ZERO–CROSSING DETECTOR WITH SUB–MICROSECOND JITTER AND CROSSTALK*

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Abstract

A zero–crossing detector (ZCD) has been built and tested with a new circuit design which gives reduced time jitter compared to previous designs. With the new design, time jitter is reduced for the first time to a value (4.2×10^{-8} seconds for a 1 Hz input signal and a 1 second measuring time) which approaches that due to noise in the input amplifying stage. Additionally, with fiber–optic transmission of the output signal, crosstalk between units has been eliminated. Incorporation of commercially available double–balanced mixers allowed two ≈ 100 MHz signals differing by 1 Hz to be compared, giving an Allan Deviation of 1.17×10^{-15} at a 1 second measuring time. The measured values are in good agreement with circuit noise calculations and approximately ten times lower than that for ZCD's presently installed in the JPL test facility. Crosstalk between adjacent units was reduced even more than the jitter. Where the old units showed crosstalk of $> 10^{-4}$ seconds between units, no crosstalk could be detected between the new ZCD's, even when operating from the same power supply.

BACKGROUND

A limitation on the present capability to characterize frequency sources with ultra–high stability is the performance of the zero crossing detector (ZCD) which is used to measure the frequency difference between two such standards.[1, 3] The ZCD functions to transform a ≈ 1 Hz sine–wave beat frequency between the sources into a square wave or train of pulses that can be characterized by a conventional counter. While the capability of the presently available system was sufficient to characterize sources until now, new standards are now available with much higher stability at short measuring times. These new standards cannot be characterized using the present performance of the ZCD.

Present ZCD's show a time jitter of approximately 10^{-6} seconds. Noise in the mixers used to generate the beat frequency between the oscillators is much smaller ($< 10^{-7}$ seconds) than the ZCD jitter, while the stability of available counters is very high, with jitter of the order of 10^{-9} seconds.[4]

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The present ZCD's also suffer from severe crosstalk problems, so that the output signal from one unit can induce a time offset in an adjacent unit by as much as 10^{-4} seconds. If the time jitter and crosstalk in the ZCD's could be reduced below 10^{-7} seconds, thus matching the performance of available low noise mixers, the new standards such as the Superconducting Cavity Maser Oscillator (SCMO) could be characterized without limitation by fluctuations in the measuring system.

PRESENT TECHNOLOGY: NOISE

Figure 1 shows a schematic of the presently used units. A low noise amplification stage filters the 1 Hz input signal and increases its amplitude as much as possible without clipping. This large signal drives a special-purpose "open loop" operational amplifier stage which operates to transform the sine wave signal to a square wave with relatively short rise and fall times. Since this second stage operates without feedback limitation to its frequency response, and since the slew rate at its input is low, a latching circuit must be included to prevent noise–induced double triggering which would otherwise occur.

Amplitude noise in the first two stages introduces a time jitter into the signal which may be estimated as follows. Suppose the signal at the input to any stage has a slew rate of $\mathcal{S}$ (volts/second) and that the stage has an equivalent input noise of N (volts/$\sqrt{\mathrm{Hz}}$) and a bandwidth of B (Hz). In this case an input amplitude jitter of $N\sqrt{B}$ (volts) will give rise to a time jitter of $N\sqrt{B}/\mathcal{S}$ (seconds). While the slew rate at the input to the first stage is low, the bandwidth of that stage is very low, thus allowing excellent overall performance, if that stage were the only limitation. However, the second stage must have a very wide bandwidth in order to give the short rise time required for proper operation of the counter. For example, second stage may require a bandwidth 10^5 times larger than the first stage, while the slew rate at its input has been increased only 15 times by the gain of the first stage. Thus it introduces $\sqrt{10^5}/15 \approx 20$ times as much time jitter as the first stage and prevents good performance in the ZCD.

PRESENT TECHNOLOGY: CROSSTALK

Crosstalk between units and phase offsets which are sensitive to details of circuit interconnections arise in the present units due to parasitic ground currents at the signal frequency. Figure 2 shows an overall schematic of the present ZCD system and identifies the parasitic ground-wire resistances. The very low frequency of the signal (1 Hz) means that skin–depth shielding effects, which usually tend to isolate AC signals, are absent. Output signals must be large enough so they can be transmitted substantial distances without degradation. This results in a substantial output current at a frequency identical to that of the input signal.

The present units are characterized by an output voltage of 2.5 V, a termination of 50 Ω, and an input slew rate of $\mathcal{S} \approx 1$ V/second. The resulting output current of $I = 2.5/50 = .05$ A can give rise to an input voltage offset of 50 μV for parasitic resistances of only .001 Ω. For an input slew rate $\mathcal{S} = 1$ V/second, a 50 μs time offset will result. However this offset depends on details of the configuration and so makes the whole system extremely sensitive to any kind of physical perturbation. Furthermore, if two or more units are operated in physical proximity to each other, and if the signals in these units have slightly different frequencies, the phase between the two will vary with time. This will induce a large, time–varying phase offset in adjacent units which can corrupt the measurements being made.

