A FIRST ACCOUNT OF LONG TERM STABILITY RESULTS OBTAINED ON VARIOUS CESIUM STANDARDS BY THE POWER SENSITIVITY MINIMIZATION TECHNIQUE.*

Andrea De Marchi
University of Ancona
Ancona, Italy.

Abstract

In an effort to improve the long term stability of Cesium beam standards available on the market a full accuracy analysis of such devices was carried out in recent years. The outcome has been published in various papers.

According to this analysis, and to measurements which have been taken to confirm it, microwave power sensitivity seems to be the most relevant parameter as far as long term stability is concerned. Power insensitive settings have been shown to exist, and a number of standards have been singularly analyzed and aligned in such a way as to minimize their power sensitivity.

In this paper the principles of this technique are reviewed and long term stability results are summarized for several standards kept in different environments. A discussion is also given of the validity of this technique for the improvement of long term stability in Cesium beam standards.

Introduction

It is known that commercially available Cesium beam standards show often frequency variations, for long averaging times, greater than expected from the shot noise of the beam. The latter appears in $\sigma_y(\tau)$ plots as the expected and well understood white frequency noise section, with $\tau^{-1/2}$ slope at short term, which at long term is usually overcome by less well understood random walk and/or flicker processes, as mentioned above. The occurrence of such long term frequency variations can be directly related to the inaccuracy of the standard. In fact it is only through long term changes of existing biases that processes other than the shot noise of the beam can affect the frequency. These changes can be induced by variations of beam, electronics or environmental conditions.

In order to understand and possibly correct this problem it is therefore necessary to study the accuracy of the whole system and describe its various biases, so that they can be reduced or at least made insensitive to whatever parameters affect them most. This has been done, and the most relevant biases in well built commercial standards, besides the C–field bias, which is clearly the biggest, but is very stable in normal operating conditions) turned out to be Rabi pulling and cavity pulling [1,2]. Both these effects are equivalent in one way or another to a power dependent background slope, near

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center frequency, in the beam CW signal vs. excitation frequency plot. This gives a power dependent error signal at center frequency when modulation is on, which in turn produces a power dependent offset in the output frequency when the servo loop is closed. As a result the most relevant factor in determining variations of these biases is the instability of the microwave power used to excite the atomic transition [2].

All other bias effects known to exist, including cavity phase shift and 2nd order Doppler shift, do not contribute to power shifts in a relevant way [1,2].

Theoretical and experimental studies have been carried out on both cavity pulling and Rabi pulling for existing standards. These studies have shown that:

1) Rabi Pulling is an oscillating function of the C–field, and a number of field values exist for which this effect vanishes [3]. Power sensitivity is also an oscillating function of C–field, and shows vanishing points if the cavity is not badly mistuned [4–6], although the period of the oscillations can not always be explained with the simple theory of [3].

2) When the cavity is carefully tuned the zero crossing points of Rabi pulling coincide with the zero power sensitivity points; if it is slightly mistuned the field values at which power sensitivity vanishes are accordingly displaced in a predictable way [6].

3) Temperature and humidity coefficients and long term stability depend on power sensitivity, and are greatly improved by operation at a power insensitive point [4–7].

These studies confirm the relevance of power sensitivity and that accuracy (i.e. the reduction of biases, at least the power sensitive ones) is the key to long term stability. It appears therefore possible to obtain better long term performances from Cs standards by either stabilizing the power or operating at a zero power sensitivity point. This work analyzes the second solution.

The fact that the existing theory not always predicts accurately the shape of the power sensitivity curve, in particular the oscillation period (it seems that it is the role played by e transitions which is in some cases yet to be understood), does not prevent experimental determination of the field values for which the power sensitivity vanishes. It is therefore always possible to pursue its optimization with a tune–up routine involving solely power shift measurements and tweaking of C–field and microwave cavity.

