STATISTICAL PROPERTIES OF HIGH PERFORMANCE CESIUM STANDARDS

D. B. Percival
U. S. Naval Observatory

ABSTRACT

The intermediate term frequency stability of a group of new high-performance cesium beam tubes (Hewlett-Packard Model 5061A Option 004) at the U. S. Naval Observatory is analyzed from two viewpoints: (1) by comparison of the high-performance standards to the MEAN(USNO) time scale and (2) by intercomparisons among the standards themselves. For sampling times up to 5 days, the frequency stability of the high-performance units shows significant improvement over older commercial cesium beam standards.

INTRODUCTION

In the last year, the Hewlett-Packard Company has begun production of a new high performance beam tube for its commercial cesium beam frequency standard, the HP 5061A. Denoted as 5061A Option 004, this new beam tube may be included in newly purchased HP 5061A's or may be fitted as a replacement for a standard beam tube in older HP 5061A's or HP 5060A's. Some of the modifications incorporated in the new beam tube include: increased microwave cavity length, reduction in cavity phase-shift, and improvement in the C-field homogeneity, all of which relate to the accuracy of the frequency produced by the beam tube; increased cesium beam flux, which should improve the frequency stability; and better magnetic shielding, which should reduce frequency changes due to external magnetic field changes. Other modifications to the new beam tube, including the new dual beam design, were made to improve the performance of the cesium beam standard when used as a portable clock and when used in field applications.[1]

The U. S. Naval Observatory, currently has eleven cesium standards with the new high performance beam tube. One of these standards has been in operation for over a year; five others have operated for five months or more. From forty days to three months worth of data for three more units is also available. The purpose of this report is to discuss the precision and frequency stability of the new high performance beam tube for averaging times from one hour to five days, with some tentative results for averaging times up to twenty days.

For PTTI applications the additional cost of the new beam tube would be justified if a requirement exists for increased frequency stability in sampling times greater than one hour. In this regard, there is a preliminary word of warning about the frequency stability values reported here. All of the frequency standards at the U.S. Naval Observatory have good operating environments. In the clock vaults, temperature varies typically by no more than one or two degrees Centigrade for periods of months. Reasonable care is taken to insure that the frequency standards are undisturbed by other electronic instruments, power outages, and operators. For poorer environments the frequency stability of the high performance beam tube will decrease significantly. The results reported here are valid only for cesium beam standards operating in good environments.

All of the data presented here were collected by the Time Service automatic data acquisition system.[2] Once per hour, an HP 5360 Computing Counter measures the five MHz phase difference at the positive going zero crossover between all of the frequency standards and three reference standards, which currently are two of the high performance cesium standards and the U.S. Naval Observatory hydrogen maser. Typically, the counter requires less than one minute to measure the phase difference between all of the frequency standards and one of the reference standards. Since both the high performance cesium standards and the hydrogen maser have excellent stability for averaging times less than one minute, and since for this paper the interest is in averaging times much greater than one minute, one may regard all the phase difference data as having been collected simultaneously. The noise contributed to the phase difference values by the measurement system itself is estimated by comparing a five MHz signal from a reference standard against itself through a cable loop. For all averaging times considered here, the measurement noise is at least one order of magnitude smaller than the best results obtained for frequency stability. To a very good approximation the measurement noise may be regarded as zero in all the computations.

One final question prior to the analysis of the data is that of independence of the frequency standards. Care is taken to insure that all of the frequency standards at the Observatory operate independently of each other. The frequency standards are separated electrically and spatially as much as is practically possible. There are currently seven different locations at the Observatory where conventional cesium standards and the new high performance standards are placed. There is no reason to believe that there is any correlation of frequency variations between any of the frequency standards at the Observatory. In addition, all of the cesium beam frequency standards have been aligned and adjusted according to manufacturer's specified procedure to produce the best possible value for the frequency of cesium from each unit.

DATA ANALYSIS

For a detailed look at the precision and frequency stability of the new high performance standards, the forty day period from 16 August, 1973 to 25 September, 1973 (MJD 41910 to MJD 41950) will also be considered, when nine high performance standards were in operation continuously at the Observatory. In this same time period, 21 conventional HP 5061A's operated continuously. We may estimate the precision in frequency of both of these groups of cesium standards by calculating for each group the average frequency with respect to MEAN(USNO) over the entire 40 day period and the standard deviation in frequency of each group. The results of these calculations are given in Figure 1. While the average frequency of each group is quite close (differing by little more than 1 part in 10^{13}), the standard deviation for the high performance units is somewhat lower than that for the conventional standards. Thus, the high performance standards were a more precise group of frequency standards than the group of conventional cesium standards. Both of these groups of cesium standards indicate that MEAN(USNO), the internal time scale generated by the U. S. Naval Observatory, is high in frequency by 5 or 6 parts in 10^{13}.

$\bar{X}$ = AVERAGE FREQUENCY OF ENSEMBLE WITH RESPECT TO MEAN (USNO)

S = STANDARD DEVIATION OF ENSEMBLE

N = NUMBER OF FREQUENCY STANDARDS IN ENSEMBLE

HIGH PERFORMANCE CESIUM STANDARDS	CONVENTIONAL H.P. 5061A CESIUM STANDARDS
N = 9	N = 21
$\bar{X} = -4.7 \times 10^{-13}$	$\bar{X} = -5.9 \times 10^{-13}$
$S = 13.5 \times 10^{-13}$	$S = 23.4 \times 10^{-13}$

Figure 1. Precision of High Performance Cesium Beam Tube

For estimates of frequency stability, the square root of the Allan variance is used extensively.[3] For the case where two consecutive frequency measurements are made with no dead time between measurements, the Allan variance may be estimated by the following:

$$\sigma_{ij}^2(\tau) \simeq \frac{1}{2n}\sum_{\ell=1}^{n}(\overline{Y}_{\ell+1} - \overline{Y}_{\ell})^2 \qquad (1)$$

In this formula, $\overline{Y}_\ell$ is the average frequency of standard i versus standard j in the ℓth interval of duration τ. All n + 1 intervals are consecutive and non-overlapping. This estimate of frequency stability is based upon the frequency variation from one time interval of length τ to the next interval. The average frequency for standard i versus standard j in any time interval is estimated by differencing the phase to phase measurements between the two standards taken at the beginning and the end of the time interval and dividing by a scaling factor.

The following equation is also important:

$$\sigma_{ij}^2 (\tau) = \sigma_i^2 (\tau) + \sigma_j^2 (\tau) \tag{2}$$

This equation states that, if standard i and standard j are statistically independent, then the variance of standard i compared to standard j equals simply the variance of standard i alone plus the variance of standard j alone.

For the forty day period under consideration, frequency stabilities for the high performance frequency standards may be derived in three different, though not entirely independent, ways: by comparison of the high performance units, first, against MEAN(USNO), the internal time scale of the U. S. Naval Observatory; second, against XMO5(USNO), a specially constructed experimental time scale; and third, against each other.

