Sigma Tau MHM-A1 Lives Again

By Skip Withrow

Acknowledgement

Without the help of Dave Howe and Bryan Owings this tale could not be told. I am grateful to consider them both mentors. Dave and Bryan have spent part of their valuable time to make introductions, answer questions both in person, by phone, and email, and especially educate. I feel like Alice in Wonderland, and I have definitely jumped down the hydrogen maser rabbit hole. Thank you both.

Prologue

In the winter of 2019, a fellow ham interested in time and frequency, and knowing my interest in hydrogen masers, introduced me to Dave Howe at a hamfest. Dave worked for both NIST and the University of Colorado and we had a remarkably interesting conversation. In passing, Dave mentioned that they had a maser at NIST that needed work and asked if I would be interested. Duh.

He invited me to NIST and we moved the maser to a lab where every week or two I would come up and play with NIST-ST1. After several months, a replaced DC/DC converter, and a rebuilt source oscillator the maser was operational again. I posted this to time-nuts just before COVID hit in the Spring of 2020.

During the debug of NIST-ST1 Dave and I spoke with Bryan Owings at Microchip (that acquired Sigma Tau/Datum/Symmetricom/MicroSemi). Bryan started with Sigma Tau in 1986 and has an incredible depth of knowledge regarding their product. I was fortunate to meet Bryan at NIST on one of his visits to service other NIST masers. Of course I had to ask if Microchip had any derelict masers sitting in the back room. He indicated no but did put me onto two that were sitting broken elsewhere.

That lead did not pan out. But in late 2020 Bryan told Dave of a maser at JPL that was in need of repair and was sitting in a storeroom. Dave knows JPL well and started negotiations to see if the maser could be acquired. I was hoping that it could be declared surplus, but that seemed to have some paperwork hurdles. Dave investigated getting it transferred to NIST, but that didn't seem to go anywhere either. Finally, Dave was able to push through a transfer to the University of Colorado.

I volunteered to transport the maser, so off to JPL I went. I have to thank Bill Diener at JPL as he was the one who called Bryan Owings when they were cleaning out the storeroom, and gave me a nice tour of the time and frequency facility (including several mercury ion clocks, a sapphire whispering gallery clock, an array of masers, and the obligatory cesiums).

Photo 1 & 2 – MHM-A1 at JPL. You can see the wires hanging out the front, there was also a pot hanging out the back corner. It was palletized, wrapped in heavy plastic, packing blankets, and finally the blue tarp.

A History of MHM-A1

The maser that I transported back to Colorado turns out to have quite a history. It was originally manufactured starting about 1982 and was delivered to Johns Hopkins University Applied Physics Laboratory in 1985. The MHM designation stands for ‘medium hydrogen maser’. Harry Peters, the founder of Sigma Tau after retiring from NASA, built one SHM (small hydrogen maser) for the Air Force. This was an active maser (with Q enhancement), but it did not have the stability he desired. He then abandoned the SHM effort in favor of the MHM, an active maser design with a larger cavity and bulb. The first two MHM units were built simultaneously, one for APL and one for the Naval Research Laboratory (NRL).

MHM-A1 was classified as a developmental maser. Later production MHM units bear some strong resemblance, but the APL unit used no etched circuit boards. Most of the circuitry was built deadbug on brass boards and enclosed in aluminum boxes. The more complicated digital circuits were assembled on perforated prototype boards.

You can read all about the development of these two units in DESIGN AND PERFORMANCE OF NEW HYDROGEN MASERS USING CAVITY FREQUENCY SWITCHING SERVOS (H. E. Peters, 38th Annual Frequency Control Symposium – 1984, time.kinali.ch/ptti/ptti1984.html p.420). As the title alludes, these were the first two masers to ever use a cavity frequency switching servo. There is a picture of the two masers on page 424.

JHU/APL used this maser for travelling clock experiments to USNO starting November 1985. You can check out PORTABLE HYDROGEN MASER CLOCK TIME TRANSFER AT THE SUBNANOSECOND LEVEL (19TH Annual PTTI Meeting 1987, time.kinali.ch/ptti/ptti1987.html p.345). There is another picture of the maser on page 355 (referred to as ST-1).