This paper is a review of the results obtained so far with this approach. Two variations have been tried in following it. One was to tune the cavity close enough to perfect tuning to make sure that zero crossings exist, and tweak the C–field onto one of them. The advantage of this is that it is easy to reduce power sensitivity well below 10^{-13}/dB. The other was to try and balance power shifts near an extreme of the Rabi pulling curve. The advantage of this was thought to be that variations of the Rabi pulling curve would in this case reintroduce power sensitivity only in the second order. Results obtained with either technique are reported here and seem promising, particularly when the first approach was used.

Review of results

Six clocks were realigned between the spring of 1986 and the fall of 1988 following the philosophy outlined above. Five of them were HP standards option 004, employing a double beam tube (the so called supertube), and one was an FTS standard. All were measured for long term stability in the initial state, for later reference, then analyzed more or less in depth prior to realignment. The purpose of this analysis was either to simply identify a zero crossing or also to improve the understanding of the different bias effects, their reciprocal importance and their power dependence. Useful information was acquired along the way toward the task of describing a suitable alignment procedure which would make use of the newly gained knowledge. A number of long runs were taken at what were considered interesting set points in order to get information on the long term stability obtained with the alignment considered. Most runs were taken with good temperature control. Some of the $\sigma_y(\tau)$ plots are reported here.

In some cases work had to be performed on the tuning of the microwave source (the SRD stage which constitutes the final step of the frequency multiplier), in order to improve stability with temperature and time of its output power, so that the requirements on power sensitivity of the standard would be relaxed.

For two HP standards a balance was sought of the power shifts due to Rabi pulling and to cavity pulling. As shown below, results obtained in this way were good, but not exceptional. All the other standards were set at a zero crossing of power sensitivity. The best long term stabilities were obtained in this way.

No fundamental difference was found between standards from the two different manufacturers in C–field periodicity and relevance of power sensitivity for long term stability. This is interesting because the electronics are based on very different design approaches in the two cases, and the servo loop modulation in particular does influence value and power sensitivity of bias effects [3,9].

In the following, numbers 1 through 6 will be used to identify the standards which have been worked on. Their manufacturer's serial numbers are given in [10] together with property indications.

Clock #1 was received from USNO in March 1986 and shipped back in September 1987 upon tube failure. After the reference long term stability run a first quick overview of the power shift curve vs C–field was done with an external microwave source which made use of a Gunn oscillator for power availability. The Gunn was phase locked on Cs frequency to the output of an external synthesis chain similar to the internal one. The following long term run at a C–field where a zero power sensitivity was found with this set–up showed that cavity pulling was important and that power sensitivity should therefore be measured with the same microwave structure used in operation. The following months were dedicated to understanding in detail the role of cavity pulling, acquiring an accurate power sensitivity curve with the cavity well tuned, and taking measurements of long term stability and temperature coefficient at different power sensitivity points. The standard was then aligned at best at a zero crossing of power sensitivity at 39 kHz, and a long term stability measurement was taken. Subsequently the C–field was moved to 38.8 kHz in order to gain information on how critical the setting really is. Results relative to this standard are reported in fig. 1 through 4. In fig.1 the power sensitivity curve is shown as measured with the cavity well tuned. In fig.2 are reported the $\sigma_y(\tau)$ plots vs AT1 of the standard before any work was done on it (fig.2a), at the 39 kHz zero crossing (fig.2b), and 200 Hz away from the zero crossing (fig.2c). It appears that great improvements in long term stability can be obtained by reducing the power sensitivity of a standard, and that for the best results knowledge of the actual zero crossing C–field and realization of the same are quite critical. In fig.3 a plot is shown of the measured long term stability vs power sensitivity, and in fig.4 is a similar plot for temperature sensitivity. The reason why the latter seems to have a limitation for low values is not clear. Most of these results were already reported in [4–6]. Measurements of 2g flip frequency variations were also taken close to zero crossing, they did suggest the existence of an effect, but the results were not conclusive enough to justify reporting at the time.

