Hydrogen Maser Frequency Standard

The intent of this discussion is to provide VLBI personnel with an overview of the hydrogen maser, its use in VLBI, and how to assess its operating condition prior to an observation. This discussion will be as generic as possible so as to encompass all types of masers. The following subjects will be addressed:

- **Role of the Frequency Standard.**
- **Requirements--Why do we use Hydrogen Masers?**
- **Principles of the Hydrogen Maser--Physics.**
- **Principles of the Hydrogen Maser--Electronics.**
- **Identifying Maser Problems**
- **Using GPS to Identify Maser Problems**

Role of the Frequency Standard

During geodetic VLBI observations, signals emitted by distant sources of radio frequency energy (quasars) are received and recorded at several antennas. At each antenna (VLBI station) a very stable frequency standard (hydrogen maser) provides a reference signal that enables time tagging of the quasar signals as they are being recorded. For each VLBI experiment, correlation of the time-tagged, recorded information from the participating antennas yields the differences among the arrival times of any specific quasar radio wave at the antennas. These time differences are used to calculate the locations of the antennas with respect to each other.

Requirements--Why do we use Hydrogen Masers?

The measurement of a VLBI baseline to a precision of 2 millimeters requires a "clock" (frequency standard) stability of approximately 1E -14 (1 x 10 to the -14 power) for a 600 second observation time. As shown in Figure 1, this corresponds to the time for radio waves to travel 2 millimeters divided by 600 seconds. A similar estimation shows that a baseline precision of 1 millimeter would require a clock stability of 5E -15 for a 600 second observation. Another way to estimate the stability requirement of the frequency standard is to calculate the time for X band waves to move one radian of phase and divide by the observation period. This yields a stability requirement of 3E -14 over a period of 600 seconds. The required stability for longer observation periods would be proportionately stricter.

Figure 2 compares the frequency stability of some commercially available frequency standards-- a rubidium standard, a cesium standard, and a hydrogen maser. For observation times of geodetic VLBI interest (hundreds to thousands of seconds) the hydrogen maser is clearly the superior choice. All properly operating hydrogen masers provide this level of stability. This is the reason why all of the masers in the worldwide VLBI network together constitute a tool that enables precise and reliable determination of global baselines.

Principles of the Hydrogen Maser--Physics

Hydrogen atoms can change energy level in several ways. According to the laws of nature (rationalized by man's "Quantum Theory of Matter"), atomic changes ("transitions") from a higher energy level to a lower energy level produce electromagnetic radiation at a frequency defined by the difference between energy levels divided by a constant.

Figure 3 shows a hydrogen atom with its one electron changing magnetic polarity. This polarity change is accompanied by a change in the interaction between the electron and the nucleus and a change in the energy level of the atom. Whenever this specific transition of the hydrogen atom occurs (called the "hyperfine transition"), electromagnetic radiation is produced at a frequency of 1,420,405,751.77 Hz (the "hydrogen maser frequency"). The hydrogen maser is a machine that takes advantage of this process.

Figure 4 shows the main features of the VLBI hydrogen maser:

1. Hydrogen molecules are stored at room temperature in a small tank (or in a hydride material in some masers).

2. An electrically controlled valve allows hydrogen to flow from the tank into a glass bulb (the "source bulb"), where pressure is kept at approximately 1/10 torr (1 torr equals 1/760 of sea level atmospheric pressure).

3. A radio frequency oscillator (5 to 10 watts) applies energy to the hydrogen in the source bulb, which causes the hydrogen molecules to separate ("dissociate") into several kinds of energetic hydrogen atoms.

4. A small hole (or holes) in the source bulb allows a stream of atomic hydrogen to flow into a region where pressure is kept at 1/10,000,000 torr.

5. The stream of hydrogen atoms flows toward the central axis of a 4 or 6 pole magnet (the "State Selector"). The State Selector provides a magnetic field that is near zero along its axis of symmetry (which is positioned on the axis of hydrogen flow) and increases radially outward from the axis. This magnetic field deflects unwanted (low energy) hydrogen atoms away from the axis and focuses high-energy atoms on the entrance to the "Storage Bulb". These high energy atoms are those required for the "hyperfine transition" described above.

6. The Storage Bulb is made of fused quartz, lined with Teflon (Dupont Chemical Company trademark) or other similar material. The Storage Bulb is contained inside a cylindrical structure (the "Cavity"), which is kept resonant at 1,420,405,751 Hz within 1 Hz. The Cavity is protected from the influence of outside magnetic fields (such as Earth's magnetic field) by four or more layers of magnetic shielding. A magnetic field (equivalent to 1/500 of Earth's magnetic field) called the "C Field" is applied to the Cavity.

7. High-energy atoms enter the Storage Bulb and bounce off its walls thousands of times over a period of approximately 1/2 to 1 second before they exit the bulb's entrance and are removed by the vacuum system. This relatively long storage time of high energy hydrogen atoms inside the Cavity (which is resonant at 1,420,405,751 Hz), combined with the action of the "C Field", in isolation from the magnetic influences of the outside environment, enable these atoms to experience the hyperfine transition and radiate energy at a frequency of 1,420,405,751 Hz.

8. In a typical hydrogen maser, the power of the 1.42xxx GHz signal emitted by the Cavity is approximately 1E-12 to 1E-13 watts. A small antenna (sometimes called the "Pickup Loop") inside the Cavity receives this signal, which is input to the maser's low noise receiver.

Principles of the Hydrogen Maser--Electronics

Phase Lock Loop

Once the cavity is oscillating, we can utilize this stable frequency to phase lock a voltage controlled crystal oscillator (VCXO), thus providing a stable, useable, frequency output from the maser.

The 1.420405751 GHz signal is coupled out of the cavity by means of a single turn pick-up loop and fed to the receiver. (Refer to Figure 5) The signal is amplified and mixed with a 1.4 GHz local oscillator signal. The output of the mixer, 20.405751 MHz, is then amplified and mixed with a second local oscillator signal of 20 MHz. The resulting signal, 405.751 KHz, is again amplified and mixed with a third local oscillator signal of 400 KHz. This final output signal, 5.751 KHz, is filtered, amplified, and sent to one input of the phase detector.

As shown in Figure 5, all local oscillator signals are derived from the VCXO.

Another buffered output of the VCXO is used to drive the synthesizer, which creates the second 5.751 KHz signal input to the phase detector.

The phase detector provides a DC control voltage back to the VCXO to correct for any phase errors between the two inputs thus completing the frequency servo loop.

Note: This description is based on the NASA NR maser phase lock loop. Other masers may use different circuit configurations or VCXO frequencies, however the end result remains the same.

