RECENT RESULTS ON THE PERFORMANCE OF EFOS, NP, AND NX HYDROGEN MASERS

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INTRODUCTION

In response to a NASA Goddard Space Flight Center (GSFC) Work Assignment, Bendix Field Engineering Corporation (BFEC) evaluated the performance of the Oscilloquartz EFOS-2 hydrogen maser along with that of NASA NX-3 and NP-2 hydrogen masers in early 1983. This paper presents the results of that evaluation.

The hydrogen maser was brought to BFEC's Hydrogen Maser Facility at Columbia, Maryland by Oscilloquartz personnel at the request of the National Radio Astronomy Observatory (NRAO) who purchased the maser from Oscilloquartz. Figure 1 shows the EFOS-2 maser soon after arriving at the BFEC Hydrogen Maser Facility. During the evaluation period, the maser was maintained by Oscilloquartz personnel. BFEC would like to thank the NRAO and Oscilloquartz personnel who made this evaluation possible and who helped BFEC perform the various tests involved.

During most of the tests, the EFOS-2 maser was intercompared with the NASA NX-3 and NASA NP-2 hydrogen masers which were both operating in hydrogen maser thermal chambers built by BFEC. For the long-term stability and temperature coefficient tests, EFOS-2 was also placed in a BFEC thermal chamber. The measurement area with the thermal chambers is shown in Figure 2. At NASA's request, the evaluation was performed on a best effort basis within the confines of existing funding. Some tests, therefore, such as a pressure sensitivity test, were not performed because of funding and time limitations even though they would have been highly desirable.

The remainder of the report describes the specific tests that were performed and the results obtained. For the reported results, all reported errors are standard errors. These are indicated in parentheses and are to be interpreted as error values on the last places of the number stated.

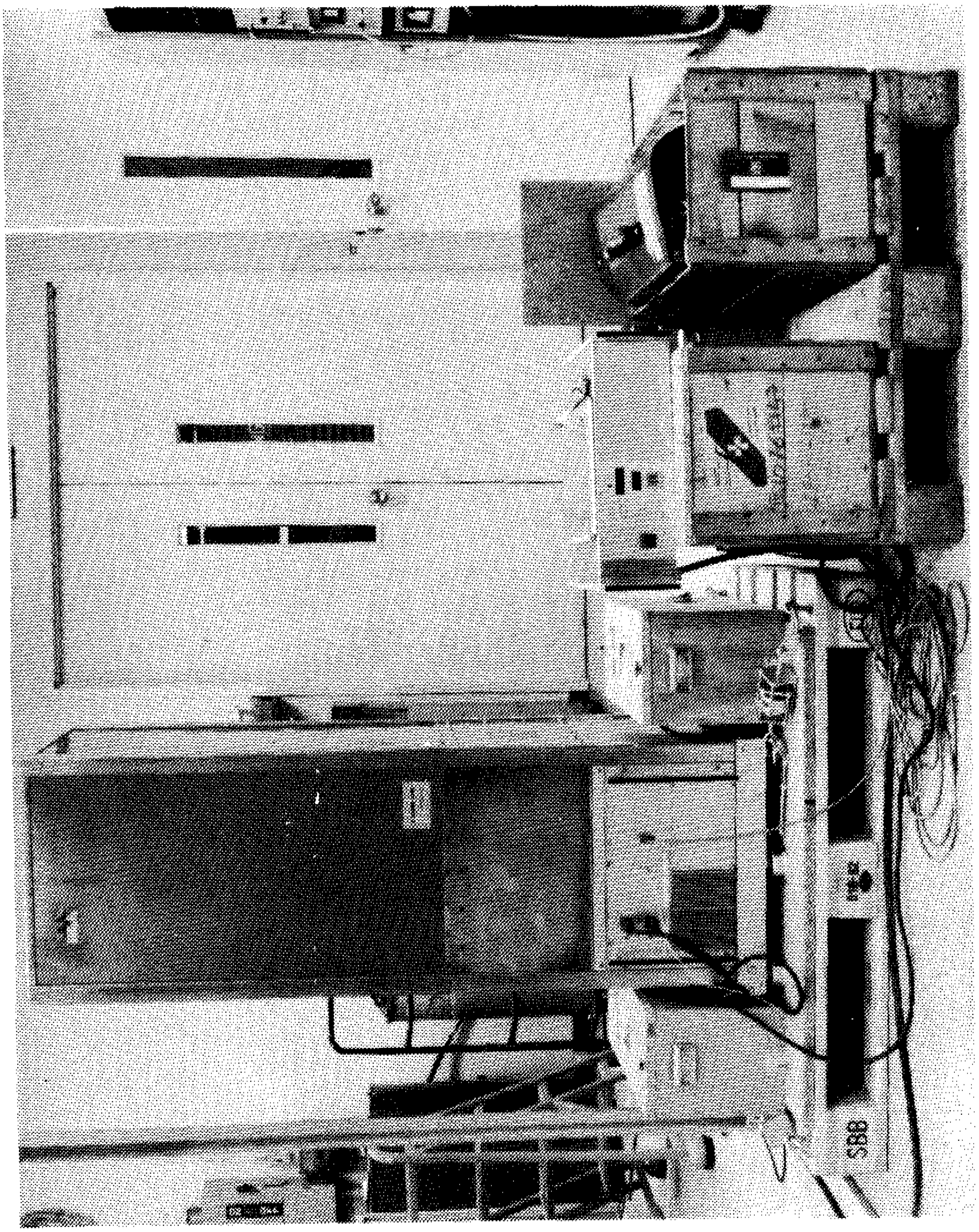

Figure 1. EFOS-2 Soon After Arriving at Bendix, Columbia

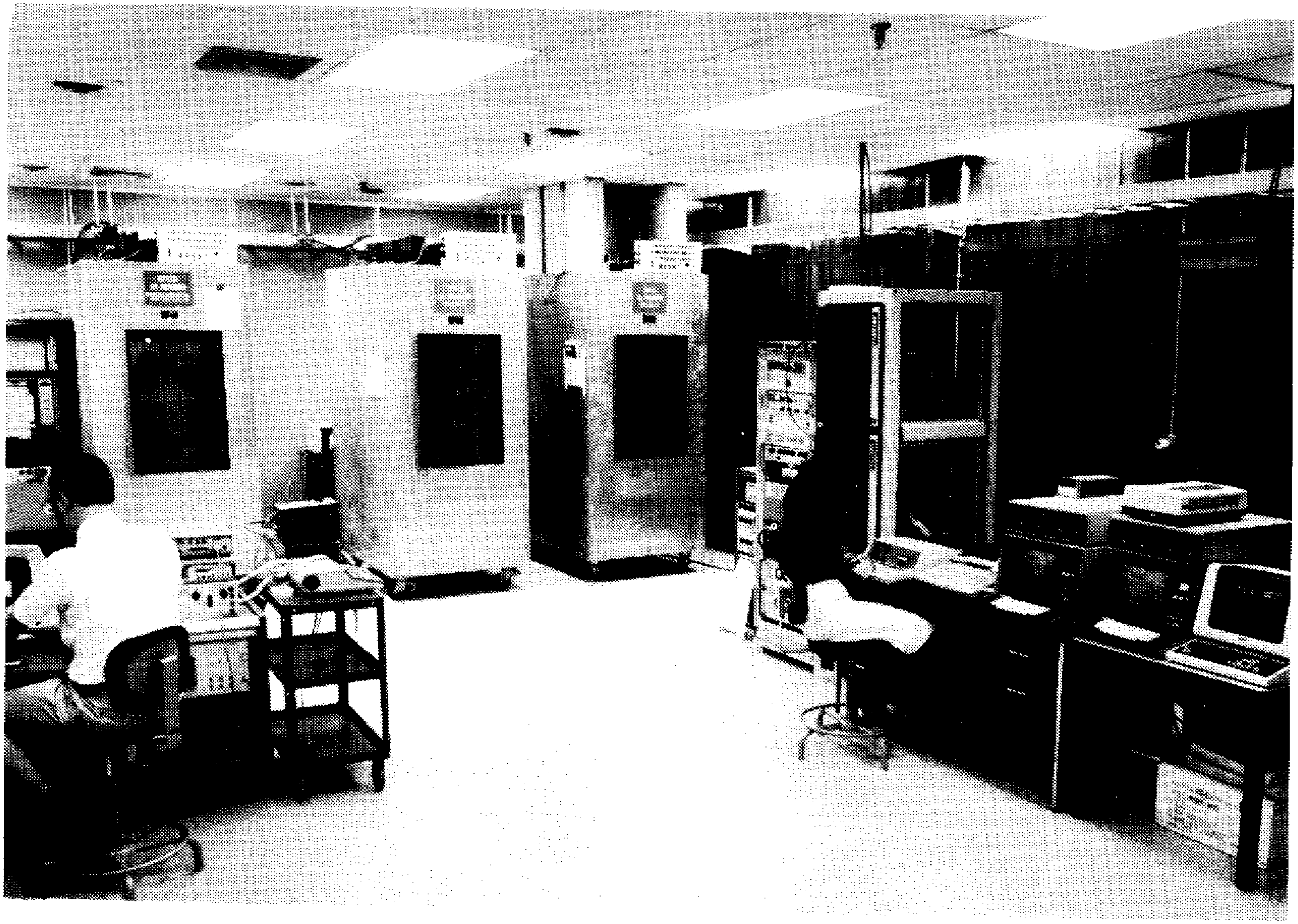

Figure 2. Measurement Area with Thermal Chambers

MAGNETIC TESTS

For the magnetic tests, the EFOS-2 hydrogen maser was placed in a large solenoid as shown in Figure 3. The solenoid was switched back and forth between +0.2 gauss and -0.2 gauss while a 100 second average frequency measurement was performed for each solenoid polarity after waiting about 20 seconds for the maser frequency to settle down. The measurements were made after Oscilloquartz personnel degaussed the EFOS-2 maser and set the maser to its recommended Zeeman and cavity settings. The results of the average of 10 measurements at each solenoid polarity are shown in Table 1.