When I picked up the maser at JPL all the documentation was gone except for a logbook that had been on top of the maser. Fortunately, there is a lot of information that can be extracted. MHM-A1 (sometimes referred to as MHM-APL) was transported to JPL in April of 1989. JPL did a bunch of environmental tests on the unit until 1992 when it appears to have gone to Stanford in April and returned in November 1992.

MHM-A1 spent the next nine years at JPL chugging along with a few problems along the way. One of the vac-ion pumps was replaced in 1997, there were problems with the +15 volt supply in 1998, and the DAC in the cavity register was replaced in December of 1998.

Then, on February 1, 1999, MHM-A1 was put online as the master clock for the deep space network (DSN). This lasted until July 8, 1999, when something went wrong, and it was taken offline.

It was determined there were outer oven temperature control problems. Efforts were made to debug through December 1999, but to no avail. It was left running (unused) until December 21, 2011 (12 years!), when it was turned off, the batteries disconnected, and moved to the storeroom. I picked the unit up at JPL in February 2021 (9 years in storage).

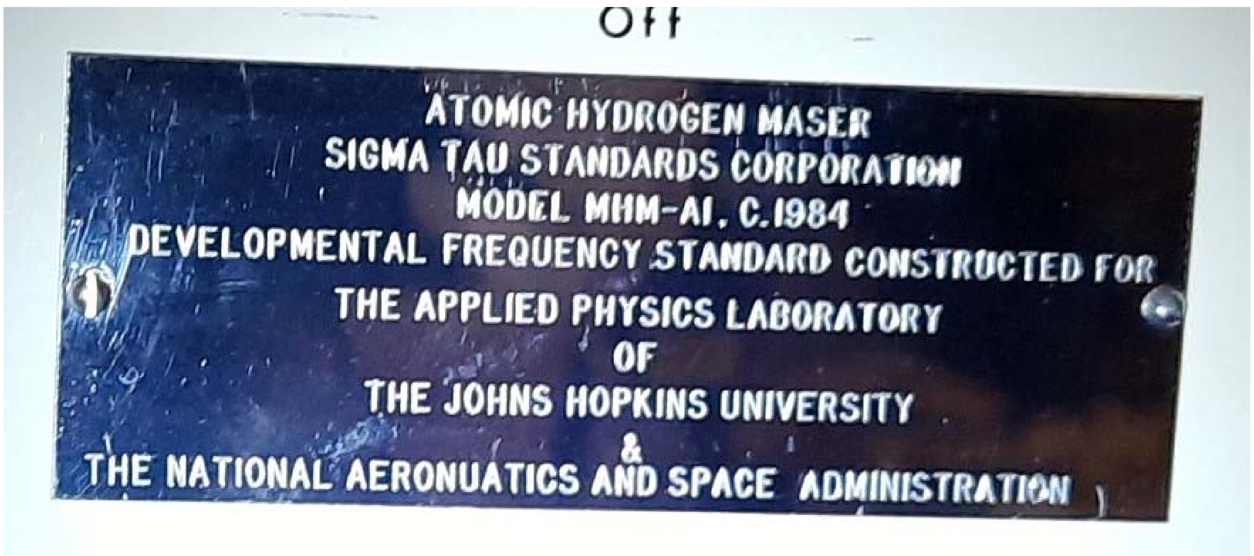


Photo 3 – This plaque is on the front of the unit and the only identifying information. It can be seen in the 1987 PTTI paper, so was there from early in its history.

The Fun Begins

So, Dave Howe said I had free reign with the maser to try and get it running and assess its stability. Twelve months later it is an ongoing effort. However, considerable progress has been made and it is a running maser.

The first assessment of the condition wasn't pretty. There was a half dozen wires hanging out of the unit from JPL's debug efforts. A trim pot was also hanging out with unknown function. When the unit was powered up the vac-ion pumps would not start, so vacuum had been lost. The pressure gauge on the hydrogen supply also read zero. And there was a known problem with the outer oven temperature control.

First thing to do was get the vacuum pumps working. I tried to mechanically pump the system, which got one of the pumps to start (the older of the two). Finally resorted to borrowing a turbo molecular pump to get both vacuum pumps to start. Then the waiting began. It took several months to get it pumped down to where I was comfortable with trying to light the unit up.