Frequency Control

Cavity Control

When a maser is constructed, great care is taken to ensure that the microwave cavity is resonant at the proper frequency. This process is a combination of mechanical as well as electrical calculations and adjustments. But there are a number of things that can affect the cavity resonance. Mechanical shock, stress, and vibration such as would be encountered in shipping can cause settling or change the alignment of the cavity hardware thus changing the frequency. This would be seen as a frequency offset and can be corrected by tuning the maser. However, long-term effects such as component aging will present themselves as a drift, i.e., frequency change over time. Most masers have internal circuitry to compensate for drift. Two methods, thermal cavity control (as in the NASA NR maser) and varactor cavity control (as in the Sigma Tau maser) are described herein.

Thermal Cavity Control (NASA NR Maser)

As shown in Figure 6, thermal cavity control maintains the proper resonant frequency by varying the amount of current applied to the heater windings on the cavity. As the temperature of the cavity varies, its size varies thus changing the resonant frequency.

The Cavity Temperature Control Pre-Amp is part of a temperature servo loop that gets feedback from one or more thermistors mounted on the cavity. The initial temperature of the cavity is set by means of the coarse temperature adjustment pot. This is a low value, multi-turn pot which provides a small adjustment range with high resolution. In addition, the pre-amp itself is temperature controlled (by another circuit) for stability.

The Cavity Temperature Control Power Amp is a separate module that provides the drive to the heater windings mounted on the cavity.

Although the circuitry described thus far would provide stable control at a given temperature, it does not have the adjustment resolution to precisely set the cavity at its proper resonant point nor does it take into account any effects of component aging.

An additional input to the Cavity Temperature Control Pre-Amp is provided so that very fine adjustments to the cavity temperature can be made. This input comes from a D/A converter that is driven by the maser microprocessor. Once the frequency drift rate is determined, the microprocessor is commanded to increment or decrement the D/A converter on a timed basis to counteract the drift.

The input to the D/A converter is known as the Cavity Register. Utilizing an 18-bit D/A converter provides a register range of 0 to 262143. Each count of the register translates to a frequency change of approximately 2.0E-16. When the cavity register reaches a limit (up or down) it is reset, the cavity temperature is adjusted accordingly with the coarse temperature control, and the process continues.

Varactor Cavity Control (Sigma Tau Maser)

Figure 7 illustrates varactor control of the cavity resonance. As the voltage to the varactor is varied, its capacitance changes, thus controlling the resonant frequency. The initial adjustment of the cavity temperature is similar to the thermal cavity control described above, however, the servo circuit is fixed at a preset temperature. Once the maser is “masing”, the cavity can be tuned by means of the Automatic Cavity Tuning Control described herein.

The Switching Varactor Control circuit alternately supplies the switching varactor with two preset voltages, in effect switching the cavity resonant frequency between two values. An IF signal sample from the receiver is rectified, filtered, and synchronously detected in the Automatic Cavity Tuning Control circuit. If the signal amplitudes at the two switched frequencies are not equal, the cavity is not at the proper resonant frequency. The Automatic

Cavity Tuning Control senses the magnitude and sign of the error and sends the proper correction signal to the Cavity Register Control.

The Cavity Register Control consists of a 24-stage up/down counter, the first eight stages being used as an averager. The remaining 16 stages are used to control a D/A converter, which, in turn, controls the cavity tuning varactor.

The Automatic Cavity Tuning Control runs continuously and, as in the thermal cavity control, will correct for frequency drift until the cavity register reaches a limit. At that time the cavity temperature will be reset and the process continued.

Synthesizer

All masers contain some type of synthesizer, either all digital or an analog/digital combination. In either case, its function is to provide a means of correcting for or introducing frequency offsets in the maser output signal while still maintaining phase lock with the stable hydrogen frequency.

Once the cavity is known to be on frequency and any long term drift is being properly corrected for, the maser can be precisely set "on frequency" with reference to some other standard by means of a synthesizer adjustment. The synthesizer frequency change is immediate, requiring no time to settle in.

Signal Distribution

Frequency Output

As shown earlier, the source of the final output signal of the hydrogen maser is a voltage controlled crystal oscillator (VCXO). This oscillator typically has only one or two outputs of its own, however its signal is required by many internal circuits as well as external equipment. It is the function of the distribution system to provide the necessary outputs required and to isolate the VCXO from the effects of extraneous signals and noise.
Figure 8 shows the frequency distribution system for the NASA NR maser as an example.

As you can see, there are many demands for the VCXO signal output. Since splitters introduce losses in the signal path, buffers are used to amplify the signal to the levels required by the circuits they feed. The buffers also provide isolation so that noise or other generated signals do not migrate between circuits. This is particularly important for the rear panel outputs since equipment connected to them will vary depending on the user. The isolation between these outputs is usually greater than 100 dB. The standard signal level of the rear panel outputs is 1 VRMS (+13 dbm) into 50 ohms.

<u>Clock Output</u>

Most masers will have a "clock" output. This is a 1 PPS signal, usually 0 to +5 VDC into 50 ohms. The pulse width may vary between masers. (The NASA NR maser pulse width is 20 milliseconds.) Figure 9 shows the clock output circuit for the NASA NR maser as an example.

The clock output circuit is basically a digital countdown circuit, dividing the VCXO output signal down to 1 PPS. Two completely separate outputs, each controlled by the microprocessor, are provided. They can be slewed independently in 200 nanosecond increments or synchronized together.

Monitor and Control

In its simplest form, the monitor and control function of the maser is provided by some analog meters and manual switches. However some masers go further, allowing remote monitoring and control of maser parameters and functions. In this manner, operating data can readily be logged to provide long-term characterization of the maser. Figure 10 shows a block diagram of the NASA NR maser Monitor & Control system as an example.
This system provides monitoring of 64 internal circuit parameters, 11 internal status monitors, as well as the status of ongoing internal maser processes. The front panel display and keypad provide local selection of monitor functions and control of numerous internal circuits such as the auto-tuner, synthesizer, cavity register, etc. In addition, the display provides a Julian date and time readout.

All of the above monitor and control functions are available remotely by means of three RS-232 I/O ports located on the rear panel of the maser. These ports can be connected directly to a local computer or to a modem for long distance monitoring.

Identifying Maser Problems

Although generally well behaved and reliable, masers do sometimes fail. Unfortunately, they sometimes fail in ways that are not blatantly apparent. Failures involving frequency stability, i.e., cavity temperature control, magnetics, synthesizer, or hydrogen source, are generally very subtle and sometimes will not become apparent until after an observation is correlated.

