# National and International Timescales

Michel ABGRALL

*Workshop : Distribution sécurisée du Temps et Systèmes spatiaux*
*13th-15th November 2024*

# Who are we? Where are we? What do we do?

- SYRTE (http://syrte.obspm.fr) stands for
  - SYstèmes de Référence Temps-Espace
  - The French National Metrology Institute (NMI) is LNE: Laboratoire National de Métrologie et d'Essais. Time & Frequency metrology is "subcontracted" to SYRTE

- SYRTE is in the middle of Paris
  - At the Observatoire de Paris

http://www.obspm.fr

- We do
  - Time reference UTC(OP), time transfer (GNSS, TWSTFT, …)
  - Clocks and related research (primary, optical, compact, space,…)
  - Inertial sensors using atom interferometry
  - Fundamental physics tests, relativity
  - …

- Reorganization of OP on 01/01/2025
  - SYRTE+IMCCE will become LTE (Laboratoire Temps Espace)
  - LNE-SYRTE will become LNE-OP

# Outline

- What is an atomic clock?
- What is a time scale?
- UTC, TAI, SI
- Time transfer techniques

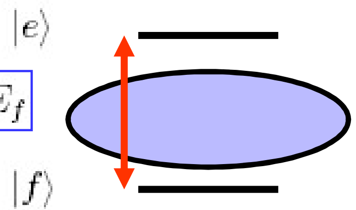
- LNE-SYRTE clock ensemble
- Atomic fountains
- UTC(OP) Timescale
- Time transfer techniques
- UTC(OP) dissemination

# What is an atomic clock?

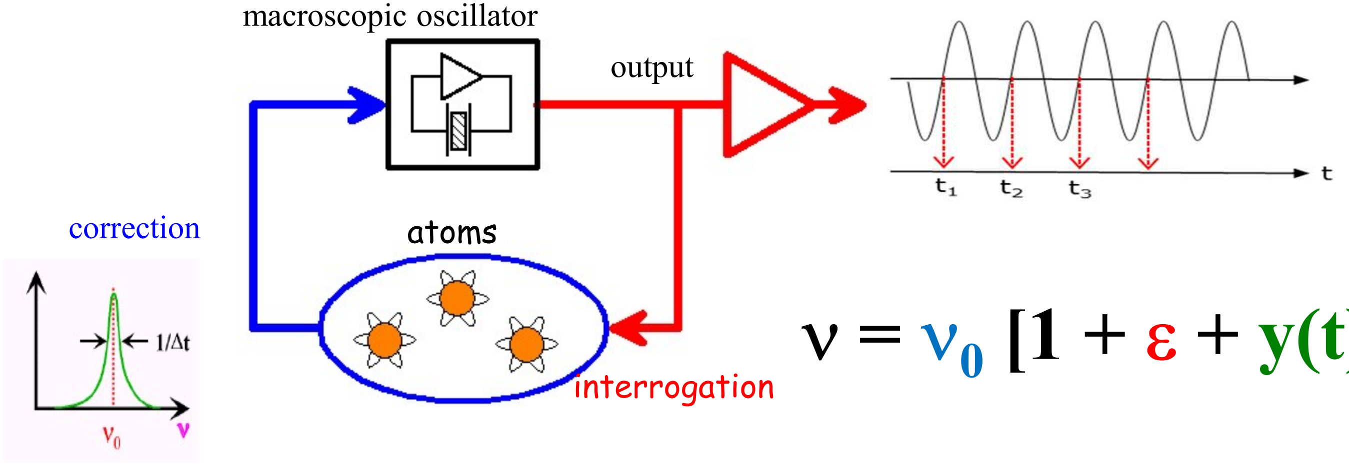
Goal: deliver a signal with stable and universal frequency

Bohr frequencies of unperturbed atoms are expected to be stable and universal

$$\hbar\omega_{ef} = h\nu_{ef} = E_e - E_f$$




Building blocks of an atomic clock




$$\nu = \nu_0 \, [1 + \varepsilon + y(t)]$$

Can be done with microwave or optical frequencies, with neutral atoms, ions or molecules

# Stability and accuracy

$$\nu = \nu_0 \, [1 + \varepsilon + y(t)]$$

**Delivered frequency** | **Frequency definition** | **Frequency bias : inaccuracy** | **Frequency noise : instability**

**Frequency definition :**

**SI second based on $^{133}Cs$ ($\nu_0$=9192631770 Hz) : primary frequency standard**

**Many secondary frequency standards ($^{87}Rb$, $^{87}Sr$, $^{171}Yb$, $^{199}Hg$, $^{88}Sr^+$, $^{171}Yb^+$, $^{199}Hg^+$, $^{27}Al^+$,…)**

**Accuracy : Type B uncertainty**

**$\varepsilon$ : fractional frequency offset**

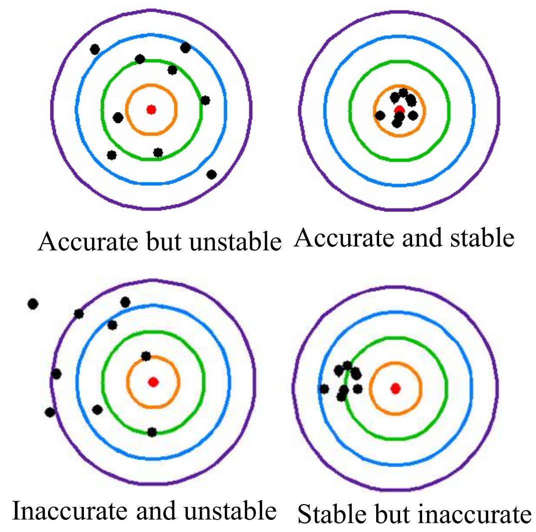
**uncertainty on $\varepsilon$**

**Stability : Type A uncertainty**

**y(t) : fractional frequency fluctuations**

**statistical properties of y(t)**

**characterized by the Allan standard deviation $\sigma_y(t)$**



# What is a timescale ?

- A time scale is defined by specifying
  - **a « scale unit » (unit of time)**
  - **an « origin » (epoch of the origin of the scale)**

