

## *International time scales*

### *Atomic standards*

*E.F. Arias*

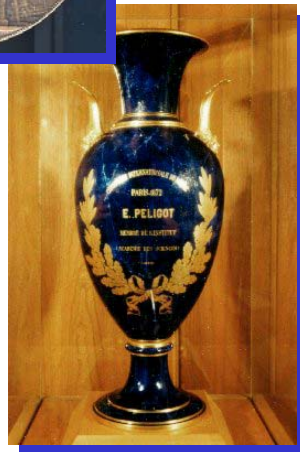


International Committee for GNSS, 2<sup>nd</sup> Meeting  
Meeting of GNSS experts  
Bangalore, 5 September 2007

# 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

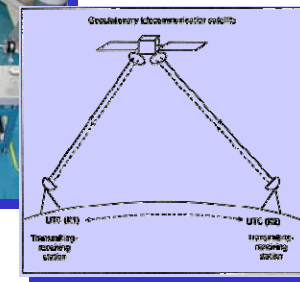
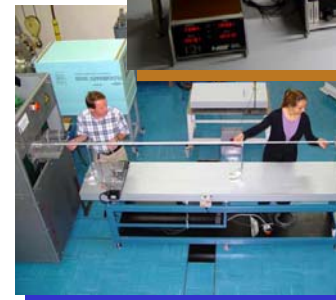
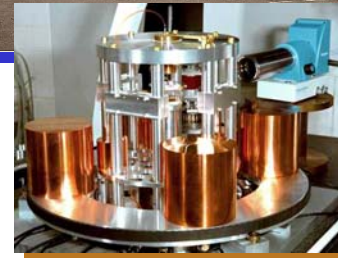
## The BIPM

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**.

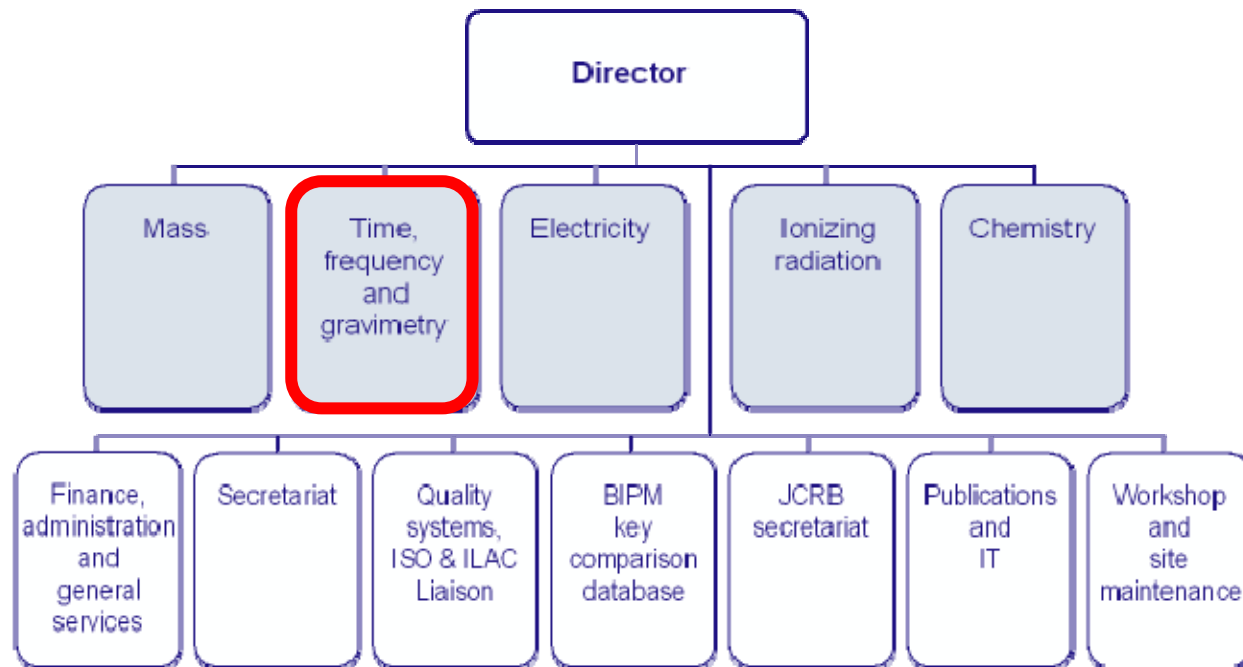
Its **mandate** is to provide the basis for a single, coherent system of measurements throughout the world, traceable to the International System of Units (SI). This task takes many forms, from **direct dissemination** of units (as in the case of mass and time) to coordination through **international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



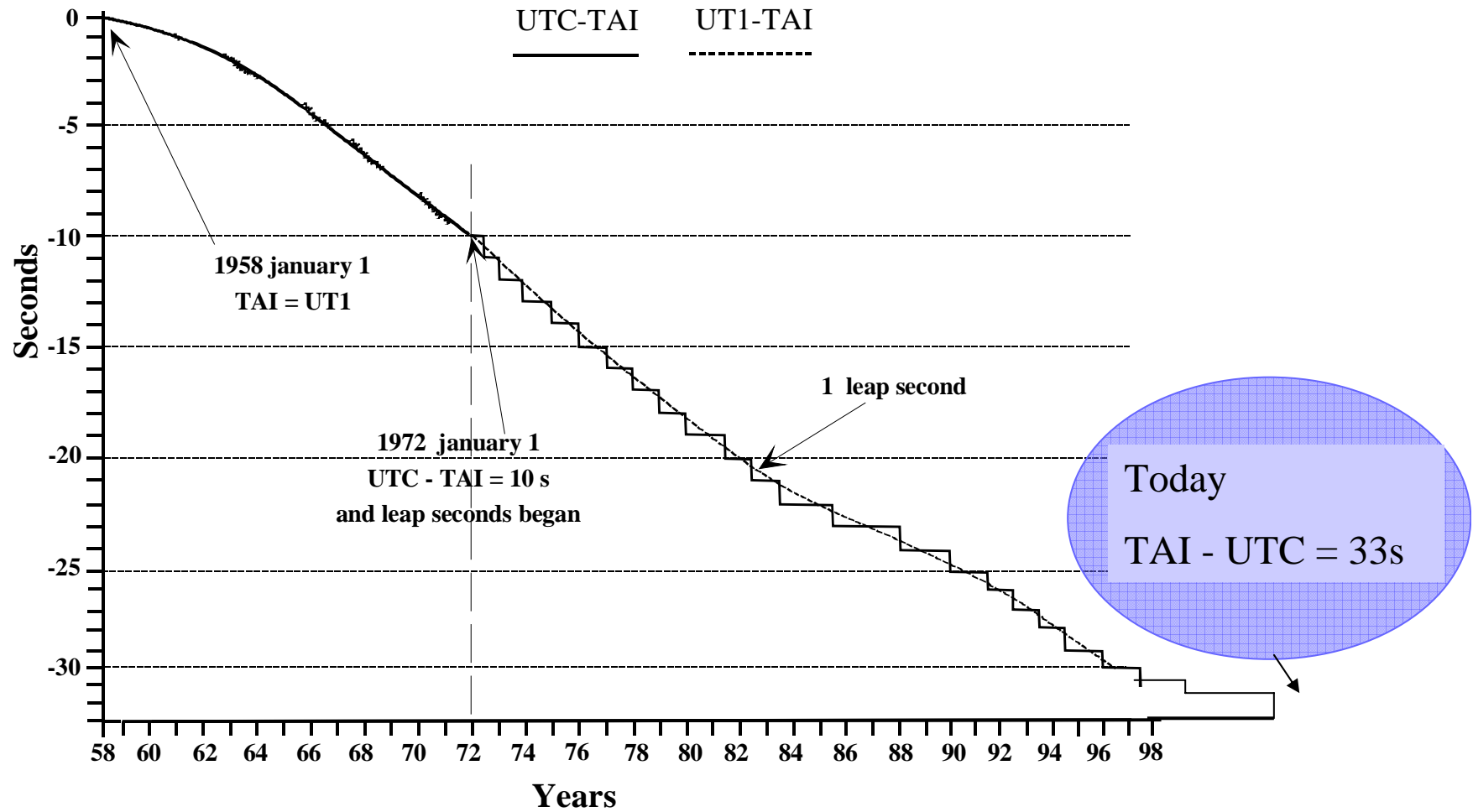
## INTERNATIONAL ATOMIC TIME TAI

- ✓ Atomic scale (14<sup>th</sup> CGPM, 1971)
- ✓ Continuous
- ✓ Calculated in post-real time at the BIPM (~10 days after the last date of data)
- ✓ Frequency stability ( $0.5 \times 10^{-15}$  @40 days)
- ✓ Unit: SI second
- ✓ Frequency accuracy ( $\sim 10^{-15}$ )
  
