# National and International Timescales : Construction and Dissemination

Michel ABGRALL, REFMET Group/Références Nationales de Temps
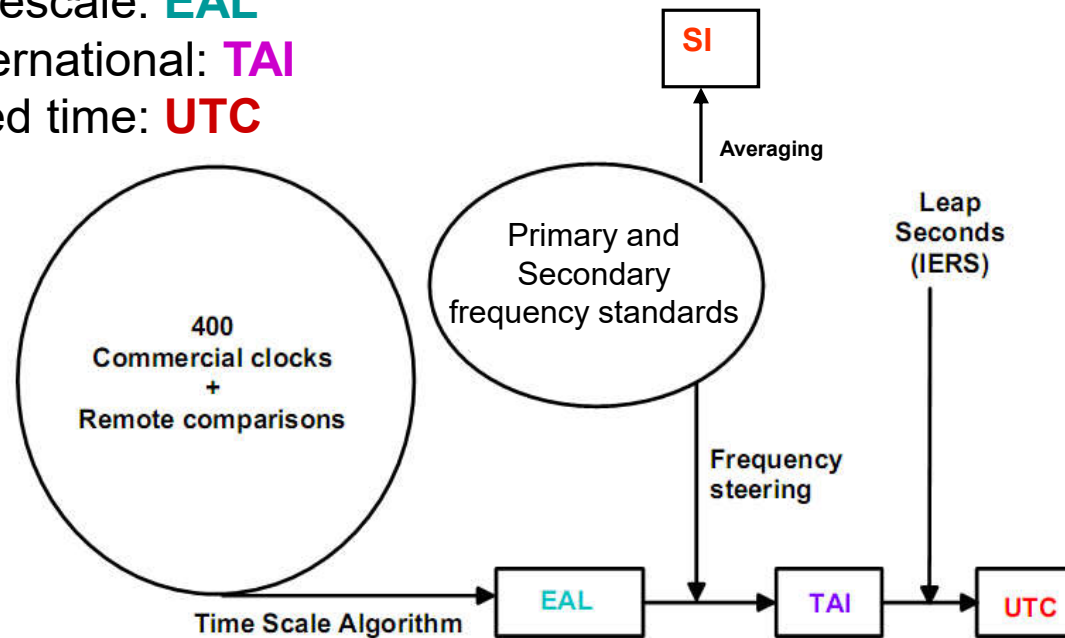*LTE Seminar, June 18th 2024*