Clock #2 was received from USNO in May 1986 and shipped back in January 1988 upon tube failure. It was then received again with a new tube in July 1988 for further research. A similar routine was initially followed as for #1, except that the power sensitivity curve was not studied as exhaustively. Instead, efforts were concentrated in optimizing the power stability and determining carefully the position of the zero crossings. Temperature sensitivity at different points was also measured for this standard, as well as frequency variations for 2g flips. The power sensitivity curve was found not to be too different from that of #1, and results for TempCo and 2g flips were also similar. In fig.5 $\sigma_y(\tau)$ plots are shown for the reference run (fig.5a) taken before work was started, and for the run taken at the zero crossing at 38.9 kHz after realignment (fig.5b). The latter stability curve is relative to the initial 60 days period of the run, when the clock was not weighed in the time scale. During this time no deviation from a white frequency noise process was observed down to the middle 10^{-15}. Because the standard was performing so well the run was continued to gain information on the long term changes that the set point may undergo. After roughly six months of exceptionally stable behaviour a frequency step of 6×10^{-14} was observed. Shortly thereafter a loop adjustment was made (the frequency change was 1.5×10^{-14}) and the power sensitivity was remeasured (it turned out to be about 1.5×10^{-14}, with an uncertainty of 1×10^{-14}). The stability in the following two months was not as good as in the previous period, as it seemed to start flickering in the high 15s. Tube failure followed soon, and when the clock was received with a new tube an extensive analysis was initiated aimed at understanding what the accuracy of a standard of this type could be. A zero crossing very close to the 39 kHz one of the previous tube was then identified, and another long term run will be taken before this clock is shipped back.

Clock #3 was received from USNO in October 1986 and is still being observed at NBS as of this late 1988. The microwave source was not properly working when the standard was received and it had to be retuned. After the reference long term stability run was taken for later reference, power sensitivity was measured to be about 1×10^{-13} per dB at the initial operating point. The standard in fact was performing very well, as is shown in fig.6a. It seemed to be a good idea to try on it a compensation between the power shifts caused by Rabi pulling and cavity pulling. A long run was also taken, at a tuning for which power sensitivity was a few parts in 10^{13}/dB, with the microwave source not tuned up for best stability. The $\sigma_y(\tau)$ plot relative to this run is shown in fig.6b. The relevance of power stability and power sensitivity is dramatically underlined by it. With the power source finally stable, and the sensitivity compensated at best, the clock was then kept in observation for a long period to gain insight on the validity of the technique. The stability plot relative to the first 60 days of this run is shown in fig.6c. A slight improvement can be noticed from the initial setting, perhaps a factor of two in long term stability. This corresponds to the measured power sensitivity improvement. It must be pointed out that applying this technique is made awkward by the trial and error process involved. It appears that smaller power sensitivities can be more easily obtained by looking for a zero crossing. The humidity coefficient after tune–up was also measured for this clock as part of a survey that was carried out at NBS early this year on several standards and reported in [8]. Its coefficient turned out to be -1.6×10^{-15}/%, a factor of three smaller than the average of the other clocks. It seems safe to assume that the effect of humidity on the output frequency would come from power variations. These could be caused for example by variations in temperature of the microwave source due to redistributions of the thermal paths.

Clock #4 was available only for a ten days in August 1987, from Falcon Air Force Basis, in Colorado Springs, and was realigned at a zero crossing of power sensitivity at 43.06 kHz. The residual power shift at that point was less than 3×10^{-14}/dB. It must be noticed that the Rabi pulling curve was very different in this tube from the one of #1 and #2. No long term run was taken at NBS before or after tweaking. The data taken prior to realignment show a flicker floor in long term stability worse than 10^{-13} relative to the USNO reference. After realignment of the C–field the long term stability was consistently about 2×10^{-14} relative to the same reference (see for example fig.7), even after several on–off cycles of the supply power. It is to be underlined that the environment around this unit was not stabilized in any way during the observation period, which put the peak to peak temperature variations in the range of several degrees centigrade and the humidity range from 30 to 50%, as shown in fig.8a and 8b. Still the standard performed at the 2×10^{-14} level.