NEW DESIGN: NOISE

Operational amplifiers are available with an equivalent input voltage noise density of 4 nV/$\sqrt{\text{Hz}}$ for frequencies above 1 Hz.[5] For a first stage input slew rate of $\mathcal{S} = 1$ V/second or greater, and a bandwidth of $B_1 = 1$ Hz, this makes possible an RMS jitter of .004 μs for the contribution of that stage. If noise due to each subsequent stage can be kept at or below this value, a ZCD circuit could be constructed with jitter substantially less than 0.1 μs. Overall performance would then be limited by the performance of available mixers.

However, the rise time τ from the final stage of the ZCD must be very short, preferably $\tau < 0.1\mu$s and so must have a large bandwidth given approximately by $B > 1/(2\pi\tau)$. While, as previously discussed, a very large bandwidth in the second stage B_2 will result in increased jitter, this bandwidth may be made somewhat greater than that of the first stage before the second–stage contribution to the jitter matches that of the first stage. This is because the slew rate has been increased by gain of the first stage G_1, thus allowing a greater equivalent input voltage noise at the second stage without increasing the time jitter. If both stages have equivalent (white) input noise, the contribution of the second stage will be less than that of the first as long as

$$B_2 < B_1 G_1^2. \tag{1}$$

All stages after the first must have a built–in limiting action because otherwise their voltage swings would be larger than allowed by available power supplies. It is possible to construct limiting amplifier stages with reduced bandwidth which are well behaved in their operation if the gain of the stage is not too large. Since the slew rate $\mathcal{S}$ is increased in proportion to the gain G of the stage, the requirement for well–behaved operation is that the time for the output voltage to slew to its limit V_{max} must be allowed by the bandwidth B of the stage. This condition on the gain of the second stage can be written;

$$\frac{G_2 \mathcal{S}_2}{V_{max}} < 2\pi B_2 \tag{2}$$

where $\mathcal{S}_2$ is the slew rate at the input to the second stage. Since the slew rate is increased by the gain of any given stage, $\mathcal{S}_2 = G_1 \mathcal{S}_1$ and we can write the gain condition for the second stage as

$$G_2 < \frac{2\pi B_2 V_{max}}{\mathcal{S}_1 G_1}. \tag{3}$$

The conditions to reduce the noise contribution of the nth stage to a value below that of the first stage can similarly be written in terms of a product over the gains of previous stages;

$$B_n < B_1 \prod_{i=1}^{n-1} {G_i}^2 \tag{4}$$

and

$$G_n < \frac{2\pi B_n V_{max}}{\mathcal{S}_1 \prod_{i=1}^{n-1} G_i}. \tag{5}$$

Note that the gain G_n is calculated in terms of the bandwidth B_n actually chosen.

Figure 3 shows a block diagram of a four stage ZCD with gains and bandwidths calculated subject to equations (5) and (6). In order to reduce overall noise to a value comparable to that due to the first stage alone we have found it necessary to add two intervening stages in between the first stage and the "wide open" stage compared to the old design shown in Figure 1. This new design allows an overall jitter of less than 0.1 μs.

NEW DESIGN: CROSSTALK

In order to eliminate the effect of output ground loop currents on the input signal, we have modified the design to eliminate both input and output ground loop currents. As shown in Fig. 4, the high current output driver has been replaced by a fiber–optic transmitter. While the transmitter requires substantial drive current (.030 A) these currents are completely contained within the chassis and power supply of the ZCD itself, and do not necessarily flow throughout the room as was previously the case. The fiber optic signals themselves cause no interference at all, and are themselves not subject to degradation by other electrical interference signals. The fiber optic receiver is connected directly to the counter input.

Ground loops at the input to the ZCD have also been eliminated. Even though the RF signals into the mixer are necessarily grounded at the outer coaxial connection, the dual–transformer design of the mixer allows a floating output (1 Hz) signal.[6] As shown in Fig. 4, all external ground loops are thus eliminated, leaving only those (not shown) which are due to power supply connections or internal to the ZCD circuitry itself. In this design the mixer is physically mounted within the ZCD module.

TEST RESULTS–NOISE

Two zero–crossing detectors have been built and tested which is based on the design shown in Figure 3. Preliminary tests using a common 1 Hz input signal with an amplitude of 400 mV P-P showed an Allan Deviation of frequency variations

$$\sigma_\nu(\tau) = 4.2 \times 10^{-8}\text{Hz} \tag{6}$$

for the two units together at a measuring time of $\tau = 1$ second. Double balanced mixers[6] were then added to the circuitry to allow comparison of two RF signals at 100 MHz. Test results shown in Fig. 5 show that the short term performance approaches a measurement floor for the Allan Deviation of relative frequency variation $\delta y = \delta\nu/\nu_o$ given by

$$\sigma_y(\tau) = \frac{1.17 \times 10^{-15}}{\tau} \tag{7}$$

for two units together. This value is approximately ten times lower than that for ZCD's presently installed in the JPL test facility. Because "bare" ZCD noise at $\nu_o = 100$ MHz would only be

$$\sigma_y(\tau) = 4.2 \times 10^{-8}/10^8 = 4.2 \times 10^{-16} \tag{8}$$

at $\tau = 1$ second, most of this noise is apparently due to the mixers. The increase above the limiting value at longer times ($\tau > 10$ seconds) is probably due to temperature fluctuations. The units were not thermally isolated but were subject to a typical laboratory thermal environment.

