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NASA TM X- 70579

# CHARACTERISTICS OF ADVANCED HYDROGEN MASER FREQUENCY STANDARDS

HARRY E. PETERS

(NASA-TM-X-70579) CHARACTERISTICS OF ADVANCED HYDROGEN MASER FREQUENCY STANDARDS (NASA) 34 p HC $3.75 CSCL 20E
N74-16191
Unclas
G3/16 28986

DECEMBER 1973

GSFC

GODDARD SPACE FLIGHT CENTER
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## ABSTRACT

Measurements with several operational atomic hydrogen maser standards have been made which illustrate the fundamental characteristics of the maser as well as the analysability of the corrections which are made to relate the oscillation frequency to the free, unperturbed, hydrogen standard transition frequency.[1,2,3] Sources of the most important perturbations, and the magnitude of the associated errors, are discussed. A variable volume storage bulb hydrogen maser is also illustrated which can provide on the order of 2 parts in $10^{14}$ or better accuracy in evaluating the wall shift.[4,5] Since the other basic error sources combined contribute no more than approximately 1 part in $10^{14}$ uncertainty, the variable volume storage bulb hydrogen maser will have net intrinsic accuracy capability of the order of 2 parts in $10^{14}$ or better. This is an order of magnitude less error than anticipated with cesium standards[6,7], and is comparable to the basic limit expected for a free atom hydrogen beam resonance standard.[8]

Since 1966 research has been undertaken at Goddard Space Flight Center to realize advanced time and frequency standards based upon atomic hydrogen. Four prototype (NP) hydrogen masers were developed early in the program, and these have since demonstrated remarkable stability, intrinsic accuracy, and longevity in many diverse applications.[9,10,11] Based upon further research, two new and improved hydrogen maser standards, NX-2 and NX-3, have more recently been constructed. Measurements have been in progress for several months with the new masers, and new measurements and experiments have also been performed with the older masers. A good deal of operational data is now available which illustrates the improvements anticipated in the new units, and the data on all units further illustrates some of the remarkable characteristics of hydrogen masers, both old and new. Stabilities well into the $10^{-15}$ range, insensitivity to magnetic perturbations or other pulling effects, and longevity expectations of many decades, are some of the characteristics illustrated.

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## I. INTRODUCTION

Amongst the growing family of frequency standard devices based upon the atomic hydrogen hyperfine transition, the field operational hydrogen maser is the most stable as well as the most fundamental device presently used for time and frequency control for general applications. (Other atomic hydrogen devices: hydrogen beam,[8,12] passive "Big Box" maser,[5] variable volume maser[5,28].) In conjunction with the other laboratory atomic standard devices, the hydrogen maser is also an exceptionally precise and versatile tool for laboratories responsible for maintenance of basic standards or for their utilization.[13,11]

There are seven continuously operating Goddard Space Flight Center (GSFC) hydrogen masers at present, and six of these are being used at GSFC at this time. Four of the seven masers are the NASA prototype masers (NP-1, NP-2, NP-3, NP-4). They were built at Goddard in 1968 and 1969, and have been used extensively since then in a variety of applications.[3,11] NP-3, the only one of these units not at GSFC, is at the Onsala, Sweden, space observatory, where it has been used in various Very Long Baseline Interferometry (VLBI) experiments since March, 1973.[18] Of the other three masers at Goddard, one is an older experimental maser, NX-1, which first oscillated in 1967, and the other two masers are two new experimental units, NX-2 and NX-3. The two new masers have been oscillating for about two months, and while some of the external electronics have yet to be completed, there is presently available operational data which illustrates several significant improvements which have been made in the new design. New measurements have also been in progress for several months with the NP masers, and thus we now have much new experimental data which illustrates some of the remarkable characteristics of both the old and the new hydrogen masers.

However, before discussing data on performance, a brief review of hydrogen maser principles would be appropriate.[19,2] This will provide the basis for a short discussion of the important fundamental perturbations to the maser oscillation frequency, which much of the later data will relate to.

## II. FUNDAMENTAL CORRECTIONS

The atomic hydrogen maser is basically a very simple device. As illustrated in Figure 1, molecular hydrogen enters the source on the left, where it is dissociated into atoms of hydrogen by an RF discharge. Neutral atoms of hydrogen emerge from this source in a beam which then passes through a magnetic state

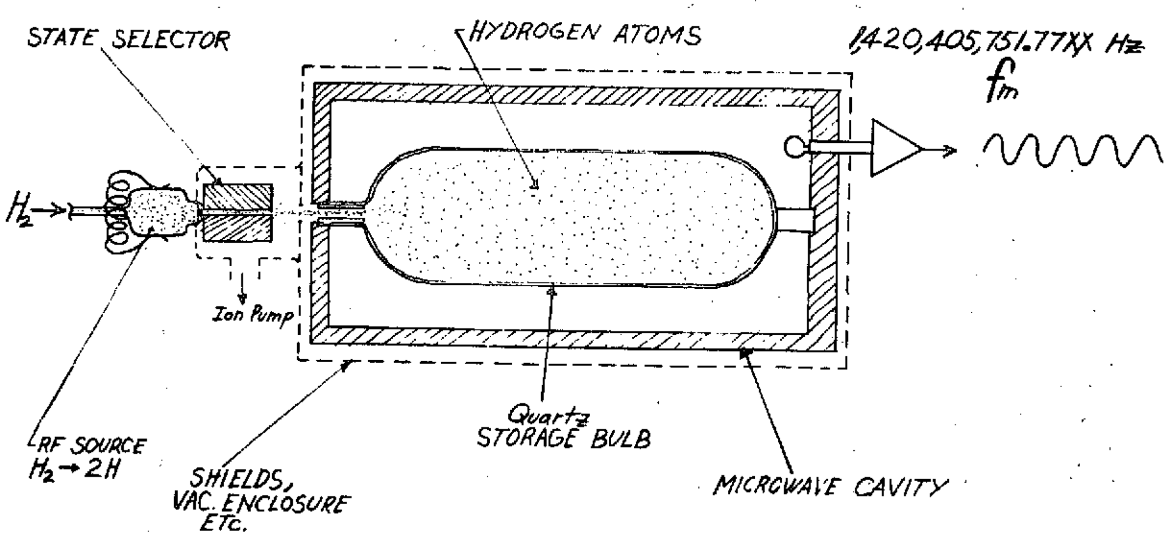

Figure 1. Atomic Hydrogen Maser Schematic

selector. In the state selector, undesired lower energy state atoms are defocussed — they are separated from the beam and pumped away. The higher energy state atoms, still in the beam, pass into a large quartz storage bulb. The bulb is located within a microwave cavity, and due to maser action, the atoms give up energy and produce a coherent output signal at the frequency of 1,420,405,751.77XX Hz.[10] To complete an actual hydrogen maser frequency standard, there are also, of course, a vacuum enclosure, magnetic and thermal shields, magnetic field coils, a thermal control system, amplifiers, synthesizers, and so forth.

But not to neglect a small, though very important detail, it must also be mentioned that the wall, that is, the inside surface of the quartz storage bulb, is coated with FEP teflon; this teflon is carefully sintered to the inside surface of the bulb at high temperature and under high vacuum. The hydrogen atoms bounce off the teflon wall with very little exchange of energy, and as we shall see later, there is therefore very little change in the output frequency due to the wall.[14,15,16,17,20] Fortunately hydrogen atoms do not attack, or chemically react, with teflon, and as everyone knows, teflon is extremely unreactive and non-sticky for most all common chemicals, so that under the high vacuum conditions of operating hydrogen maser frequency standards, the inherent physical properties of the wall surface are preserved rather indefinitely.