But I needed hydrogen to do that. I ended up opening the pinch off for the H2 supply and attaching plumbing that would allow me to refill with a small H2 bottle.

With vacuum and hydrogen, it was time to light it up. Which, unbelievably, it did – for a while. Try as I might I could not get it to relight, so it was time to pull the source oscillator. Well, there's a problem – one of the mica caps is just about burned in half. So there goes another couple of months working on the source oscillator, getting it lit (for a while), and working on the source oscillator some more.

In the meantime, I lose hydrogen pressure (from a leak in my plumbing). So, it's order more H2 and work on the H2 plumbing.

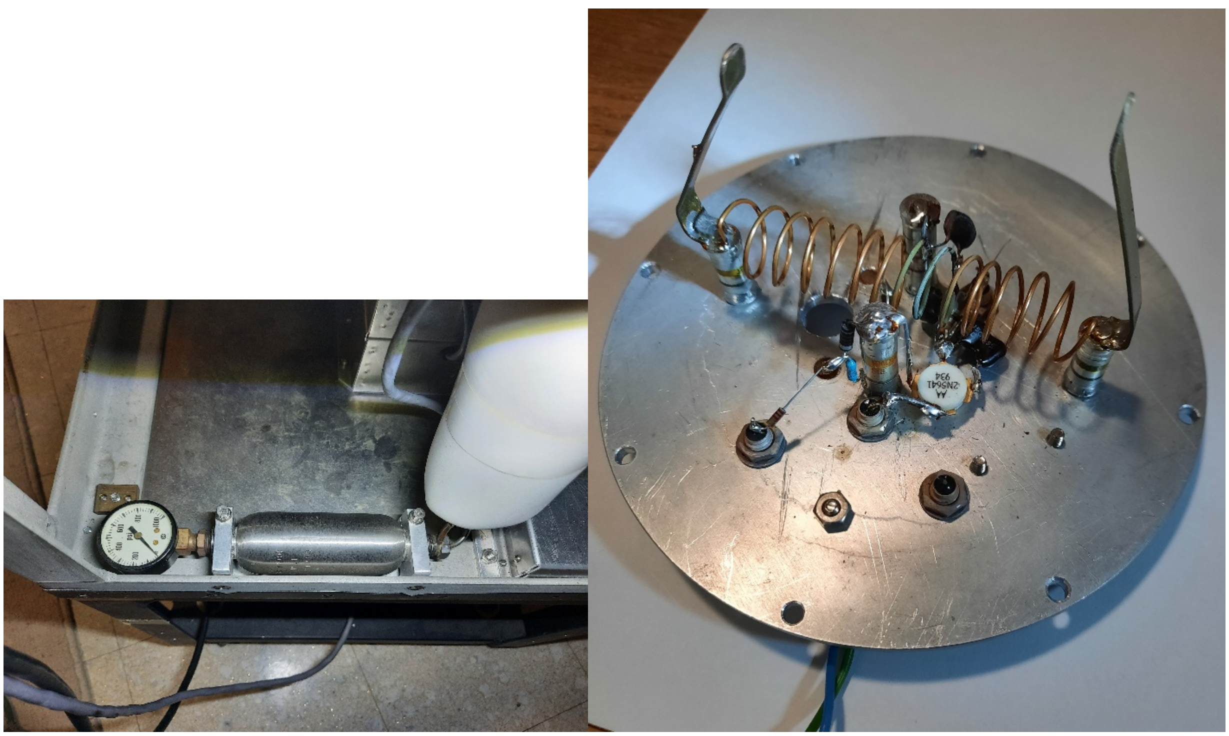
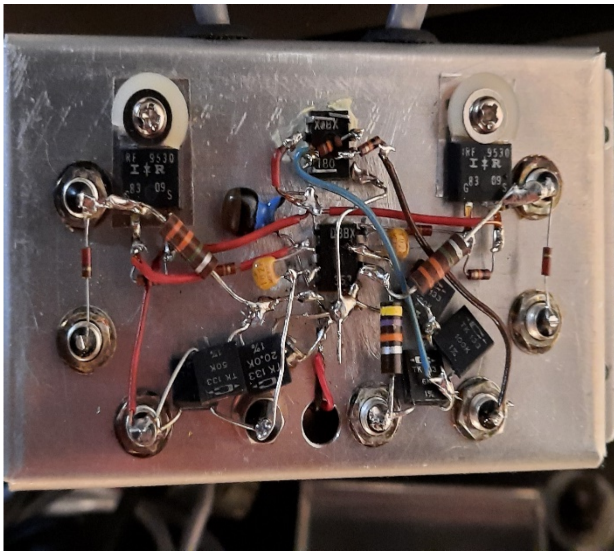


