International time scales

Atomic standards

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International Committee for GNSS, 2nd Meeting
Meeting of GNSS experts
Bangalore, 5 September 2007

OUTLINE

- International coordination for metrology;
- International time scales TAI and UTC;
- Atomic standards
  - Industrial atomic standards
  - Primary frequency standards
  - Secondary frequency standards
- Concluding remarks

BRIEF HISTORY OF THE METRE CONVENTION

The Metre Convention

- 1869 - Emperor **Napoleon III approved** by decree a report of the French Ministry for Agriculture and Trade proposing the **creation of an international scientific commission** to propagate the use of metric measurements and to facilitate trade and comparisons of measurements between States, and to carry out the construction of an international metre prototype.

- 1870-1872 - The **International Metre Commission** is held in Paris. Their work led to the foundation of the Metre Convention.

- **20 May 1875** - The **Metre Convention** is signed in Paris by representatives of **17 nations**. It establishes a **permanent organizational structure for** member governments to act in common accord on **all matters relating to units of measurement** through the actions of the **CGPM**, **CIPM**, and **BIPM**.

CONFÉRENCE GÉNÉRALE DES POIDS ET MESURES

The CGPM

Is made up of **representatives** of the governments of the **Member States** and **observers** from the **Associates** of the CGPM.

Meets in Paris once **every four years**; the 23rd CGPM will be held in November 2007.

At each meeting

- it receives a **report** of the **International Committee for Weights and Measures** (CIPM) on **work accomplished**
- it discusses and examines the arrangements required to ensure the **propagation and improvement** of the International System of Units (**SI**)
- it endorses the **results** of new fundamental metrological determinations and various scientific resolutions of international scope; and
- it decides all major issues concerning the organization and development of the BIPM, including the **budget of the BIPM** for the next four-year period.

COMITÉ INTERNATIONAL DES POIDS ET MESURES

The CIPM

Is made up of **eighteen individuals**, each from a different Member State. Its principal task is to **promote worldwide uniformity in units of measurement** by direct action or by submitting draft resolutions to the CGPM.

Meets annually and, its duties include:

- discusses the **work of the BIPM**;
- discusses reports presented to it by its **Consultative Committees**;
- discusses metrological work that Member States decide to do in common and sets up and coordinates **activities between specialists in metrology**;
- makes appropriate **Recommendations**;
- issues an **Annual Report** on the **administrative and financial position of the BIPM** to the Member States;
- commissions **reports** in preparation for CGPMs and others such as the SI Brochure.

BUREAU INTERNATIONAL DES POIDS ET MESURES

The BIPM

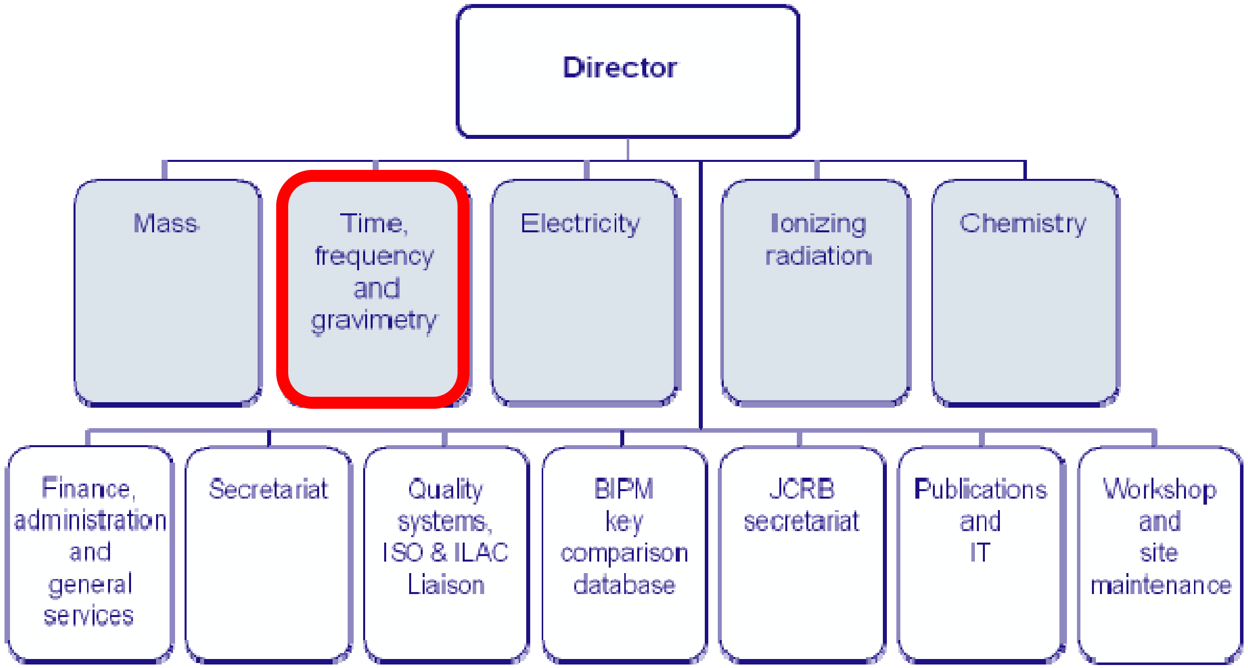
It has **headquarters** near Paris, France. It is **financed** jointly by the **Member States** and **Associates**, and operates under the exclusive **supervision of the CIPM**.

Its **mandate** is to provide the basis for a single, coherent system of measurements throughout the world, traceable to the International System of Units (SI). This task takes many forms, from **direct dissemination** of units (as in the case of mass and time) to coordination through **international comparisons** of national measurement standards (as in length, electricity and ionizing radiation).

It maintains **scientific laboratories** in areas of: mass, time, frequency and gravimetry, electricity, ionizing radiation, and chemistry.

It has an international **staff** of over 70 and its status vis-à-vis the French Government is similar to that of other **intergovernmental organizations**.

BIPM ORGANIGRAMME



INTERNATIONAL TIME SCALES TAI AND UTC

- The BIPM is responsible for **realizing, maintaining and disseminating** the international reference time scales;
- International time keeping is the result of the cooperation of many laboratories and organizations distributed worldwide;
  - IAG, GGOS, ITU-R, IERS, IGS, ICG, CGSIC, …
- The efforts of the community dealing with time metrology are focused towards the construction of time scales adapted to the most demanding applications
  - Continuity
  - Reliability
  - Accessibility
  - Frequency stability of order 10^{-15}
  - Frequency accuracy of order 10^{-15} (traceability to the SI second)

INTERNATIONAL ATOMIC TIME TAI

- ✓ Atomic scale (14th CGPM,1971)
- ✓ Continuous
- ✓ Calculated in post-real time at the BIPM (~10 days after the last date of data)
- ✓ Frequency stability (0.5 x 10^{-15} @40 days)
- ✓ Unit: SI second
- ✓ Frequency accuracy (~10^{-15})

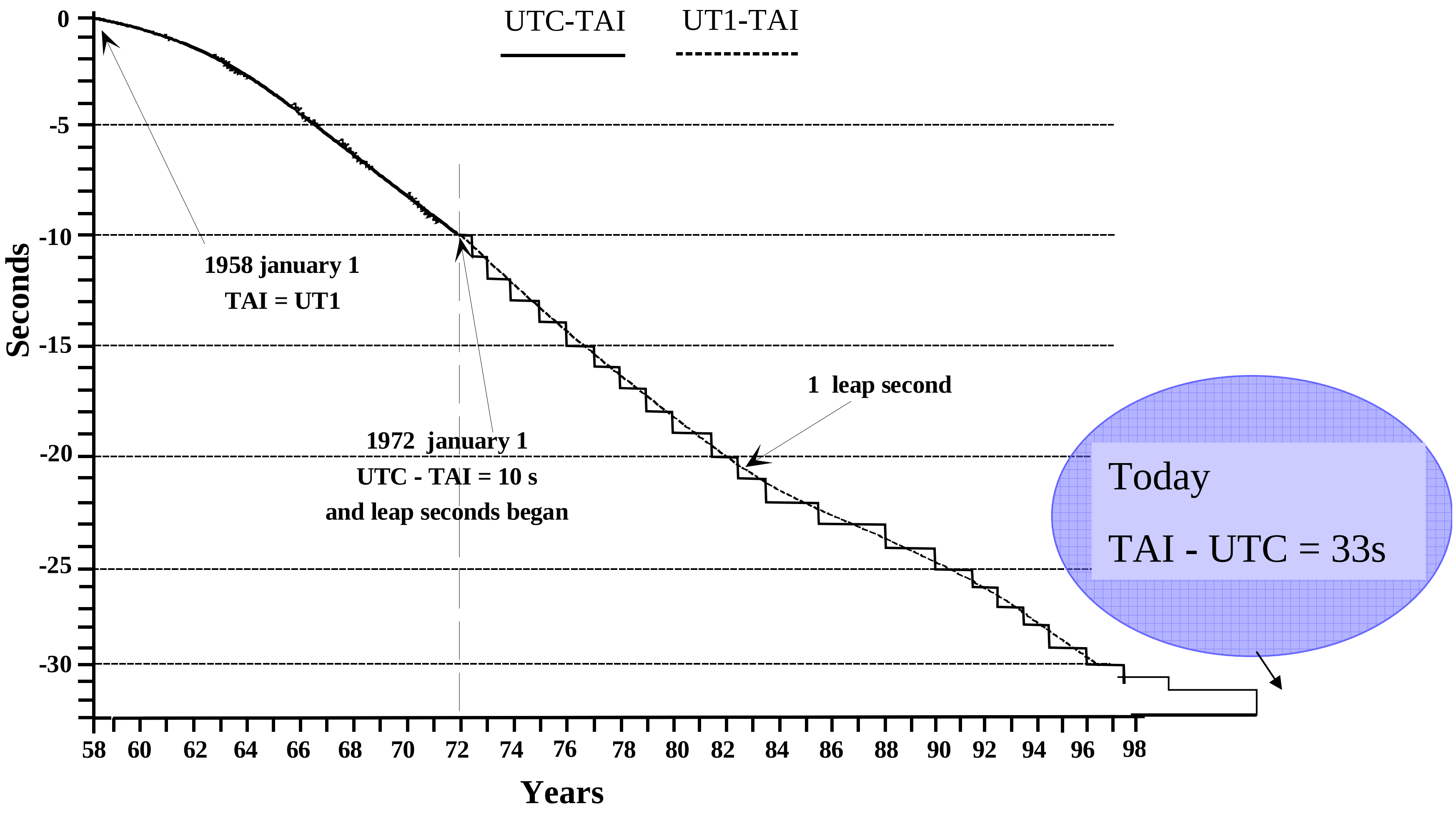
- ✓ Clocks
- ✓ Time signals
- ✓ Legality

