Timing applications for GNSS

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IGS partnership with the BIPM

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Gérard Petit
Bureau International des Poids et Mesures
Time section
• BIPM general mission

• Timing activities
  – International time scales: TAI, UTC
  – clocks in TAI
  – clock comparison in TAI, GNSS role

• IGS/BIPM
  – contribution to the improvement of TAI
  – comparison of IGS and BIPM timing results
Bureau International des Poids et Mesures

• Ensure world-wide unification of physical measurements:
  – agreement on the definition and realization of units;
  – establishment of national standards of demonstrable international equivalence;
  – international harmonization of laws and regulations related to metrology.
International time scales (atomic)

- TAI (International Atomic Time)
  - Unit is 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 caesium 133 atom (second of the SI).
  - Uniform time scale.
  - High stability in the long term ($0.6 \times 10^{-15}$, ~ 40 days).
  - Accuracy conferred by using the reported measurements of the PFS. Relative departure of the duration of the TAI interval from the SI second ($d$) is $0.5 \times 10^{-14}$ to $1.0 \times 10^{-14}$.
    
    $u = 0.2 \times 10^{-14}$
International time scales (atomic)

- UTC (Coordinated Universal Time)
  - Defined to fulfil mainly the need of a time scale somehow related to the rotation of the earth.
  - Conceptually identical to TAI but suffering from 1 second time steps (TAI - UTC = 32 s today).
  - UTC is the reference time scale for worldwide time coordination.
  - UTC is calculated at the BIPM in concertation with the IERS on the basis of readings of clocks in the national laboratories.
  - Local realizations of UTC named UTC(k) are broadcast by time signals.
TAI/UTC

• Calculated in differed time on the basis of monthly blocks of data.
• Clock data provided by the participating laboratories.
• Organisation of international time links for clock comparison.
• Appropriate methods of time transfer.
• Primary frequency standard measurements.
• Algorithm to elaborate a time scale which fulfils the required characteristics: stability in the long term and frequency accuracy.
Clocks participating in TAI

- HP5071A 68%
- H masers 16%
- Other 16%
Clock weighting stability

- independent clocks,
- relative weights,
- upper limit to clock weights,
- weight of a clock remains constant on the 30 days of the interval of computation,
- iterative process based on the previous interval to predict the clock frequencies on the following interval (random walk frequency modulation…),
- weight determination based on 12 intervals of computation (one year)
  - deweighting (annual frequency variations, long term drifts),
  - detection of abnormal behavior
Clock weights (stat.)

• 11% of clocks at $\omega_{\text{max}}$
  – 14% are H-masers
  – 79% are HP5071A

• Over the H-masers
  – 10% are at $\omega_{\text{max}}$

• Over the HP5071A
  – 13% are at $\omega_{\text{max}}$
Clock comparison in TAI

- Loran-C, TV links (before)
  - (several hundreds of ns uncertainty)
- GPS C/A-code single-channel common-view
  - (3-10 ns uncertainty)
- GPS C/A-code multi-channel common view
  - (ns uncertainty)
- TWSTFT
- GPSP3
IGS products in TAI

• Single-frequency GPS C/A links in TAI are corrected by using:
  – Precise IGS orbits
  – Ionospheric maps from CODE

• Schedule for (monthly) Circular T
  – standard dates are MJD ending by 4 / 9
  – deadline for data submission of month M is 5th M+1
  – process of calculation starts (hopefully) on 6th M+1

• Latency is essential for the choice of IGS products
Access to other time scales

• GPS Time
  – UTC-GPS Time, Circular T, every day at 0hUTC

• GLONASS Time (same)

• Future:
  – GALILEO Time
  – IGS Time
BIPM differential calibrations of GPS time equipment

Uncertainty 3 ns (1 $\sigma$)

- In 2001-2004 campaigns were carried out
  - West and central Europe, Asia-Pacific region, North America

- About 20 laboratories out of the 50 that participate in TAI have been calibrated in the period

- Goal: developing operational strategies to exploit geodetic GPS methods for improved time and frequency comparisons.
- IGS: dual frequency carrier-phase based geodetic techniques.
- BIPM: time and frequency transfer by single-frequency GPS C/A common views and TWSTFT.
- IGS+BIPM: global time and frequency comparisons at the sub-ns level by using GPS carrier phase and geodetic techniques.
Actions

• Hardware requirements (1-pps input in timing receivers)
• Software requirements (BIPM time transfer format CGGTTS) --> P. Defraigne
• Calibration of receivers (Ashtech Z12-T, …) --> G. Petit
• Integration of time laboratories into the IGS network --> next slide
# IGS stations located at BIPM time laboratories