As you examine the things that happen to an atom as it passes into the maser storage bulb, and finally, after a second or so re-emerges and is pumped away, a good picture of the fundamental forces that disturb (or perturb, as we say) the oscillation frequency is easily visualized. Figure 2 shows the most significant perturbations.

$$f_m = f_o + \underline{\Delta f_D} + \underline{\Delta f_{C-SE}} + \underline{\Delta f_H} + \underline{\Delta f_W}$$

$f_m \equiv$ Maser Oscillation Frequency   $f_o \equiv$ Unperturbed Transition Frequency

| PERTURBATIONS | EQUATION | OPERATING OFFSET | ERROR |
|---|---|---|---|
| Special Relativity Time Dilation | $\underline{\Delta f_D} = -\frac{v^2}{2c^2} f_o$ | $4.5 \times 10^{-11}$ | $\epsilon < 10^{-14}$ |
| Cavity & Spin Exchange Pulling | $\underline{\Delta f_{C-SE}} = (K_c \Delta f_c - \alpha_{SE}) \Delta\nu_l$ | $0$ | $\epsilon < 10^{-14}$ |
| Magnetic Field | $\underline{\Delta f_H} = K_H H^2$ | $1 \times 10^{-12}$ | $\epsilon < 10^{-14}$ |
| Wall Reflection Phase Shift | $\underline{\Delta f_W} = \frac{C_w A}{V}(1 - \alpha_f \Delta T)$ | $2 \times 10^{-11}$ | $? < \epsilon < 2 \times 10^{-12}$ |

Figure 2. Most Significant Correction Factors to the Hydrogen Maser Frequency

The atom has a velocity, so there is a Doppler shift. It is, however, only the special relativity time dilation effect. The atomic clock of the traveling hydrogen atom runs slower than such a clock would if stationary in our observers laboratory. There is no first order Doppler shift in hydrogen masers, since the average velocity of the atom is very effectively zero with respect to the standing wave phase in the maser cavity. The Doppler correction is given by $\Delta f_D$ (the first equation in Figure 2). This correction is by far the largest correction to the hydrogen maser frequency. It is actually $4.5 \times 10^{-11}$. But, it is also the easiest perturbation to correct for, since the velocity depends precisely on the temperature, and a measurement accurate to only .07°C is adequate to bring the Doppler error below one part in $10^{14}$. In typical hydrogen masers, we are dealing with temperature stabilities measured in microdegrees per day, so the Doppler effect has no effect on stability, or reproducibility either, and will not be discussed further in this paper.

The second perturbation, $\Delta f_{C-SE}$, is the result of both cavity pulling and spin-exchange pulling.[21] Both cavity pulling and spin-exchange are proportional to the atomic line width. This is given by $\Delta\nu_\ell$ in the second equation. The line width can be changed very quickly and easily in hydrogen masers by changing the density of atoms in the storage bulb. Many publications describe automatic (as well as manual) systems for correcting for cavity and spin-exchange pulling.[22,23,24,3] Later, some data will be presented showing the effect of one such "Auto Tuner" on maser stability.

The actual operating offset due to cavity and spin exchange pulling is zero when tuned, and the absolute error is less than one part in $10^{14}$. However, in certain operational situations there can be small uncorrected random variations in cavity frequency which effect maser stability, as shall be seen later.

The third perturbing factor shown in Figure 2 is $\Delta f_H$ — this is the variation of maser frequency with applied internal magnetic field. $\Delta f_H$ is a quadratic effect, so magnetic instabilities become very small as the field is reduced towards zero. (See Appendix $I_g$ for more details on field inaccuracy effects.) Hydrogen masers operate at extremely small values of magnetic field. The two new experimental masers oscillate well at fields below 10 microgauss, and the older NP units can go lower than 30 microgauss. At typical operating fields of 700 microgauss, the entire magnetic correction is only $1 \times 10^{-12}$, and the field can be measured or set with extremely great accuracy by using Zeeman frequency measurements.[2,25] One part in $10^{14}$ is simple to do. Later, some curves are given which illustrate the precision of the magnetic correction, as well as the stability of the field over long periods of time. One of the most important points for users of hydrogen masers is that these field measurements can be made simply and quickly without disturbing the output phase or frequency significantly.

The last factor shown is the wall shift, given by $\Delta f_W$. The wall shift varies precisely with the surface to volume ratio (A/V) of the storage bulb (see Appendix $I_a$). It also varies slightly with temperature — this is given by $\alpha_T \Delta T$; but the temperature factor is less than 1% of the total, and creates no problem, so only the surface to volume factor need be discussed. The total wall shift is typically 2 parts in $10^{11}$ in oscillating hydrogen masers[10] (NASA NX and NP masers). However, one special design "Big Box" experimental maser device, which was conceived by scientists at Harvard University,[4,5] has a wall shift a factor of 10 smaller, approximately 2 parts in $10^{12}$. It is very fortunate that the wall shift is not a large effect, since then it does not really take a very precise experiment to determine the offset accurately. In the past, the main method of determination has been to operate the maser with bulbs of different volumes, and by doing this many research laboratories[13,14,15,16,17,20] have published accuracies of better than 2 parts in $10^{12}$.

## III. HOW FREE IS THE HYDROGEN ATOM?

Since the wall shift is so important for metrology, as well as for understanding the methods for making good hydrogen maser time and frequency standards with long term stability and uniformity, it is important to examine in more detail the conditions under which an atom exists within the maser storage bulb. An important question, it is clear, is "how FREE is the atom?" And also, how scientifically understandable are the methods for determining wall shifts? That is the theme of Figure 3. Here we have a 5.5 liter bulb. The atom enters the bulb with a velocity of 2.6 kilometers per second, bounces around approximately 20,000 times, and after a second or so departs. The average distance traveled between wall bounces is 12 cm. The atom also collides about 50 times with hydrogen molecules, which has negligible effect on the frequency,[26] and about 4 times with other hydrogen atoms. The latter results in the spin-exchange correction, with a very small frequency shift effect which is accurately corrected for by auto-tuning, as discussed previously. Only when the atom is within about 1 Å ($10^{-8}$ cm) of the wall is there any appreciable energy exchange or perturbation, so the total disturbed path length is 2 Å per collision. The ratio of perturbed path length to free flight path length is therefore one part in $10^9$.

Consider the diagram in the center of Figure 3. The total free path distance, in free fall, within an ultrahigh vacuum environment, is 2 kilometers; that is over one mile, while the total disturbed path distance is $2 \times 10^{-4}$ cm. So one of the most appropriate visualizations of the hydrogen maser, is that it is equivalent to a free atom beam tube over a mile long between disturbing interactions with the fields at the ends. You can, if you will, compare the end fields (the walls, that is) to the RF fields, the phase shifts, and other mode fields or misalignment problems, etc., encountered in some atomic beam resonance standards, where the disturbed path length is the half wavelength of a 10 GHz transition,[13,6,7] 1.5 cm, compared to $2 \times 10^{-4}$ cm for hydrogen.

That is really a very good analogy — and this picture also illustrates why the other perturbations, magnetic fields, temperature, etc., are so small with hydrogen masers; this one mile hydrogen beam tube is folded over and entirely contained within the volume of a single mode cavity, so that the magnetic and RF fields are effectively identical over the entire one mile distance. A single magnetic field measurement on a maser establishes the field value over the entire path. People working with cesium beam basic standards, where many Zeeman coils are often placed at several intervals along the beam to measure the field, and the cesium atom only has one shot through the field, so to speak, may particularly appreciate this analogy.