At the time of the tests there were not available RF signals at 100 MHz signals with a stability greater than $1 \times 10^{-14}/\tau$, and so to measure the contribution of the ZCD's themselves, the two units were independently attached to the same source, and the time jitter between their output pulses was measured. In this way noise on the input signals was largely cancelled while noise due to the individual mixers and ZCD's was not.

DETAILED NOISE ANALYSIS

We consider three types of noise as contributing substantially to the overall performance of the ZCD: Flicker voltage noise in the first stage of the ZCD, white noise from all stages, and flicker phase noise in the RF mixer. Throughout this section we assume a slew rate of $\mathcal{S} = 1$ V/second, recognizing that the actual value may be up to $\mathcal{S} = 3$ V/second, giving somewhat lower time jitter for the same voltage fluctuation.

Following the conventions of IEEE Standard PAR–P–1139, we define the parameters;

$$D = \frac{1.038 + 3\ln(2\pi f_h \tau)}{4\pi^2} \tag{9}$$

and

$$E = \frac{3f_h}{4\pi^2} \tag{10}$$

where f_h is the upper cutoff frequency and τ is the measuring time; so that the Allan Variance of frequency fluctuations $\delta\nu$ may be written:

$$\sigma_\nu^2(\tau) = D[fS_\phi(f)]\tau^{-2} \tag{11}$$

for flicker phase noise, and

$$\sigma_\nu^2(\tau) = E[S_\phi(f)]\tau^{-2} \tag{12}$$

for white phase noise, where f is the fluctuation frequency, ν_o is the RF frequency, and $S_\phi(f)$ is the spectral density of phase fluctuations. We also use an Allan Deviation defined by

$$\sigma_\nu(\tau) = \sqrt{\sigma_\nu^2(\tau)}. \tag{13}$$

Using a 1 Hz cutoff frequency and $\tau = 1$ second measuring time, we approximate the constants by $D = .166$ and $E = .0756$.

Because of their nonlinear nature, it is not clear how to treat the flicker noise for ZCD stages after the first (linear) stage. However, the effect of low frequency noise in these subsequent stages is apparently reduced by the gain of the first stage, and so we will ignore their contribution. The manufacturer indicates a flicker voltage noise for our configuration of 6 $\mathrm{nV}/\sqrt{f}$ $(/\sqrt{\mathrm{Hz}})$ RMS. For a slew rate of $\mathcal{S} = 1$ V/second, this results in an RMS time jitter of 6×10^{-9} seconds in a 1Hz bandwidth at an offset of $f = 1$ Hz, a phase jitter for the 1Hz signal larger by 2π, and a spectral density of phase fluctuations given by

$$S_\phi(f) = \left[2\pi \times 6 \times 10^{-9}\mathrm{V}/\mathcal{S}\right]^2/f. \tag{14}$$

The measurements reported earlier measured the combined deviation for two nominally identical ZCD's. For the operational frequency $\nu_o = 1$ Hz of these tests of two "bare" ZCD's, Eqs. 11 and 13 combine with twice the value given by Eq. 14 to predict a Deviation at $\tau = 1$ second of

$$\sigma_\nu(1) = 2.17 \times 10^{-8}\mathrm{Hz}. \tag{15}$$

The contribution due to white amplifier noise is approximately the same size. The design procedure for the ZCD given an earlier section allows similar white noise contributions for each succeeding stage, for an effective value 4 times larger than that for a single stage. Thus the manufacturer's specification of 4 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$ RMS for each device gives rise to an effective spectral density of

$$S_\phi(f) = 4 \times \left[2\pi \times 4 \times 10^{-9}\mathrm{V}/\mathcal{S}\right]^2. \tag{16}$$

Combining this result with Eqs. 12 and 13 gives a contribution to the two–device test of

$$\sigma_\nu(1) = 1.96 \times 10^{-8}\text{Hz} \tag{17}$$

for the white noise of the ZCD.

The combined results of flicker and white amplifier noise compare very favorably to the measured value for tests of the bare ZCD which gave a value previously discussed of $\sigma_\nu(\tau) = 4.2 \times 10^{-8}$ Hz at $\tau = 1$ second measuring time.

The contribution due to the double–balanced mixer to RF tests can be similarly evaluated on the basis of Eqs. 11 and 13. Addition of the mixers caused the frequency deviation to more than double, increasing from 4.2×10^{-8} Hz to 1.17×10^{-7} Hz at $\tau = 1$ second averaging time. This increase implies a flicker phase noise (per mixer) of -135 dB/f ($/\sqrt{\text{Hz}}$). This value compares favorably to -140 dB/f ($/\sqrt{\text{Hz}}$), the lowest measurement system noise reported to date.[7]

TEST RESULTS–CROSSTALK

Figures 6 and 7 show the results of identical crosstalk measurements on the old and new ZCD's, respectively. Here, in each test a (buffered) 100 MHz signal from a hydrogen maser provided a reference for each of two ZCD's, while the test signals for each unit differed by approximately 0.01 Hz. The beat frequencies characterized were 1 Hz and ≈ 1.01 Hz. We show results for the channel in each case with a beat frequency of exactly 1 Hz, as generated by an offset generator from the original 100 MHz signal. The two units in each case had a common ground and were powered by a single power supply.

