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CGSIC, 2022
Report from NIST

GNSS operations/Time transfer

- New NIST GNSS receiver
- Calibrations
- Subscription-based NIST time service

Scientific research and data analysis

- Exploring fundamental physics using atomic clocks: universality of gravitational redshift, relativistic geodesy
- Topics on more resilient GNSS
June 2022: NIST primary receiver and antenna upgrades

- June 15, 2022: Results of CAL_ID 1001-2020 implemented
- Internal delays 28.2 ns and 26.3 ns for GPS P1 and P2
- Ref. delay: 93.0 ns
June 2022: NIST primary receiver and antenna upgrades

RMS Multipath

Multipath < 0.30 cm
Time Transfer with GPS carrier phase: NIST-PTB

Link stability before and after (two month intervals)

\[ \sigma_{\tau}(\tau), \sigma_{T}(\tau), \sigma_{\gamma}(\tau), \text{ Mod } \sigma_{\gamma}(\tau), \text{ MDEV} \]
Calibrations update: Group 2 (G2)

- NRC : Ottawa, Canada / Cal_Id:1019-2017
- CNM : Queretaro, Mexico / Cal_Id:1011-2017
- CNMP : Panama / Cal_Id: 1011-2017
- INXE,ONRJ: Brazil / Cal_Id: 1012 -2020
- AGGO,INTI,ONBA: Argentina / Cal_Id: 1014 -2021

Completed
Performance: UTC(NIST)
Performance: UTC(NIST)
NIST Time Services

GNSS independent
A brief history of clocks at NIST [slide credit: Chris Oates]
Testing universality of gravitational redshift (UGR)

UGR $\rightarrow$ Gravity affects the rate of clocks

Fractional frequency shift, \[ \frac{\Delta f}{f} = (1 + \epsilon) \frac{\Delta \Phi}{c^2} \]

$\Delta \Phi \rightarrow$ gravitational potential difference w.r.t. geoid

$c \rightarrow$ speed of light in vacuum

Einstein’s general relativity: \[ \epsilon = 0 \]
Comparing with Gravity Probe A (GPA) [Vessot, R.F.C. et al. 1980, PRL]

<table>
<thead>
<tr>
<th></th>
<th>GPA,1976</th>
<th>Clock on Mt Evans, 202?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height difference (km)</td>
<td>10,000</td>
<td>2.75</td>
</tr>
<tr>
<td>Experiment duration (hr)</td>
<td>$\sim 1$</td>
<td>$\sim 10$</td>
</tr>
<tr>
<td>Oscillator uncertainty, $\delta \left( \frac{\Delta f}{f} \right)$</td>
<td>$10^{-14}$</td>
<td>$10^{-18}$</td>
</tr>
<tr>
<td>$\epsilon$ (theory)</td>
<td>25 parts per million</td>
<td>6 parts per million</td>
</tr>
<tr>
<td>$\epsilon$ (measured)</td>
<td>$\sim 125$ parts per million</td>
<td>$\sim 12$ parts per million?</td>
</tr>
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Gravitational considerations as clocks get better

Geoid: Equipotential surface coinciding with the mean sea level

- What is the acceptable precision/uncertainty on the definition of the geoid?
- What is the effect of rising (not very predictable) sea level?
- Local (short baseline) clock comparisons depend on mapping area under few tens of sq-km with gravimeters, spirit levelling
- Fractional frequency uncertainty for locations around NIST (2017) $\sim 10^{-19}$
- All measurements assign an uncertainty of zero for pivot (NGS marker) with respect to the geoid
Consider the NGS marker Q407 at NIST:

The equivalent fractional frequency due to uncertainty on Q407 with respect to the geoid using the latest geopotential model

\[ \sim 7 \times 10^{-18} \]

In order to compare distant clocks, one may have to first use very precise clocks for accurately determining the geoid (chronometric levelling).
1. Define based on the frequency of a transition in one atom. Other atomic transitions would be “secondary representations”
   + Already done with cesium
   + Easy to describe and understand
   – The “best atom” could be different in a few years
   – Based on the chosen atom, labs might have to build a new standard once a decision is made

2. Define a standard based on the weighted average of several transitions
   + Could include many atoms whose weights adapt over time based on performance
   + Would reduce risk to labs since all standards could be used
   – Complex and hard to explain in simple terms

3. Define frequency by fixing the value of another fundamental constant, for example, the Rydberg constant
   + Would be consistent with the other definitions of the SI units
   – Would degrade the accuracy of the definition (uncertainty in $R_\infty$ is $2\times10^{-12}$)
Resilient GNSS timing by including doppler data: spoofing

[in collaboration with Prof. Neil Ashby, CU Boulder]

Navigation equations

\[ c\delta t - \hat{e}_j \cdot \delta \vec{r} = |\vec{r}_0 - \vec{r}_j| - c(t_0 - t_j), \]

where

\[ \hat{e}_j = \frac{\vec{r}_0 - \vec{r}_j}{|\vec{r}_0 - \vec{r}_j|}. \]

Navigation equations with doppler terms

\[
\left( \frac{\vec{v}_0 - \vec{v}_j}{|\vec{r}_0 - \vec{r}_j|} \right) \cdot \delta \vec{r} + \hat{e}_j \cdot \delta \vec{v} = c \left( \frac{\Delta f}{f} \right)_j - (\vec{v}_0 - \vec{v}_j) \cdot \hat{e}_j
\]
Resilient GNSS timing by including doppler data: spoofing
[in collaboration with Prof. Neil Ashby, CU Boulder]

Pros:
- Can be used to detect excursions using single point solutions
- Can validate excursions in the orbital parameters as determined from the navigation message
- Method can be applied to all constellations

Cons:
- Expensive (computing power)
- Not all receivers provide doppler information

Would be very useful if navigation messages are made available to the user by a trusted source that is independent of the receiver.
Acknowledgement

Contact information:

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Optical frequency standards: Chris Oates (chris.oates@nist.gov)

NIST timescale: Jeff Sherman (jeff.sherman@nist.gov)
Discussion topic

Would users benefit from a real-time GPS navigation message made available on a secure website?

Any strong objections?

Suggestions? Use cases?