Timing for VLBI

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IVS TOW Meeting
Haystack -- March 12, 2001
What is VLBI?
Oscillators and Clocks

Frequency and Time

Oscillator
- Pendulum
- Escapement Wheel
- Crystal Oscillator
- Oscillator Locked to Atomic Transition
  - Rubidium (6.8 GHz)
  - Cesium (9.1 GHz)
  - Hydrogen Maser (1.4 GHz)

Events occurring at a defined FREQUENCY
nsec -- minutes

Integrator and Display
- Gears
- Electronic Counters

Long-Term TIME
seconds - years
What Timing 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 ~10° signal coherence for ~1000 seconds at 10 GHz we need the two oscillators at the ends of the interferometer to maintain relative stability of $\approx \frac{10^\circ}{(360^\circ \cdot 10^{10} \text{Hz} \cdot 10^3 \text{sec})} \approx 2.8 \cdot 10^{-15}$ @ 1000 sec.

To correlate data acquired at 16Mb/s, station timing at relative levels ~50 nsec or better is needed. After a few days of inactivity, this requires $\approx \frac{50 \cdot 10^{-9}}{10^6 \text{sec}} \approx 5 \cdot 10^{-14}$ @ $10^6$ sec.

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

Since VLBI defines UT1, we need to control $[\text{UTC(USNO)} - \text{UTC(VLBI)}]$ to an accuracy ~100 nsec or better.
Clock Performance -- The Bottom Line . . .
Setting VLBI Clocks Time & Rate with GPS

- **Compare two distant clocks by observing the same GPS satellite(s) at the same time** (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
  - Allows Geodetic Community to use VLBI Site and provides you Ionosphere data

- **Blindly use the Broadcast GPS Timing Signals** (much like WWVB)
  - Single Frequency L1 only (until 2004)
  - Yields ~10 nsec results with < $1000 hardware
ONSALA H-Maser vs "TAC" GPS

Avg RMS = 31.8 nsec

UTC Date, 1995
Joe Taylor tests TAC Accuracy at Arecibo

- Dots: Cesium-TAC
- Line: Cesium-UTC(NIST)

UTC(NIST)-TAC
ave=-0.016, rma=0.024 μs
An Isolated, Remote VLBI Site -- Urumqi in Xinjiang Province, China
How to get ~30 nsec timing even with S/A

- 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.
- These steps were automated in the SHOWTIME and TAC32Plus Software.
Some Things about my “TAC” have changed in the Past 2 Years . . .

- Based on the GPS “W1K” (August 21, 1999) scare, we got NASA to implement TACs (and their commercial clone, the CNS Clock) at NASA VLBI + SLR stations. This included our developing the new TAC32Plus Windoze support software, deploying new WIN98/2000 computers and HP53131A Time-Interval counters, and integrating the package with the LINUX VLBI PCFS. With this setup, we routinely were getting ~15-20 nsec RMS timing even with S/A turned on.

-- AND --

- DoD turned off S/A in May, 2000

-- AND --

- Motorola discontinued the ONCORE VP receiver in late 1999
TIC = Time Interval Counter
TIC-TAC = TIC plus TAC

TIC-TAC PC Provides via the LAN:
- Logged Timing Data by FTP
- Counter Readings by Telnet
- Station Epoch Time by XNTP

Recommended Clock and Timing Setup for a Mark4 VLBI Station
Before S/A was turned off . . .
GGAO (Goddard Geophysical & Astronomical Observatory)
Let Us Now Discuss . . .

- What happened when S/A was turned off.

- Some recent results obtained with prototypes of a new, low cost timing receiver:

  OEM Chipset: SiRFStar 1
  Receiver Hardware: Axiom Navigation’s Sandpiper
  with Custom Firmware by Reza Abtahi/CNST

- A comparison of the new SiRF-based receiver with the venerable Motorola VP receiver.