A comparison of the figures shows that, under these conditions, the old units show a sinusoidal variation of the time residuals for the 100 MHz signal of more than 10^{-12} seconds and a false peak in the Allan Deviation of nearly 3×10^{-14} at a measuring time of $\tau \approx 30$ seconds. The sinusoidal variation in the time residuals indicates a crosstalk between ZCD's of 10^{-12} seconds increased by the frequency ratio 10^8 Hz/1 Hz, or 10^{-4} seconds. The new units, as shown in Fig. 7, show no observable crosstalk, but instead allow the performance of the offset generator to be properly characterized.

DISCUSSION

Characterization of the instabilities in frequency sources requires a means of analyzing the frequency variations of the source under test while using another oscillator as a reference. For sources with ultra–high stability, this is typically done by offsetting the RF output frequency of one of the sources by a very small difference frequency ν_d, (typically $\nu_d = 1$ Hz) and then combining the output signals from the two sources in a semiconducting "double balanced" mixer to give an output at the difference frequency (1 Hz).

In this circumstance any frequency variation $\delta\nu_o$ in the source under test gives rise to an identical variation in the difference frequency,

$$\delta\nu_d = \delta\nu_o \tag{18}$$

and a correspondingly larger variation in relative frequency variation;

$$\frac{\delta\nu_d}{\nu_d} = \frac{\nu_o}{\nu_d}\frac{\delta\nu_o}{\nu_o} \tag{19}$$

if the RF output frequency ν_o is much larger than the difference frequency ν_d.

For example, for a 100 MHz output frequency and 1 Hz difference, the fractional uncertainty is increased by ν_o/ν_d = 100MHz/1Hz= 10^8 times. Thus, if the standards have a stability of $\delta f/f = 10^{-13}$, the 1Hz beat frequency will show a much larger variation of $\delta f/f = 10^{-5}$.

Measurement of the difference frequency ν_d is obtained by measurement of its period. If the time jitter of the ZCD is δt_z, and the time of measurement is τ, an uncertainty in the difference frequency ν_d is introduced

$$\frac{\delta \nu_d}{\nu_d} = \frac{\delta t_z}{\tau} \tag{20}$$

which in turn results in an uncertainty in the measured frequency of the standard ν_o given by

$$\frac{\delta \nu_o}{\nu_o} = \frac{\nu_d}{\nu_o}\frac{\delta \nu_d}{\nu_d} = \frac{\nu_d}{\nu_o}\frac{\delta t_z}{\tau}. \tag{21}$$

Equation (21) shows that a limit is placed on our measurement capability by ZCD jitter which decreases linearly with increasing measuring time τ. This limit also depends on the operating frequency ν_o of the frequency sources which are being characterized, and the beat frequency ν_b used to drive the ZCD. The highest available operating frequency for available frequency sources is typically 100 MHz. Increased operating frequencies may be available in the future, but for the present, the cost of transmitting and conditioning higher frequencies would be substantially greater than for 100 MHz signals. The difference frequency ν_d is operated at 1 Hz to allow measurements to be made at least every second. It is important to be able to characterize standards at short measuring times, and a lower limit $1/\nu_d$ to the time of characterization is determined by the difference frequency ν_d.

Thus there are important reasons why the operating frequency is not higher than 100 MHz and the difference frequency is at least as high as 1 Hz. Taking these values as given and using Eq. (21), the $1\mu s$ jitter of present ZCD's limits our measuring capability to

$$\frac{\delta \nu_o}{\nu_o} = \frac{10^{-14}}{\tau}. \tag{22}$$

Until recently, hydrogen maser standards presented the best possible stability for all time periods from 1 second to approximately 10,000 seconds.[8] The short term stability of hydrogen masers is approximately given by $\delta f/f = 10^{-13}/\tau$. Because these values are 10 times larger than that given by Eq. (22), the hydrogen maser standards can be well characterized using the old ZCD's.

However, newly developed superconducting standards are 10 times more stable than the hydrogen masers at short measuring times.[9] These standards show a stability of less than 1×10^{-14} at 1 second and so could not be well characterized at an operational frequency of 100 MHz. However, results reported here represent a ten-fold improvement over that given in Eq. (22), allowing such characterization of the new standards for the first time.

ACKNOWLEDGEMENTS

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Figure Captions

Figure 1 Block diagram of existing JPL zero–crossing detector design which has been in use for many years. Stage one must be a purely amplifying and filtering stage (no limiting) in order to provide a well–defined noise bandwidth for the measurements taken. The JPL units use a μa709–type operational amplifier for the second stage to allow a high switching speed with low noise.

Figure 2 Block diagram of the measurement system including parasitic resistances in the various signal and power paths. Since the output current is substantial, and with a frequency identical to that of the input, output–input coupling corrupts the phase of the input signal. Crosstalk between units similarly results in phase shifts at adjacent units which is dependent on the phase difference between the signals at the two units. Because the frequency is so low (1 Hz), penetration depths are large and parasitic resistances alone can be used to estimate this coupling.