- ✓ Frequency reference

COORDINATED UNIVERSAL TIME UTC

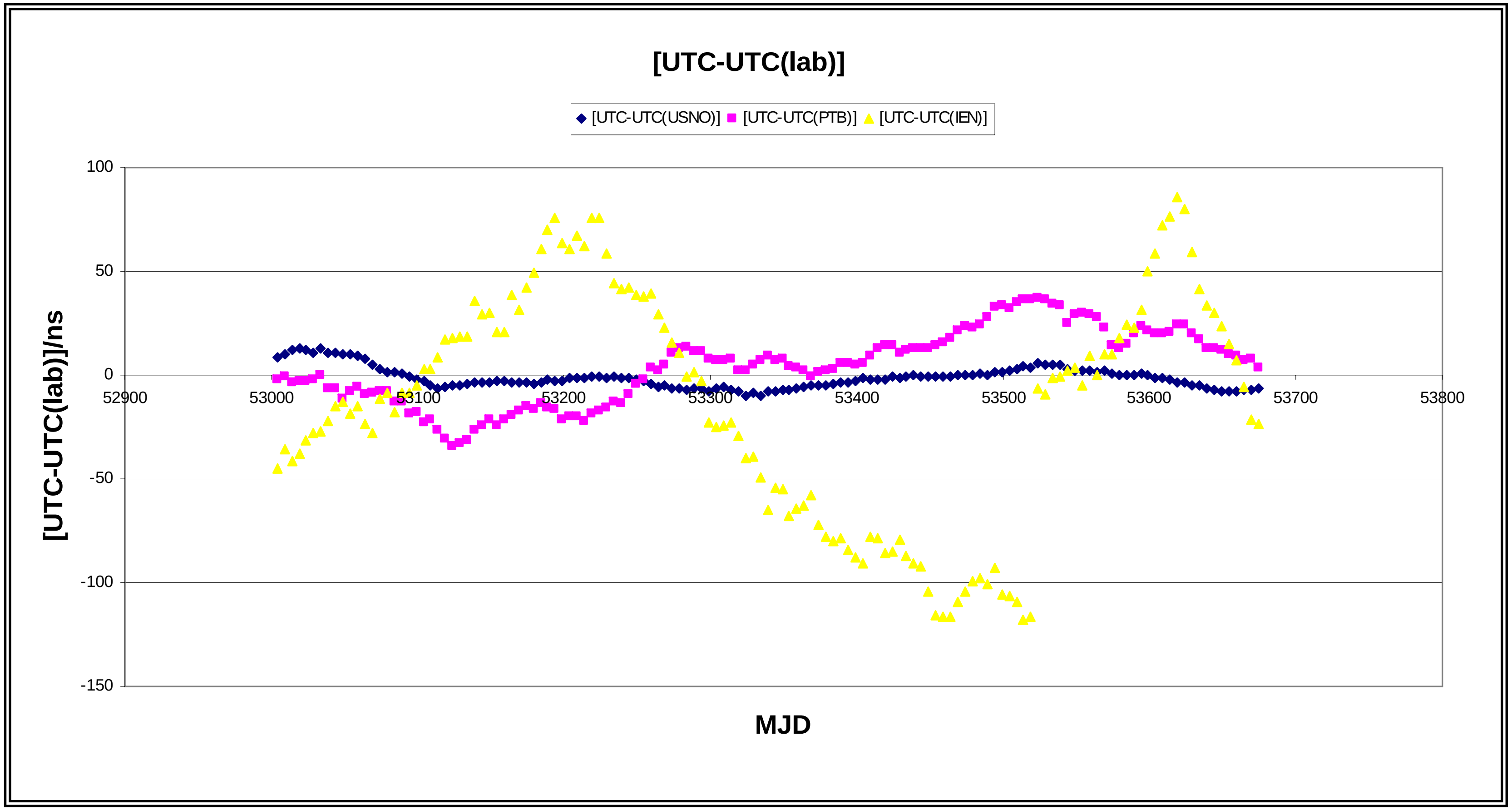
- ✓ Atomic time scale (ITU-R, Rec. 460, 1970; 460-1, 1974)
- ✓ Continuous with one-second steps at irregular intervals (leap second)
- ✓ Differs from TAI in an integer number of seconds (33 s at present)
- ✓ Represents UT1 within 0.9 s
- ✓ Post-processed (~10 days after last date of data)
- ✓ Unit is the SI second
- ✓ Frequency stability and accuracy (idem TAI)
- ✓ Represented by clocks
  - Local approximations UTC(k), [*UTC*-*UTC*(*k*)] < 100 ns (recomm.)
- ✓ Disseminated
  - Circular T, CCTF-K001.UTC (delayed time)
  - Time signals (real time approximations in time laboratories)
- ✓ Legal applications
  - Basis of legal times

UTC and leap seconds

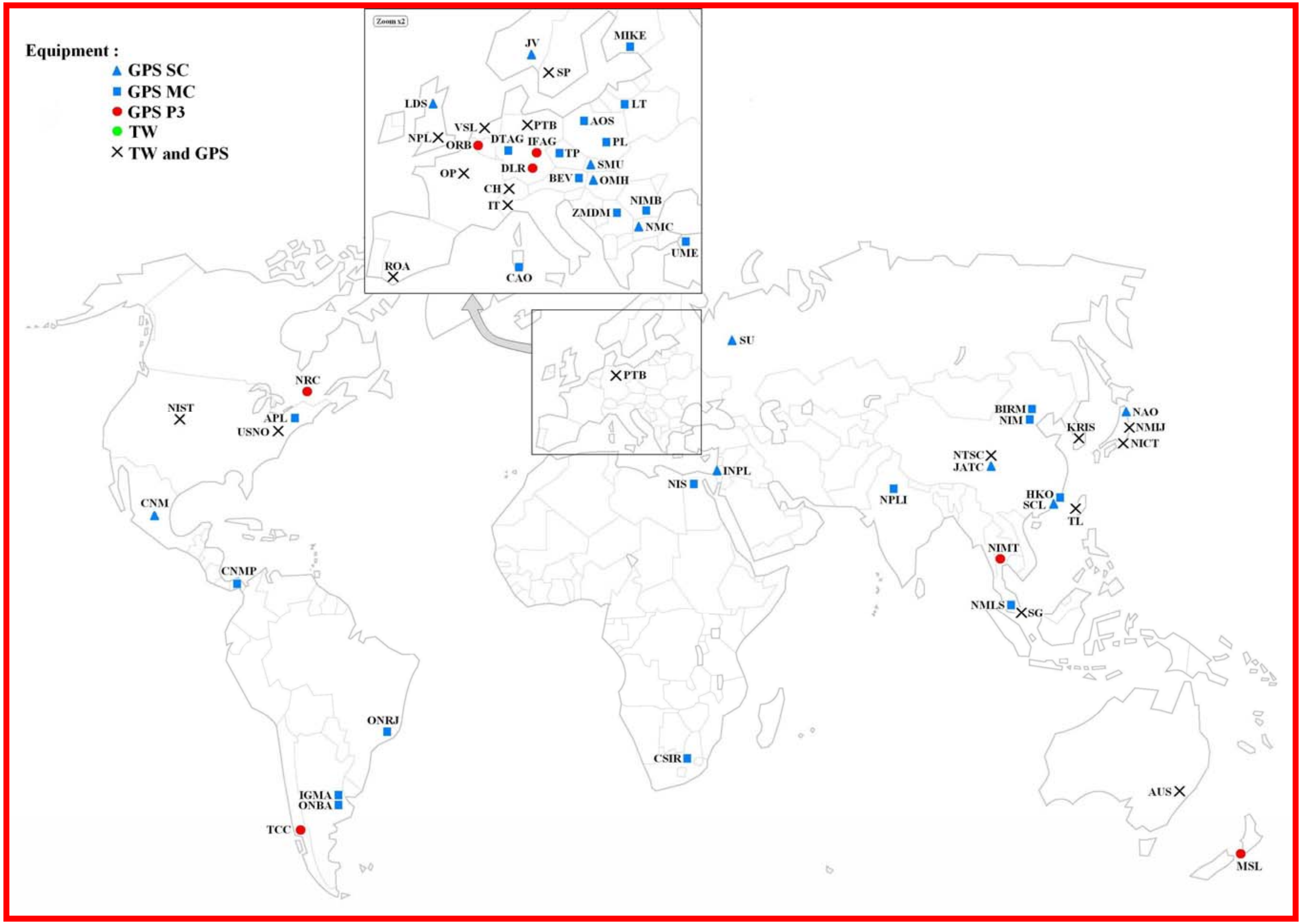


PHYSICAL REPRESENTATIONS OF UTC

- UTC(k)
  - ✓ Local realization of UTC at laboratory k (59 at present)
  - ✓ [*UTC*-*UTC*(*k*)] < 100 ns (recomm.)
  - ✓ Disseminated by time signals following the ITU-R recommendations
  - ✓ [*UTC*-*UTC*(*k*)] every five days published monthly in Circular T
  - ✓ Some UTC(k) are physically representad by a clock (eventually plus a microphase-stepper)
  - ✓ Some UTC(k) are evaluated from a clock ensemble

