustment, or experiment. Where appropriate for display, the initial frequency bias of each maser has been removed, however, no direct corrections were made to frequency drift data.

The USNO designations are in delivery order, and Figure 4 provides a maser-count as a function of time.

Figures 5 and 6, differing only in the scale of their vertical axes, show the long-term frequency variations of the USNO masers. The legends identify each time series by the USNO sequence number of the maser, which roughly corresponds to the delivery date. However, the delivery date does not necessarily correspond to the age of the maser, and recent masers were in general delivered by the manufacturer sooner after construction (by 6-9 months) than in times past. Figure 7 depicts the average frequency drift as a function of time.

Table 1. Time and magnitude of frequency adjustments applied to masers for this analysis.

USNO Designation	MJD	Adjustment ns/day
NAV02	48200	-90
NAV03	50217	+4
NAV03	51943	-4
NAV03	52807	83
NAV05	52100	-47
NAV09	50215	2
NAV09	51800	11
NAV09	52165	-7
NAV09	52685	-5
NAV09	52949	12
NAV10	50857	9
NAV12	49944	31
NAV14	51600	-6

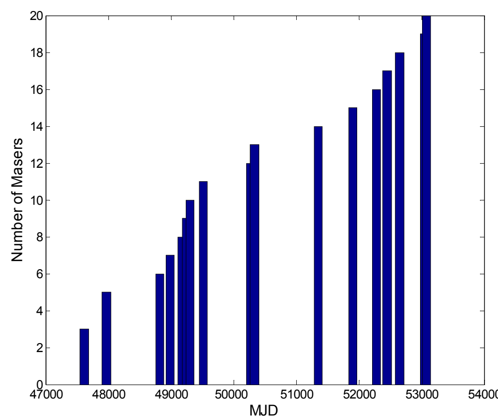

Figure 4. Count of operational USNO masers as function of time.

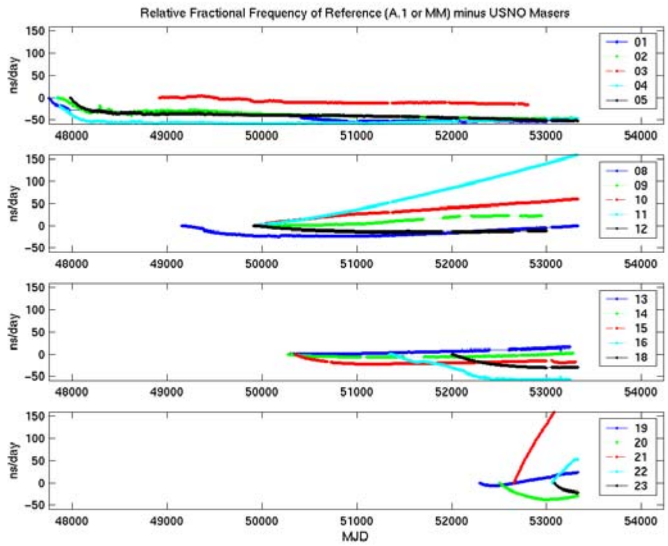

Figure 5. USNO maser frequencies. Masers are identified by their USNO designations. NAV 1 through NAV8 are referenced to A.1, and the others are referenced to the USNO Maser Mean. The maser NAV15 failed on MJD 53307 due to a problem within its physics package.