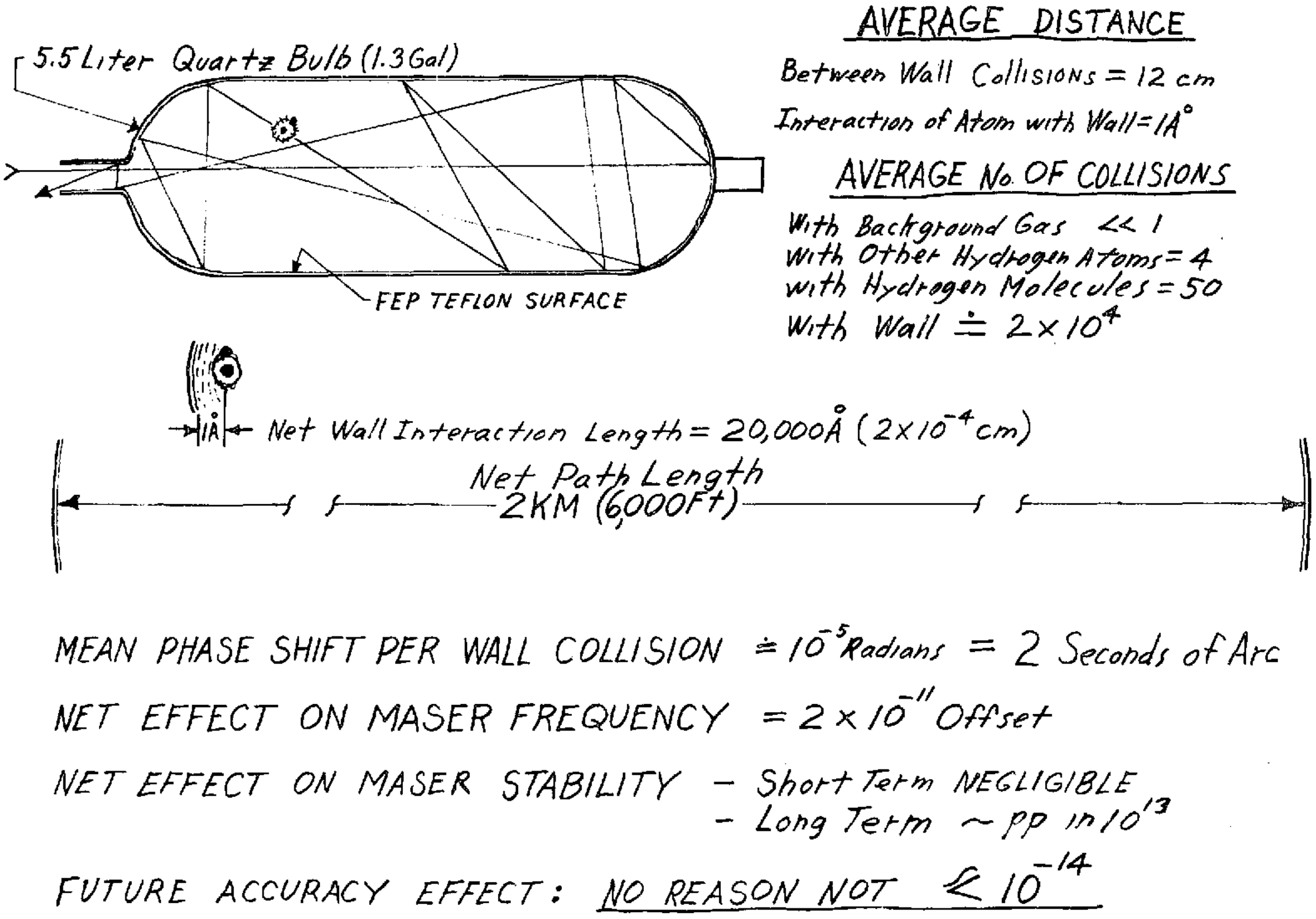

Figure 3. How FREE Is the Atom in the Maser Storage Bulb?

Note that the phase shift per wall bounce is only 2 seconds of arc! And this is at the frequency of the 21 cm line of hydrogen — 1420 MHz. It takes an atom 46 microseconds on the average, to go the 12 cm from wall to wall, and this corresponds to 65,000 cycles of the oscillation, in unperturbed space, while one cycle is perturbed to the extent of 1.5 seconds of arc (approximately $1.2 \times 10^{-6}$ cycle). That is what accounts for the 2 parts in $10^{11}$ offset in maser frequency, due to the wall.

## IV. VARIABLE VOLUME MASER

But why can we predict inaccuracy effects no larger than $1 \times 10^{-14}$ for this tremendous, elongated, beam device? The main reason is that we can change the path length, the effective distance between wall interaction regions, without changing the wall area, or its basic properties. Thus we can change the number of wall bounces per second, without changing the wall. That is the idea of the flexible bulb maser.[4,27]

Figure 4 shows one new and attractive embodiment of the idea. This is a "Variable Volume" maser. The storage bulb is of teflon sheet, which is formed into a convoluted, flexible, bellows. The volume is changed merely by compressing or extending the bellows. The frequency shift is approximately 3 parts in $10^{11}$ when extended, and twice that amount when compressed to half volume. The curve at the lower right illustrates the ease and accuracy with which one can extrapolate to infinite bulb volume. These flexible bulb masers completely overcome the problem of "understanding" the details of the interaction of the atom with the wall. Just by changing the number of wall encounters per unit path length, the problem is reduced to precise geometry. We do not have to solve the wall interaction, it is circumvented, in a clear cut, scientifically valid manner. Appendix I gives a more detailed discussion of potential error sources with a variable volume hydrogen maser which is presently being developed at GSFC.

## V. MAGNETIC FIELD AND CAVITY TUNING

Leaving the wall shift for the present, some data on the other perturbations will now be presented. Figure 5 shows the variation of the frequency of the NP-1 hydrogen maser as the internal magnetic field was changed. The frequency of NP-1 was measured with respect to NP-3. For the period of the measurements, NP-3 was sufficiently stable to introduce negligible error as a referency standard. (See Section VI on stability.) The magnetic field was measured by making Zeeman frequency measurements. The horizontal axis gives the Zeeman frequency; the fractional change in maser frequency is shown vertically in parts

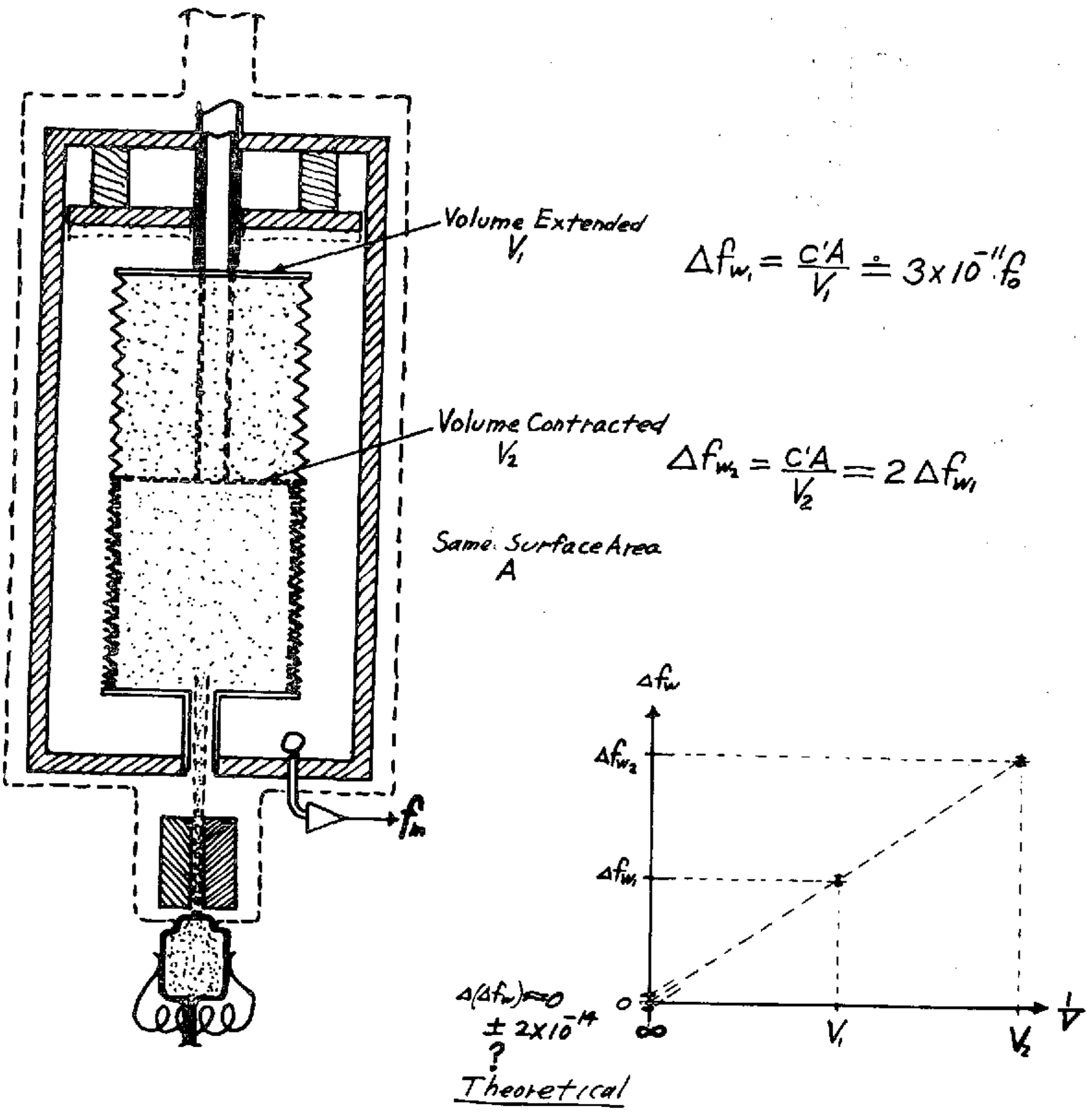

Figure 4. Variable Storage Bulb Volume Hydrogen Maser

in $10^{13}$. The solid line in the top figure is the theoretical curve, and the X's are experimental points. Except at fields below 200 or 300 microgauss, there is no significant difference between data and theory. This can be seen better in the bottom curve, which shows the difference between calculated and measured points.

