Systèmes de Référence Temps-Espace

"Operational" Activities of the REFMET Team: Atomic Fountains, Timescales Generation and Dissemination

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38th European Symposium on Occultations Projects, August 31st 2019

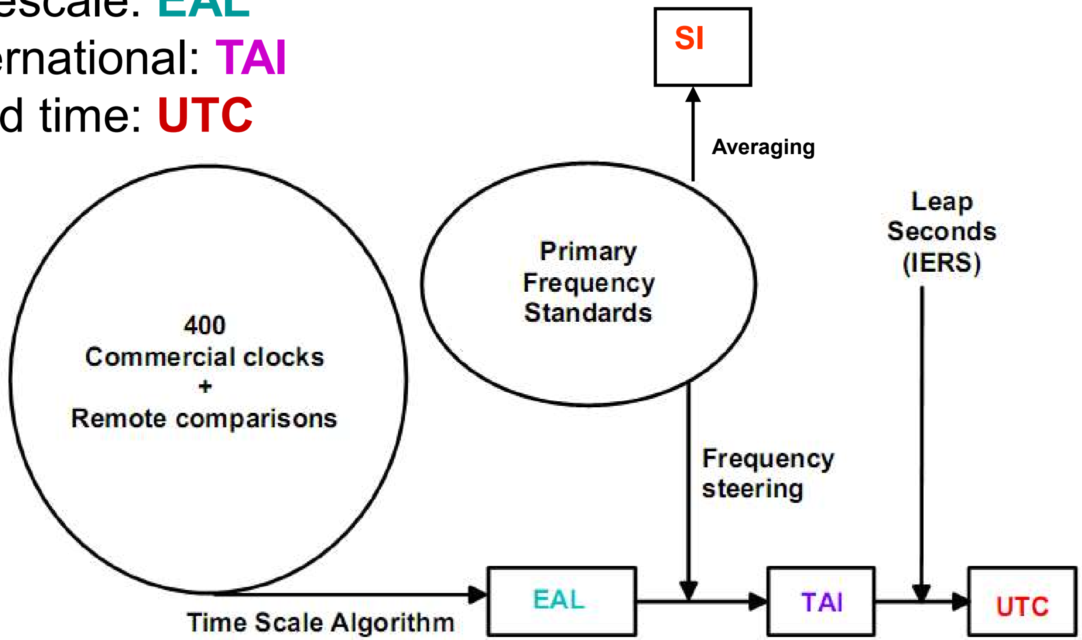
Outline

- 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