- ~~✓ Clocks~~
- ~~✓ Time signals~~
- ~~✓ Legality~~
  
- ✓ Frequency reference

## COORDINATED UNIVERSAL TIME UTC

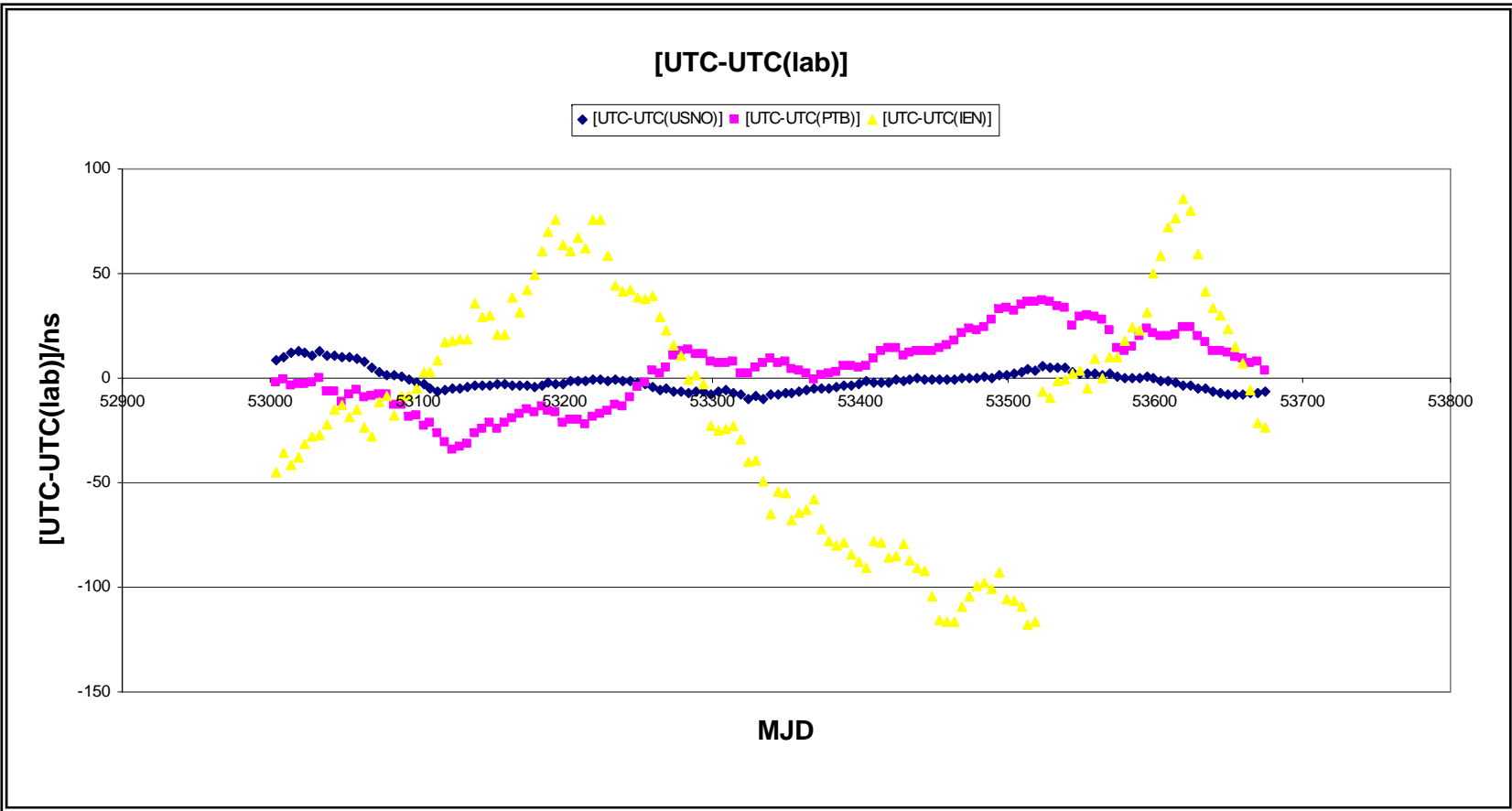
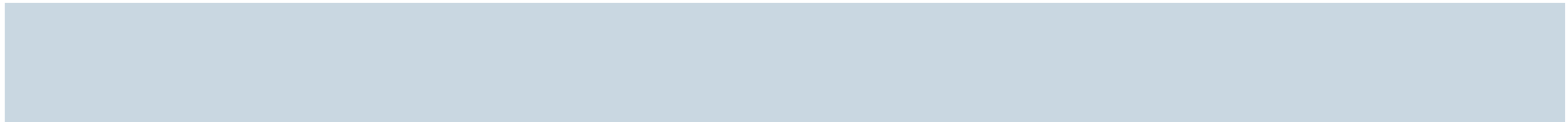
- ✓ Atomic time scale (ITU-R, Rec. 460, 1970; 460-1, 1974)
- ✓ Continuous with one-second steps at irregular intervals (leap second)
- ✓ Differs from TAI in an integer number of seconds (33 s at present)
- ✓ Represents UT1 within 0.9 s
- ✓ Post-processed (~10 days after last date of data)
- ✓ Unit is 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