Clock #5 was carried to NBS by USNO personnel in September 1987, and was worked on for

5 days before being carried back to USNO. No long term data are available for the clock before realignment, as the tube had just been changed. The technique used in this case was the one seeking balance between power shifts, but the time available was not enough to complete a satisfactory job. As a result the residual sensitivity was about 1×10^{-13}/dB, which would yield a long term stability in the middle 14s with a stable microwave power source.

Clock #6 is an FTS clock, and was analyzed at the Aerospace Corp. with an automatic measurement system. The power sensitivity curve obtained is shown in fig.9. The curve does not substantially differ from that of HP tubes, although it seems to die out faster at high C–fields. The uncertainty in these measurements is too big to determine the zero crossing points with the precision necessary to guarantee high long term stability. However no further testing was done. Two runs at the Zeeman frequencies indicated in fig.9 are being taken at NBS starting last October 10. The stability corresponding to the point at 37 kHz as obtained from the initial 20 days of the present run is shown in fig.10. The 20 days run taken at 44 kHz appeared to yield a stability floor around 10^{-13}.

Conclusions

A review of the work performed in the last three years on the improvement of long term stability in Cesium beam standards by the power minimization technique, and a first account of the results obtained shows that indeed power sensitivity is the single most important parameter in determining the level of the observed flicker and random walk processes. Since other parameters are much less important it turns out to be possible to improve long term stability either by stabilizing the power or by reducing the sensitivity. Environmental sensitivity is also reduced in this way. Setting the C–field very close to a zero crossing of power sensitivity appears to be an easier and more effective technique than trying to compensate the shifts due to different effects. Finding a zero crossing with sufficient precision and realigning a standard requires approximately two weeks in the present state of development with the equipment used in this work.

Potential shortcomings of using this technique as a solution to the long term stability problem are the following:

1) The position of power insensitive points is velocity distribution dependent. Because of this it may vary with small changes in the beam optics (related to mechanical stress or deflecting magnets relaxation), with the direction of the gravitational field, and obviously from tube to tube. Therefore a standard should sit in the position in which it was tweaked, with respect to the gravitational field, and that it must be realigned whenever the Cesium tube is substituted due to end of its life.

2) Operation at a particular Zeeman frequency is required. If the synthesizer is not readjusted this may impose an offset in the output frequency which may not be acceptable to some users. Even when the offset is acceptable, or the synthesizer is readjusted to match the new C–field, this fact inhibits the freedom of tuning the output of the standard by acting on the C–field.

3) Once the standard is carefully aligned, power sensitivity can be reintroduced during the life of the tube by variations in time, due to the environment or to ageing, in anything that contributes to the alignment of the C–field with the power insensitive points. Examples of such variables are C–field current, cavity tuning and any velocity distribution determining element mentioned above.

References

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[9] A.De Marchi, A.Premoli, G.D.Rovera: "Effects of servo-loop modulation in atomic beam frequency standards employing a Ramsey cavity", IEEE Trans. UFFC-34,6 (1987).

[10] #1: HP1653 of USNO
#2: HP1343 of USNO
#3: HP2315 of USNO
#4: HP 660 of USNO
#5: HP 583 of USNO
#6: FTS168 of Aerospace

Fig.1

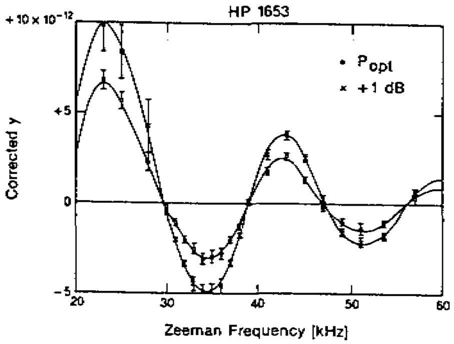


Fig. 1. Experimental results for Rabi pulling of one standard analyzed. Reported relative frequency data y are measured residual differences from AT1 (NBS) once C-field and synthesizer offsets are removed.

