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SYstèmes de Référence Temps-Espace

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS LNE

SORBONNE UNIVERSITÉ CRÉATEURS DE FUTURS DEPUIS 1257

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NPL National Physical Laboratory

Optically Steered Time Scale Generation at OP and NPL and Remote Comparisons

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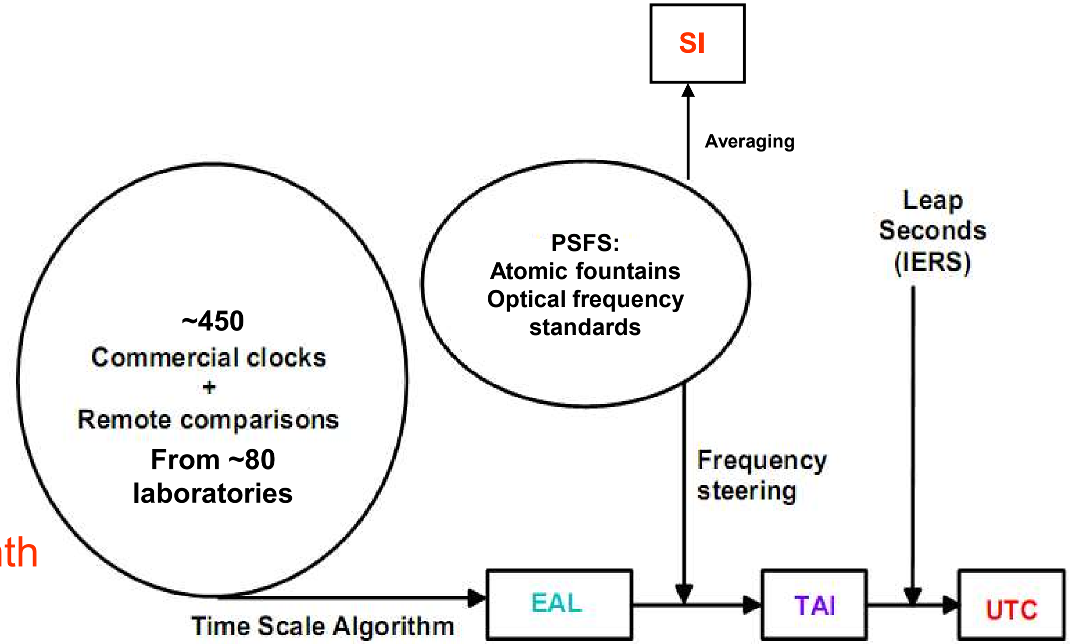
EMPIR EURAMET

Outline

- Context
- Present for both labs
  - The experimental setup
  - The algorithm implemented
  - The local results
- Distant comparison of the experimental time scales
- Summary and outlook

UTC, TAI, SI calculated by the BIPM

The BIPM produces each month
- The free running timescale: **EAL**
- Temps atomique international: **TAI**
- Universal coordinated time: **UTC**
- The **SI** Second



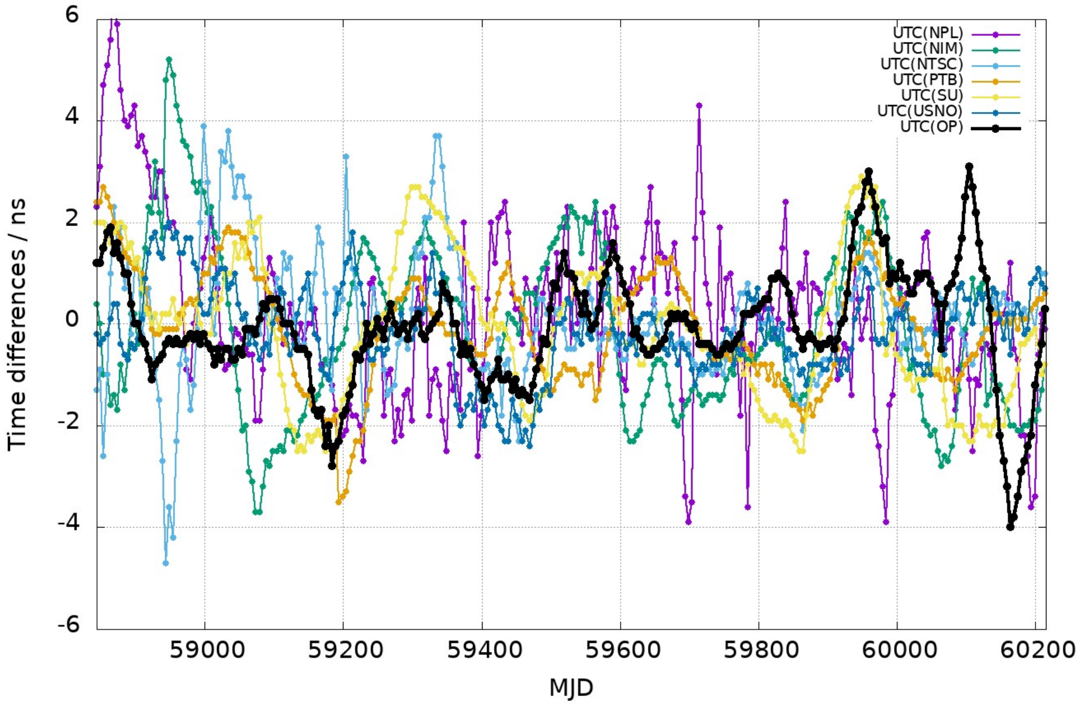
- UTC: « paper » timescale calculated for the previous month
- NMIs and DIs produce predictions of UTC: UTC(k)
- **UTC – UTC(k)** published in the **Circular T**

