UVLBI MEMO #012

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To: UVLBI Group / Greg Weaver (JHU-APL)
From: S. Doeleman, A. E.E. Rogers, D. Fields, B. Freund (ARO)
Subject: SC11 Crystal Performance and Use in Characterizing H-Masers in the Field

Abstract:
MIT Haystack Observatory borrowed a 5MHz crystal oscillator from the JHU Applied Physics Labs for use in testing Hydrogen Maser stability. The crystal (labeled 'SC11') proved to be extremely stable with better stability than a Maser at integration times of 1 second, and stability comparable to a Maser at 10 second integration times. The SC11 crystal was also compared to an Oscilloquartz 8607 5MHz crystal (BVA). This memo summarizes some of the findings.

1. Test Setup:

To measure relative stability of two frequency standards, we used a TSC 5115A phase noise test setup that was purchased from Timing Solutions (since acquired by Symmetricom). The TSC unit takes two inputs up to 20MHz and calculates phase noise and Allan Standard Deviation, which are displayed as plots and tables.

2. SC11 Crystal Compared to SAO Maser P8:

The SC11 crystal was transported to the Submillimeter Telescope Observatory (SMTO) on Mt. Graham in Arizona. P8 had been compared to other Masers in the Smithsonian Astrophysical Observatory (SAO) labs and then shipped to the SMTO, where it was installed in a temperature controlled room. VLBI at 230GHz was planned at this station, and at this frequency, coherence losses due to Maser instability can be high. SC11 is stable enough to check that transporting the maser had not altered the stability characteristics measured in the lab in the 1 to 10 second range. The SC11 crystal was hand carried to the SMTO on 10 Mar 07 and powered up soon after arrival at the site.

Figures 1-3 show comparison of the SC11 crystal with P8 at three different Hydrogen flux settings for P8. Higher Hydrogen flow increases the signal-to-noise of the 1420MHz hyperfine splitting line from the maser cavity, and should increase the short term stability of the maser. We noted a dramatic increase in stability going from pressure settings of 650 and 700 to 750. Setting the Hydrogen flux this high is not done for normal Maser operation and will reduce the lifetime of the vac-ion pump plates. After the experiment in April 2007, the Hydrogen Maser flux was reduced to 500. Tables of the Sigma-Tau measurements are shown in Tables 1-3.

Since the Sigma-Tau of the P8 Maser and the SC11 crystal are adding in quadrature, we estimate that for SC11, 1, $\sigma_y(1s)<1.6x10^{-13}$, $\sigma_y(10s)<5x10^{-14}$, and $\sigma_y(100s)<1x10^{-13}$ (seen in the plot for which P8 pressure is set to 750). The performance of SC11 was such that the stability of P8 could be determined in the field to be sufficient for 230GHz VLBI (see section 4 below).