In the first method, MEAN(USNO) is used to estimate the frequency stability of each of the nine high performance standards. In Equations 1 and 2, standard i would be a high performance unit, while standard j would be the MEAN(USNO) time scale. For this discussion, a brief review of the salient features of the MEAN(USNO) time scale is helpful. Basically, out of all the cesium standards available at the Observatory, the best 14 to 20 of these are selected to generate MEAN(USNO). Each standard included in MEAN(USNO) is given a weight of one, so that the time scale will not depend on the behaviour of two or three seemingly well-behaved standards.[4] In the forty day period under consideration, MEAN(USNO) was generated by eighteen cesium standards, of which fourteen were conventional standards and four of which were high performance standards. In using MEAN(USNO) to evaluate the high performance standards, there is some difficulty, since four of the nine high performance units were contributors to MEAN(USNO). Theoretically, frequency stability measures for these four units would be too optimistic. In practice, however, since each standard constituted a little less than 6% of MEAN(USNO), to a reasonable first approximation, any one of the contributing standards may be considered as being independent of MEAN(USNO). A more serious problem is the following: in Equation 2, a stability estimate is derived for the left hand side of the equation, the variance of standard i versus MEAN(USNO). To estimate the variance of standard i alone, an estimate of the variance of MEAN(USNO) is required. For averaging times less than 2 days, good estimates of this variance may be derived, but for longer averaging times, good estimates are generally not available. However, if it is assumed that the variance of MEAN(USNO) is equated to the variance of standard i alone, then an upper bound for the variance of standard i alone is produced.

The second method used to evaluate the frequency stability of the high performance units involves an experimental time scale, denoted as XM05(USNO). Preliminary analysis of the frequency stability of the high performance beam tube indicated that the high performance units were about five times more stable than conventional cesium standards for averaging times of the order of one or two days. As an experiment, for the forty day period under consideration, the XM05(USNO) time scale was derived by giving the four high performance standards in the MEAN(USNO) time scale of weight of five each and the fourteen conventional cesium standards a weight of one each. Unbiased estimates may be derived for the frequency stability of the remaining five high performance units against this experimental time scale. Since the four high performance units in XM05(USNO) each constitute about 15% of this experimental time scale, frequency stability estimates for these units would be somewhat too optimistic.

The third and final method for estimating frequency stability involves intercomparisons of the high performance units themselves. The following equation is utilized:

$$\sigma_i^2(\tau) = 1/2\,(\sigma_{ij}^2(\tau) + \sigma_{ik}^2(\tau) - \sigma_{jk}^2(\tau)) \qquad (3)$$

By intercomparing three frequency standards the variance of each standard alone may be estimated. By intercomparing the nine high performance standards, one obtains 28 different, though not independent, estimates of the variance of each standard alone. These may be averaged to produce a single estimate for each clock. This method, known as the three corner hat method, has one serious problem when comparing standards with approximately the same frequency stabilities. If the estimates of the variances on the right hand side of Equation 3 have large uncertainties (which will be true when *n* in Equation 1 is small), then the estimate for the variance alone might turn out to be negative. For *n* equal to seven (which is the case for five day averaging periods when the data sample length is forty days), an average of three of the 28 estimates for eight of the nine high performance units was negative; for the ninth standard, seventeen of the 28 estimates were negative. For sampling times less than or equal to two days, where n is greater than or equal to nineteen, very few of the individual estimates for the variance turned out to be negative. In practice, any estimate less than zero was dropped before the final averaging.[5]

Figure 2 shows the results of the three types of frequency stability analysis for the high performance standard denoted as Cs 660/1S. Here the square root of the Allan variance is plotted as a function of the sampling time. Cs 660/1S was not a member of MEAN(USNO) or consequently of XM05(USNO) during the forty day period under consideration. The high performance beam tube in Cs 660/1S is the original beam tube for the unit. Cs 660/1S was in operation for approximately two months before the forty day period analyzed here. All three cuves follow approximately the $\tau^{-1/2}$ behaviour typical for cesium beam standards. As is to be expected, the three corner hat estimates for the frequency stability are smaller than the upper bound estimates produced by comparing Cs 660/1S to MEAN(USNO) and XM05(USNO). For shorter sampling times, the three corner hat estimates are considerably below the other two estimates. Both time scales are limited in these sampling regions by white noise. For longer sampling times, the three estimates begin to converge as the stabilities of both MEAN(USNO) and XM05(USNO) are improving faster than the stability of Cs 660/1S alone. For τ equal to five days, all three estimates differ by less than 2×10^{-14}. The most believable estimates over the entire range of sampling times are the unbiased three corner hat estimates.

The stability curves for Cs 660/1S given in Figure 2 are typical of the results obtained for eight of the nine high performance units. The results for the ninth unit, Cs 783/1S, are shown in Figure 3. At intervals varying from one to three days during the forty day period under consideration, Cs 783/1S was physically inverted 180° and left in its new position until the next inversion. While this procedure is not a definitive test of how the high performance beam tube will perform under non-laboratory conditions, it does indicate that disturbances to a high performance unit decrease its frequency stability significantly. The standard deviation for Cs 783/1S for averaging times of five days was a factor of four poorer than that for the undisturbed Cs 660/1S.

To supplement this statistical analysis, we would like to know how much confidence to attach to the estimates of the square root of the Allan variance. For the MEAN(USNO) method and the XM05(USNO) method, the variance of the Allan variance may be estimated using the methods discussed by Lesage and Audoin.[6] For the three corner hat method, however, it is not clear how to produce a confidence interval for the estimate of the variance of a single standard alone. To check the three corner hat method roughly, consider the following procedure. Estimates have been produced both of the variance of each high performance unit versus MEAN(USNO) and of the variance of each high performance unit alone using the three corner method. Combining these results for each high performance standard (except for Cs 783/1S, the unit which was being inverted) produces eight different estimates for the variance of MEAN(USNO) alone. The results for these computations for τ equal to two days are shown in Figure 4. Since the standard deviation of the standard