The departure from the calculated curve at very low fields has very significant meaning regarding field inhomogeneities and departures from ideal tuning curves

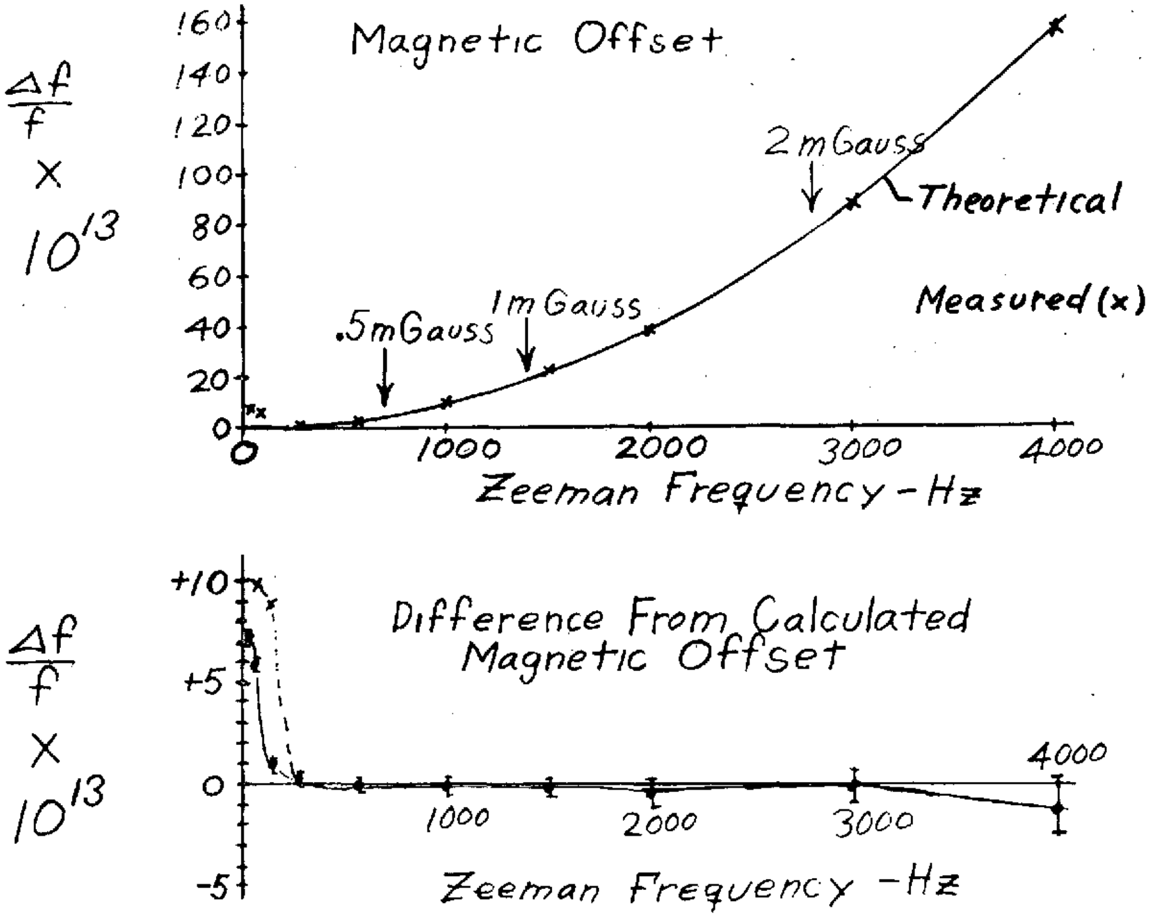

Figure 5. NP-1 Hydrogen Maser Magnetic Correction

which have been published in the literature, as discussed later. Figure 5 also illustrates that in the usual operating range of the NP and NX hydrogen maser frequency standards, between 500 microgauss and several milligauss, the magnetic correction procedure is fully valid.

Another very interesting experiment which was performed in conjunction with the magnetic field experiment just discussed had to do with the accuracy of the cavity tuning correction. Using the NP-1 and NP-3 masers, which have automatic tuning systems[3], the corrected frequencies of the masers, as well as the cavity tuning corrections, were observed while operating at fields from less than 1 milligauss up to fields of 10 milligauss. There was no change in the tuned cavity frequency as the field was changed from one value to another, nor were there any differences in the absolute frequencies when proper correction was made for the field. The precision of this experiment was three parts in $10^{14}$.

This, as well as other data, shows there are no significant tuning anomalies with the NP design of maser. Tuning discrepancies have been published for very different designs of laboratory experimental masers when magnetic field inhomogeneities were known to be present,[25,28] so the present experiment was an important one to confirm the NP tuning accuracy (see Appendix $I_g$ for further discussion of this point).

The next question regarding magnetic fields may be, how stable is the field with time? Figure 6 shows the magnetic field corrections which were measured on one of the NP masers (NP-4) for long periods of time. The upper curve shows eight months of operation, using a nominal field setting of 700 microgauss. The field was checked at weekly intervals, and only if the error exceeded 10 microgauss

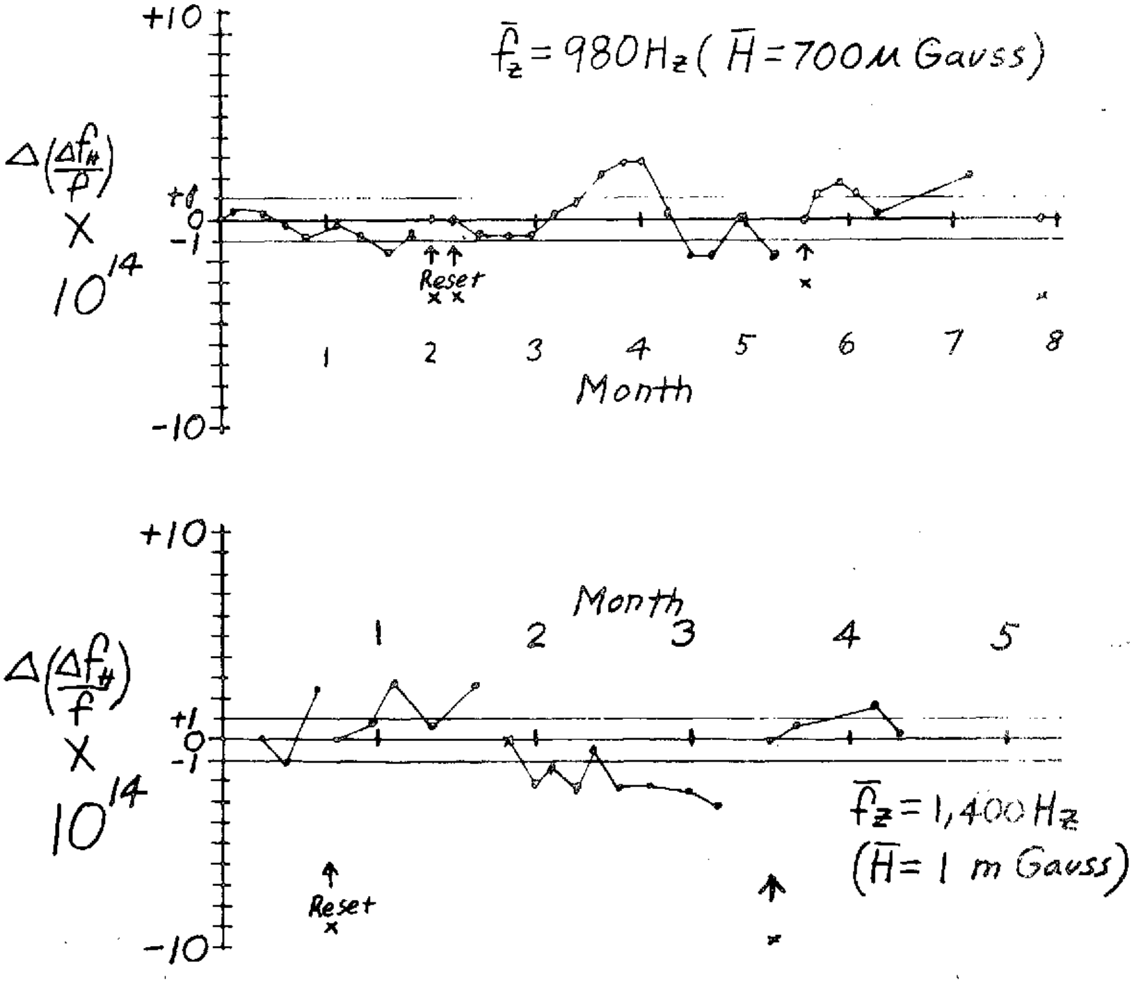

Figure 6. Magnetic Field Correction Variation NP-4 Hydrogen Maser

was it reset. Many of the resettings made were due to known external causes, such as nearby equipment movement, or to experimental work going on nearby. The maser was not in an exceptionally isolated environment for either period shown here.