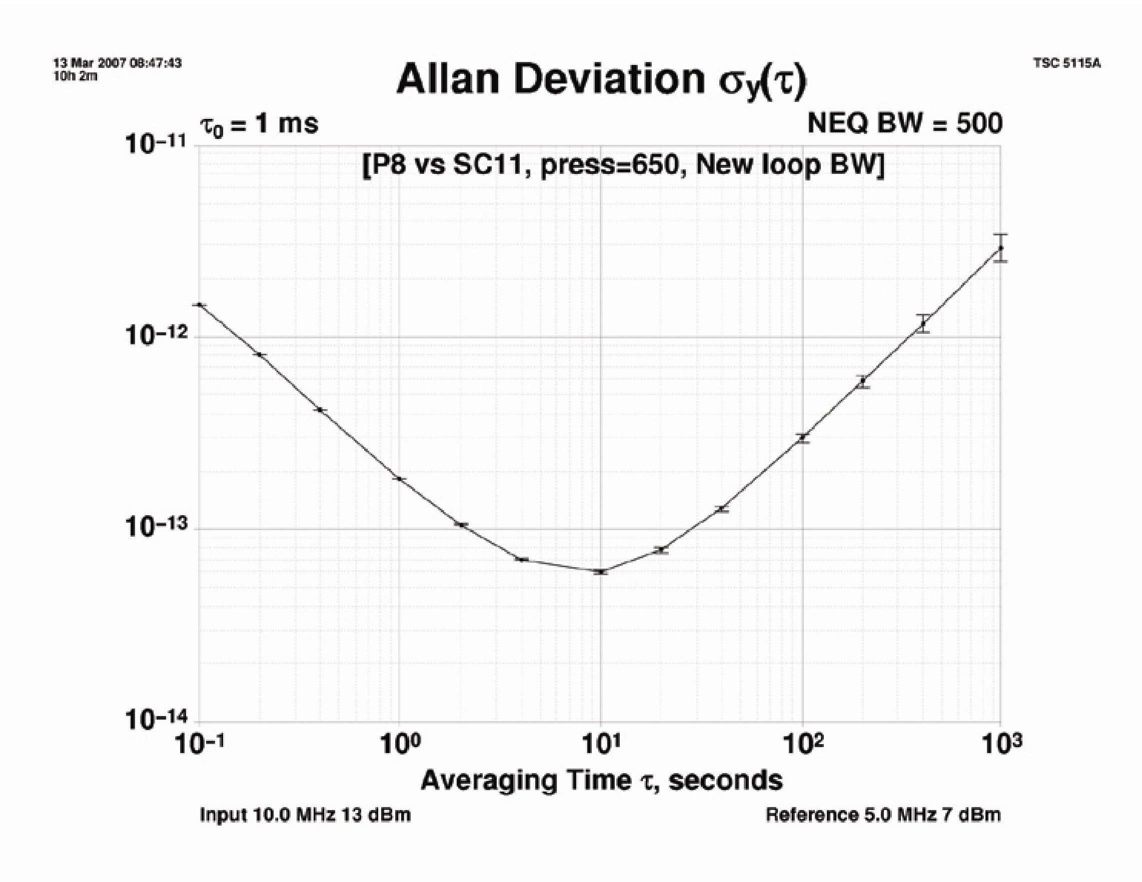

Fig 1: Sigma Tau plot of H-Maser P8 vs. SC11 with P8 pressure setting = 650.

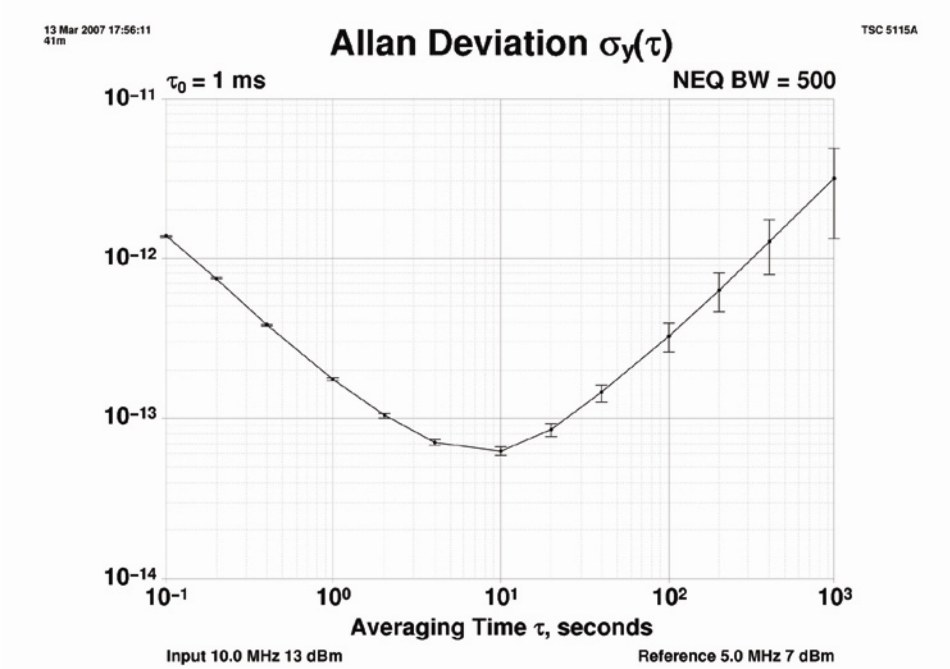

Fig 2: Sigma Tau plot of H-Maser P8 vs. SC11 with P8 pressure setting = 700.