# Outline

- UTC, TAI, SI

- LNE-SYRTE clock ensemble

- Atomic fountains

- UTC(OP) Timescale

- Satellite time transfer techniques

- UTC(OP) dissemination

# UTC, TAI, SI calculated by the BIPM
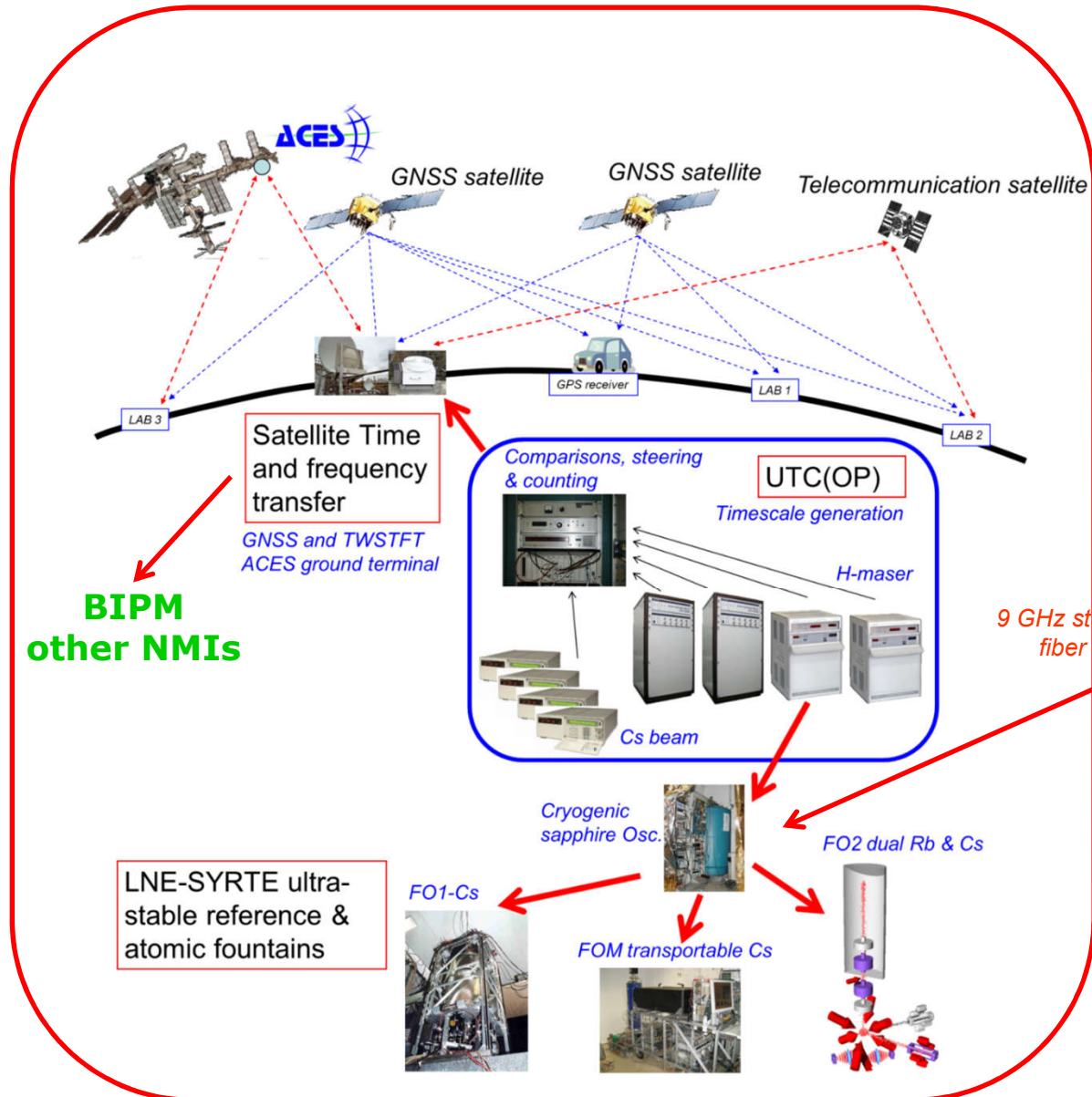
