l'Observatoire de Paris | SYRTE

Systèmes de Référence Temps-Espace

National and International Timescales : Construction and Dissemination

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS LNE

SORBONNE UNIVERSITÉ

PSL UNIVERSITÉ PARIS

cnrs

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Assemblée Générale FIRST-TF, October 21st-22nd 2021

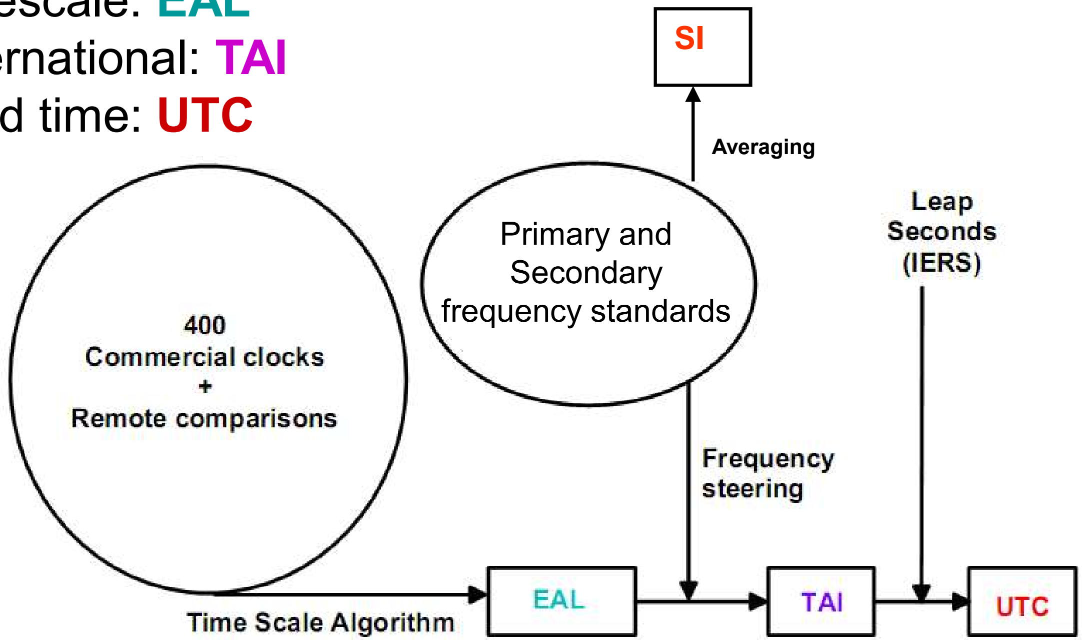
Outline

- UTC, TAI, SI
- LNE-SYRTE clock ensemble
- Atomic fountains
- UTC(OP) Timescale
- Time transfer techniques
- UTC(OP) dissemination

UTC, TAI, SI calculated by the BIPM

The BIPM produce each month

- •The free running timescale: **EAL**
- •Temps atomique international: **TAI**
- •Universal coordinated time: **UTC**
- •The **SI** Second