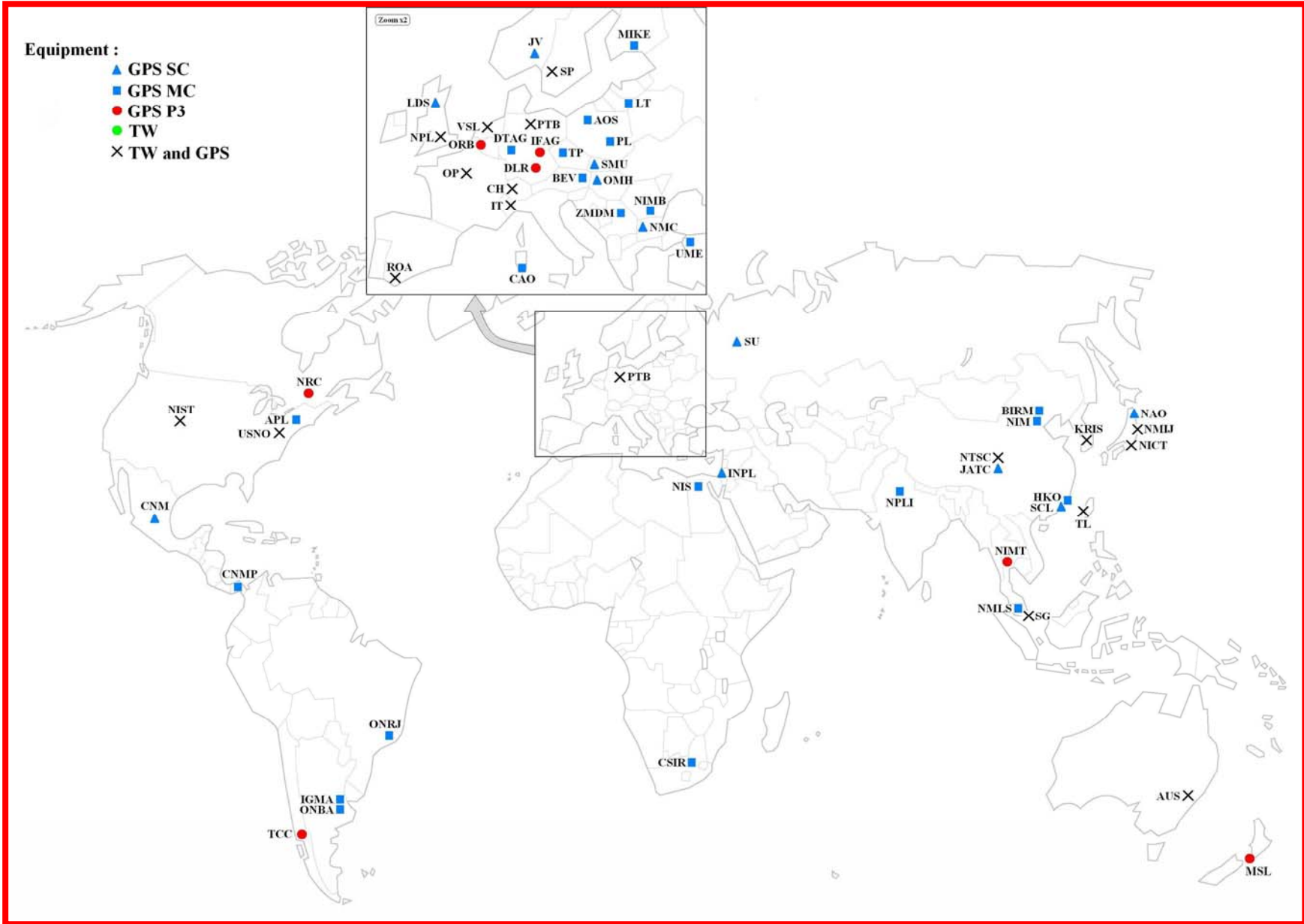
# UTC and leap seconds



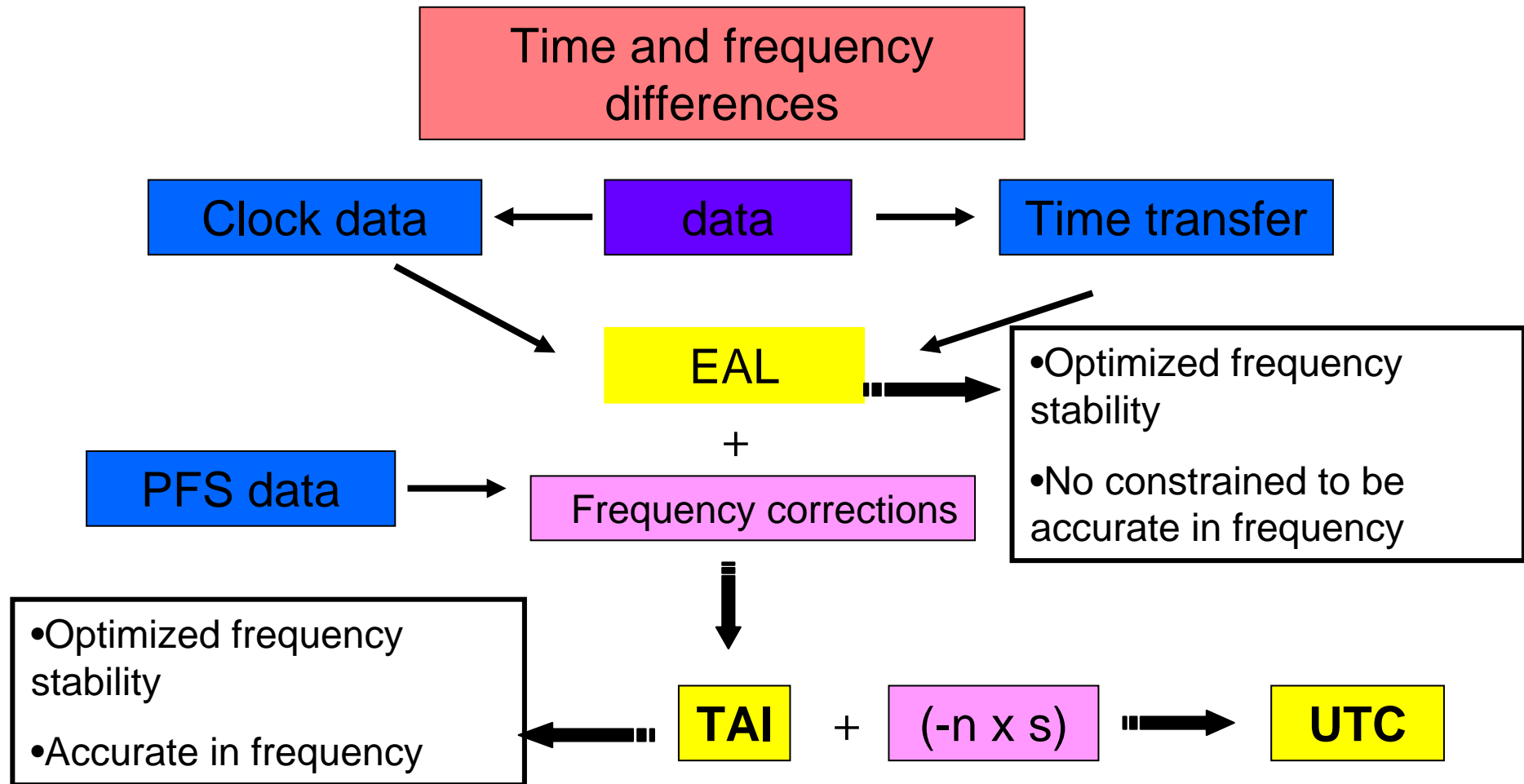
## PHYSICAL REPRESENTATIONS OF UTC

- 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 represented by a clock (eventually plus a microphase-stepper)
  - ✓ Some UTC(k) are evaluated from a clock ensemble