**The BIPM** produce each month
- The free running timescale: **EAL**
- Temps atomique international: **TAI**
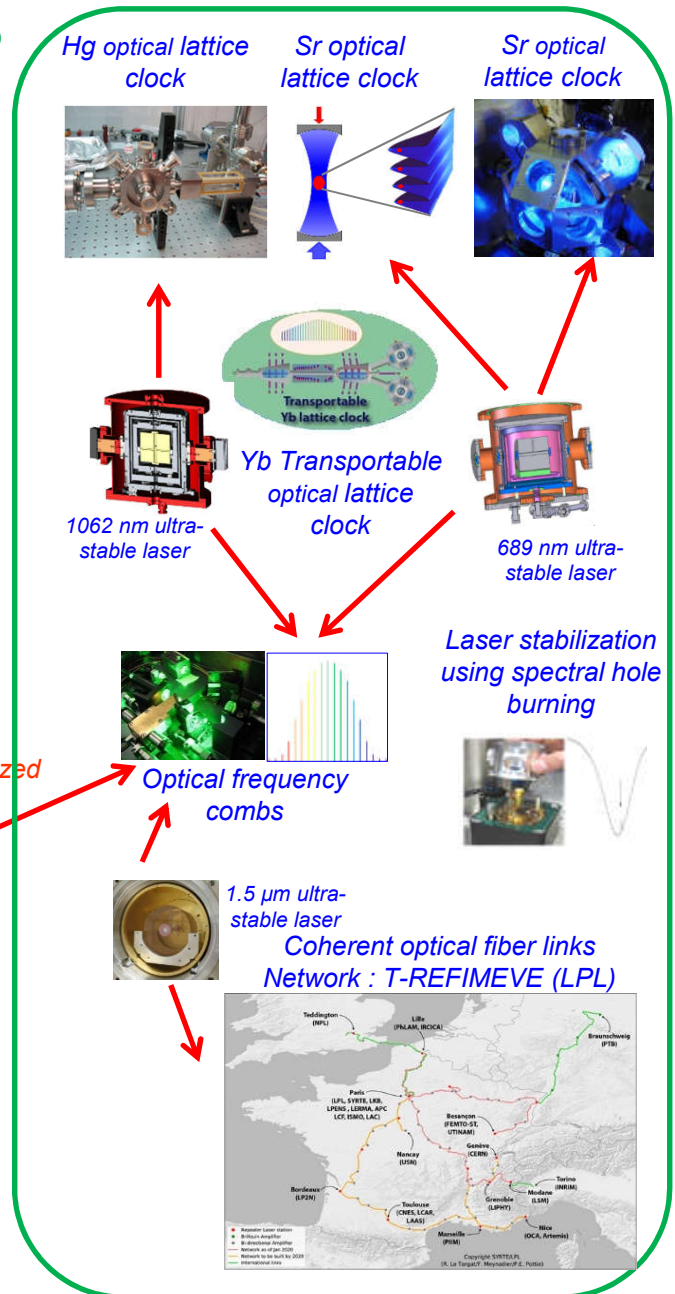- Universal coordinated time: **UTC**
- The **SI** Second