UTC uncertainty is in the low 10^{-16} dominated by the atomic fountains

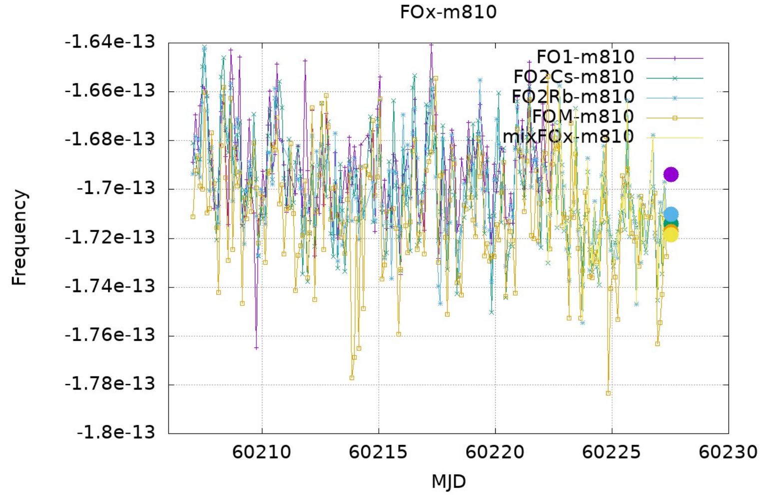
Fountain based UTC(k)

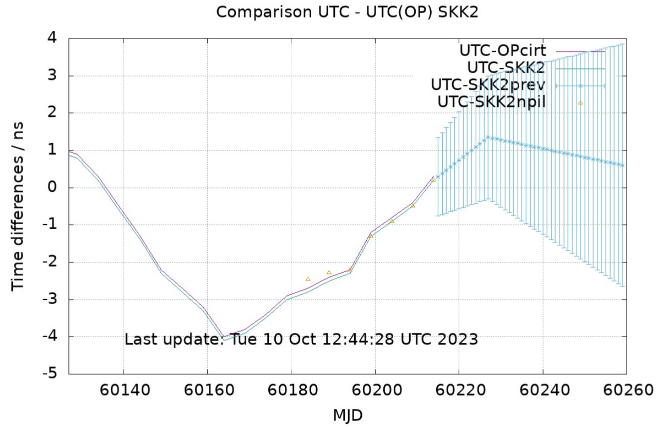
- Best UTC(k) based on Active Hydrogen Masers
- Steering with a latency of ~*d* by local atomic fountains
- Additional fine steering updated monthly

UTC-UTC(k) comparisons since beginning of 2020



Example of the method implemented at OP





➢ Maintained at few ns from UTC

3 x 10^{-16} frequency offset corresponds to 1 ns cumulated phase over 40 *d*

Expected improvement with OFS

With OFS presenting inaccuracies in the 10^{-17} - 10^{-18} range, one can expect an improvement in international and national time scales by more than an order of magnitude

- Roadmap for the redefinition of the SI second

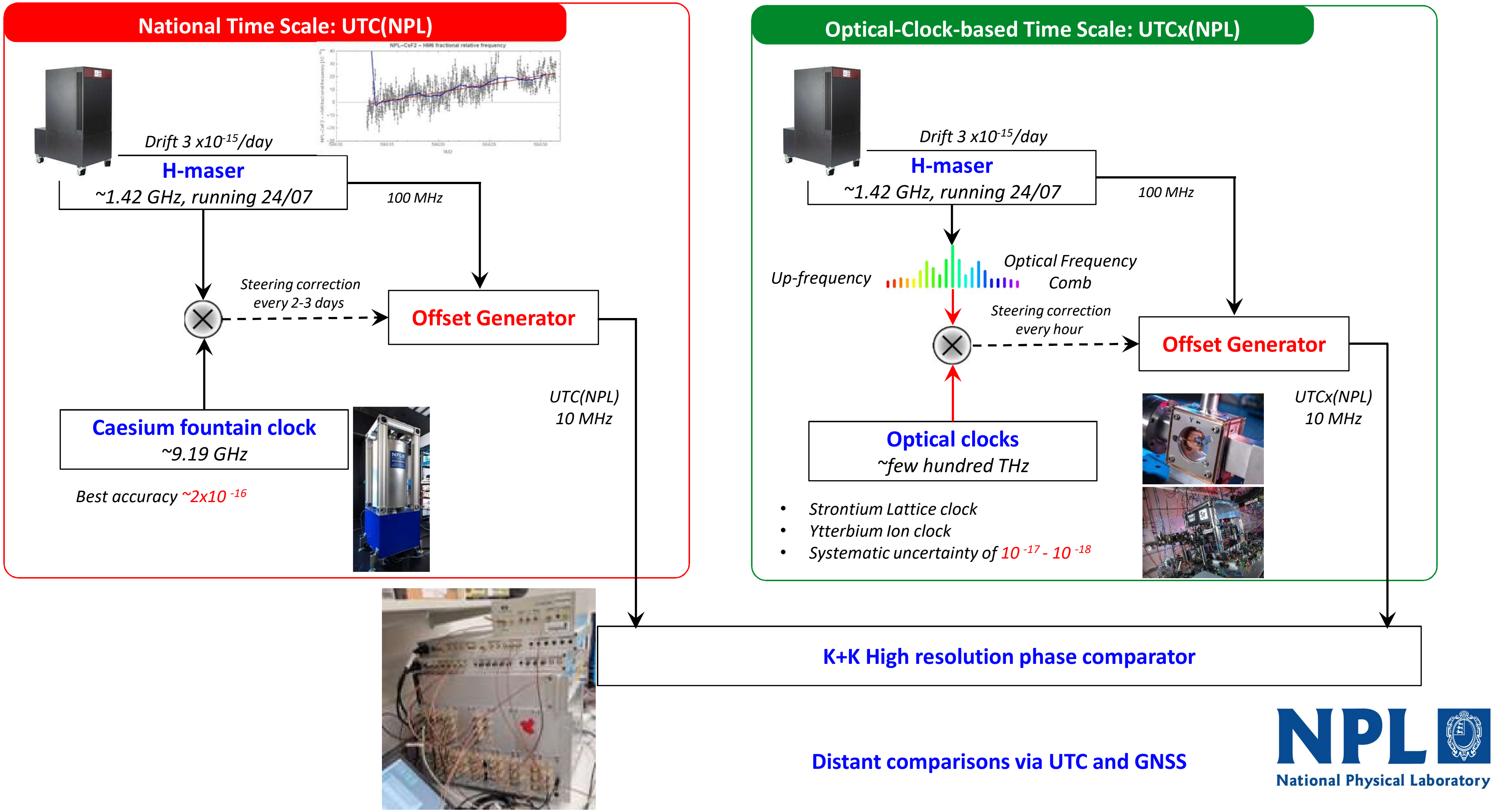
- Active research in many groups based on simulations and experiments to explore the potential of using optical clocks to maintain time scales as accurate as a few 100 ps
- Many studies to trade off between the impact of the discontinuities and the latency in the data availability of OFS and the achievable performance of optically steered time scales

