35th Annual Precise Time and Time Interval (PTTI) Meeting

THE STATE OF THE ART IN AMATEUR TIMEKEEPING

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Abstract

One might assume precise time metrology is the exclusive domain of national scientific laboratories, military infrastructure, or professional calibration centers. But there are a number of amateurs who in recent years have built home timing labs purely as a hobby, the performance of which now rivals that of some national labs. An even larger number of individuals, perhaps hundreds, own atomic standards and use them to satisfy or fuel their curiosity about the world of ultra-precise timekeeping.

The following paper describes an extreme case of one home timing lab. First, its motivation and history: from a pair of wrist watches 30 years ago, accurate to seconds per week, to a pair of active hydrogen masers today, stable to parts in ten to the 15th.

Second, its accomplishments: in the form of Web-published experiments, including stability analysis of TCXO and OCXO, stability comparison of 12 GPS-disciplined oscillators, probing the cesium hyperfine clock transition, hydrogen maser auto-tuning results, GPS performance with and without selective availability, homemade software tools, and PC-based instrumentation systems.

Finally, the paper describes the technical challenges that a home timing lab faces, many of which are the same challenges as a national timing laboratory, though on a smaller scale. Solutions to such problems as budget, power, temperature, space, redundancy, time transfer, security, computer logging and networking, and automated operation are discussed.

INTRODUCTION

Twenty years ago it would have been unlikely for a private individual to have an atomic clock at home. With few exceptions, precise time technology was used exclusively by professionals at national scientific laboratories, the military, and a small number of specialized commercial companies.

But in the past 10 years, an abundance of military, dot-com, and telecom surplus has made it possible for motivated individuals to obtain yesterday's start-of-the-art timing technology for personal use today. High-end precise timekeeping instruments, such as atomic frequency standards and frequency counters, VLF receivers and phase comparators, and Loran-C- and GPS-disciplined oscillators can be hunted and purchased for cents on the dollar.

Today, hundreds of individuals own rubidium, cesium, or GPS-based frequency standards and are keeping time at home to fractions of a microsecond. Many of these people are ham radio operators who have a technical appreciation of, and need for, precise frequency. Some are retired military personnel who are nostalgic for gear they used years ago in the service. A few are curious engineers who enjoy the challenge of building clocks with ever increasing accuracy. Others are clock and watch collectors who want to augment their mechanical collections with specimens of modern electronic timekeepers.

Whatever the circumstances, precise timekeeping is a historically rich, intellectually stimulating, and technically challenging field. Amateur time enthusiasts join mailing lists such as *time-nuts* or *TACGPS*. The latter was started by Dr. Tom Clark about 10 years ago to freely share his clever, low-cost, PC-software-controlled, Motorola VP GPS receiver-based precise timing solution. In short, some of us have caught the "time bug" and are on the slippery slope of ever greater frequency stability and more precise time.

The following sections are a view into my clock collection, time & frequency experiments, and home timing laboratory.

ATOMIC CLOCK COLLECTION

People collect just about anything: books, stuffed animals, postage stamps, cars, vacuum tubes, clocks, and watches. Some of us have a hobby of collecting modern and vintage electronic instruments related to precise time: oscillators, atomic frequency standards, phase comparators, time code displays, and radio (WWV, WWVB, Loran-C), or satellite time/frequency receivers (GOES, GPS).

Over the years, my collection has grown to include instruments from companies such as Austron, Astrodata, Berkeley, Bliley, Datum, Efratom, FEI, Fluke, FTS, General Radio, Hewlett-Packard/Agilent, Kinemetrics, Odetics, Oscilloquartz, Sigma Tau, Stanford Research, Spectracom, Sulzer, Symmetricom, Systron-Donner, Tracor, Trak, True Time, TST, and Vectron. Photos of the collection may be found on my Web site. There are frequency standards ranging from a vintage 1 kc General Radio tuning fork oscillator to a modern 100 MHz Sigma Tau hydrogen maser, representing stabilities from 10^{-3} to 10^{-15}.

MUSEUM OF HP CLOCKS

The photo below shows a complete collection of Hewlett-Packard time & frequency instruments, representing some of the best technology from the mid 1950's to the present.

On the left, from bottom to top, are cesium standards HP 5060A, 5061A, 5061B, 5062c, 5065A (rubidium), and 5071A. On the right are quartz frequency standards HP 100ER (vacuum tube), 101A (transistor), 103AR, 104AR, 106B, 107AR, and 105B.

In the center are electro-mechanical frequency divider analog clocks HP 113AR, 113BR and digital clock 115BR; time comparator 114BR, WWVB receiver comparator 117A, digital clocks K21-5321B, 59309A with K10-59992A standby power supply, UT2 time scale translator K10-117A, mechanical relay Nixie tube clock HP

571B, and HP01 LED wristwatch.