The key to successfully recognizing failures lies in the monitoring of maser data. It is important that the operator be familiar with the nominal values of key operating parameters, particularly those that indicate phase lock. If these parameters are off, then other parameters can be useful in troubleshooting the problem.

Most masers will have a means of monitoring, via meters or serial data, at least the following parameters:

- IF Level
- VCO Control Voltage
- Phase Lock Voltage
- Power Supply Voltages
- AC Power
- Various Temperatures and/or Heater Currents

Phase Lock Problems

The main thing to be concerned with prior to an observation is that the maser is in phase lock. Without phase lock, the data recorded during an observation will be meaningless since the frequency standard essentially becomes the internal VCXO, whose stability is several orders of magnitude less than that required for VLBI. The following parameters, in relation to each other, are the primary indicators of phase lock condition:

IF Level

The IF level is an indication of the strength of oscillations in the maser cavity. There is generally a pretty wide range over which the IF level can vary while still maintaining phase lock, however; no IF level means no phase lock. If the IF level has changed from its nominal value but the VCO control voltage and phase lock indicators are still okay, then the maser should be useable for VLBI, however, there will probably be a frequency offset. If there is no IF level, then the VCO control voltage and phase lock indicators will also be off their normal reading.

VCO Control Voltage

The VCO control voltage is an indication of where in the control range of the VCXO the phase detector is maintaining phase lock. (Some masers utilize a zero center meter while others use a zero to full-scale type.) Again, there is a range through which this voltage may vary while still maintaining phase lock. If this voltage has changed from its nominal value and the phase lock indicator is still okay, then the maser should be useable for VLBI.

Phase Lock Voltage

The phase lock voltage indicator shows whether the phase detector is operating within its capture range. There are different types of phase lock indicators. Some masers use a go/no-go indication such as an LED, while others utilize an analog reading of some type. The LED type is fairly self-explanatory and depends on the particular maser. The analog type gives a linear indication of where in the capture range the phase detector is operating. Again, there is a range through which this voltage may vary while still maintaining phase lock. If this voltage has changed from its nominal value but is still within range, then the maser should be useable for VLBI.

Note:
For masers that show the "purple light", this is NOT an indication of phase lock! It only shows that hydrogen molecules are being "dissociated" into hydrogen atoms in the source assembly. Although poor quality of the "purple light" can be indicative of a problem, good quality does not necessarily indicate a properly operating maser.

There may be minor long term changes to the above three parameters as components age, however, any sudden change could be indicative of a problem and should be investigated. Possible causes could be:

- VCXO (Off frequency.)
- Hydrogen source problems. (Contamination, pressure, state selection, source oscillator.)
- Vacuum system. (Pump failure, vacuum leak.)
- Cavity temperature change. (Controller failure, heater winding, thermistors.)
- Magnetic problems. (Maser is magnetized, C Field change.)

Power Supply Problems

Typically, when power supplies fail, they fail completely. When this happens, the maser will most likely exhibit noticeable problems such as no output or complete loss of phase lock, depending upon which supply failed. Low power supply voltage may or may not cause problems depending on the maser circuitry. (For example, if the internal circuitry utilizes local voltage regulators, the power supply voltage could vary a volt or two before becoming apparent to the operator.) If a change in power supply voltage is detected, it should be investigated immediately.

AC Power Problems

Make sure the maser has AC power prior to starting an observation. Although most masers have standby battery power, the batteries will not last the length of an observation.

Temperature Problems

The temperature control circuitry plays an essential part in the proper operation of the hydrogen maser. Temperature control problems will show up as a frequency offset, frequency drift, or, in worst case, loss of phase lock. (It takes less than 0.5 degrees C. change in cavity temperature to render a maser useless!) The method by which a maser monitors the temperature control circuitry, i.e., temperature vs. heater current, will determine how subtle a change an operator may be able to detect. Changes in heater current will be apparent before a change in the related temperature will appear. It is also important to remember that the temperatures within a maser are related. If you see one heater current go up, chances are another may go down. Variations in the ambient temperature of the maser environment will cause the heater currents to change as they try to maintain their temperatures.

Minor long-term changes of temperature or heater currents will occur due to component aging, however, sudden changes may be indicative of a problem. If changes are detected, check for phase lock before observing. Also check to see if the changes might be explained by a difference in the ambient temperature of the maser environment. Investigate the problem as soon as possible.

Using GPS to Identify Maser Problems

GPS data is instrumental in the characterization of maser performance. Long term data monitoring and analysis allows determination of frequency offset and drift. GPS data is also necessary for setting the time position of the maser.

Additionally, GPS data can be used to identify certain maser problems. Most problems that affect the frequency of the maser will eventually show up in the GPS data. The magnitude of the problem will determine how fast it will become noticeable. (The more subtle the problem, the longer it will take to become apparent.) GPS cannot, however, detect frequency stability problems down to the level that might corrupt VLBI data. Raw GPS data scatter is in the few hundred-nanosecond range. With averaging, this can be improved to tens of nanoseconds. Maser stability is normally in the femtosecond range, well below what GPS can resolve. Stability problems at this level will not become apparent until correlation.

Problems that might become apparent through GPS data are:

Loss of Phase Lock

This would generally show up as the data taking off in one direction and the rate would depend upon where in the control range the phase detector had been controlling the VCXO.

Thermal Problems

This could exhibit itself in several ways. It may show up as a change in the slope of the data (frequency offset), a curve in the data (frequency drift), or a combination of both.

Magnetic Problems

Magnetic problems usually show up as a change in the slope of the data (frequency offset).

1PPS Problems

This typically appears as a step or steps in the data but usually does not change the slope. The steps are generally additive in nature. In other words, the data (time position) will not return to its original position. If it does, it is more likely to have been a bad data point and not a clock step.