European Joint Research Program ROCIT : Robust Optical clocks for International Time scales

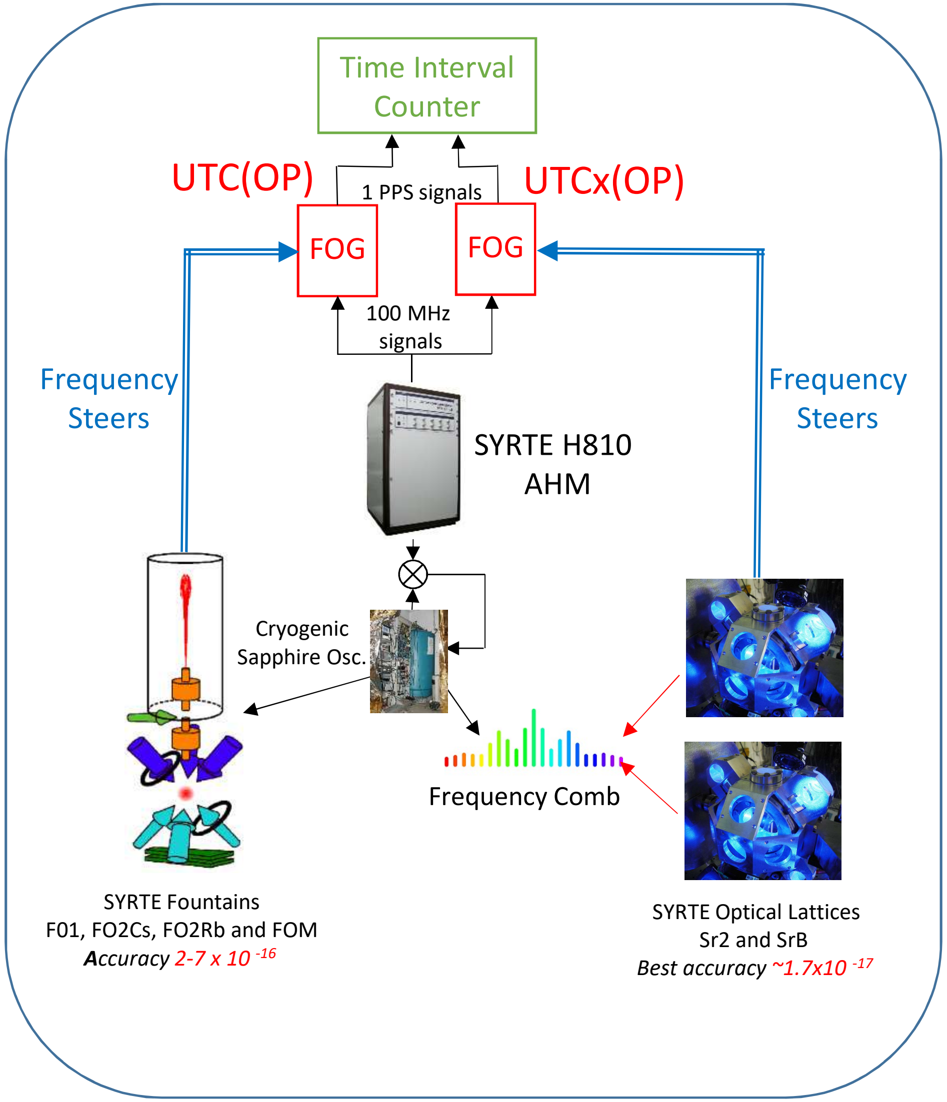
- To improve robustness and automate operation including on-the fly validation and evaluation of OFS
- To investigate consistency of OFS (frequency ratio and absolute measurements) through a coordinated program of frequency comparisons.
- To incorporate new OFS into UTC via the submission of data to the BIPM.
- To demonstrate, both by simulations and experiments, methods for incorporating OFS into UTC(k)

Experimental time scales UTCx(k) operated in parallel to local time scale UTC(k) at the same time at NPL and OP during the March 2022 ROCIT OFS comparison campaign

UTCx(NPL) Experimental Setup



UTCx(OP) Experimental Setup



- UTC(OP) and UTCx(OP) based on the same H-maser feeding two different Frequency Offset Generators
- Maser H810 (VCH-1003M, op. since Feb 2012)
- Frequency drift ~$10^{-16}/d$
- Atomic fountains and optical clocks share the same local oscillator (CSO phase locked to the H Maser)
- Automatic data processing and FOG steering of both timescales
- Local comparison using an SR620 Time Interval Counter
- Distant comparisons via UTC and GNSS

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Steering Algorithms main features