Photo 4 & 5 – A picture of the H2 bottle when the covers were taken off (the palladium leak is under the insulation at right) and the RF side of the source oscillator. Definitely some current was going through the center part of the coil, the mica cap that was partially burned in half is at the back across that turn of the coil.



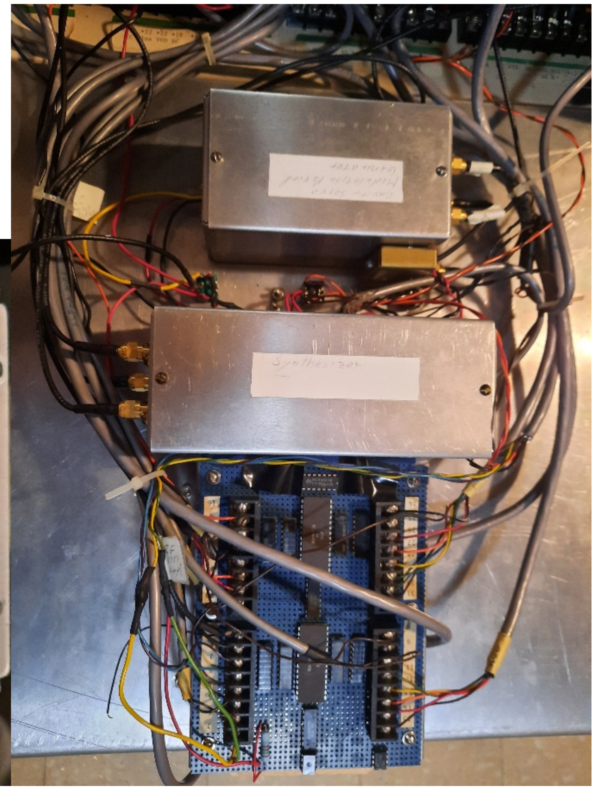


Photo 6 & 7 – Typical construction techniques used in the maser. At left is the Lower Support and Outer Oven power amplifier. At right is the view of the back of the front panel when folded down, the MPG and synthesizer are in the aluminum boxes and the telemetry perf board is below them (the display meter is underneath).

The Outer Oven Rears Its Ugly Head

By September of 2021, the maser was finally lit, but no I.F. reading (it was not masing). An email from Bryan Owings suggested that I needed to measure the cavity resonance frequency. To do this the top of the maser has to be disassembled to get down to the vacuum chamber and connection to the internal cavity antenna. This was done and a synthesized frequency generator used to deliver a signal to the cavity and look at the reflected energy via a directional coupler and power meter.

By disconnecting the oven heaters and powering them with lab supplies I could control the cavity and outer oven heaters and plot temperature (inner oven thermistor value) versus resonant frequency. With all the wires and cables running out of the unit and all the test equipment sitting around it looked like the maser was on life support. After a little tweaking I thought I had it spot on and buttoned things up.

That is when I noticed the outer oven voltage doing strange things occasionally. My trusty chart recorder came in handy, and I discovered that the outer oven was intermittently (very) noisy. The worst of both worlds, intermittent and noisy. I chased this problem for at least a month. And finally came to the conclusion that the outer oven thermistor was noisy after lots of debug of the control amplifier. So, tore down the insulation and magnetic shield on the circumference to get to the thermistors and replaced them. Put it all back together and fired it up, nope, same problem. I should know better, always open the loop to debug a closed loop system. So, after another debug session found that there is a power driver amplifier mounted in another part of the maser. Indeed, that is where the noisy component resided. JPL would have never found the problem with their trimpot hanging out the side of the unit as they were debugging closed loop as well.

What a relief to get that problem behind me. So, there is vacuum, hydrogen, source is lit, wow there is I.F. Houston, we have a maser!