On the average, the data shows that there will normally be no change in correction over one or two parts in $10^{14}$ from time to time, and it also shows that the field does not drift badly over extended periods. In the lower curve, the field setting was at 1.4 milligauss, twice that in the upper curve. The field perturbations are expected to increase in proportion to the field value, so the larger deviations shown in the lower curve are exactly what may be expected.

A most important point for keepers of standard frequency and time which is demonstrated by these curves, is that one can measure the magnetic correction in the hydrogen maser precisely and repeatedly without interruption of the maser output signal, with usually negligible effect on the phase, and with no remnant effect on the frequency of the maser.

These curves show only the long term effects — the shorter term variations of field are usually quite small; in a typical laboratory the minute to minute and day to day variations have been observed, and these are usually less than a few microgauss. So magnetic variations typically have small effects on maser stability, although as we are now pushing stabilities into the $10^{-15}$ or $10^{-16}$ range, field variations or corrections may become much more important in the future.

## VI. STABILITY DATA

Figure 7 gives three frequency comparisons between hydrogen masers under different operating conditions. First consider the bottom plot. This shows the fractional frequency variation between the NP-3 maser and one of the new masers, NX-2. The 1,000 second to 10,000 second stability is between 3 to 5 parts in $10^{15}$ (Allan variance[29]). There is no significant drift. Note that these masers were not being tuned — it is the free running stability in the lower curve. The average untuned linear drift rate, due to cavity drift, among the NASA prototype (NP) masers is $5 \times 10^{-15}$ per day. Thus when using these masers in field applications for periods of a few weeks or less, one would not usually want to use auto tuning except, perhaps, in the initial setup.

If you have a second hydrogen maser, and use it for a tuning reference, you can tune to and maintain less than one part in $10^{14}$ tuning correction on a daily basis. In the center plot in Figure 7, the frequency of NP-3 is compared with NP-1, and both maser cavities are being independently tuned with respect to a third maser

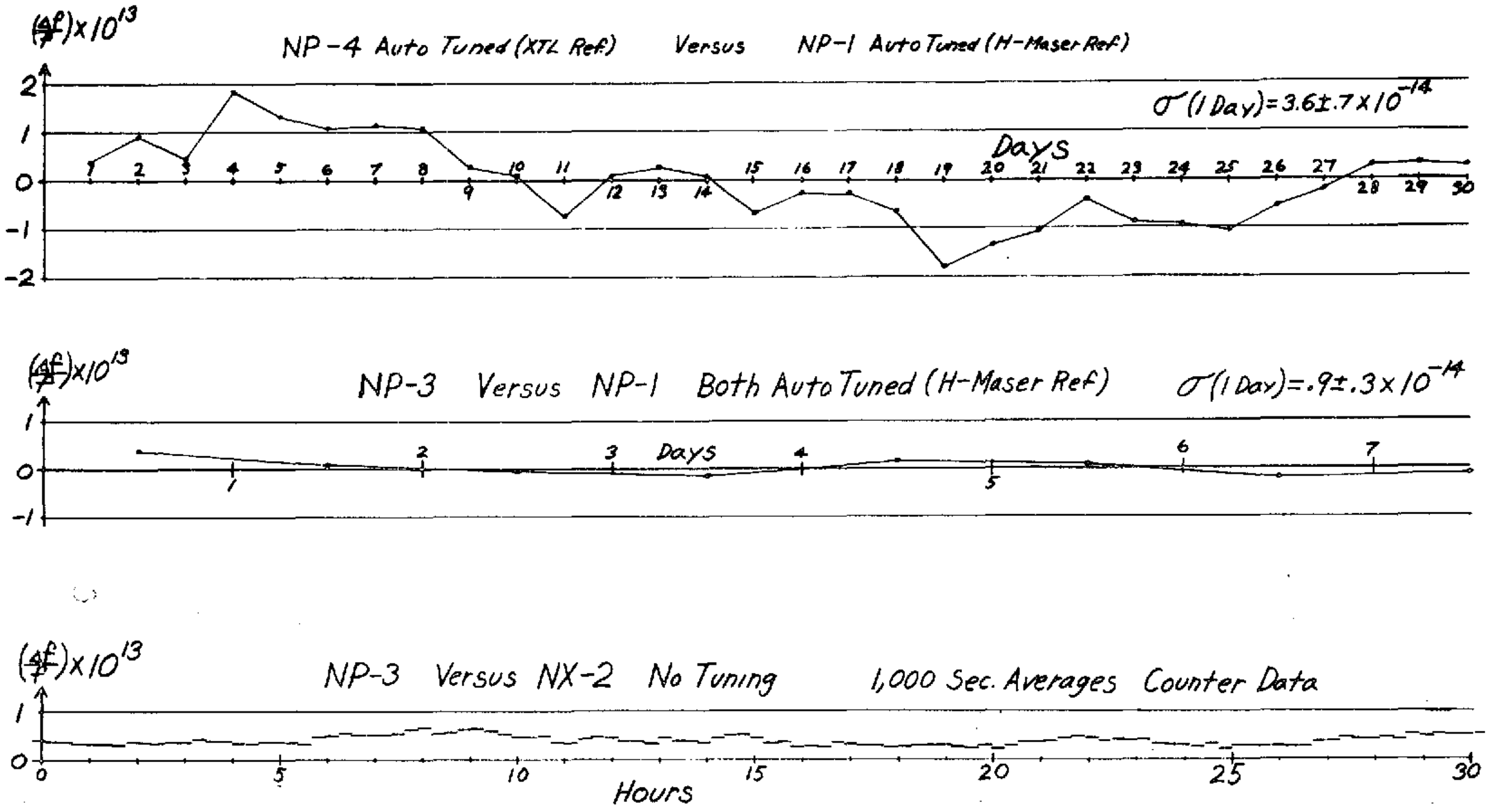

Figure 7. Hydrogen Maser Frequency Comparisons

(NX-2). The fractional frequency deviation (Allan variance) is $9 \times 10^{-15}$ for a days averaging time in this plot. The absolute tuning correction quickly becomes negligible for longer measuring times when tuning with respect to a second hydrogen maser. But even so, when looking for a few parts in $10^{15}$ stability for times shorter than a day, auto tuning would not normally be used (or would be discontinued during the period of a particular measurement).

In field operation situations, where one NP type hydrogen maser is available, and an absolute frequency referency is still desired, the maser may use a good crystal oscillator as the tuning reference. However, the day to day frequency variations will then be greater, and this is shown in the top plot in Figure 7. Here the frequency variation between NP-4, with its cavity tuned continuously with respect to a crystal oscillator, was measured with respect to NP-1, which used another hydrogen maser as a tuning reference. Due to the randomness of the crystal tuning data, the stability for a days averaging time is now $3.6 \times 10^{-14}$. But the error tends towards zero as the square root of time, so even with a crystal tuning reference, very long term (months) inaccuracy due to cavity and spin-exchange pulling should become less than one or two parts in $10^{14}$.

The linear cavity drift rate has not yet been resolved accurately on the NX-2 and NX-3 masers. From measurements for periods of a few weeks it appears to be less than two parts in $10^{15}$ per day. But much more time will be required to measure this effect on the new masers precisely.