Table 1. Magnetic Sensitivity:

$\Delta f/f/\Delta H = 5.2(36)\times 10^{-14}$/gauss
for $\Delta H = 0.4$ gauss

TEMPERATURE COEFFICIENT

For the temperature coefficient test, the EFOS-2 maser was placed in a BFEC thermal chamber. After the EFOS-2 maser was in the thermal chamber more than 41 hours and after the maser was operating 22 hours without any environmental disturbances, the thermal chamber was stepped from 28C to 23C. Figure 4 shows the frequency response of the EFOS-2 maser to this temperature step. The results obtained from this data are shown in Table 2.

Table 2. Temperature Sensitivity in Thermal Chamber:

$\Delta f/f//\Delta T = -7.00(47)\times 10^{-14}$/C
for $\Delta T = -5.4$C and after 22 hours

Time Constant in Thermal Chamber = 4.02(33) hours

Caution must be used, however, in using this data because the time constant of the hydrogen maser was severely shortened in the thermal chamber because of the high-speed air flow around the maser. (In a room with relatively still air, the maser was observed to have a time constant of more than 12 hours.) The measurement results given represent a good measurement of a static temperature sensitivity (theoretically one with infinite settling time), but do not give a true picture of the maser behavior after 22 hours in a normal laboratory environment. In a normal laboratory environment, from the difference in the time constants, one would expect the temperature sensitivity after 22 hours to be 16 percent lower or about -6×10^{-14}/C.