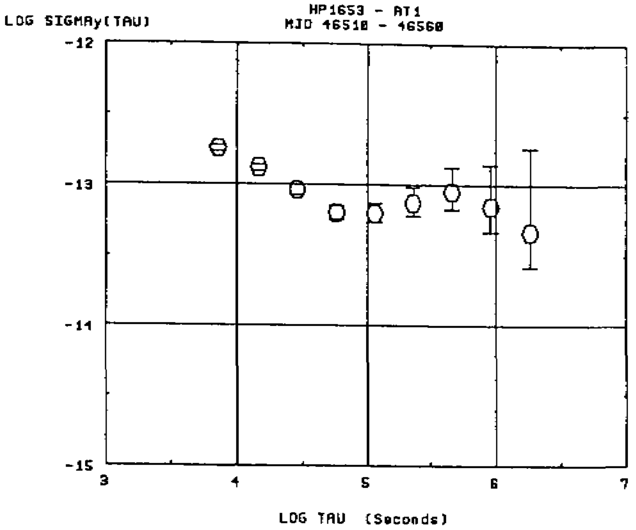
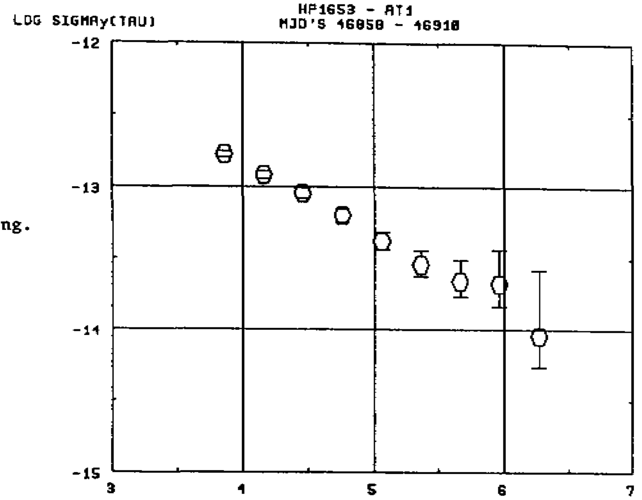


Fig.2a - f_z = 53 kHz, initial setting.

Fig.2b

f_z= 39 kHz zero crossing.



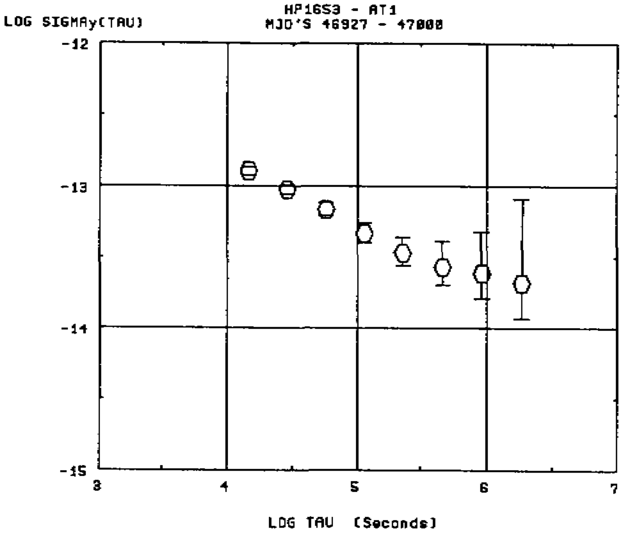


Fig. 2c
f_z= 38.8 kHz
200 Hz from
zero crossing.