In many ways, the most informative and satisfactory description of performance of a frequency standard lies in the real time frequency or phase comparison data under conditions similar to those in which the standard is to be used. For very long baseline interferometry, the usual signal frequencies may run from 10 MHz to 20 GHz or higher, and one limit to the useful integration time is set by the stability of the local frequency standards.[30]

If you are looking at VLBI fringes you are in effect beating the two local oscillators together at some high frequency, like 10 GHz, and do not want the beat frequency or phase rate to change by more than some small amount, typically 1 radian from the average, during the measurement interval. Also, any random noise on the local oscillator directly contributes to the uncorrelated noise flux. — So if the output frequencies of two standards are multiplied to 10 GHz, and the phase and frequency variation observed directly, a vivid picture is obtained of how the standards affect the data. Figure 8 shows beats between two hydrogen masers (NP-3 compared to NX-2) in which the usual 5 MHz output frequencies have been multiplied to X-Band, 9.18 GHz actually, and these X-Band signals are combined in a balanced mixer whence a beat (difference frequency) is obtained. Figure 8 is a photograph of the strip chart data. The same nominal beat frequency occurs

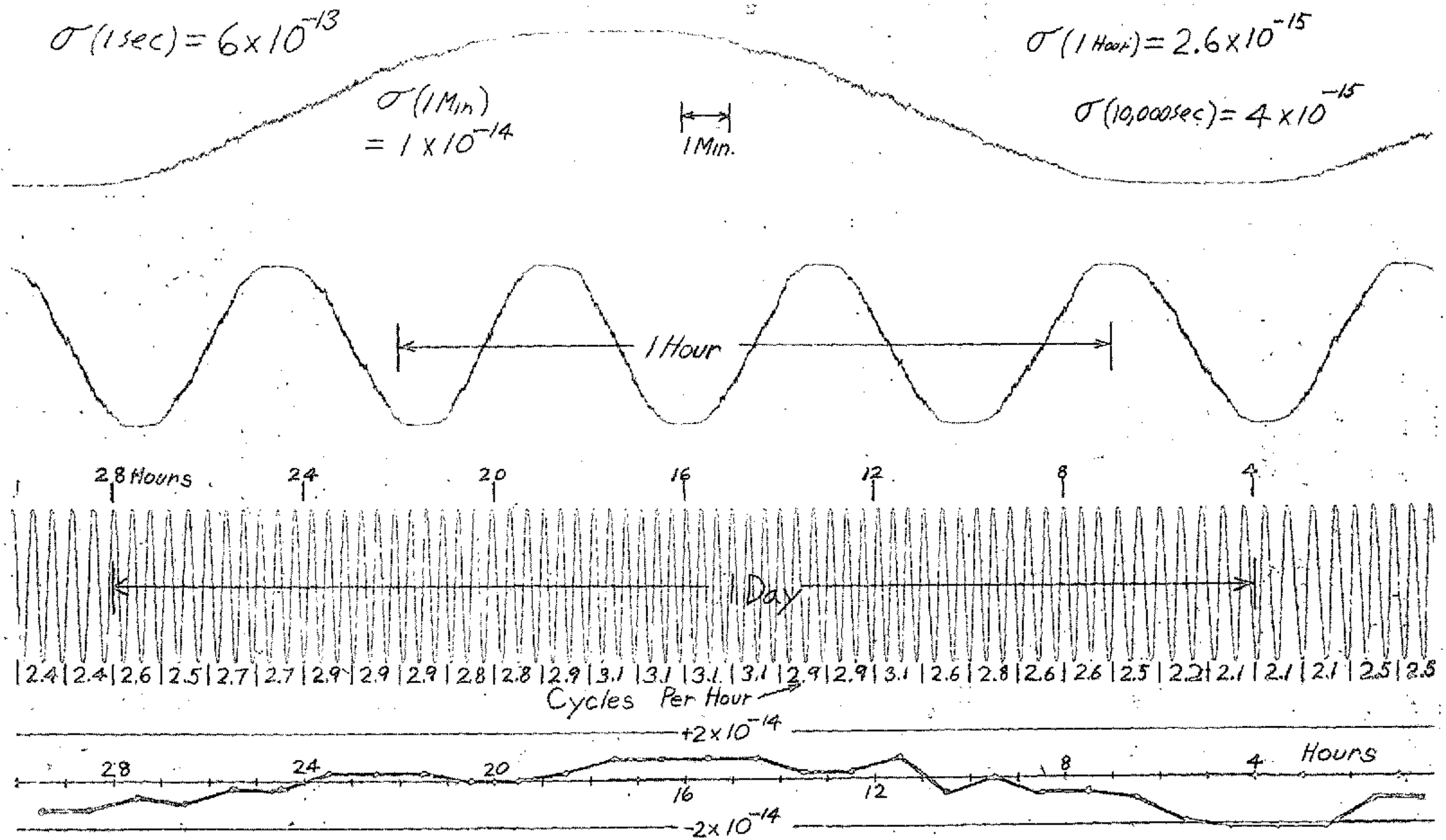

Figure 8. 9.18 GHz Phase Comparison between NP-3 and NX-2 Hydrogen Masers

in all of the three plots, but near the bottom the chart speed is 1 inch per hour, in the center it is 15 inches per hour, and at the top 1 inch per minute.

For those who may be familiar with 1 microsecond phase plots taken between two 1 MHz signals, Figure 8 is similar, except there is 10,000 times greater resolution. One cycle corresponds to 109 picoseconds ($1.09 \times 10^{-10}$ sec) accumulation of time between signals. The average frequency difference is 2.6 cycles per hour, which corresponds to a fixed frequency offset between signals of 8 parts in $10^{14}$ (8 nanoseconds per day). A change of 1 cycle per hour in beat frequency is equivalent to a change of $3 \times 10^{-14}$ in signal frequency. As seen from the one day's data at the bottom, where the number of cycles per hour is shown, typical changes are of the order of 0.1 cycle per hour, or 3 parts in $10^{15}$. A statistical analysis (Allan variance) gives $2.6 \times 10^{-15}$ fractional stability for 1 hour measuring intervals, and $4 \times 10^{-15}$ for 10,000 seconds (which is about 3 hours). At the bottom of Figure 8 the hourly frequency variation is plotted, with a scale of $2 \times 10^{-14}$. The peak to peak excursion in this 28 hour period was 3 parts in $10^{14}$.

Analysis shows that in a VLBI application, if using these two masers, it would be feasible to integrate for at least 1 hour at X-Band (for 1 radian error) and for over 4 hours at S-Band (2 GHz).

## VII. NEW MASER CHARACTERISTICS

Only a brief description of the improved design characteristics of the NX-2 and NX-3 hydrogen masers will be given at this time, since the final receiver and auto tuner systems are just now being completed. The stability data is thus presently limited by the noise level of the breadboard receiver system used. Also, considerable time will be required, of course, to fully evaluate long term performance.

The new masers oscillate with ten times more power than the older NP masers, $5 \times 10^{-12}$ watts of beam power versus $5 \times 10^{-13}$ watts. The theoretical stability for one second measuring intervals is 2 parts in $10^{14}$ with a 10 Hz bandwidth.[31] Present measurements give $2.5 \times 10^{-13}$ for one second averaging, and $2.5 \times 10^{-15}$ for 100 seconds averaging. For 1,000 seconds to 10,000 seconds the stability is $3 \pm 2 \times 10^{-15}$. The long term drift of the new masers, without cavity tuning, has not been precisely determined, but preliminary measurements of a few weeks duration indicate it is of the order of $2 \times 10^{-15}$ per day or less.

The new masers also operate with approximately half the hydrogen flow of the older NP masers. The NP units have pump element life expectancy, as determined experimentally by accelerated life tests, of 10 to 15 years (see Appendix II). They have been operating continuously now for between 4 to 5 years with no replacement required. Thus the new masers should have on the order of 20 years of pump element life expectancy due to hydrogen saturation. However, the new maser pump connections have high vacuum valves which seal off the maser vacuum system from the pumps, so that a pump may be quickly exchanged without breaking maser vacuum. There are two ion pumps on the new system, one of these evacuates the maser storage bulb and focussing magnet region, and pumps essentially only hydrogen; the other pump evacuates the outer vacuum system, and so removes any external gas which diffuses thru the main vacuum seals. This differential two compartment system assures that background gas pressure in the maser bulb, other than hydrogen, is kept extremely low, and that maser frequency will not be perturbed by relatively active molecules, such as oxygen.

The increased efficiency of the state selection and beam optics of the new masers was achieved by using a new, more efficient, design of quadrupole electromagnetically variable state selector which has a much greater acceptance angle from the source exit collimator than the fixed hexapolar magnets used previously.[3] Gaps between poles in the new state selectors provide relatively high pumping speed for unfocussed hydrogen, so that the state selector to storage bulb collimator (entrance) distance could be reduced by a factor of two, to 13 cm vs 26 cm in the NP's. Additionally, the new masers use larger bulb collimator diameters and larger collimator length (1 cm dia. × 10 cm long vs .6 cm dia. × 2.5 cm long in the NP masers).