The collection also includes hundreds of original operation and service manuals for this vintage equipment (some of this literature is harder to find than the instruments themselves), as well as books, magazines, catalogs, journals, and articles related to precise time & frequency, both historical and current.

SOURCES

Where on earth does all this old gear come from? Amateurs scour local surplus electronics stores, hamfests, test-equipment dealers on the Web, and online auction sites such as eBay. With careful searching, no deadlines, and some luck, it is simple to obtain a surplus WWVB, GOES, Loran-C, or GPS receivers for well under $100. Similarly, high-quality ovenized quartz, rubidium, or even cesium frequency references can be found for several hundred dollars. Sub-nanosecond frequency counters can sometimes be found for as little as $25. Thus, for a very modest price a persistent amateur today can own, and experiment with, precise time instruments that were world-class and unaffordable a decade or two ago.

SOME EXPERIMENTS

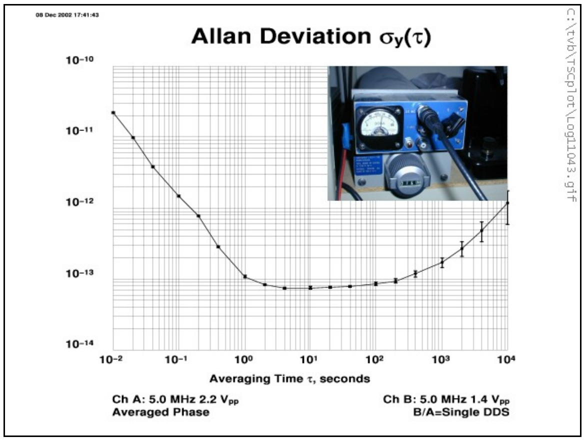
However, collecting is only a small, but necessary, part of the hobby. The technical reward is using and experimenting with all the equipment. Some surplus standards require repair, some need only adjustment, some work perfectly upon arrival, some appear to have personalities and need careful monitoring. All of this is a learning experience for the amateur. The following is a sampling of recent experiments with quartz, cesium, and hydrogen maser standards.

QUARTZ OSCILLATOR STABILITY

Surplus oscillators are everywhere; large and small, old and new, useful and boat anchors. Part of the fun is finding old but well-known oscillators and, assuming they work at all, seeing how *well* they work. Newer is not always better; some oscillators from 30 years ago have phenomenal performance by any standard. Still, older is not necessarily better; although a quartz resonator may age well, there are dozens of other components or adjustments that decay over decades. So the only way to be sure is to make measurements.

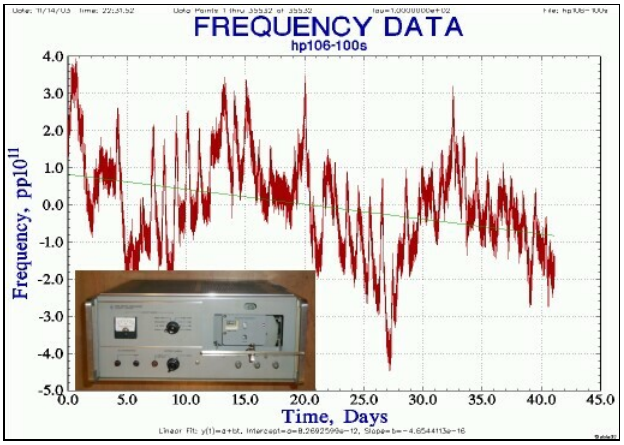
SULZER 2.5C QUARTZ OSCILLATOR

The following is the performance of a classic 2.5 MHz AT-cut Sulzer 2.5C oscillator. This one has short-term stability under $3\text{x}10^{-13}$. Not bad for a surplus 40-year old oscillator.



HP 106B FREQUENCY STANDARD

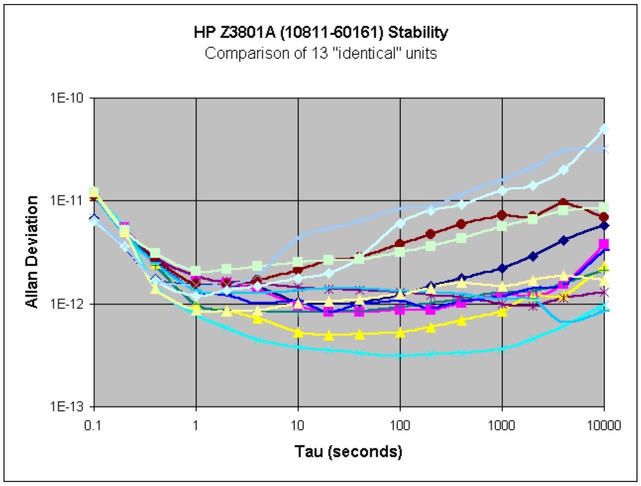
The HP 106B is another amazing quartz oscillator; the ultimate quartz frequency standard made by Hewlett-Packard in the 60's. Featuring a 5 MHz AT-cut crystal, all circuitry was within the outer or inner oven to improve performance. In addition to fantastic short-term stability, down near 2x10^{-13}, it also has the lowest drift rate I have encountered in quartz. Below is a plot of a 40-day measurement where a net frequency drift rate of -4x10^{-13}/day was observed. It is interesting to note that the diurnal temperature fluctuations are the same order of magnitude as 40 days of drift.