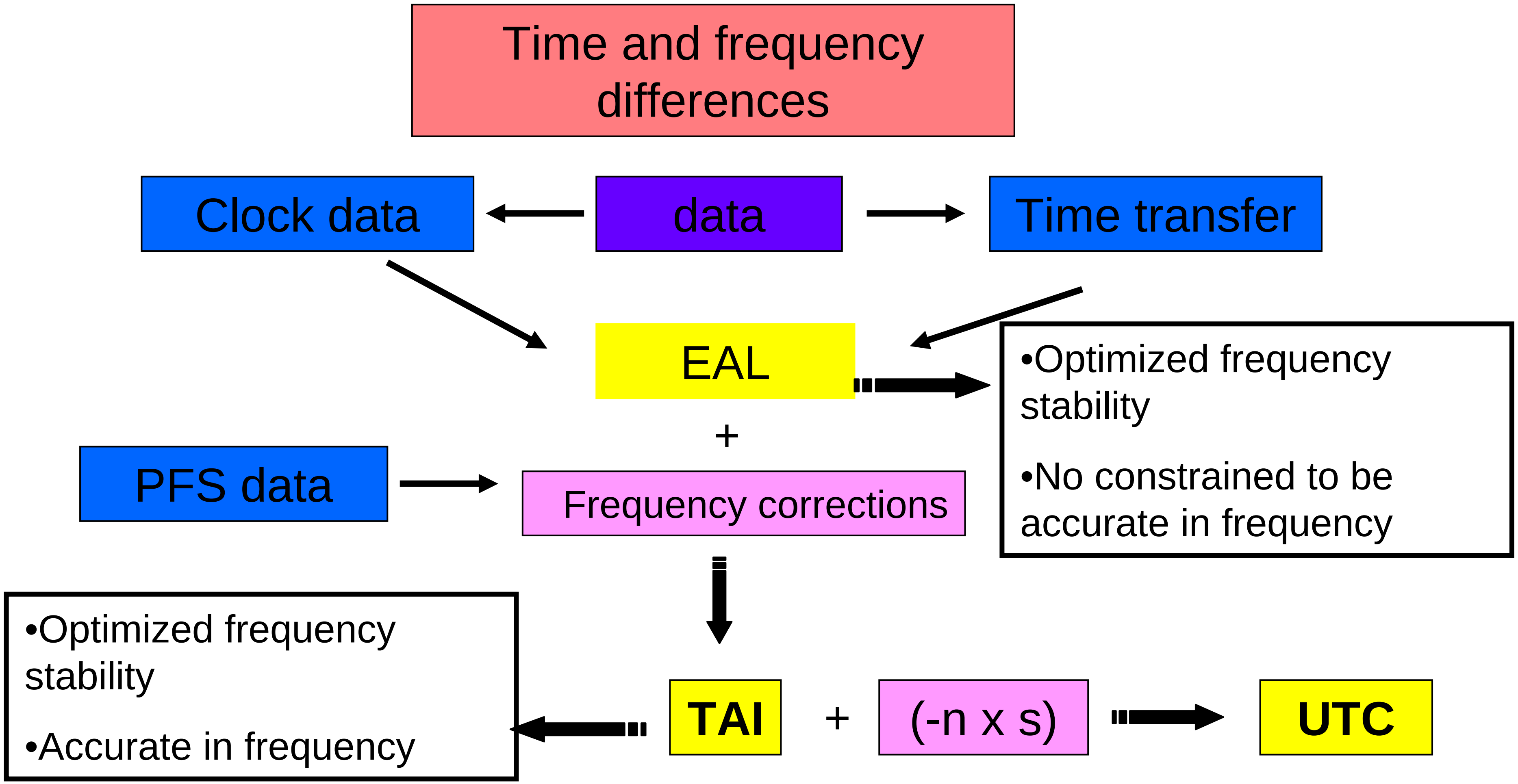


[UTC-UTC(lab)]
[UTC-UTC(USNO)]
[UTC-UTC(PTB)]
[UTC-UTC(IEN)]
100
50
0
-50
-100
-150
52900
53000
53100
53200
53300
53400
53500
53600
53700
53800
[UTC-UTC(lab)]/ns
MJD



Equipment :
GPS SC
GPS MC
GPS P3
TW
TW and GPS
Zoom x2
JV
MIKE
SP
LDS
LT
VSL
PTB
AOS
NPL
ORB
DTAG
IFAG
PL
TP
SMU
DLR
OP
BEV
OMH
CH
IT
NIMB
ZMDM
NMC
UME
ROA
CAO
SU
PTB
NRC
NIST
APL
USNO
BIRM
NIM
NAO
KRIS
NMIJ
NICT
NTSC
JATC
INPL
NIS
NPLI
HKO
SCL
TL
CNM
NIMT
CNMP
NMLS
SG
ONRJ
CSIR
AUS
IGMA
ONBA
TCC
MSL

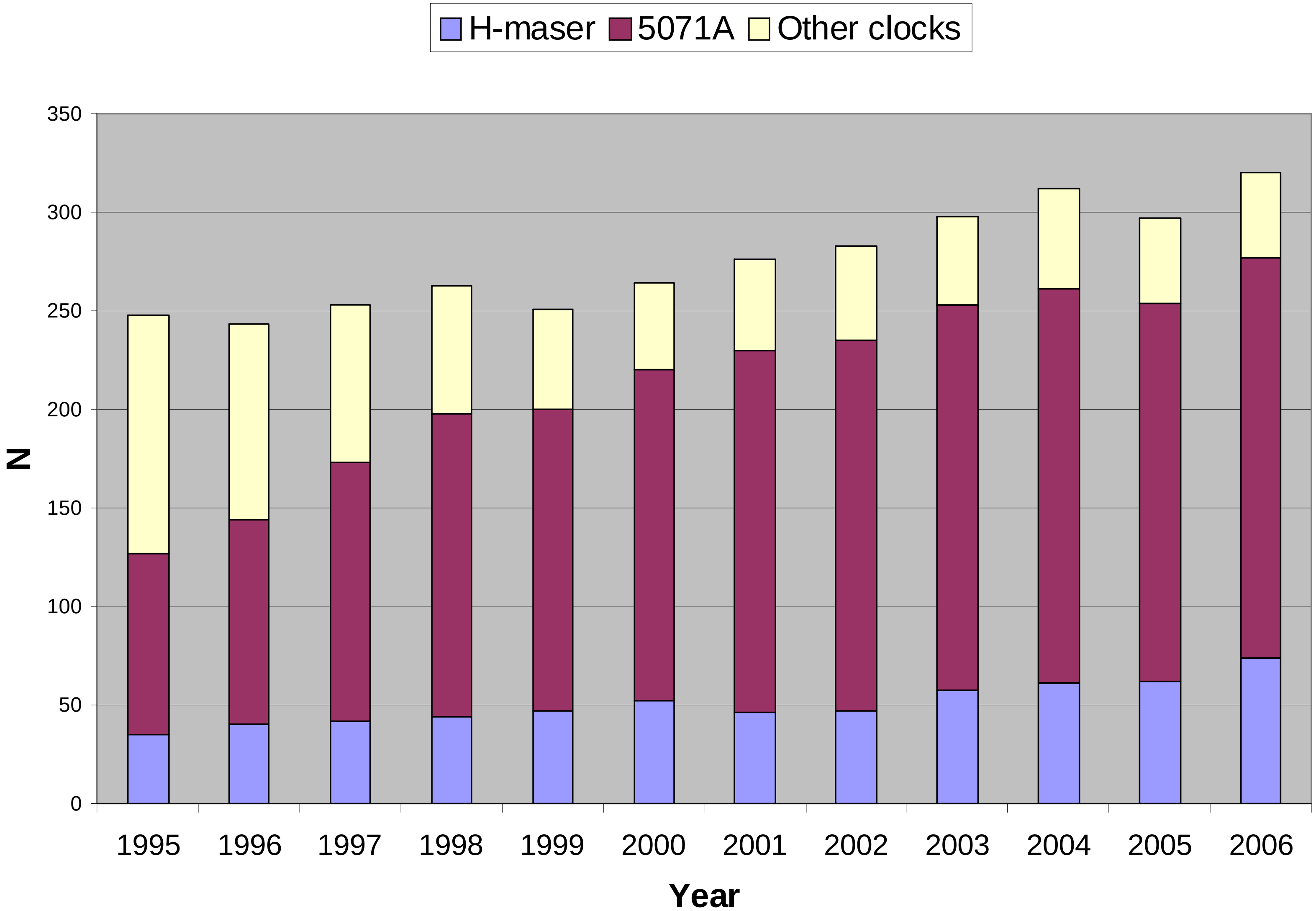
ALGOS (algorithm for calculation)