- Frequency calibration of the H-maser by the OFS
- On the fly correction of the OFS frequency shifts at the 10^{-16} level
- Validation off the metrological chain (short local links, combs, local oscillators)
- ➢ With a low latency to better compensate for the real time H-maser fluctuations

- Combination of OFS data
- Extrapolation in case of missing data
- ➢ To improve robustness and reduce the effect of dead times

No steering towards UTC

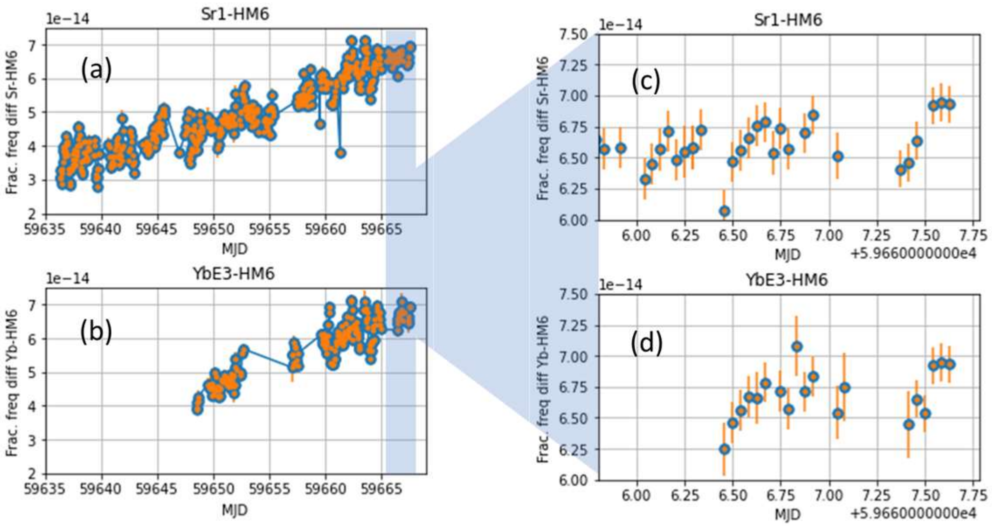
- ➢ Independent time scales
- ➢ Realize the SI second
- ➢ Short experiment duration

UTCx(NPL) Steering Algorithm

2021 recommended frequency values

171Yb+(E3)	642121496772645.0	6.0E-16	642121496772645.12	1.9E-16
87Sr	429228004229873.0	4.0E-16	429228004229872.99	1.9E-16

Fractional Frequency Difference (FFD) between NPL-Sr1/Yb+E3 and HM6



- Fractional frequency difference between optical clocks and the maser HM6: determined hourly with a latency of 10-16 minutes.
- HM6_u frequency:
  - Scattering: ~1.5×10^{-14} for 1 day
  - Drift: ~1.12×10^{-15} per day

Steering Routine:

Each hour, after validation of clock and comb data and applying an additional $\pm 5 \times 10^{-13}$ outlier filtering for safety

The applied fractional frequency steer was determined via 3 scenarios:

- Case 1: >25% of the 1-h dataset from both clocks is marked as valid. The FFD is computed for each clock and the steering computed using a weighted mean where the weight of clock X is proportional to $\left(\sqrt{N_X}/\sigma_X\right)^2$
- Case 2: >25% of 1-h dataset from a single clock is marked as valid. The FFD of that clock is used.
- Case 3: >75% of data from both clocks is marked as invalid or the $|FFD| > 5 \times 10^{-13}$, the appropriate steer is predicted using previous steers and HM6's drift behaviour.

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UTCx(NPL) Experimental Results

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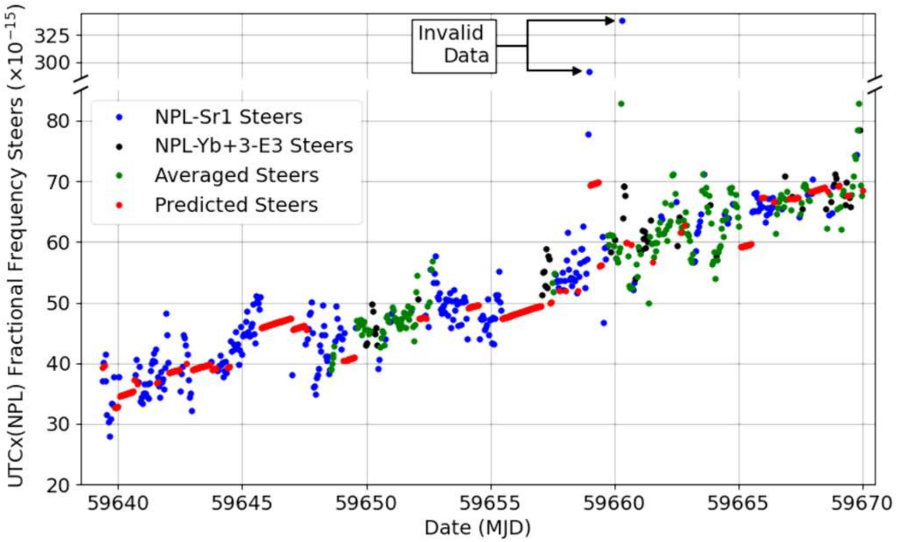
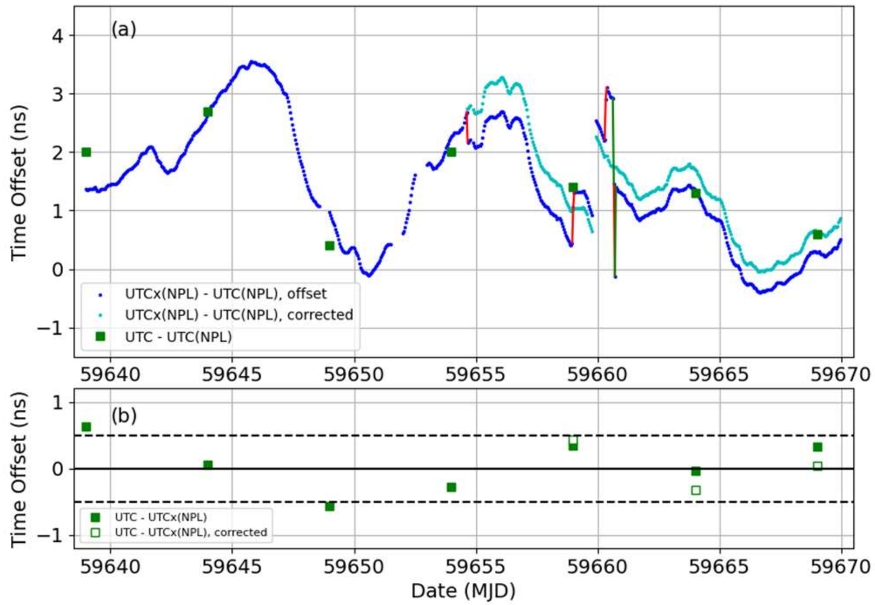
Optical UTCx(NPL) Time Scale Steering