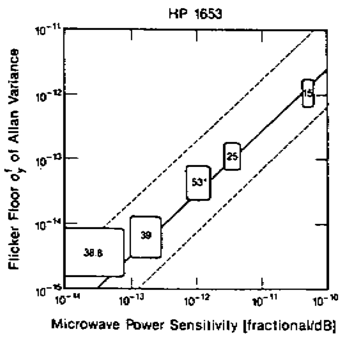


Fig3Measured flicker floor levels of square root of Allan variance, $\sigma_y(\tau)$ of one standard analyzed, as function of microwave power sensitivity. Corresponding Zeeman frequency is indicated in kHz in box at each point. Box brackets uncertainty for each point. Dotted lines above and below solid line are examples of where flicker floor values may be for microwave power generators more and less stable than one in standard under test.

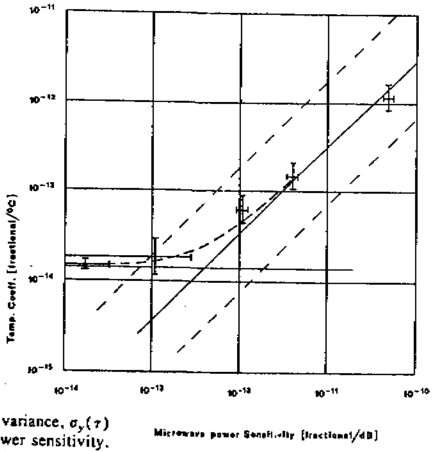


Fig.4

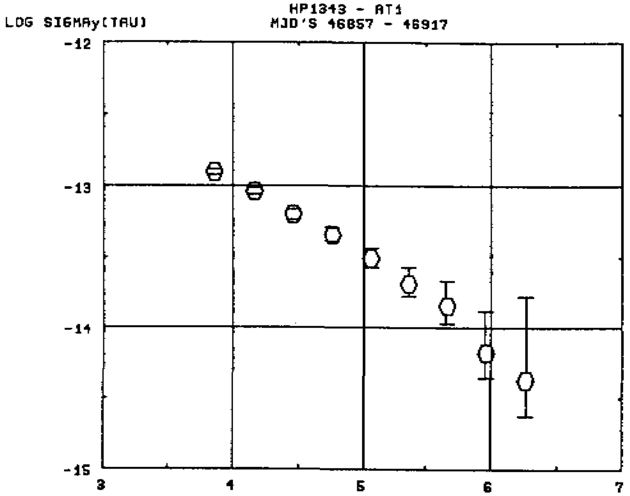


Fig. 5b
f_z = 38.9 kHz
zero crossing.

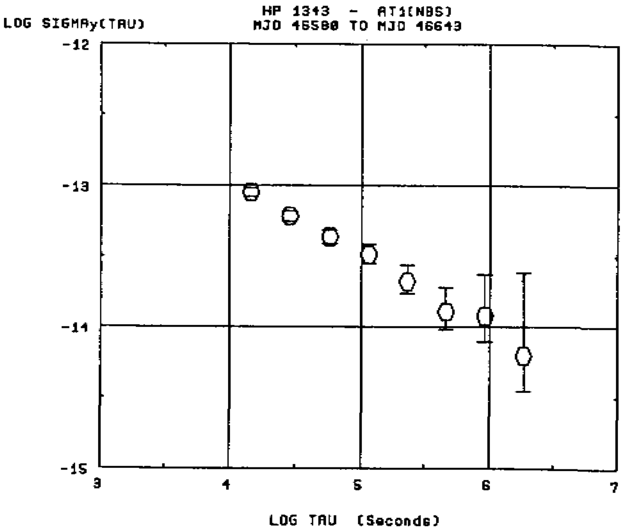


Fig. 5a
f_z= 53 kHz
initial setting.