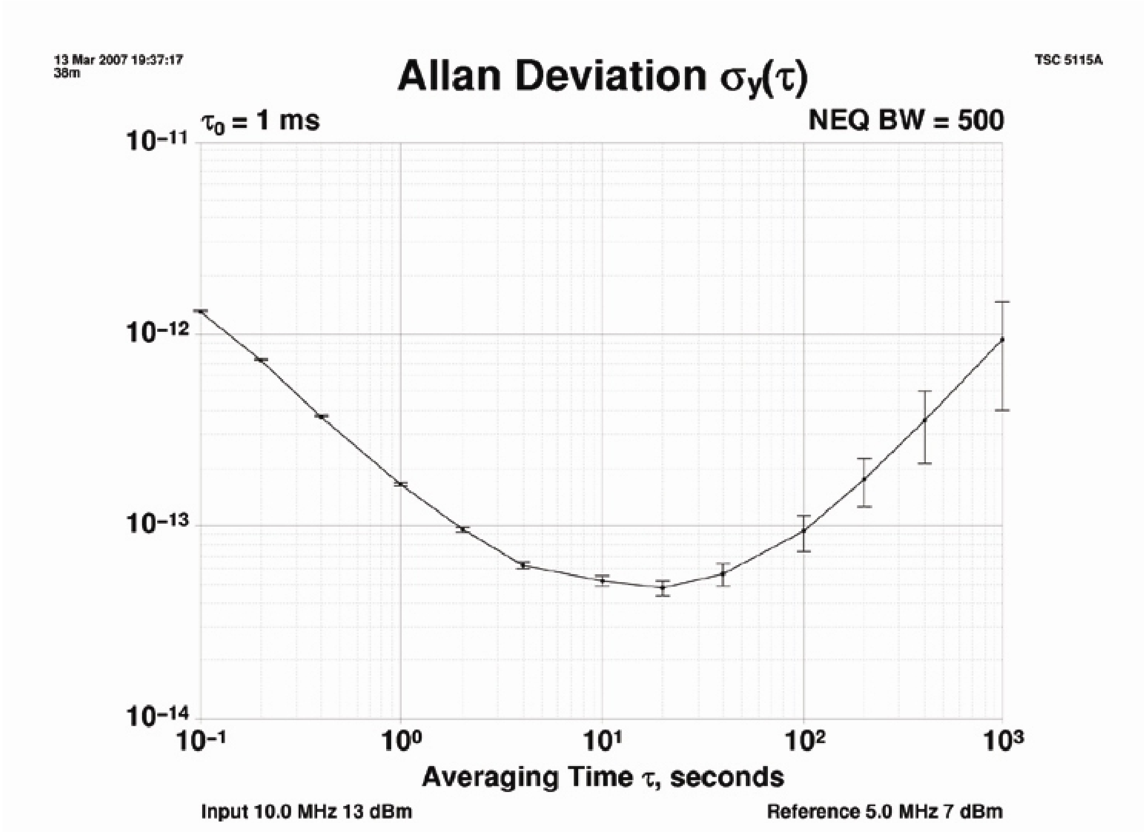

Fig 3: Sigma Tau plot of H-Maser P8 vs. SC11 with P8 pressure setting = 750.