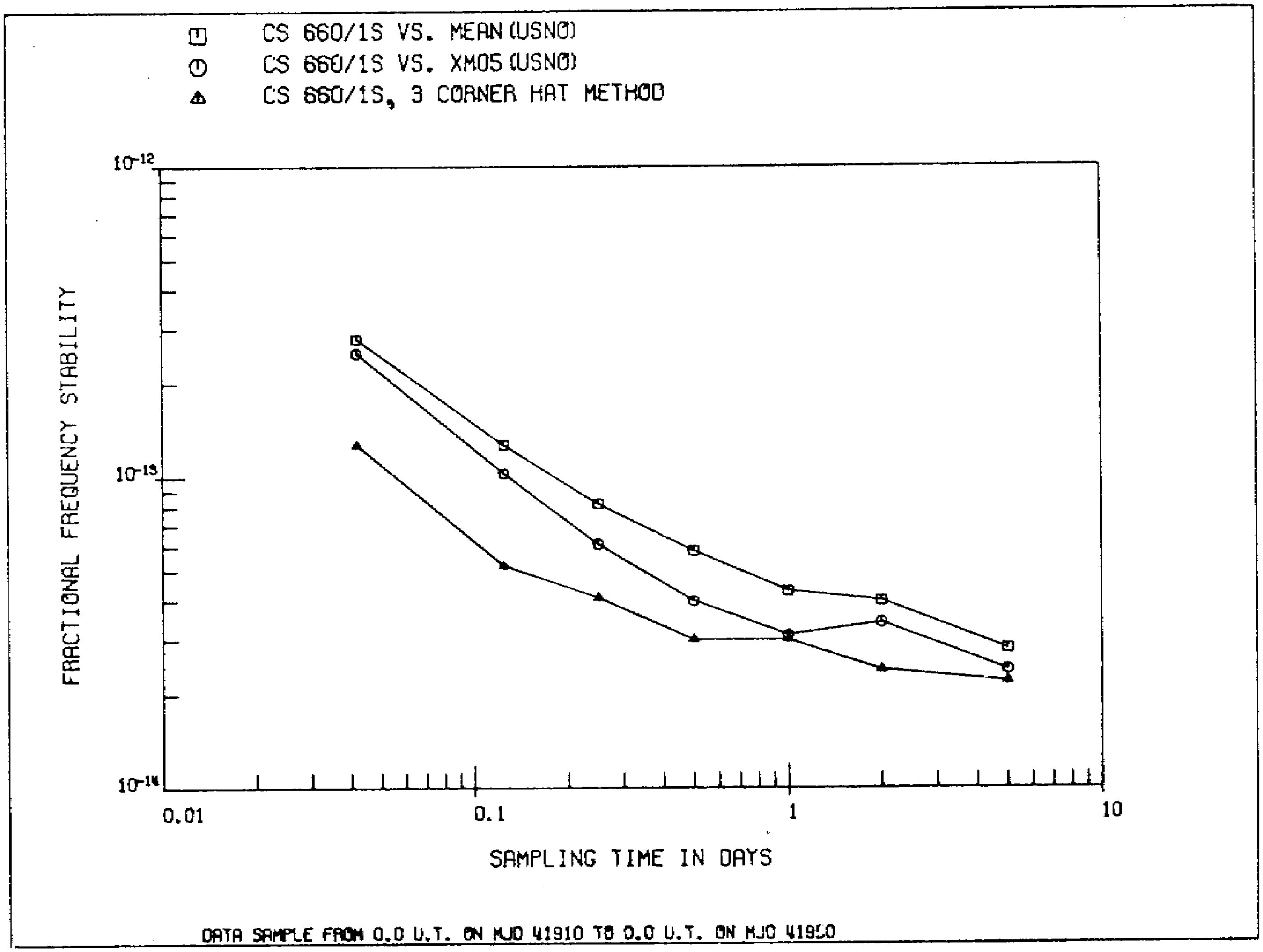
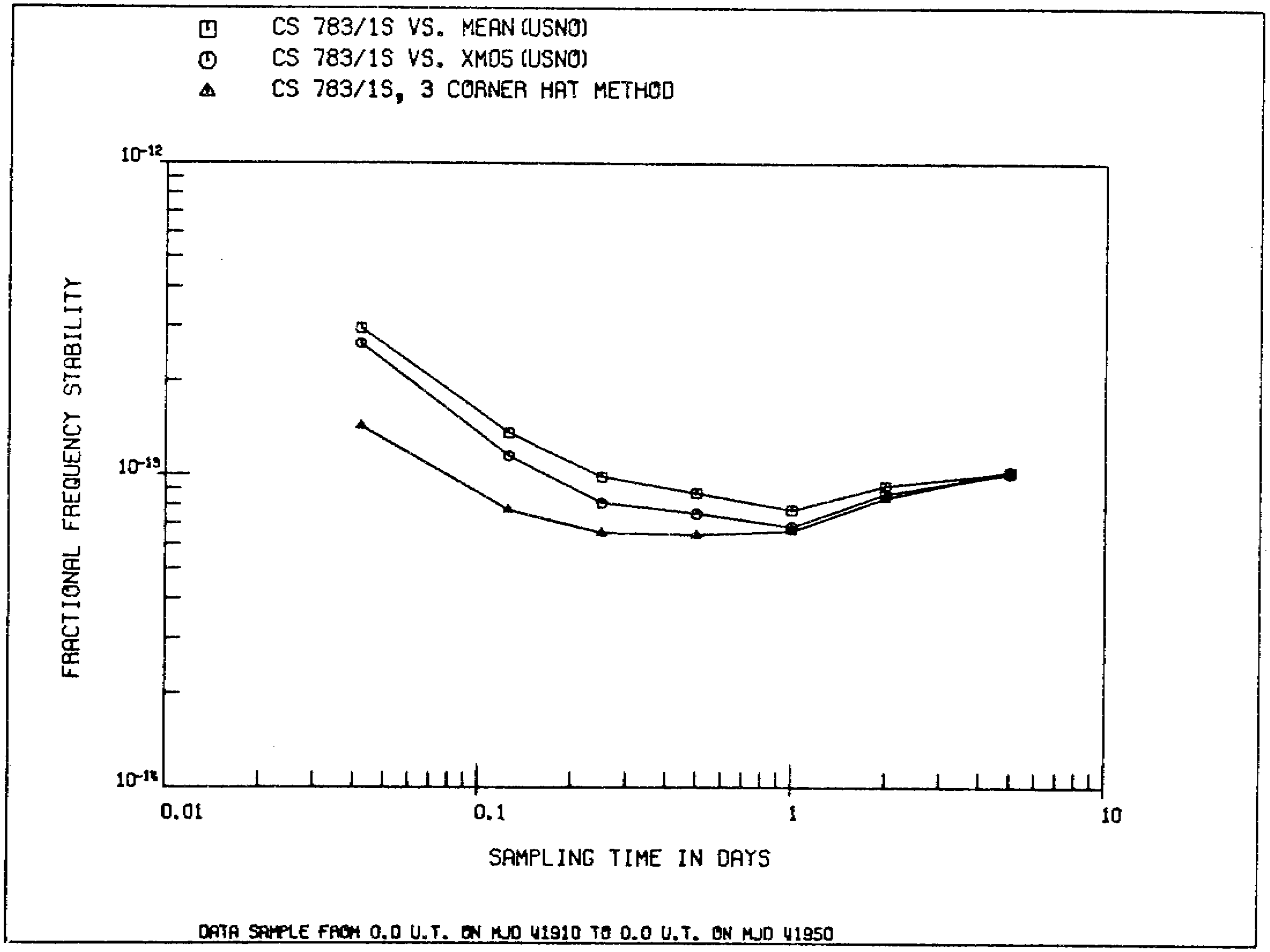