- Realized by a clock, i.e. a frequency standard based on a stable and periodic process
- The clock output frequency is often steered (frequency calibration)
- The origin must be specified (time calibration vs reference point)

Dominant remaining process after frequency calibration is flicker frequency noise which corresponds to random walk in time

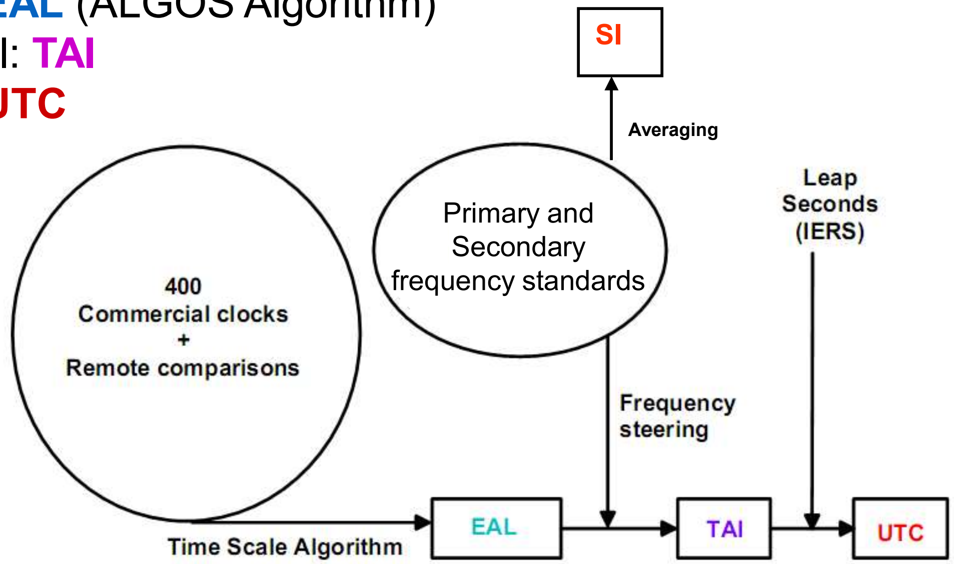
➢ Divergence of free running timescales with time
➢ International time scales calculated by the BIPM to maintain consistency of time references worldwide

Algorithms for clock combination (averaging, robustness, clock stability vs averaging periods, operation continuity, …) : paper timescale

# UTC, TAI, SI calculated by the BIPM

**The BIPM** produce each month

- The free running timescale: **EAL** (ALGOS Algorithm)
- Temps atomique international: **TAI**
- Universal coordinated time: **UTC**
- The **SI** Second on the Geoid

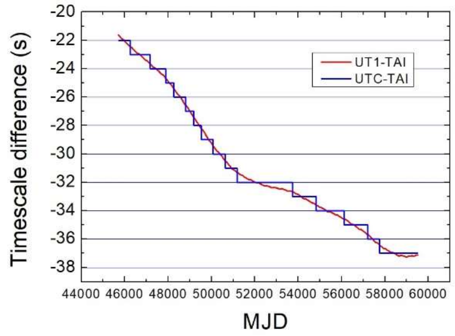



- UTC maintained close to UT1: |UTC – UT1| < 0,9 s

  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

Leap seconds since 1984

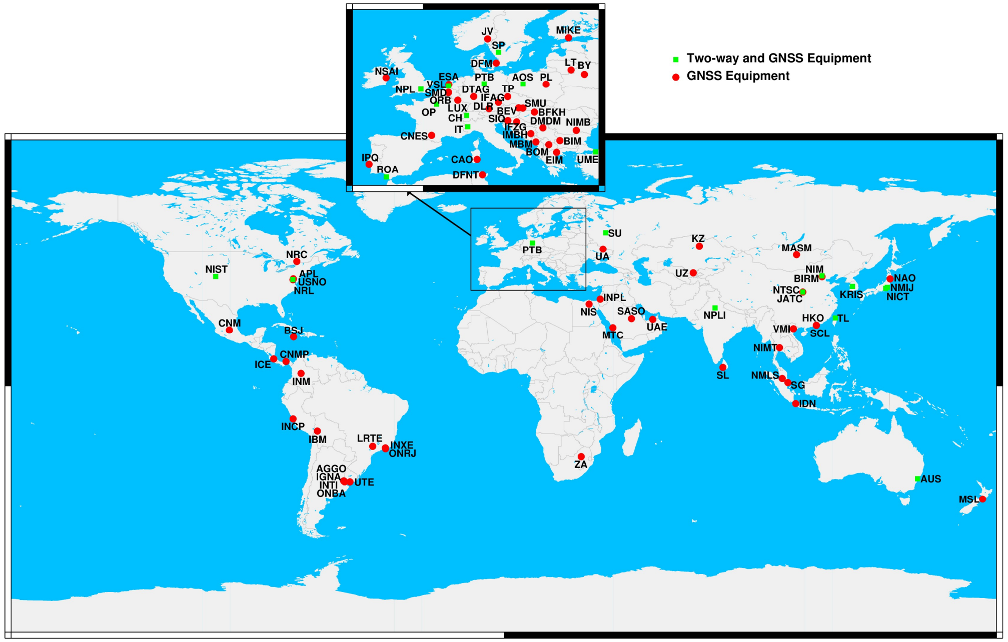


# UTC, TAI, SI calculated by the BIPM

Calculated monthly using data provided by ~80 laboratories

- Monthly clock data file (UTC(k) – Hi) in the 5 d BIPM grid (MJD ending in 4 and 9)
- Time transfer daily file (GNSS, TW)
- Data to be provided before the 4th of the following month (calendar date)
- Results published a few days later in the Circular T

Geographical distribution of the laboratories that contribute to TAI and time transfer equipment (2024)




Rapid UTC calculated weekly on a daily grid using data provided by ~60 laboratories, more than 300 clocks