Summary

It is not expected that the VLBI operators be able to troubleshoot and repair a hydrogen maser. The intent of this presentation was to give the operator some means of determining the operational readiness of the maser prior to observing. But, in order to do this, the operators must be familiar with their maser's key operating parameters. A daily, or even once per observation, log of parameters such as phase lock indicators (IF level, VCO voltage, & phase lock voltage), power supply voltages, ambient temperature, and GPS time position would be most helpful in establishing a baseline against which the operational readiness can be measured and could also help in predicting failures. This could be a handwritten log or, if your maser is capable, a dump of operating parameters to a computer. As most masers have a "personality", there is usually no fixed operating range for a given parameter that will be useful in determining the operational status. The operator needs to look for "changes" in parameters that would affect the maser's performance. In order to detect these changes, a baseline must be established.

$$\text{Required Stability} = \frac{\dfrac{\text{Baseline Precision}}{\text{Speed of Light}}}{\text{Observation Period}}$$

$$= \frac{\dfrac{2 \text{ Millimeters}}{3 \times 10^{11} \dfrac{\text{Millimeters}}{\text{Second}}}}{600 \text{ Seconds}}$$

$$= 1 \times 10^{-14}$$

---------------- **OR** ----------------

$$\text{Required Stability} = \frac{\text{Time For X-Band Waves To Move One Radian Of Phase}}{\text{Observation Period}}$$

$$= \frac{\dfrac{1 \text{ Radian}}{8 \times 10^{9} \dfrac{\text{Cycles}}{\text{Second}} \times 2\pi \dfrac{\text{Radians}}{\text{Cycle}}}}{600 \text{ Seconds}}$$