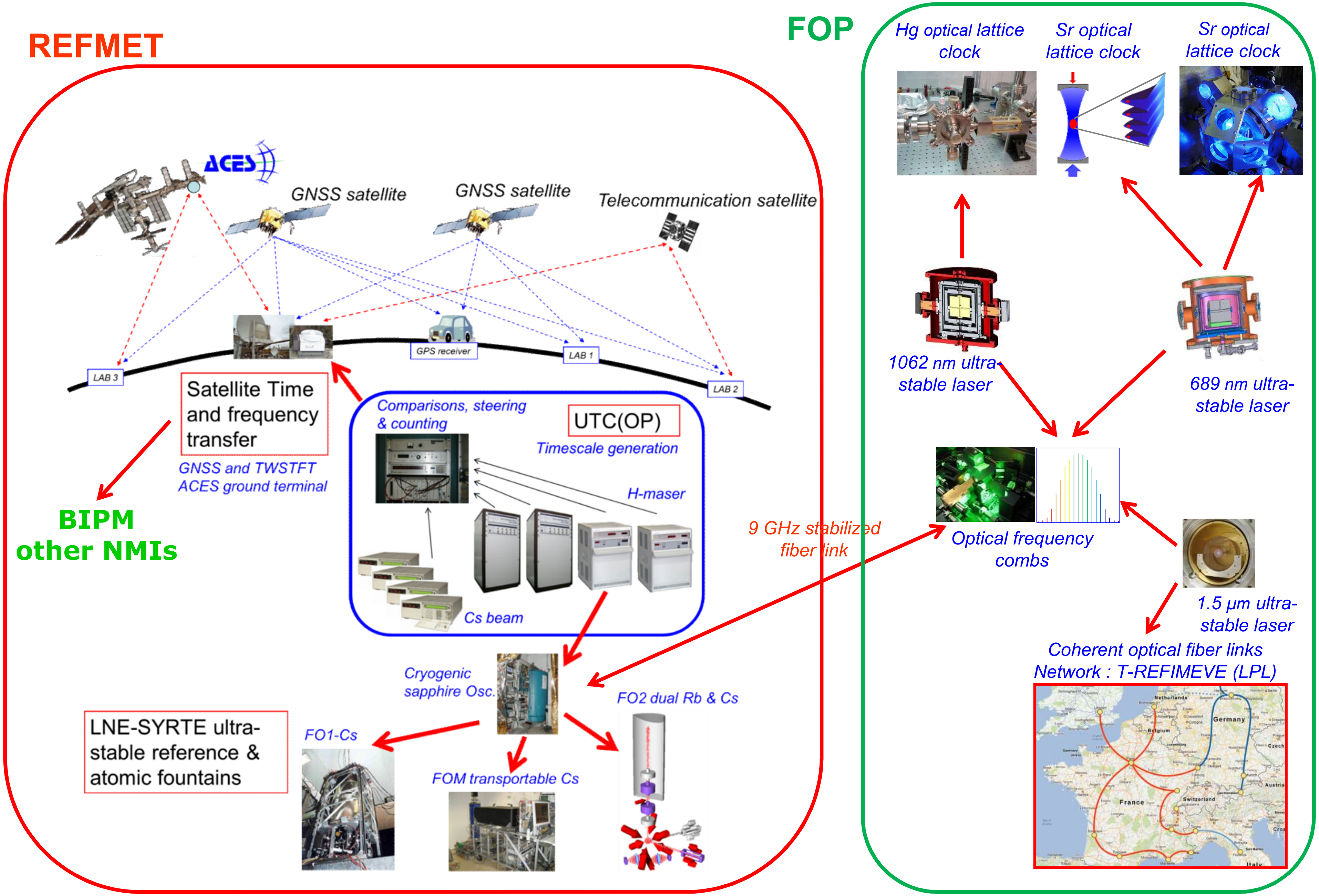


- ▪UTC maintained close to UT1: |UTC – UT1| < 0,9 s

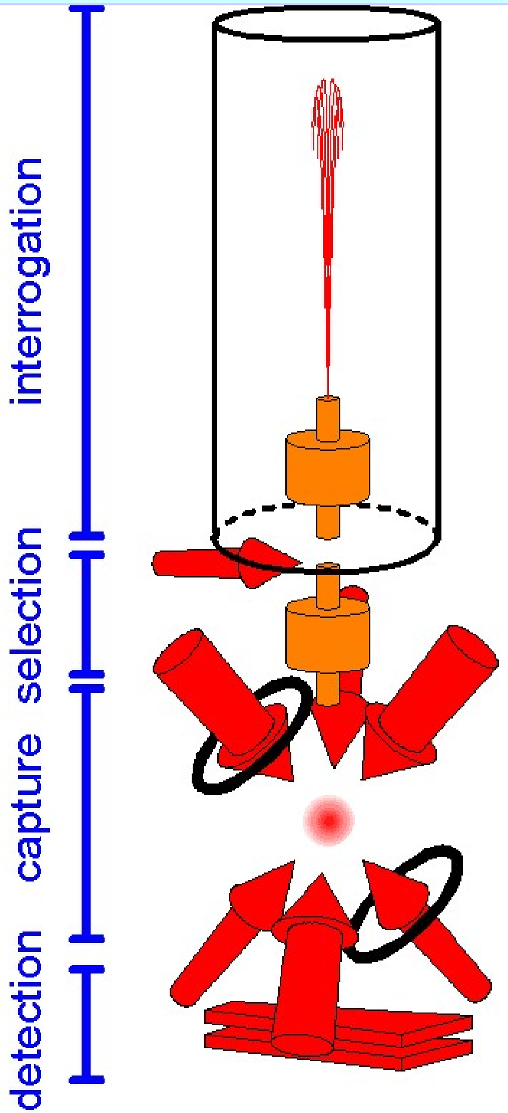
  UTC – TAI = - 37 s since January 1st 2017
- ▪UTC: « paper » timescale calculated for the previous month
- ▪NMI produce predictions of UTC: UTC(k)
- ▪**UTC – UTC(k)** published in the **Circular T**

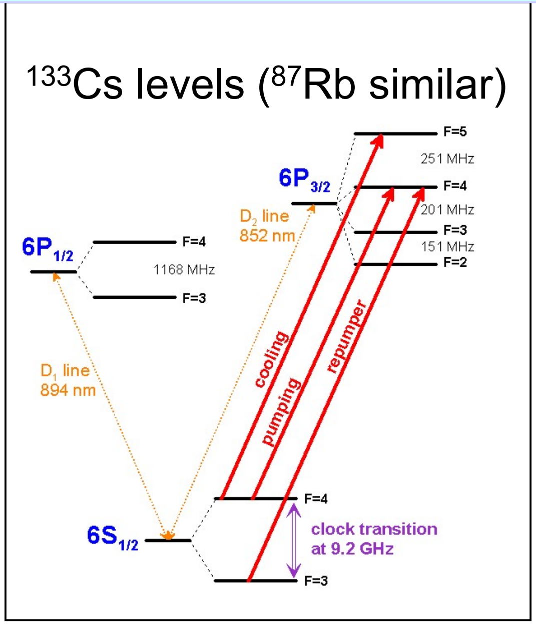
- ▪The SI Second : an averaging of PSFS data provided by a few NMI