Although the bulb exit relaxation time is decreased in the new masers to .75 seconds, versus 1.3 seconds in the NP units, there is not a corresponding decrease in line Q. This is due to the fact that the line Q of the NP masers was found by experience to be limited by relaxation processes within the bulb, so that the maximum oscillating line Q was 4 to $5 \times 10^9$. With the new geometry the line Q is $3.3 \times 10^9$, and is much more limited by the bulb exit time constant. Thus the long term stability, which depends predominantly on line Q rather than oscillator power,[31] is not degraded significantly, while short term stability, which varies as the square root of power, is improved by approximately a factor of 3.

The shorter bulb time constant also decreases the susceptibility of the maser oscillation level to disturbances due to magnetic inhomogeneities. In addition, the magnetic conditions have been improved by the placement of an additional magnetic shield over the entire maser and pump assembly. As indicated previously, the new masers oscillate well at fields less than 10 microgauss (by Zeeman frequency measurement), and as an improvement of a factor of 10 or more in incremental shielding factor is expected, magnetic perturbations should be proportionately less significant than the NP results previously described in Section V.

The cavity frequency control system and the temperature controls on the new masers are similar in principle to those on the NP units.[3] The cavity is of aluminum alloy 6061T-6, and the external frequency control is accomplished by varying the balance conditions on the temperature sensor bridge. Improved integrated circuit operational amplifiers were available when the new masers were designed, and additionally, temperature servo time constants, and other details of the system have been improved. The use of aluminum for the cavity, rather than a material with smaller temperature coefficient of expansion such as metallized fused silica, CER-VIT,[32] or ULE[33] titanium silicate, is an outgrowth of early experiments with aluminum cavities at GSFC which were originally intended to establish the realizable limits of temperature control stability[3], as well as to determine the relative predominance of factors other than temperature which affect cavity frequency. At this point it is interesting to note that the present stability of the NX and NP masers of 2.6 parts in $10^{15}$ for 1,000 seconds measuring times means that the cavity is electrically, mechanically, and thermally stable to 2.6 parts in $10^{10}$. (The cavity pulling is proportional to the ratio of the cavity Q to the line Q, which is approximately $10^{-5}$ in the present designs.) Since the cavity diameter is 25 cm (10 inches), the above stability indicates that the cavity diameter is stable to .6 Å (1 Å = $10^{-8}$ cm). This is less than one atomic hydrogen diameter! Needless to say, many factors other than temperature enter into stability considerations at the 1 Å level, and such things as high thermal conductivity, thermal isolation, mechanical rigidity, electrical opaqueness, etc., are indeed very important. Since aluminum has an expansion coefficient of approximately $2.6 \times 10^{-5}$ at operating temperatures of 40°C, the present maser stability indicates the cavities are thermally stable to $10^{-5}$ °C.

Long term temperature stability data has been accumulating for many years with the NP maser design. The corrections which the auto tuner makes to the maser cavity give a maximum estimate for thermal drift. The average value of $5 \times 10^{-15}$ per day for the NP masers (NP-1: $1 \times 10^{-14}$, NP-2: $\pm 1 \times 10^{-15}$, NP-3: $2 \times 10^{-15}$, NP-4: $-7 \times 10^{-15}$; per day) gives an average thermal drift of 30 microdegrees Celcius per day. Experience with the NP's has shown that this drift is due as much to the instabilities of the "fixed" metal film resistors used in the thermal sensing network as to the instabilities of the selected thermistor beads used. (Veeco TX1821 preconditioned glass thermistor bead-in-glass probe; these are nominally 50 K Ohm probes which are guaranteed stable to .1% per year.) In the new masers, the bridge resistor temperature coefficients were evaluated, and the completed bridges independently tested for temperature coefficient. With the above precautions, the NX-2 and NX-3 temperature servos are essentially the same simple DC bridge and operational amplifier system used on the earlier masers. A significant improvement in thermal control is obtained with the new masers, as indicated by the present stabilities; however, measurement of the true level must wait until the final receiver system is completed.

The new maser standards retain all of the desirable features of the NP masers. They are self contained (on a single chassis), operate for up to 6 hours on standby batteries, can be easily moved on their own dollies, and have several well buffered standard frequency output signals. They also contain a very stable crystal oscillator (Oscilloquartz[36] B 5400) as the cavity tuner reference, and they are smaller than the NP units, being only 132 cm (52 inches) high (versus 182 cm for the NP's).

Most of the design effort has been directed towards optimizing performance, since the main goals of the hydrogen maser research program have been to provide the most stable, reproducible, accurate, long lived, and reliable standard for those ground based applications where these factors are most critical. Perhaps the most critical of considerations, considering the long term cost of present time and frequency standard systems, is the fact that the components which are most likely to be unreliable in the hydrogen maser standard are external to the vacuum system, and these factors, such as receivers, synthesizers, power supplies, electronic components, etc., are easily and inexpensively maintained or repaired without changing any basic maser frequency determining elements, or the long term properties of the maser as a standard.

Experience has also shown that there are no large variations in the stability properties of one maser or another of the NP (or NX) type, so that selection of best units for time standard ensemble systems, as presently practiced, would not be nearly so important as is the case with the other standards in use today. With the exception of the very long term instabilities which may be related to changes in the storage bulb surface, all the important fundamental corrections to the maser oscillating frequency may be quickly evaluated on operational hydrogen masers. Thus a most important characteristic which separates operational hydrogen maser standards from other atomic standards, is that each unit is, in itself, a standard which is most closely related to an invariant atomic transition frequency, and so has "intrinsic" accuracy, rather than being necessarily related through calibration procedures with particular instruments which are evaluated for accuracy and maintained by specialists, usually in national standards laboratories.

# APPENDIX

## I. WALL SHIFT INACCURACY EFFECTS WITH VARIABLE VOLUME HYDROGEN MASER

The particular design of the variable volume maser illustrated in Figure 4 has several features which minimize potential error sources. A brief outline of these errors and the techniques available for their determination will be given here.[35] A variable volume maser as illustrated is presently being developed at GSFC, and a more comprehensive presentation of this work is anticipated at a later date.

### a. Wall Shift Relationship

If $\phi_c$ is the phase shift per wall collision and $\phi_d$ is the average phase accumulated in the time $T_d$ spent by the atom at average velocity $\bar{v}$ to go the average distance between wall collisions, $\lambda$, then to a very good approximation,

$$\left(\frac{\Delta f}{f}\right)_w = \frac{\phi_c}{\phi_d} = \frac{\phi_c}{2\pi f T_d} = \frac{\phi_c \bar{v}}{2\pi f \lambda} . \tag{A1}$$

We wish now to find $\lambda$ for a bulb of arbitrary shape having a volume V and surface area A.

From elementary thermodynamics the total collision rate of atoms with the wall is given by

$$N_c = \frac{n \bar{v} A}{4} .$$

Here n is the atom density. If $N_T$ is the total number of atoms in the bulb, then the collision rate per atom (frequency of wall collision for each atom) is given by

$$\frac{N_c}{N_T} = \frac{\bar{v}}{\lambda} .$$

Since $$N_T = n V ,$$

it follows that

$$\frac{\bar{v}}{\lambda} = \frac{\bar{v}\,A}{4\,V},$$

therefore

$$\lambda = \frac{4\,V}{A}. \qquad \text{(A2)}$$

The effect of the bulb collimator may be taken into account by noting that the average pressure in the collimator is 1/2 the bulb pressure, so that the effective bulb volume is

$$V = V_b + \frac{V_c}{2}$$

and the effective bulb area is

$$A = A_b + \frac{A_c}{2}.$$

The above approximation is excellent since typical collimator volumes and areas are less than one part in $10^3$ of the bulb values.

Using (A2) in (A1) we obtain

$$\left(\frac{\Delta f}{f}\right)_w = \frac{\phi_c\,\bar{v}\,A}{4\,\omega\,V}.$$

Thus the relationship of wall shift to the ratio of surface area and volume is a very precise and fundamental dependence. The precision depends only on the assumption that hydrogen behaves as an ideal gas, and that pressure and temperature equilibrium occurs; these are valid assumptions to many orders of magnitude in the present case.