# ALGOS (algorithm for calculation)





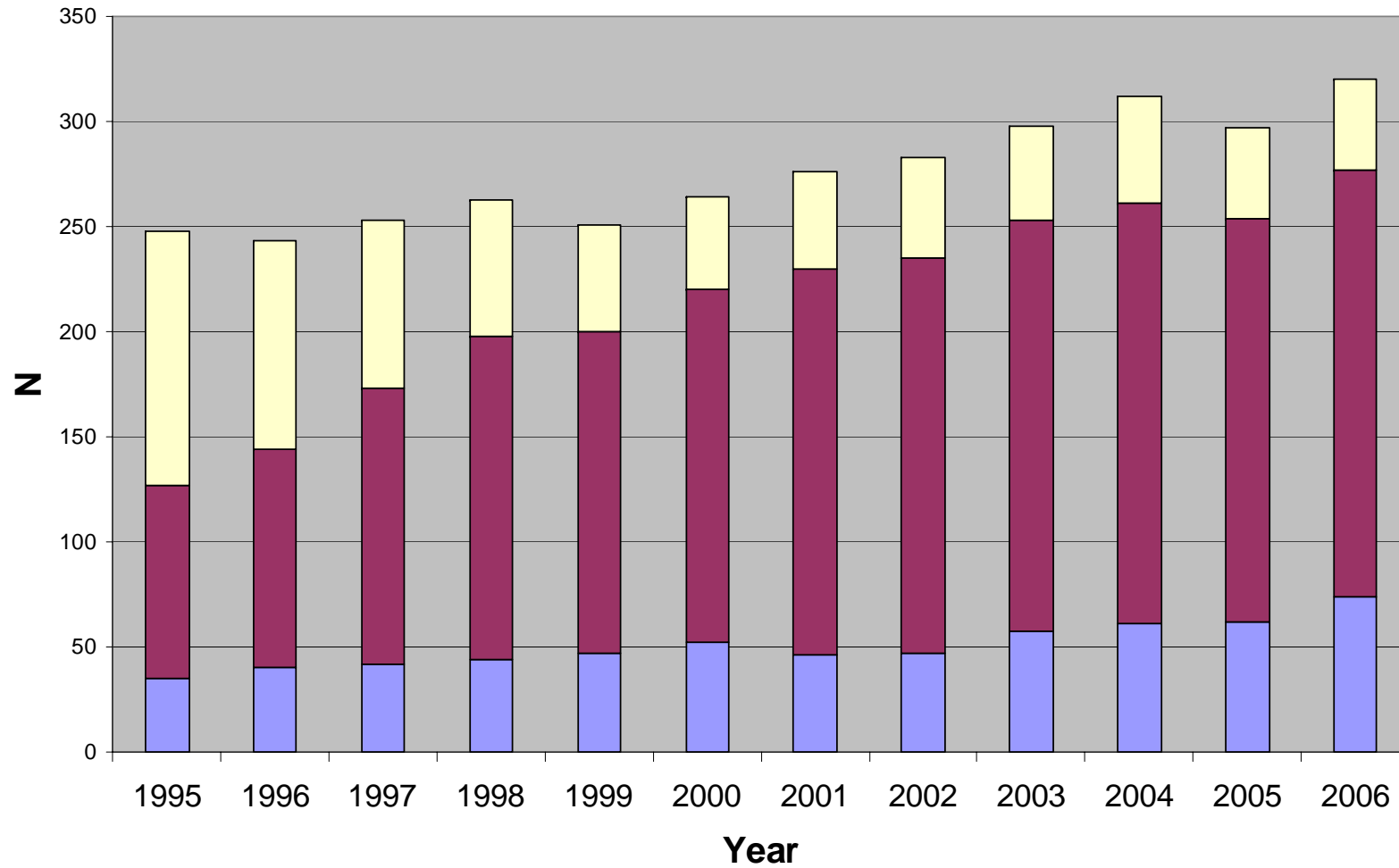
# ATOMIC STANDARDS – INDUSTRIAL CLOCKS

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



# CLOCKS CONTRIBUTING TO TAI/UTC

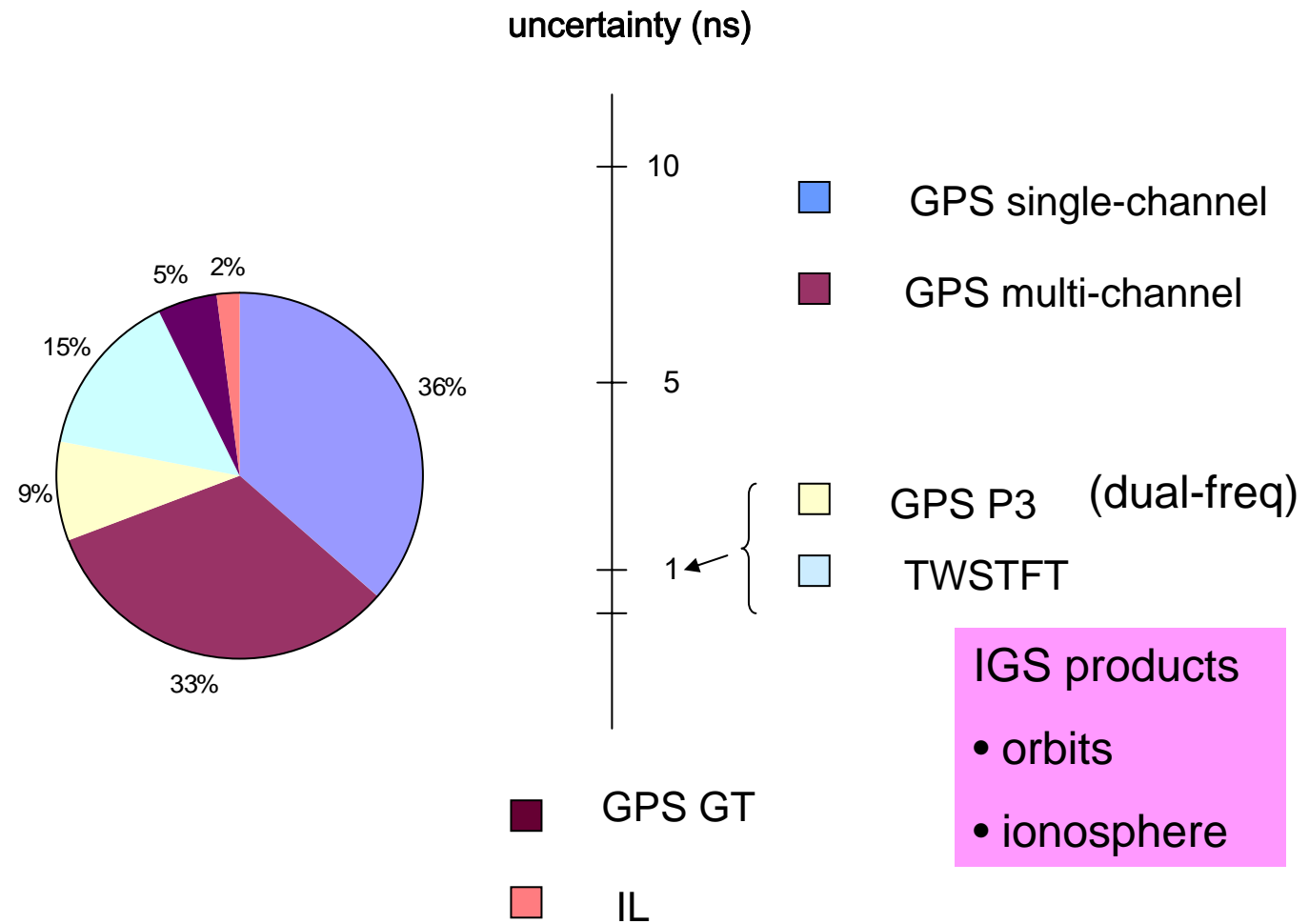
■ H-maser ■ 5071A ■ Other clocks

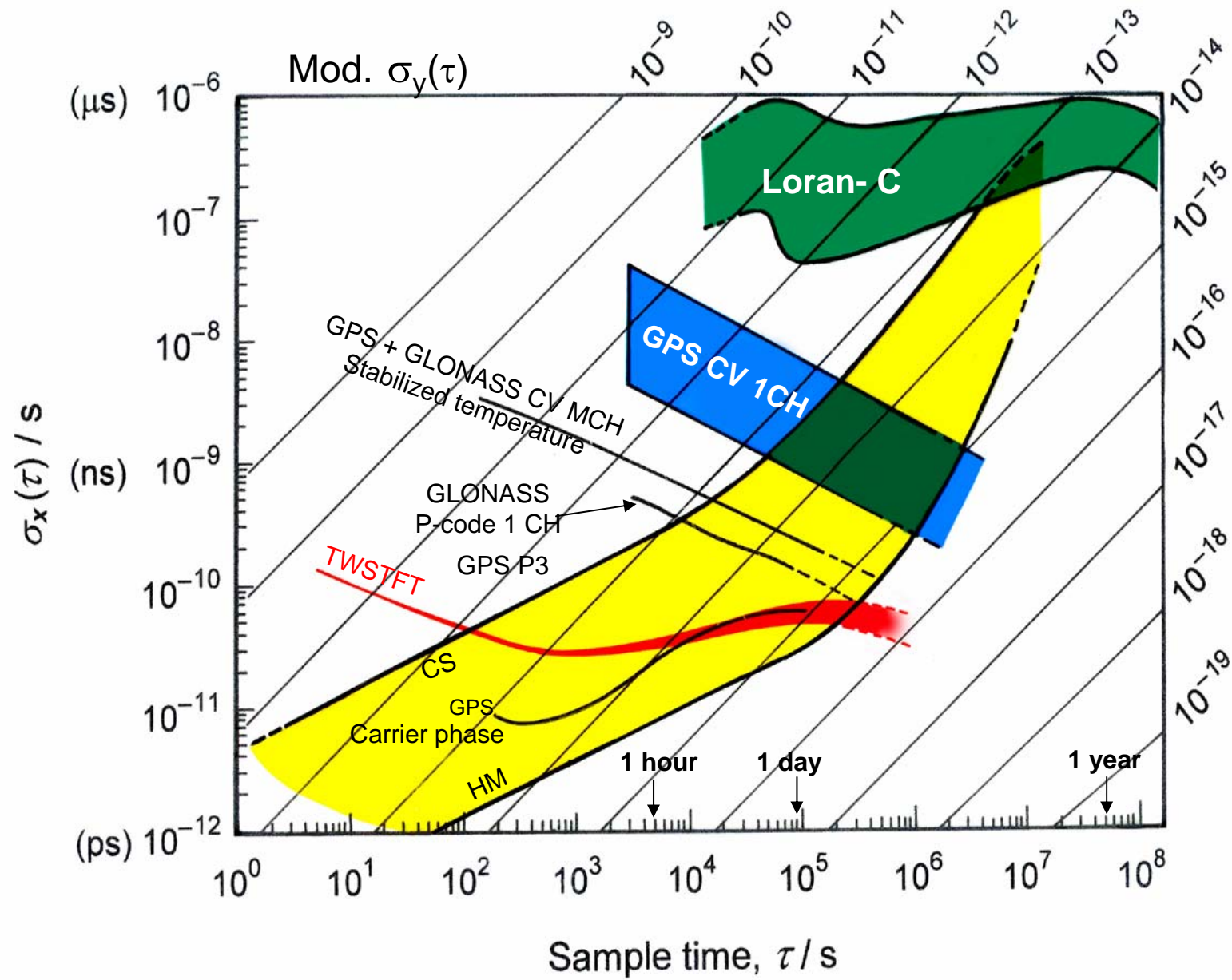


## CLOCK COMPARISON

- 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

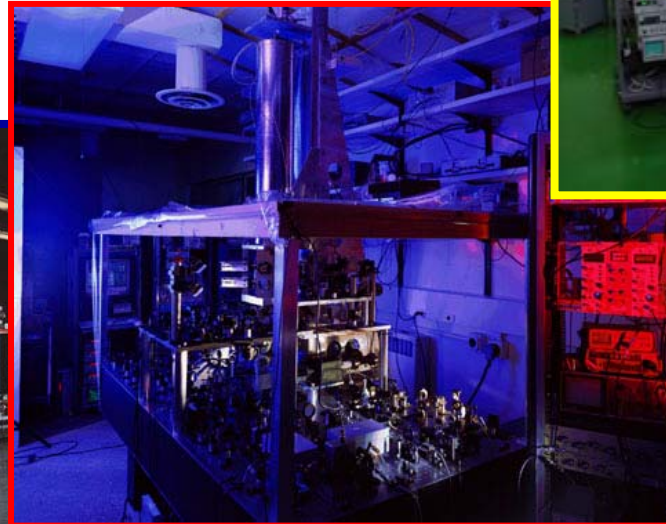
# SATELLITE CLOCK COMPARISON





# PRIMARY FREQUENCY STANDARDS

- 11 regularly reporting measurements to BIPM
  - from 6 time metrology laboratories
- 7 are Caesium fountains
  - frequency accuracy 0.5 to  $4 \times 10^{-15}$
- 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 to 0.8) $\times 10^{-15}$	Discontinuous	H maser	3 / 20 to 35 d
NICT-O1	Beam /Opt.	$6 \times 10^{-15}$	Discontinuous	UTC(NICT)	2 / 20 to 30 d
NIST-F1	Fountain	$0.3 \times 10^{-15}$	Discontinuous	H maser	3 / 30 to 40 d
NMIJ-F1	Fountain	$4 \times 10^{-15}$	Discontinuous	H maser	3 / 10 to 15 d
PTB-CS1	Beam /Mag.	$8 \times 10^{-15}$	Continuous	TAI	12 / 30 d
PTB-CS2	Beam /Mag.	$12 \times 10^{-15}$	Continuous	TAI	12 / 30 d
PTB-CSF1	Fountain	$1.1 \times 10^{-15}$	Discontinuous	H maser	2 / 10 to 15 d
SYRTE-FO1	Fountain	$0.4 \times 10^{-15}$	Discontinuous	H maser	2 / 15 d
SYRTE-FO2	Fountain	$0.4 \times 10^{-15}$	Discontinuous	H maser	3 / 5 to 15 d
SYRTE-FOM	Fountain	$1.2 \times 10^{-15}$	Discontinuous	H maser	1 / 15 d
SYRTE-JPO	Beam /Opt.	$6 \times 10^{-15}$	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