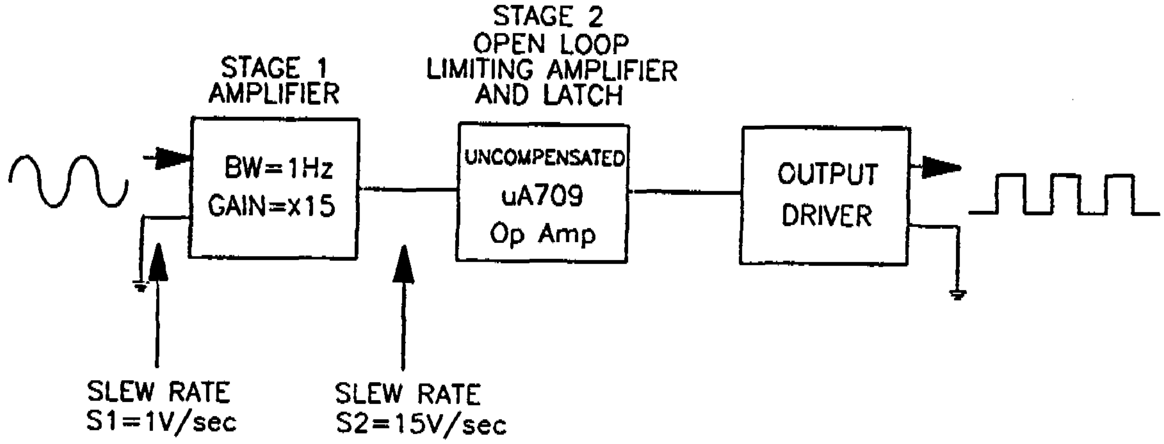
Figure 3 Block diagram of the new ZCD design. Multiple limiting stages with increasing slew rates and bandwidths allow an overall time jitter which is not appreciably larger than that due to noise contributions of the first stage alone. Since input signals with varying amplitudes must be accommodated, circuit bandwidths in stages 2 and 3 have been chosen to allow slew rates up to three times higher than the values given.

Figure 4 Block diagram of the RF frequency measurement system including the new ZCD. Ground loops involving both input and output signals are eliminated. Signal input uses symmetric outputs from a double–balanced mixer. Signal output is by means of fiber optic coupling, which eliminates the large ground loop currents associated with high–level signal output.

Figure 5 Results of a test of two of the new ZCD's. Measured stability is expressed in terms of an inferred Allan Deviation of relative frequency variation for the 100 MHz signal sources being compared. The values, on a per unit basis, would be smaller by $1/\sqrt{2}$ than those shown. Short term performance of $10^{-15}/\tau$ corresponds to a time jitter of 10^{-7} seconds, a value 10 times lower than that for ZCD's previously available. Longer term instabilities are somewhat higher, probably due to thermal fluctuations. The units were not thermally isolated, but subject to ordinary laboratory thermal environment. Because RF signals were not available with noise as low as these circuits, identical RF signals were fed to the mixers for each ZCD, and the differential jitter was measured. In this way, the noise of the source is largely cancelled, while noise in the mixers and ZCD's themselves does not.

Figure 6 Measurement of crosstalk between two of the older ZCD's. Here the RF ($\approx$ 100 MHz) signals to the unit being characterized differed by exactly 1 Hz while the signals to an adjacent unit differed by $\approx$ 1.01 Hz. The effect of the resultant 100 second beat between the signals is very apparent here, showing a sinusoidal time residual variation of more than 10^{-12} seconds. The rise in Allan Deviation for time periods approaching 100 seconds is due to this time variation and is more than 30 times larger than the actual deviation between the signals.

Figure 7 Crosstalk test of the new ZCD's using exactly the same setup as described in the previous figure. There is no evidence of crosstalk with a $\approx$ 100 second period. The offset generator which was used to generate the 100 MHz + 1 Hz RF signal is the limiting factor in this test ($\approx 1 \times 10^{-14}$ at $\tau = 1$ second).



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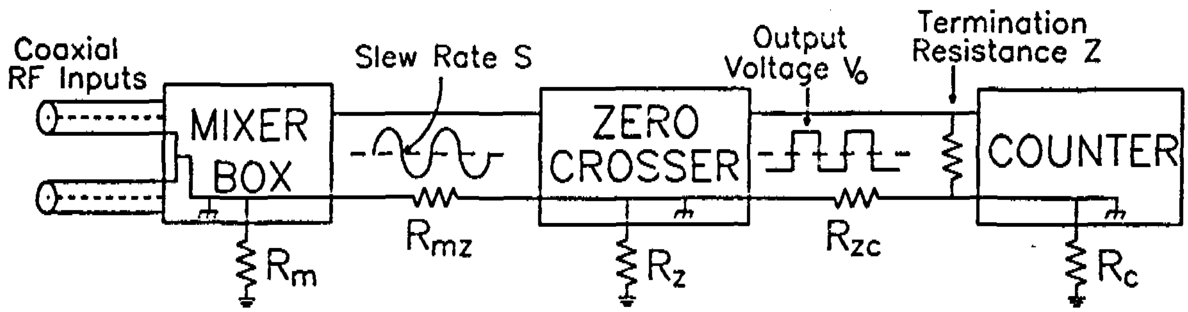