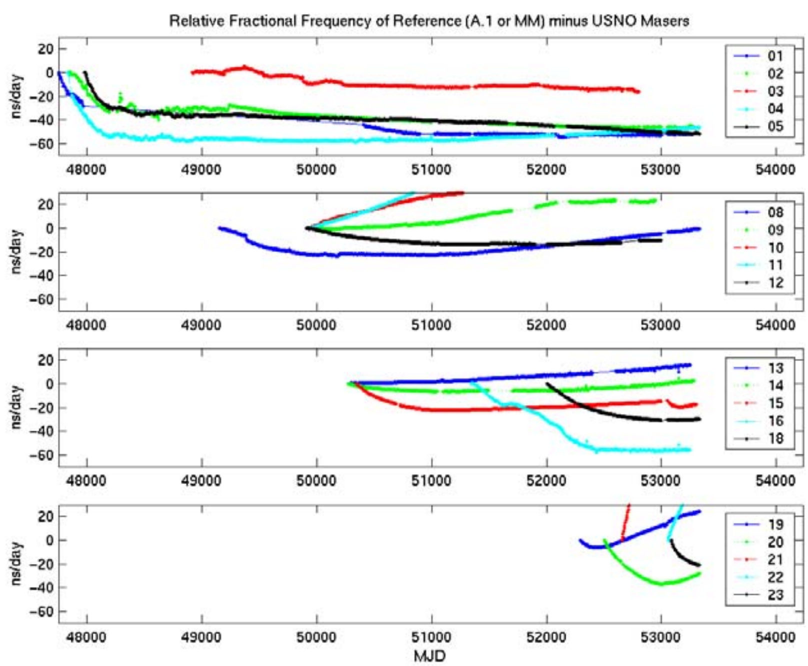

Figure 6. Same as in previous figure, but with an expanded vertical scale.

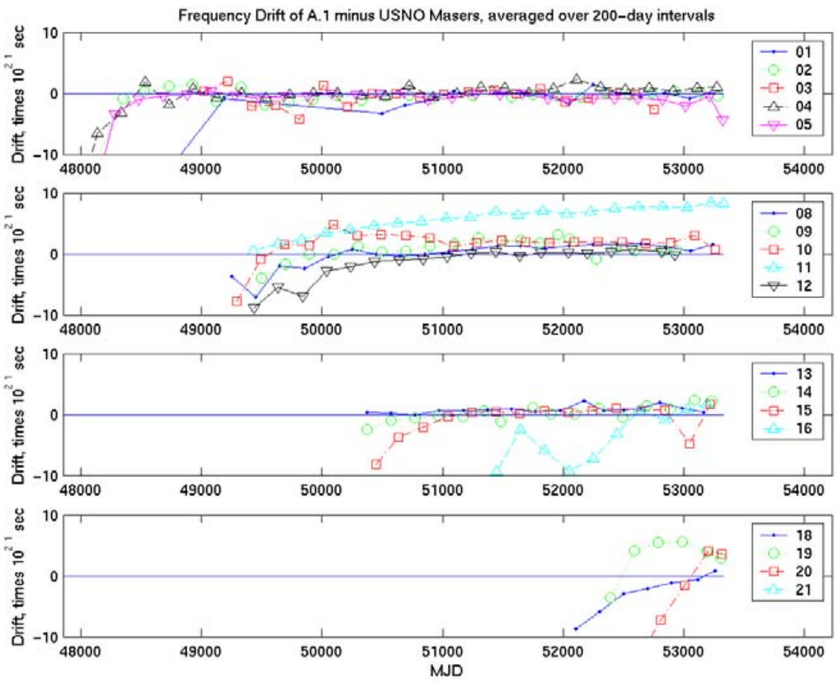

Figure 7. Frequency drifts of USNO masers located in Washington, DC (USNO-DC), computed by differencing frequencies at endpoints of 200-day intervals. Since MJD 49000, the frequency drifts between the A.1, UTC, and TT (BIPM03) have been less than 10^{-21}/sec. The maser NAV21 has drifts of order 4-5 10^{-20}/sec.

STATISTICAL MEASURES

The most commonly used standard timekeeping statistical measure is the Allan deviation **[7]**, which is related to the second difference of clock phase data and is sensitive to the frequency drift. In situations wherein the overall drift is known or assumed to be constant, the Hadamard deviation **[8]**, related to the third difference of clock phase data, often proves more useful as a measure of the clock stability because it is insensitive to constant frequency drift and measures the change in the frequency drift.

In order to provide a very general analysis of the observed stability of our masers, the data were broken into consecutive 100-day intervals, and their statistics were computed in several ways. To minimize the sensitivity of the computations to environmental disturbances or component failure, the median Allan deviation of the 100-day intervals for the smallest (2.7 days) and largest (10.7 days) available averaging times, τ, are reported in Figures 8-9. The analogous median Hadamard deviations are reported in Figures 10-11.

The USNO Maser Mean is used as the frequency reference because, from the time of its inception, it has been more stable than A.1 over the averaging times presented. While the individual maser instabilities, as measured with A.1, are only somewhat larger than those measured with the MM over the time range shown, they are much larger before MJD 49000; those analyses are not presented, because the discrepancies are likely due to the instabilities of the A.1 timescale reference over those times.