☐ CS 660/1S VS. MEAN (USNO)
○ CS 660/1S VS. XM05 (USNO)
▲ CS 660/1S, 3 CORNER HAT METHOD
FRACTIONAL FREQUENCY STABILITY
10^{-12}
10^{-13}
10^{-14}
0.01
0.1
1
10
SAMPLING TIME IN DAYS
DATA SAMPLE FROM 0.0 U.T. ON MJD 41910 TO 0.0 U.T. ON MJD 41950

Figure 2



DATA SAMPLE FROM 0.0 U.T. ON MJD 41910 TO 0.0 U.T. ON MJD 41950

Figure 3

CLOCK	σ CLOCK, MEAN	σ CLOCK	σ MEAN
653/1S	0.32 x 10^{-13}	0.25 x 10^{-13}	0.20 x 10^{-13}
660/1S	0.40	0.24	0.32
431/1S	0.44	0.39	0.20
761/1S	0.35	0.27	0.22
571/1S	0.28	0.17	0.22
656/1S	0.45	0.38	0.24
654/1S	0.40	0.30	0.26
651/1S	0.36	0.27	0.24
			$\bar{X}$ = 0.24
			S = 0.04

Figure 4. For $\tau = 2$ Days

deviation of MEAN(USNO) is quite small (5 x 10^{-15}), one may conclude that the estimates produced by the three corner hat method are reasonably good. For sampling times less than two days, the results are similar. For τ equal to five days, there are some problems with negative variance again, but if these values are disregarded, the results look fairly good.

For the purpose of comparison, one may estimate the variance of several conventional cesium standards over the same forty day period by using the three corner hat method. Here a conventional cesium standard is compared against all possible combinations of two of the eight undisturbed high performance units. Since two standards with small variances are used to estimate the variance of a third standard with a larger variance, we should get good estimates for the frequency stability of a conventional cesium standard. Figure 5 shows frequency stability plots for three conventional cesium standards (Cs 276, Cs 147/1, and Cs 533/1) and one high performance unit (Cs 651/1S) for comparison. Cs 276 is a HP 5060A which has been in operation since October 1967. Cs 147/1 is an early HP 5061A which has operated since December 1968. Cs 533/1 is a more recent HP 5061A which has been in operation since May 1972. All four stability curves in Figure 5 show the $\tau^{-1/2}$ behaviour characteristic of cesium standards. Cs 651/1S, the high performance unit, was at least three times more stable than any of the conventional cesium standards.

Enough data have been collected to produce preliminary estimates of the frequency stability of the high performance beam tube for averaging times up to twenty days. For these longer averaging times, the three corner hat method is not applicable due to insufficient overlap of available data. Stability estimates for these averaging times are derived by comparing the high performance units against MEAN(USNO).

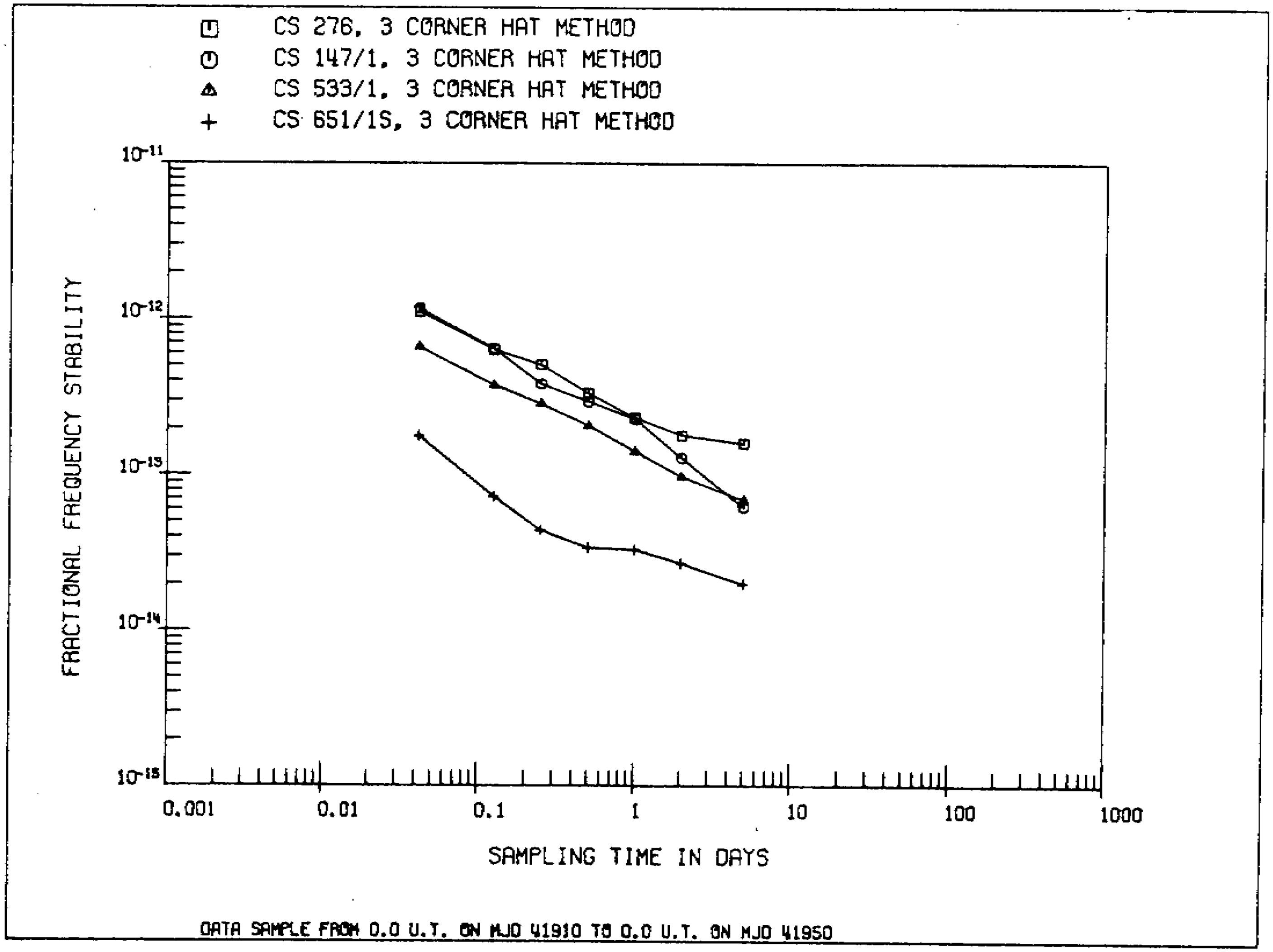

CS 276, 3 CORNER HAT METHOD
CS 147/1, 3 CORNER HAT METHOD
CS 533/1, 3 CORNER HAT METHOD
CS 651/1S, 3 CORNER HAT METHOD
FRACTIONAL FREQUENCY STABILITY
10^-11
10^-12
10^-13
10^-14
10^-15
0.001
0.01
0.1
1
10
100
1000
SAMPLING TIME IN DAYS
DATA SAMPLE FROM 0.0 U.T. ON MJD 41910 TO 0.0 U.T. ON MJD 41950

Figure 5

Before producing the standard sigma versus tau plots, it is useful to examine a few frequency versus time plots. These plots contain some information which is lost when conversion is made to the sigma versus tau representation. For the purpose of comparison, Figure 6 shows the five day average frequencies (computed in one day increments) over a 360 day period for a three year old conventional HP 5061A, Cs 497/1, against MEAN(USNO). This cesium standard is one of the better conventional HP 5061A's at the U. S. Naval Observatory. It was a contributor to MEAN(USNO) over the entire period shown in Figure 6. The peak-to-peak variation in frequency of Cs 497/1 versus MEAN(USNO) over this 360 day period was about 6 x 10^{-13}.