13 Mar 2007 08:47:55
10h 2m

Allan Deviation $\sigma_y(\tau)$

TSC 5115A

τ_0 = 1 ms NEQ BW = 500

Avg. Time (s)	Allan Deviation $\sigma_y(\tau)$	Error Estimate
0.001	4.6609×10^{-11}	$\pm 7.68\times10^{-15}$
0.002	2.2617×10^{-11}	$\pm 5.27\times10^{-15}$
0.004	1.22201×10^{-11}	$\pm 4.03\times10^{-15}$
0.01	6.4351×10^{-12}	$\pm 3.35\times10^{-15}$
0.02	3.8608×10^{-12}	$\pm 2.84\times10^{-15}$
0.04	2.7326×10^{-12}	$\pm 2.85\times10^{-15}$
0.1	1.4638×10^{-12}	$\pm 2.41\times10^{-15}$
0.2	8.026×10^{-13}	$\pm 1.87\times10^{-15}$
0.4	4.158×10^{-13}	$\pm 1.37\times10^{-15}$
1	1.833×10^{-13}	$\pm 9.55\times10^{-16}$
2	1.057×10^{-13}	$\pm 7.79\times10^{-16}$
4	7.01×10^{-14}	$\pm 7.31\times10^{-16}$
10	6.03×10^{-14}	$\pm 9.94\times10^{-16}$
20	7.79×10^{-14}	$\pm 1.82\times10^{-15}$
40	1.284×10^{-13}	$\pm 4.23\times10^{-15}$
100	2.99×10^{-13}	$\pm 1.55\times10^{-14}$
200	5.90×10^{-13}	$\pm 4.34\times10^{-14}$
400	1.18×10^{-12}	$\pm 1.22\times10^{-13}$
1000	2.92×10^{-12}	$\pm 4.76\times10^{-13}$
2000	5.8×10^{-12}	$\pm 1.32\times10^{-12}$
4000	1.14×10^{-11}	$\pm 3.57\times10^{-12}$
10000	2.9×10^{-11}	$\pm 1.42\times10^{-11}$

Table 1 : Sigma Tau table of H-Maser P8 vs. SC11 with P8 pressure setting = 650.

13 Mar 2007 17:56:19
41m

TSC 5115A

Allan Deviation $\sigma_y(\tau)$

τ_0 = 1 ms

NEQ BW = 500

Avg. Time (s)	Allan Deviation $\sigma_y(\tau)$	Error Estimate
0.001	4.5255×10^{-11}	$\pm 2.86 \times 10^{-14}$
0.002	2.2766×10^{-11}	$\pm 2.04 \times 10^{-14}$
0.004	1.2144×10^{-11}	$\pm 1.54 \times 10^{-14}$
0.01	6.204×10^{-12}	$\pm 1.24 \times 10^{-14}$
0.02	3.678×10^{-12}	$\pm 1.04 \times 10^{-14}$
0.04	2.567×10^{-12}	$\pm 1.03 \times 10^{-14}$
0.1	1.370×10^{-12}	$\pm 8.67 \times 10^{-15}$
0.2	7.51×10^{-13}	$\pm 6.72 \times 10^{-15}$
0.4	3.831×10^{-13}	$\pm 4.85 \times 10^{-15}$
1	1.751×10^{-13}	$\pm 3.50 \times 10^{-15}$
2	1.042×10^{-13}	$\pm 2.95 \times 10^{-15}$
4	7.09×10^{-14}	$\pm 2.84 \times 10^{-15}$
10	6.32×10^{-14}	$\pm 4.00 \times 10^{-15}$
20	8.5×10^{-14}	$\pm 7.57 \times 10^{-15}$
40	1.45×10^{-13}	$\pm 1.82 \times 10^{-14}$
100	3.3×10^{-13}	$\pm 6.46 \times 10^{-14}$
200	6.4×10^{-13}	$\pm 1.75 \times 10^{-13}$
400	1.27×10^{-12}	$\pm 4.75 \times 10^{-13}$
1000	3.1×10^{-12}	$\pm 1.78 \times 10^{-12}$

Table 2: Sigma Tau plot of H-Maser P8 vs. SC11 with P8 pressure setting = 700.