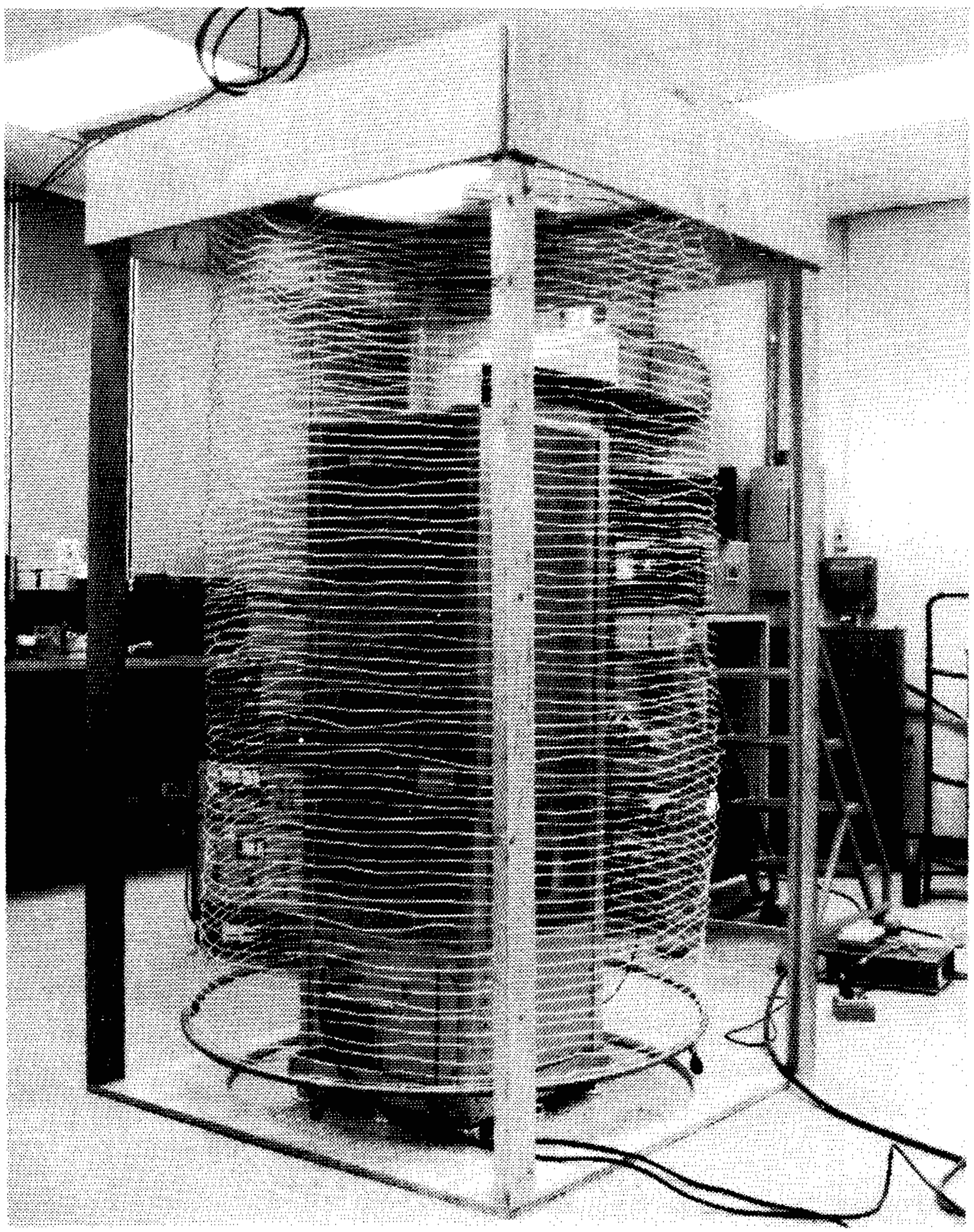

Figure 3. EFOS-2 in the Test Solenoid

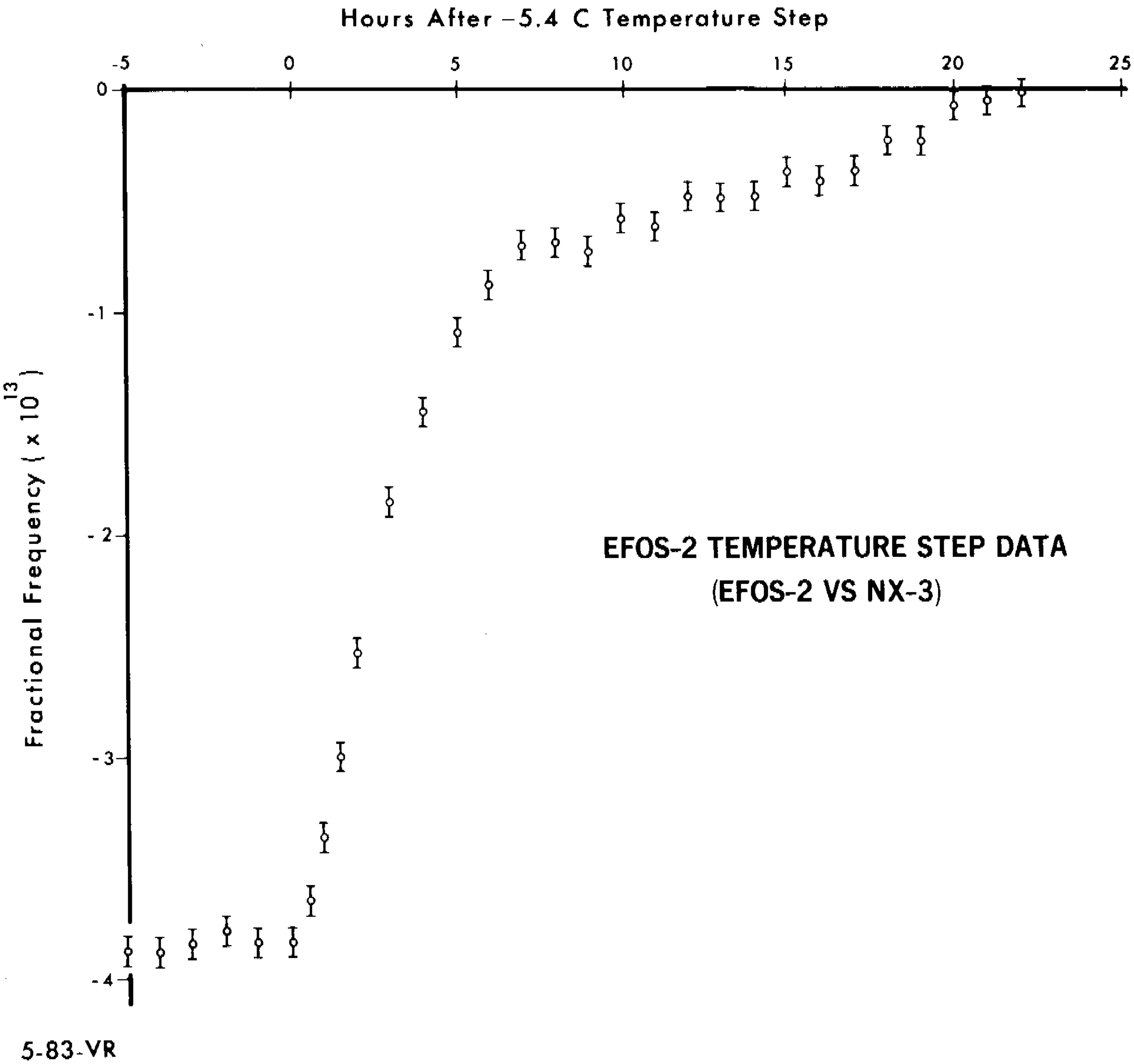

Figure 4. EFOS-2 Frequency Response to Temperature Step

The errors in Table 2 are based totally on the short-term noise of the data. The data in Figure 4 though, seems to indicate that the data is not completely described by a single time constant. With hindsight, it would have been better to have taken data for another day but time constraints forced us to move on to other tests.

SHORT TERM STABILITY

Short-term stability tests were run comparing EFOS-2 to NP-2 and NX-3, but an anomalous noise level of about 0.6ps, probably caused by ground loops between the masers in the thermal chambers, clouded the data. We therefore reran the tests with both ports of our measurement system measuring EFOS-2 versus NX-3 in order to subtract out the noise of the measurement system. The theory behind this technique is as follows.

The time average of the fractional frequency offsets out of the two beat frequency ports is given by:

$$y_A = y + y_a \tag{1a}$$

$$y_B = y + y_b \tag{1b}$$

where y_A and y_B represent the total offsets, where y_a and y_b represent the contributions of the 2 measurement systems, and where y represents the contribution of EFOS versus NX-3. Differencing (1a) and (1b), we obtain approximately:

$$y_d = y_a - y_b \tag{2}$$

Taking the Allan variance of this quantity yields an estimate of the total system noise:

$$\sigma_d^2 = \sigma_a^2 + \sigma_b^2 \tag{3}$$

assuming the noise processes are independent. Summing (1a) and (1b) yields:

$$y_s = 2y + y_a + y_b \tag{4}$$

The Allan variance of this becomes:

$$\sigma_s^2 = 4\sigma_y^2 + \sigma_a^2 + \sigma_b^2 \qquad (5)$$

again assuming that all noise processes are independent. Combining (3) and (5) yields our desired estimate of the Allan variance of the masers alone:

$$\sigma_a^2 = (\sigma_s^2 - \sigma_d^2)/4 \qquad (6)$$

If all the noise sources are not independent, there would be deviations from (6) due to correlations between y, a, and b. These correlations could only occur through some environmental parameter affecting the measurement system and the masers or 60 Hz interference. Temperature and other similar environmental parameters usually affect the performance of masers and measurement systems only for averaging times of 1000 seconds or longer. Since we are only considering stabilities up to 100 seconds, these effects would not cause any problems.

The 60 Hz interference, however, is another matter. It would cause short term correlations which could generate positive or negative correlation terms. (Positive terms would cause our estimate of the masers' stability to be high and negative terms would cause our estimate of the masers' stability to be low.) The sign of 60 Hz correlations is a periodic function of the averaging time with a period equal to the 60 Hz period, so 60 Hz interference usually causes Allan deviate data, as a function of averaging time, to have scatter from a smooth power law behavior larger than the statistical error bars associated with the data (unless the averaging times under consideration just happen to be exact multiples of the 60 Hz period). Therefore, smoothness of the data is a good test for the presence of 60 Hz effects. In the data presented later in the paper using this analysis, there is no such evidence of 60 Hz correlation problems.

Equation (2) is only approximately true because, if the zero crossings of the beats of the 2 ports are not exactly synchronized, there will be an extra term equal to:

$$y_e = y(t,\tau) - y(t+\varepsilon,\tau) \qquad (7)$$

where:

$$y(t,\tau) = \frac{1}{\tau}\int_t^{t+\tau} y(t')dt'$$

If the synchronization error between the beats, ε, is much less than, t_c, the correlation time of the low-pass filters in the phase comparators used to generate the beats, (7) makes a negligible contribution to Allan deviate. Numerically for $\varepsilon << t_c$, (7) yields an Allan deviate of:

$$\sigma_e = (\varepsilon/\tau)2^{\frac{1}{2}}\sigma_y(t_c, \tau)$$

or, because the dominant noise for short averaging times is white noise:

$$\sigma_e = (\varepsilon/t_c)2^{\frac{1}{2}}\sigma_y(\tau, \tau + 1s) \qquad (8)$$

For the data taken, $\varepsilon < 0.4$ ms and $t_c = 12$ ms, σ_e is only 0.047 times σ_y. Thus, for our case, σ_e makes a negligible contribution in estimating σ_y.

The results obtained after the system noise is subtracted out are shown in Table 3.

Table 3. Short-Term Stability of EFOS-2 Versus NX-3:

NOTE: All Allan deviates are divided by an extra square root of 2 to normalize to one maser deviate. The noise bandwidth is approximately 12 Hz. The statistic used is $\sigma_y(2, \tau, \tau + 1s)$.

TAU	SIGMA	NUMBER OF POINTS USED
1s	$2.05(46)\times10^{-13}$	410
10s	$3.29(47)\times10^{-14}$	380
100s	$4.66(47)\times10^{-15}$	480

LONG-TERM STABILITY

Long-term stability data was taken for 3.75 days comparing NX-3 with EFOS-2 and NP-2. The data was taken as nearly contiguous 1054 second averages of the two intercomparison beat periods of the 5 MHz signals from the masers. For measurement puposes, NX-3 was offset approximately 0.95Hz lower than the other masers. The period counters used to take the data were reset between readings so the dead time between the data and the lack of synchronization between the data channels is on the order of 1 second. In order to obtain a direct comparison of EFOS-2 and NP-2, the EFOS-2 versus NX-3 and NP-2 versus NX-3 data was differenced to produce a derived EFOS-2 versus NP-2 channel of data. The data is plotted in Figure 5 with frequency drifts removed and with arbitrary frequency offsets so the data can be compared on the same plot.