UTCx(NPL) Results



☺ Time offset between UTC and UTCx(NPL): Within ±0.64 ns

Technical glitches:

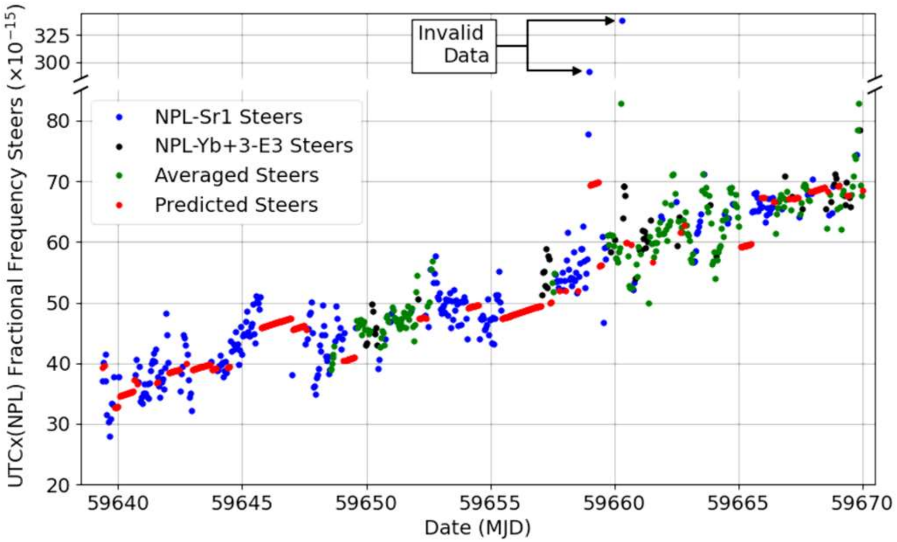
☹ Offset generator phase jumps caused 0.5/1.5 ns steps at MJD 59654.6/59661.0.

☹ Data validation issues where incorrectly "marked as valid" data caused too-large steering parameters to be applied, accumulating phase over time at MJD 59658.9/59660.2

☺ Glitches can be corrected in-situ by applying an opposite frequency steer until the phase is recovered.

UTCx(NPL) Experimental Results

Optical UTCx(NPL) Time Scale Steering



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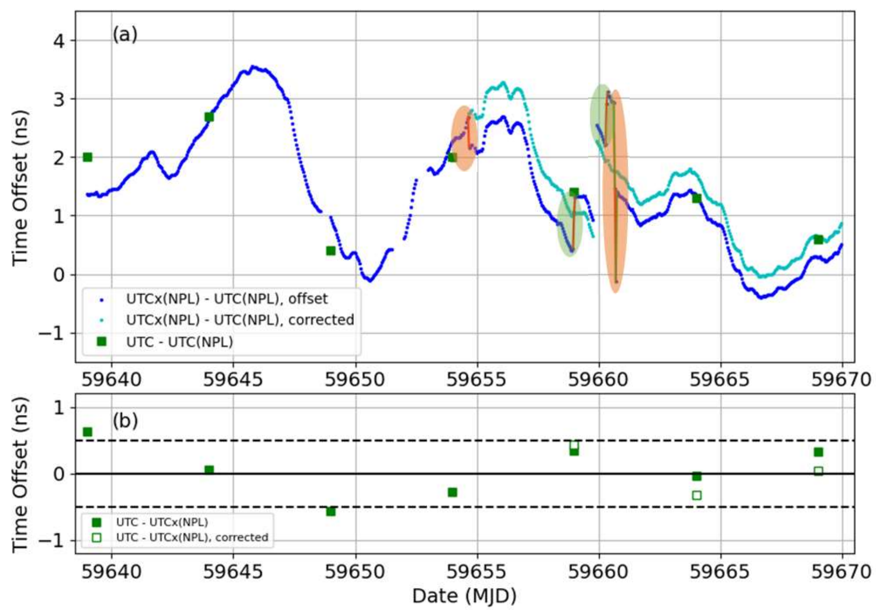

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UTCx(OP) Steering Algorithm

- Exploitation of the 1 s sampled SYRTE Sr2 and SrB Strontium optical lattice data **corrected from the systematics**, available within a few seconds latency
- Every 5 minutes, on the 1s sampled data:
  - Remove outliers larger than 2×10^{-12}
  - Perform a 5 σ outliers rejection after removing a linear fit
- Every 1 hour:
  - Computation of data averaged over 0.1 d + additional 5 σ outliers rejection => **pack of data**
  - Extrapolation of the H Maser frequency at the current time, based on past 5 days of data => **extrap. data**
  - Computation with Sr2 and SrB independently and using a concatenation of both for tests
  - Output of **concatenation** of both used for the FOG steering during the experiment
- FOG Steering updated hourly:
  - If the last valid pack is **older than 0.4 d**: the steering is based on the extrapolated value
  - If not, we take the last **valid** pack data for the steering
  - If the difference between the previous steering and the new one is larger than 2×10^{-14} the steering is not updated.