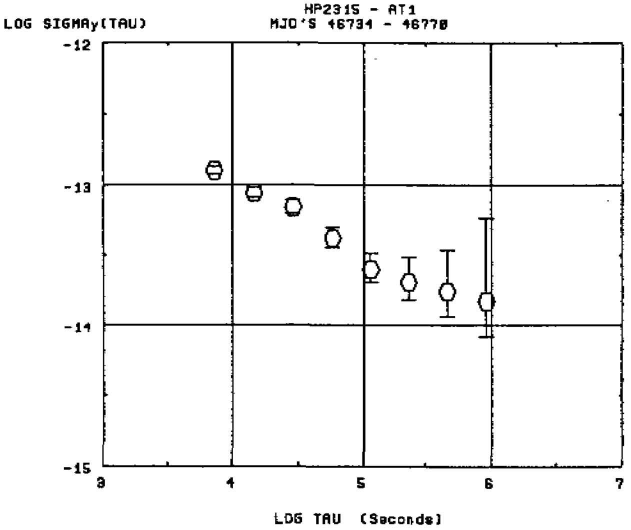


Fig. 6a
f_z= 53 kHz
inizial setting.

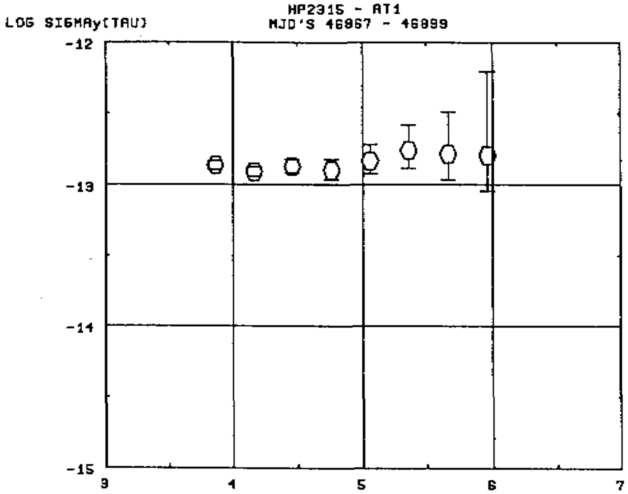
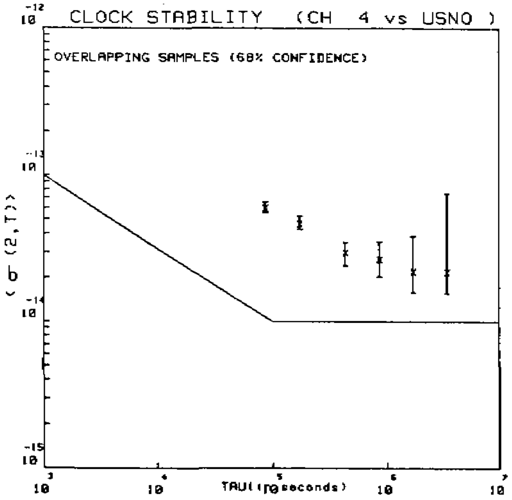


Fig. 6b
f_z= 53 kHz
$5\mathrm{x}10^{-13}$/dB Power coefficient,

Unstable Power.



SIGMA	PAIRS	TAU	LOWER_BAR	UPPER_BAR
5.93E-14	86	10	5.54E-14	6.52E-14
4.64E-14	78	20	4.29E-14	5.22E-14
2.95E-14	63	50	2.41E-14	3.46E-14
2.65E-14	60	100	2.02E-14	3.51E-14
2.19E-14	50	200	1.57E-14	3.82E-14
2.16E-14	20	400	1.55E-14	7.52E-14