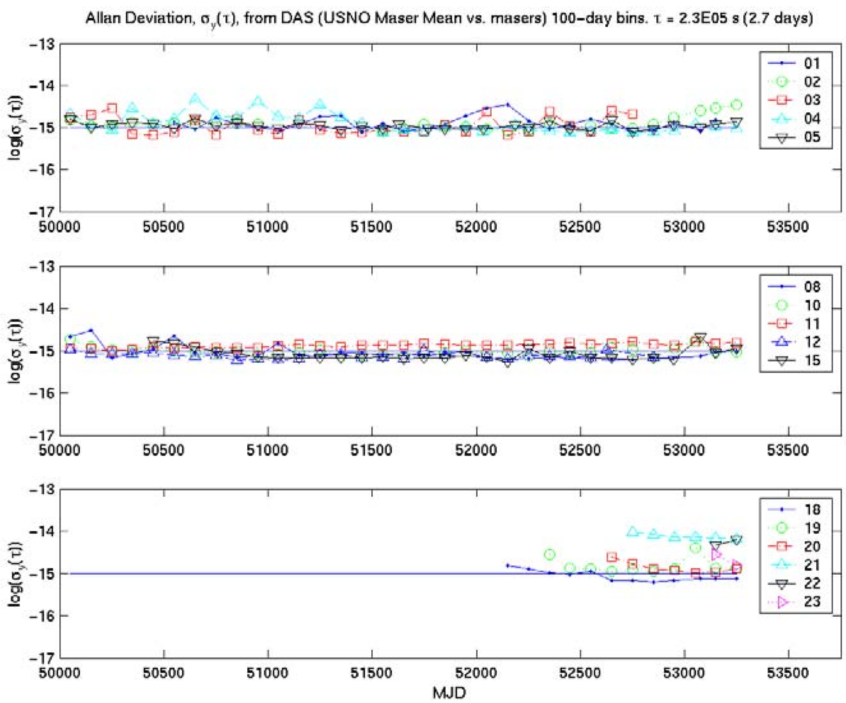

Figure 8. Allan deviation of individual USNO-DC masers for τ = 64 hours (2.7 days), computed in 100-day batches.

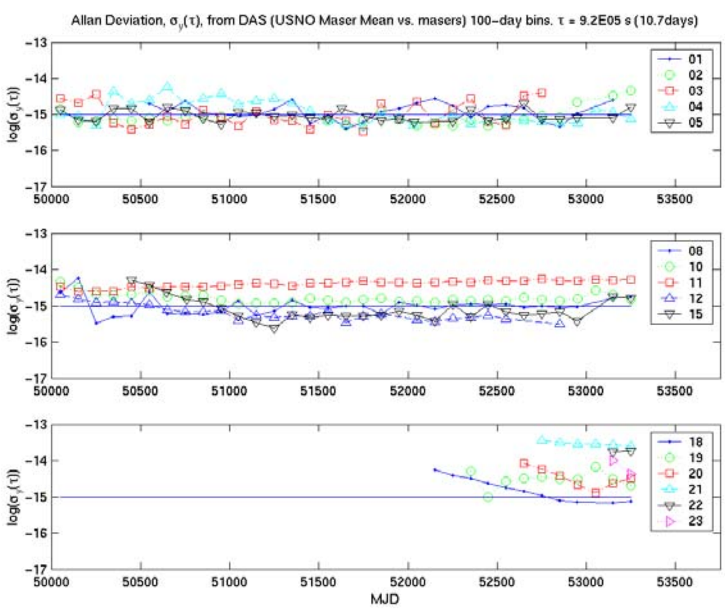

Figure 9. Allan deviation of individual USNO-DC masers for τ = 256 hours (10.7 days), computed in 100-day batches.