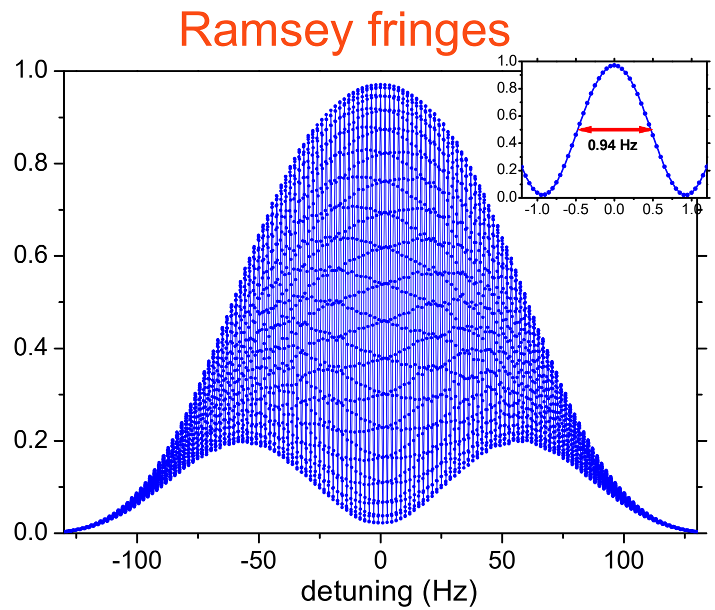
SYRTE atomic clock ensemble

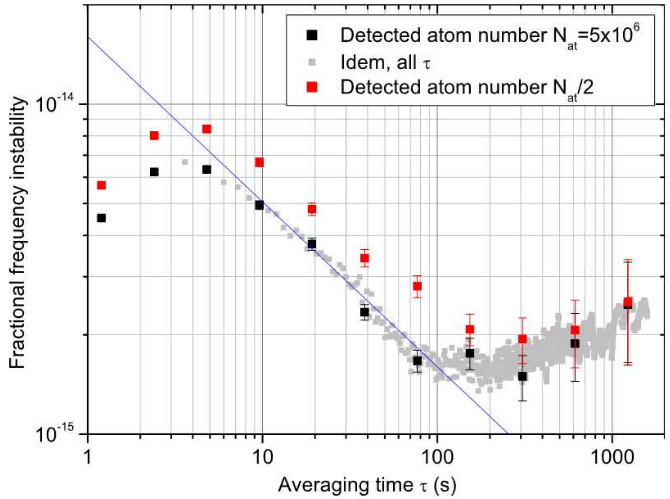


Atomic fountain clocks









Atomic quality factor:

$$Q_{at} = \nu_{ef}/\Delta\nu \simeq 9.8 \times 10^9$$

Best frequency stability (Quantum Projection Noise limited): $1.6\text{x}10^{-14}$ @1s

Best accuracy: $(2\text{-}3)\text{x}10^{-16}$

About 20 fountains in operation or under development (LNE-SYRTE, PTB, INRIM, NPL, VNIIFTRI, NRC, NIM, METAS, NIST, USNO, JPL, NICT, NMIJ, KRISS, AOS, NPLI, …)

SYRTE Fountain performances

- Fountain Stability

$\sigma_y(\tau=1s)$ at high atomic densities routinely over the past years

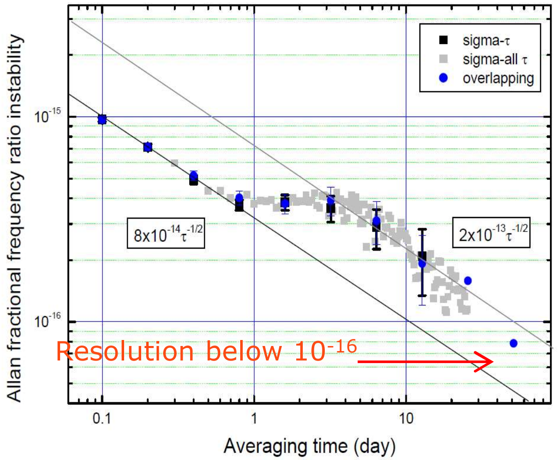
FO1	3.3×10^{-14}
FO2-Cs	3.5×10^{-14}
FOM	6.0×10^{-14}
FO2-Rb	3.2×10^{-14}

- Fountain Accuracy

Uncertainty budget (x 10^{-16})

	FO1	FO2-Cs	FOM	FO2-Rb
Quadratic Zeeman Shift	-1277.79 ± 0.40	-1937.02 ± 0.30	-314.42 ± 1.90	-3503.75 ± 0.7
BlackBody Radiation	169.97 ± 0.60	172.26 ± 0.80	166.50 ± 2.30	127.22 ± 1.45
Collisions and Cavity Pulling	131.95 ± 1.66	105.71 ± 1.06	20.60 ± 3.09	4.34 ± 1.26
Distributed Cavity Phase Shift	-0.07 ± 2.40	-0.9 ± 1.0	-0.7 ± 2.75	-0.35 ± 1.0
Microwave Lensing	-0.65 ± 0.65	-0.7 ± 0.7	-0.9 ± 0.9	-0.7 ± 0.7
Spectral Purity and Leakage	<1.0	<0.5	<1.5	<0.5
Ramsey & Rabi pulling	<0.2	<0.1	<0.1	<0.1
Second-Order Doppler Shift	<0.1	<0.1	<0.1	<0.1
Background Collisions	<0.3	<1.0	<1.0	<1.0
Total without Red Shift	**-976.59 ± 3.25**	**-1660.65 ± 2.15**	**-128.92 ± 5.48**	**-3373.24 ± 2.63**
Red Shift	-69.08 ± 0.25	-65.54 ± 0.25	-68.26 ± 0.25	-65.45 ± 0.25
Total with Red Shift	**-1045.67 ± 3.3**	**-1726.19+/-2.2**	**-197.18 ± 5.5**	**-3438.69 ± 2.6**