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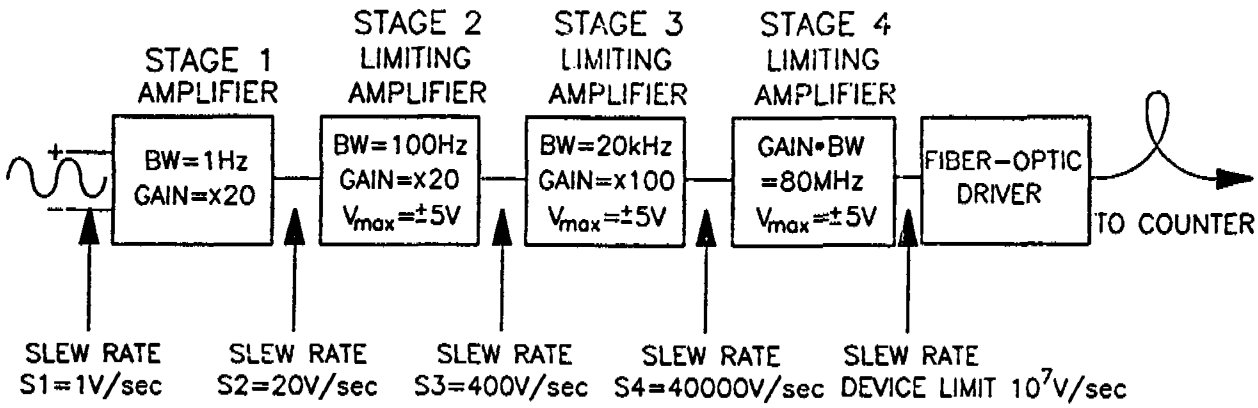

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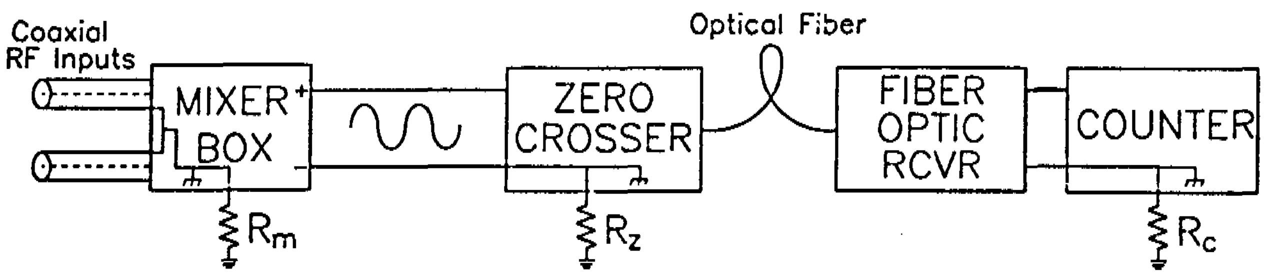

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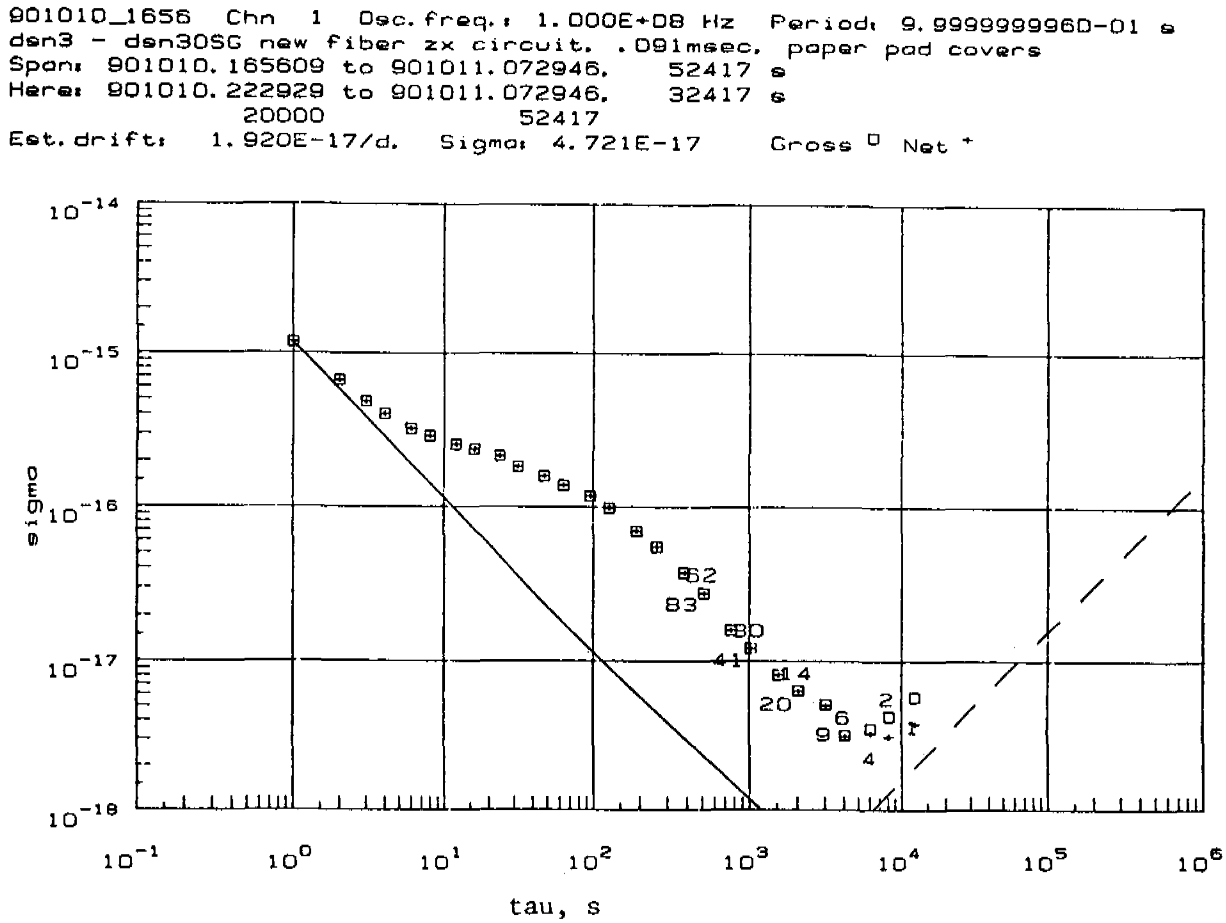