Z3801A GPS-DISCIPLINED OSCILLATORS

The Z3801A is a Hewlett-Packard *SmartClock* GPS-disciplined receiver. After years of successful service in the telecom industry, at least a thousand of these devices appeared on the surplus market. It was a chance for amateurs to obtain a very high quality GPSDO for not much more than $200. These units contain a variation of the excellent model 10811A SC-cut 10 MHz oscillator. While the long-term performance of a GPSDO is a function of the GPS receiver system, the short-term performance is dominated by the quality of the OCXO.

Below is a composite plot of 13 different Z3801A receivers showing that, although they all have the same OCXO part number (10811-60161), and although they all meet specifications, their performance can vary by a factor of 30. Quartz oscillators are as much art as science.



CESIUM HYPERFINE TRANSITION

A person curious about precise time learns early on that the second was redefined in 1967 as *the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom*. Detailed references on the subject include wave-looking resonance plots or wing-looking magnetic splitting diagrams. Clearly, the 9.192 GHz cesium peak is not as simple as popular perception or the concise definition suggests.

EXPERIMENTAL SETUP

One does not need to rely on books or build their own primary frequency standard to experience the cesium peak first-hand. It turns out to be quite simple to recreate the resonance plots at home, as all the difficult physics has already been built within a typical commercial cesium-beam frequency standard.

In a vintage Hewlett-Packard cesium standard, a 5 MHz quartz oscillator is used to generate both a 9180 MHz and a 12.631nnn MHz signal, which are then mixed to produce the 9192.631nnn MHz microwave frequency. In normal operation, through a clever audio modulation scheme, the RF 5 MHz OCXO is operated as a VCO locked to the peak of the microwave cesium resonance.

The procedure to manually probe the cesium resonance is:

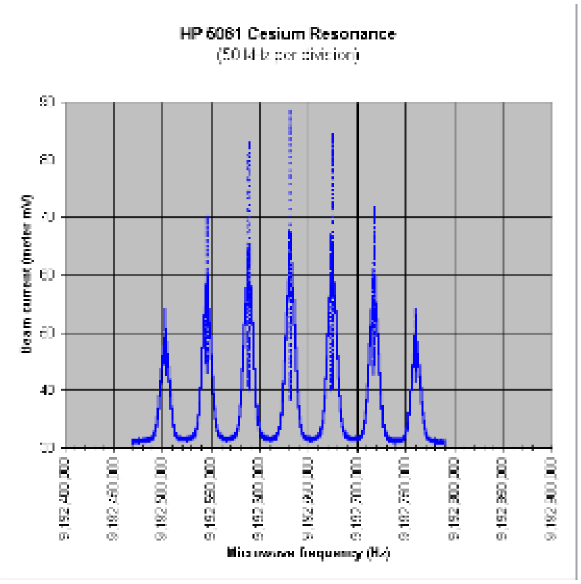
- Operate the 5061A cesium standard in open loop, thereby disabling the VCO.
- Keep the cables that generate 9180 MHz intact.
- Remove the cables from the 12.631 MHz internal synthesizer.
- Replace them with an external GPIB-controllable RF synthesizer (HP 3325A).
- Set the front panel meter switch to *Beam I*.
- Monitor the voltage across the meter with a GPIB-controllable DMM (HP 3456A).

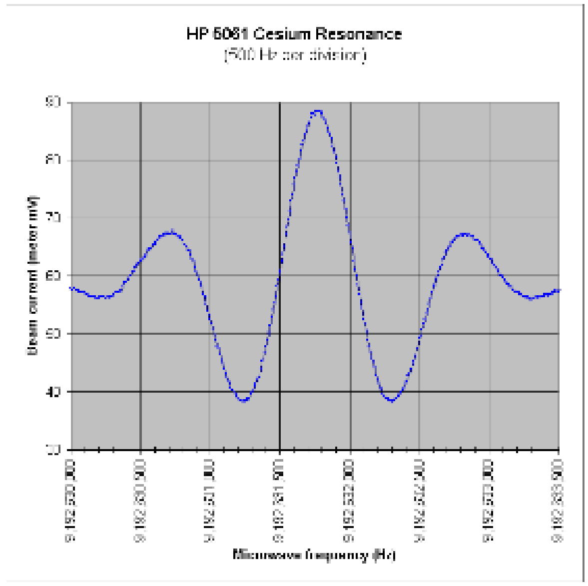
A DOS PC running a QBASIC program through a serial-to-GPIB converter was used to step the RF frequency about 12.6 MHz and take average beam current voltage readings at every step. The range, resolution, and precision of the scan can be varied. The results are stunning: not only is the center peak visible, but also the side peaks around it, and by extending the frequency down to 12.4 MHz and up to 12.8 MHz, all seven peaks.