Long term stability of ν_{Rb}/ν_{Cs} with dual FO2 over 6 months



- **Fountain Routine Operation:**

•Differential measurement by varying the atomic density and extrapolate to 0 to evaluate cold collisions

•Sequential verification (every 1 h) of the Bfield and of the temperature in the interrogation zone

•Periodical verification of the DCP (Tilt, Asym1/Asym2)

•Periodical verification of perturbations on the interrogation signal synchronous to the clock cycle

•Periodical verification of Bfield Map

•Periodical verification of light shifts

Contribution to the accuracy of TAI

- Fountain data analysis
- ✓ Automatic data processing and parameters monitoring
- ✓ Refined processing for final data analysis
- ✓ Fountain local comparison over synchronous operation

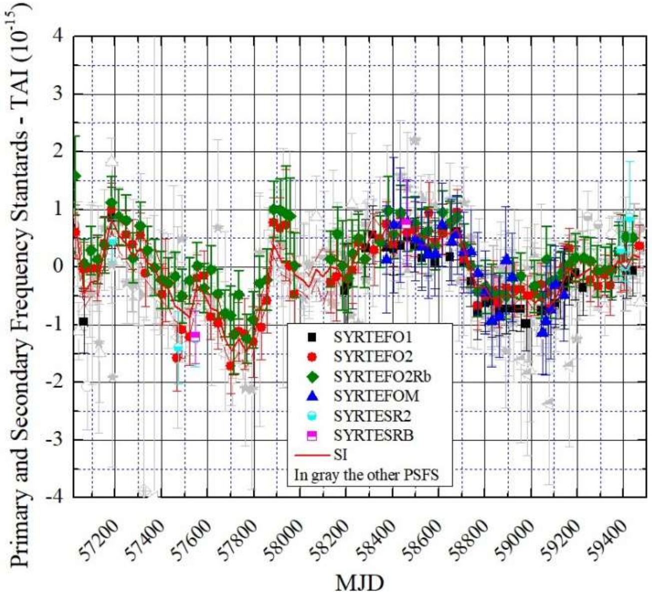
- Calibration of TAI by SYRTE fountains

One report corresponds typically to a quasi continuous measurement of a H-maser frequency for 20 to 30 days

$u_B \sim 2\text{-}6 \times 10^{-16}$ $u_A \sim 1\text{-}2 \times 10^{-16}$ $u_{link/maser} \sim 0.5\text{-}2 \times 10^{-16}$

- About 40-50 % of the calibration reports sent to the BIPM worldwide were provided by the SYRTE fountains over the past years, mainly by FO2-Cs and FO2-Rb (uptime of ~85%) with 11 to 14 reports per year

Data extracted from the BIPM *Circular T 325-405 (i.e. since 2015)*

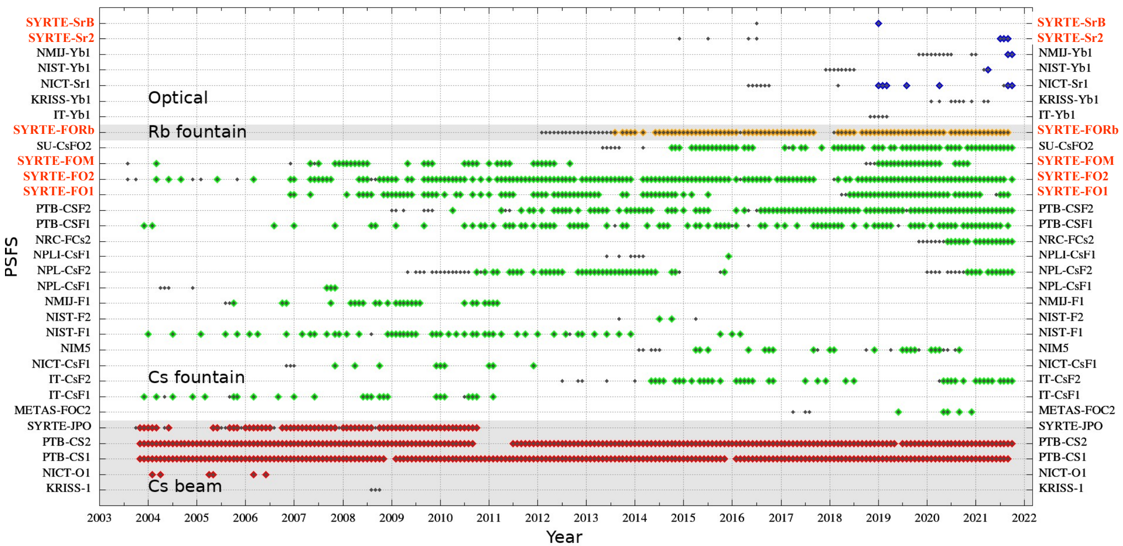


- Initiation of a process for Including SFS with FO2-Rb included in the steering of TAI starting July 2013

➢ Same process applied for optical frequency standards (up to now SYRTE, NICT, NIST, INRIM, NMIJ, KRISS)

➢ **An important step towards a possible future redefinition of the SI second based on optical frequency standards**

Graphical representation of all evaluations of Primary and Secondary Frequency Standards reported since Circular T 190.
Enhanced color dots indicate evaluations carried out within the month of TAI computation.