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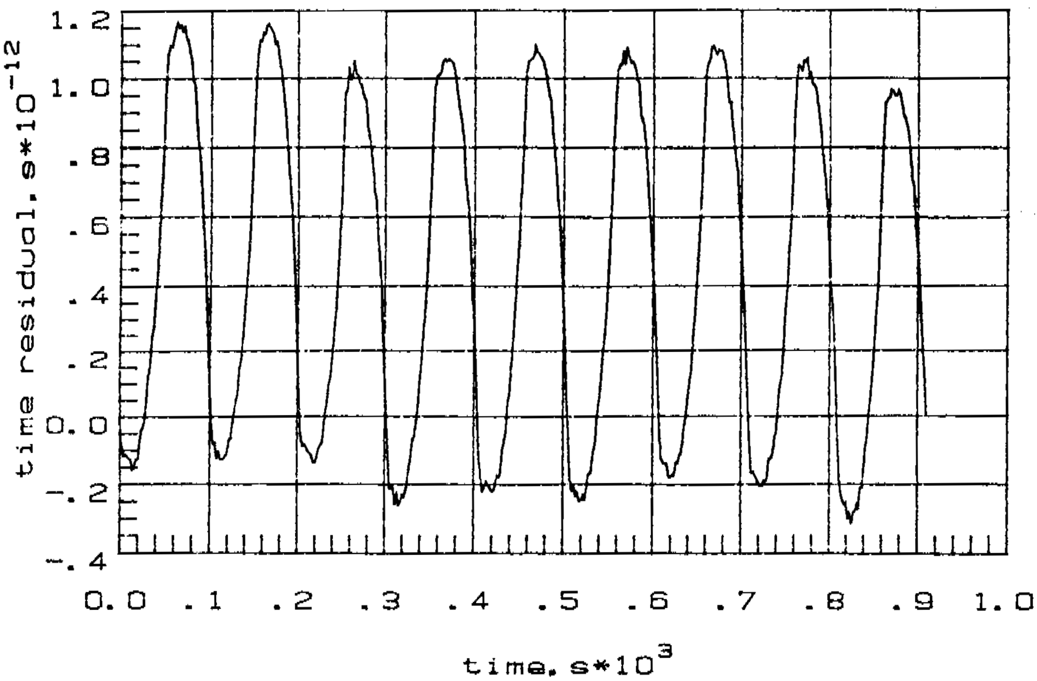