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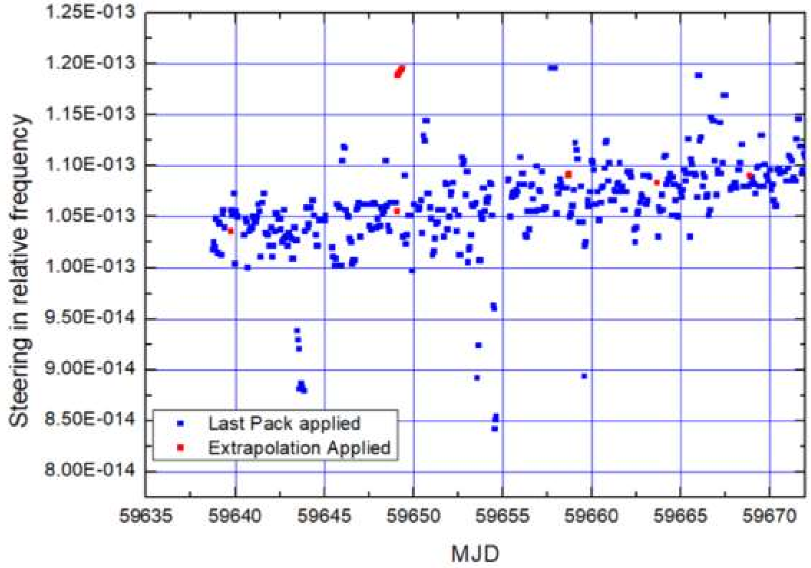
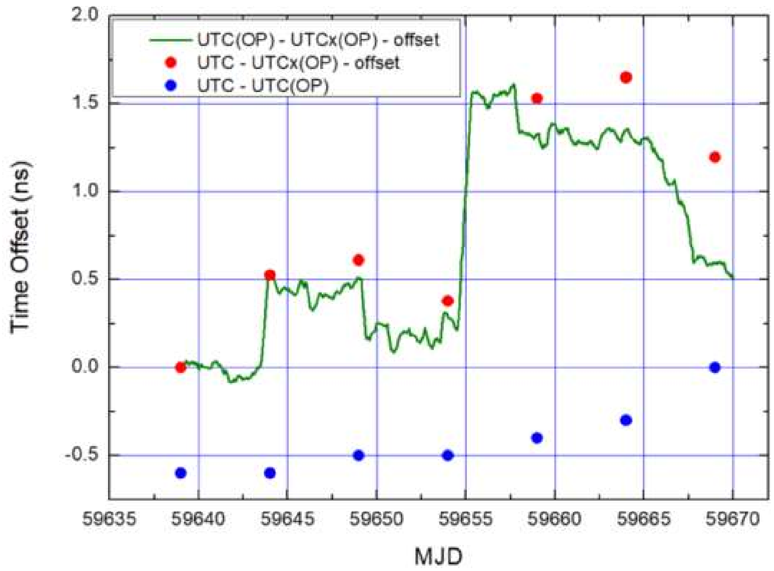
UTCx(OP) Experimental Results

- Applied steering stems mainly from the last pack of data, thanks to the almost continuous operation of the entire chain
- Some remaining outliers just below the last threshold of 2 x 10^{-14}

- Comparison to UTC(OP) and UTC over the 30 d period
  - Initial arbitrary offset removed for all comparisons to UTCx(OP)
  - Phase jumps at different epochs (around MJD 59643.8, 59649.2, 59654.5 and 59657.8) due to outliers just below the threshold
  - For the event around MJD 59654.5, the steering remained blocked until a manual intervention because the new valid steering was just above the last threshold

- During the experiment
  - [UTC(OP) – UTCx(OP)|<1.7 ns
  - [UTC – UTCx(OP)|<1.7 ns
  - [UTC – UTC(OP)|<0.6 ns





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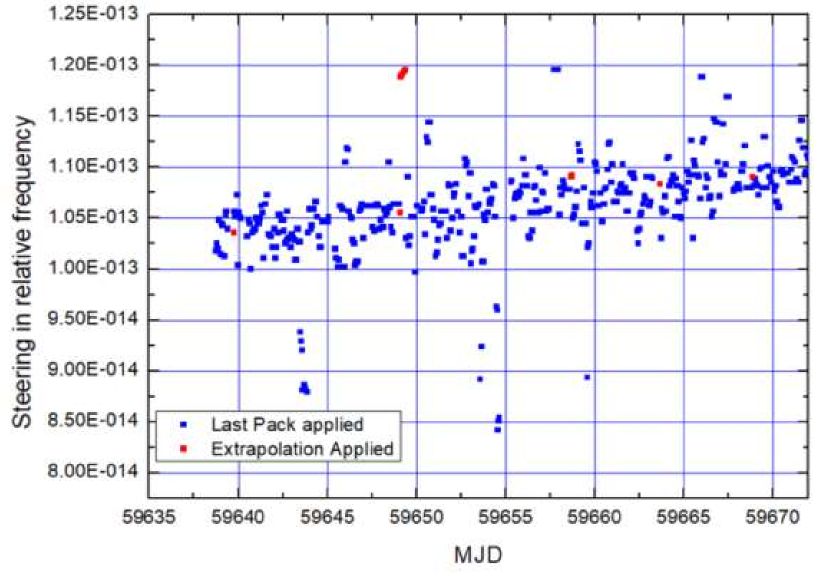