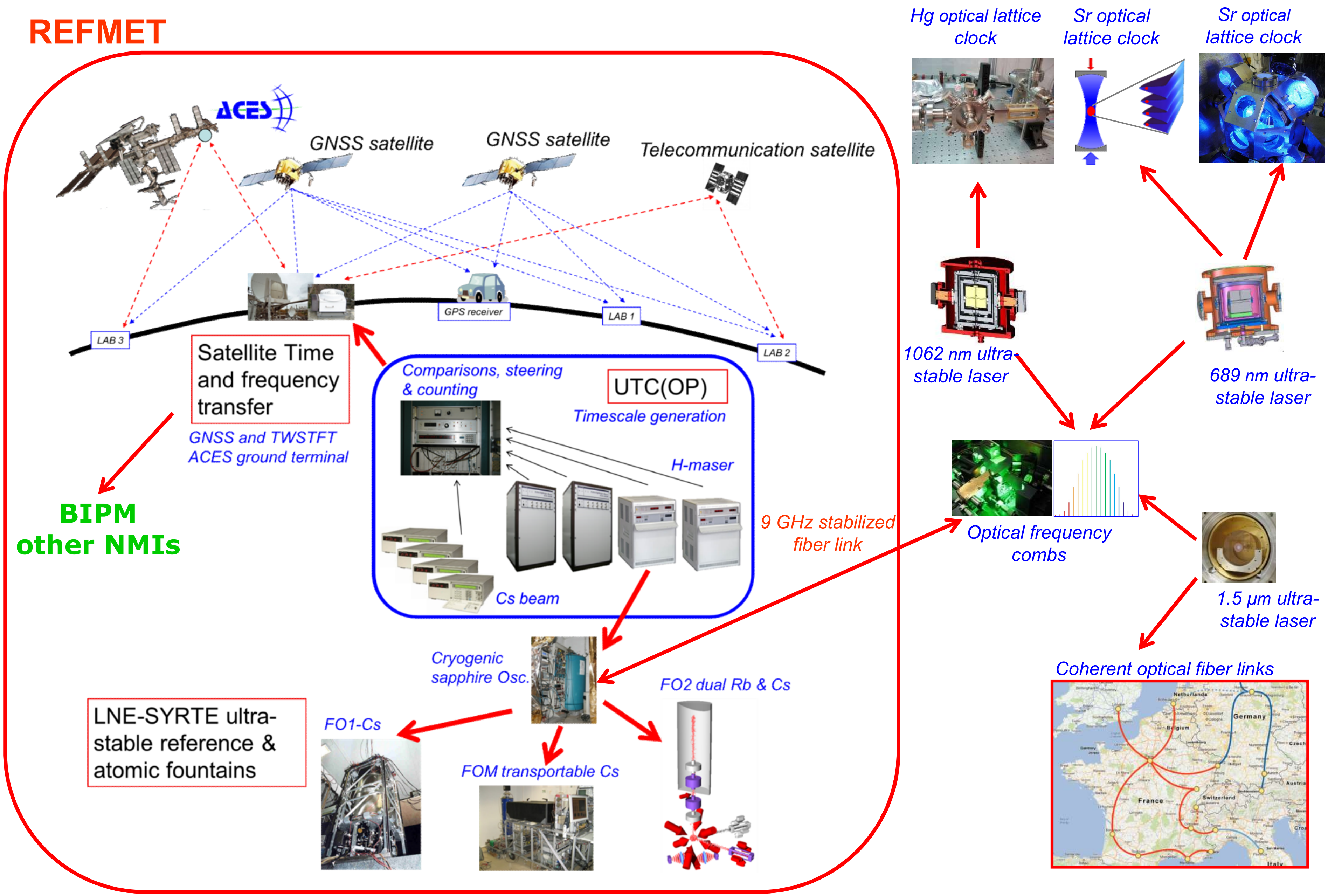


- UTC maintained close to UT1: |UTC – UT1| < 0,9 s

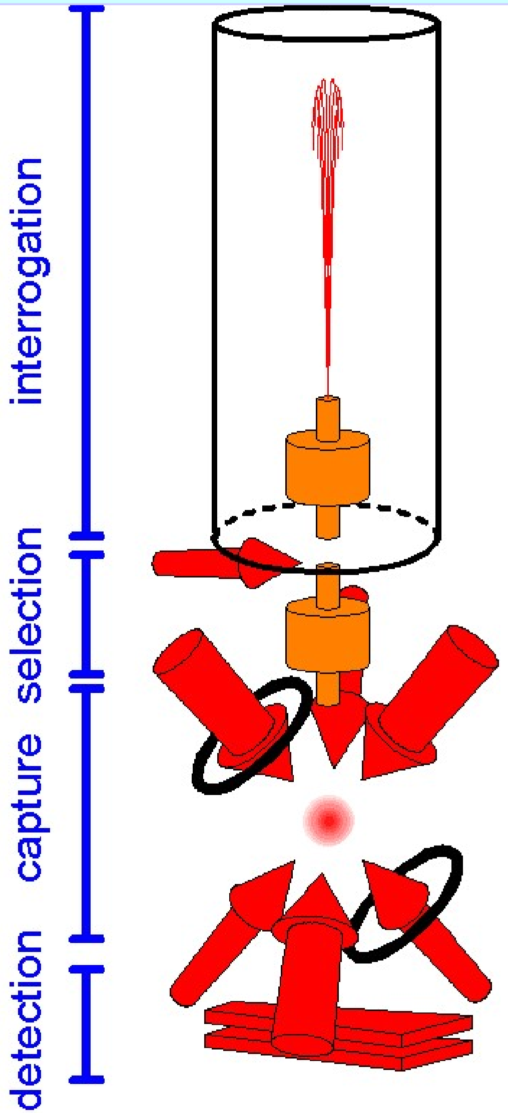
  UTC – TAI = - 37 s since January 1st 2017
- UTC: « paper » timescale calculated for the previous month
- NMI produce predictions of UTC: UTC(k)
- **UTC – UTC(k)** published in the **Circular T**