- 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
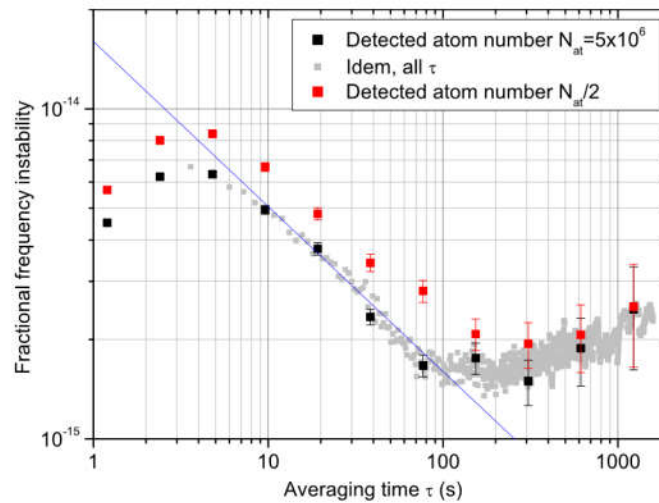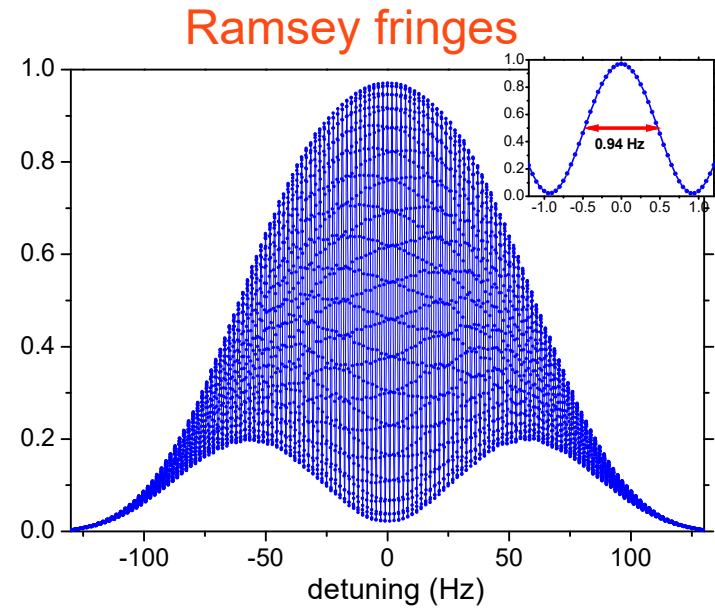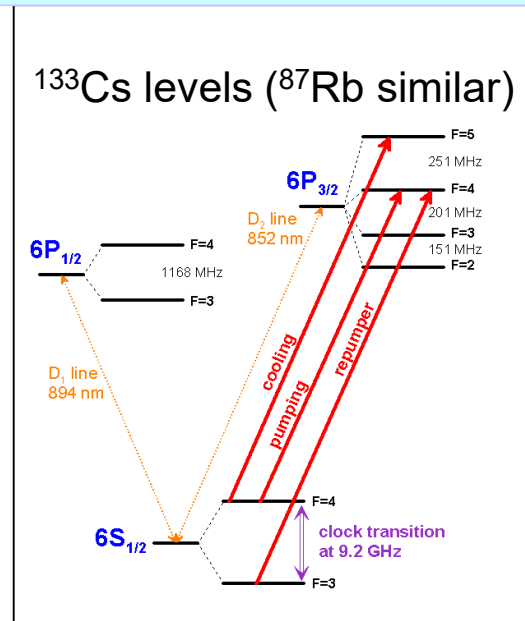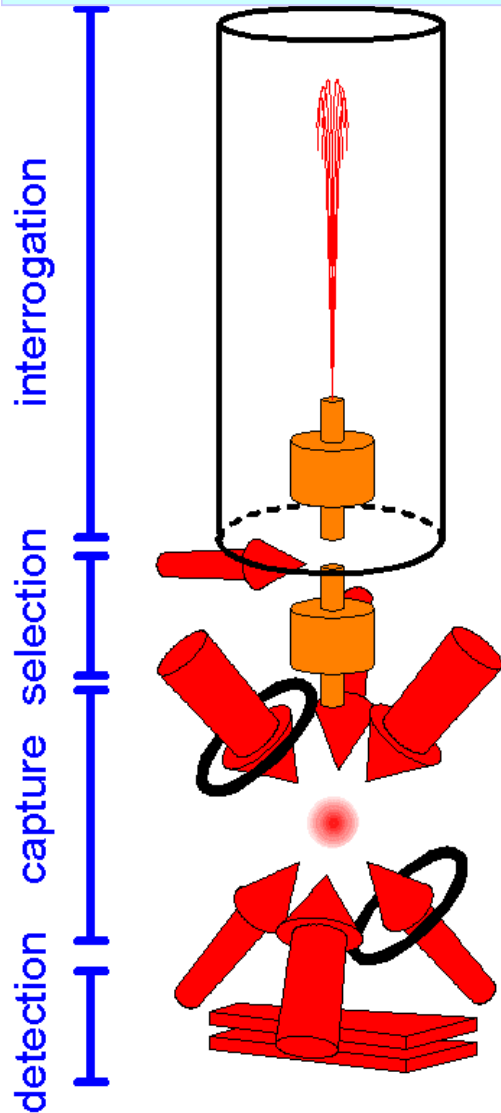
# SYRTE atomic clock ensemble