The following photos show the equipment setup and a view of the DMM while reading the peak beam current at the synthesizer setting of 12.631 770 MHz + 9180 MHz = 9 192 631 770 Hz.

RESULTS

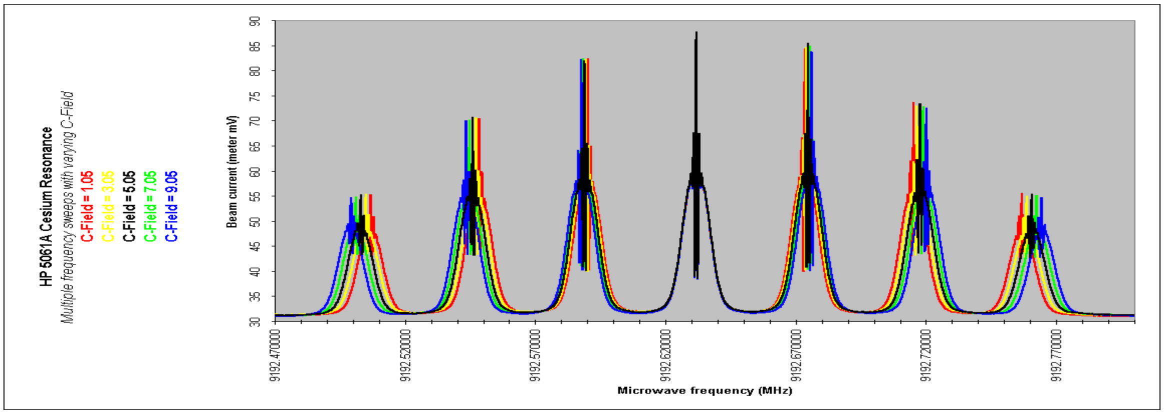
Below are two of the resulting scans. In the first, all seven peaks are visible and, in the second, the central peak only. For this cesium tube, the width of the center peak is about 500 Hz (in agreement with HP specifications). At 9192 MHz, this represents a relative width of 5 x 10^{-8}, creating new respect for how a 5061A cesium standard is accurate to parts in 10^{-11} and stable to parts in 10^{-12}.





All of this is obvious to physicists that work at national standards labs or commercial timing companies, but it is a special treat for an amateur to be able to recreate today, in the kitchen, what was leading-edge physics decades before. As a written definition, 9192631770 Hz sounds cold and abstract, but here as a resonance experiment performed on a desktop in front of your eyes, it feels very alive and tangible.

Finally, the seven peaks spread in frequency in the presence of a magnetic field – with the central peak least affected (which is why it is used as the clock transition). The 5061A has a C-field adjustment and the following is a plot showing the peaks while varying the C-field from near minimum to near maximum in 5 steps (the outer peaks shift up to 10 kHz at the highest C-field setting). One with greater physics education than I would be able to analyze all these data and confirm what quantum mechanics predicts about Zeeman splitting, Rabi pedestals, Ramsey fringes, and the like.



HYDROGEN MASER AUTO-TUNING

Active hydrogen masers that are cavity auto-tuned have less frequency drift and, thus, better long-term stability at the expense of slightly degraded short-term stability (for tau between 10^3 to 10^4 seconds).

The KVARZ CH1-75 active hydrogen maser has a cavity auto-tuning mode (called AFCC I) requiring an extremely stable external frequency reference. In my lab, a Sigma Tau maser provides the stable 100 MHz reference for the KVARZ maser tuning. The tuning is accomplished by varying the voltage to a varactor diode inside the cavity (the variable capacitance slightly changes the cavity Q). A 12-bit DAC generates the voltage. Every other 1, 10, 100, or 1000 seconds (user-selectable), based only on the sign of the measurement, the DAC is incremented or decremented by one bit. The current DAC value can be displayed (as a four-digit octal number) on the front of the instrument.

For serious analysis, a computer record of DAC values, rather than a human readable LED display, is required. It was a challenge to automatically record the changing DAC values. Several invasive hardware solutions to this problem were considered. But a software engineer prefers a software solution.