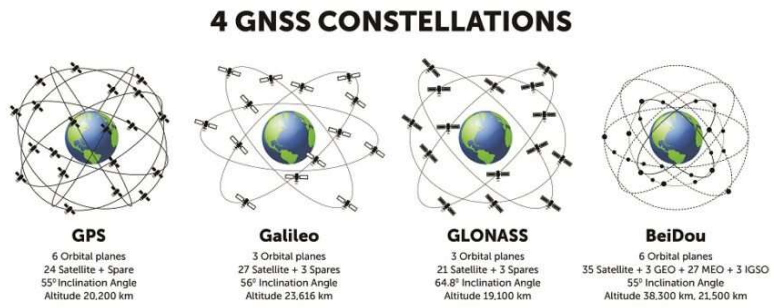
|UTCr – UTC(k)|~1-2 ns

# Time transfer : GNSS

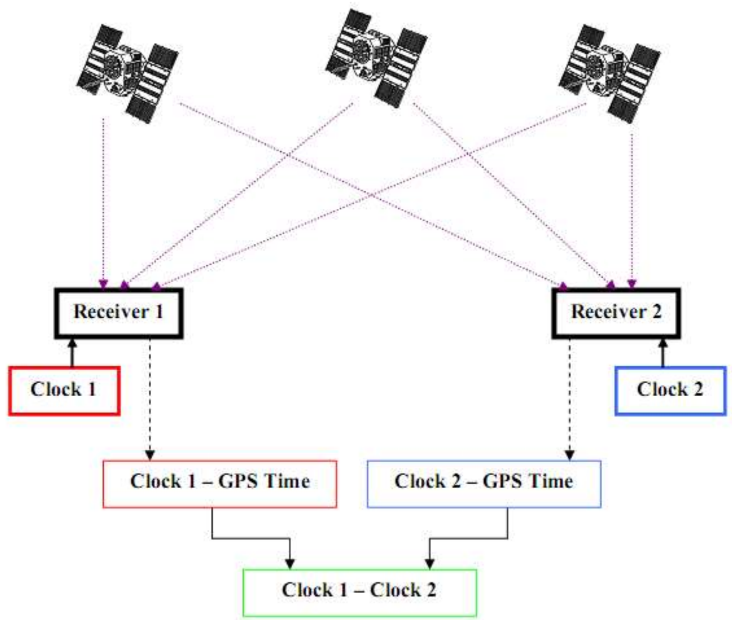
GNSS : Global Navigation Satellite Systems

- GPS (USA, GPS Time based on UTC(USNO))
- GLONASS (Russia, GLONASS Time based on UTC(SU))
- GALILEO (EU, GST based on a combination of 5 European UTC(k): PTB, OP, ROA, SP, IT)
- BDS (China, BDT based on UTC(NTSC))

Emitted signals in L band (1.2 – 1.6 GHz)




Observations data : observed pseudo distance for each satellite
Navigation data : broadcast satellite position and onboard time
Standard data formats : Rinex files, CGGTTS files

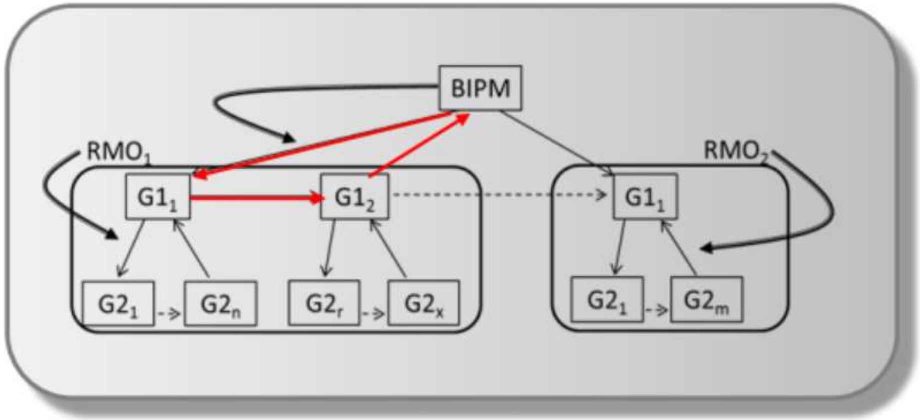


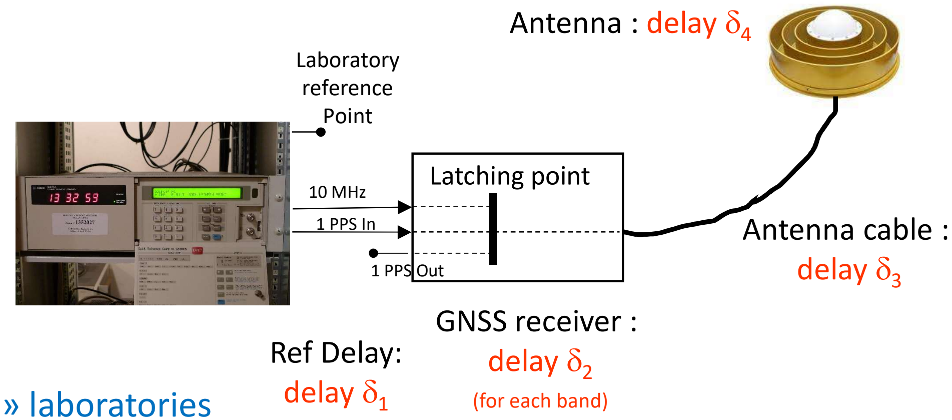

Computation techniques:

Single frequency C/A: atmospheric delays based on a model
Ionofree combination (GPS: P1/P2 = P3 ; GAL:E1/E5a=E3 ; BDS: B1c/B2c=B3)

- Common view
- All in View
- Carrier/phase techniques: PPP, iPPP
  - Solving phase ambiguity
  - additional products provided by IGS with some latency

# TAI GNSS links calibration




The BIPM is responsible to organize link relative calibrations of « Group 1 » laboratories

G1 laboratories are currently

- NIST, USNO in South and North America (SIM)
- OP, PTB, ROA, INRIM in Europe (EURAMET)
- TL, NICT, NIM, KRISS in Asia and Oceania (APMP)
- SU in COOMET