# Atomic fountain clocks

## $^{133}$Cs levels ($^{87}$Rb similar)

$6P_{3/2}$
- F=5, 251 MHz
- F=4, 201 MHz
- F=3, 151 MHz
- F=2

$6P_{1/2}$
- F=4, 1168 MHz
- F=3

$D_2$ line 852 nm

$D_1$ line 894 nm

cooling
pumping
repumper

$6S_{1/2}$
- F=4
- F=3

clock transition at 9.2 GHz

interrogation

selection   capture

detection

## Ramsey fringes

0.94 Hz

detuning (Hz)

Detected atom number $N_{at}=5\times10^6$
Idem, all $\tau$
Detected atom number $N_{at}/2$

Fractional frequency instability

Averaging time $\tau$ (s)

## Atomic quality factor:

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

Best frequency stability (Quantum Projection Noise limited): $1.6\times10^{-14}$ @1s

Best accuracy: $(2-3)\times10^{-16}$

*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, NTSC, …)*
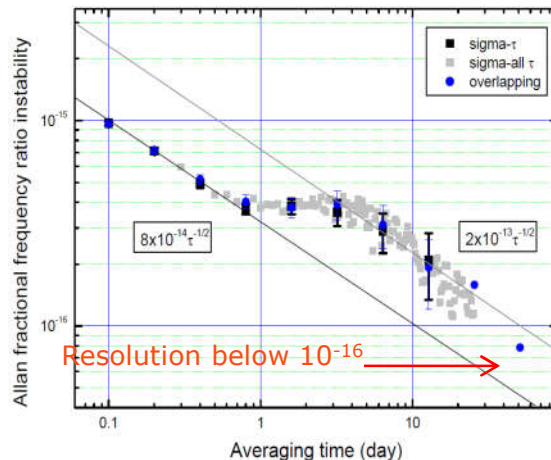
# SYRTE Fountain performances

- **Fountain Stability**    - **Fountain Accuracy**    Uncertainty budget (x $10^{-16}$)

$\sigma_y(\tau=1s)$ at high atomic densities (CSO or Comb stabilized to an optical cavity )

| | 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** |

| | |
|---|---|
| FO1 | 3.3 x $10^{-14}$ |
| FO2-Cs | 3.5 x $10^{-14}$ |
| FOM | 6.0 x $10^{-14}$ |
| FO2-Rb | 3.2 x $10^{-14}$ |

Long term stability of $\nu_{Rb}/\nu_{Cs}$ 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 20-30 % of the calibration reports sent to the BIPM worldwide were provided by the SYRTE fountains over the past years

- **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, NPL)

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

Data extracted from the BIPM
*Circular T 325-437 (i.e. since 2015)*
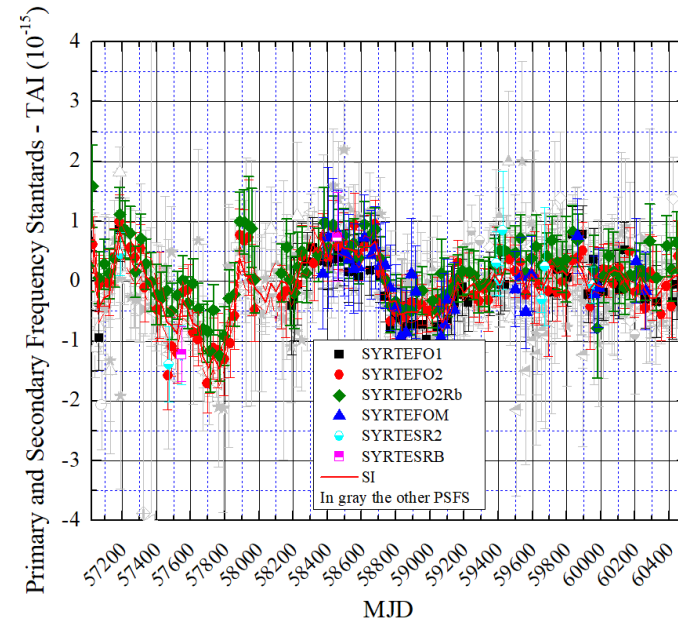