ATOMIC STANDARDS – INDUSTRIAL CLOCKS

	Stability	Accuracy
Cs standard (st. tube)	5×10^{-14} @ 5 days	1×10^{-12}
Cs standard (high perf.)	1×10^{-14} @ 5 days	5×10^{-13}
H- maser (active)	$< 7 \times 10^{-16}$ @ 1 day	

CLOCKS CONTRIBUTING TO TAI/UTC

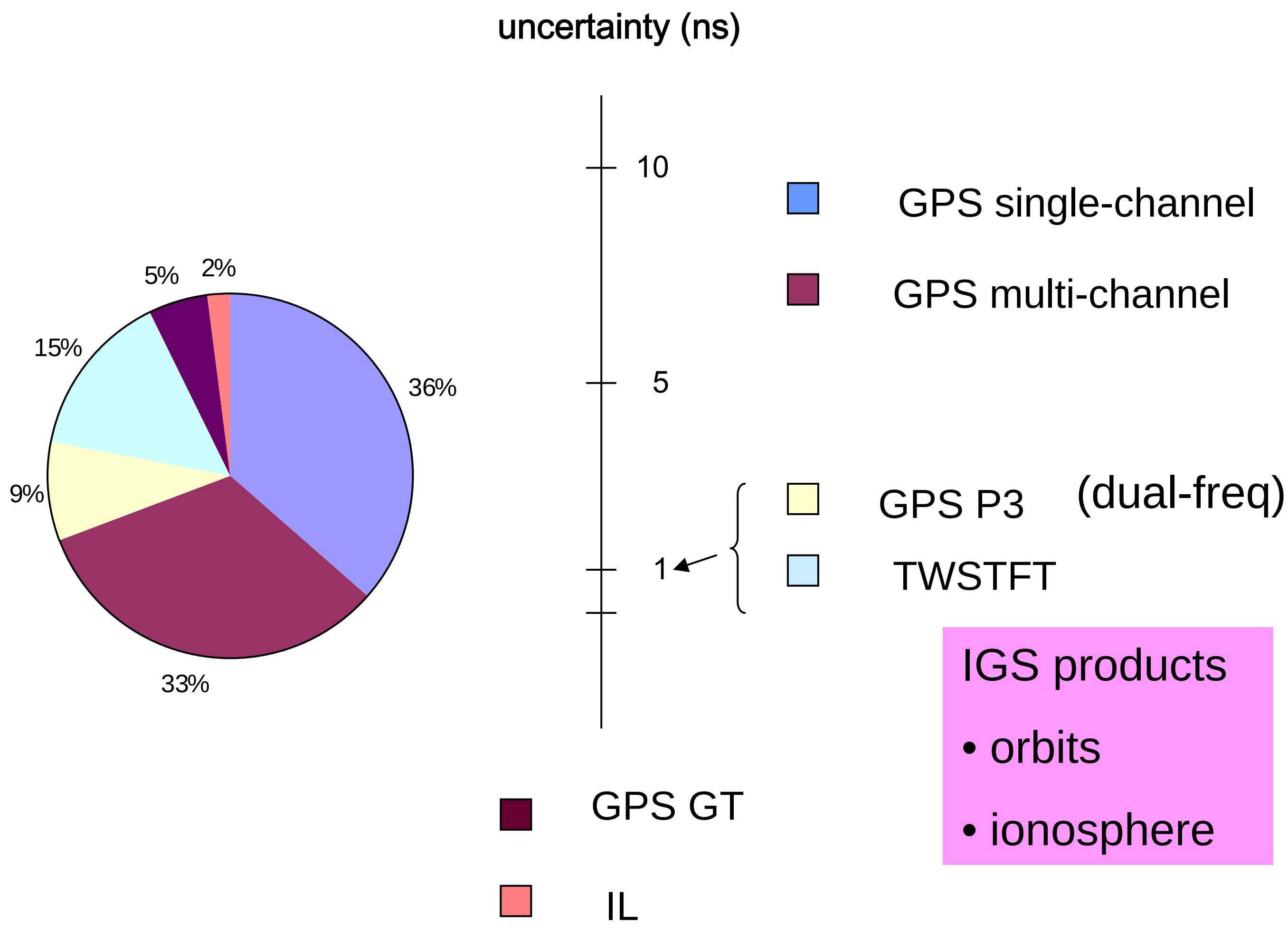


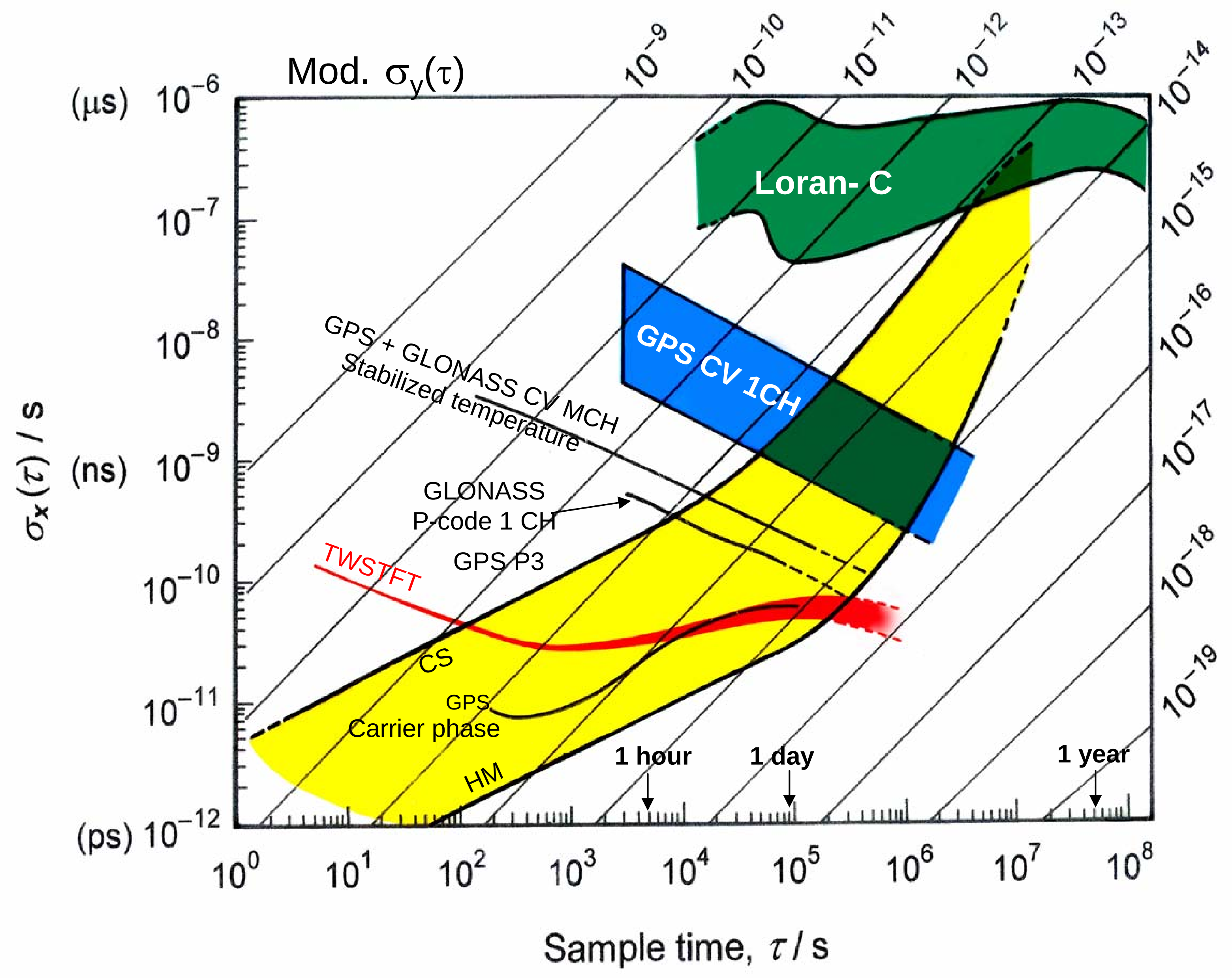
CLOCK COMPARISON

- Basic data for the construction of TAI/UTC
- Is the major constraint
- Techniques to compare distant clocks
  - **Minimise the measuring noise that is added to clock data**

- Since 1990s
  - Global Navigation Satellite Systems
    - GPS (currently)
    - GLONASS (coming soon)
    - Galileo (in preparation)
  - Two-way satellite time and frequency transfer

SATELLITE CLOCK COMPARISON





Mod. $\sigma_y(\tau)$
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
(µs) 10^{-6}
10^{-7}
10^{-8}
(ns) 10^{-9}
10^{-10}
10^{-11}
(ps) 10^{-12}
$\sigma_x(\tau)$ / s
Loran- C
GPS CV 1CH
GPS + GLONASS CV MCH
Stabilized temperature
GLONASS
P-code 1 CH
GPS P3
TWSTFT
CS
GPS
Carrier phase
HM
1 hour
1 day
1 year
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8
Sample time, τ / s

PRIMARY FREQUENCY STANDARDS

- 11 regularly reporting measurements to BIPM
  - from 6 time metrology laboratories
- 7 are Caesium fountains
  - frequency accuracy 0.5 to 4 × 10^{-15}
- improve the accuracy of TAI

Typical characteristics of the calibrations of the TAI frequency provided by the different primary standards in 2006