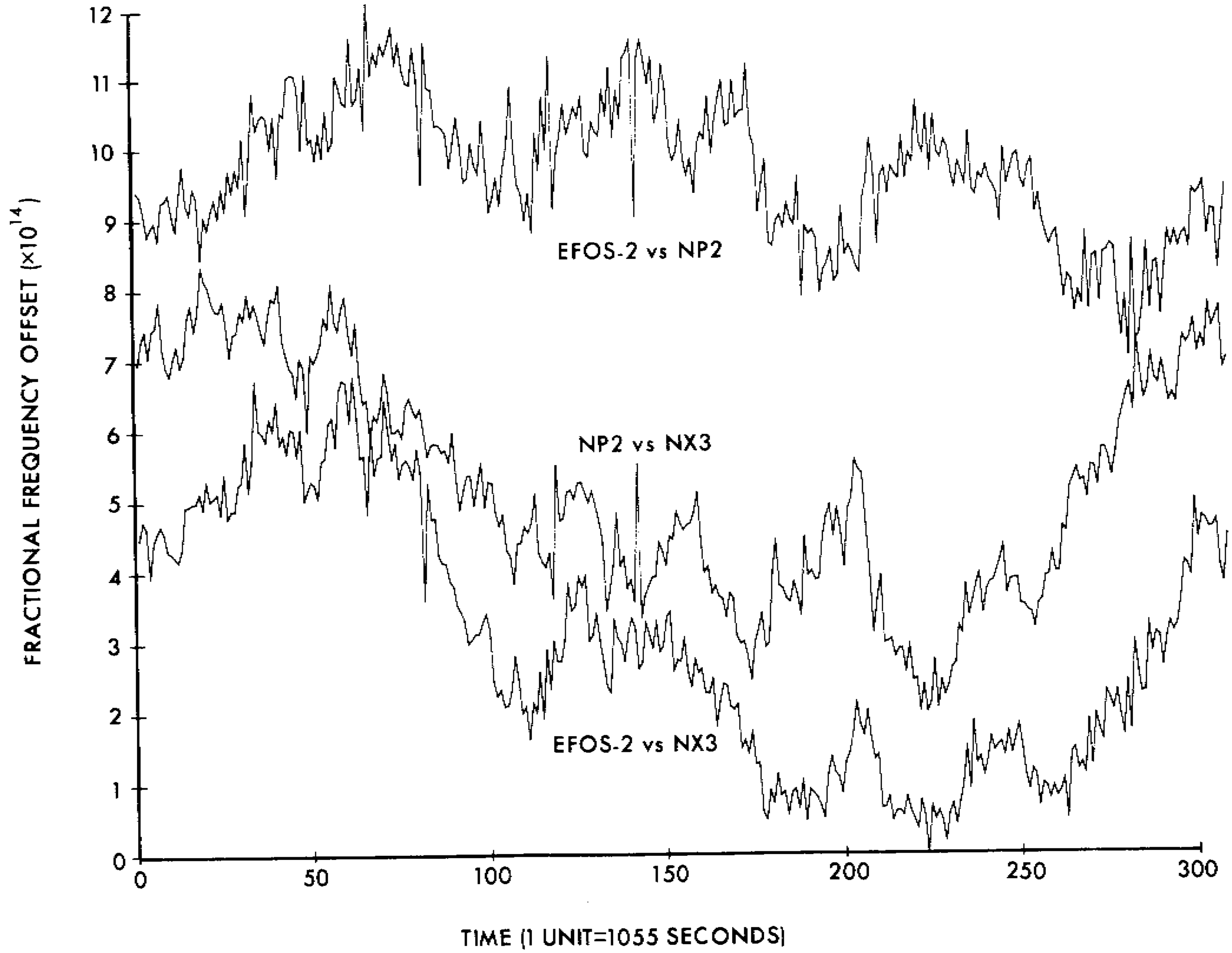

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Figure 5. Frequency Data with Frequency Drifts Removed and with Arbitrary Frequency Offsets

To analyze the data, a sliding Allan variance technique was used (D. Allan and J. Barnes, "A Modified 'Allan Variance' with Increased Oscillator Characterization Ability," 35th Annual Frequency Control Symposium, Philadelphia, 27-29 May, 1981). In our version of this technique, 2 consecutive frequency averages over N samples were generated by arithmetically averaging the first N consecutive samples and the next N consecutive samples. In general, arithmatic averages are not equivalent to the time averages normally used to generate the Allan variance. However, when the Allan fractional frequency deviate behaves as $\tau^{\varepsilon-\frac{1}{2}}$ where $\varepsilon >= 0$, a time average is equivalent to an arithmetic average of smaller time averages for computing variances. This is true for the hydrogen masers under consideration for averaging times of 100 seconds or greater (which can be verified a posteriori).

The first estimate for the sliding Allan variance is then created by squaring the difference between these two consecutive arithmetic averages and dividing by 2. Succesive Allan variance estimates are generated by sliding each of the 2 consecutive averages by one 1054-second data point and by similarly differencing, squaring, and dividing the data by 2. This process is carried out until there are no longer 1054-second data points to create successive averages. Then, all the estimates are averaged to produce a single estimate. In summary, the formula used is:

$$s_y^2(M) = \frac{1}{2N'M^2} \sum_{j=1}^{N'} \left(\sum_{i=j}^{M+j-1} y_i - \sum_{i=M+j}^{2M+j-1} y_i \right)^2 \tag{9}$$

where $N' = N-2M+1$ and M is the averaging time in multiples of the averaging time of the original data y_i.

The advantage of using the sliding Allan variance technique is that it produces a better estimate of the theoretical Allan variance, especially for small data samples. When the Allan fractional frequency deviate behaves as τ^{ε} where $\varepsilon <= -\frac{1}{2}$, the sliding technique produces a statistically better estimate for the same number of samples. When the Allan fractional frequency deviate behaves as τ^{ε} where $\varepsilon > -\frac{1}{2}$, the formal statistical advantage of the sliding variance tends to disappear, but the sliding variance still produces an estimate which is much more representative of an ensemble average for relatively small samples. For example, for quasi-periodic noise processes, the sliding variance averages over all phases of the process with a data sample only 3 times the quasi-period. Of course, one of the reasons this is true is that the sliding estimate technique is closer to the infinite time averaging used in theoretical definition of the Allan variance.

The conventional method for estimating the Allan variance yields a fractional error for the Allan deviate estimate given by:

$$\sigma(\sigma_y) / \sigma_y = 1 / (2^{\frac{1}{4}} \times F^{\frac{1}{2}}) \tag{10}$$

when the differences of the average frequencies used to compute the Allan variance are normally distributed. F is the number of degrees of freedom and is given by:

$$F = N_\tau - 1 \tag{11}$$

where N_τ is the number of average frequency samples used to compute the Allan variance. For the sliding average technique, (10) is used to define the number of degrees of freedom. For this technique, F is usually greater than it is for the conventional method. As a worst case it is:

$$F = T/\tau - 1 \tag{12}$$

where τ is the averaging time and T is the total elapsed time for the set of data. This worst-case value of F is used to estimate the errors of the sliding Allan variances computed in this report.

The results of a sliding Allan variance computation on the EFOS-2 versus NX-2 data, the NP-2 versus NX-3 data, and the derived EFOS-2 versus NP-2 data are shown in Table 4. Notice the anomalously high value in the derived EFOS-2 versus NP-2 data for 1054 seconds. This is an artifact of using a derived channel as opposed to a directly measured channel. Because the frequency averages of the differenced channels are not completely synchronized, the contribution of NX-3 to the data does not completely cancel. A residual term is left of the difference of the average fractional frequency offset of NX-3 of the same form as Equation 7. When the data points are averaged over N values, this NX-3 term acts like a white noise term because only fluctuations over 1054 seconds will contribute to the NX-3 difference. This means that the NX-3 contribution to Allan variance of the derived channel is reduced by 1/N for the longer averaging times. Because the EFOS and NP-2 contributions to the Allan variance stay the same or get worse as the averaging time is increased, the NX-3 contribution to the Allan variance very quickly becomes negligible.

A three-corner hat estimate of the Allan variance of each of the masers was run on the data. For averaging times greater than 52x1054 seconds, the estimated variance of NP-2 became negative.

Table 4. Long Term Allan Deviate Data (Page 1)