- A discussion of the timing accuracy that can be obtained with single-frequency receivers now that S/A is off.
What happened when S/A went away?
The Motorola ONCORE VP Receiver ...
What happened when S/A went away?
The SiRF/Axiom prototype receiver . . .

SiRF/Axiom Sandpiper vs GGAO H-Maser
T. Clark 2 May 2000

ION -- Sept. 20, 2000
Salt Lake City
~3 nsec/day Maser Rate Change on ~Nov.22

GGAO H-MASER vs. GPS during Nov/Dec 2000

TAC = Motorola ONCORE VP (8.8) Receiver

Prototype SiRF-based Receiver

GGAO Maser showed rate offset of ~20.4 nsec/day = ~2.36 x 10^{-13} during December, 2000

ONCORE RMS Noise

SiRF RMS Noise
TIC = Time Interval Counter
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Recommended Clock and Timing Setup for a Mark4 VLBI Station
Some TAC32Plus Screens in Windows 2000
TAC32Plus: DISPLAYS UTC TIME
TAC32Plus: DISPLAYS Local Station Sidereal Time (LMST)

UTC Time from GPS
UTC Day: 070 19:27:55.000
UTC Time: 02:00:03.60

Eastern Standard Time
Latency: -1

Sidereal Time
Local Mean Sidereal Time: 02:00:03.60
Greenwich Mean Sidereal Time: 00:46:00.71
Modified Julian Day: 51973.81105

GPS Navigation Data

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<th>Alt(MSL)</th>
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<td>-71° 29.27853'</td>
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<td>163.49m</td>
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<tr>
<td>Avg: 42° 37.38703'</td>
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<td>130.53m</td>
<td>163.49m</td>
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Eb/No

9 Visible
6 Tracked
**TAC32Plus: DISPLAYING TIME-INTERVAL COUNTER READINGS WITH CORRECTIONS**

- **4.0417**

- **UTC Time from GPS**
  - UTC Day #070, 17:24:12.000
  - Sunday, 11 March 2001
  - GPS Week = 1105

- **PC Time**
  - 12:24:11.996
  - Eastern Standard Time
  - Latency: -1

- **Sidereal Time**
  - Local Mean Sidereal Time: 23:56:00.27
  - Greenwich Mean Sidereal Time: 04:41:57.39
  - Modified Julian Day: 51879.27514

- **GPS Navigation Data**
  - Lat: 42° 37'.36703"
  - Long: -71° 29'.27853"
  - Alt (GPS): 130.53m
  - Alt (MSL): 163.49m

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- **Eb/No**
  - AS
  - Not Looked

- **Code Search**
  - 8 Visible
  - 7 Tracked

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For Help, press F1

Position Hold

Motorola V6P, Bin, 6 ch, Y10.0, has DGP5, T-RAIM
If the Maser 1PPS Tick occurs \textbf{BEFORE} the UTC Second.

High Accuracy
\textit{Maser - to - GPS:}
Time Interval Average and Sawtooth Correction in TAC32+

\textbf{Maser - to - Formatter:}
Formatter \textit{Advance} Lags Maser and the offset \textit{Should be constant}.

\textbf{GPS - to - Formatter:}
The Measurement that the Correlators want.

\textbf{GPS JITTER}
\textbf{"True Time" UTC(USNO)}

\textbf{H-Maser}
Maser 1PPS
5 MHz
Formatter 1PPS

\textbf{TAC-2}
GPS

\textbf{START}
\textbf{STOP}
GPS 1PPS
If the Maser 1PPS Tick occurs *AFTER* the UTC Second.

High Accuracy Maser-to-GPS:
- Removal of N usec bias, Time Interval Average, and Sawtooth Correction in TAC32+ software.

TAC GPS 1PPS is offset by N usec to be later than the Maser's 1PPS.

Maser-to-Formatter: Formatter *Always* Lags Maser and the offset *Should* be constant.