Primary Standard	Type /selection	Type B std. Uncertainty	Operation	Comparison with	Number/typical duration of comp.
IT-CSF1	Fountain	$(0.5 \text{ to } 0.8)\times10^{-15}$	Discontinuous	H maser	3 / 20 to 35 d
NICT-O1	Beam /Opt.	6×10^{-15}	Discontinuous	UTC(NICT)	2 / 20 to 30 d
NIST-F1	Fountain	0.3×10^{-15}	Discontinuous	H maser	3 / 30 to 40 d
NMIJ-F1	Fountain	4×10^{-15}	Discontinuous	H maser	3 / 10 to 15 d
PTB-CS1	Beam /Mag.	8×10^{-15}	Continuous	TAI	12 / 30 d
PTB-CS2	Beam /Mag.	12×10^{-15}	Continuous	TAI	12 / 30 d
PTB-CSF1	Fountain	1.1×10^{-15}	Discontinuous	H maser	2 / 10 to 15 d
SYRTE-FO1	Fountain	0.4×10^{-15}	Discontinuous	H maser	2 / 15 d
SYRTE-FO2	Fountain	0.4×10^{-15}	Discontinuous	H maser	3 / 5 to 15 d
SYRTE-FOM	Fountain	1.2×10^{-15}	Discontinuous	H maser	1 / 15 d
SYRTE-JPO	Beam /Opt.	6×10^{-15}	Discontinuous	H maser	11 / 20 to 30 d

Reports of operation of PFS are regularly published in the BIPM Annual Report

IMPROVEMENT IN ATOMIC FREQUENCY STANDARDS

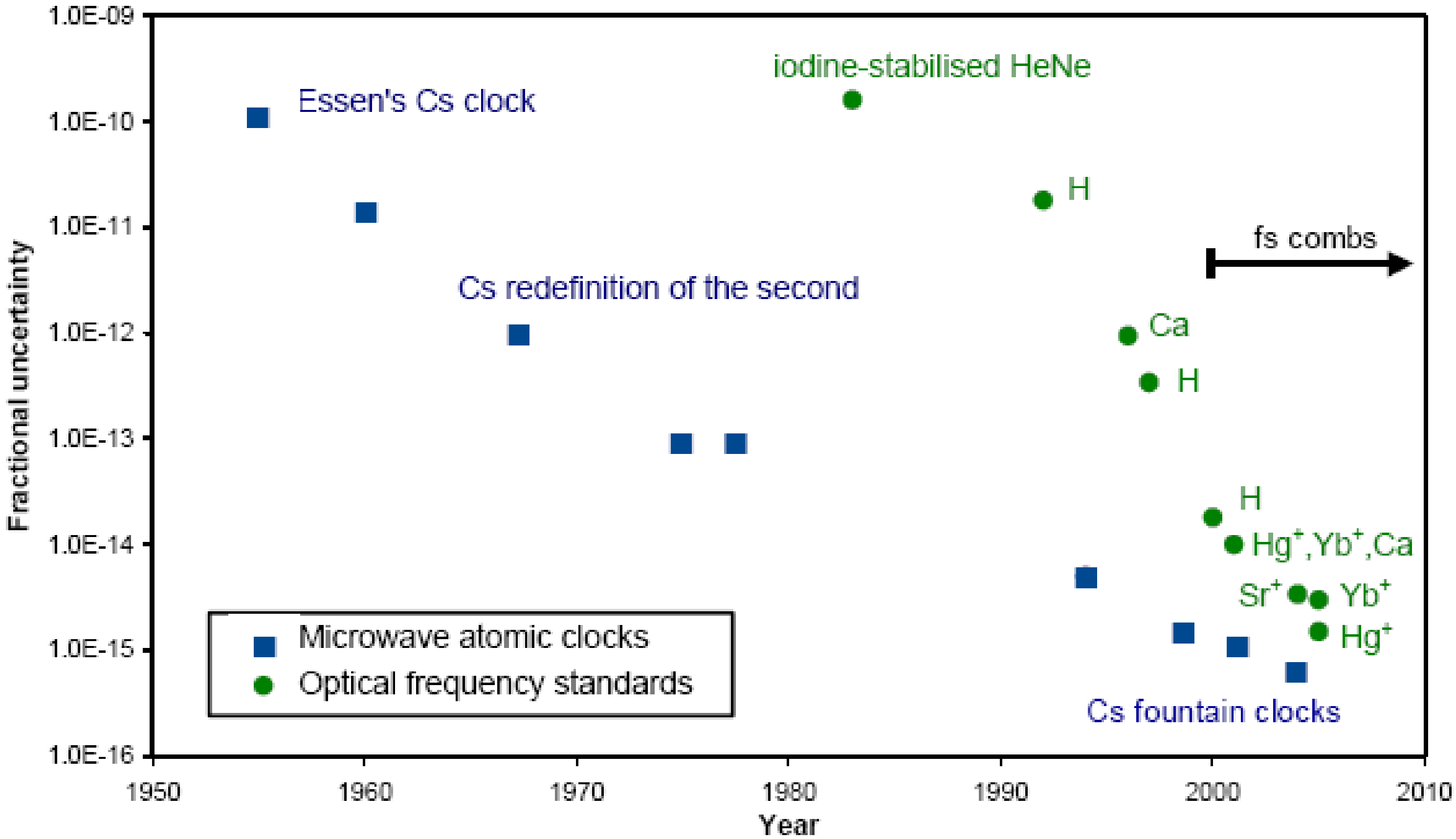


Figure 1: Improvements in atomic frequency standards

Gill & Riehle 2006

SECONDARY REPRESENTATIONS OF THE SECOND

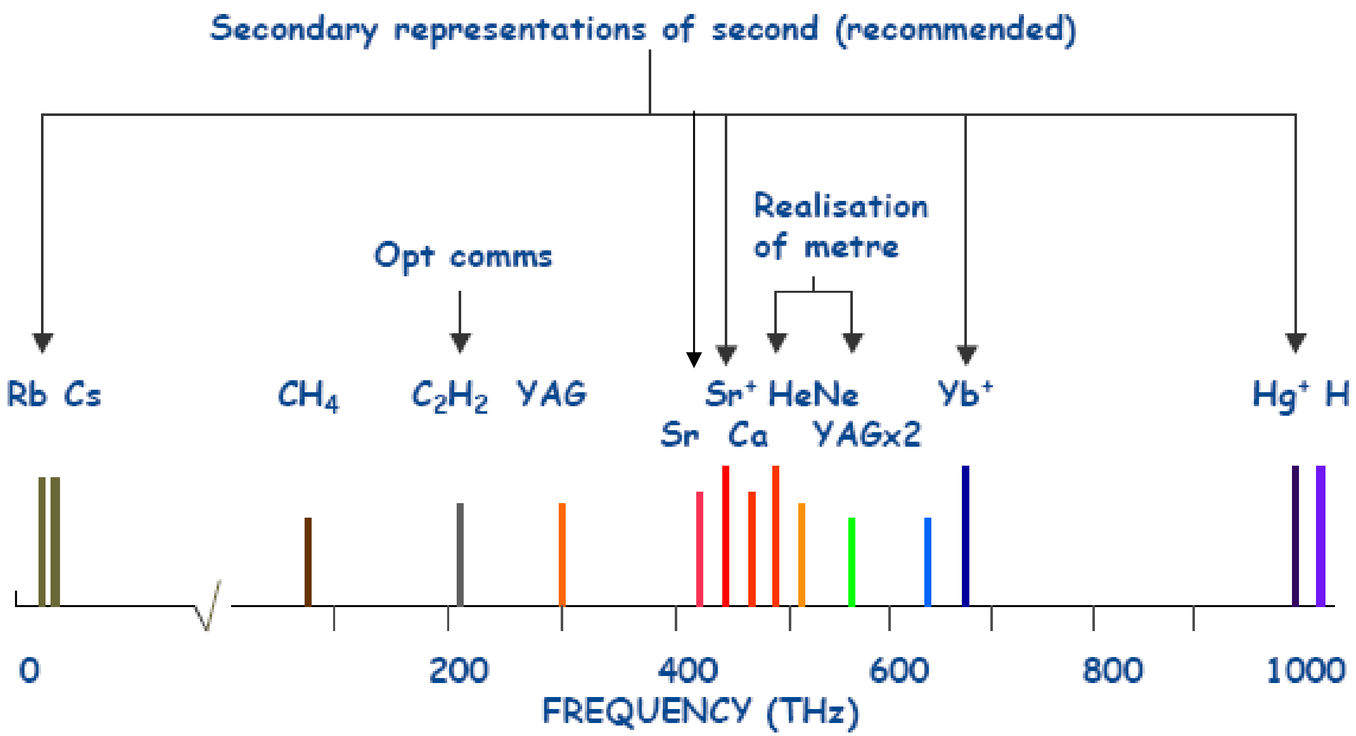


Figure 2: Example of a unified list of recommended radiations

Gill & Riehle 2006

CONCLUDING REMARKS

- Time scales establishment is an example of the **benefits of coordination** between national metrology institutes and international organisations;
- It takes advantage of the **diversity of fields** related to timing activities (Earth sciences, astronomy, satellite navigation, telecommunications, technology developments, etc.);
- It creates **a strong motivation in national laboratories** to improve their capacities;
- GPS has dramaticaly improved time transfer;
- Diversity of GNSS (GPS, GLONASS, Galileo, GNSS augmentations) requires **coordination** between service providers and receiver developers;
- The progress in the construction of new frequency standards request that **highly accurate time and frequency transfer** be possible on a routine basis (GNSS/ TW carrier phase, …)

By W. Lewandowski, 29/10/02

- One clock can provide a time scale, but not a reference
- A large clock ensemble is necessary, if possible worlwide spread
- The algorithm is based on differences of clock readings
- Clock comparisons need of highly performing time transfer techniques (sub-nanosecond level has been achieved)

Why the BIPM?