$$= 3 \times 10^{-14}$$

Figure 1. Stability Requirement For VLBI Frequency Standard

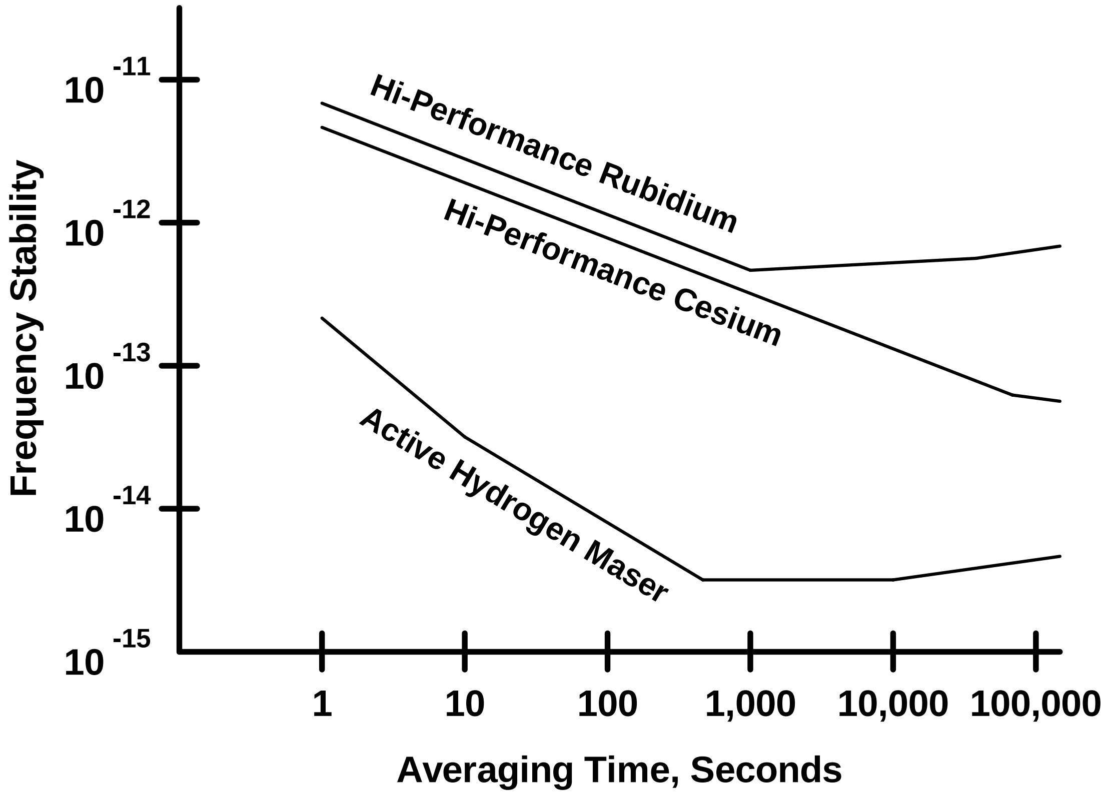

Figure 2
The Hydrogen Maser is the Preffered
VLBI Frequency Standard

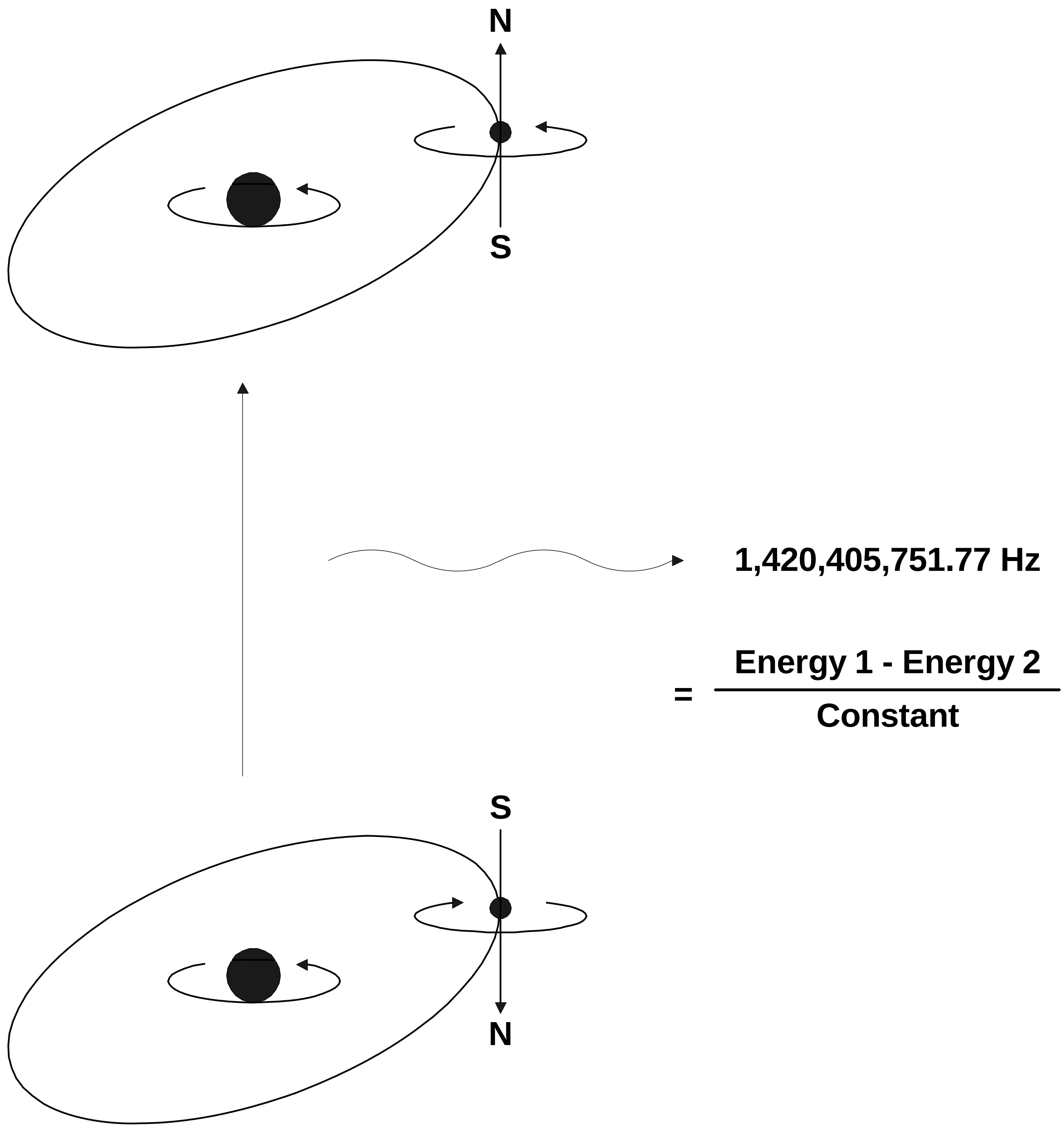

Figure 3

The Hydrogen Atom--