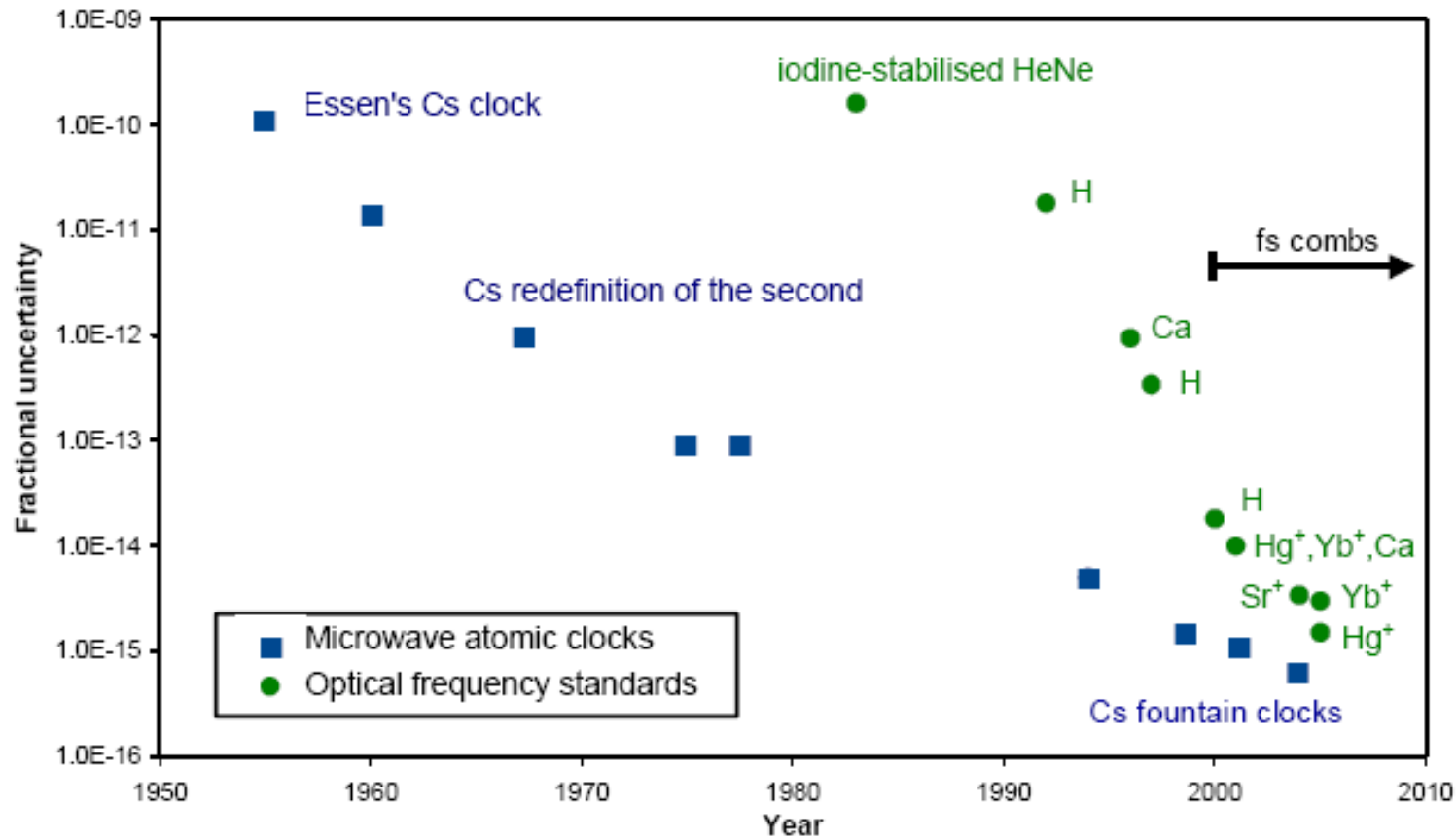


Figure 1: Improvements in atomic frequency standards

Gill & Riehle 2006

# SECONDARY REPRESENTATIONS OF THE SECOND

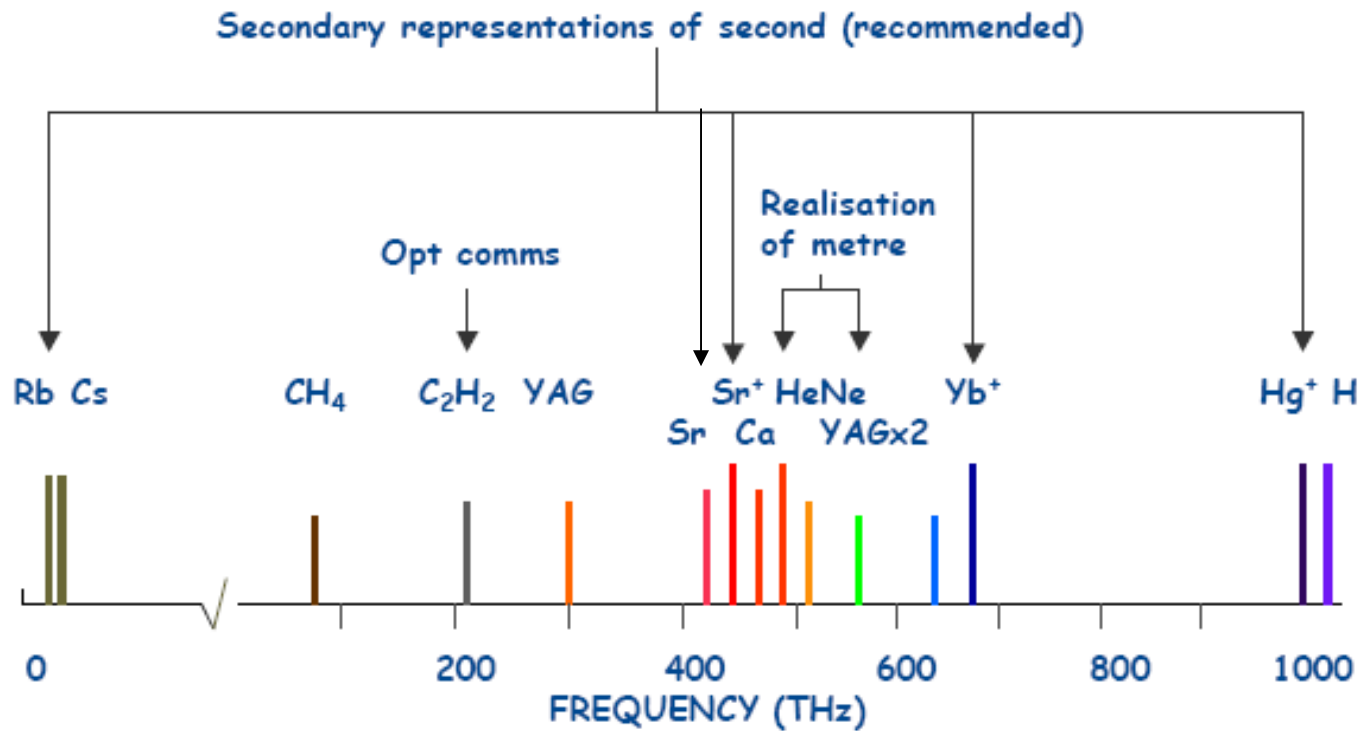


Figure 2: Example of a unified list of recommended radiations

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 dramatically 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 worldwide 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

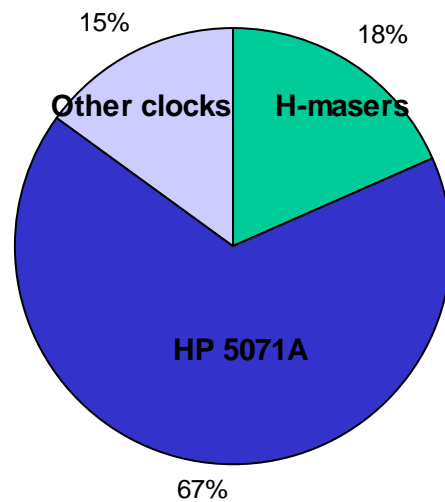
- Data provision
  - Fixing formats (CCTF WGGTTS) and deadlines for submission
  - Establishing protocols for reporting data of primary frequency standards (CCTF WG on PFS)
  - Coordinating data acquisition in the 59 participating laboratories, i.e. date for the data, equipment, observations (CCTF WG 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**

$$\omega_{\max} = 2.5 / N$$

12% of clocks

15% of HP5071A

8% of H-masers

$$\sigma_{\min} = 6 \times 10^{-15}$$

**1999**

$$\omega_{\max} = 0.700\%$$

55% of clocks

65% of HP5071A

42% of H-masers

$$\sigma_{\min} = 16 \times 10^{-15}$$

## 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

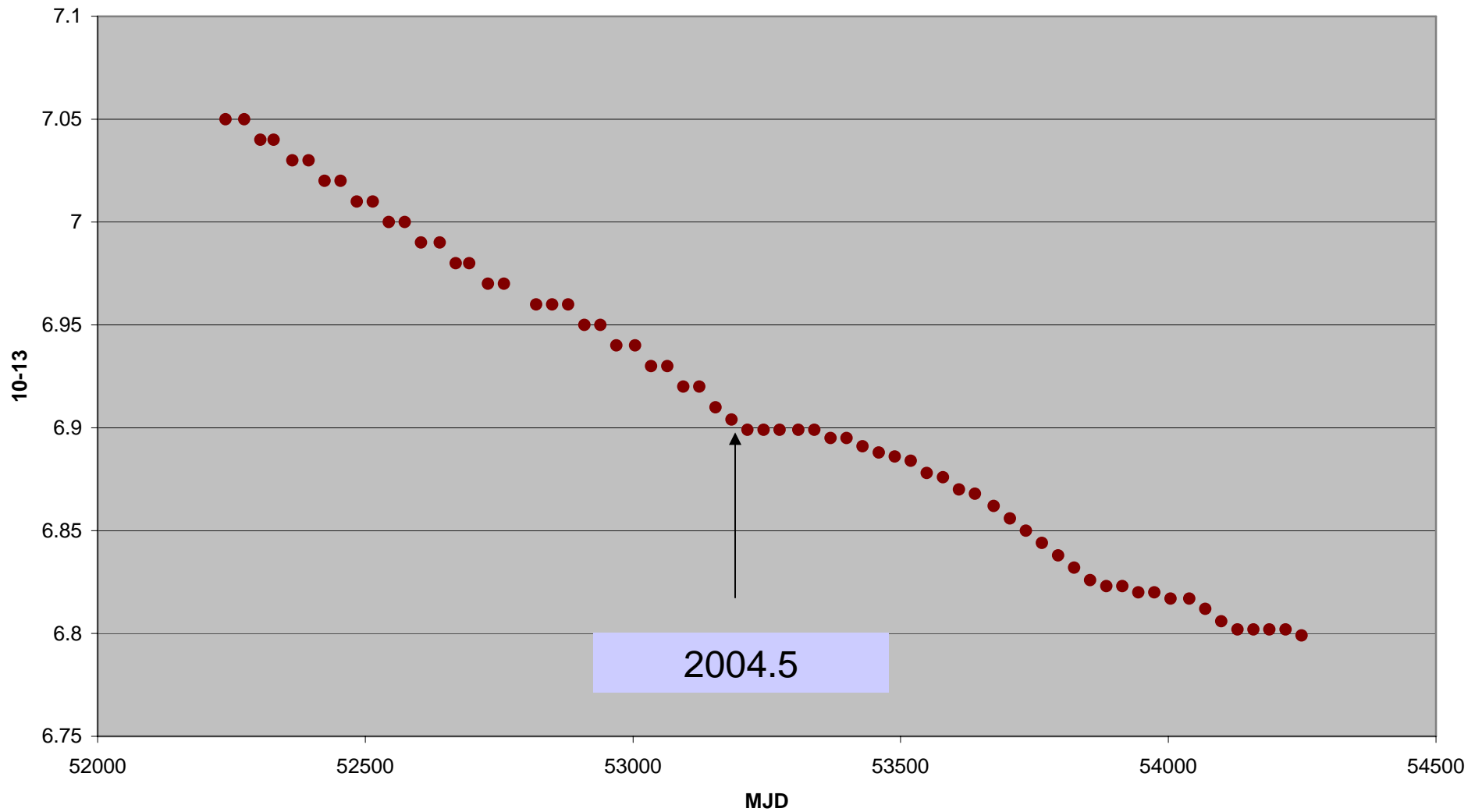
- Change in the frequency offset between TAI and EAL to maintain the accuracy
- Stability is preserved (frequency fluctuations  $1-2 \times 10^{-15}$ )
- New strategy since 2004.5