- It received the mandate from the member states;
- Highest competences in metrology;
- Independent, supporting all metrology laboratories, but mostly those from less developed countries;
- Committes and working groups supporting and assessing the activities in the scientific sections;
- Fruitful cooperation with national metrology laboratories for the advance of the science of measuring.

Coordination: a crucial task

- Data provision
  - Fixing formats (CCTF WGGTTS) and deadlines for submission
  - Establishing protocoles for reporting data of primary frequency standards (CCTF WG on PFS)
  - Coordinating data acquisition in the 59 participating laboratories, i.e. date for the data, equipment, observations (CCTF WG on TWSTFT)
  - « Initiating » of new contributors
  - Organizing and running campaigns of time transfer equipment calibration
  - Establishing a strategy for clock comparison between labs (international time links)

Coordination: a crucial task

- Data processing and calculation

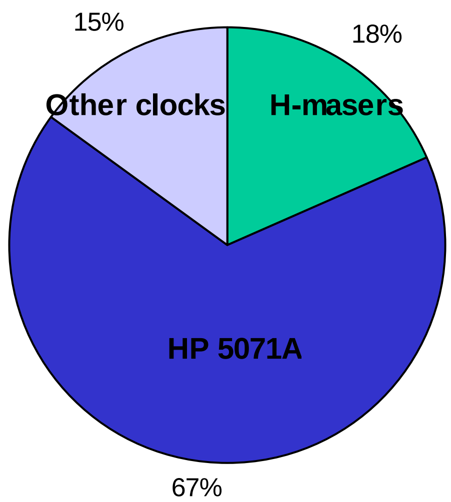
  - Establishing a strategy for calculation (CCTF WG on TAI)
  - Monitoring the behavior of the participating clocks (400)
  - Interacting with other organizations competent in time metrology or related (IGS, IAG, IAU, ITU, IERS, etc)

- Dissemination of results

  - Monthly by *Circular T* and key comparison in time CCTF-K001.UTC
  - Annual Report on time activities
  - Internet

Clocks (cont.)

Participating clocks 2007



2006

ω_{max} = 2.5 / N

12% of clocks

15% of HP5071A

8% of H-masers

σ_{min}= 6x10-15

1999

ω_{max} = 0.700%

55% of clocks

65% of HP5071A

42% of H-masers

σ_{min}= 16×10^{-15}

Clocks (cont.)

- Clock frequency prediction
  - Random walk frequency modulation

    Typical for commercial Cs clocks for averaging times 20 – 70 days.

    Most probable frequency value for an interval is the value estimated over the previous interval of the same duration.

  - Need to consider modes of frequency prediction for other type of clocks

    H-masers (linear drift)

Improvements in the algorithm

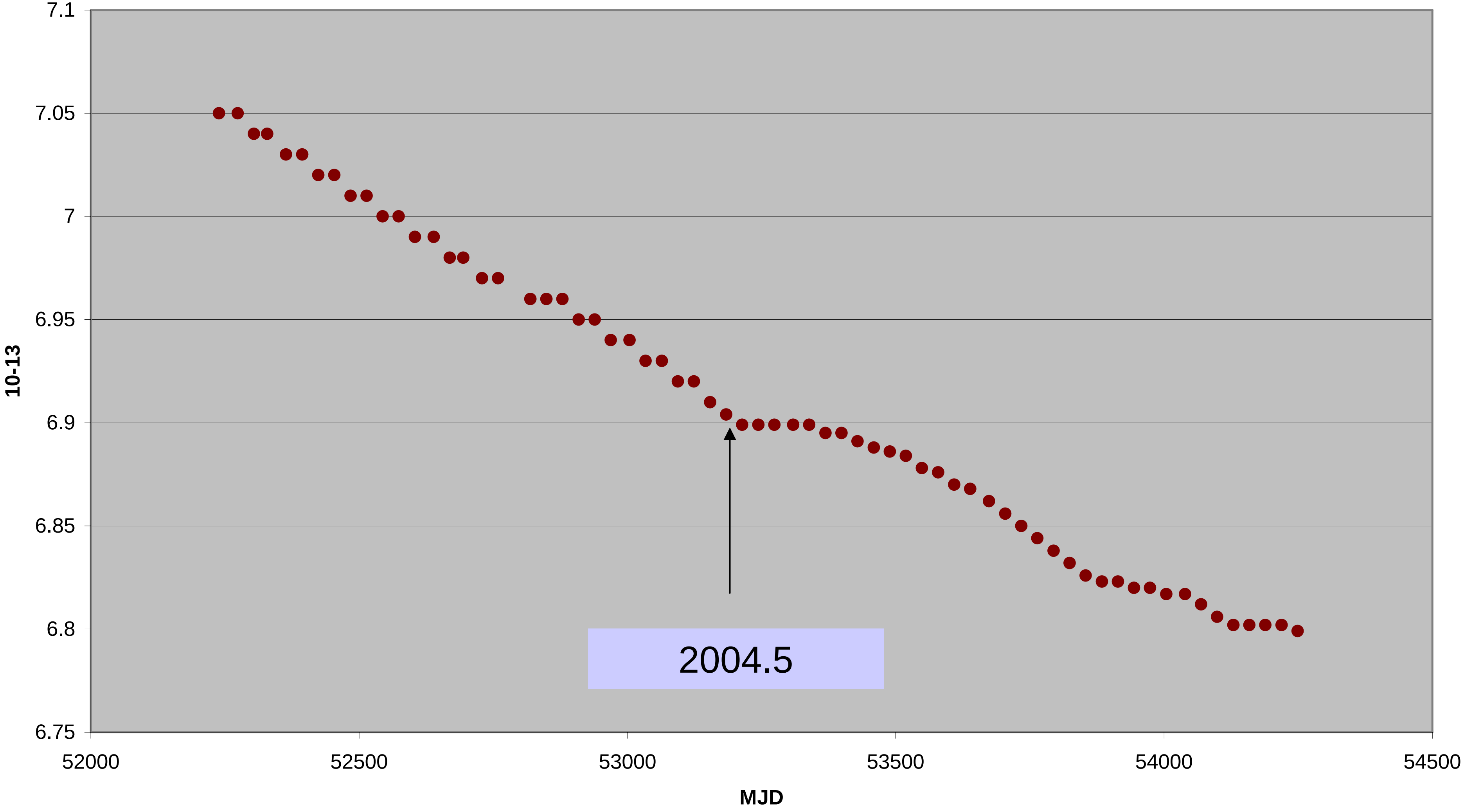
- Frequency steering
  - Change in the frequency offset between TAI and EAL to maintain the accuracy
  - Stability is preserved (frequency fluctuations 1-2×10^{-15})
  - New strategy since 2004.5

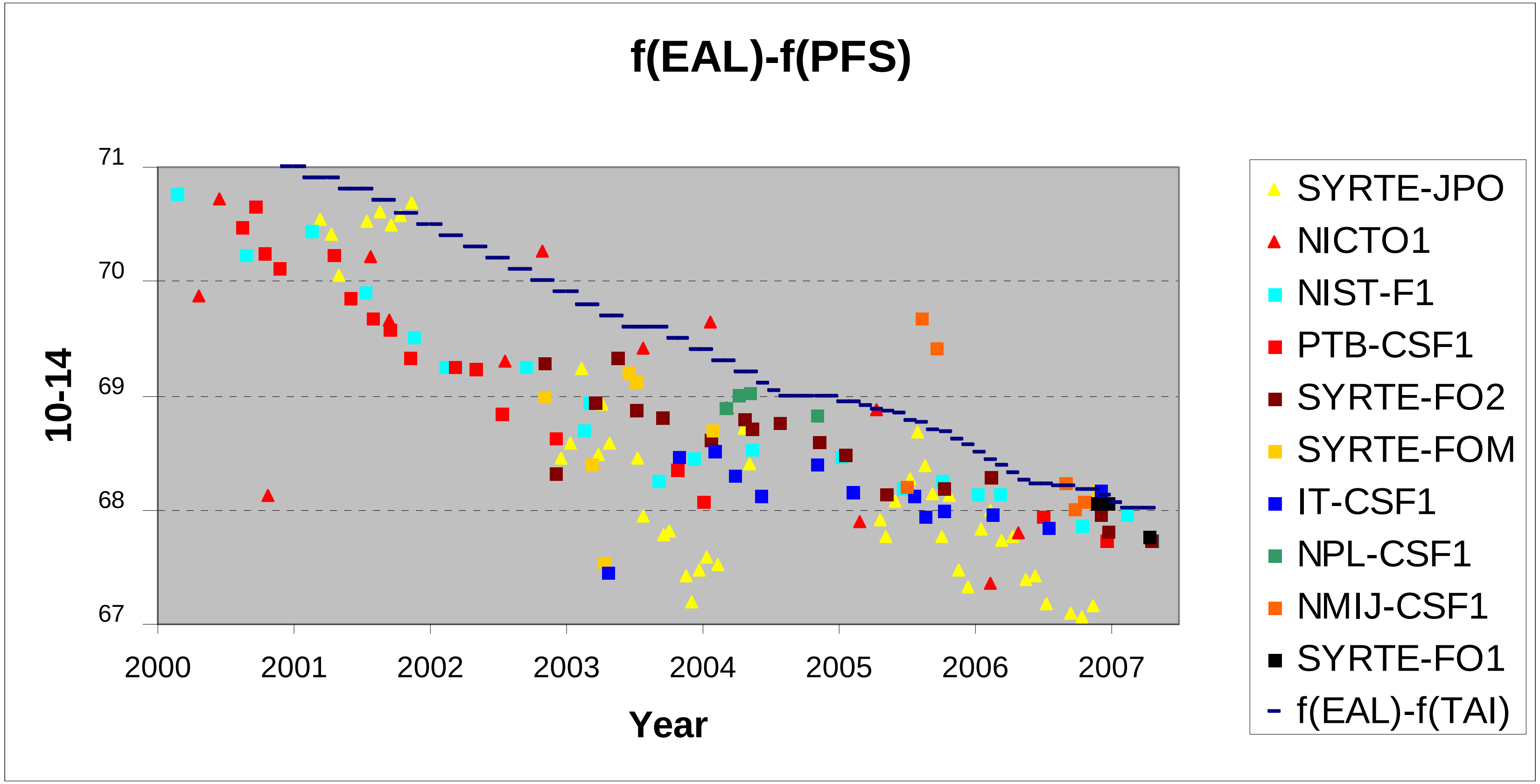
- Frequency correction of 1×10^{-15}, every two months