13 Mar 2007 19:37:23
38m

TSC 5115A

Allan Deviation $\sigma_y(\tau)$

τ_0 = 1 ms

NEQ BW = 500

Avg. Time (s)	Allan Deviation $\sigma_y(\tau)$	Error Estimate
0.001	4.5231×10^{-11}	$\pm 2.98 \times 10^{-14}$
0.002	2.2734×10^{-11}	$\pm 2.12 \times 10^{-14}$
0.004	1.2135×10^{-11}	$\pm 1.60 \times 10^{-14}$
0.01	6.191×10^{-12}	$\pm 1.29 \times 10^{-14}$
0.02	3.527×10^{-12}	$\pm 1.04 \times 10^{-14}$
0.04	2.439×10^{-12}	$\pm 1.02 \times 10^{-14}$
0.1	1.308×10^{-12}	$\pm 8.63 \times 10^{-15}$
0.2	7.32×10^{-13}	$\pm 6.83 \times 10^{-15}$
0.4	3.725×10^{-13}	$\pm 4.92 \times 10^{-15}$
1	1.667×10^{-13}	$\pm 3.48 \times 10^{-15}$
2	9.59×10^{-14}	$\pm 2.83 \times 10^{-15}$
4	6.24×10^{-14}	$\pm 2.60 \times 10^{-15}$
10	5.19×10^{-14}	$\pm 3.42 \times 10^{-15}$
20	4.79×10^{-14}	$\pm 4.46 \times 10^{-15}$
40	5.7×10^{-14}	$\pm 7.42 \times 10^{-15}$
100	9.4×10^{-14}	$\pm 1.94 \times 10^{-14}$
200	1.8×10^{-13}	$\pm 5.03 \times 10^{-14}$
400	3.6×10^{-13}	$\pm 1.44 \times 10^{-13}$
1000	9.3×10^{-13}	$\pm 5.33 \times 10^{-13}$

Table 3: Sigma Tau table of H-Maser P8 vs. SC11 with P8 pressure setting = 750.

3. SC11 Crystal Compared to Oscilloquartz 8607 BVA Crystal:

After the April 2007 experiment, SC11 was brought back to Haystack for comparison with the NASA Maser NR4 and an Oscilloquartz 8607 BVA Crystal purchased in August 2007. Figures

4-6 show Sigma-Tau results for tests of all three comparisons between SC11-NR4-BVA, and the values are shown in Tables 4-6.

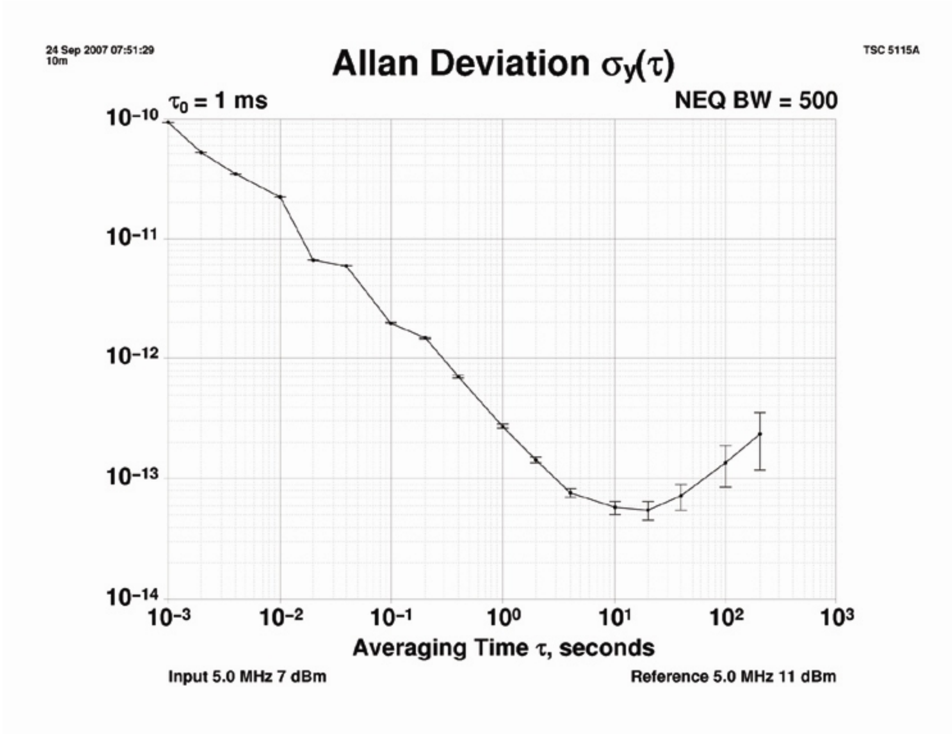

Figure 4: Sigma Tau plot of H-Maser NR4 vs. SC11.