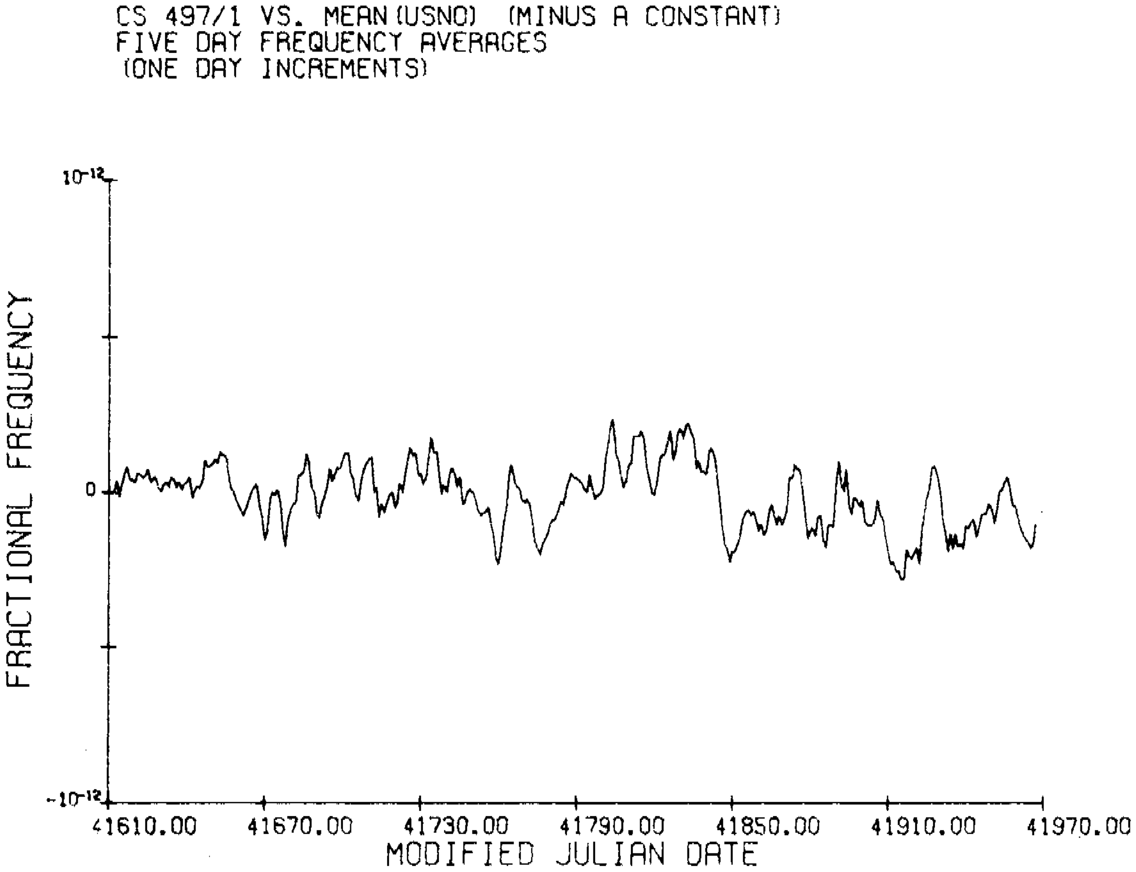


Figure 6

Figure 7 shows the frequency variations of Cs 571/1S versus MEAN(USNO) over the same 360 day period. Cs 571/1S is the one high performance unit which has been in operation for over a year. For the first 120 days shown in the plot, Cs 571/1S was not a contributor to MEAN(USNO), but after that period it was