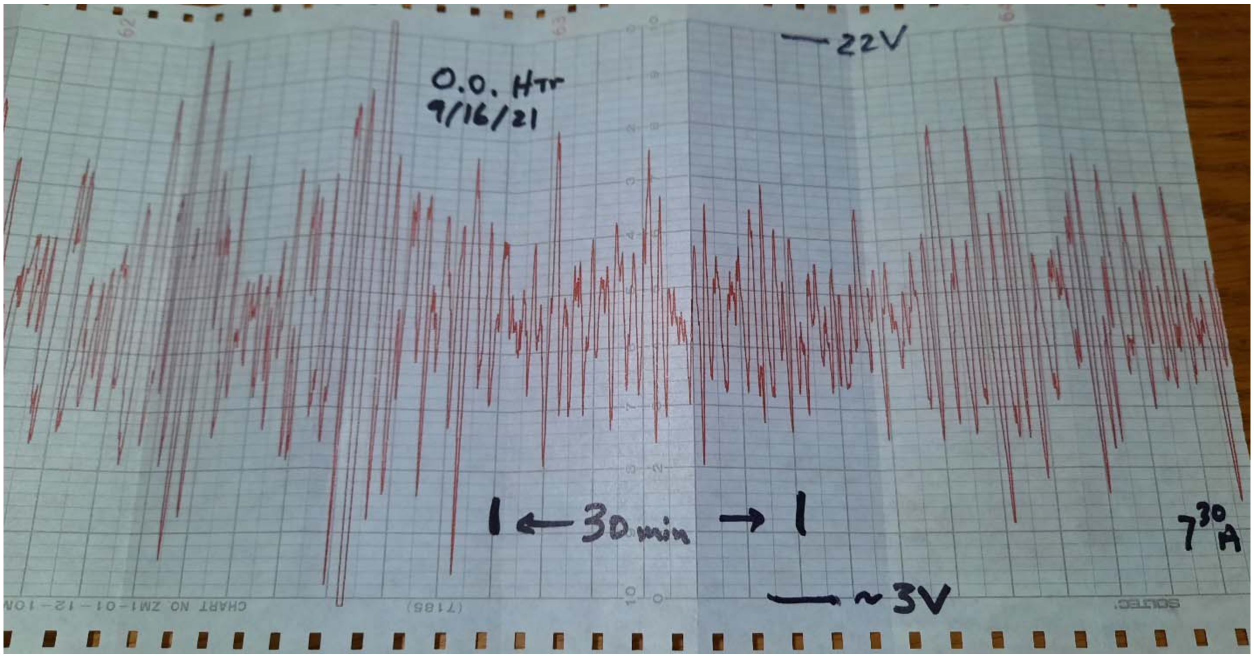


Photo 8 – This is not what you want to see when it comes to maser temperature control.

Not So Fast

There is no doubt this was significant progress for a maser that had not been touched in over 20 years. Also, about this time Bryan Owings sent me a scan of the original MHM-A1 manual that he had found. The original had obviously been printed on a dot matrix printer, it screamed 1980's. Unfortunately, there were no schematics. To this point I had been relying on a copy of the NIST-ST1 manual which did have schematics. The block diagrams were basically the same, and in most areas the schematics were helpful, though a lot of reverse engineering has occurred in certain areas.

NIST-ST1 was manufactured in 1989-1990 some twenty units later, and by that time a third vac-ion pump had been added, a LOCK detection circuit had been added, the cavity servo was done with a varactor diode instead of modulation of the cavity oven, a 100MHz output had been added, and a microprocessor had been added such that telemetry could be dumped via a serial port.

Reading the original MHM-A1 manual gave me a chance to step back and look at the big picture instead of being laser focused on the particular problem at hand. To this end, I went through all the telemetry channels and discovered that one of the 24 volt supplies was reading zero. The maser uses two redundant 24 volt supplies. On this maser one is inside the unit and the other is in the lower rack and also charges the battery. It was the lower one that was dead, its output voltage is set a bit higher than the other supply and assumes the primary role (to keep heating inside the cabinet to a minimum). However, it had died and I had been running on the supply inside the maser cabinet the whole time. The dead supply was replaced and now the supply in the cabinet is performing its backup role. The supply must have died during the 12 years that the unit set unattended as the last entry in the logbook shows it good.