Realization of the French Timescale UTC(OP)

- Universal Coordinated Time realized at Observatoire de Paris
- Real time representation of UTC for France
- Base for Legal time in France

- ➢ Autonomous time reference over 30/40 d relying only on LNE-SYRTE facilities
- ➢ Real contribution to international timekeeping (/GPS time, etc..)

- ➢ Pivot for French contributions to international timescales (PSFS, commercial clocks)
- ➢ Time reference provided to French laboratories and to society

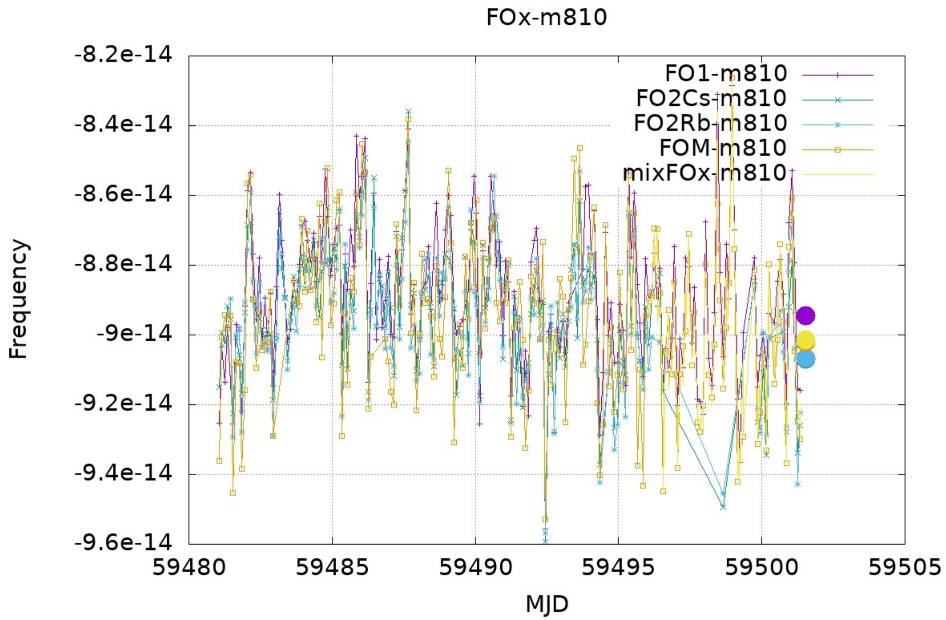
- ➢ Accuracy, stability and reliability mandatory

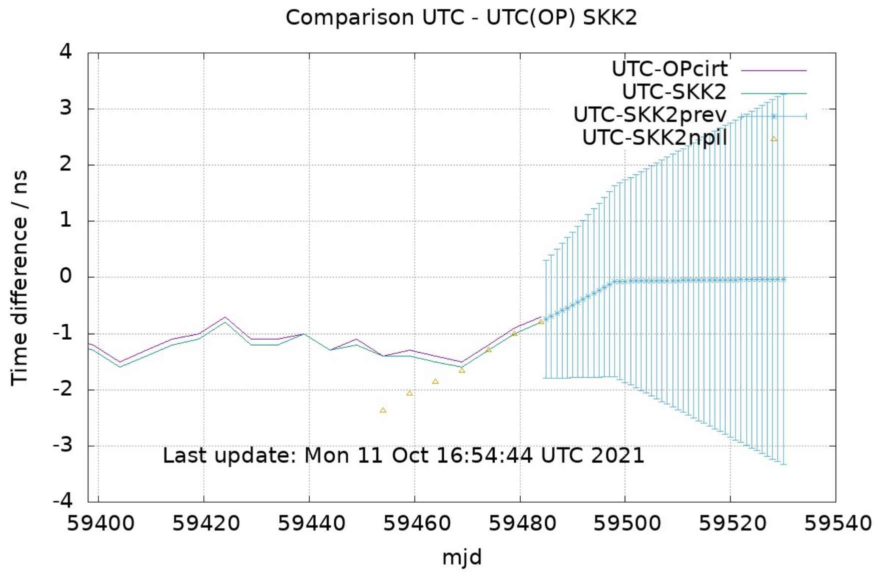
- ➢ Combines the operation continuity of commercial clocks (H-masers) and the stability and accuracy of atomic fountains

Steering algorithm

- New method based on a steered hydrogen maser since October 2012
- Automatic data processing for fountain monitoring (hourly) providing daily frequency calibrations of our 5 H-Masers by the 4 fountains at the low 10^{-15} level
- Daily main steering using a linear fit of the fountain calibrations over the past 5 days updated automatically
- Additional steering of a few 10^{-16} towards UTC updated monthly using the last available *Circular T* compensating for:
  - The slope of UTC(OP) – UTC
  - Half of the phase difference over the following month