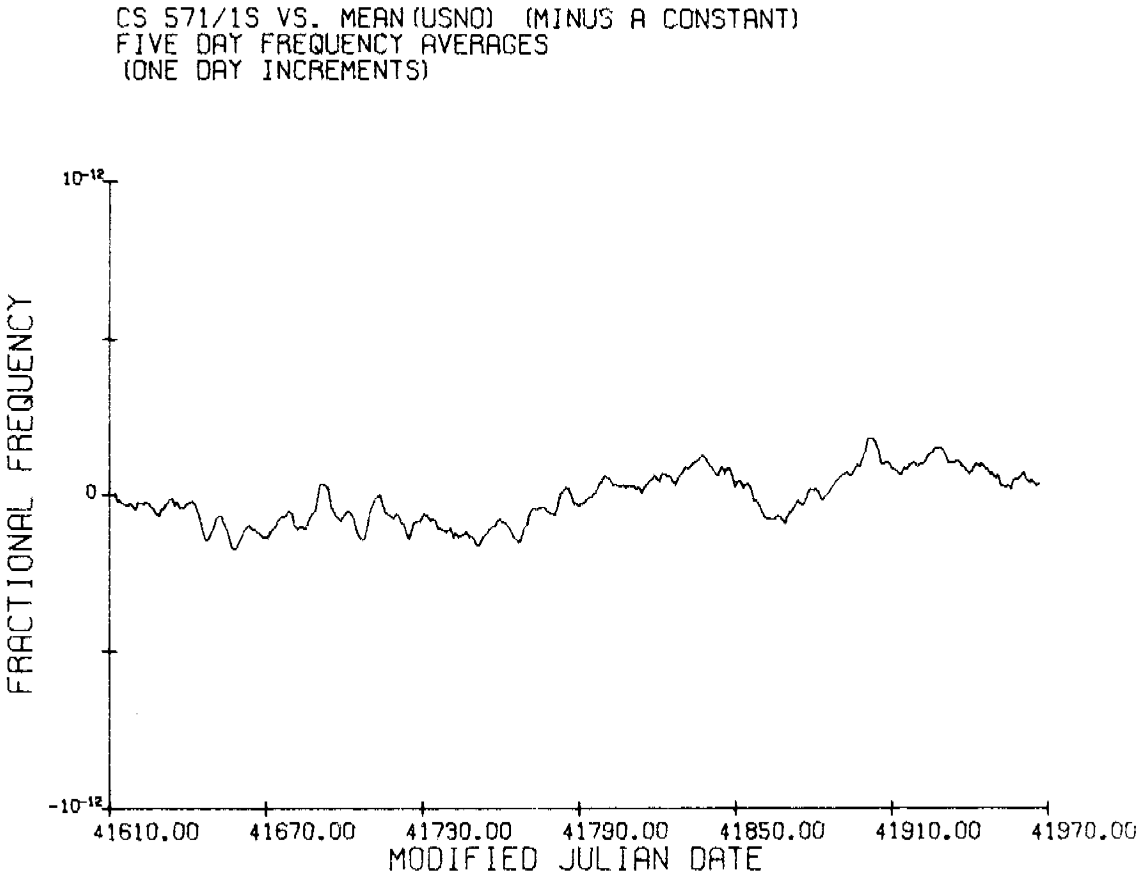


Figure 7

included in the time scale. The peak-to-peak variation in frequency with respect to MEAN(USNO) over the entire 360 day period was about 3×10^{-13}. There was no significant drift in the frequency of Cs 571/1S over this period. This performance was typical for the high performance units with two exceptions. One high performance standard exhibited a drift in frequency with respect to MEAN(USNO) of 3×10^{-13} for the 180 day period it was in operation. The frequency variations of the second exception, Cs 431/1S, are shown in Figure 8. Cs 431/1S is an HP 5061A with a high performance beam tube as a replacement for its original conventional beam tube. The high performance beam tube in Cs 431/1S was one of the first made by Hewlett-Packard. Generally this standard performed well, but it exhibited some large frequency excursions. In particular, there was one frequency excursion of 7×10^{-13} and another excursion of 4×10^{-13} in the opposite direction. After both of these excursions, the frequency of the standard returned approximately to its previous frequency. This anomalous behaviour has not been observed in any other high performance unit. There are

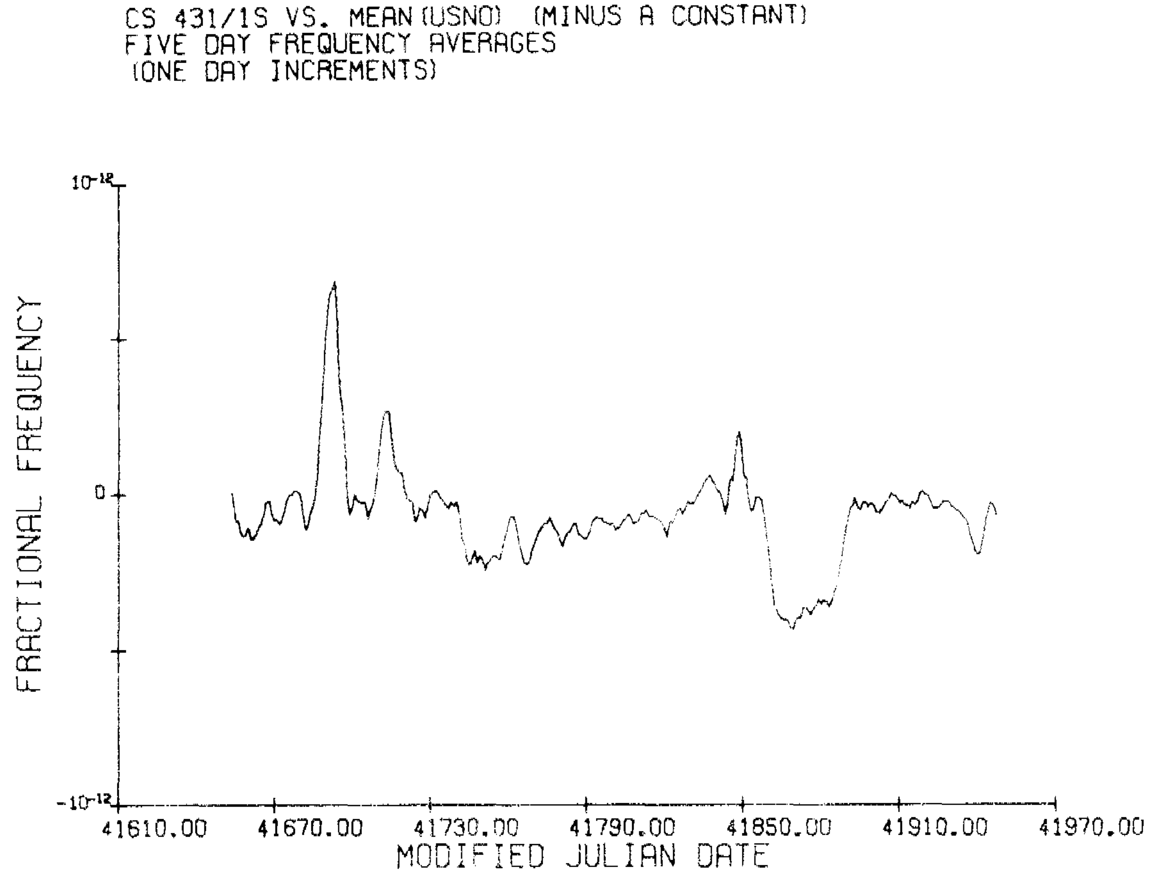


Figure 8

no obvious explanations for these frequency excursions. For the forty day period discussed earlier in this paper, this standard performed as well as any of the other high performance units.

Figure 9 shows the sigma versus tau plot for Cs 571/1S versus MEAN(USNO) for the same 360 day interval shown in Figure 7. The error bars are based on the uncertainty in the characterization of frequency stability for f^{-1} noise, as derived by Lesage and Audoin.[6] For averaging times longer than five days, it is questionable whether the high performance beam tube is more stable than some of the better conventional beam tubes. For the other high performance units (except for Cs 431/1S), the stability estimates for sampling times greater than five days were about the same.

Figure 10 summarizes the frequency stability results presented in this paper. For averaging times less than five days, the typical standard deviation listed in