But I was still having intermittent problems with keeping the source lit. Some of it was my fault from tweaking on the source oscillator. I learned – if it ain't broke, leave it alone. The question was, was I having problems with the H2 supply, the vac-ion pumps, or the source oscillator? To answer the question five channels of the telemetry had to be monitored. On the APL maser there are 32 channels of telemetry data that are selected via 5 toggle switches on the front panel and displayed on a 4-1/2 digit panel meter. A very tedious exercise when multiple channels are involved. There is also the option to supply the five binary digit address and read the analog voltage via a DB-25 connector on the rear panel.

Bryan Owings suggested that I needed to log the maser on a continuous basis. So a LabJack data acquisition device was acquired and hooked to a WiFi USB port server. I wrote a python script to collect all 32 channels of data and store it in a database every hour. My son actually wrote the database user interface that takes a start date and end date (via dropdown calendars) and channel(s) selection via check boxes and produces an auto-scaled graph of the data. It works very nicely and has been a huge help.

Next step was to turn on the cavity servo and see if it would lock. This servo works by modulating the cavity frequency with a varactor diode and detecting the output amplitude at the higher and lower frequency. A synchronous detector is used to steer the cavity temperature such that the I.F. amplitude is the same for both modulation periods (cavity centered on hydrogen frequency).

The process is worse than watching paint dry. The nominal cavity heater runs between 24-95mW. The cavity itself is made from about 40 lb. of copper with glass components inside and a thermal mass of 5000 W-s/°C. The thermal time constant of the maser is well over a day. The servo loop acquisition runs even slower than this, so it is very much a wait and see process.

With the cavity servo turned on the cavity register started incrementing (which cools the cavity). After several days it finally hit the upper limit, meaning the cavity was too hot. Looking at the I.F. signal I knew I was close, but another session with the temperature control settings was in order. Which meant disassembly down to the top of the vacuum chamber where they resided.

This was also about the time I decided to add the backup batteries that had been removed before leaving JPL. Googling the Exide battery that was in the manual got me nowhere. But after making some measurements I acquired two Group 75 batteries and made slight modifications to get them to fit the hold down brackets.

One day while waiting for temperatures to settle I decided to examine all the telemetry channels. I had never really looked at the mundane (mostly power supply) values in any detail. Before the database it was almost impossible to discern trends but now examining historical data was easy, and with the auto-scaling graphs great detail could be seen when an individual channel was observed.

This is when I noticed that the VCO supply (which also feeds the output buffers and receiver circuits) had about .4 volt of variation in it. How could this be? The 23 volt main bus that fed it was stable, and there was a filter between that and the VCO bus. Turns out the filter choke was about 2 ohms, so there was a 200mA variation in supply current. When I put a voltmeter on the VCO bus you could indeed see the voltage going up and down. Time for the trusty chart recorder again, which showed a very interesting square wave with a 15 second period. Nothing in a maser runs that slow!

With a little more tracing (and a quick accidental short of the +23 bus that extinguished the source, dammit) the culprit was clearly the VCO itself (an Austron 1120L). The heater was operating in a bang-bang mode and the data sheet clearly says it is a proportional oven. The oscillator was extracted from the maser and opened up (I have worked on several similar Austron 1150 units in the past) where two open wet slug tantalum capacitors were found to be the problem. The unit was repaired, reassembled, and installed back in the maser. The VCO bus voltage is now steady as a rock (as it is meant to be), most likely this failure also happened during the 12 year unattended operation period as well.