SLIDING ALLAN DEVIATE / SQUARE ROOT OF 2 SI3 DAT MAY 17,1983

DRIFT REMOVED. DRIFT PER POINT:EFOS-NX3=-.534234E-15 NP2-NX3= .112323E-16 EFOS-NP2=-.545467E-15

THE FRACT ERROR (FOR ALLAN DEVIATES) ASSUMES A NORMAL DISTRIBUTION FOR THE SIGMA'S

TAU IS IN UNITS OF 1054 SECONDS

FRACTIONAL FREQUENCY IN UNITS OF 1E-15

TAU	EF-NX	NP-NX	EF-NP	# OF PTS	DEG. OF FREEDOM
1	2.10793 +/- .143069	2.09486 +/- .142182	3.00632 +/- .204044	305	307
2	1.75399 +/- .168631	1.9443 +/- .186928	2.1796 +/- .20955	303	153
3	1.82084 +/- .214753	2.09442 +/- .24702	2.02016 +/- .238261	301	101.667
4	2.0336 +/- .277407	2.29682 +/- .313312	2.02169 +/- .275781	299	76
5	2.28238 +/- .348665	2.51577 +/- .38432	2.1203 +/- .323906	297	60.6
6	2.52812 +/- .423767	2.72954 +/- .45753	2.24133 +/- .375695	295	50.3333
7	2.75549 +/- .499714	2.94528 +/- .534134	2.38977 +/- .43339	293	43
8	2.96507 +/- .575807	3.14597 +/- .610937	2.54852 +/- .494915	291	37.5
9	3.15799 +/- .651559	3.32825 +/- .686688	2.69836 +/- .556727	289	33.2222
10	3.34015 +/- .727637	3.49733 +/- .761879	2.84156 +/- .619022	287	29.8
11	3.51369 +/- .804153	3.65052 +/- .835468	2.97533 +/- .680943	285	27
12	3.68018 +/- .881195	3.79223 +/- .908023	3.09852 +/- .74192	283	24.6667
13	3.83686 +/- .957841	3.92331 +/- .979423	3.20803 +/- .80086	281	22.6923
14	3.98876 +/- 1.03511	4.05063 +/- 1.05116	3.31042 +/- .859074	279	21
15	4.13822 +/- 1.11348	4.17005 +/- 1.12205	3.40194 +/- .915369	277	19.5333
16	4.2844 +/- 1.19266	4.28521 +/- 1.19288	3.49014 +/- .971559	275	18.25
17	4.42273 +/- 1.27124	4.39469 +/- 1.26318	3.57928 +/- 1.0288	273	17.1176
18	4.55728 +/- 1.35021	4.5001 +/- 1.33327	3.66526 +/- 1.08592	271	16.1111
19	4.68427 +/- 1.42833	4.59885 +/- 1.40228	3.75035 +/- 1.14355	269	15.2105
20	4.80369 +/- 1.5054	4.69418 +/- 1.47108	3.82917 +/- 1.2	267	14.4
21	4.90816 +/- 1.57886	4.78368 +/- 1.53882	3.90171 +/- 1.25511	265	13.6667
22	5.01872 +/- 1.65531	4.87057 +/- 1.60644	3.96858 +/- 1.30894	263	13
23	5.11455 +/- 1.72785	4.96459 +/- 1.67719	4.02778 +/- 1.36071	261	12.3913
24	5.19819 +/- 1.79703	5.05479 +/- 1.74746	4.08065 +/- 1.4107	259	11.8333
25	5.28595 +/- 1.86835	5.13743 +/- 1.81585	4.12859 +/- 1.45927	257	11.32
26	5.37226 +/- 1.93989	5.22301 +/- 1.88599	4.17392 +/- 1.50718	255	10.8462
27	5.43927 +/- 2.00506	5.30646 +/- 1.9561	4.21555 +/- 1.55396	253	10.4074
28	5.52094 +/- 2.07621	5.37622 +/- 2.02178	4.25535 +/- 1.60027	251	10
29	5.59414 +/- 2.1448	5.4594 +/- 2.09314	4.29095 +/- 1.64516	249	9.62069
30	5.66879 +/- 2.21455	5.52777 +/- 2.15946	4.3206 +/- 1.68787	247	9.26667
31	5.74315 +/- 2.2848	5.59785 +/- 2.227	4.343 +/- 1.72778	245	8.93548
32	5.80566 +/- 2.35088	5.66863 +/- 2.29539	4.35794 +/- 1.76465	243	8.625
33	5.86429 +/- 2.41582	5.74023 +/- 2.36471	4.36504 +/- 1.79819	241	8.33333
34	5.95293 +/- 2.49375	5.81504 +/- 2.43598	4.36542 +/- 1.82872	239	8.05882
35	6.03312 +/- 2.56893	5.88971 +/- 2.50787	4.35845 +/- 1.85585	237	7.8
36	6.10807 +/- 2.64258	5.95331 +/- 2.57562	4.34329 +/- 1.87907	235	7.55556
37	6.17938 +/- 2.71531	6.03346 +/- 2.65118	4.31938 +/- 1.898	233	7.32432
38	6.25898 +/- 2.79236	6.10064 +/- 2.72171	4.28675 +/- 1.91247	231	7.10526
39	6.33664 +/- 2.86928	6.16882 +/- 2.79329	4.24593 +/- 1.92259	229	6.89744
40	6.40457 +/- 2.94245	6.23208 +/- 2.86321	4.19737 +/- 1.9284	227	6.7
41	6.48038 +/- 3.01991	6.2822 +/- 2.92756	4.14031 +/- 1.92942	225	6.5122
42	6.54544 +/- 3.093	6.32846 +/- 2.99047	4.0759 +/- 1.92604	223	6.33333
43	6.61816 +/- 3.17034	6.3649 +/- 3.04902	4.00305 +/- 1.91761	221	6.16279
44	6.68526 +/- 3.24564	6.39212 +/- 3.10332	3.92389 +/- 1.90502	219	6
45	6.75824 +/- 3.32445	6.41746 +/- 3.15682	3.84089 +/- 1.88938	217	5.84444
46	6.83023 +/- 3.40347	6.4446 +/- 3.21131	3.75561 +/- 1.8714	215	5.69565
47	6.88502 +/- 3.47449	6.46241 +/- 3.26122	3.66794 +/- 1.85101	213	5.55319
48	6.98791 +/- 3.57058	6.48261 +/- 3.31239	3.58141 +/- 1.82998	211	5.41667

Table 4. Long Term Allan Deviate Data (Page 2)

49	7.05484 +/- 3.64916	6.50358 +/- 3.36402	3.49414 +/- 1.80737	209	5.28571
50	7.13807 +/- 3.73691	6.52584 +/- 3.4164	3.40926 +/- 1.78481	207	5.16
51	7.22447 +/- 3.82721	6.53951 +/- 3.46435	3.32292 +/- 1.76034	205	5.03922
52	7.30848 +/- 3.91711	6.56203 +/- 3.51704	3.24031 +/- 1.7367	203	4.92308
53	7.37322 +/- 3.99744	6.60697 +/- 3.58202	3.1646 +/- 1.71571	201	4.81132
54	7.45446 +/- 4.08746	6.63679 +/- 3.63912	3.09389 +/- 1.69646	199	4.7037
55	7.56465 +/- 4.19438	6.68071 +/- 3.70426	3.02892 +/- 1.67945	197	4.6
56	7.63961 +/- 4.28275	6.73419 +/- 3.77517	2.97431 +/- 1.66739	195	4.5
57	7.73541 +/- 4.38371	6.78108 +/- 3.84288	2.9298 +/- 1.66034	193	4.40351
58	7.82789 +/- 4.4838	6.82544 +/- 3.9096	2.89477 +/- 1.65812	191	4.31034
59	7.91684 +/- 4.58285	6.86818 +/- 3.97581	2.86824 +/- 1.66035	189	4.22034
60	7.98871 +/- 4.67287	6.9292 +/- 4.05313	2.85004 +/- 1.66709	187	4.13333
61	8.06663 +/- 4.76723	6.97077 +/- 4.1196	2.8402 +/- 1.67851	185	4.04918
62	8.15055 +/- 4.866	7.01618 +/- 4.18877	2.83712 +/- 1.69381	183	3.96774
63	8.21818 +/- 4.95588	7.04808 +/- 4.25026	2.84162 +/- 1.7136	181	3.88889
64	8.30867 +/- 5.06039	7.10503 +/- 4.32731	2.85164 +/- 1.73679	179	3.8125
65	8.40561 +/- 5.16988	7.13167 +/- 4.38634	2.86772 +/- 1.76379	177	3.73846
66	8.48788 +/- 5.27134	7.18721 +/- 4.46357	2.8888 +/- 1.79407	175	3.66667
67	8.54575 +/- 5.35842	7.23483 +/- 4.53643	2.91346 +/- 1.82682	173	3.59701
68	8.6321 +/- 5.46415	7.27138 +/- 4.60281	2.9408 +/- 1.86154	171	3.52941
69	8.71496 +/- 5.56863	7.30656 +/- 4.6687	2.97009 +/- 1.89781	169	3.46377
70	8.81218 +/- 5.68331	7.32661 +/- 4.72521	3.00101 +/- 1.93547	167	3.4
71	8.88111 +/- 5.78069	7.36958 +/- 4.79684	3.03285 +/- 1.97407	165	3.33803
72	8.97707 +/- 5.89661	7.40876 +/- 4.86646	3.06617 +/- 2.01402	163	3.27778
73	9.07213 +/- 6.01304	7.41982 +/- 4.91788	3.10131 +/- 2.05556	161	3.21918
74	9.14095 +/- 6.11304	7.43911 +/- 4.97492	3.13759 +/- 2.09827	159	3.16216
75	9.21439 +/- 6.21694	7.47925 +/- 5.04624	3.17587 +/- 2.14276	157	3.10667
76	9.32994 +/- 6.35037	7.49511 +/- 5.1015	3.21658 +/- 2.18935	155	3.05263
77	9.40487 +/- 6.45728	7.54822 +/- 5.18253	3.25896 +/- 2.23756	153	3
78	9.49614 +/- 6.5764	7.57685 +/- 5.24723	3.30264 +/- 2.28719	151	2.94872
79	9.60301 +/- 6.7075	7.60465 +/- 5.31169	3.3477 +/- 2.3383	149	2.89873
80	9.68228 +/- 6.82045	7.65131 +/- 5.38978	3.39275 +/- 2.38994	147	2.85
81	9.80774 +/- 6.96716	7.71666 +/- 5.48171	3.43782 +/- 2.44214	145	2.80247
82	9.87368 +/- 7.07277	7.7467 +/- 5.54916	3.48199 +/- 2.49424	143	2.7561
83	9.975 +/- 7.20474	7.79056 +/- 5.62696	3.52495 +/- 2.546	141	2.71084
84	10.0503 +/- 7.31903	7.82627 +/- 5.69939	3.56819 +/- 2.59849	139	2.66667
85	10.1614 +/- 7.46052	7.87791 +/- 5.78396	3.60988 +/- 2.65037	137	2.62353
86	10.2655 +/- 7.59819	7.90623 +/- 5.85194	3.65118 +/- 2.70248	135	2.5814
87	10.363 +/- 7.73228	7.95291 +/- 5.934	3.69207 +/- 2.7548	133	2.54023
88	10.455 +/- 7.86339	7.98266 +/- 6.00392	3.73272 +/- 2.80746	131	2.5
89	10.5524 +/- 7.99987	8.03221 +/- 6.08928	3.77296 +/- 2.86031	129	2.46067
90	10.6275 +/- 8.12051	8.0525 +/- 6.15292	3.81343 +/- 2.91385	127	2.42222
91	10.7415 +/- 8.27202	8.0785 +/- 6.22127	3.85398 +/- 2.96796	125	2.38462
92	10.8628 +/- 8.43073	8.11789 +/- 6.30039	3.89495 +/- 3.02292	123	2.34783
93	10.9364 +/- 8.55374	8.15367 +/- 6.37724	3.9354 +/- 3.078	121	2.31183
94	11.036 +/- 8.69814	8.1931 +/- 6.45748	3.97589 +/- 3.13364	119	2.2766
95	11.1176 +/- 8.82958	8.2363 +/- 6.54126	4.01776 +/- 3.19091	117	2.24211
96	11.2011 +/- 8.96363	8.27091 +/- 6.61879	4.05946 +/- 3.24858	115	2.20833
97	11.2934 +/- 9.106	8.31072 +/- 6.70102	4.10136 +/- 3.30697	113	2.17526
98	11.3656 +/- 9.23322	8.34605 +/- 6.78019	4.14485 +/- 3.36721	111	2.14286
99	11.4552 +/- 9.37571	8.39848 +/- 6.87389	4.1898 +/- 3.42922	109	2.11111
100	11.5417 +/- 9.51692	8.42375 +/- 6.94594	4.237 +/- 3.49369	107	2.08
101	11.6259 +/- 9.65742	8.49742 +/- 7.05863	4.28593 +/- 3.56023	105	2.0495
102	11.7058 +/- 9.79547	8.52227 +/- 7.13148	4.33567 +/- 3.62811	103	2.01961
103	11.8096 +/- 9.95484	8.57978 +/- 7.23228	4.38746 +/- 3.69839	101	1.99029
104	11.8901 +/- 10.0959	8.63914 +/- 7.3355	4.44066 +/- 3.77057	99	1.96154
105	11.9842 +/- 10.2497	8.69318 +/- 7.43503	4.49524 +/- 3.84465	97	1.93333
106	12.1019 +/- 10.4253	8.7492 +/- 7.53708	4.55044 +/- 3.92002	95	1.90566
107	12.219 +/- 10.602	8.80988 +/- 7.64401	4.60669 +/- 3.99706	93	1.8785
108	12.3017 +/- 10.7503	8.86616 +/- 7.748	4.66391 +/- 4.07572	91	1.85185