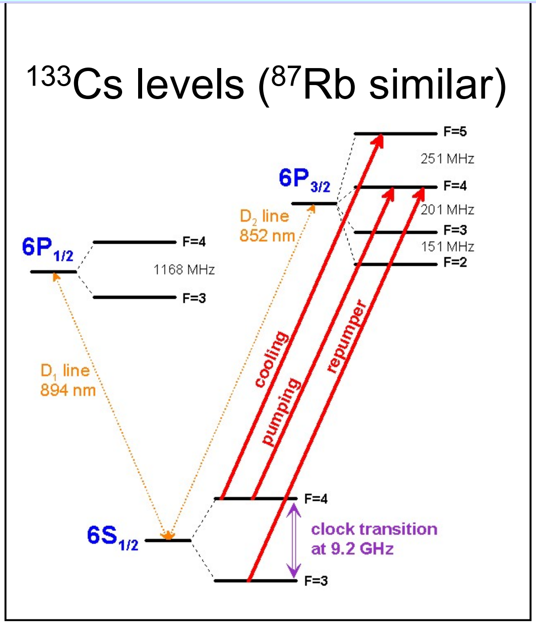
- The SI Second : an averaging of PFS data provided by a few NMI

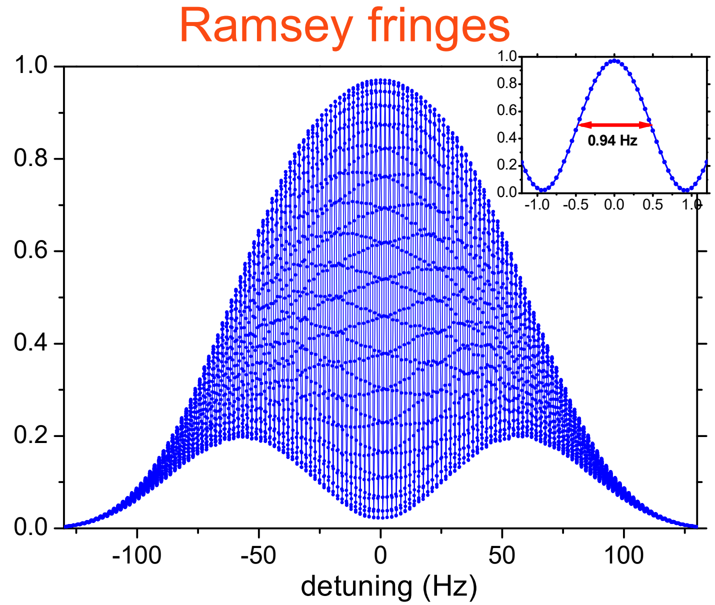
SYRTE atomic clock ensemble

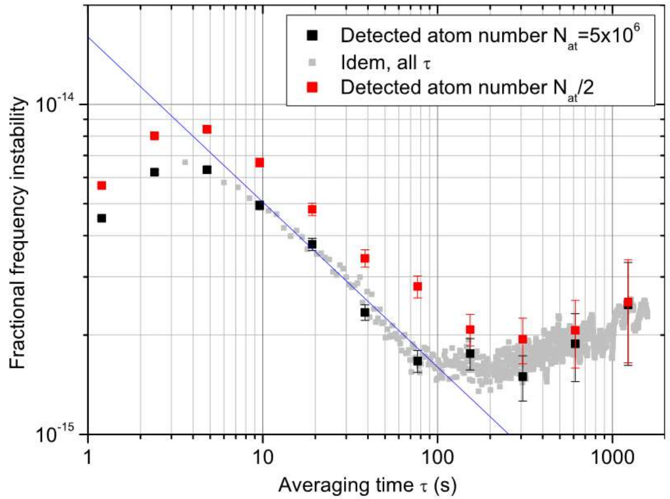


Atomic fountain clocks









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, METAS, NIST, USNO, JPL, NICT, NMIJ, NIM, KRISS, VNIIFTRI, AOS, NPLI, NRC…) with an accuracy a few 10^{-15} and $<10^{-15}$ for a few of them.