The storage bulbs in the NP and NX masers are cylinders with straight section length $L \doteq 28$ cm and diameters $D \doteq 15$ cm and with hemispherical ends, also of diameter D. For this case it is found

$$\lambda = \left(\frac{4V}{A}\right) = \frac{2}{3} D \left(\frac{D + \frac{3}{2} L}{D + L}\right). \tag{A3}$$

$\lambda$ is calculated from the above equation to be approximately 12.1 cm. In the case of a spherical bulb, which is typically used in many other hydrogen masers, it is seen that (A3), with $L = 0$, reduces to the more familiar equation.

$$\lambda = \frac{2}{3} D.$$

b. Surface to Volume Ratio Determination

Several methods are available for determination of the effective value, or change in value, of surface to volume ratio. First, it may be measured initially by gas volume measurement or similar techniques. It may also be calculated from scaled measurements. If care is taken in making the bellows, so that the diameter remains constant as the bellows is compressed or extended, then the volume change is directly proportional to the change in length, and may be easily determined by counting the turns of the compression screw.

The bulb relaxation time constant is given by $T = V/F$ where F is the collimator pumping speed. Thus measurement of line Q changes, which depend upon T, give the effective volume change. One of the simplest methods to measure line Q is to measure the change in maser frequency as the cavity frequency is changed. If the cavity Q is constant, or if it is measured carefully, the line Q and thus the effective volume change can be measured precisely. Other techniques such as pulsed stimulated emission, decay rates using shuttered beams, and transient response measurements,[2] may also be used. These techniques are well established, precise, and straightforward. It should be noted that basically only the ratio of volumes (or ratio of measures of $T_b$) are required to make the absolute wall shift determination.

### c. Change in Wall Surface Properties Due to Strain

It is estimated that there will be on the order of 1% surface strain as the bulb volume is changed. There is no reason to suppose that the phase shift per collision with the wall is a very strong function of this amount of strain,[35] however the experimental conditions are designed to minimize any associated error. For example, if the change in phase shift is a linear function of the strain, it will cancel in the bellows maser design, since the convex and concave convolutions alternate in compression and extension. That is, as the bulb is compressed, the inside obtuse angle surface will be stressed positively (stretched), while the inside acute angle surface will be stressed negatively.

If, however, the phase shift is a function of the absolute magnitude of the surface strain (a quadratic function for example), then a non-linear curve of frequency versus inverse volume will be obtained, and the error may be determined by making measurements at one or more intermediate volumes. Additionally the strain is maximum only at localized areas of the surface, so that the net wall pulling of that part of the bulb is only a fraction of the total effect. Thus, it does not appear likely that surface strain effects will be a very significant limitation to accuracy.

### d. Cavity Instabilities Due to Flexible Bulb

The material of the bulb sides is .5 mm thick teflon. The ends are teflon coated quartz plates. The RF electric field is approximately maximum at the side wall position, so the cavity frequency changes due to dielectric position changes are primarily a function of the teflon wall position (or of the quartz bulb side wall position in fixed bulb masers). The teflon thickness is 3/10 the thickness of typical quartz bulb walls, and the dielectric constant of teflon is approximately 1/2 that of quartz. The frequency effect is proportional to the square root of the dielectric constant, and to the relative thickness, so the teflon bulb cavity pulling effect is approximately 2/10 that of a quartz bulb. In addition, in the expanded position the bulb volume is approximately twice that of an NP maser bulb, so the line Q is increased by a factor of 2, with a corresponding decrease in cavity pulling.

In experience with experimental masers using relatively loosely mounted quartz bulbs, it was found that as long as the maser was not physically shaken or vibrated, no unacceptable instabilities arose in regard to experimental measurements. Since both the mass of the teflon material and its effect on cavity frequency are reduced by as much as a factor of 10, it is not anticipated that instabilities will be a fundamental problem. Additionally, such instabilities as may occur are random, rather than systematic in nature, and long term frequency determinations with regard to stable fixed bulb masers will minimize any instability problem.

### e. Filling Factor

To assure oscillation the filling factor of the maser must exceed a certain minimum value. (See Ref. 19 for definition of filling factor and other maser oscillation conditions.) For a centrally located cylindrical bulb 15 cm in diameter and 40 cm long, within a cavity 25 cm diameter by 50 cm long, the filling factor is calculated to be .48. At a contracted volume of 50%, the filling factor is .24. With the favorable oscillation thresholds of a maser using the NASA elongated cavity design, these factors allow a relatively wide range of beam intensity variation while oscillating. Thus tuning corrections can be accurately made, and experimental determinations of wall shift may be made at several significantly different flux levels so as to evaluate second order inaccuracy effects.

### f. Errors Due to Density Variations

First, it should be noted that the position of the bulb bottom end, as well as the size and shape of the bulb collimator illustrated in Figure 4, are to remain fixed as the volume is changed. The collimator is also designed so that the bulb time constant is much less than other relaxation times at low oscillation levels. Since the exit pumping speed of the collimator does not change, the pressure in the bulb, which is the product of the collimator speed and the throughput, may be kept constant, or be changed controllably, independently of the bulb volume. Thus wall surface properties which are solely a function of the density of atoms (or molecules, hydrogen or otherwise) will not change as the volume is changed. Therefore the maser may be tuned for removal of cavity and spin-exchange pulling while maintaining identical density conditions for both the expanded or contracted volume, at either high or low beam flux.

As a precaution against background gas pressure being significantly high, or to minimize pressure changes due to manipulation of the bulb, the bulb is evacuated by a separate system as in the new NX masers. Ultra high vacuum conditions are maintained by using only ion pumps, and bellows type rotary feed throughs are used for manipulation. Thus accuracy evaluations may be done repeatedly over long time spans without contamination of the system.

### g. Cavity and Spin-Exchange Tuning Errors Due to Magnetic Field Inhomogenieties

It has been shown by Crampton[28] that certain types of magnetic field inhomogeneities can cause an error in the cavity and spin-exchange correction procedure. However, the field inhomogeneities required to create significant error are very much greater than those present in the GSFC hydrogen maser designs. The primary source of the most critical type of inhomogeneity, namely radial DC field gradients, are the center entrance hole in the magnetic shield cap and the associated correcting coils which are used reduce the resulting effect. The correcting coils are not required or used in the GSFC masers since the shield apertures are relatively very small. (2.5 cm diameter versus 10 cm to 16 cm typically used in other masers.) Radial gradients due to either external fields or to fields applied with the internal field coils are thus very much less. This, as well as other favorable parameters, such as very large line Q due to use of large volume bulbs and certain favorable geometrical factors associated with use of very elongated cavities, accounts for the experimentally verified lack of "Inhomogeneity tuning errors" in the Goddard masers. It is also to be noted that such errors are removable for accuracy purposes, if they were present, by operating at sufficiently high field.[2,25]

## II. VACUUM PUMP ELEMENT LIFETIME

Experiments were performed prior to selecting vacuum pumps for the NP masers to determine the useful life expectancy of pump elements of different types. Some prior data was already available with 75 and 240 liter per second pumps used on early Varian Associates hydrogen masers.[19,34] Two other manufacturers pumps which were also possible candidates for use in the NP masers were tested at GSFC in 1966 and 1967. These were the Ultec Corp. 150 liter per second diode type pump, and the General Electric Co. 100 liter per second triode type pump. Both these units pumped approximately 3 moles of $H_2$ gas in a period of 6 months. Due to the relatively small stray magnetic field of the Ultec pump, it was chosen for the NP masers. However, it was clear that the triode pump had excellent starting characteristics, as well as better capability for pumping inert gasses.

For the NX-2 and NX-3 masers, a new triode configuration pump was selected (Varian Associates 60 liter per second Noble VacIon pump). These pumps had been tested in operation with other experiments,[8] and had the expected starting and gas pumping features desired, as well as relatively small stray magnetic field.

By observing the drop in pressure in the one liter hydrogen storage vessel of the NP masers over the years, the total H flow rate has been found to be between .10 and .16 moles per year. The rate for the new NX masers is .05 to .08 moles per year. Thus the NP pump element life expectancy, ideally, is between 20 and 30 years. However, with a factor of 2 safety factor, 10 to 15 years may be realistically expected. However, the pump which pumps most of the hydrogen in the NX masers is separated from other background gas by partitioning, so it is simulating quite well the ideal conditions which occur in pumping experiments (where gasses other than hydrogen are essentially excluded). Thus 15 years of continuous pump operation should be conservatively expected, and 20 to 30 years life may actually be experienced before replacement is required.

It should be mentioned in fairness to all manufacturers of vacuum pumps, that it appears that most Penning discharge type pumps (ion pumps) with cathode area comparable to the pumps mentioned, would likely work very well at the low hydrogen flux of masers similar to the NP and NX designs. The magnetic field conditions, size, shape and cost, may be the most significant differences to consider.

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