Table 4. Long Term Allan Deviate Data (Page 3)

109	12.3846 +/- 10.9	8.93225 +/- 7.8615	4.72199 +/- 4.15594	89	1.82569
110	12.4894 +/- 11.0704	8.95919 +/- 7.94127	4.7808 +/- 4.23762	87	1.8
111	12.6044 +/- 11.2514	9.00835 +/- 8.04139	4.83962 +/- 4.32014	85	1.77477
112	12.6885 +/- 11.4064	9.04995 +/- 8.13551	4.89848 +/- 4.40352	83	1.75
113	12.8043 +/- 11.5914	9.0841 +/- 8.22359	4.95595 +/- 4.48648	81	1.72566
114	12.8834 +/- 11.7447	9.12727 +/- 8.32051	5.0133 +/- 4.57017	79	1.70175
115	12.9744 +/- 11.9101	9.14547 +/- 8.39525	5.06754 +/- 4.65184	77	1.67826
116	13.044 +/- 12.0572	9.17077 +/- 8.47699	5.12011 +/- 4.73276	75	1.65517
117	13.1491 +/- 12.2386	9.19203 +/- 8.5555	5.16968 +/- 4.81169	73	1.63248
118	13.2481 +/- 12.4158	9.20984 +/- 8.63125	5.21568 +/- 4.88802	71	1.61017
119	13.3342 +/- 12.5825	9.23348 +/- 8.71296	5.25817 +/- 4.96175	69	1.58824
120	13.4189 +/- 12.7493	9.24567 +/- 8.78431	5.29589 +/- 5.03163	67	1.56667
121	13.4779 +/- 12.8929	9.26806 +/- 8.8658	5.33127 +/- 5.09988	65	1.54545
122	13.5928 +/- 13.0915	9.27917 +/- 8.93697	5.36398 +/- 5.16617	63	1.52459
123	13.6653 +/- 13.2508	9.30997 +/- 9.0276	5.39422 +/- 5.23062	61	1.50407
124	13.742 +/- 13.4156	9.31461 +/- 9.09336	5.42163 +/- 5.29284	59	1.48387
125	13.8064 +/- 13.5697	9.31059 +/- 9.15091	5.44668 +/- 5.35326	57	1.464
126	13.8906 +/- 13.7445	9.31682 +/- 9.21881	5.46923 +/- 5.41169	55	1.44444
127	13.9356 +/- 13.8818	9.31479 +/- 9.27883	5.4915 +/- 5.4703	53	1.4252
128	13.9914 +/- 14.0309	9.32116 +/- 9.34752	5.51221 +/- 5.52779	51	1.40625
129	14.0502 +/- 14.1843	9.29337 +/- 9.38208	5.53197 +/- 5.58477	49	1.3876
130	14.1114 +/- 14.3413	9.26815 +/- 9.41916	5.5513 +/- 5.64175	47	1.36923
131	14.1437 +/- 14.4701	9.24788 +/- 9.46125	5.56845 +/- 5.69693	45	1.35115
132	14.1747 +/- 14.5983	9.2042 +/- 9.47925	5.57957 +/- 5.7463	43	1.33333
133	14.2126 +/- 14.7346	9.17409 +/- 9.51102	5.58633 +/- 5.7915	41	1.31579
134	14.2182 +/- 14.8381	9.14532 +/- 9.54409	5.59055 +/- 5.83431	39	1.29851
135	14.2661 +/- 14.9867	9.10666 +/- 9.56666	5.59587 +/- 5.87854	37	1.28148
136	14.2666 +/- 15.0863	9.056 +/- 9.57633	5.59886 +/- 5.92055	35	1.26471
137	14.3008 +/- 15.2223	9.01283 +/- 9.59359	5.5999 +/- 5.96073	33	1.24818
138	14.3063 +/- 15.3285	8.96581 +/- 9.60643	5.59753 +/- 5.99748	31	1.23188
139	14.2808 +/- 15.4019	8.92941 +/- 9.6304	5.5992 +/- 6.03875	29	1.21583
140	14.2835 +/- 15.5061	8.88724 +/- 9.64792	5.599 +/- 6.07823	27	1.2
141	14.255 +/- 15.5767	8.8398 +/- 9.65943	5.59543 +/- 6.11424	25	1.1844
142	14.2416 +/- 15.6641	8.8264 +/- 9.70803	5.59234 +/- 6.15094	23	1.16901
143	14.2144 +/- 15.7366	8.78392 +/- 9.7246	5.59319 +/- 6.19217	21	1.15385
144	14.215 +/- 15.8403	8.73804 +/- 9.73713	5.59618 +/- 6.23604	19	1.13889
145	14.2064 +/- 15.9343	8.69331 +/- 9.75063	5.60079 +/- 6.28199	17	1.12414
146	14.1795 +/- 16.008	8.66588 +/- 9.78339	5.60768 +/- 6.33082	15	1.10959
147	14.1986 +/- 16.1342	8.64892 +/- 9.828	5.61985 +/- 6.38598	13	1.09524
148	14.1927 +/- 16.2327	8.62932 +/- 9.86972	5.63501 +/- 6.445	11	1.08108
149	14.243 +/- 16.3966	8.63165 +/- 9.93678	5.6674 +/- 6.52433	9	1.06711
150	14.3506 +/- 16.6281	8.68053 +/- 10.0582	5.71935 +/- 6.62706	7	1.05333
151	14.607 +/- 17.0356	8.82805 +/- 10.2958	5.82804 +/- 6.79702	5	1.03974
152	15.2832 +/- 17.9404	9.23091 +/- 10.8358	6.10738 +/- 7.16922	3	1.02632
153	18.61 +/- 21.9879	11.2397 +/- 13.2799	7.44906 +/- 8.80114	1	1.01307
154	0 +/- 0 0 +/- 0	0 +/- 0 -1	1		

In this regime, the EFOS-2 versus NP-2 data is about half that of the other data channels. It is obvious that both EFOS-2 and NP-2 are more stable than NX-3 unless EFOS-2 and NP-2 are moving up and down in frequency together. Under these conditions, it is apparent that the three-corner hat method amplifies the small differences between the EFOS-2 versus NX-3 data and the NP-2 versus NX-3 data beyond that which is statistically significant. We have therefore decided that using the three-corner hat data would be misleading. Instead we recommend that, as a best estimate of EFOS-2's stability:

1. the EFOS-2 versus NX-3 data be used from 1x1054 to 3x1054 seconds.

2. the EFOS-2 versus NP-2 data be used beyond 3x1054 seconds.

BEST ESTIMATE OF EFOS-2 STABILTY

Figure 6 shows our best estimate of EFOS-2's fractional frequency stability from 1.054 seconds to 153x1054 seconds. For 1 to 100 seconds the short-term stability estimates of EFOS-2 versus NX-3 are used. For 1054 to 3x1054 seconds the long-term data of EFOS-2 versus NX-3 are used . Beyond 3x1054 seconds, the long-term data of EFOS-2 versus NP-2 are used.

FREQUENCY DRIFT OF THE MASERS

The relative drifts of the masers derived from the long-term data are shown in Table 5.