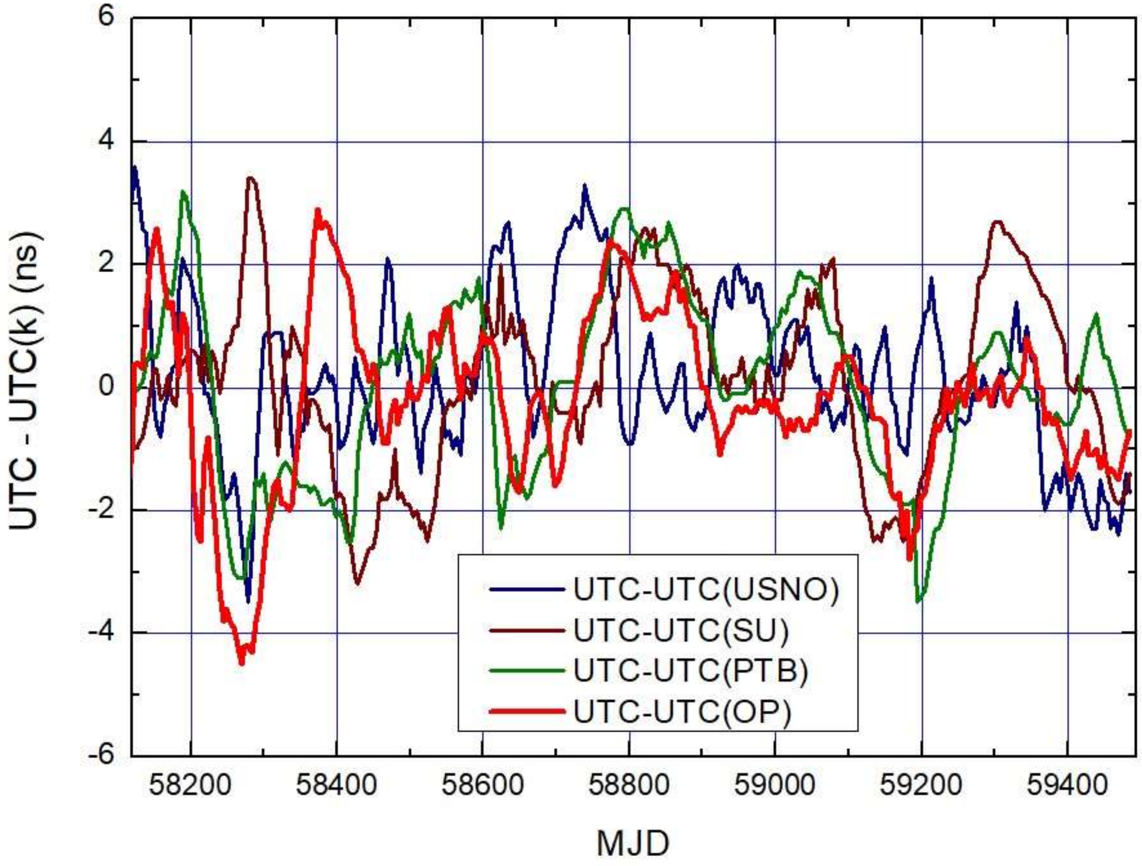
H-Maser prediction

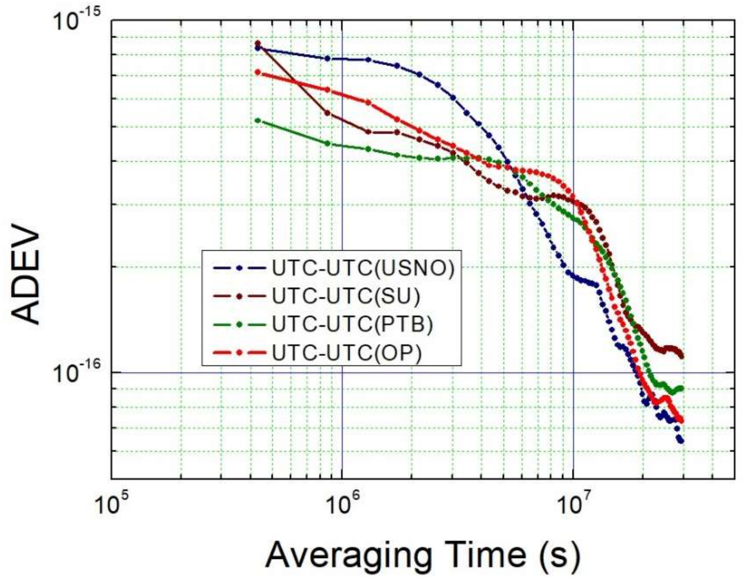




UTC(OP) Performances

Comparison of a few UTC(k) to UTC since beginning of 2018





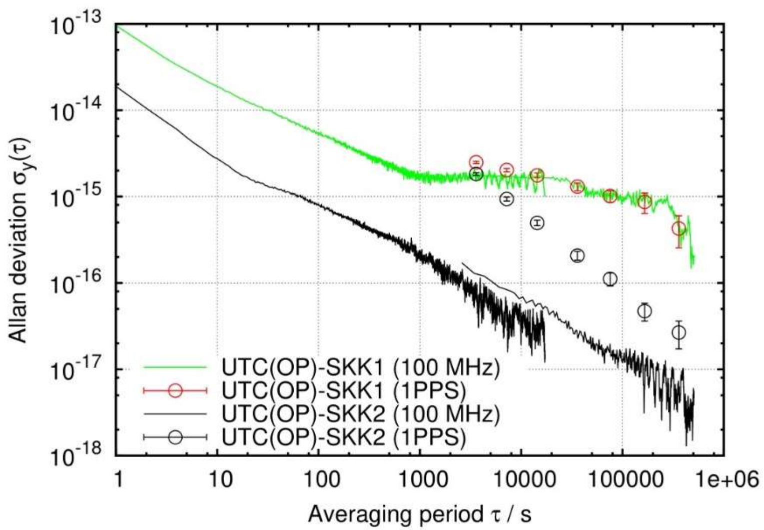
- ➢ UTC(OP) is one of the best real time realizations of UTC
- ➢ Departure of a few ns since the implementation of the new method
- ➢ Approaching the uncertainty of the time transfer links

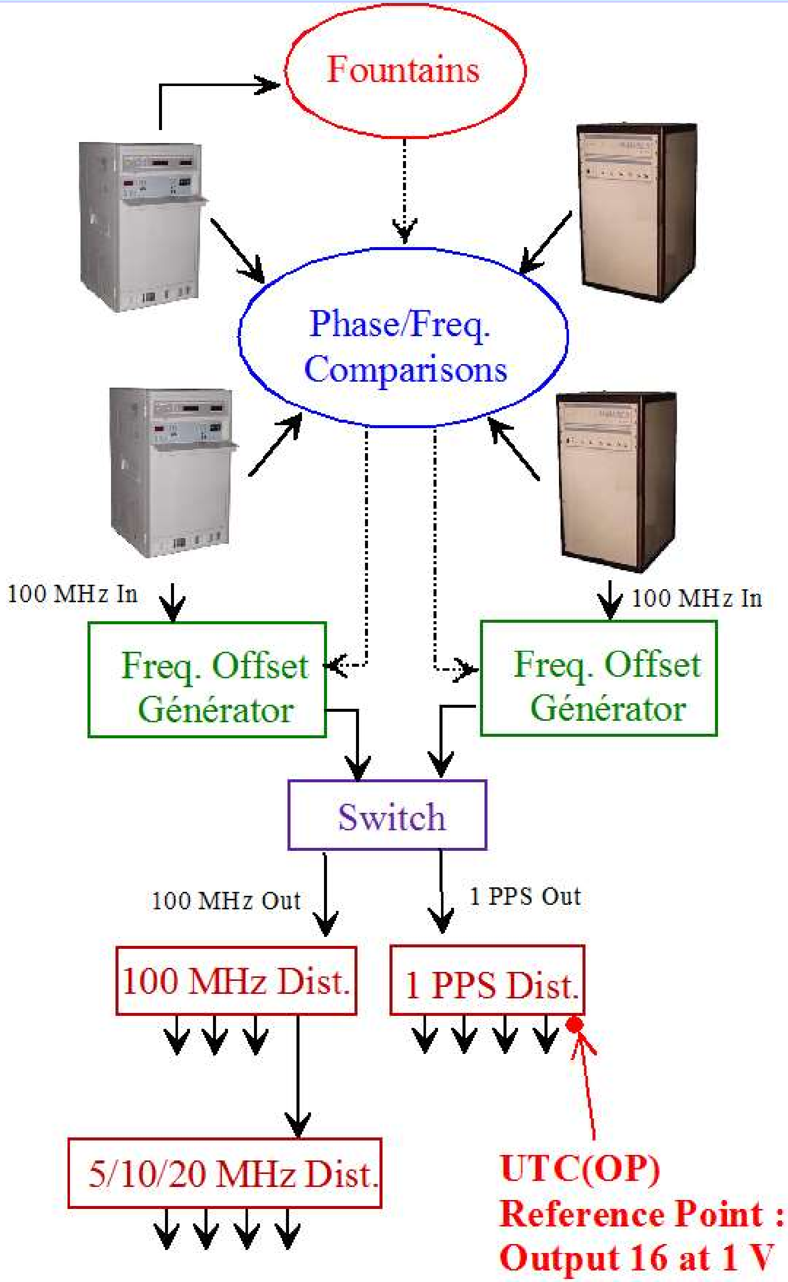
Redundant timescales

- Calibration of each maser against each fountain available in real time
- Two nominal timescales based on two H-Masers using new 100 MHz frequency offset generators and a switch
- A complete second similar system using two other H-Masers for additional redundancy and experiments
- Two other timescales with older micro-phase stepper

> Simulations and experiments for improving the steering algorithm
> Combination of H-Masers
> Tests using calibrations from optical clocks

Local comparison of redundant timescales





Time Transfer Techniques

Two Way Satellite Time and Frequency Transfer (TWSTFT)

- Satre Modems, Frequency up/down conversion to the Ku band, Geostationary satellite
- 2 stations (EU/USA, EU/ASIA + experiments)
- Satellite simulator for accessing the stability of the internal delays
- TWSDR : Emission using Satre Modem, Reception using SDR
- TWSDR traveling equipment for link calibration