SYRTE Fountain performances

- Fountain Stability

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

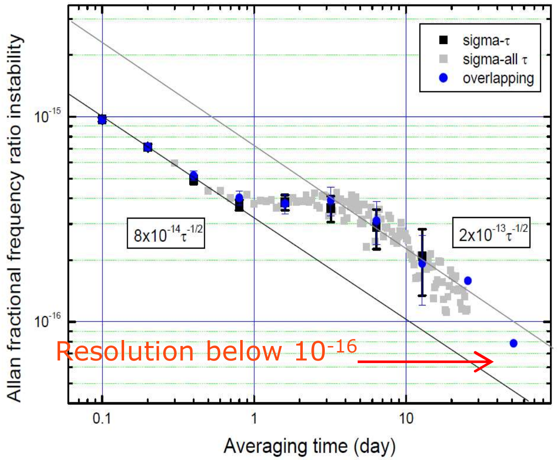
FO1	3.3×10^{-14}
FO2-Cs	3.5×10^{-14}
FOM	6.0×10^{-14}
FO2-Rb	3.2×10^{-14}

- Fountain Accuracy

Uncertainty budget (x 10^{-16})

	FO1	FO2-Cs	FOM	FO2-Rb
Quadratic Zeeman Shift	-1280.61 ± 0.40	-1934.38 ± 0.30	-323.28 ± 1.9	-3502.02 ± 0.7
BlackBody Radiation	169.44 ± 0.60	170.69 ± 0.60	166.67 ± 2.3	126.07 ± 1.35
Collisions and Cavity Pulling	126.17 ± 1.49	125.85 ± 0.97	43.47 ± 8.69	4.00 ± 0.95
Distributed Cavity Phase Shift	-0.97 ± 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	**-986.62 ± 3.17**	**-1639.44 ± 2.04**	**-114.74 ± 9.8**	**-3373.00 ± 2.45**
Red Shift	-69.08 ± 0.25	-65.54 ± 0.25	-68.26 ± 1.0	-65.45 ± 0.25
Total with Red Shift	**-1055.49 ± 3.18**	**-1704.97+/-2.05**	**-183.00 ± 9.86**	**-3438.45 ± 2.46**

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

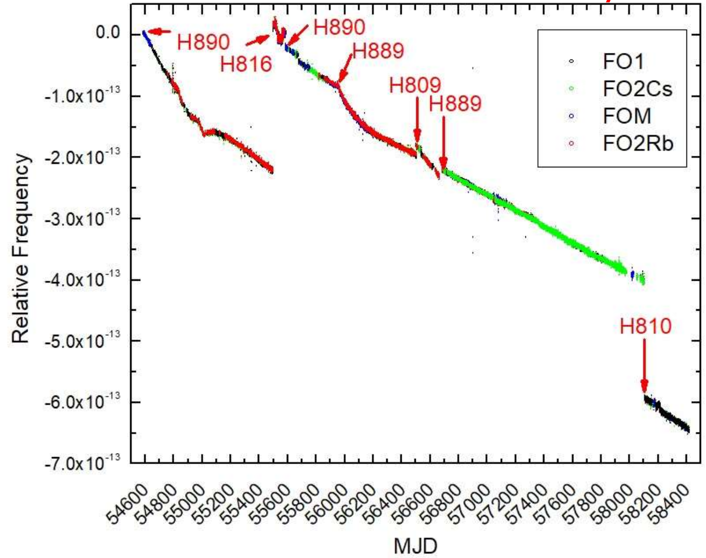
One report corresponds typically to a quasi continuous measurement of a H-maser frequency for 20 to 30 days

$u_B \sim 2\text{-}4 \times 10^{-16}$ $u_A \sim 1\text{-}2 \times 10^{-16}$ $u_{link/maser} \sim 0.5\text{-}2 \times 10^{-16}$