Graphical representation of all evaluations of Primary and Secondary Frequency Standards reported since Circular T 190. Enhanced color dots indicate evaluations carried out within the month of TAI computation.
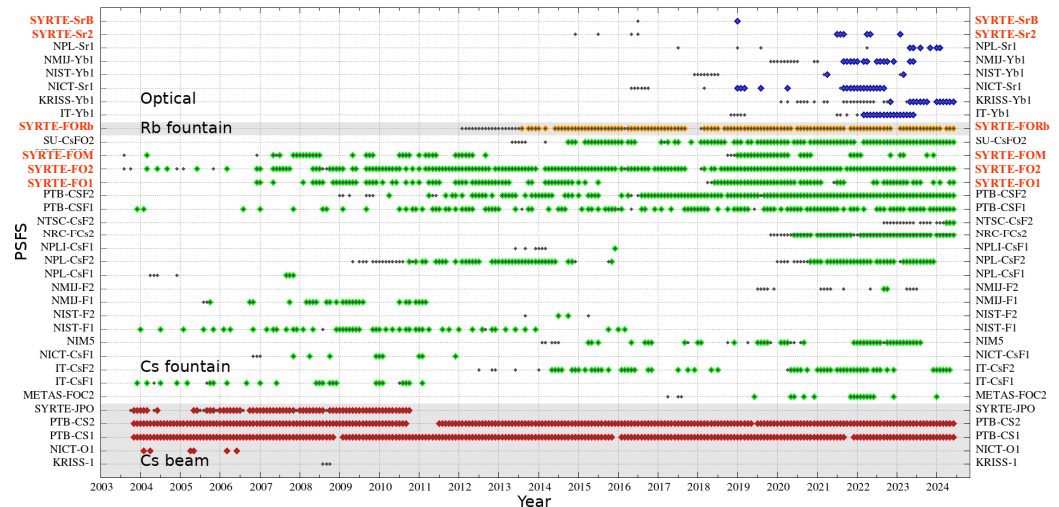
# Realization of the French Timescale UTC(OP)

- 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 (/GNSS 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

■Based on a steered hydrogen maser

■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
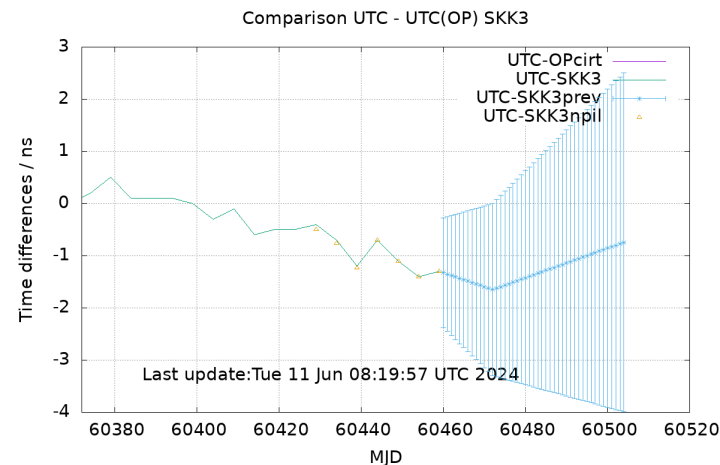
■Half of the phase difference over the following month