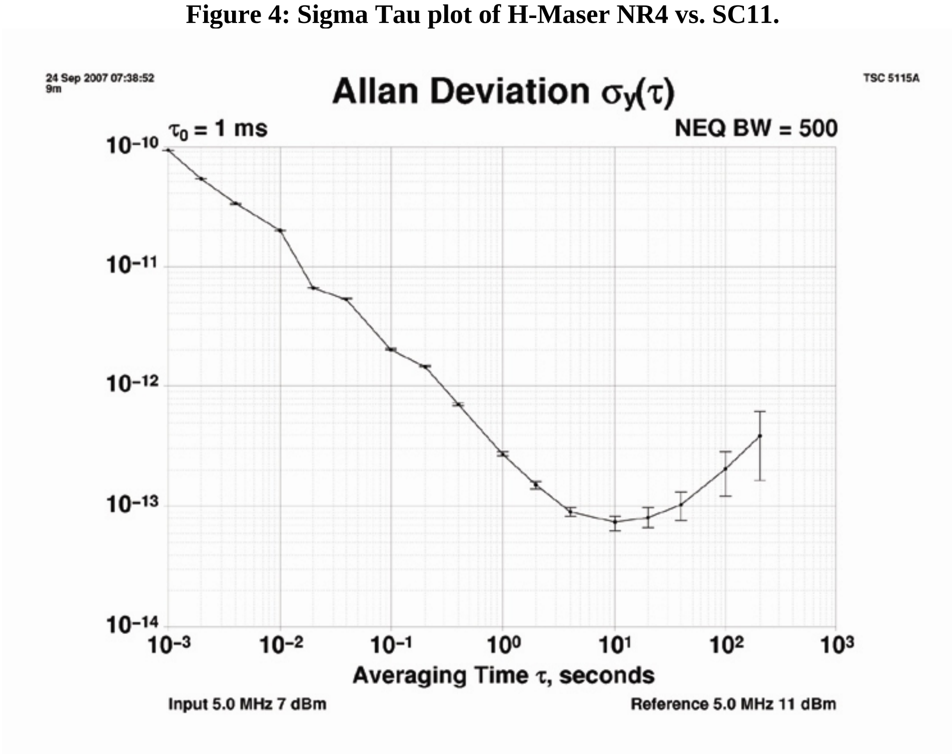

Figure 5: Sigma Tau plot of H-Maser NR4 vs. BVA.

