It’s About Time !!!!!

Timing for VLBI

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**The difference between Frequency and Time**

**Oscillators and Clocks**

- **Oscillator**
  - Escapement Wheels & Pendulums
  - Crystal Oscillators
  - Cavity Oscillators
  - Oscillator Locked to Atomic Transition
    - Rubidium (6.8 GHz)
    - Cesium (9.1 GHz)
    - Hydrogen Maser (1.4 GHz)

- **Integrator and Display = Clock**
  - Gears
  - Electronic Counters
  - Real Clocks

**Events that occur with a defined**

- **FREQUENCY**
  - nsec -- minutes

- **LONG-TERM TIMING**
  - seconds - years

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**What “Clock” Performance Does VLBI Need?**

- The VLBI community (Radio Astronomy and Geodesy) uses Hydrogen Masers at 40-50 remote sites all around the world. To achieve $\approx 10^\circ$ signal coherence for $\approx 1000$ seconds at 10 GHz we need the 2 clocks (oscillators) at the ends of the interferometer to maintain relative stability of $\approx \frac{10^\circ}{(360^\circ \times 10^{10} \text{Hz} \times 10^3 \text{sec})} \approx 2.8 \times 10^{-15} @ 1000 \text{ sec.}$

- In Geodetic applications, the station clocks are modeled at relative levels $\approx 30 \text{ psec}$ over a day $\approx 30 \times 10^{12}/86400 \text{ sec} \approx 3.5 \times 10^{-16} @ 1 \text{ day}$

- To correlate data acquired at 16Mb/s, station timing at relative levels $\approx 50 \text{ nsec}$ or better is needed. After a few days of inactivity, this requires $\approx 5 \times 10^{-14} @ 10^6 \text{ sec}$

- Since VLBI now defines UT1, VLBI needs to control $\mid \text{UTC}_{(USNO)} - \text{UTC}_{(VLBI)} \mid$ with an **ACCURACY** (traceable to USNO) $\approx 100 \text{ nsec} - 1 \mu\text{sec}$

- To detect problems, VLBI should monitor the long-term behavior of the Hydrogen Masers (at least) every hour with **PRECISION** $\approx 10-50 \text{ nsec}$
**Allan Deviation – A graphical look at clock performance**

![Allan Deviations of Typical Clocks](image)

Why do we need to worry about “Absolute Time” (i.e. Clock Accuracy) in VLBI?

• The **ONLY** real reason for worrying about “absolute time” is to relate the position of the earth to the position of the stars:

  • Generating Sidereal Time to point antennas.
  • Measuring UT1 (i.e. “Sundial Time”) to see changes due to redistribution of mass in/on the earth over long periods of time (a.k.a. “The Reference Frame”)
  • Knowing the position of the earth with respect to the moon, planets and satellites.
  • Making the correlation and Data Analysis jobs easier
Why do we need to worry about “Absolute Time” (i.e. Clock Accuracy) in VLBI?

At the stations this means that we will need to pay more attention to timing elements like

- Frequency Standard and Station Timing
- The lengths of all signal & clock cables
- The geometry of the feed/receiver to the antenna.
- Calibration of instrumental delays inside the receiver and backend. The development of new instrumentation is needed.
- The care with which system changes are reported to the correlators and the data analysts.

*Note -- If the axes don’t intersect, then an “offset axis” model of the antenna is used*
VLBI’s “REAL” Clocks (#2)

This is the “clock” that is used to analyze VLBI data

VLBI’s “REAL” Clocks (3)

This is the “clock” the correlator uses to make fringes
Setting VLBI Clock Time & Rate with GPS
-- 3 possible ways--

- **Compare two distant clocks by observing the same GPS satellite(s) at the same time** (also called **Common View**)
  - Requires some intervisibility between sites
  - Requires some near-Real-Time communication
  - Links you directly to the “Master Clock” on the other end at ~1 nsec level

- **Use Geodetic GPS receivers** (i.e. as an extension of the IGS network)
  - Requires high quality (probably dual frequency) receiver (TurboRogue, Z12, etc), but it’s hard to gain access to the internal clock.
  - Requires transferring ~1 Mbyte/day of data from site
  - Requires fairly extensive computations using dual-frequency data to get ~300 psec results with ionosphere corrections
  - Allows Geodetic community to use VLBI Site (and H-Maser) for geodesy
  - Difficult to obtain “Real Time” clock pulses!

- **Blindly use the Broadcast GPS Timing Signals as a clock**
  - Yields “Real Time” ~10-30 nsec results with ~$1000 hardware
  - Single Frequency L1 only (until 2008?) causes ionospheric error

Timing at an Isolated, Remote VLBI Site --
Urumqi in Xinjiang Province, China

Rick’s TAC32 Software
Tom’s old 8 channel “TAC”
HP53132A Counters
Rick’s New 12-channel “CNS CLOCK II” (not yet in use)

An Early Example of “Blind” GPS Timing with a 6 channel receiver

ONSALA H-Maser vs "TAC" GPS

Avg RMS = 31.8 nsec

UTC Date, 1995
Before S/A was turned off (8-channel) . . .