### Redundant Timescale
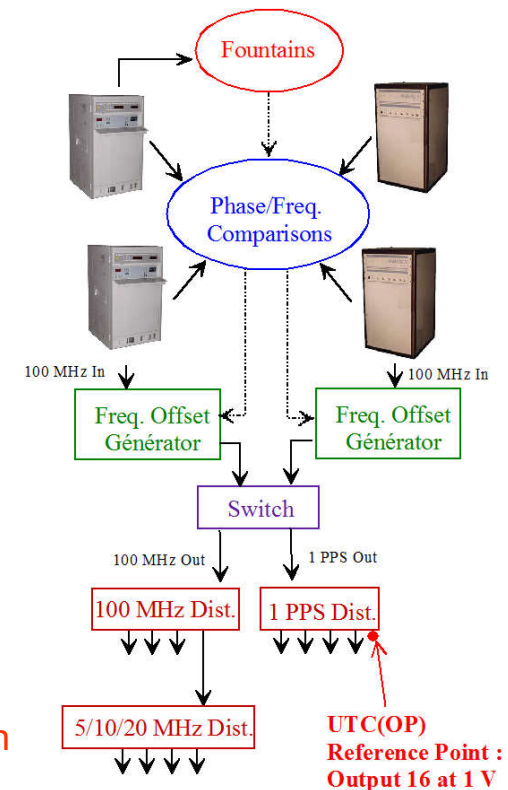

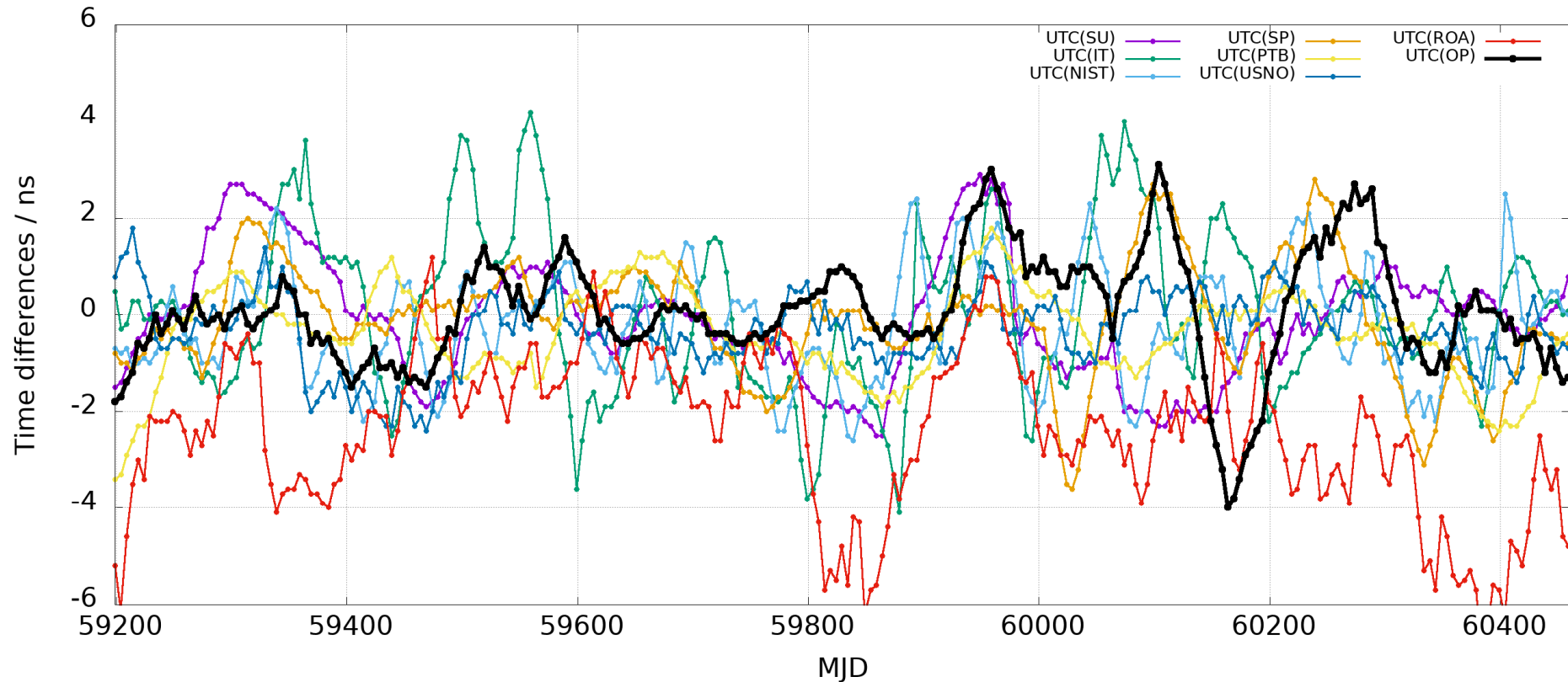
### H-Maser prediction
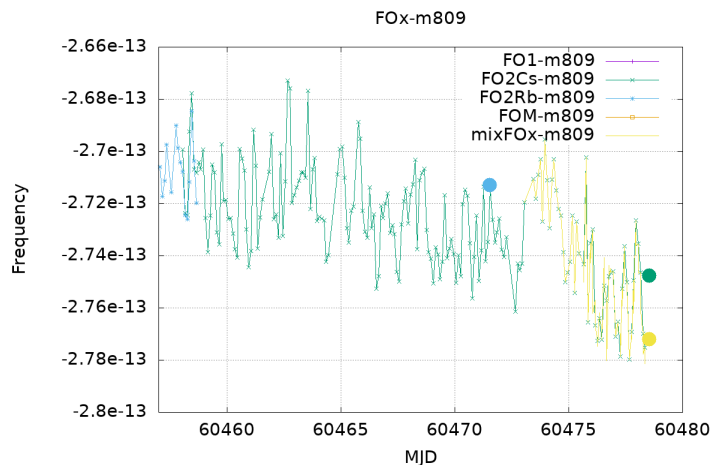