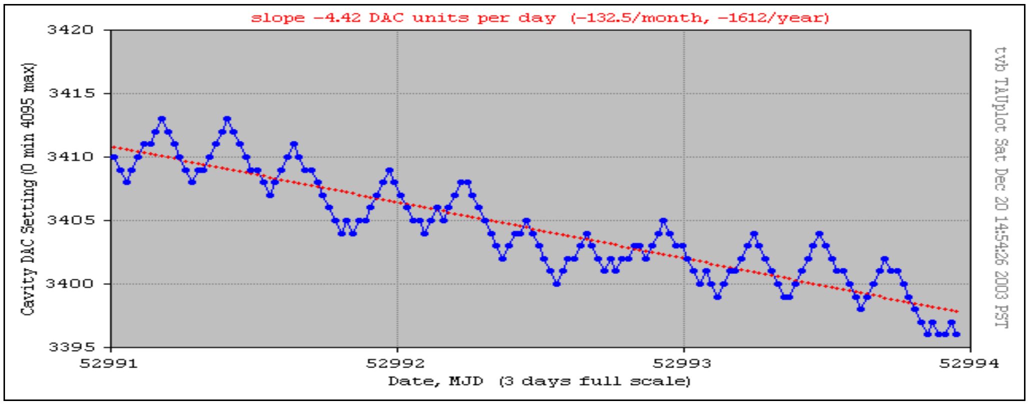
SOFTWARE SOLUTION

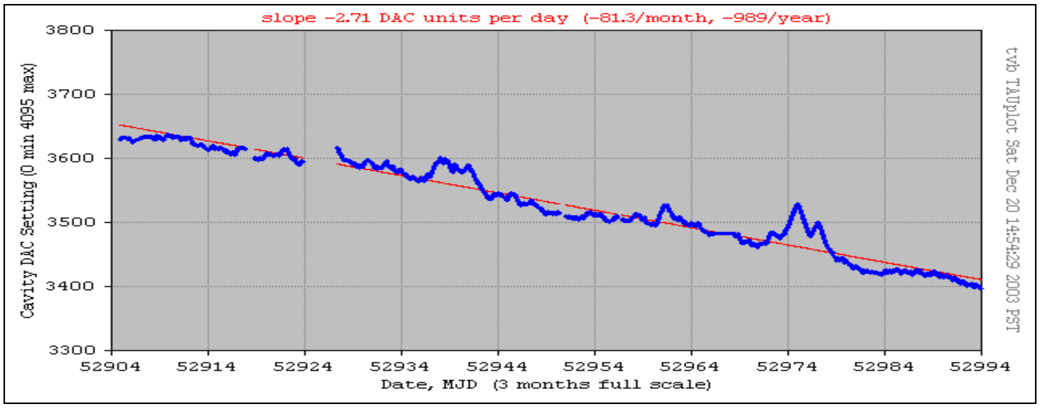
Most modern high-performance frequency standards have an RS-232 interface to control and query a large number of internal operating parameters. The CH1-75 does not have such an interface, so a webcam was used to periodically capture a photo (shown right) of the front panel displayed DAC value in order to generate long-term cavity tuning plots. The pixels of the LED digits in each of the JPG images are deciphered and converted to an ASCII log file with a homebrew OCR software tool. Graphs of this growing log file are then automatically produced using a homebrew plot tool.

The graphs are then periodically uploaded to my Web site for viewing.

RESULTS

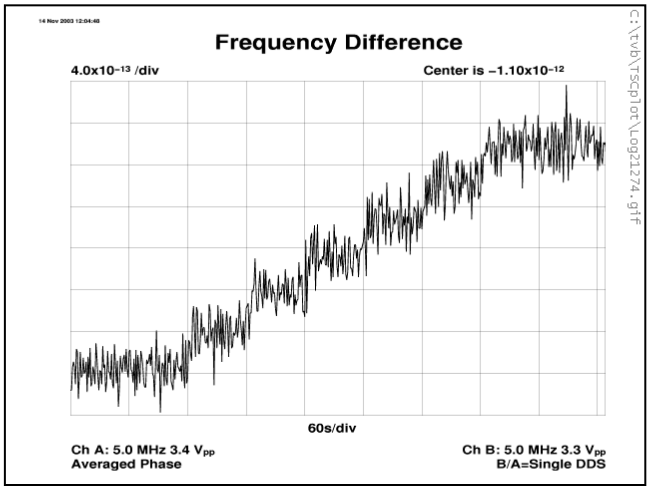
Approximately every 2000 seconds, a cavity measurement cycle completes and the DAC increments or decrements by one bit. The webcam slightly oversamples by capturing a photo of the front panel LED display every 30 minutes (1800 seconds). Thus, a complete history of every DAC change is logged. Below are two plots: the first covers 3 days and shows single-bit steps of the DAC and the second covers 3 months and shows a long-term trend.





DAC CALIBRATION

The DAC is clearly attempting to tune the cavity. In the short-term it appears to take a few steps above and below the ideal value; in the long-term it is presumably compensating for some cavity drift. In order to correlate DAC bits to absolute frequency, a calibration experiment was performed: the DAC was manually stepped from 1000 (octal) to 7000 (octal) in steps of 1000 (octal). Initiating a step every 60 seconds resulted in the plot below.



It can be seem from the plot that a total of six steps increase the frequency by about $2x10^{-12}$. Since each step is 1000 octal (512 decimal), the resolution of the DAC is 6.6×10^{-16} per bit. The 3-month trend was
-2.71 DAC bits per day, so the maser frequency drift being removed by cavity auto-tuning is -1.7×10^{-15} per day.