GGAO (Goddard Geophysical & Astronomical Observatory)

VLBI Trailer & H-Maser

GPS Trailer

5M “MV-3” VLBI Antenna

Planned Location for new VLBI2010 Antenna

CODE GPS Antenna
How we got ~30 nsec timing in 1995

- Start with a good timing receiver, like the Motorola ONCORE
- Average the positioning data for ~1-2 days to determine the station’s coordinates. With S/A on, a 1-2 day average should be good to <5 meters. Or if the site has been accurately surveyed, use the survey values.
- Lock the receiver’s position in “Zero-D” mode to this average.
- Make sure that your Time-Interval Counter (TIC) is triggering cleanly. Start the counter with the 1 PPS signal from the “house” atomic clock and stop with the GPS receiver’s 1PPS.
- Average the individual one/second TIC reading over ~5 minutes.
- All these steps have been automated in my SHOWTIME and in CNS System’s TAC32+ Software using a barebones PC
All that is ancient history. In the new millennium, let’s now discuss . . .

- Sawtooth and Glitches – Some Receiver Defects
- Some results obtained with Motorola’s newer low cost timing receiver, the M12+ and M12M
- “Absolute” Receiver Calibration
- The post-Motorola era & new developments

What happened when S/A went away?
Using 8-channel Motorola ONCORE VP Receiver . . .

Note that Average is not in the middle of the max/min "road"!
An example of 1PPS Sawtooth & Bad Glitches
Motorola’s low cost UT+ Oncore (v3.1)
An example of 1PPS sawtooth with Motorola’s 12-channel M12+ receiver

What is the sawtooth effect ????

- For the older Oncore, F=9.54 MHz, so the 1/F sawtooth has a range of +/- 52 nsec (104 nsec peak-to-peak)

- The newer M12+ & M12M have F ≈ 40 MHz, so the sawtooth has been reduced to +/- 13 nsec (26 nsec).
VLBI's annoying problem caused by the sawtooth timing error

- When the formatter (Mark 5 sampler) needs to be reset, you have to feed it a 1PPS timing pulse to restart the internal VLBI clock. After it is started, it runs smoothly at a rate defined by the Maser's 5/10 MHz.

- The **average** of the 1pps pulses from the GPS receiver is "correct" but any single pulse can be in error by ±13 nsec (or ±52 nsec with the older VP & UT Oncore receivers) because of the sawtooth.

- Once you have restarted the formatter with the noisy 1 PPS signal, you then measure the actual (GPS minus Formatter) time that you actually achieved.

Or, you can use the 1PPS from a new CNS Clock II which has the sawtooth "dither" removed.

Errors due to the sawtooth do not compromise VLBI data quality

- All the Motorola receivers report the error on the **next** 1 PPS pulse with a resolution of ~1 nsec as a part of the serial data message.

- TAC32 reads the HP53131/2 counter and the GPS data message and corrects the answer.

But, wouldn't it be good if the GPS receiver didn't have any sawtooth error, and that every 1 PPS pulse could be trusted?
How can the Sawtooth noise be eliminated ???

Motorola GPS Timing Receiver

1PPS with sawtooth noise

Programmable Delay Line with 150 psec steps
(Dallas/Maxim DS1020)

“Clean” 1PPS

PIC Microprocessor generates the correction for the NEXT 1PPS tick

Serial Data

RS-232

The Future is here now!
The CNS Clock II

1994 – 2004: the TAC

and

1PPS Sawtooth Correction Option

Data available on RS-232, USB 2.0, Ethernet LAN, RS-485 and solid state relay Ports
Full NTP Server for your LAN TNC GPS Antenna Connector Buffered 1 PPS outputs GPSDO 10 (or 5) MHz output

Available Since January 2005

CNS Clock II Block Diagram

- Priority Select + Matrix
- RS-232 USB
- Ethernet With NTP
- NTP+ Web +FTP TCP+UDP IP Stack
- GPS Module
- Precision 1PPS
- 1PPS
- 100PPS
- Antenna
- 1PPS
- 10MHz
- Steered 10MHz TCXO or OCXO
- Protocol Converter
- RS422
- RS422 SSR
- Waveform Generator
- IRIG/Option
- Serial Data

Does the hardware 1PPS correction work?

- Hardware vs. Software 1PPS Corrections
- Data logged by Tac32Plus, April 19, 2009 UTC (Day 109)
- ©2009 CNS Systems, Inc., plot by Richard M. Hambly
- RED = Raw 1PPS
- GREEN = Hardware Corrected Data
- BLUE = Software Sawtooth Corrected Data
- Violet = Correction Difference
- 9.0 nsec RMS
- 0.7 nsec RMS
- 2.5 nsec RMS
- 2.8 nsec RMS
- 0.00
Does the hardware 1PPS correction really work?