Source of the Maser Frequency

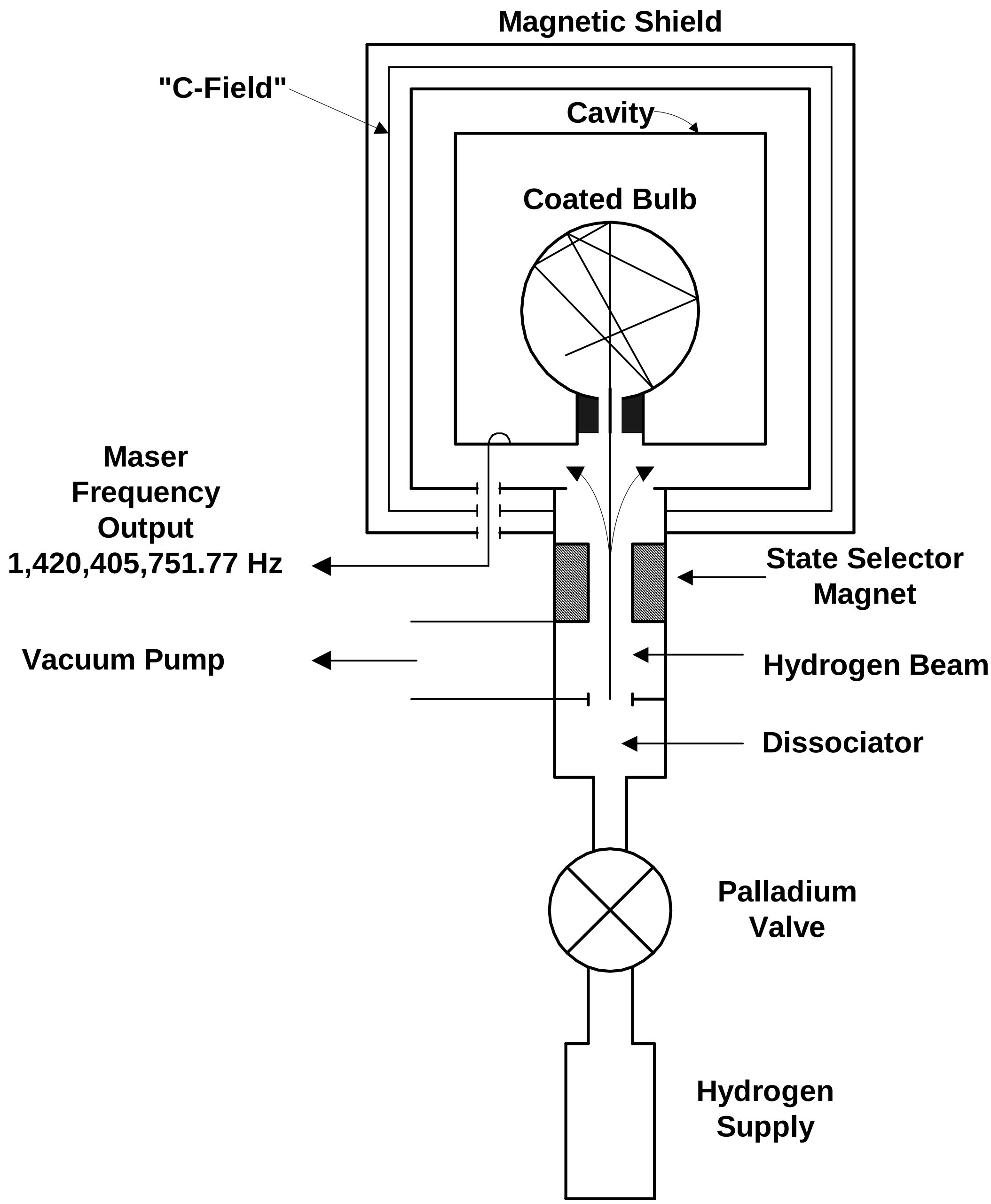

Figure 4
Schematic of Active Hydrogen Maser

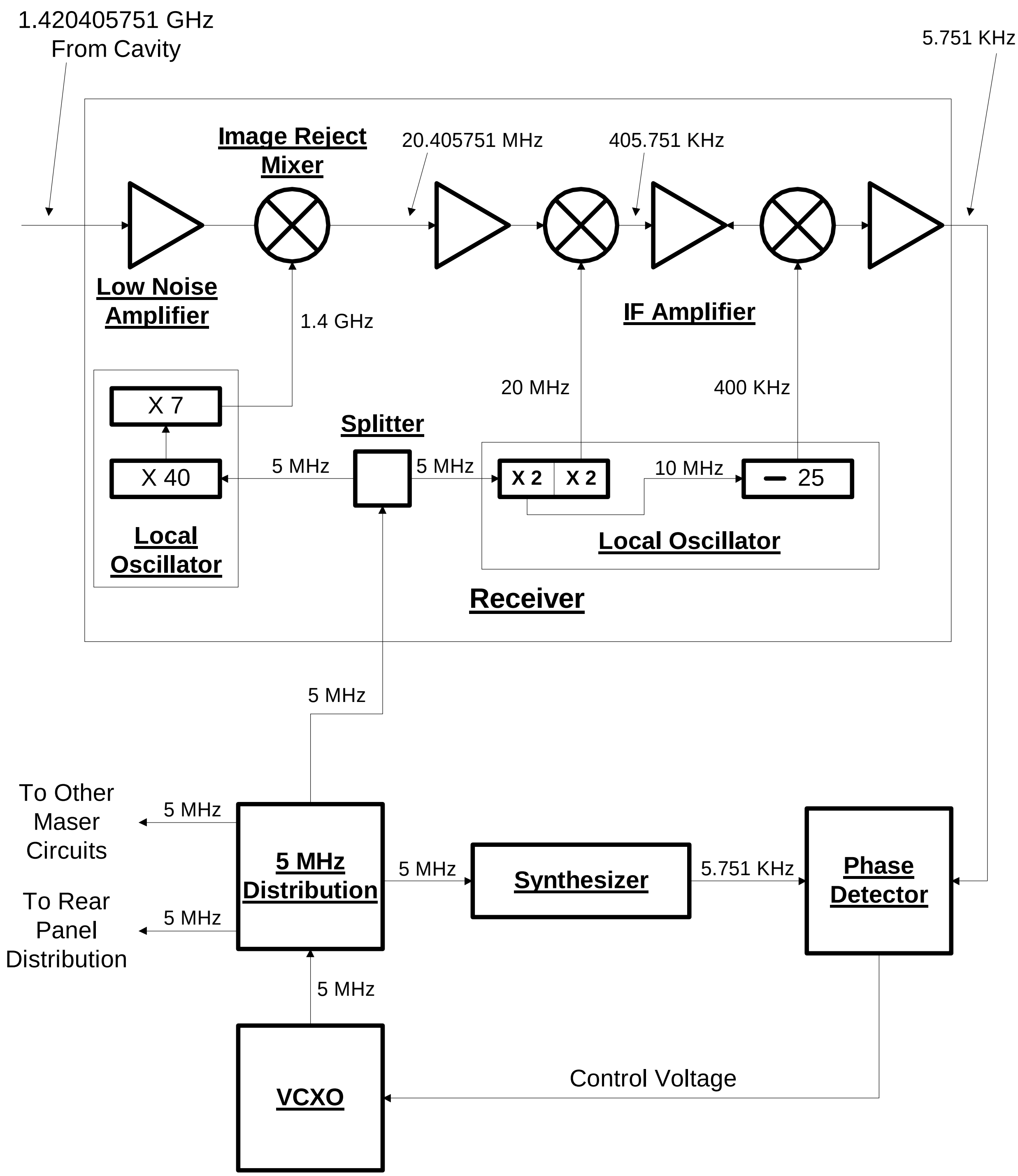

Fig. 5 NASA NR Maser Phase Lock Loop

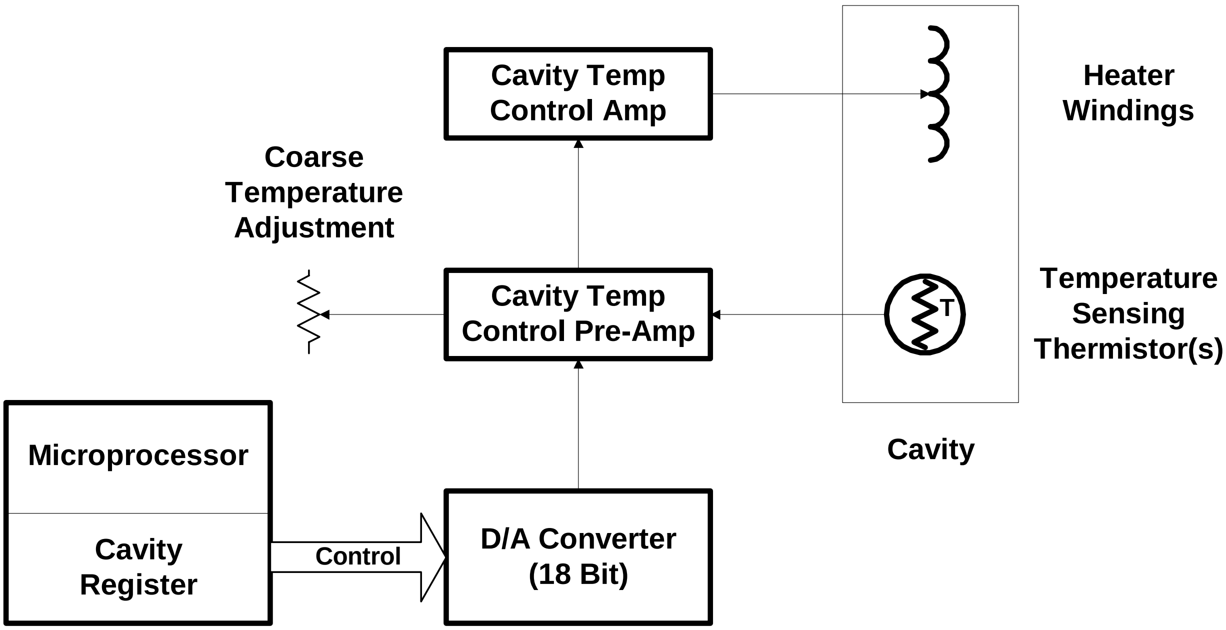

Fig. 6 Thermal Cavity Control
(as in the NASA NR Maser)