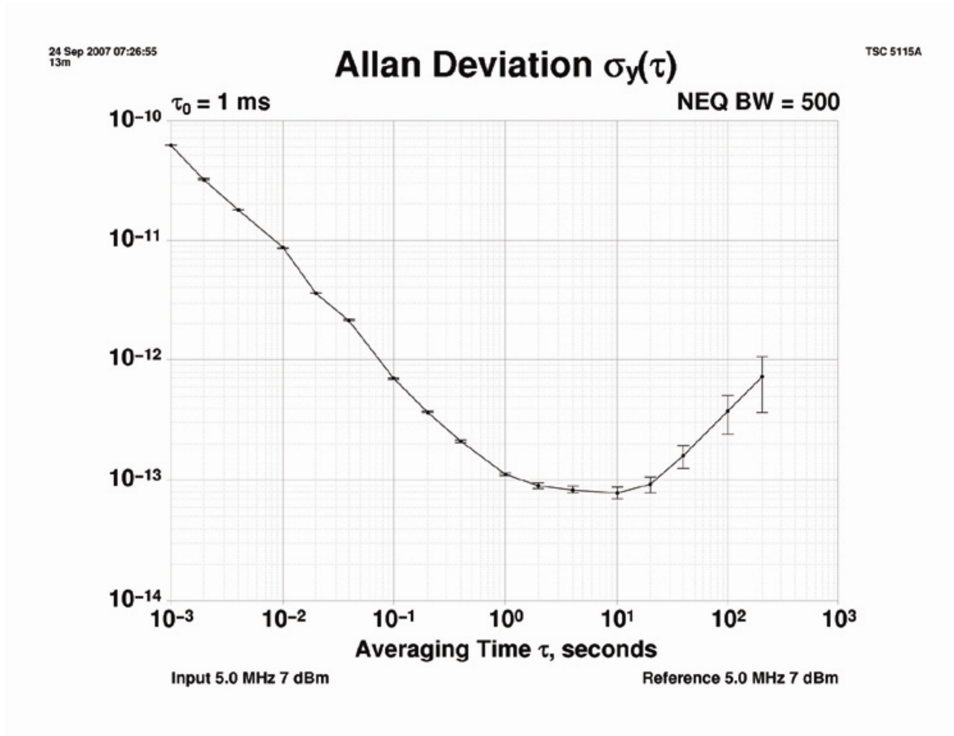

Figure 6: Sigma Tau plot of SC11 Crystal vs. BVA.

24 Sep 2007 07:51:34
10m

TSC 5115A

Allan Deviation $\sigma_y(\tau)$

τ_0 = 1 ms

NEQ BW = 500

Avg. Time (s)	Allan Deviation $\sigma_y(\tau)$	Error Estimate
0.001	9.101×10^{-11}	$\pm 1.15\times10^{-13}$
0.002	5.110×10^{-11}	$\pm 9.11\times10^{-14}$
0.004	3.456×10^{-11}	$\pm 8.71\times10^{-14}$
0.01	2.214×10^{-11}	$\pm 8.83\times10^{-14}$
0.02	6.567×10^{-12}	$\pm 3.70\times10^{-14}$
0.04	5.885×10^{-12}	$\pm 4.69\times10^{-14}$
0.1	1.980×10^{-12}	$\pm 2.50\times10^{-14}$
0.2	1.479×10^{-12}	$\pm 2.64\times10^{-14}$
0.4	7.11×10^{-13}	$\pm 1.79\times10^{-14}$
1	2.74×10^{-13}	$\pm 1.09\times10^{-14}$
2	1.44×10^{-13}	$\pm 8.09\times10^{-15}$
4	7.7×10^{-14}	$\pm 6.15\times10^{-15}$
10	5.7×10^{-14}	$\pm 7.22\times10^{-15}$
20	5.5×10^{-14}	$\pm 9.83\times10^{-15}$
40	7.3×10^{-14}	$\pm 1.80\times10^{-14}$
100	1.4×10^{-13}	$\pm 5.14\times10^{-14}$
200	2.4×10^{-13}	$\pm 1.17\times10^{-13}$

Table 4: Sigma Tau table of H-Maser NR4 vs. SC11.

24 Sep 2007 07:38:57
9m

Allan Deviation $\sigma_y(\tau)$

TSC 5115A

τ_0 = 1 ms — NEQ BW = 500

Avg. Time (s)	Allan Deviation $\sigma_y(\tau)$	Error Estimate
0.001	9.270×10^{-11}	$\pm 1.25\times10^{-13}$
0.002	5.336×10^{-11}	$\pm 1.02\times10^{-13}$
0.004	3.287×10^{-11}	$\pm 8.88\times10^{-14}$
0.01	1.990×10^{-11}	$\pm 8.50\times10^{-14}$
0.02	6.565×10^{-12}	$\pm 3.96\times10^{-14}$
0.04	5.348×10^{-12}	$\pm 4.57\times10^{-14}$
0.1	2.032×10^{-12}	$\pm 2.74\times10^{-14}$
0.2	1.469×10^{-12}	$\pm 2.81\times10^{-14}$
0.4	7.10×10^{-13}	$\pm 1.92\times10^{-14}$
1	2.74×10^{-13}	$\pm 1.17\times10^{-14}$
2	1.50×10^{-13}	$\pm 9.08\times10^{-15}$
4	9.0×10^{-14}	$\pm 7.69\times10^{-15}$
10	7.4×10^{-14}	$\pm 9.95\times10^{-15}$
20	8.2×10^{-14}	$\pm 1.55\times10^{-14}$
40	1.05×10^{-13}	$\pm 2.77\times10^{-14}$
100	2.1×10^{-13}	$\pm 8.31\times10^{-14}$
200	3.9×10^{-13}	$\pm 2.23\times10^{-13}$