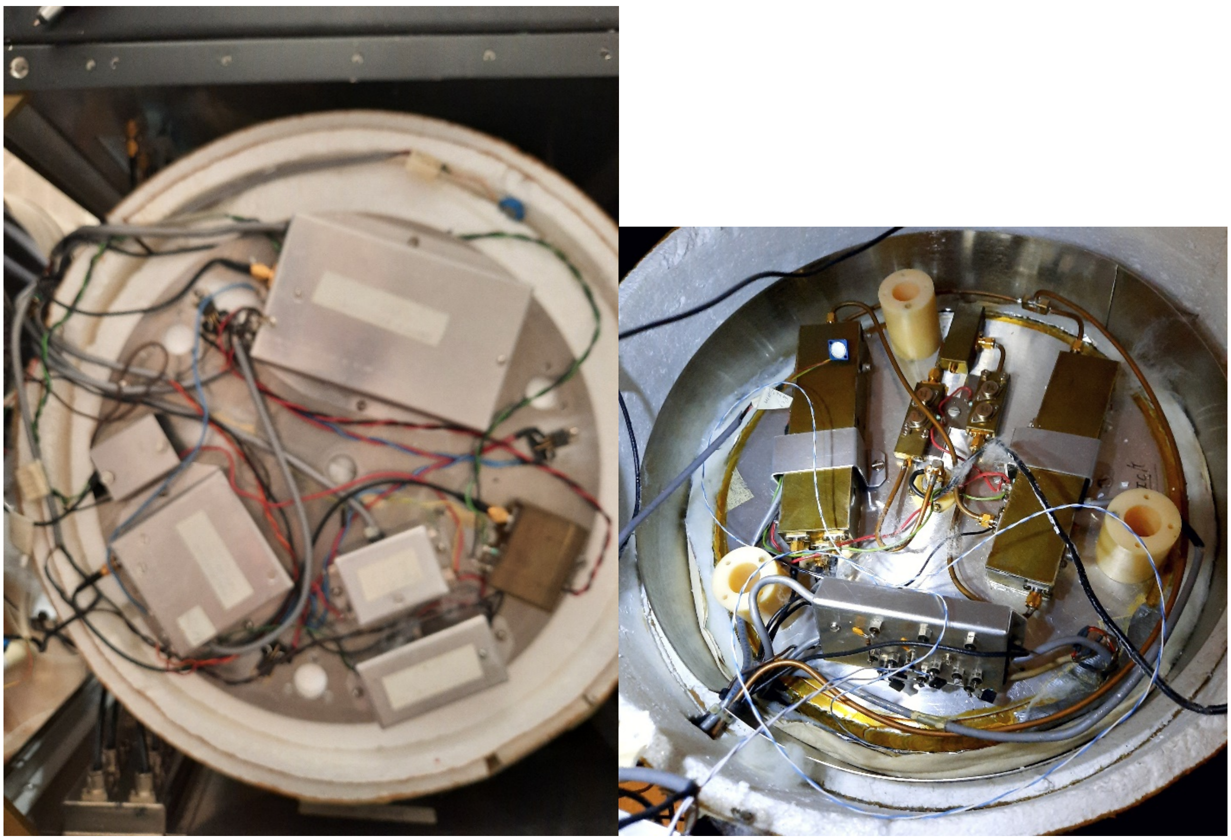


Photo 9 & 10 – A (not so good) picture of the Top Plate. At right is the top of the bell jar with the RF electronics attached. The temperature controller for the cavity, outer oven, and lower support has been tipped up to access the circuitry.

It Finally All Comes Together

I was so close that I could taste it. With the cavity and outer oven temperature control resistors exposed the inner oven was first adjusted (by monitoring the modulated I.F.) to get it on frequency.

Then, the outer oven was adjusted to fine tune the inner oven voltage while maintaining a reasonable outer oven heater voltage.

Another session of waiting, and it all comes together. What a feeling when you see the ramp of the cavity register suddenly flatten out on the telemetry graph! The cavity servo was locked, MHM-A1 was truly a maser again.

Now I was down to the tweaking stage. One of the things that I did was increase the I.F. level just a touch by increasing the H2 flow to get it above 1.0 volt.

At this point I hooked up a GPS frequency monitoring system for the first time and was surprised that the frequency was much closer than I expected. After letting it run overnight the maser measured -4.0x10E-13 slow. An appropriate adjustment was made to the synthesizer to get it closer to being on frequency.