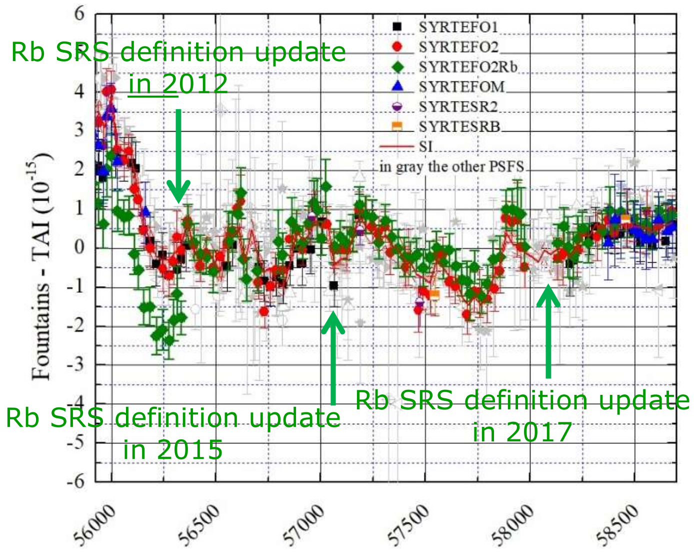
- About 50 % of the calibration reports sent to the BIPM worldwide were provided by the SYRTE fountains over the past years, mainly by FO2-Cs and FO2-Rb (uptime of ~85%) with 11 to 14 reports per year

- Initiation of the process for SFS with FO2-Rb
- ➢ Calibrations by FO2-Rb used as a SFS submitted to BIPM in Jan. 2012 and evaluated by the WG PSFS
- ➢ FO2-Rb calibration reports included in Circular T starting June 2012
- ➢ Included in the steering of TAI starting July 2013
- ➢ An important step towards a possible future redefinition of the SI second based on optical

Continuous monitoring of the SYRTE reference maser since 10 years



Data extracted from the BIPM *Circular T 289-379 (i.e. since 2009)*



Status and prospects of the fountains

Following deep refurbishment of the 3 fountains needed after continuous operation for more than 10 years

- Accuracy budget and atom physics experiments
  - Investigations on the recoil shift expected to be 7x 10^{-17} in FO1 and FO2, never observed
  - Effect of background gas collisions
  - Rb/Cs cold collision measurements with FO2

- Timescales
  - Contributions to the realization of the international time references TAI, SI, UTC
  - Continuous calibrations for the steering of UTC(OP)

- In collaboration with FOP
  - Absolute frequency measurement of optical secondary representation of the second in the frame of the redefinition of the SI second in 2026
  - 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

- Improving time and frequency transfers
  - Distant comparisons using new satellite T&F transfer (TW-CP, TW SDR, GPS IPPP, GALILEO and other GNSS)
  - Comparisons to other European NMI via phase coherent optical fiber links

- Fundamental physics tests
  - Testing the stability of fundamental constants and gravitation, search of dark matter

- Contributing to ACES mission
  - as high performances clocks part of SYRTE ground segment
  - for providing the best possible time reference for the ACES MWL

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

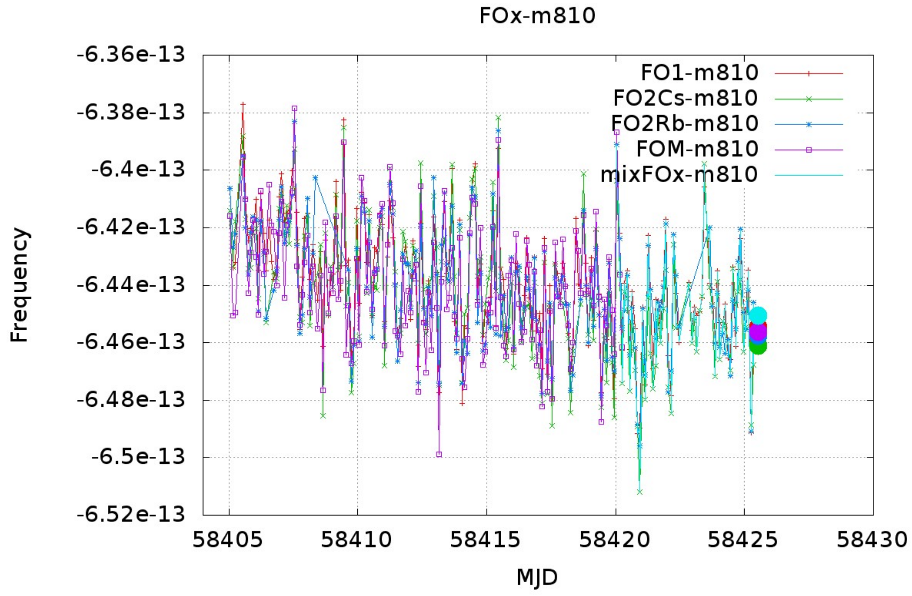
➢ Accuracy, stability and reliability mandatory