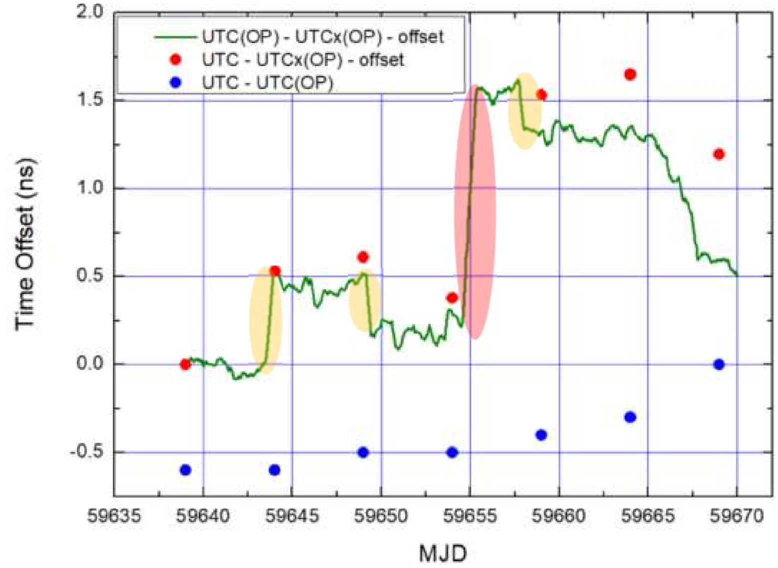

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UTCxS(OP) Simulation Results

- Timescales simulated using Sr2 and SrB independently
- Manual filtering of remaining outliers

- Comparison to UTC(OP) and UTC over the 30 d period
  - Initial arbitrary offset removed for all comparisons to UTCxS(OP)
  - [UTC(OP) – UTCxSrB(OP)]| < 400 ps
  - [UTC(OP) – UTCxSr2(OP)]| < 700 ps
  - [UTC – UTCxSrB(OP)]| < 600 ps
  - [UTC – UTCxSr2(OP)]| < 1.3 ns

- Larger fluctuations for UTCxSr2(OP) by the end of the period where the clock was not in operation for about 2 *d*

- Over the first 25 d, positive trend of about 2×10^{-16} of UTC – UTCxSrB(OP) and UTC – UTCxSr2(OP)

- Same order of magnitude as d=-yTAI= 1.6×10^{-16} as published in Circular T411 (green line)
  - [TT – UTCxSrB(OP)]| < 200 ps
  - [TT – UTCxSr2(OP)]| < 900 ps

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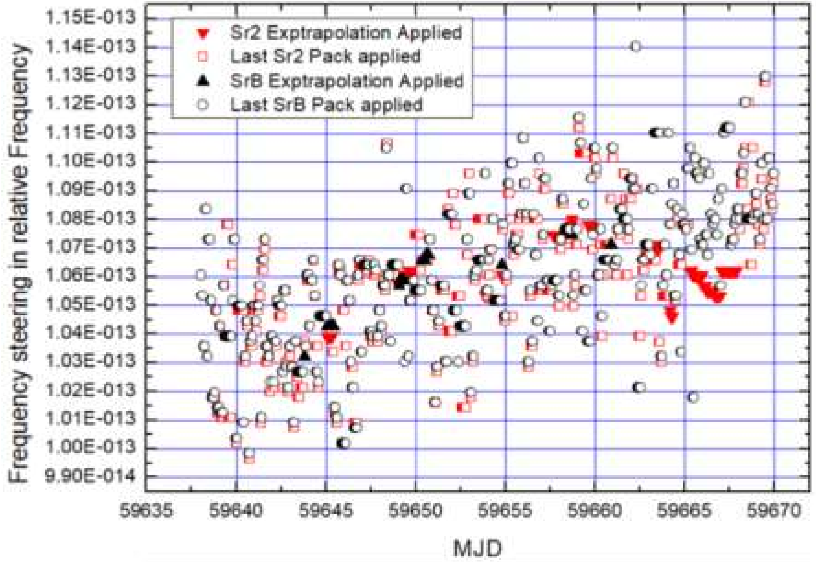
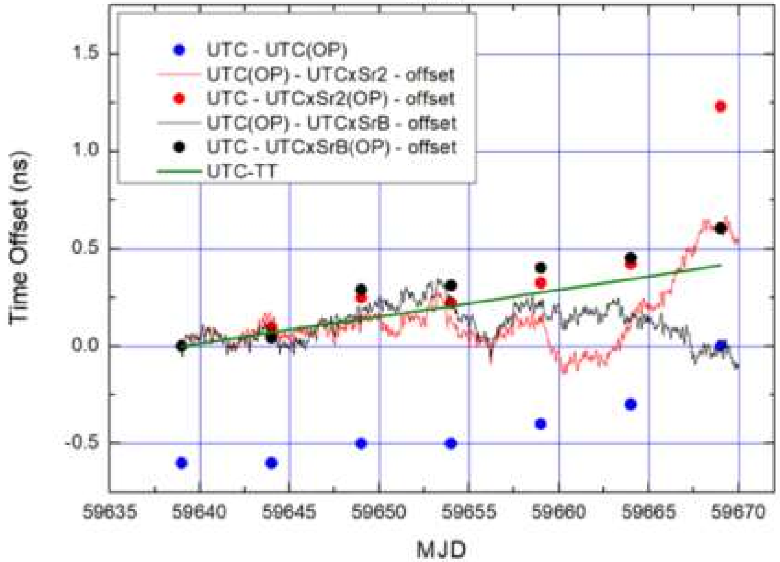
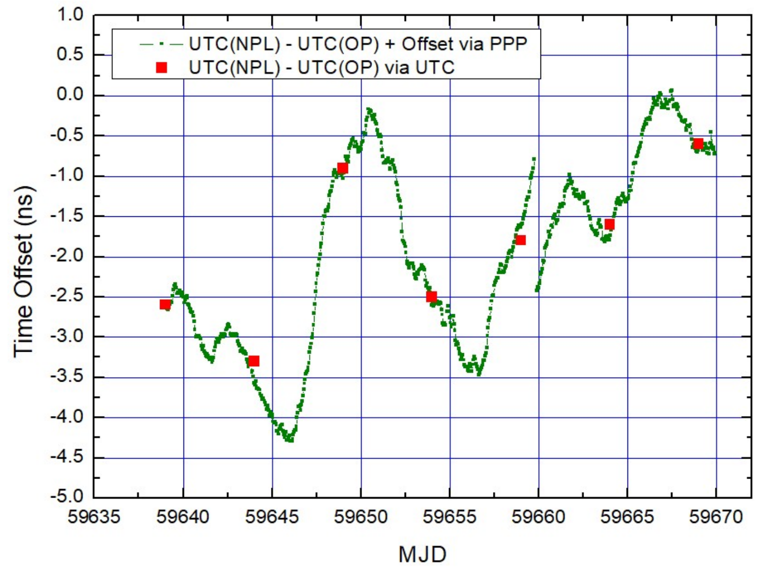