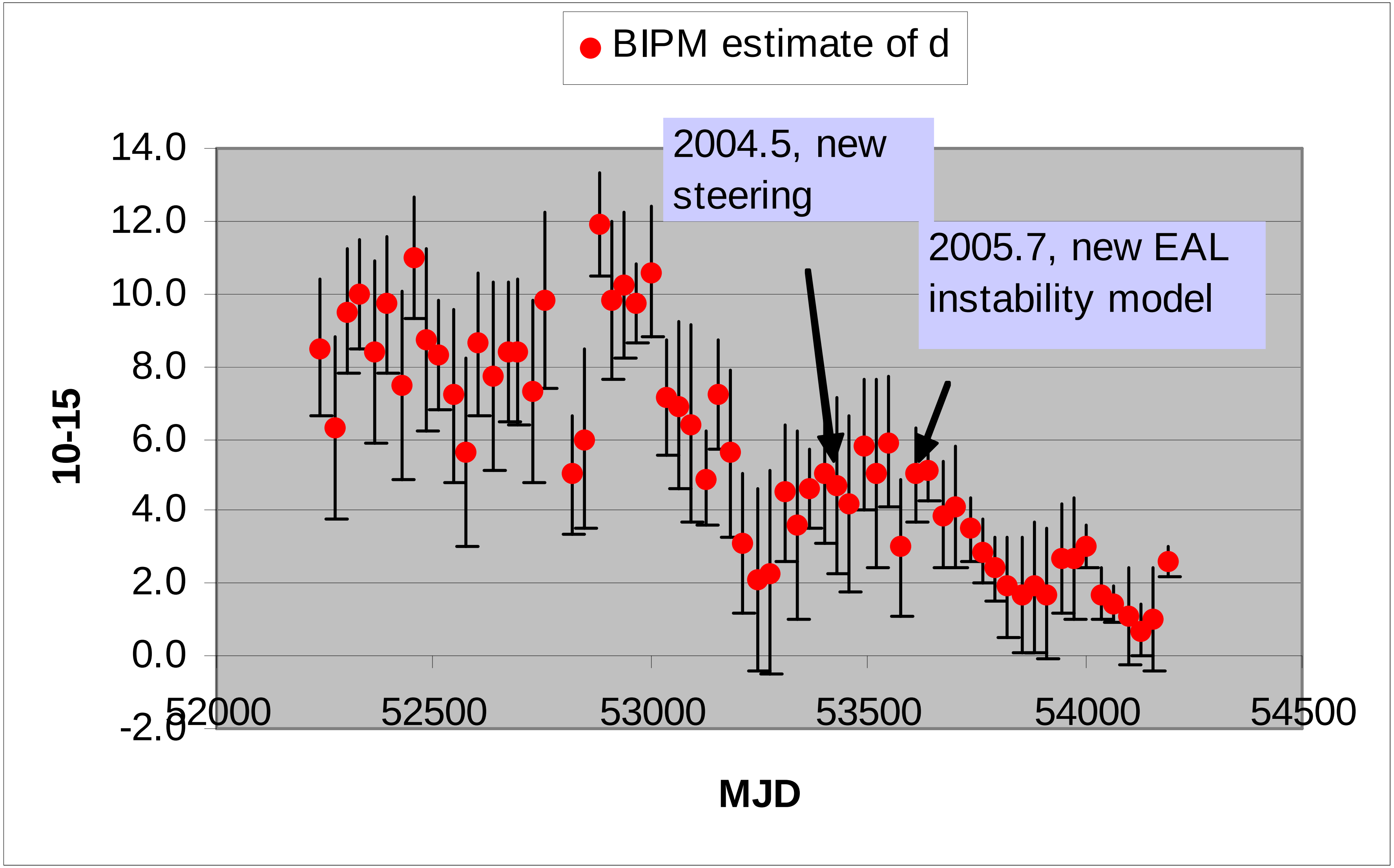
→

- Variable frequency correction up to 0.7×10^{-15}, every month

TAI frequency steering




f(EAL)-f(PFS)
10-14
71
70
69
68
67
2000
2001
2002
2003
2004
2005
2006
2007
Year
SYRTE-JPO
NICTO1
NIST-F1
PTB-CSF1
SYRTE-FO2
SYRTE-FOM
IT-CSF1
NPL-CSF1
NMIJ-CSF1
SYRTE-FO1
f(EAL)-f(TAI)



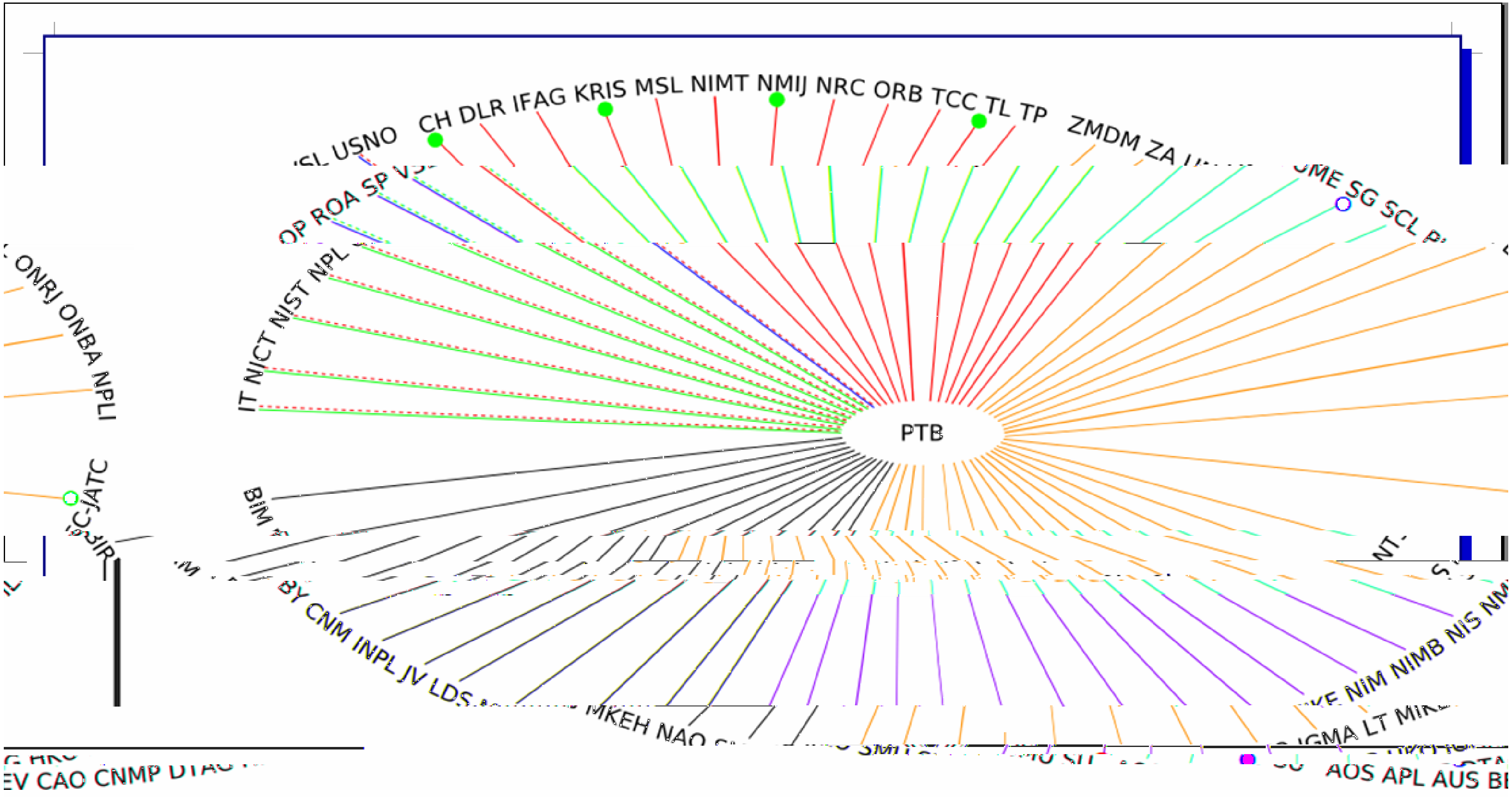
BIPM estimate of d
2004.5, new steering
2005.7, new EAL instability model
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
10-15
52000
52500
53000
53500
54000
54500
MJD

Improvements in the algorithm

- Uncertainty of the link between the PFS and TAI
  - Since February 2004 *Circular T* provides u_A, u_B for time links in TAI
  - Since January 2005 *Circular T* provides u_A, u_B for [*UTC*-*UTC*(*k*)]