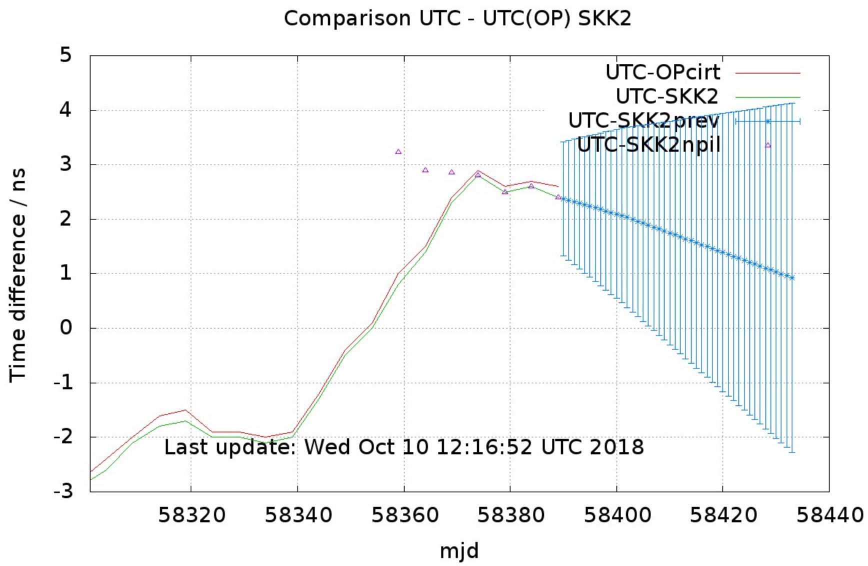
➢ Combines the operation continuity of commercial clocks (H-masers) and the stability and accuracy of atomic fountains

Steering algorithm

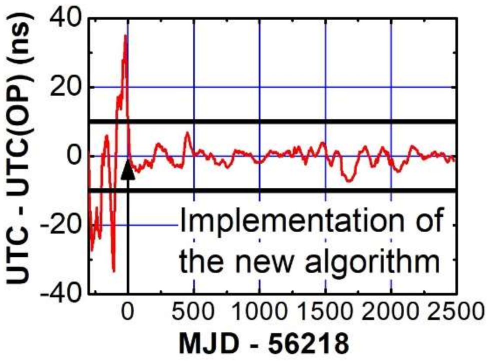
- New method based on a steered hydrogen maser since October 2012
- Automatic data processing for fountain monitoring (hourly) providing daily frequency calibrations of our 4 H-Masers by the 3 fountains at the low 10^{-15} level
- Daily main steering using a linear fit of the fountain calibrations over the past 20 days updated automatically
- Additional ~10^{-15} steering 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