It is not known at this point if the short- and long-term cavity auto-tuning charts are nominal for this model of maser. Or are they unique to the one in my lab, or a side effect of less-than-perfect environmental control, or some sort of interaction between two cavity-tuning masers?

RECORDING THE OBSCURE

As a final and less serious example of amateur experiments, we look for needles in haystacks. Professionals have long since solved the important issues involving precise time but, like the field of astronomy, there is room for amateurs to find and document obscure events. In some cases, experiments are set up ahead of time in order to catch the future event. In other cases, one goes through existing logs to find a past event.

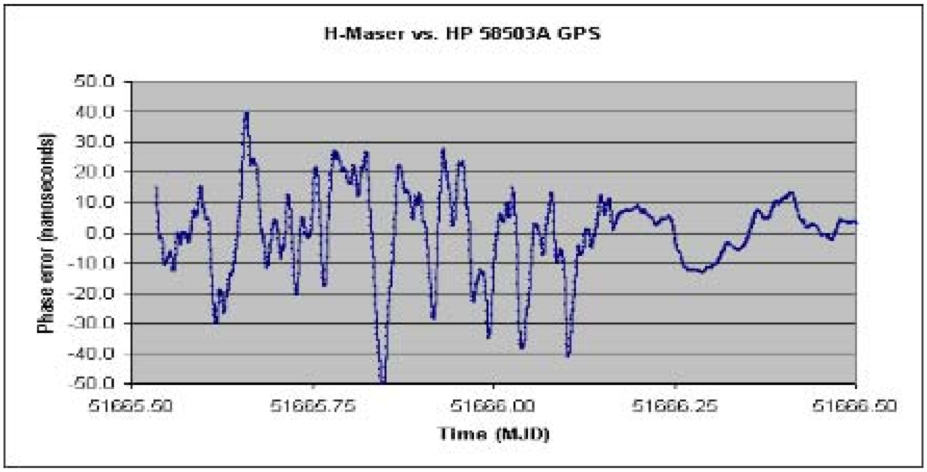
WWVB LEAP SECOND

Below is a recording of the most recent leap second (31 December 1998). This plot was made by amplitude sampling the 60 kHz WWVB carrier every 20 milliseconds. The trace (L = Low power) shows that the leap second itself is transmitted by WWVB neither as a 200 ms “0” bit nor a 500 ms “1” bit, but as an 800 ms position marker bit.

```
1998-12-31.23:59:56/LLLLLLLLLLLLLLLLLLLLLLLLLL------------------------
1998-12-31.23:59:57/LLLLLLLLLLL---------------------------------------
1998-12-31.23:59:58/LLLLLLLLLLL---------------------------------------
1998-12-31.23:59:59/LLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLL---------
1998-12-31.23:59:60/LLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLL---------
1999-01-01.00:00:00/LLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLL---------
1999-01-01.00:00:01/LLLLLLLLLLL---------------------------------------
1999-01-01.00:00:02/LLLLLLLLLLL---------------------------------------
```

GPS SA OFF

On 1 May 2000, GPS S/A (Selective Availability) was suddenly turned off. The following is a 24-hour phase plot between a GPS disciplined receiver (HP 58503A) and a local atomic standard, clearly showing the transition when S/A was turned off. The rms noise was reduced from about 20 ns to 6 ns.