RMO are responsible for link relative calibrations of G2 labs by G1 labs

G1/G2 Scheme since 2015 for GPS (C1, P1/P2), since 2019 for GALILEO (E1/E5a) and since 2024 for BEIDOU (B1c/B2a)

Conventional uncertainties :

G1 labs/BIPM : 1.5 ns

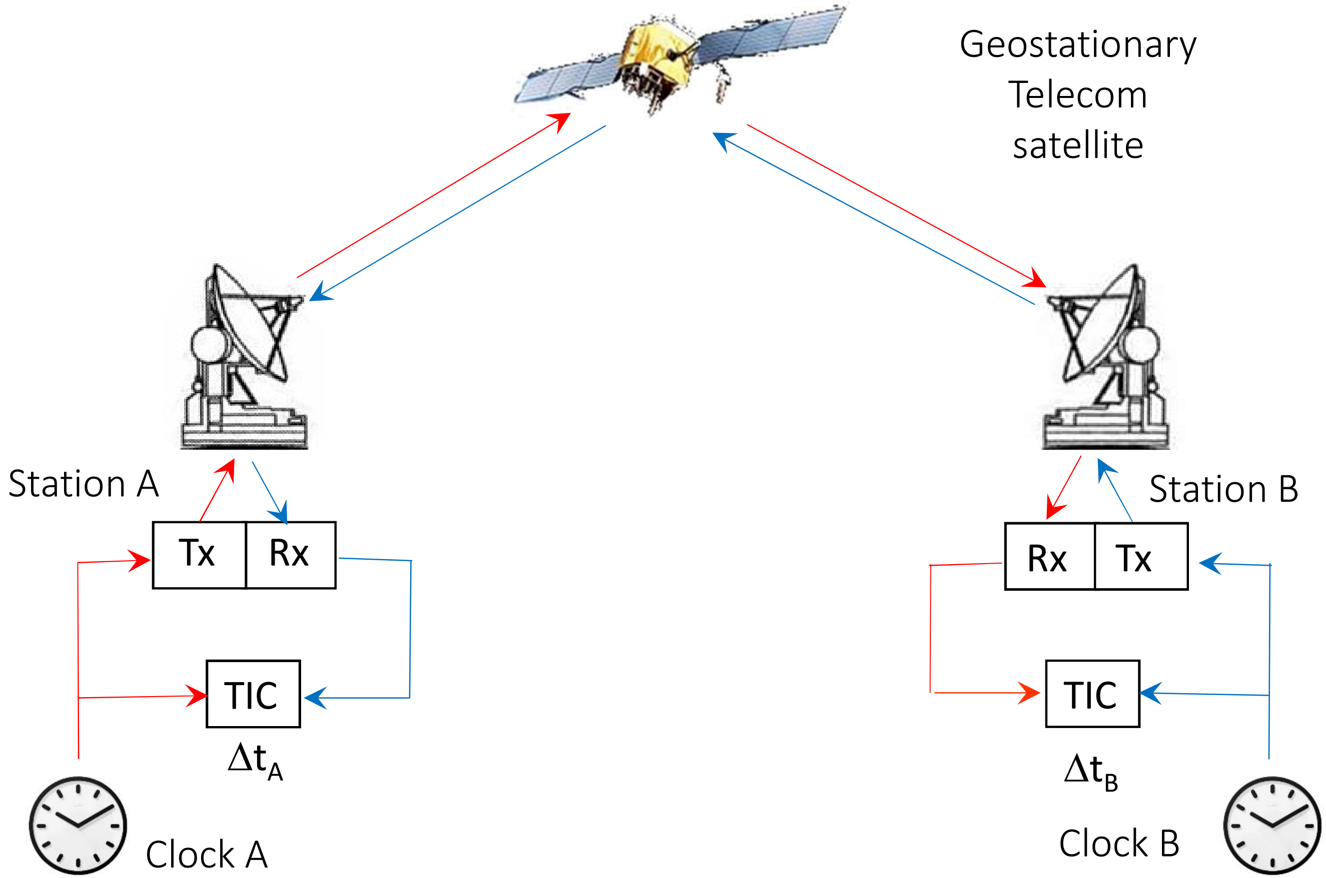
G2 labs/G1 labs :

- calibration trip with closure (CC) : 2.5 ns
- direct calibration (DC) : 4 ns
- absolute calibration (AC) : 5-7 ns (perform by third party)

Possibility to perform a transfer of calibration by the UTC(k) lab

# Time transfer: TWSTFT

Two-Way Satellite Time and Frequency Transfer: TWSTFT




Clock(A)-Clock(B) = 1/2 [$\Delta t_A$ - $\Delta t_B$] + corrections

# Time transfer : TWSTFT

Satre Modem (2 channel system) ~70 MHz + specific PRN code and freq. offset for each lab

- Up/Down converter + LNA in Ku band: 11 – 14 GHz
- Parabolic antenna (diameter a few meters)
- Available bandwidth allocated on a telecom satellite
- TAI sessions during odd hours (3 mn per pair of labs)
- Accuracy 1-2 ns

TWSTFT network:

- Europe/Europe and Europe/USA : T -11N satellite
- Europe/Asia and Asia/Asia: ABS-2A satellite
- Asia regional (E 172B satellite)
- ➢ About 10 UTC(k) links in recent periods
- ➢ Availability and performances of Asia/Asia and Asia/Europe links not stable
- ➢ Link calibration using TW or GPS mobile station

TWSDRR : Emission using Satre Modem, Reception using SDR (Software Defined Radio)
PTB-OP first operational TAI link since March 2020