"True Time" UTC (USNO)
To Make Sure TAC32 is Logging the “true” Maser-to-GPS Time Interval:

Offset GPS LATE if needed to be certain that GPS 1PPS is later than Maser 1PPS.

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

Allow the software to correct for all timing offsets.

Allow software to correct the 1PPS pulse-to-pulse jitter.
Haystack Maser -- 9/11 March 2001

Slope = 120 nsec/day = 845 nsec/week
Maser frequency error =
\[ \frac{120 \times 10^{-9}}{86400} = 1.39 \times 10^{-12} \]

RMS Noise in 5 minute bins, usec

Running in 3-D
Setup Mode

"Zero-D Timing Mode"
SPECIAL CASE: If you need to use the TAC to re-synchronize the Maser's 1PPS Signal.
TIC = Time Interval Counter
TIC-TAC = TIC plus TAC

TIC-TAC PC Provides via the LAN:
- Logged Timing Data by FTP
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- Station Epoch Time by XNTP

Recommended Clock and Timing Setup for a Mark4 VLBI Station
To Activate the 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 as your Station’s SNTP Network Timer Server:
Why do we need to worry about “Absolute Time” (i.e. Accuracy) in VLBI?

• To get the correlators to line up for efficient processing, the relative time between stations needs to be known to ~ 100 nsec.

• The correlators maintain their “magictables” that relates the GPS timing data reported by different stations to each other.

• In the past, geodetic and astronomical VLBI data processing has been done by fitting the data with “station clock polynomials” over a day of observing, and then discarding these results as “nuisance parameters” that are not needed for determining baseline lengths, source structure, etc.

• The uncalibrated and unknown offsets now range from 1-10 usec at many VLBI stations.
**TIC** = Time Interval Counter

**TIC-TAC** = TIC plus TAC

**Detailed Diagram and Text:**

- **HPS3131A MASER to GPS**
- **TAC-2 GPS**
- **TAC32+ on Windows PC**
- **Ts232 I/Q**
- **5 MHz to Mk4 Rack and to Rcvr Front End**
- **Formatter**
  - **1PPS SYNCH**
  - **Formatter 1PPS OUT**
- **Normal Station Time-Interval Counter**
  - **MASER to FORMATTER**
- **Recommended Clock and Timing Setup for a Mark4 VLBI Station**
- **INTERNET CONNECTION TO THE WORLD**

**TIC-TAC PC Provides via the LAN:**
- Logged Timing Data by FTP
- Counter Readings by Telnet
- Station Epoch Time by XNTP
The Real Signal Path

The Path VLBI Analysis Assumes

VLBI's "REAL" Clocks (1)

The Real Signal Path
VLBI's "REAL" Clocks (2)

This is the "clock" that is used to analyze VLBI data (when the Phase Cal works)
This is the “clock” the correlator uses to make fringes.
Why do we need to worry about “Absolute Time” (i.e. Accuracy) in VLBI?

The **ONLY** 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.
- Knowing the position of the earth with respect to the moon, planets and even the GPS satellites.

We have solved the mysteries of Plate Tectonics and have left it to GPS to clean up the details. Our new major challenge is involved studies of Earth Rotation and the orientation of the earth with respect to the starts and planets.
Why do we need to worry about “Absolute Time” (i.e. 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 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.
Where to get information?

These Slides and related material:
ftp://aleph.gsfc.nasa.gov/pub/IVS_TOW/
and our Salt Lake City ION 2000 paper:
http://gpstime.com

Information on Rick Hambly’s CNS Clock, a commercial clone of my TAC-2:
http://www.cnssys.com

A kit form version of my TAC-2 is still available from TAPR:
http://www.tapr.org

To try a TAC2/TAC32+ xntp Network Time Server running in Win2K (the same receiver that produced the ONCORE results presented here):
tac.ggao.nasa.gov
ditto for the prototype SiRF Timing receiver shown here:
tomcat.ggao.nasa.gov
and for ONCORE TAC-2 receiver on a LINUX xntp server:
gpstime.com