### Monthly steering and prediction

# UTC(OP) Performances

Comparison of a few UTC(k) to UTC since beginning of 2021

UTC-UTC(k) comparisons



- ➢ UTC(OP) is one of the best real time realizations of UTC
- ➢ Departure of a few ns
- ➢ Approaching the uncertainty of the time transfer links
- ➢ 3 x 10⁻¹⁶ frequency offset corresponds to 1 ns cumulated phase over 40 *d*

# Satellite 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)
- TWSDRR : Emission using Satre Modem, Reception using SDR
- TWSDRR 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)
- Traveling equipment for relative calibration (OP72/OP74)
- Group1 lab (OP, PTB, ROA, INRIM in EURAMET) for the relative calibration of GNSS stations of TAI labs
- ✓ Accuracy 1-3 ns
- ➤ Experiments on absolute calibration of GNSS receivers
- ➤ Advanced techniques such as iPPP with BIPM and CNES
- ➤ Comparisons using GALILEO signals, BEIDOU in near future

- ▪ TWSDRR: main time transfer for TAI contributions
- ➤ TWSTFT/GPSPPP and GPS as backups

**Multi-techniques comparisons:** PPP, iPPP, TWCP, TW broadband, TWSDR, Fiber networks, ACES MWL/ELT

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

TWSTFT antennas at OP



GNSS antennas at OP

# 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/Safran, 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)

Web page https://heurelegalefrancaise.fr/
- As a replacement to the speaking clock (1933-2022)

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
- Industrial contract SCPTime (Secure Certified Precise Time)

ALS162 Signal (162 kHz) Former name « France-Inter grandes ondes »
- Collaboration with ANFR, TDF, FH, LTFB, SYRTE
- Local commercial clocks 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

White rabbit in collaboration with FOP disseminates UTC(OP) on the REFIMEVE Network

Bulletin H published monthly summarizing the main results

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

# 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 REFIMEVE, at National and European scale, via phase coherent optical fiber links, advanced time transfer, White Rabbit
  - Multi techniques comparisons

- **Atomic fountains**
  - Investigations on the microwave lensing expected to be $7 \times 10^{-17}$ never observed
  - Contributions to the realization of the international time references TAI, SI, UTC
  - Continuous calibrations for the steering of UTC(OP)

- **In collaboration with FOP**
  - Exploitation of the ultra stable microwave reference generated from an optical frequency comb referenced to an ultra stable laser as a redundancy for a 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

- **Contributing to ACES mission**
  - With high performance clocks part of SYRTE ground segment
  - For providing the best possible time reference for the ACES MWL

# Thank you !

The permanent staff of REFMET:

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