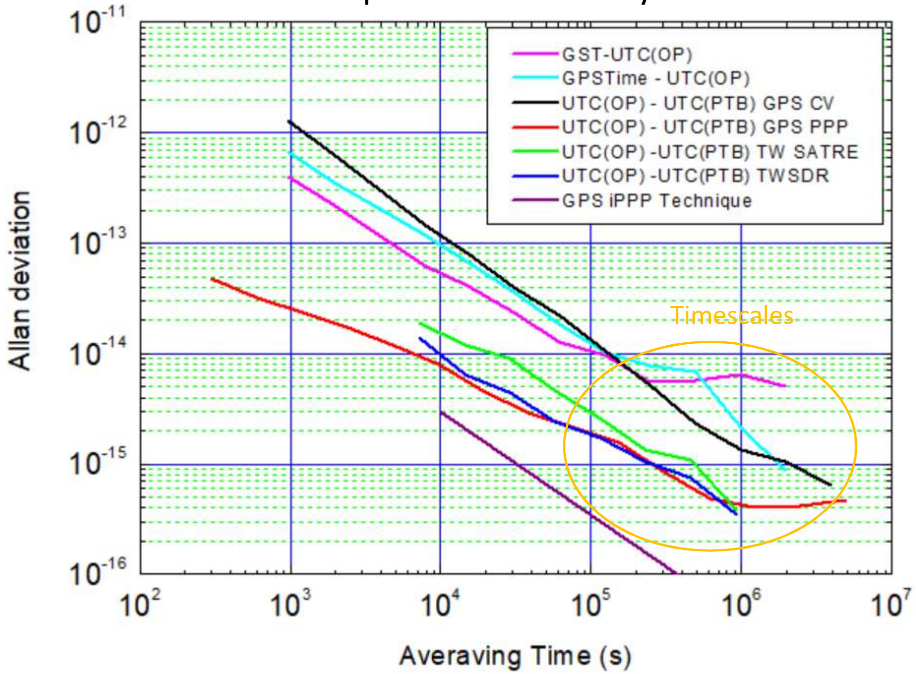
NICT modem (emission and reception, GPS PRN code)
Regularly operated in Asia/Asia and experimented in Europe/Europe

Other developments by OP/OB, Chinese, Italian, Swedish and Russian groups

Past and future experiments: TWCP/Broadband TW/TWSDR

# Time transfer performances

Examples of link stability



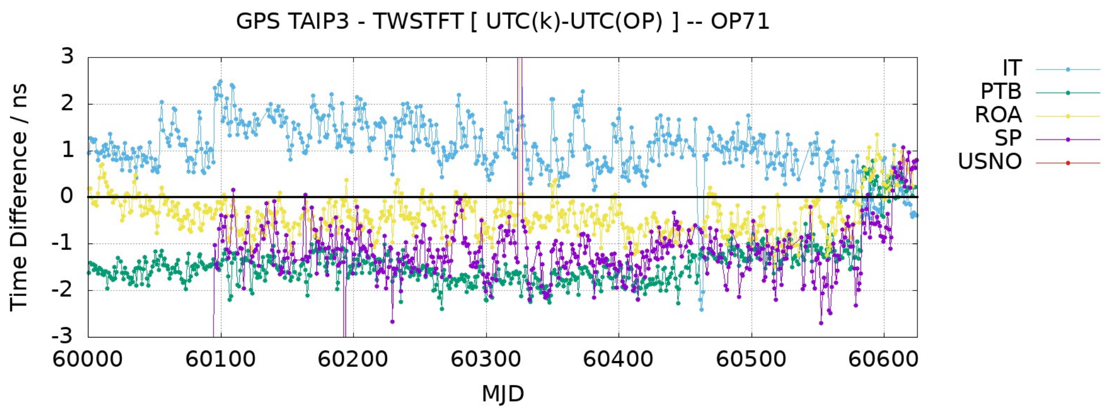

Accuracy TW ~1 ns
Accuracy GNSS ~1.5 - 3 ns

GPS carrier/phase techniques require IGS products that are available with some latency

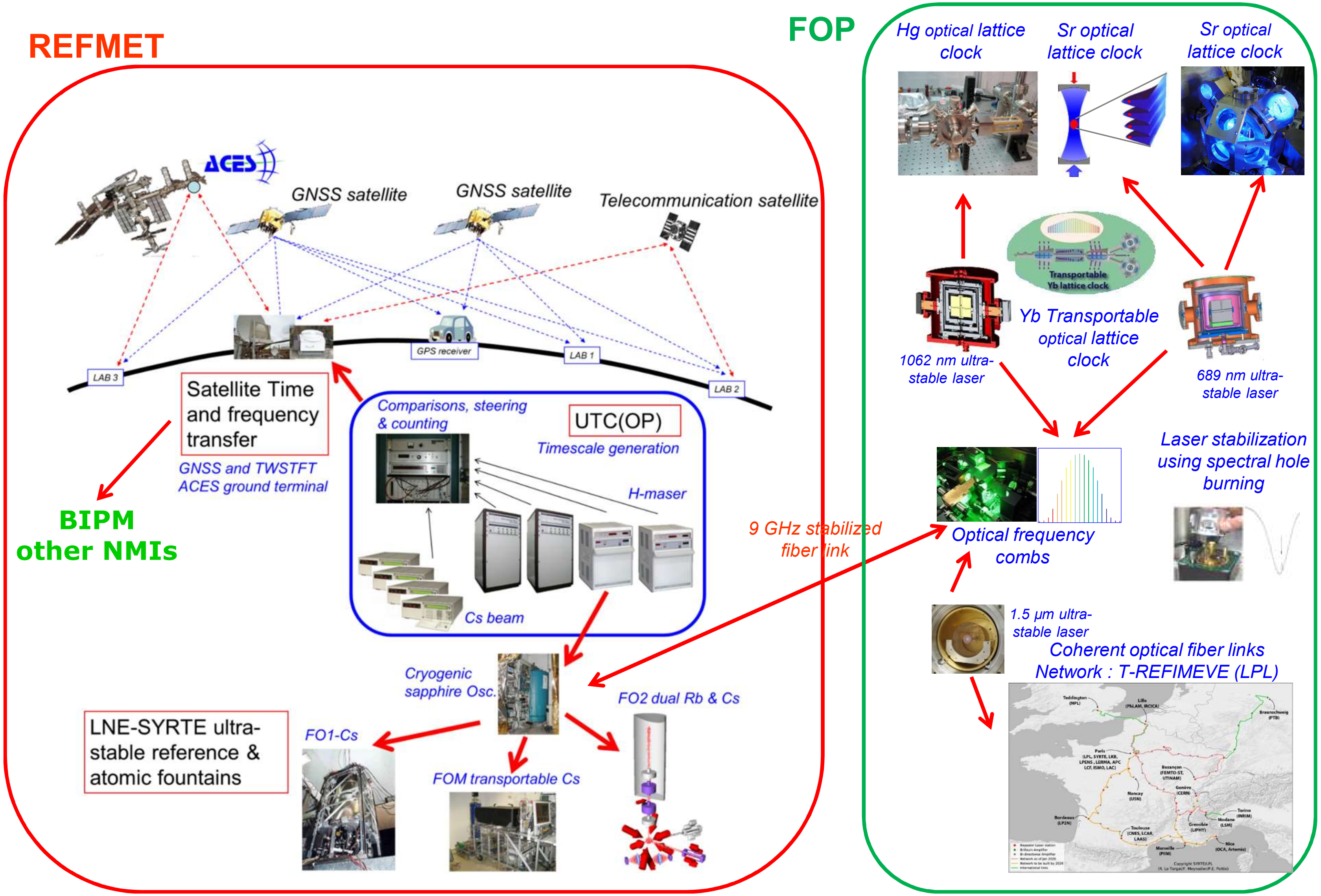
Ongoing developments on fiber links at national and continental scale