Table 5. Relative Frequency Drift of the Masers over 3.75 Days:

EFOS-2 vs NX-3	$= -4.4(20)\times10^{-14}$/day
NP-2 vs NX-3	$= 0.1(20)\times10^{-14}$/day
EFOS-2 vs NP-2	$= -4.5(28)\times10^{-14}$/day

During the period from January 14, 1983 to March 18, 1983 NP-2 was monitored relative to UTC(USNO) via LORAN-C, portable clock, television line 10, and GPS receiver. A quadratic fit of the data yields a frequency drift rate relative to UTC(USNO) of $-6.55(8)\times10^{-15}$/day. Using this value and the previous data, the frequency drifts of the 3 masers relative to UTC(USNO) over the 3.75 day measurement period were calculated. The results of this calculation are shown in Table 6.

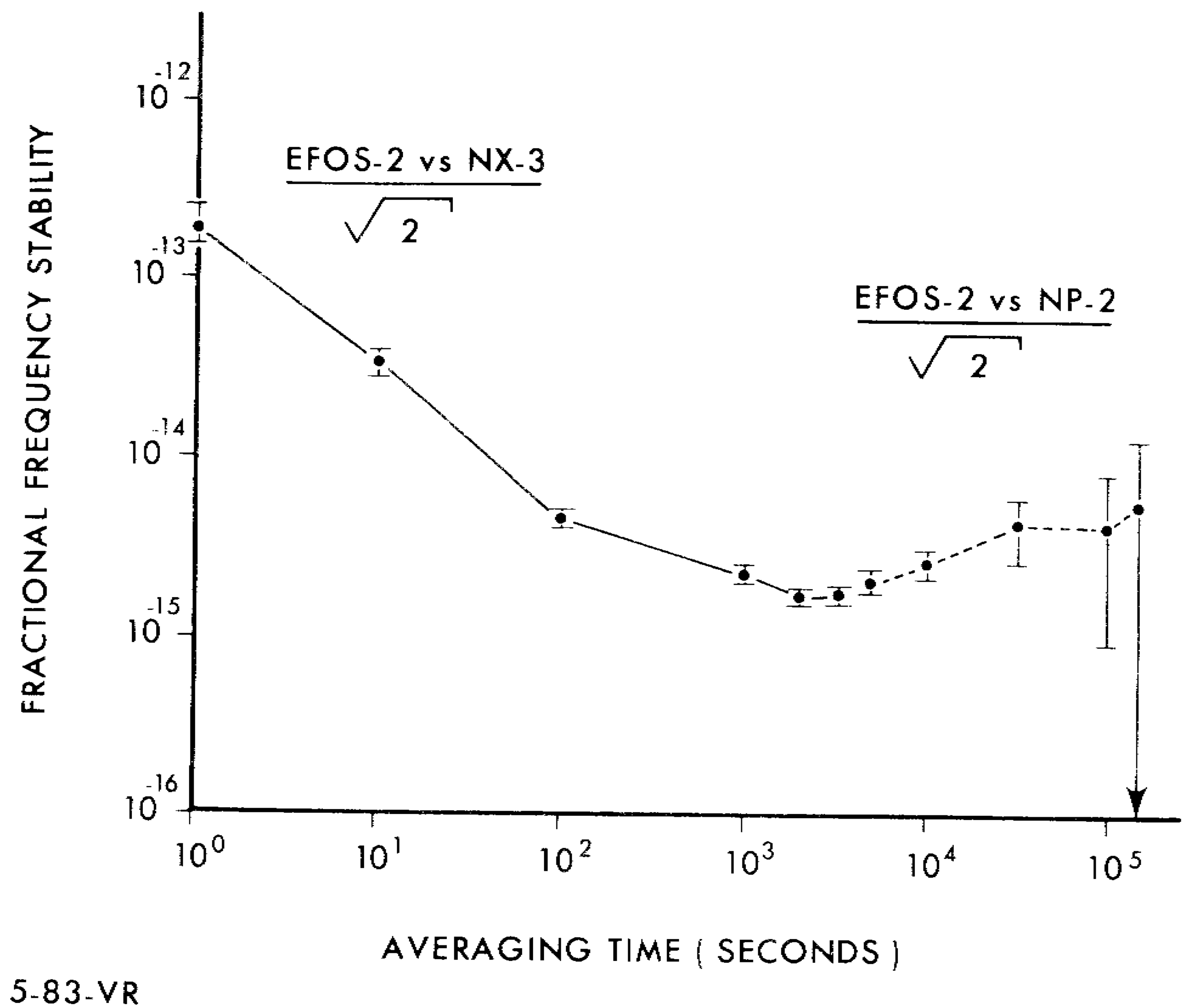

Figure 6. Best Estimate of EFOS-2 Frequency Stability

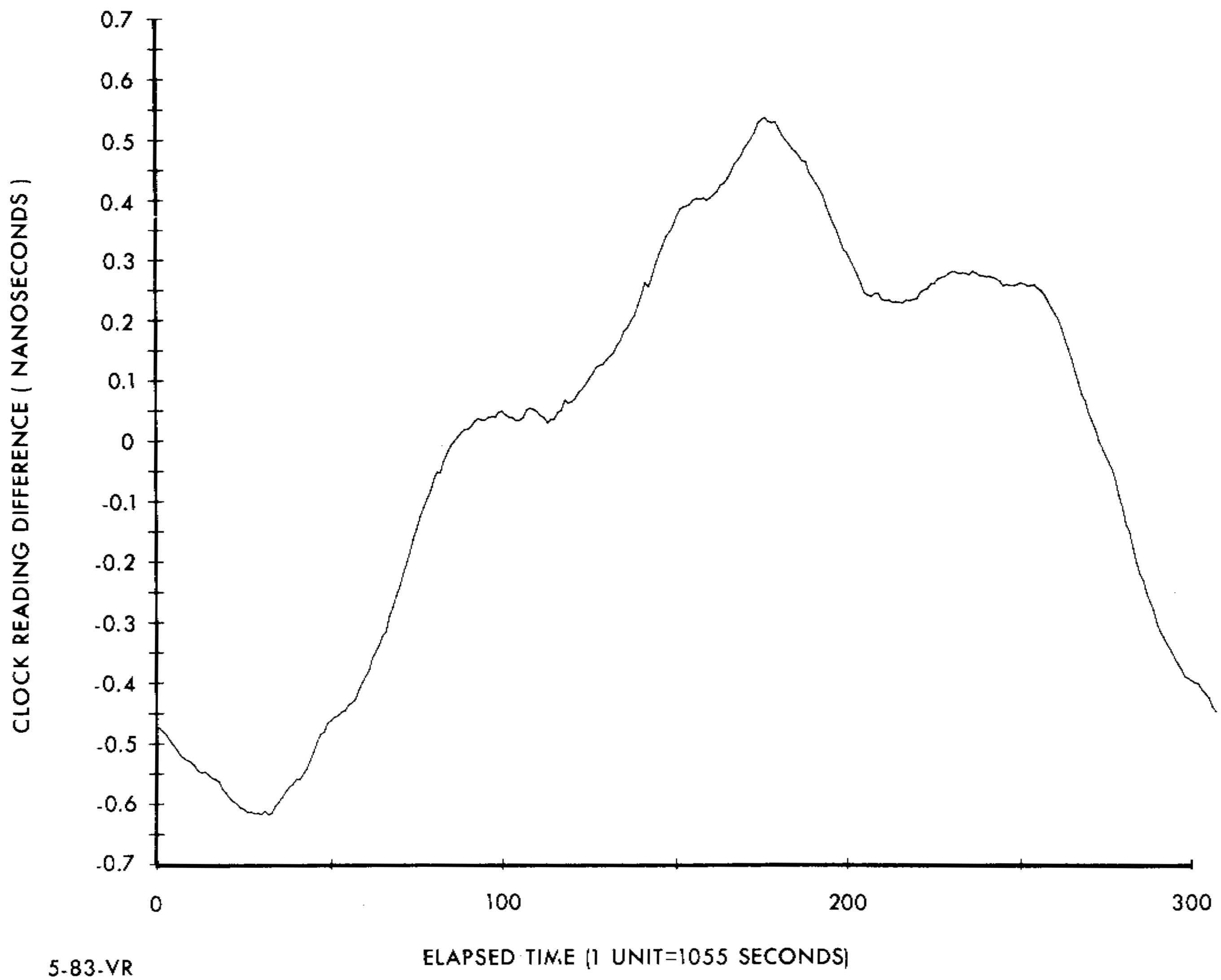

Figure 7. Clock Reading Difference Between EFOS-2 and NP-2 Over 3.75 Days with Average Clock Reading, Frequency Offset and Frequency Drift Removed

Table 6. Frequency Drifts of the Masers Relative to UTC(USNO):

$$\text{EFOS-2 vs UTC(USNO)} = -5.1(29)\times10^{-14}/\text{day}$$

$$\text{NP-2 vs UTC(USNO)} = -6.55(8)\times10^{-15}/\text{day}$$

$$\text{NX-3 vs UTC(USNO)} = -0.7(22)\times10^{-14}/\text{day}$$

PREDICTED LONG-TERM GROUP DELAY RESIDUALS

Clock reading difference (ϕ/ω_0) data between EFOS-2 and NP-2 can be generated by numerically integration the derived EFOS-2 versus NP-2 fractional frequency offset data. The results of this integration are shown plotted in Figure 7 with a quadratic function of time removed (average clock reading, frequency offset, and frequency drift removed). This figure also represents a prediction of the expected group delay residuals from a 3.75-day VLBI run using EFOS-2 and NP-2 when both are in thermal chambers.