- The expression for the fractional frequency transfer uncertainty of a PFS reporting an evaluation into TAI has been updated since September 2006, using the uncertainties for [*UTC*-*UTC*(*k*)]

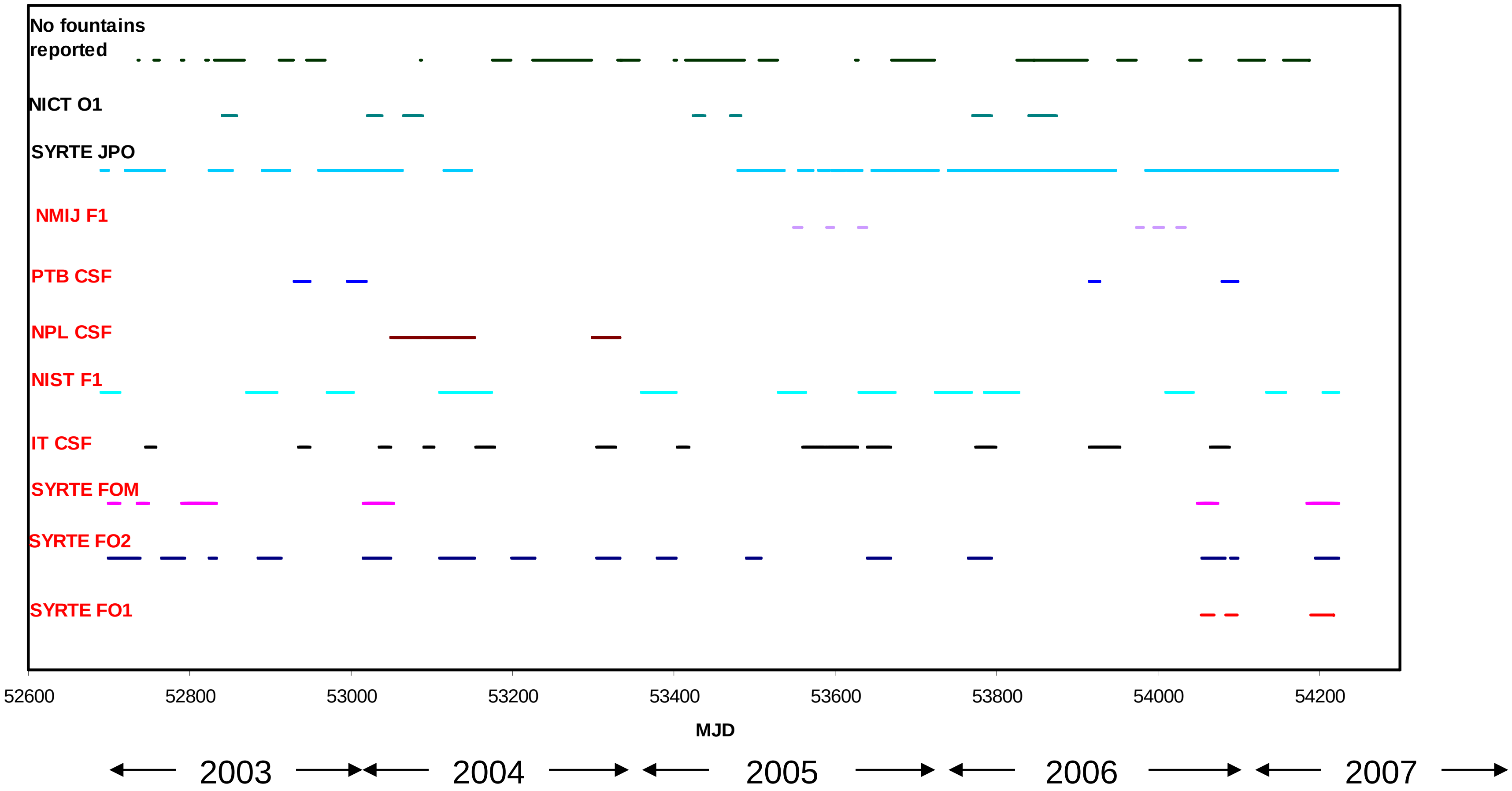
$$u_{l/TAI} = 3x10^{-14}/\tau \quad \longrightarrow \quad u_{l/TAI} = \left(\frac{\sqrt{u_A(k)_1^2 + u_A(k)_2^2}}{86400 \cdot \tau_0} \right) \Bigg/ \left(\frac{\tau}{\tau_o} \right)^x$$

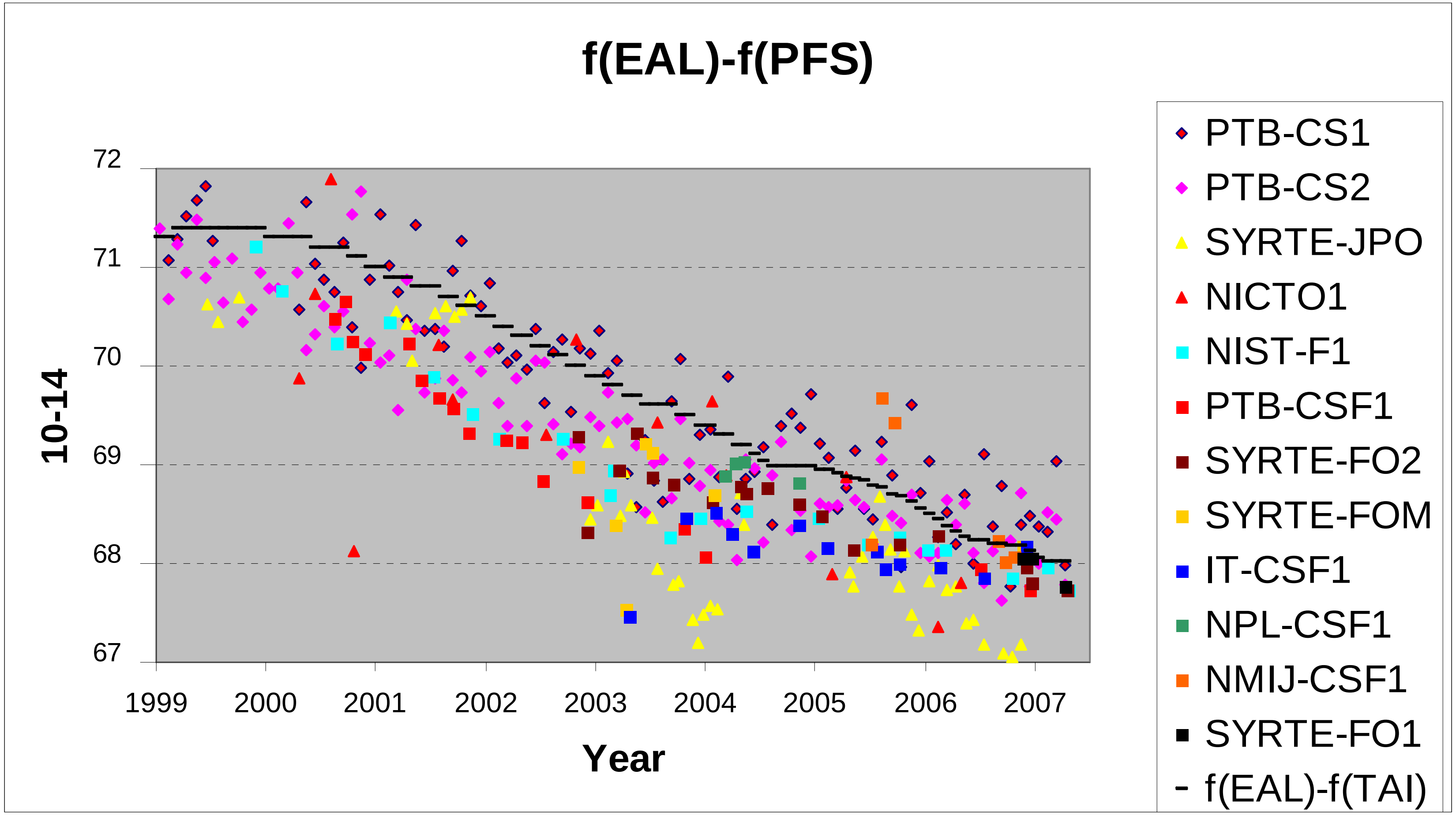


Laboratory equipped with TWSTFT (not yet used)	
TWSTFT by Ku band with X band back-up	GPS AV multi-channel link
TWSTFT link	GPS AV multi-channel back-up link
GPS AV single-channel link	GPS AV dual frequency link
GPS AV single-channel back-up link	GPS AV dual frequency back-up link

BIPM

Intervals of evaluation of PFS reported for TAI since January 2003





f(EAL)-f(PFS)
72
71
70
69
68
67
10-14
1999
2000
2001
2002
2003
2004
2005
2006
2007
Year
PTB-CS1
PTB-CS2
SYRTE-JPO
NICTO1
NIST-F1
PTB-CSF1
SYRTE-FO2
SYRTE-FOM
IT-CSF1
NPL-CSF1
NMIJ-CSF1
SYRTE-FO1
f(EAL)-f(TAI)

BRIEF HISTORY OF THE METRE CONVENTION

The Metre Convention and the SI

- 1889 - CGPM sanctions the international prototypes for the **metre** and the **kilogram**. Together with the astronomical **second** as unit of time, these units constituted the basis of the present unit system.
- 1954 - the introduction of the **ampere**, the **kelvin** and the **candela** as base units is approved by the CGPM.
- 1960 - the CGPM names the unit system as the **International System of Units (SI)**
- 1971 - the CGPM adds the **mole** as the unit for amount of substance, bringing the total number of base units to seven.