<table>
<thead>
<tr>
<th>IGS Site</th>
<th>Time Lab</th>
<th>GPS Receiver</th>
<th>Freq. Std.</th>
<th>City</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMC2</td>
<td>AMC *</td>
<td>AOA SNR-12 ACT</td>
<td>H-maser</td>
<td>Colorado Springs, CO, USA</td>
</tr>
<tr>
<td>BOR1</td>
<td>AOS</td>
<td>AOA TurboRogue</td>
<td>cesium</td>
<td>Borowiec, Poland</td>
</tr>
<tr>
<td>BRUS</td>
<td>ORB</td>
<td>Ashtech Z-XII3T</td>
<td>H-maser</td>
<td>Brussels, Belgium</td>
</tr>
<tr>
<td>KGN0</td>
<td>CRL *</td>
<td>Ashtech Z-XII3</td>
<td>cesium</td>
<td>Koganei, Japan</td>
</tr>
<tr>
<td>MDVO</td>
<td>IMVP</td>
<td>Trimble 4000SSE</td>
<td>H-maser</td>
<td>Mendeleevo, Russia</td>
</tr>
<tr>
<td>MIZU</td>
<td>NAO</td>
<td>AOA Benchmark</td>
<td>cesium</td>
<td>Mizusawa, Japan</td>
</tr>
<tr>
<td>NPLD</td>
<td>NPL *</td>
<td>Ashtech Z-XII3T</td>
<td>H-maser</td>
<td>Teddington, UK</td>
</tr>
<tr>
<td>NRC1</td>
<td>NRC *</td>
<td>AOA SNR-12 ACT</td>
<td>H-maser</td>
<td>Ottawa, Canada</td>
</tr>
<tr>
<td>NRC2</td>
<td>NRC *</td>
<td>AOA SNR-8100 ACT</td>
<td>H-maser</td>
<td>Ottawa, Canada</td>
</tr>
<tr>
<td>OBE2</td>
<td>DLR</td>
<td>AOA SNR-8000 ACT</td>
<td>rubidium</td>
<td>Oberpfaffenhofen, Germany</td>
</tr>
<tr>
<td>OPMT</td>
<td>OP</td>
<td>Ashtech Z-XII3</td>
<td>H-maser</td>
<td>Paris, France</td>
</tr>
<tr>
<td>PENC</td>
<td>SGO</td>
<td>Trimble 4000SSE</td>
<td>rubidium</td>
<td>Penc, Hungary</td>
</tr>
<tr>
<td>PTBB</td>
<td>PTB *</td>
<td>AOA TurboRogue</td>
<td>H-maser</td>
<td>Braunschweig, Germany</td>
</tr>
<tr>
<td>SFER</td>
<td>ROA *</td>
<td>Trimble 4000SSI</td>
<td>cesium</td>
<td>San Fernando, Spain</td>
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<tr>
<td>SPT0</td>
<td>SP</td>
<td>JPS Legacy</td>
<td>cesium</td>
<td>Boras, Sweden</td>
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<tr>
<td>TLSE</td>
<td>CNES</td>
<td>AOA TurboRogue</td>
<td>cesium</td>
<td>Toulouse, France</td>
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<tr>
<td>TWTF</td>
<td>TL *</td>
<td>Ashtech Z-XII3T</td>
<td>cesium</td>
<td>Taoyuan, Taiwan</td>
</tr>
<tr>
<td>USNO</td>
<td>USNO *</td>
<td>AOA SNR-12 ACT</td>
<td>H-maser</td>
<td>Washington, DC, USA</td>
</tr>
<tr>
<td>WTZA</td>
<td>IFAG</td>
<td>Ashtech Z-XII3T</td>
<td>H-maser</td>
<td>Wettzell, Germany</td>
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<tr>
<td>WTZR</td>
<td>IFAG</td>
<td>AOA SNR-8000 ACT</td>
<td>H-maser</td>
<td>Wettzell, Germany</td>
</tr>
</tbody>
</table>

- participates in two-way satellite time transfer (TWSTT) operations
Use of GPS dual-frequency P code observations in TAI

- TAI P3 pilot experiment (April 2002)
- Calibrated Ashtech Z12T receivers
- Data since mid-2002
- 7 TAI P3 links compared to other techniques in TAI
  - TWSTFT, GPS C/A SC
- Long term time stability of order 1.0 ns (1 $\sigma$)
- Start introducing TAI P3 links in TAI (July 2003)
  - DLR/PTB
  - IFAG/PTB
  - ORB/PTB
GPS P3 links