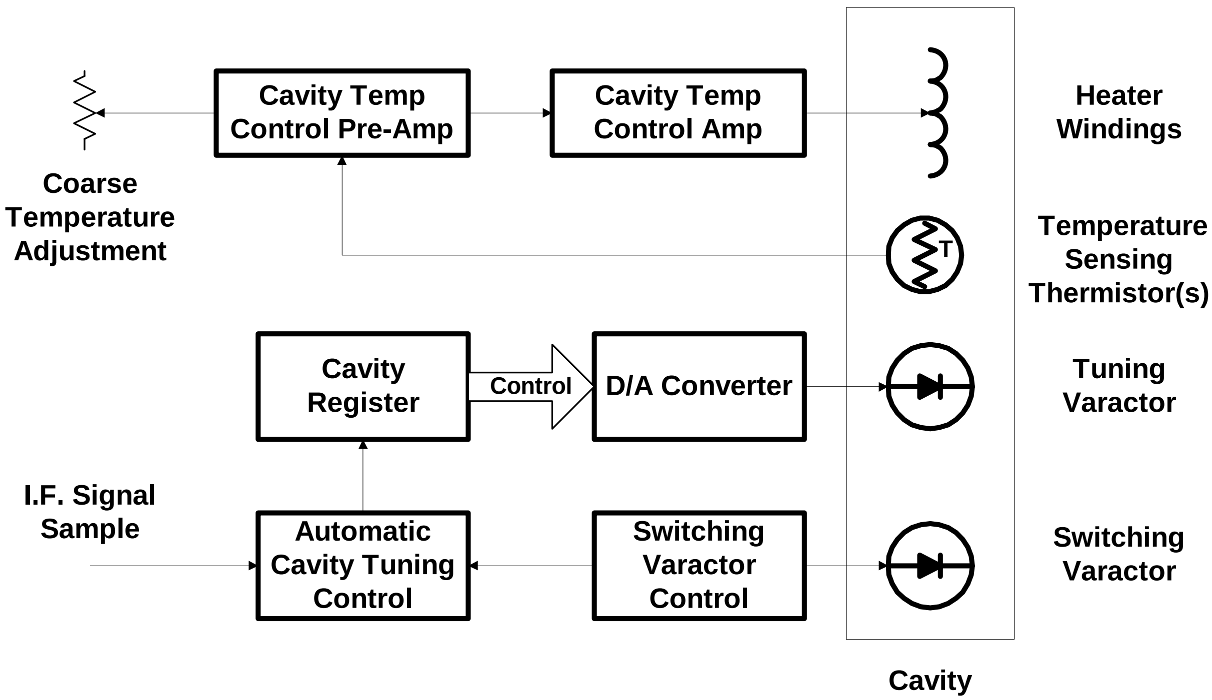

Fig. 7 Varactor Cavity Control
(as in the Sigma Tau Maser)