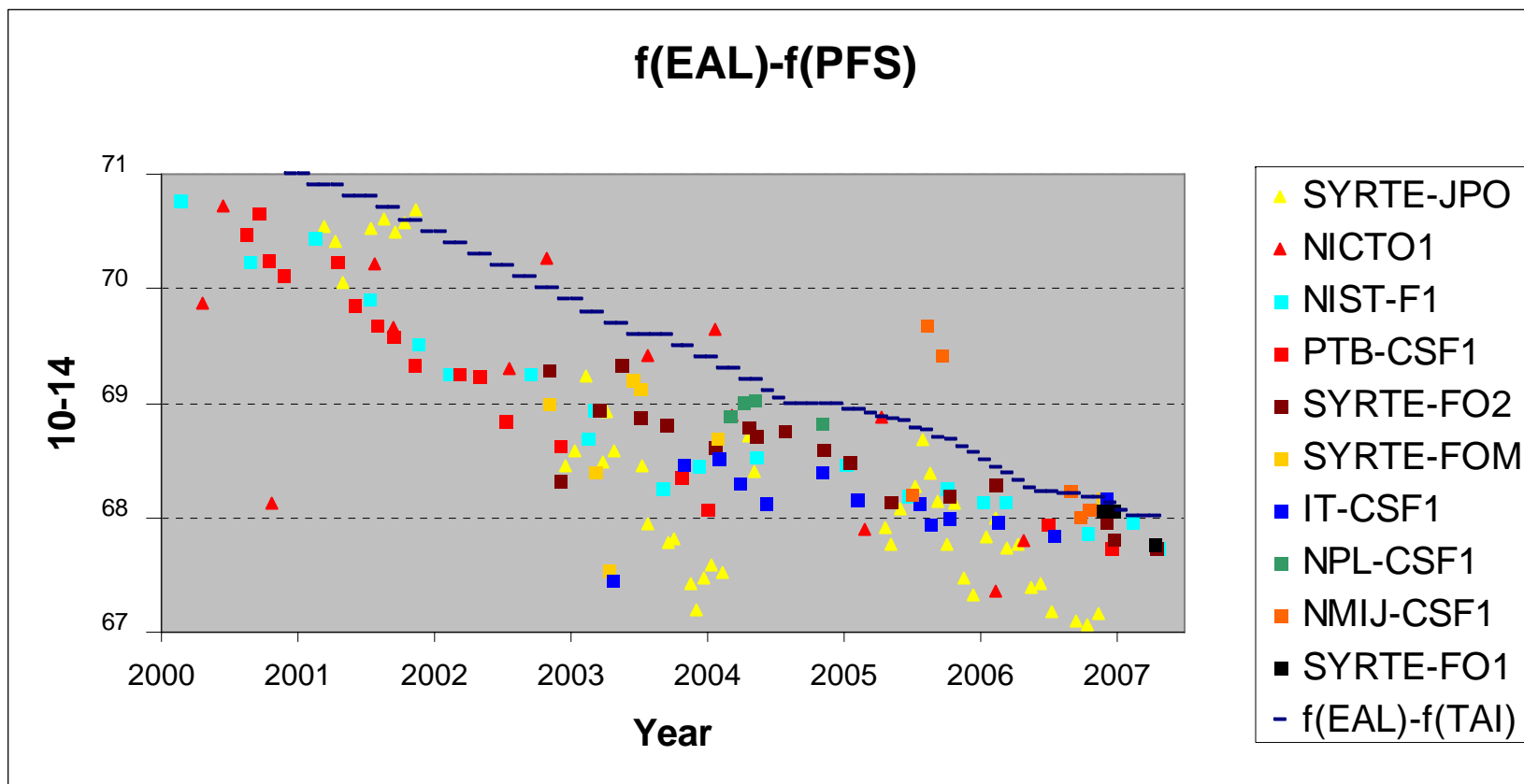
•Frequency correction of  $1 \times 10^{-15}$ , every two months

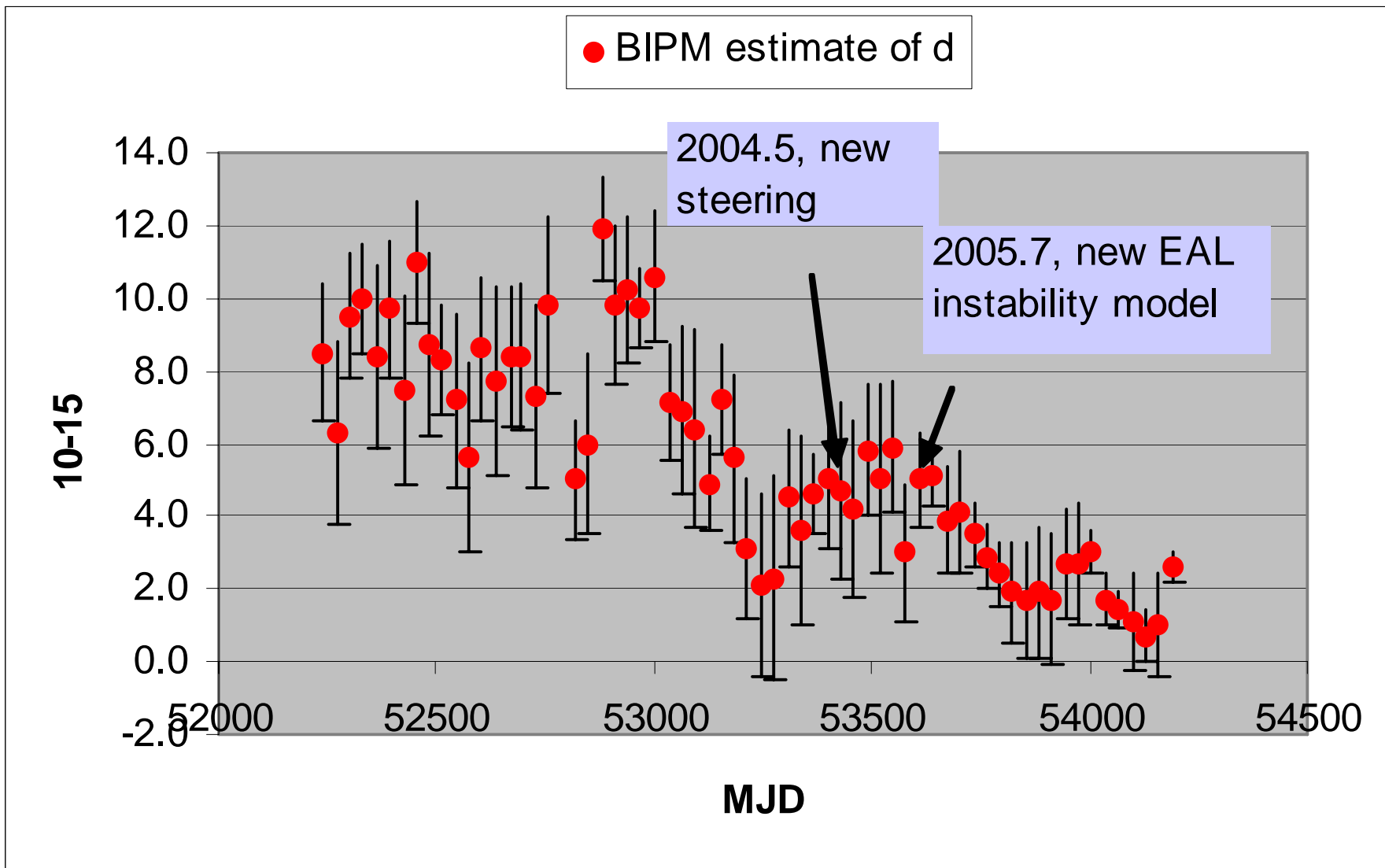
•Variable frequency correction up to  $0.7 \times 10^{-15}$ , every month