**YES II**

**CNS Systems’ Test Bed at USNO**

Calibrating the “DC” Offset of M12+ receivers with 2.0 Firmware in 2002

We have observed that the ONCORE firmware evolution from 5.x ⇒ 6.x ⇒ 8.x ⇒ 10.x has been accompanied by about 40 nsec of “DC” timing offsets. Motorola tasked Rick to make the new M12+ receiver be correct.

Tac32Plus software simultaneously processes data from four Time Interval Counters and four CNS Clocks, writing 12 logs continuously.

Time Interval Counters compare the 1PPS from each CNS Clock (M12+) against the USNO’s UTC time tick.

This is the “Gold Standard” “A” receiver that we used for subsequent calibrations.
Individual M12 Clock Performance

"Gold" Receiver (A) average "DC" offset = -0.6 ns

Comparing four M12+ Timing Receivers

Motorola M12+ V2.0 vs. USNO

Data logged by Tac32Plus, Sep 4 - Sep 16, 2002 UTC (Days 247 - 259)

Data is sawtooth corrected. Averaging Period is 100 seconds.

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What Happened on 9/7/02?

September 7, 2002.
This picture is a two hour composite of 85 different photos spanning 21:07 thru 23:10 EDT on Sept. 7th (01:07 thru 03:10 UTC Sep. 8).

September 8, 2002.
This picture is a four hour composite of 140 different photos spanning 20:00 thru 24:00 EDT on Sept. 8th (00:00 thru 04:00 UTC Sep. 9).

Each picture was an 87 second exposure with 3 seconds between frames. The trails on the picture are all due to airplanes. The bright loop is from a plane on final approach into BWI airport. Camera = Canon D60 shooting Hi Resolution JPEG at ISO 100 with TC-80 timer. Lens = Sigma f/2.8 20-40 mm set to 20 mm @ f/4.5.

Short Baseline Test (USNO to NASA GGAO)

Comparing two new Motorola M12+ GPS Timing Receivers over the 21.5 km baseline between the US Naval Observatory (USNO) and the NASA Goddard Geophysical & Astronomical Observatory (GGAO).

Both data sets compare the GPS timing receiver to a local Hydrogen Maser clock. On both, a linear fit to remove constant clock offset and drift has been applied.
Current M12 Receiver Status

- All the varieties of the Motorola M12+/M12M timing receiver show similar performance.
- All the Motorola samples (including the 4 receivers in the 2002 test) appear to agree with UTC(USNO) to better than ±10 nsec.
- Motorola has made a business decision to get out of the GPS timing business.
  - The M12M timing receiver is now being manufactured by iLotus LTD in Singapore. For information see: http://www.synergy-gps.com/content/view/20/34/
  - GPS performance of the iLotus receivers is better than Motorola
- The iLotus M12Ms that we have seen show a bias errors up to ~30 nsec as compared with our "Gold" reference Motorola receiver.
- The reasons for the biases (Hardware? Firmware?) are unknown.

What Else is New ?

- The CNS Clock II now is a fully functioning NTP Time Server for your LAN.
- CNS Systems is delivering the CNS Clock II with iLotus M12M receivers and the hardware sawtooth remover.
- Rick continues to support the Windows-based TAC32 and Tac32Plus PC software.
- RSN (Real! Soon! Now!) there will be an open source, GPL Linux version of TAC32!
  - This is the result of a collaboration between Rick and an unnamed US Government organization.
  - If any of you would like to help with the conversion of the code to C++ with QT V4, contact Rick.
Where to get information?

These Slides and related material:
http://gpstime.com

Information on the CNS Clock and the CNS Clock II:
http://www.cnssys.com

For ONCORE/TAC-2 receiver used as a LINUX NTP network time server:
http://gpstime.com

To contact Tom: mailto:K3IO@verizon.net
To contact Rick: mailto:Rick@cnssys.com, 410-987-7835

Some Typical TAC32Plus Screens in Windows 2000/XP
Be Certain that you have selected the POSITION HOLD "Zero-D" Timekeeping Mode.
You should NOT be operating in 3-D Navigation mode!!
To Make Sure TAC32 is Logging the “true” Maser-to-GPS Time Interval:

- Offset GPS LATE if needed to be certain that the actual GPS 1PPS is AFTER the Maser’s 1PPS. TAC32 will do the arithmetic to make the log data be correct.

- Be certain to account for the lengths of all coax cables.

- Allow the TAC32 software to correct for all timing offsets.

- Allow software to correct counter reading for 1PPS pulse-to-pulse jitter. Select “OFF” if using a new CNS Clock II with the Precision 1 PPS Option.
To Activate the LAN Telnet Link between TAC32Plus and the LINUX PC Field System, Hit Control-T:

Then Click on the check-box and the OK button

To Use TAC32Plus PC as your Station’s SNTP Network Timer Server:

The new CNS Clock II includes an Ethernet port for use as a low jitter, precise NTP Time Server on your LAN. See Rick for details.