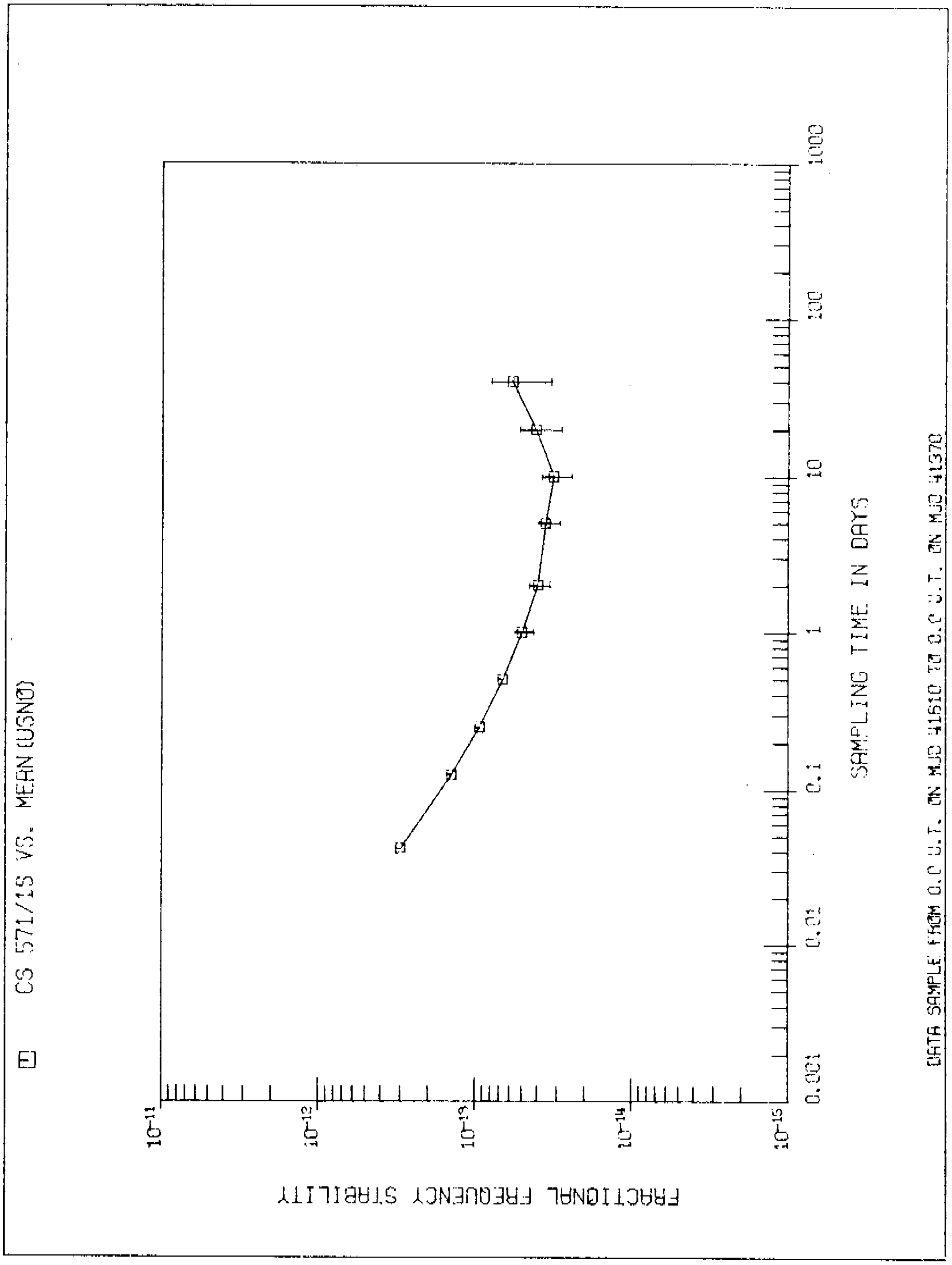

CS 571/15 VS. MEAN(USNO)
FRACTIONAL FREQUENCY STABILITY
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
10⁻¹⁵
0.001
0.01
0.1
1
10
100
1000
SAMPLING TIME IN DAYS
DATA SAMPLE FROM 0.0 U.T. ON MJD 41510 TO 0.0 U.T. ON MJD 41370

Figure 9

τ	TYPICAL σ (τ)	UNCERTAINTY
1 HR	1.5×10^{-13}	0.2×10^{-13}
12 HR	0.4	0.1
1 DAY	0.3	0.1
5 DAY	0.3	0.1
10 DAY	0.4	0.2
20 DAY	0.4	0.3

Figure 10. Summary of High Performance Beam Tube Behaviour

Figure 10 is based upon the three corner hat method. For five day averaging times frequency stability, estimates from the three corner hat method and the MEAN(USNO) method were combined to produce the typical standard deviation. For averaging times greater than five days, the MEAN(USNO) method alone was used to derive the typical standard deviation. The values for the uncertainty include both the variations in frequency stability found among the high performance units and the uncertainty in the estimates themselves.

ACKNOWLEDGEMENTS

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QUESTION AND ANSWER PERIOD

DR. VESSOT:

Are there any questions?

QUESTION:

I was struck by your remark that you said you used the manufacturer's recommended procedure to calibrate the clocks, and you just put the Zeeman signal into the clock, and then turning the C-field until you get it?

MR. PERCIVAL:

Yes.

QUESTION:

We have found that the flying clocks which were being banged around by the laborers riding on the back of a pickup truck in the rain, or getting tossled around in aircraft and so forth and so on, needed re-setting of the C-field quite frequently, and we have come across a method that seemed to get a little better accuracy than the factory procedure. I would like to discuss it with you afterwards.

MR. PERCIVAL:

Okay.

DR. VESSOT:

You probably subjected the tube to more environmental tests than just traveling with this thing.

QUESTION:

Yes, they were banged around quite a bit.

DR. VESSOT:

Any other questions?

DR. REDER:

Your peak to peak variations show a very pronounced oscillating behaviors. Do you have any explanation for this?

DR. VESSOT:

Fritz, it is a mood cycle. It is every 30 days, I noticed this, and then some of the others had a 90 day mood cycle.

MR. PERCIVAL:

If you look at a lot of time series data just eye balling it, I have an idea that your mind picks out periods that don't actually exist. What you are looking at and what you think are periods, are not really found if you made a time series analysis of these things and tried to dig out the frequencies.

DR. VESSOT:

Dr. Reder and I have used our own eyeball spectrum analyzers and seen this, and I thought I was the only one.

MR. PERCIVAL:

Yes, it would be something to follow up, and I agree, they do look rather suspicious.

DR. BARNES:

Jim Barnes of the Bureau of Standards.

I would commend you on a very fine paper. I enjoyed it.

I would make one comment only, in that people commonly use non-overlapping estimates for estimating the Allen variance, and if you do that, the paper gives you a very good means of estimating confidence intervals.

If you are willing to give up that method of estimating confidence intervals, you can use overlapping estimates and get improved confidence. You don't always know what it is, but you know it is at least as good as the last you have run.

MR. PERCIVAL:

Yes, but I was using the m equal 2 case here, in which case there is no real difference. You would only get that if you are using m equal 4 to shift along and get the thing.

DR. BARNES:

If your sample is displaced, if your one sample time, tau, is displaced a small increment or small fraction of tau for your next estimate --

MR. PERCIVAL:

Oh, I see. In other words, shift in say 15 minutes, or something like that.

DR. BARNES:

Use all of the data available for each Allen variance sample. You can improve the confidence intervals by an unknown amount.

MR. PERCIVAL:

Right.

DR. VESSOT:

I find that the most hair raising part of this is the possibility of getting an imaginary value of sigma, which doesn't give you much confidence in statistics.

MR. WALCEK (Hewlett-Packard):

It seemed to me that you said that 431 was a standard 5061 with a retrofitted high performance tube?

MR. PERCIVAL:

Yes.

DR. WINKLER:

That cesium 431, to my knowledge, was a standard cesium with standard electronics. However, it was outfitted from the beginning with a high performance beam tube, one of the first beam tubes which were produced in the spring of 1971.