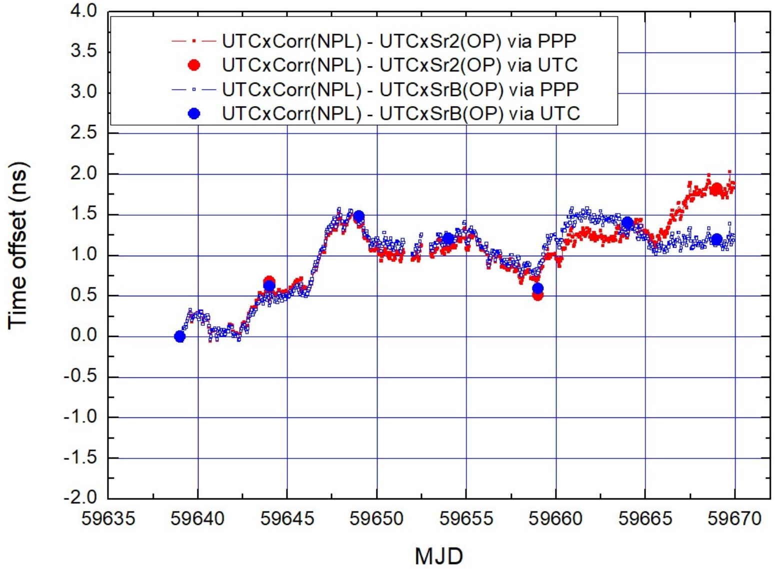


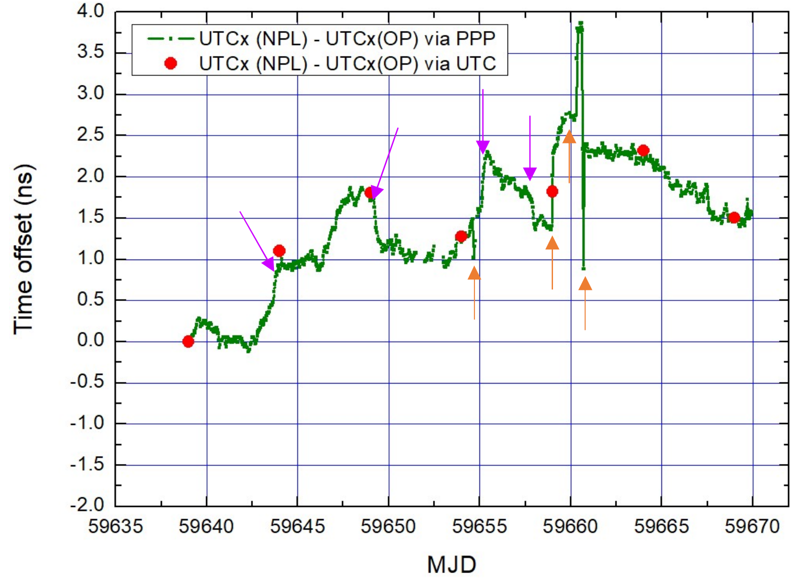
Comparison of Optically Steered Timescales

- Comparison of distant timescales UTCx(NPL) and UTCx(OP)
  - Via UTC
  - Via GPS PPP

- Comparisons remain within a few ns
- Experimental timescales difference dominated by the events in both labs
- Simulated/corrected timescales difference below 2 ns, a factor of 2 better than UTC(k) realizations







Summary and outlook

- ✓ Among the first attempts to generate optically steered time scales
- ✓ First optically-driven timescales compared directly, better than corresponding UTC(k) comparison

Further tests in the future, in parallel to developments to improve optical clocks and metrological chains
No additional infrastructure needed to pursue such tests

Further work:

- ➢ Improve again reliability of operation the metrological chain and clocks
- ➢ Improve the validation thresholds to better flag invalid data
  - Improve threshold on outlier filtering
  - Adaptive intervals for estimating the slope of the flywheel to better detect glitches
  - …
- ➢ Improve algorithms to deal with missing data:
  - Better combine clocks (weighed mean/simple mean)
  - Self-adaptive duration for extrapolation
  - Tests with intermittent operation of the clocks
  - Performances depending on the predictability of the maser
- ➢ Tests over longer periods
  - Steering towards UTC
  - UTC will also benefit from the increasing number of contributing OFS

Thank You!

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