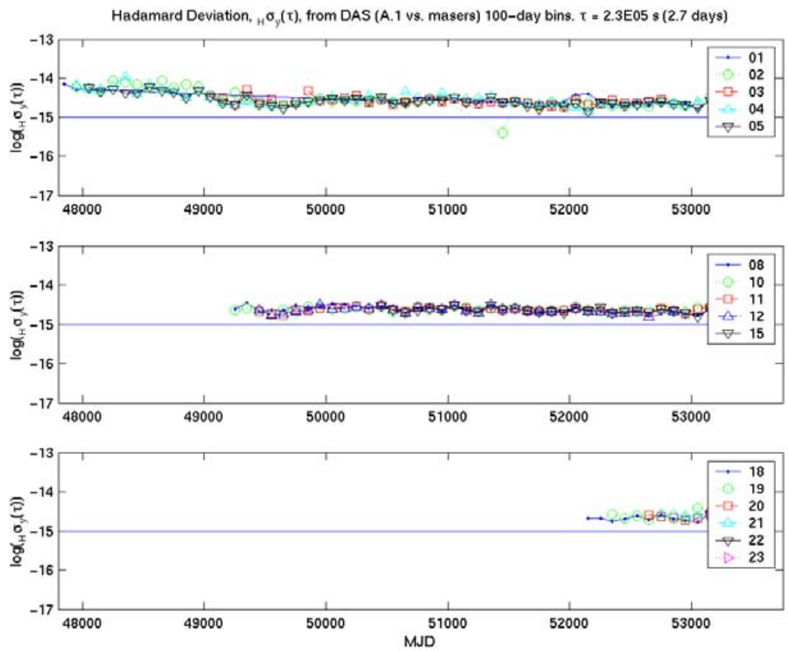

Figure 10. Hadamard deviation of individual USNO-DC masers for τ = 64 hours (2.7 days), computed in 100-day batches.

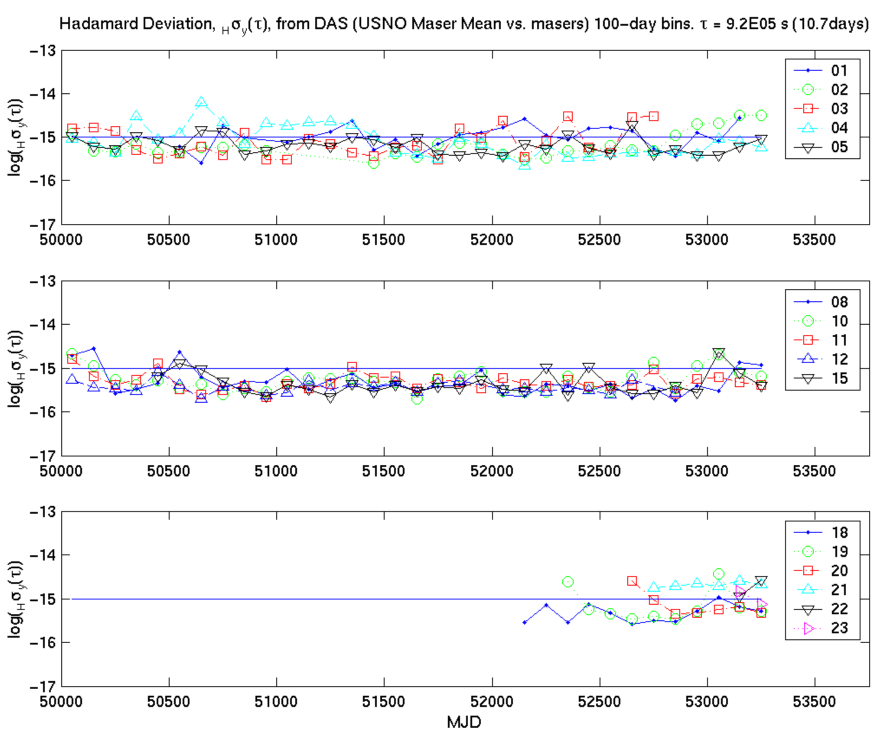

Figure 11. Hadamard deviation of individual USNO-DC masers for τ = 256 hours (10.7 days), computed in 100-day batches.

CONCLUSIONS

Although this paper is intended to be more phenomenological and operations-centered rather than analytic, it is observed that the frequency drifts of the USNO masers were initially on the order of 10^{-20}/sec, and after several years, they generally fell by an order of magnitude, with some masers' drifts becoming slightly negative. Despite the long-term changes in observable frequency drifts, the masers' sub-monthly stabilities and frequency drift variations, as measured by the Allan and Hadamard deviations since the USNO Maser Mean was defined in 1995, remain generally unchanged over time.

The data do not allow the determination of the cause of the frequency drifts or other variations. Aging of the cavity Teflon coating **[9]**, changes in the vacuum composition, changes in the magnetic field or shielding, or variations in the capacitance or resistance of key circuit elements could singly, or in concert, be responsible.

DISCLAIMER

The U.S. Naval Observatory cannot endorse a product. The manufacturers are identified for technical clarity, and the reader is cautioned that the past performance of commercial products, as observed at the USNO, is not necessarily a valid indicator of how any such products or similar products will perform elsewhere or in the future.

ACKNOWLEDGEMENTS

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