NUMBER OF
FILTERED POINTS
22

Fig. 7
f_z= 43.06 kHz

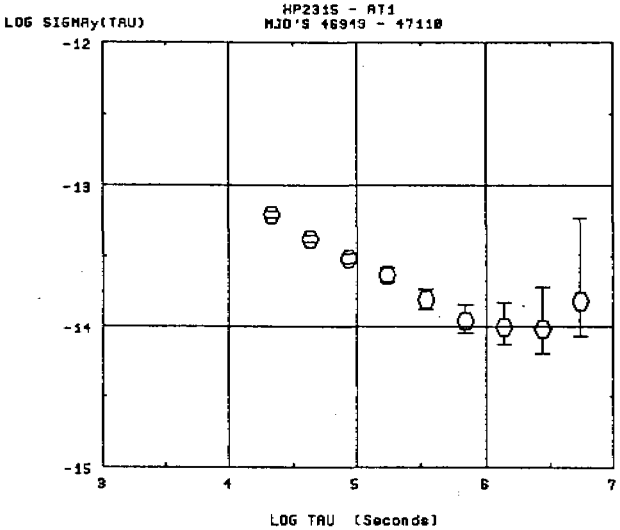


Fig. 6c
f_z= 53 kHz
Compensation by cavity tuning.

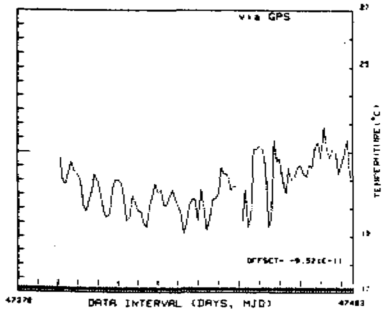


Fig. 8 a

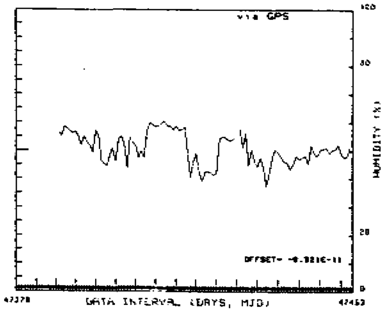
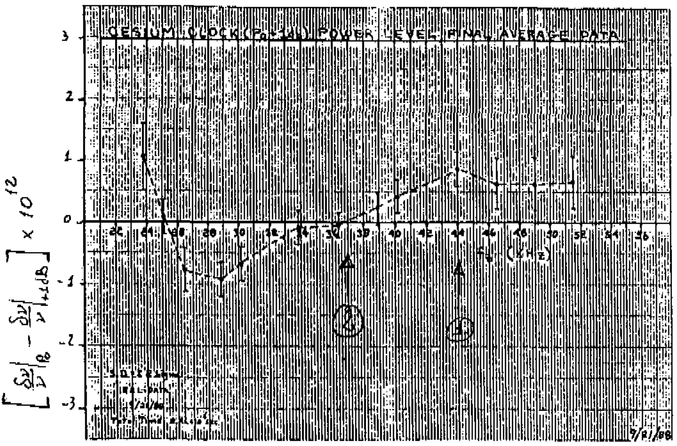


Fig. 8b

Fig. 9



Zeeman Frequency kHz

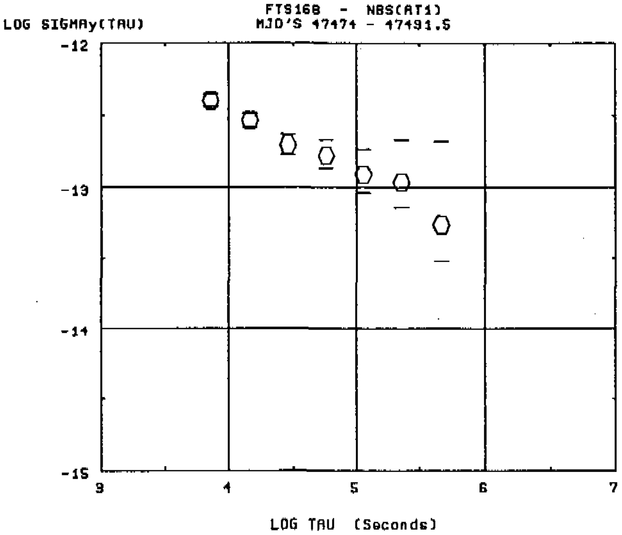


Fig. 10
f_z= 37 kHz