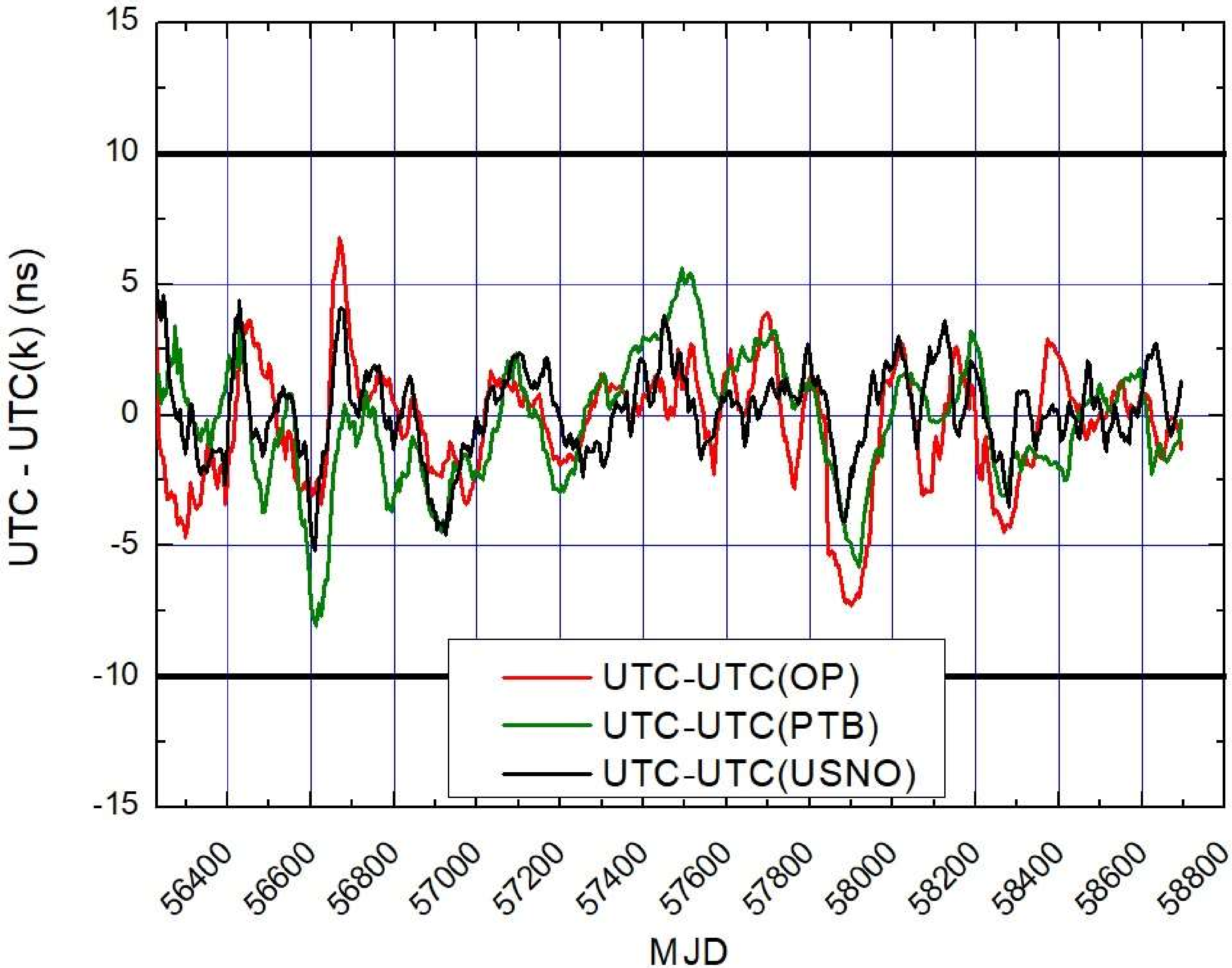
H-Maser prediction





UTC Performances



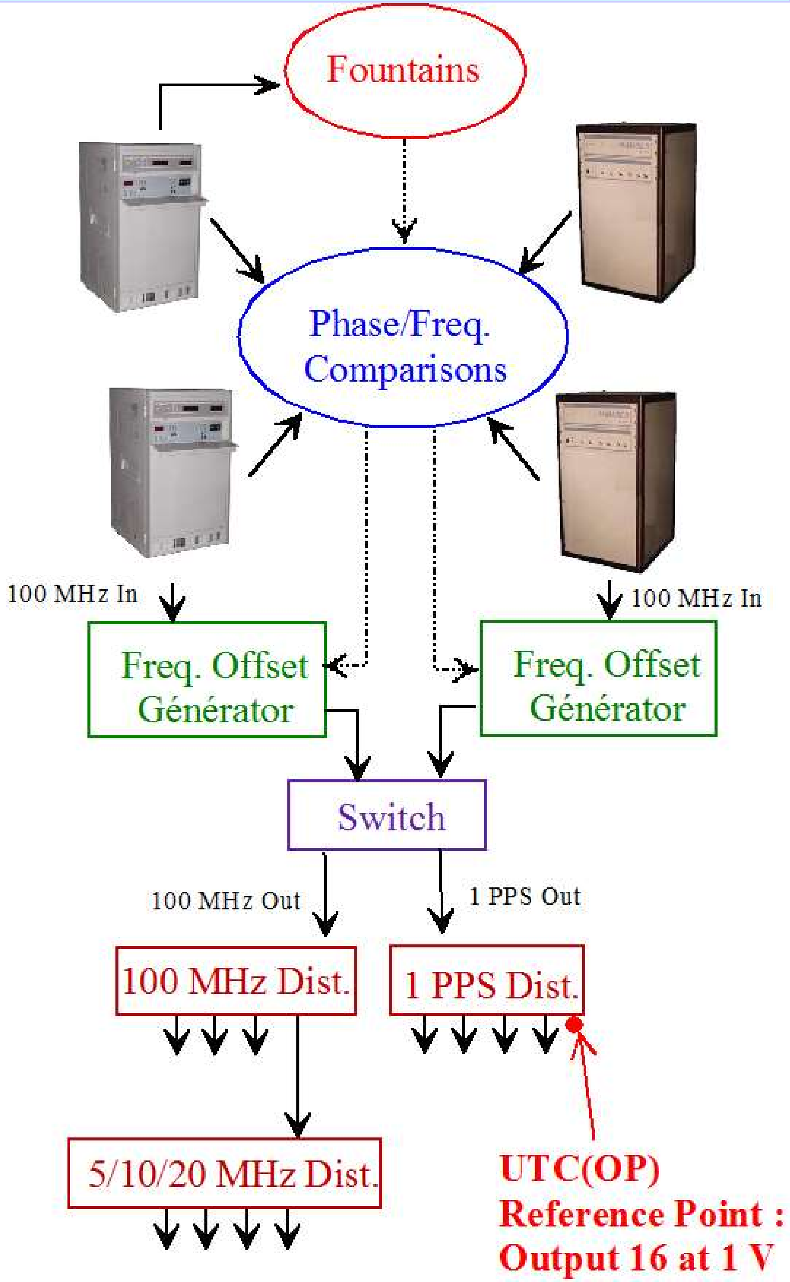


- UTC(OP) is one of the best real time realizations of UTC
- Departure of a few ns since the implementation of the new method
- Approaching the uncertainty of the time transfer links

Redundant timescale

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

- Additional 100 MHz devices being implemented
- Simulations and experiments for improving the steering algorithm
- Preparation for using calibrations from optical clocks



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
- ✓ 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 OP71/OPM6/OPM9
- Geodetic station
- Traveling equipment for relative calibration
- Group 1 lab (with PTB and ROA in EU) for the relative calibration of GPS stations of TAI labs
- ✓ Accuracy 1-3 ns
- ➢ Experiments on absolute calibration of GNSS receivers
- ➢ First experiments using GALILEO signals

- ▪ TWSTFT/GPS PPP: main time transfer for TAI contributions
- ➢ GPS and TWSDR 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 PTF and of the participating labs

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

Improving measurement techniques for the measurement of cable delays, experiments on multipath in GNSS

Infrastructure for the ACES microwave ground terminal

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), DCNS (French navy)