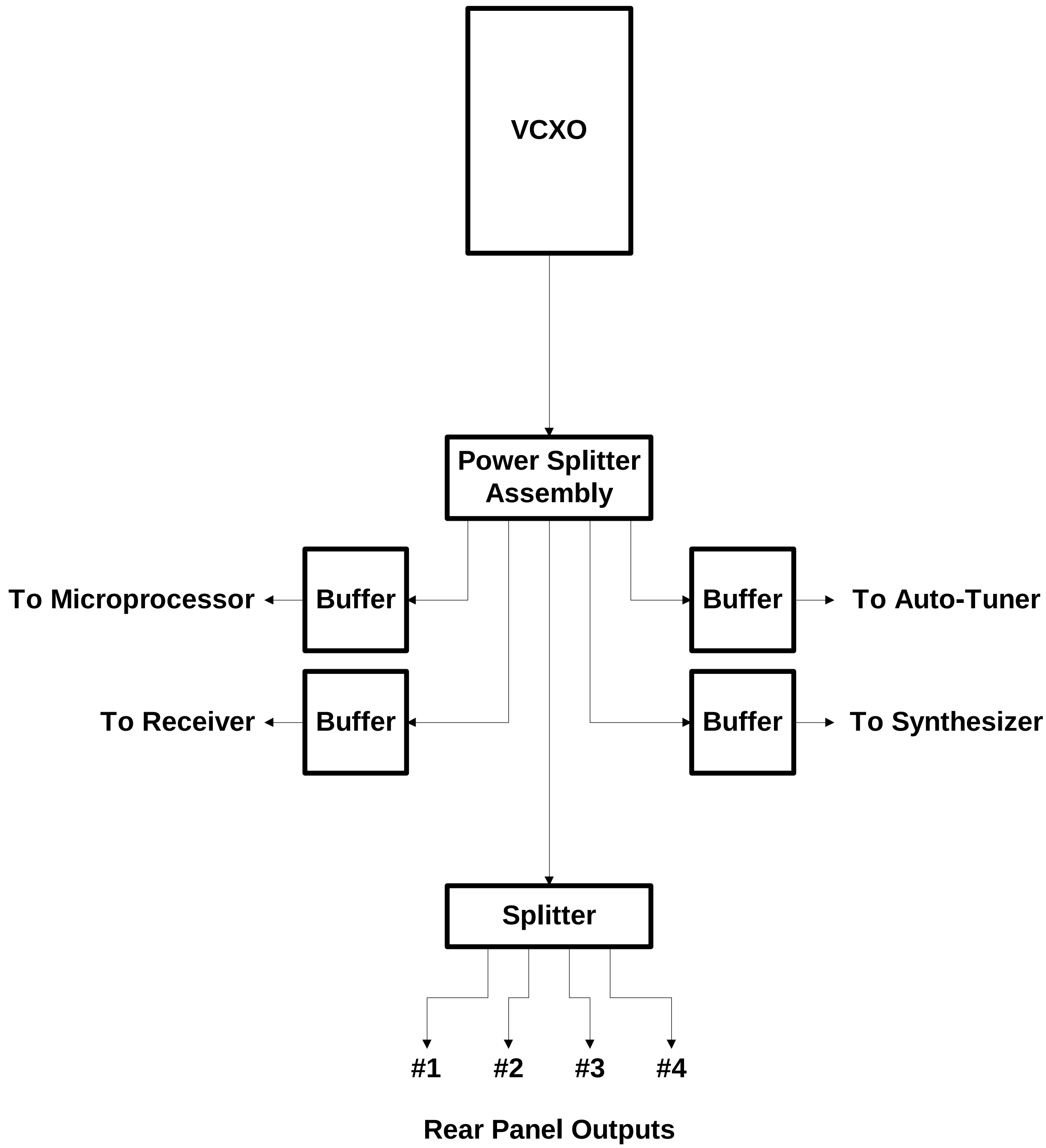

Fig. 8 NASA NR Maser Frequency Distribution

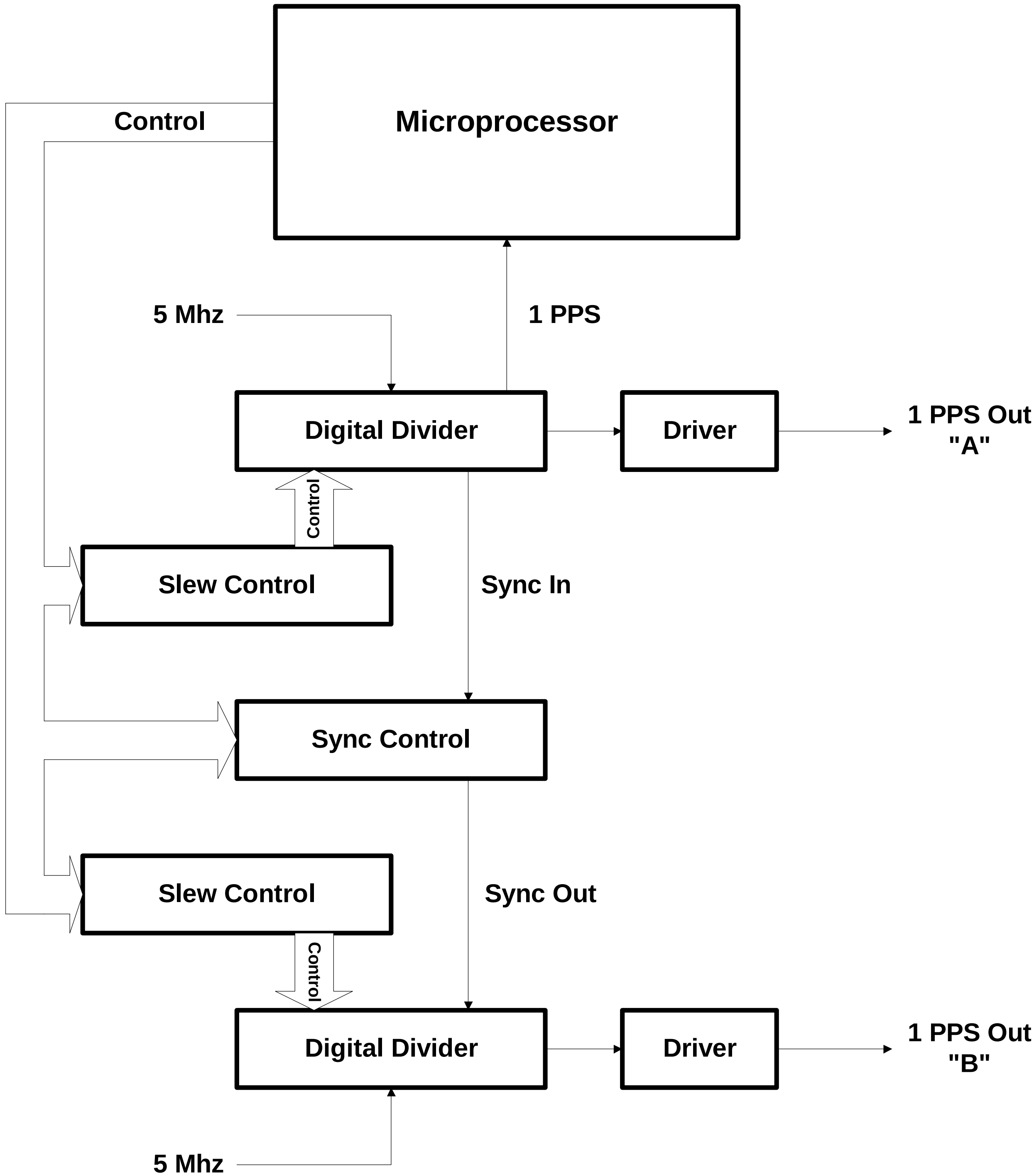

Fig. 9 NASA NR Maser Clock Output

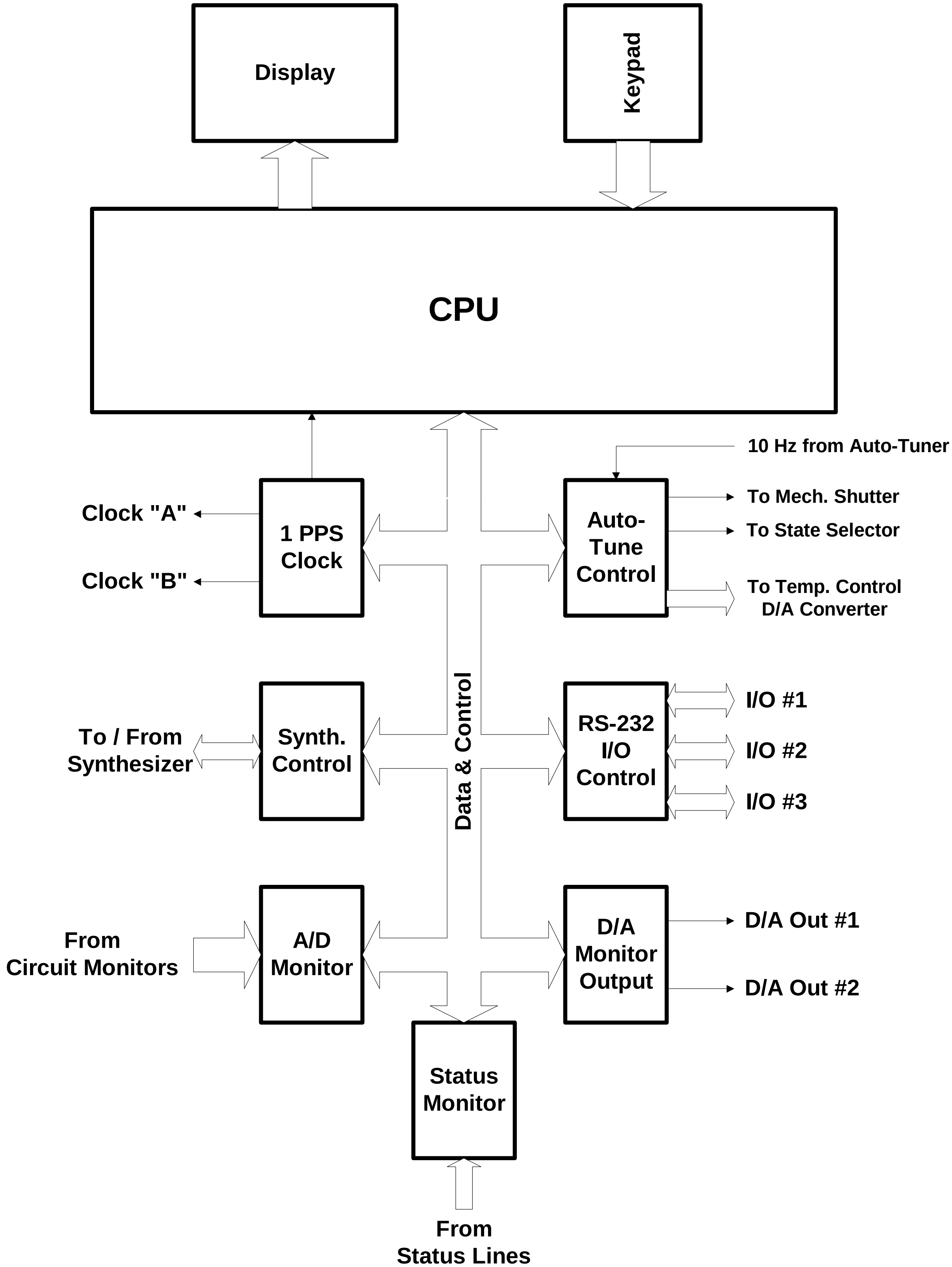

Fig. 10 NASA NR Maser Monitor and Control