- Orders of magnitude better depending on the technique (optical carrier, RF, Elstab, White Rabbit, …)
- Dark fiber, dark channel
- Frequency/Time

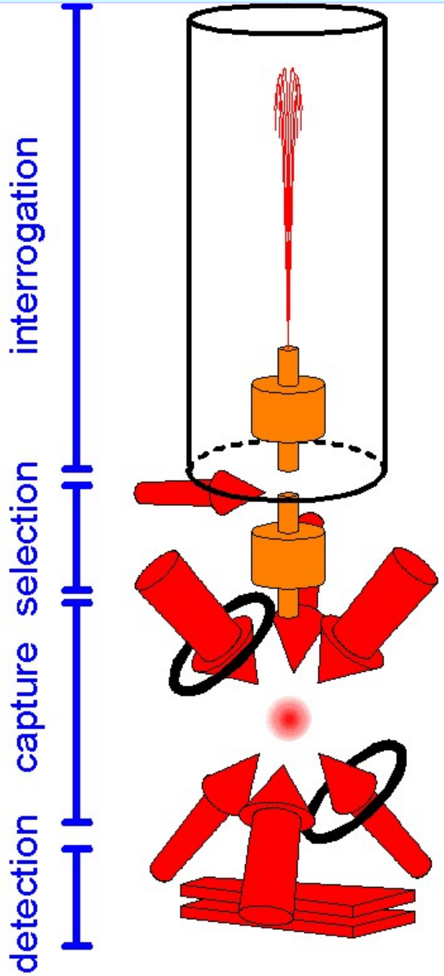
Example of satellite link closure

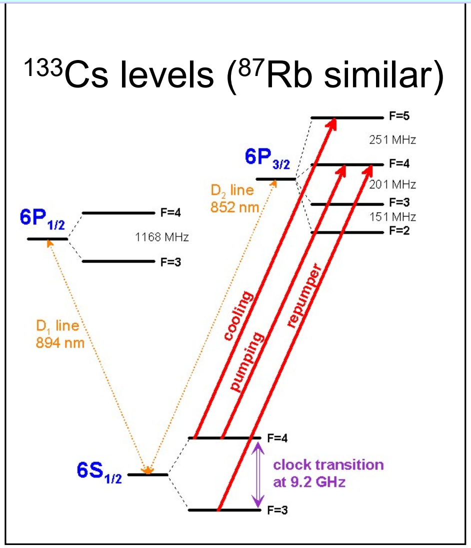


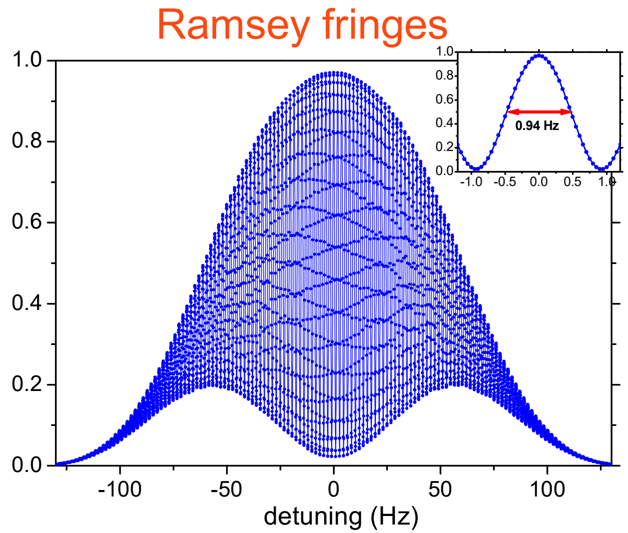
# SYRTE atomic clock ensemble

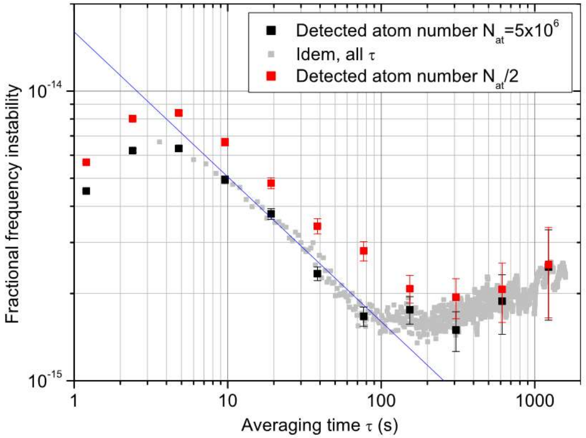


# Atomic fountain clocks




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, NTSC, …)*

# SYRTE Fountain performances

- Fountain Stability

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

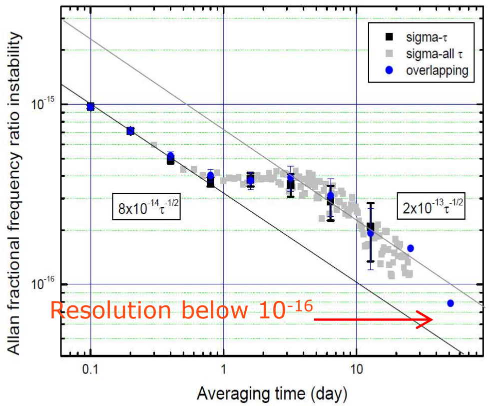
| | |
|---|---|
| FO1 | $3.3 \times 10^{-14}$ |
| FO2-Cs | $3.5 \times 10^{-14}$ |
| FOM | $6.0 \times 10^{-14}$ |
| FO2-Rb | $3.2 \times 10^{-14}$ |