- Long term instability of GPS P3 links is of order 1.0 ns (1σ)
- Equivalent to the performance of TW links, at least twice better than GPS C/A links
<table>
<thead>
<tr>
<th>Laboratory</th>
<th>GPS P3 equipment</th>
<th>TW equipment</th>
<th>GPS C/A equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEN</td>
<td>Ashtech Z12T</td>
<td>MITREX 2500A</td>
<td>3S Nav. GNSS-300T (MC)</td>
</tr>
<tr>
<td>BNM/SYRTE (OP)</td>
<td>Ashtech Z12T</td>
<td></td>
<td>NBS TTR5 (SC)</td>
</tr>
<tr>
<td>PTB</td>
<td>Ashtech Z12T</td>
<td>TimeTech/SATRE</td>
<td>AOA TTR5 (SC)</td>
</tr>
<tr>
<td>USNO</td>
<td>Ashtech Z12T</td>
<td>MITREX 2500</td>
<td>AOS SRC TTS-2 (MC)</td>
</tr>
<tr>
<td>NRC</td>
<td>Ashtech Z12T</td>
<td></td>
<td>(SC)</td>
</tr>
<tr>
<td>CRL</td>
<td>Ashtech Z12T</td>
<td>AOA/Atlantis</td>
<td>3S Nav. R-100 (MC)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AOA TTR6 (SC)</td>
</tr>
<tr>
<td>NMIJ</td>
<td>Ashtech Z12T</td>
<td>AOA/Atlantis</td>
<td>AOA TTR6 (SC)</td>
</tr>
<tr>
<td>TL</td>
<td>Ashtech Z12T</td>
<td>AOA/Atlantis</td>
<td>AOA (SC)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Link</th>
<th>Distance</th>
<th>Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEN-PTB</td>
<td>800 km</td>
<td>P3, TW, C/A SC</td>
</tr>
<tr>
<td>OP-PTB</td>
<td>700 km</td>
<td>P3, C/A SC</td>
</tr>
<tr>
<td>CRL-PTB</td>
<td>8300 km</td>
<td>P3, C/A SC</td>
</tr>
<tr>
<td>USNO-PTB</td>
<td>6300 km</td>
<td>P3, TW</td>
</tr>
<tr>
<td>NRC-USNO</td>
<td>700 km</td>
<td>P3, C/A SC</td>
</tr>
<tr>
<td>NMIJ-CRL</td>
<td>70 km</td>
<td>P3, TW, C/A SC</td>
</tr>
<tr>
<td>TL-CRL</td>
<td>2100 km</td>
<td>P3, TW, C/A SC</td>
</tr>
</tbody>
</table>
UTC(USNO) - UTC(PTB): 2002/10-2003/11

- P3-TW(Ku): RMS = 0.9 ns
- RMS = 0.9 ns

UTC(CRL) - UTC(PTB): 2002/09-2003/11

- P3-C/A SC: RMS = 1.7 ns
UTC(NMIJ) - UTC(CRL): 2002/12-2003/11

- P3-C/A SC: RMS = 0.7 ns
- P3-C/A SC: RMS = 1.1 ns

NMIJ-CRL [P3-TW(edited)] 2002/12-2003/11: RMS = 1.0 ns
Links to other organizations

- IAU WG on RCMAM
- IERS Conventions Product Centre, with USNO
- IGS WG on Clock Products
- Sector member ITU-R
- AIG - UGGI
UTC(USNO) - UTC(PTB): 2002/10-2003/05

P3-TW(Ku): RMS = 1.0 ns
UTC(IEN) - UTC(PTB): 2002/10-2003/11

- P3-C/A SC: RMS=2.2 ns
- : RMS=1.4 ns
- : RMS=1.4 ns

MJD vs. ns
UTC(IEN) - UTC(PTB): 2002/10-2003/11

- P3-TW: RMS = 1.0 ns
- : RMS = 1.1 ns
- : RMS = 1.2 ns
UTC(OP) - UTC(PTB): 2003/08-2003/11

P3-C/A SC: RMS = 1.6 ns
UTC(NRC) - UTC(USNO): 2003/04-2003/11

\[
\begin{align*}
\text{P3-C/A SC: RMS = 2.5 ns} & \quad \text{For } X: \text{ RMS = 1.8 ns} \\
& \quad \text{For } Y: \text{ RMS = 1.3 ns}
\end{align*}
\]