GPS RECEIVER TIME GLITCH

Just a few weeks ago, on 27 November 2003, a *256-weeks-since-the-last-leap-second* timing glitch occurred in some GPS receivers. Below is a Motorola Oncore VP trace of that obscure event. Fortunately, because the hour was 62 o'clock, simple error checking in any host software would reject the erroneous message.

```
@@Ba 0b1b07d3173b39000d8ace0a343cfde5... 11/27/2003 23/59/57.000887502
@@Ba 0b1b07d3173b3a000dbf300a343cfde5... 11/27/2003 23/59/58.000900912
@@Ba 0b1b07d3173b3b000df3950a343cfee5... 11/27/2003 23/59/59.000914325
@@Ba 0b1d07d33e1c0f000e27fa0a343cffe5... 11/29/2003 62/28/15.000927738
@@Ba 0b1c07d3000000000e5c5a0a343cffe5... 11/28/2003 00/00/00.000941146
@@Ba 0b1c07d3000001000e90bc0a343d00e5... 11/28/2003 00/00/01.000954556
@@Ba 0b1c07d3000002000ec51f0a343cffe5... 11/28/2003 00/00/02.000967967
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AN EXTREME AMATEUR TIME LAB

Over the span of 10n years, my lab has evolved from a HP 5245L Nixie tube frequency counter and HP 117A VLF receiver on a desk, to quartz, rubidium, and cesium standards on shelves in the garage, to a spare bedroom full of working and vintage timing instruments, to an in-ground environmentally controlled isolated storage room containing a dozen cesium and two active hydrogen maser frequency standards, time interval counters, WWVB, GOES, Loran-C, and GPS receivers, computers, backup power sources, and more. Following are photos of the upstairs lab, which holds most of the historical collection and the isolated downstairs lab, where the sensitive instruments are located.

PROBLEMS

Putting together a serious time lab is difficult. A ham shack with a single GPS receiver, rubidium clock, and a universal counter provides almost all the functionality an amateur would actually need, but little of the challenge. Adding many more clocks, searching for the best reference for any given tau, creating a time scale, maximizing robustness, and adding automation is a challenge orders of magnitude greater.

A modest timekeeping hobby does not need to be expensive. An unbelievable amount of high-quality test equipment, including frequency standards, GPS receivers, time-interval counters, and PC's can be had for cents on the dollar if one has enough patience to find it. Some rare pieces take months or even years to find, or to find at a bargain price. Almost everything in this lab came from local electronics surplus stores, used test equipment dealers on the Web, trades with fellow collectors, and eBay auction items. It's a slow way to build a lab (and unacceptable in the business world), but perfect for the amateur on a budget.

Setting up a precise frequency and time lab becomes increasingly difficult as each zero is added to the level of precision. More equipment takes more space, uses more power, and requires more cooling. Stable frequency standards deserve backup power; a time scale double backup. Unattended operation requires computer monitoring. Computers require software. Computer hardware and operating system software are notoriously unreliable; redundant data logging is sometimes necessary. Vibration and visitors becomes a problem. Live experiments and "production" systems don't mix well. Security becomes a problem. Equipment sometimes fails. Phase or frequency jumps take time to solve. Loose cables become a problem. BNC connectors are a problem. Temperature control is a persistent problem.

SOLUTIONS

There are two lab areas at the house now: a spare upstairs bedroom is a hands-on, working lab and an isolated, ground level, insulated, air conditioned storeroom with thick concrete floor is a limited access lab for frequency standards in the time scale. This helps with thermal problems, security, and vibration.

Our house now has an 8 KW natural gas-fueled generator for backup mains power. Each lab has a 5 KW UPS (dirt cheap from a local failed dot-com) with additional levels of UPS and lead acid DC battery power providing 120 VAC and 12, 24, and 48 VDC. In addition, the cesium and hydrogen maser standards in the time scale have internal and external battery backup. Frequency is easy; time is hard.

Temperature monitoring is accomplished with a variety of sensors. TempTrax RS-232 sensors are used to monitor GPS antenna, HVAC, and outside temperatures to a resolution of 0.1°C. Vaisala HMP probes monitor inside lab temperatures with a resolution of 0.01°C. Finally, the ambient temperature around the Sigma Tau maser is monitored with a resolution of 0.001°C using a HP 2804 quartz thermometer system.

Several networked PC's monitor dozens of channels of environmental, cesium and hydrogen maser instrument status, frequency, and time interval data using RocketPort PCI and Edgeport USB serial port expanders. The upper and lower labs are connected with multiple Heliax RF cables, RS-232 and LAN links, and GPIB over duplex fiber-optic cables.

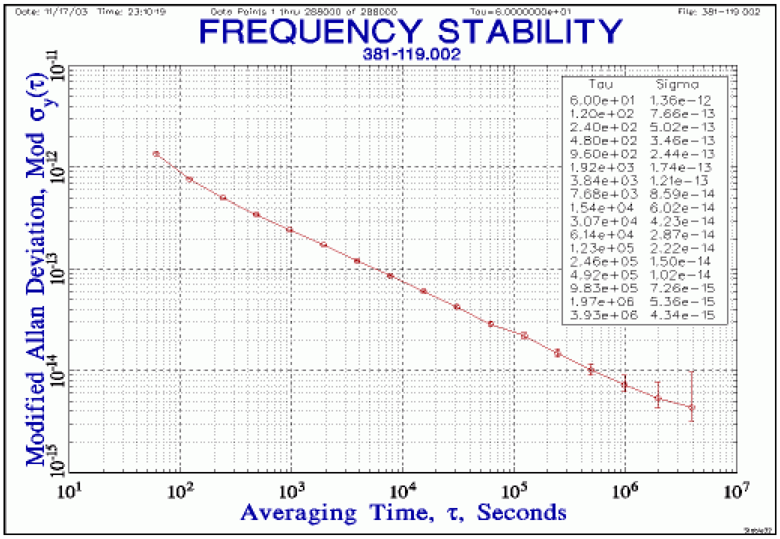