✓ Accuracy 1-2 ns

➢ Developments: TWCP/Broadband TW/TWSDR

GNSS (GPS/GALILEO/GLONASS/BEIDOU)

- About 10 receivers from different manufacturers (multi channels, multi frequency, multi GNSS)
- Main station OPMT/OPM2 being replaced by a new station OP73/OP75
- Geodetic station
- Traveling equipment for relative calibration (OP72/OP74)
- Group1 lab (OP, PTB, ROA in EU) for the relative calibration of GNSS stations (GPS+GALILEO) of TAI labs

✓ Accuracy 1-3 ns

➢ Experiments on absolute calibration of GNSS receivers

➢ First experiments using GALILEO signals, BEIDOU in near future

▪ TWSDR/GPS PPP: main time transfer for TAI contributions

➢ TWSTFT and GPS as backups

Contributions to GALILEO:

- UTC(OP) included in the steering of GST (OP, PTB, ROA, SP, INRIM): time transfer data provided daily
- Relative calibration of GPS stations of the PTFs and of the participating labs

Multi-techniques comparisons: PPP, iPPP, TWCP, TW broadband, TWSDR, T2L2, Ajisai, Fiber networks

Dissemination of UTC(OP)

EGNOS: European Geostationary Navigation Overlay System

- Plane navigation
- RIMS-PAR connected to UTC(OP): ENT-UTC, ENT-UTC(OP) in real time
- Preparation for the implementation of EGNOS V3

GPS CV comparisons to 12 French laboratories

- Observatories: OCA, OB, ON
- National institutions: CNES, DGA (2 centers), the French navy
- Industry: Orange (3 centers), Spectracom Orolia, Keysight Technologies

Time difference to UTC(OP) available daily (accuracy 2-10 ns)

GPS PPP using NRCAN software with OB, OCA, CNES (H-Masers)

SYREF System, operated by OB, referenced to UTC(OP) for frequency calibrations in ~10 other labs

Temps Atomique Français TA(F)

•« Paper » timescale TA(F) computed monthly from 20-30 industrial clocks (9 French labs)

•Weighted averaging of clock data based on ARIMA

•Frequency steering using fountain calibrations

•Collected clock (Cesiums and H-Masers) data also sent to the BIPM and included in EAL computation

➢ Ongoing study to include H-Masers in TA(F) computation

Dissemination of UTC(OP)

Speaking clock : 3699

- Since 1933…
- 4 redundant systems referenced to UTC(OP) or cesium beams
- Dissemination by Orange network
- Accuracy 50 ms (analogic network)

Network Time Protocol (NTP)

- 2 Stratum 1 servers referenced to UTC(OP)
- Stratum 2 servers available to the public (~1E6 query/h)
- Uncertainty ~10 ms depending on the network characteristics

ALS162 Signal (162 kHz) Former name « France-Inter grandes ondes »

- Collaboration with ANFR, TDF, FH, LTFB, SYRTE
- 2 Cesium beams connected via GPS CV to UTC(OP)
- ~1 MW emitter located in Allouis, in the center of France
- Accuracy : ~10^{-12} with the carrier; ~1 ms with the code

SCPTime (Secure Certified Precise Time)

- Dvpt. initiated in 2014 by Gorgy Timing, Syrlinks, Muquans, Eolas, Tronics, Tyleos OP, OB, LNE, …
- NTP/PTP + distribution and supervision system for certification
- Main servers in operation at OP since mid 2018
- Operational activity since beginning of 2021 (contract OP-SCPTime)

White rabbit in collaboration with FOP

Bulletin H published monthly summarizing the main results

24h/24 & 7d/7 Operation, Quality management system (ISO 17025), Service Level Agreement

Prospects

- Timescales
  - UTC(OP) steering algorithm currently close to the optimum
  - Combination of H-Masers (UTC(OP) and TA(F))
  - Tests using calibrations from optical clocks
  - UTC and UTC(k) will gradually with optical clocks
- Time and frequency transfers
  - Distant comparisons using satellite T&F transfer techniques (TW-CP, TW SDR, GPS IPPP, GALILEO and other GNSS), absolute and relative calibrations
  - Comparisons/dissemination via T-REFIMEVE, at National and European scale, via phase coherent optical fiber links, advanced time transfer, White Rabbit
  - Multi techniques comparisons
- Atomic fountains
  - Contributions to the realization of the international time references TAI, SI, UTC
  - Continuous calibrations for the steering of UTC(OP)
  - Investigations on the microwave lensing expected to be 7×10^{-17} never observed
- Optical clocks and oscillators
  - Characterization of the future ultra stable microwave reference generated from an optical frequency comb referenced to an ultra stable laser as a redundancy for the cryogenic sapphire oscillator
  - Absolute frequency measurement of optical secondary representation of the second (locally, remotely and via TAI) in the frame of the redefinition of the SI second in 2026
- Fundamental physics tests (stability of fundamental constants and gravitation, search of dark matter, …)
- Contributing to ACES mission
  - with high performance clocks part of SYRTE ground segment
  - for providing the best possible time reference for the ACES MWL

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Thank you !