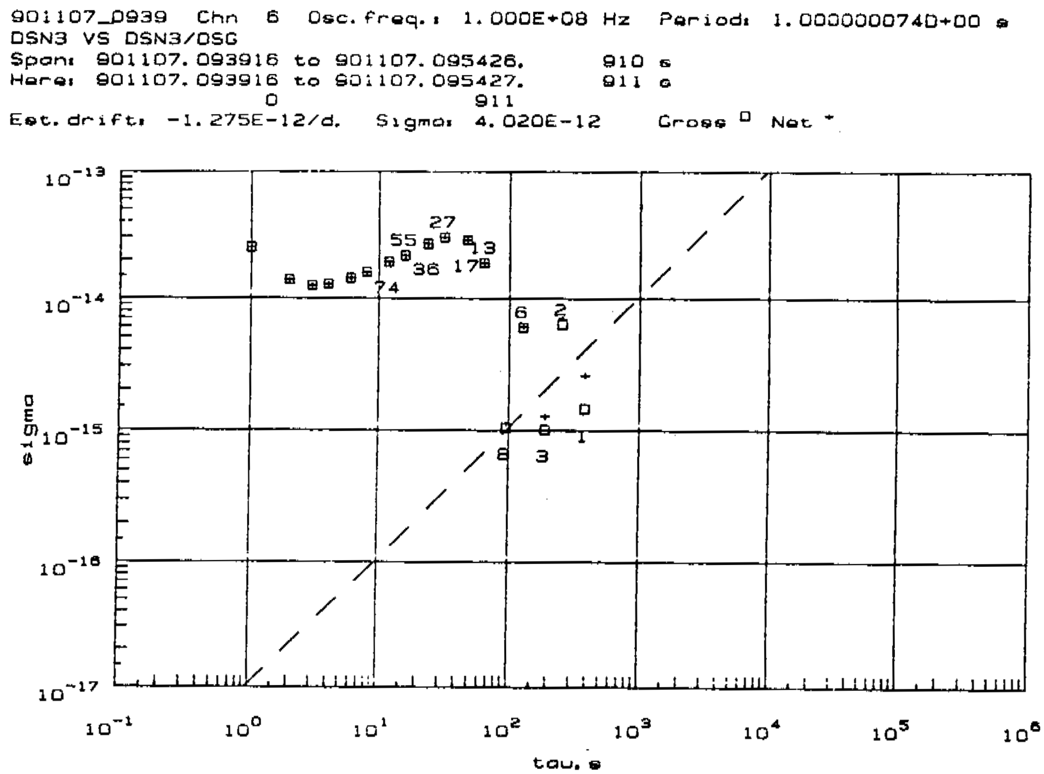

Figure 6. Measurement of crosstalk between two of the older ZCD's. Here the RF ($\approx$ 100 MHz) signals to the unit being characterized differed by exactly 1 Hz while the signals to an adjacent unit differed by $\approx$ 1.01 Hz. The effect of the resultant 100 second beat between the signals is very apparent here, showing a sinusoidal time residual variation of more than 10^{-12} seconds. The rise in Allan Deviation for time periods approaching 100 seconds is due to this time variation and is more than 30 times larger than the actual deviation between the signals.

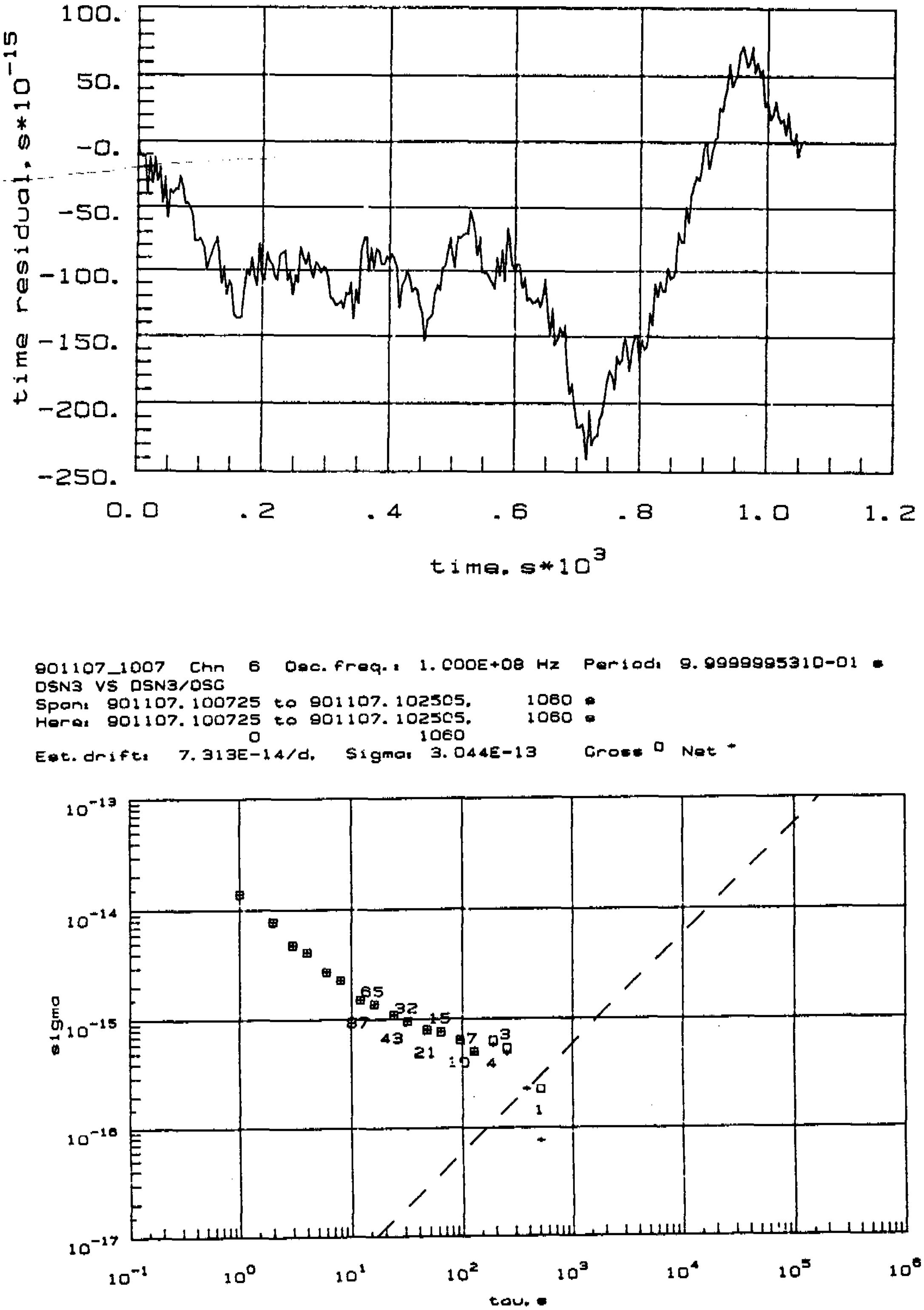

Figure 7. Crosstalk test of the new ZCD's using exactly the same setup as described in the previous figure. There is no evidence of crosstalk with a $\approx$ 100 second period. The offset generator, which was used to generate the 100 MHz + 1 Hz RF signal, is the limiting factor in this test ($\sigma(\tau) \approx 1 \times 10^{-14}/\tau$).