- Fountain Accuracy

Uncertainty budget ($\times 10^{-16}$)

| | 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 $\nu_{Rb}/\nu_{Cs}$ 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

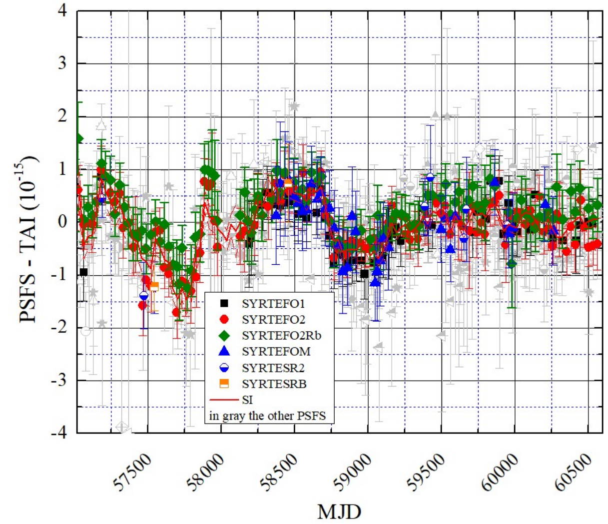
✓ Automatic data processing and parameters monitoring
✓ Refined processing for final data analysis
✓ Fountain local comparison over synchronous operation

- 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

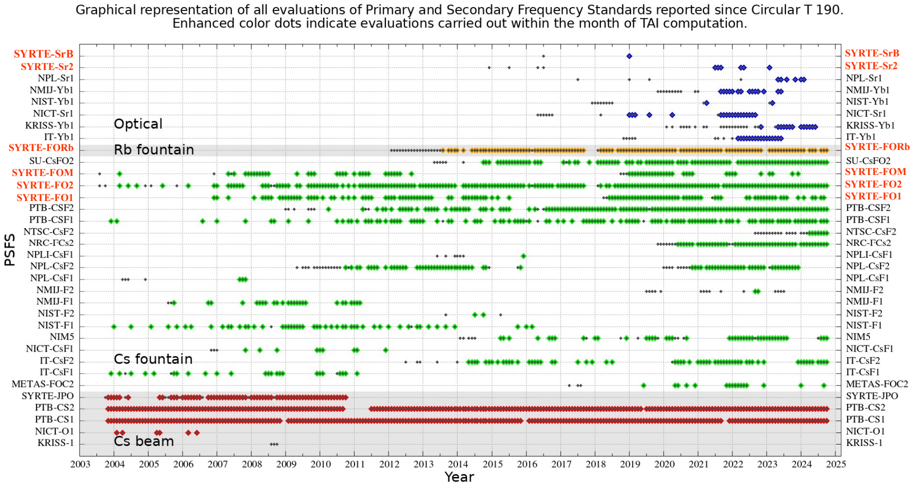
Data extracted from the BIPM
*Circular T 325-441 (i.e. since 2015)*




- 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, NPL)

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



# 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

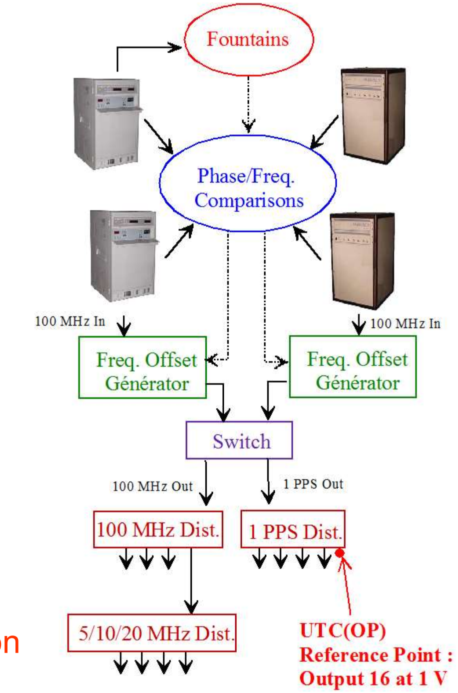
▪ Automatic data processing for fountain monitoring (hourly) providing daily frequency calibrations of our 5 H-Masers by the 4 fountains at the low $10^{-15}$ level

▪ Daily main steering using a linear fit of the fountain calibrations over the past 5 days updated automatically

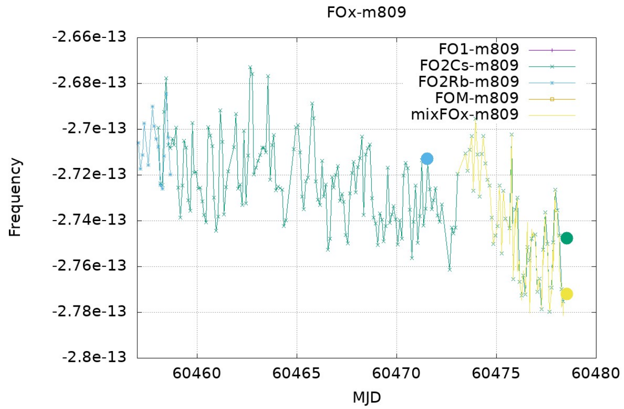
▪ Additional steering of a few $10^{-16}$ towards UTC updated monthly using the last available *Circular T* compensating for:

- The slope of UTC(OP) – UTC
- Half of the phase difference over the following month