- Industry: Orange (3 centers), Spectracom Orolia, Keysight Technologies

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

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 data also sent to the BIPM and included in EAL computation

Dissemination of UTC(OP)

Speaking clock : 3699
- Since 1933…
- 4 redundant clocks referenced to UTC(OP) or cesium beams
- Dissemination by Orange network
- Accuracy 50 ms (analogic network)

ALS162 Signal (162 kHz) Former name « France-Inter grandes ondes »
- 2 Cesium beams connected via GPS CV to UTC(OP)
- ~1 MW emitter located in Allouis, in the center of France
- Collaboration with ANFR, TDF, CFHM, LTFB, LNE-SYRTE
- Accuracy : ~10^{-12} with the carrier; ~1 ms with the code

Bulletin H published monthly summarizing the main results

Network Time Protocol (NTP)
- 2 Stratum 1 servers referenced to UTC(OP)
- Stratum 2 servers available to the public (300 000 query/h)
- Uncertainty ~10 ms depending on the network characteristics

SCPTime (Secure Certified Precise Time)
- Industrial collaboration
- Main servers installed and connected to UTC(OP)
- Distribution and supervision system ongoing implementation
- Beginning of the service foreseen in 2019

Laboratory tests on PTP (Precise Time Protocol), White rabbit in collaboration with FOP

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

Thank you !

l'Observatoire de Paris — SYRTE

Systèmes de Référence Temps-Espace

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