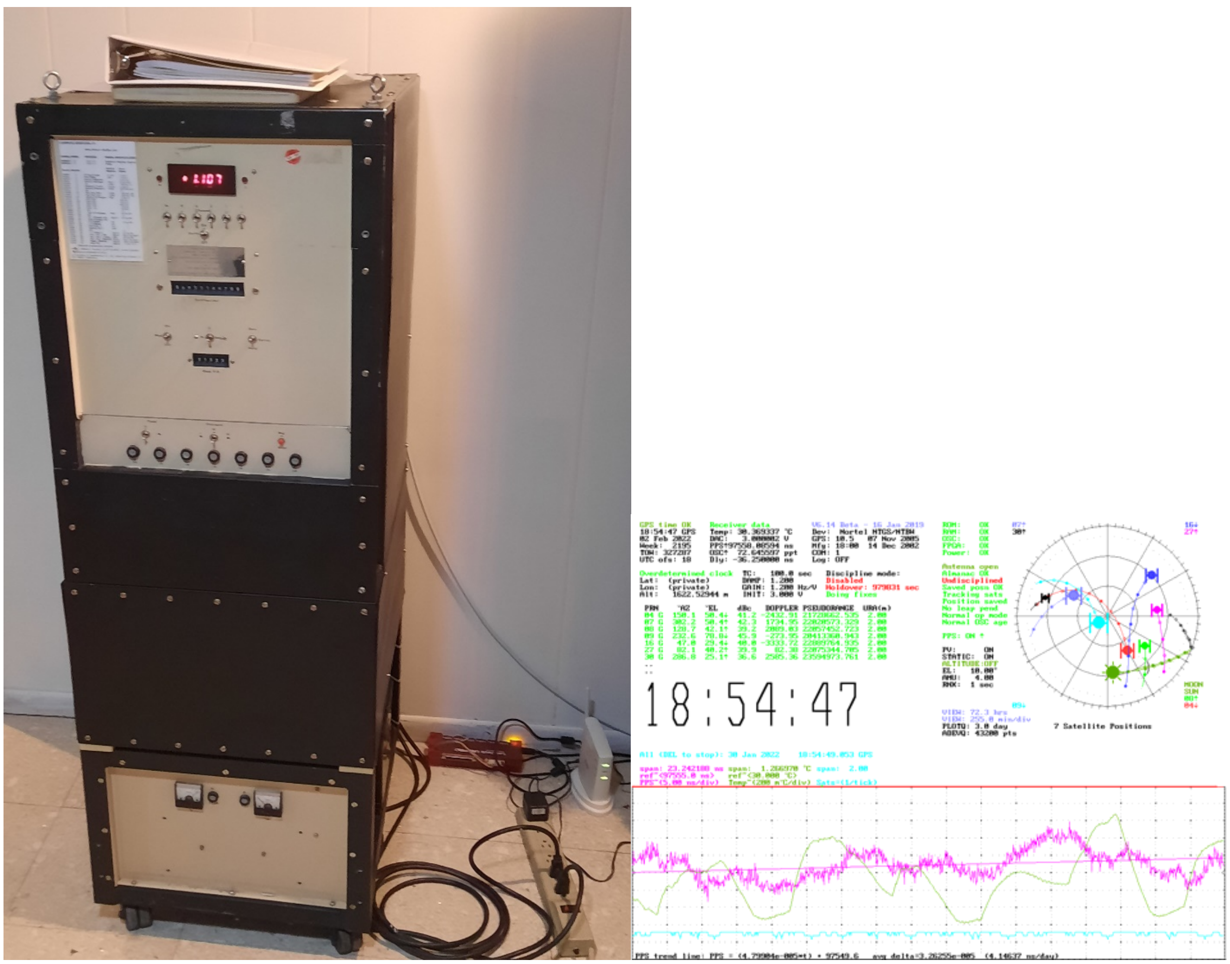


Photo 11 & Chart 1 – MHM-A1 is running again. Still a few screws to put in the covers. Have it running about 4ns slow over three days a little more than a week after first cavity register LOCK.

Hydrogen Maser 102

I have to admit I feel like I have made a lot of headway with MHM-A1. But it seems like there is a long road ahead as well. There is the issue of degaussing, that I really would like to avoid, but may be necessary. The C-field and neck coil settings may need to be adjusted. Spin exchange tuning with the modulation period generator (MPG) is also an exercise that I have never tried but probably should.

Beyond that there are aging and stability that need to be evaluated. I'm hopeful that GPS can be used with long enough observation times. The possibility of using post processing of L1/L2 data is being considered to get higher accuracy.

So, there are a few more chapters to be written in this story. Hopefully, it is not another year down the road until the next report. And my wife keeps asking me – "and you think this is fun?"