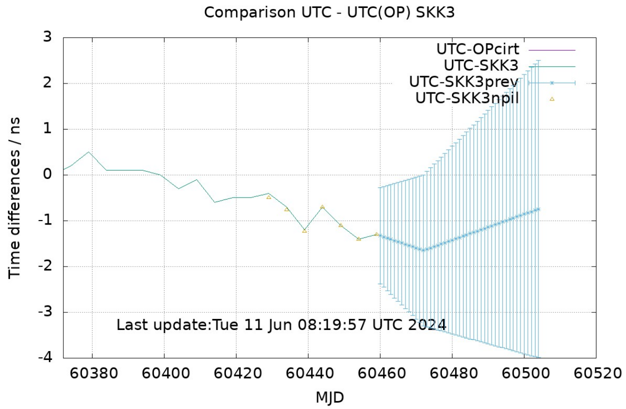
## Redundant Timescale



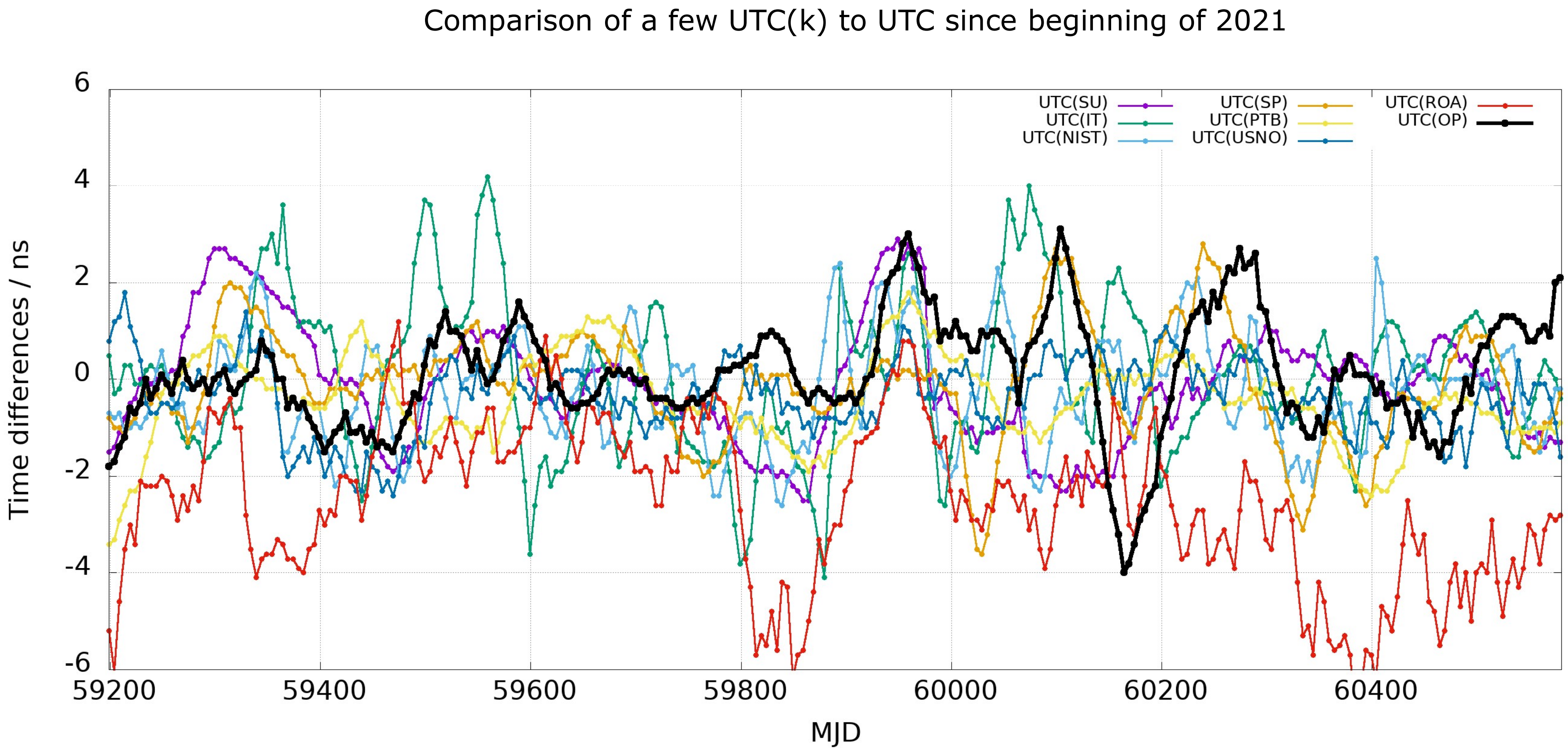

## H-Maser prediction




## Monthly steering and prediction



# UTC(OP) Performances




- 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
- $3 \times 10^{-16}$ 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

TWSTFT antennas at OP

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

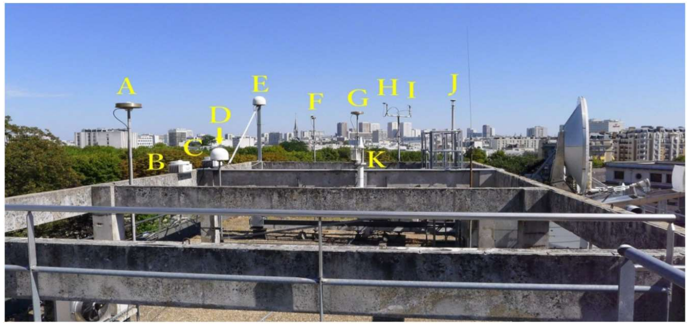
➢ Advanced techniques such as iPPP with BIPM and CNES

➢ Comparisons using GALILEO signals, BEIDOU in near future

- TWSDRR: main time transfer for TAI contributions

➢ TWSTFT/GPSPPP and GPS as backups

GNSS antennas at OP




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

# 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
- SCPTime (Secure Certified Precise Time) : Industrial contract with EASII IC

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 : $\sim 10^{-12}$ 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)
- Optical clocks and oscillators
  - 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

SYRTE Observatoire de Paris | PSL

**Thank you !**