Table 5: Sigma Tau table of H-Maser NR4 vs. BVA.

24 Sep 2007 07:27:07
13m

Allan Deviation $\sigma_y(\tau)$

TSC 5115A

τ_0 = 1 ms — NEQ BW = 500

Avg. Time (s)	Allan Deviation $\sigma_y(\tau)$	Error Estimate
0.001	6.144×10^{-11}	$\pm 6.82\times10^{-14}$
0.002	3.192×10^{-11}	$\pm 5.01\times10^{-14}$
0.004	1.7649×10^{-11}	$\pm 3.92\times10^{-14}$
0.01	8.533×10^{-12}	$\pm 2.99\times10^{-14}$
0.02	3.619×10^{-12}	$\pm 1.80\times10^{-14}$
0.04	2.147×10^{-12}	$\pm 1.51\times10^{-14}$
0.1	7.05×10^{-13}	$\pm 7.83\times10^{-15}$
0.2	3.70×10^{-13}	$\pm 5.81\times10^{-15}$
0.4	2.099×10^{-13}	$\pm 4.66\times10^{-15}$
1	1.130×10^{-13}	$\pm 3.96\times10^{-15}$
2	8.98×10^{-14}	$\pm 4.46\times10^{-15}$
4	8.4×10^{-14}	$\pm 5.86\times10^{-15}$
10	7.8×10^{-14}	$\pm 8.63\times10^{-15}$
20	9.2×10^{-14}	$\pm 1.44\times10^{-14}$
40	1.61×10^{-13}	$\pm 3.56\times10^{-14}$
100	3.7×10^{-13}	$\pm 1.31\times10^{-13}$
200	7.2×10^{-13}	$\pm 3.57\times10^{-13}$

Table 6: Sigma Tau table of SC11 vs. BVA.

4. Maser Performance:

The time over which a VLBI baseline can coherently integrate depends on the stability of the frequency standards used at each antenna roughly as:

$$\omega\tau\sigma_y(\tau) < 1$$

where ω is the observing frequency in radians/sec, $\sigma_y(\tau)$ is the square root of the Allan variance (the Allan standard deviation), and the limit keeps rms phase fluctuations below 1 radian. The signal loss on a two station VLBI baseline due to instability in the frequency standards is then approximately

$$Loss = 1 - e^{-(\omega\tau\sigma_y(\tau))^2}$$

If the SC11 and BVA crystals have comparable Sigma-Tau at 1 second, then the measured value when both are compared (Table 6), yields $\sigma_y(1s)=8x10^{-14}$ (though this is probably an upper limit since the specs on the BVA crystal show it to a little worse than this). So, the 1s Sigma-Tau for P8 at a pressure setting of 750 (see Table 3) will be

$$\sigma_y(1s) = \sqrt{(1.7\times10^{-13})^2 - (0.8\times10^{-13})^2} = 1.5\times10^{-13}$$

The Sigma-Tau for Hydrogen Masers will typically follow a $\sigma_y \sim \tau^{-1}$ trend from short integration times to ~8-10seconds. So, in the field, one could assume that $\sigma_y(10s)\sim1.5x10^{-14}$ for P8. The critical point is that at 1 second, the SC11 and BVA crystals are both much better than the masers, and so provide a much needed way to verify the maser's τ=1sec Sigma-Tau in the field, from which extrapolations to τ=10sec can be made.

If $\sigma_y(10s)\sim2x10^{-14}$ for P8, then the estimated VLBI signal loss would be ~8%.