MR. WALCEK:

Well, I think it will turn out that that tube was an early version of the higher performance tube.

DR. WINKLER:

I think that is correct.

MR. WALCEK:

It probably is not representative of the so-called standard tube.

DR. WINKLER:

I don't think Mr. Percival has claimed that. In fact, he has pointed out that it was an early bird. We have moved it around from one site to the other, initially when we got it, and we have noticed a considerable temperature sensitivity.

The first environment, into which it was put, was not a temperature controlled room, it was in fact subject to considerable fluctuations, I would say, five degrees centigrade typically, and the cesium behaved very poorly. In fact, you could see on the phase plot, 100 nanosecond full scale phase plot, you could see the instant of a temperature change.

And then it was moved into one of our best environments, and I think almost all of the data referred to these environments after that moment.

MR. PERCIVAL:

Yes, right.

DR. VESSOT:

Are there any other questions?

MR. LIEBERMAN (NAVELEX):

On the 783, which you said was inverted 180 degrees, do you think that was due to the tube, or the crystal? Do you find the same thing on the standard tube?

MR. PERCIVAL:

Well, I am sorry, because I don't think I can answer your question. I don't know enough about the electronics involved to answer it competently.

We haven't really performed these types of tests on any of our other standards. We were asked to do this for Professor Alley at the University of Maryland in order to give him an idea of what this thing would do in outer space, and so we just kind of did it as a side experiment, and we have never tried this as an exact experiment with a conventional 5061.

I think it would be worthwhile to try, but the trouble is that we try to maintain all of our standards at the observatory in good environments so we can use them for our time scale. That is our business. And we really aren't in the business of testing the durability of standards under strange conditions. And to make, of course, a thorough analysis, you would want to shake the unit and vibrate it and twist it.

QUESTION:

Oh, we can do that.

DR. VESSOT:

I would like to ask a question.

Was this tube realigned magnetically after being inverted?

MR. PERCIVAL:

No.

DR. VESSOT:

In that case, it is possible there was some change in the east-west axis, and you rotated it that way.

DR. WINKLER:

No, no. The beam tube was not readjusted according to procedure, and it is my belief that what we see is an affect of mechanical stress in the cavity. If you turn the beam tube upside down, the mechanical situation will be different. From some of the data that I have seen, the frequency shift was quite repeatable.

Remember, on one side we had a frequency shift of two parts in 10 to the 14th different from the reference standard, and the other side there was something like between 8 and 10 parts in 10 to the 14th.

So, the very fact that it produced a rather repeatable frequency variation, a little less than about 10 to the 13th, makes me believe that what we see is an effect of the mechanical change, not of a magnetic change, which would be very difficult to explain (in view of the observed remanences and hysteresis) why it comes back to the same frequency within parts in 10 to the 14th.

DR. VESSOT:

These are reproducible affects.

DR. WINKLER:

Well, I don't doubt that the magnetic field isn't a major influence in all atomic frequency standards. No question about that. But in that particular instance of turning a standard upside down regularly I believe it is, foremost, a mechanical problem.

DR. VESSOT:

The earth magnetic field alone is more like a half a Gauss in this region.

But if you were to invert the field, I would think you might see something from magnetic reasons alone. However, this is moot, a moot point.

MR. ACRIVOS:

By the way, NAVSAT did produce a report on this test. It was done in a magnetic environment test several years ago, and there were two atomic types of cesiums tested, one was an H.P. and the other was an Atomichron. It was done for a magnetic test. It was inverted, and it did show differences, and these were recorded in the report.

I believe it was Navy Facilities at Patuxent that did the test.

DR. REDER:

One question on the same point. I have a question to somebody who knows something about crystals.

Isn't it so that when you turn a crystal oscillator upside down that you get a rather large change? The answer possibly is that if the crystal wasn't exactly adjusted, the servo gain wasn't enough to bring it back.

VOICE:

That was my question, that if you do get enough change in the crystal --

DR. VESSOT:

I think the point is that it is remarkable that it stayed as stable as it did after being changed as much as it did.

Another question.

QUESTION:

I would like to pursue the question that the gentleman raised a while ago.

Have you ever applied barometric test data in your analysis to question any dependency on this parameter?

MR. PERCIVAL:

Maybe I should talk to you afterwards to get a better idea of what exactly you mean.

DR. VESSOT:

I think the question raised was that is it possible that barometric pressure fluctuations might affect the rate of the cesium clocks differently, and thus show this seemingly very large excursion.

I can tell you that we have seen such affects with hydrogen masers, and learned how to fix them. However, I can't visualize a mechanism for the cesium beam tube that would do it, other than some flexure of the cavity.

DR. ALLEY:

I would like to explain just why we have asked for this to be done, to turning the clock upside down.

The point is, it is exceedingly difficult to simulate the conditions of free fall on the Earth for any length of time, and one way of approximating what might happen to a clock in free fall is to see what happens when you change the acceleration by 2 G, rather than by 1 G. If it is reproducible, one has some confidence that when it goes to free fall, you would know that it would fall in between these two extremes. So, this is the background.

DR. VESSOT:

Thank you, Dr. Alley.

Mr. Kern.

MR. KERN (Frequency & Time):

During the period of your measurements, were there any automatic degaussing provisions in this equipment?

MR. PERCIVAL:

No. The units were aligned initially and placed in one of our vaults, and just left to run with no further degaussing at all. It was initially degaussed, but not during the test.

DR. BARNES:

One very quick question.

You turned the instrument so it went through a full cycle in two days, is that correct?

MR. PERCIVAL:

Approximately, yes.

DR. BARNES:

Did you have a data point at two days?

On the sigma tau plot, was it 1, 2, 5, 10?

MR. PERCIVAL:

Yes, it was two days, right.

DR. BARNES:

If it were exactly reproducible, and you were modulating at a period of two days, then it would have to have an inordinately low value at two days. The fact that it didn't implies that there is hysteresis.

MR. PERCIVAL:

I am sure it wasn't done exactly every two days, because we didn't have somebody come in on the weekends and do it. We at least had a weekend variation.

DR. VESSOT:

Dr. Rueger.

DR. RUEGER (APL):

We were wondering about the use of inverting like this, too. Rather than being the physical forces, the thermal gradients, we thought, would be upset, and we thought that might be a larger affect than the stress on the mechanical parts.

DR. VESSOT:

I think you may have hit on a nerve.

MR. HYATT:

I think the comment from APL is correct. It is most likely a thermal effect. At least, to our knowledge, that is the largest coefficient we have, and the magnetic orientation for a two gauss change probably could only explain a part in 10 to the 14th. The oscillator, being sensitive to orientation is also in the order of two or three parts in 10 to the 14th.

However, there is a sensitivity of approximately a part in 10 to the 13th per degree C on the overall instrument, and certainly turning it over will make a significant difference in the cooling.

DR. VESSOT:

As I see there are no other questions, we will have our coffee.