One day residuals were determined from the clock reading data by fitting out a quadratic function of time from one day sections of data randomly chosen out of the 3.75 days of data. The results of 11 such random samples are:

Table 7. Predicted One Day Group Delay Residuals with Quadratic Polynomials Removed

RMS RESIDUAL = 83(50) ps

QUESTIONS AND ANSWERS

MR. WALLS:

Fred Walls, N.B.S. Victor, I don't understand how you get eleven data points from three-and-a-half days worth of data. They are certainly not independent and to do RMS on that gives a very misleading answer if you are trying to say you have 83 picoseconds. I don't believe it.

MR. REINHARDT:

No, they are not independent and the purpose of picking 11 points is to make them not independent.

MR. WALLS:

What do you mean, you only have three and one-half days worth of data, how can you get 11 - you can take different sets.

MR. REINHARDT:

What we attempted to do there in picking more than three samples, from three-and-a-half days of data is to randomize the starting point of the data relative to the data, its equivalent to doing the modified Allan variance. When you have data with very strong correlations, if you pick a certain starting point, your data is very susceptible to the phase of any fluctuation relative to your starting point; and to get a better measurement of the average data over that period, what we did, we took random samples of uncorrected data, perform the one day fit.

MR. WALLS:

Yes, but I think that's only reasonable if you say its stationary and its white, and you can't prove that either is true on such a short data set. I don't think it is a reasonable analysis.

MR. REINHARDT:

No. The error bars are just recorded there. We didn't take the fluctuations for 11 points and divide them by the square root of n.

MR. WARD:

Have you any idea about what the coupling mode was?

MR. REINHARDT:

Coupling mode for what?

MR. WARD:

Why was it correlated?

MR. REINHARDT:

What we are talking about is, if you take one day samples out of three-and-a-half days' data, and take more than three-and-a-half samples, it will overlap in the samples. The data is correlated, but the method I am using here, is equivalent to using the modified Allan variance, you are getting better use of your data by basically sliding your one day sample across your measurement interval rather than taking successive samples. And what I found in these long term data with very low frequency terms you have to be extremely careful because, by chance, you may just pick a phase of the data such that your errors cancel. I haven't been able to quantify this yet; but I think Dave Allan has done some work on this. I have better confidence in the sliding Allan variance for data that is non-stationary than I do with the conventional way of taking the Allan variance because of the sliding method. It averages over all phases of these random patterns much better. I haven't found a way to quantify that, but it produces a better result and it's more typical of an average result.

MR. ALLAN:

Dr. Barnes has gone through and looked at that quite carefully, and in fact, you do gain quite a bit by the overlapping estimate as it is sometimes called. I think I understand what you are doing, Victor. And the only problem I have with it is that what we are addressing is a non-white process for the VLBI people. It's their need, they want coherance over the tracking time. I think you just have to do what you have to do to satisfy their need. It's a very reasonable approach.

MR. REINHARDT:

Basically they are using a statistic that is meant for stationary processes to describe a non-stationary process. They want the result of the RMS residual of a one-day run. That's what they want to know. So what we are doing by picking random samples, we just didn't have an algorithm at that point to slide things over. It's equivalent to the sliding Allan variance. It's equivalent to taking a least squares fit at the start of the data, getting an estimate for the residual after doing only a one-day fit on the data, and then sliding the data, and just averaging this fit. It certainly gives you no worse result than taking sequences, and I have confidence that this gives a better result. Mathematically for flicker of frequency noise or worse it gives you no better result. But I have better confidence that it is more typical of an average error than if I had just taken three samples out of the data.

MR. KUHNLE:

JPL. Victor, what do you think the temperature coefficient might have been on the maser if the air flow had been considerably lower, like in a room?

MR. REINHARDT:

All I can do is quote what I've been told. Oscilloquartz people told me they got on the order of 5 in 10^{14} in Switzerland. They remeasured that at NRAO and got on the order of 6 in 10^{14} per ^{o}C. Maybe the Oscilloquartz people want to speak for themselves at this point.

MR. BUSCA:

Oscilloquartz. The temperature coefficient is something which should be defined in a more accurate way, in the sense that the data you get depends on how you measure the temperature coefficient itself. We make the test simply by raising the room temperature by 1^{o}C, in a similar way is doing Bob VEssot, and we measured before shipping the maser a value of $10^{-14}/^{o}$C. That was the last measured value. When we talk about a maser with an aluminum cavity as we are, people immediately said "This is not for a maser, because there is a problem of frequency sensitivity with temperature." We feel that if you put the maser in a big room and change the total room temperature by 1^{o}, the time constant is on the order of 12 hours of the maser, and the final temperature coefficient under this condition is on the order of $2x10^{-14}/^{o}$C.

DR. WINKLER:

I think this is very true, and in other words. Temperature coefficients of such systems are senseless and should not be specified in this way. What you should give is the step response of the system. The step response is a transient which may end without any displacement of the frequency after 24 hours or 36 hours. The question of the step response, one should measure it differently. By making a single step, you depend on air temperature, air flow, heat conduction and all of these things. What we should do. Expose the maser to a psuedo-random sequence of temperature changes + and - one degree and after 3 to 5 weeks you cross-correlate. Then the random variations will be suppressed and systematic. The effect of the temperature will be available and you get a very clean step response to temperature. The simple temperature coefficient as it is usually given is too simplistic a concept and leads into trouble.

MR. REINHARDT:

What muddies the water even further, is that we are dealing with non-stationary noise processes and these wall coefficients assume these things are reproducible. The problem in the lab is that when you make the measurements, they are not reproducible. When the device does not return to the same frequency, what do you do? There are other cases like the barometric pressure coefficient. You get two coefficients , an adiabatic and an isothermal, because depending on how fast the pressure is changed, you get different results. We have definitely seen these effects in masers. JPL saw this as a secondary temperature effect. This problem of coefficients is much more suited to devices which are stationary. It's a problem we have to live with.

DR. VESSOT:

I want to clear the record. We put our equipment in a box which we made out of rather poor insulating material and we have a rather substantial fan blowing the air within the box for the tests to make sure we do not have temperature gradients from above and below. This is a blower of considerable size, not a casual motion to the air.

The question of coefficient: it is clear that there are many things that will move. We have found that if we make a sudden step temperature change which we use in an attempt to diagnose what is going on, that in the early phases of the change, we see a change in frequency which moves rather rapidly and has a plus sign. We associate that with a phase change within the receiver system itself. And then there is a very long change carried on for 6 to 8 hours, which we think is effecting the maser itself. The comments by Dr. Winkler as a manner of getting through the noise, a matter of coherency detection, is clearly the only way to get through it. But, I must recommend that these step sizes be long enough to represent the long-term stationary end point behavior of the maser. This is one manner of describing it. If, on the other hand, we are in a room where the temperature fluctuates rather rapidly, then this other term will depend on it. So I think you have to set up sort of a Green's function approach, to say what is the response, and then you go and ask what is the stimulus of the room and then follow through that. It is not easy to do. The best thing to do is make them as immune as possible and stop worrying.

MR. PETERS:

A comment, that has not been properly brought out yet. The thermal control system, the thermal gain is highly dependent upon the insulation quality-conductivity. This is highly dependent on air flow when you are talking about atmospheric conduction and convection. Your time constant is actually a measure of the change in thermal conductivity which you have created and which changes your nominal thermal gain. So that it points out that one probably wants to use a minimal of air flow or at least something typical of the situation where you are going to use the maser.

If you put a rapid flow in, you are throwing in rapid and untypical changes. You are also changing the actual value because the thermal gain depends on this very strongly. In this case it could be a factor of 2 or something like that.

MR. REINHARDT:

A comment on what Bob Vessot said. You can see in this data, unfortunately we had to truncate it because we were under a time limit. I would love to let the maser sit here for 3 days. There were clearly 2 time constants here and that further complicates the issues, especially in hydrogen masers. You get short time constants, long time constants, the coefficients in some masers cancel, they add in others and you clearly, if you do this right, you have to do what Dr. Winkler does, but even more so than a step change, probably a square wave function and sweep the changes. You have to fully characterize the response.

DR. WINKLER:

Excuse me. I did not make myself clear. You expose the maser to a psuedo-random sequence of steps and they contain, or should contain all frequencies, even very low ones, so you are picking up the transient response of the system, which includes the response to all frequencies. That is the only way to describe a system response, properly.

MR. REINHARDT:

I see, you make random steps in time.