A set of HP5370B, HP53132A, SR620, and TSC5110A instruments are used to make time interval measurements among all the standards at resolutions of 1 ns to 100 fs.

Because the lower lab is intentionally difficult to physically access, a goal is to make it autonomous, using remote control where possible and reporting all clock status over the Web. That way, whether I'm in the house or away on a family vacation, the lab still operates and its status and performance can be monitored through my Web site.

Although mine is perhaps the most advanced home timing lab, it is not alone. Doug Hogarth (www.niceties.com) has been operating a continuous 5071A time scale at home for almost 4 years and uses dual-frequency carrier-phase GPS receivers with postprocessing to monitor and steer his time scale. Jim Jaeger (www.clockvault.com) has recently acquired a maser and is building a time lab at his home. And there are many others in various stages of this hobby.

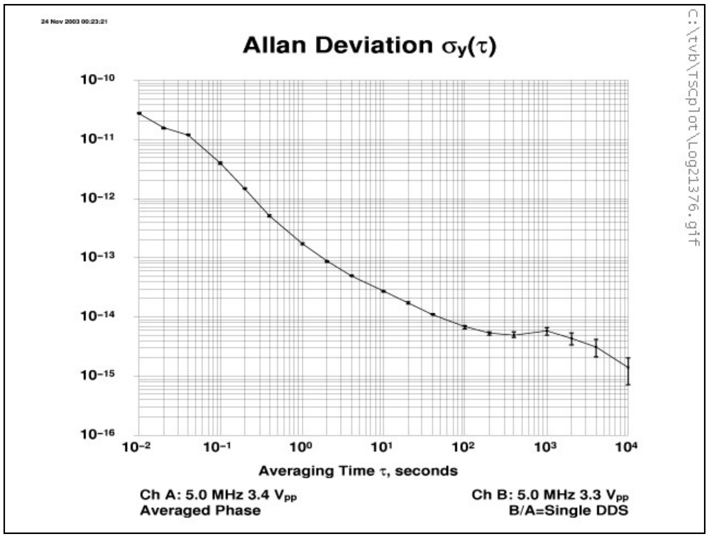
PERFORMANCE AND GOALS

From only parts-per-million frequency stability 10 years ago, the performance of my time lab is now low parts in 10^{-15}. Below is a plot of a pair of high-performance 5071A cesium standards, showing a slight hint of approaching a noise floor below 5×10^{-15} after running 200 days.



The following plot of two active hydrogen masers (Sigma Tau vs. KVARZ) shows stability below 2×10^{-15}

at 10,000 seconds.



But there is more work ahead. The lab temperature regulation needs to be improved. Additional environmental and clock data will be plotted on the Web site. Smoke and temperature auto-shutdown mechanisms need to be installed. Various AC and DC failure scenarios need to be tested. Maser cavity tuning issues need to be resolved. GPS common view with other amateur sites needs to progress. An Ashtech Z12T GPS receiver needs to be calibrated to check absolute UTC phase. Several idle cesium standards need to be powered up and added into the time scale. Experimentation with AOG/maser steering algorithms can then start. PC hardware and operating system down time needs to be reduced.

So this amateur time lab shares much in common with the national time labs: part museum, part library, part workbench, and part standards laboratory. Setting up a time lab at home gives one great insight, awe, and respect for what the personnel at national timing labs have accomplished over the years and how much work it is to keep them running without interruption.

CONCLUSION

A long-term interest and deep curiosity about time, an atomic clock collection, a passion for precise measurement and experimentation, and the challenge of ever better timekeeping have resulted in a home time lab that rivals those of some national physical laboratories. With the flood of surplus electronics available and technical metrology articles present on the Web, the world of precise time and time interval is now more accessible to the curious amateur. Although at present I cannot officially contribute to UTC through the BIPM, my lab generates UTC (tvb).

Experiments and lab reports, historical information, and a virtual time & frequency museum can be found on my Web site: www.LeapSecond.com.

My thanks to fellow amateur timekeepers for their help, to the staff of NIST and USNO who have so generously shared data with me, and to many sympathetic professionals at commercial time & frequency companies who have donated equipment or spent time answering many questions over the years.

My thanks especially to my three young children for never pressing buttons on Daddy's time machines without permission and to my wife, Lesley, for her extreme patience and grace.

QUESTIONS AND ANSWERS

CHRISTINE HACKMAN (University of Colorado): You showed a bunch of Allan deviation plots and I am wondering what are you measuring all your clocks against? What are you using for your reference clock?

TOM VAN BAAK: Okay, that is always an interesting problem. Years ago, when I only had quartz, of course you have to try to find your best quartz and use that as a reference. Then I remember getting my first surplus M-100 rubidium oscillator. Then that was the golden standard that I compared everything against. And so, I, as well as many of you, play this game where you are always trying to get a better reference.

The advantage of having a maser at home is that for measuring most things, any sort of GPS-disciplined oscillator, most cesiums, any kind of quartz, or rubidium, you actually don’t even have to subtract out the background of the maser. It is just that good. However, actually I have three masers, back in the camp where you just don’t have anything better. That is one reason why fellow time enthusiast, Doug Hogarth, who has done actually a lot of work with time scales, and I have an Ashtech Z-12T. Hopefully, we will do common view with that to try to get more long-term calibration with the maser.

There is no free lunch. Every time you push the envelope, there is always something else to learn, something else to fight.