# TAI frequency steering









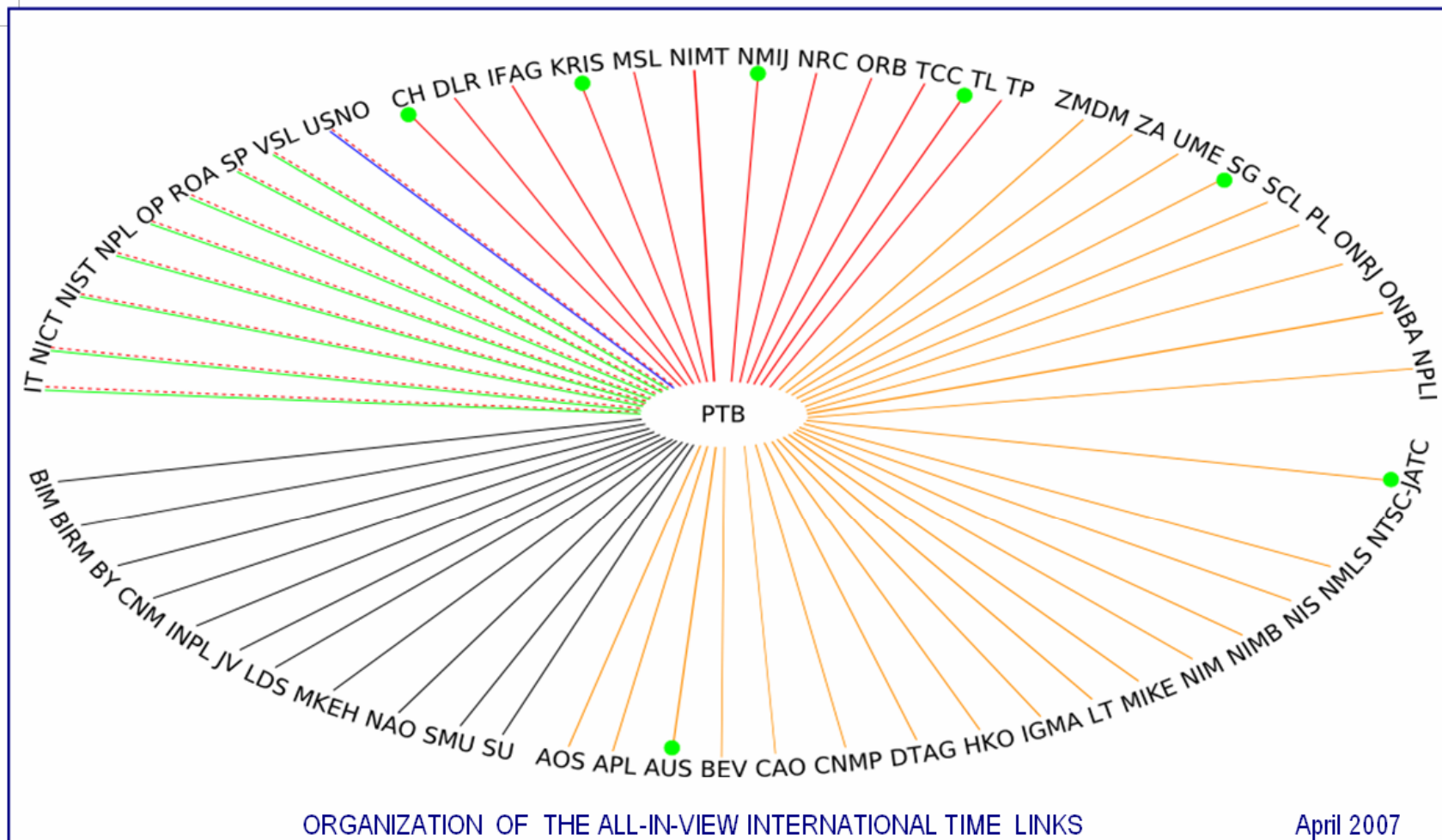
# Improvements in the algorithm


- 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  $[UTC-UTC(k)]$

$$u_{l/TAI} = 3 \times 10^{-14} / \tau$$

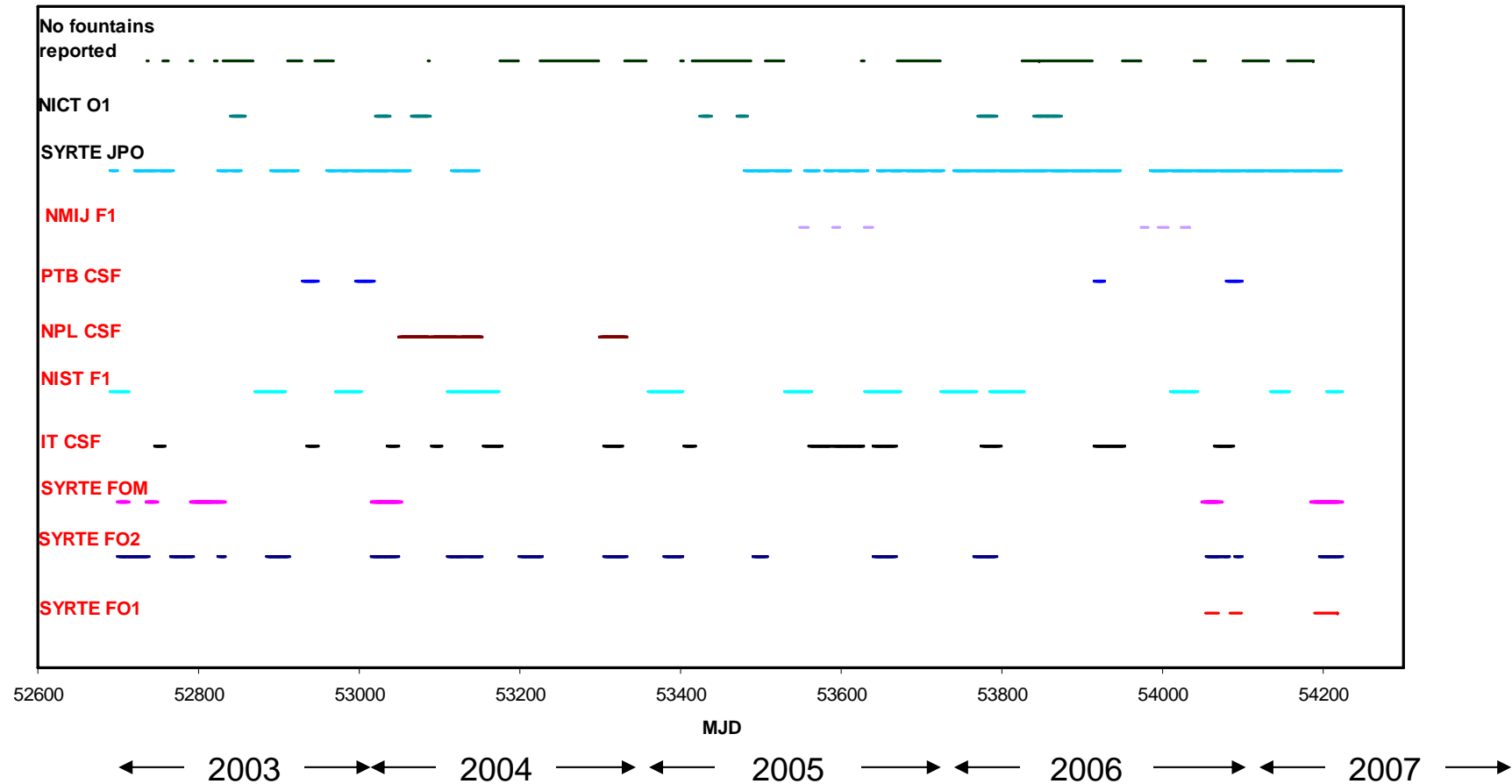


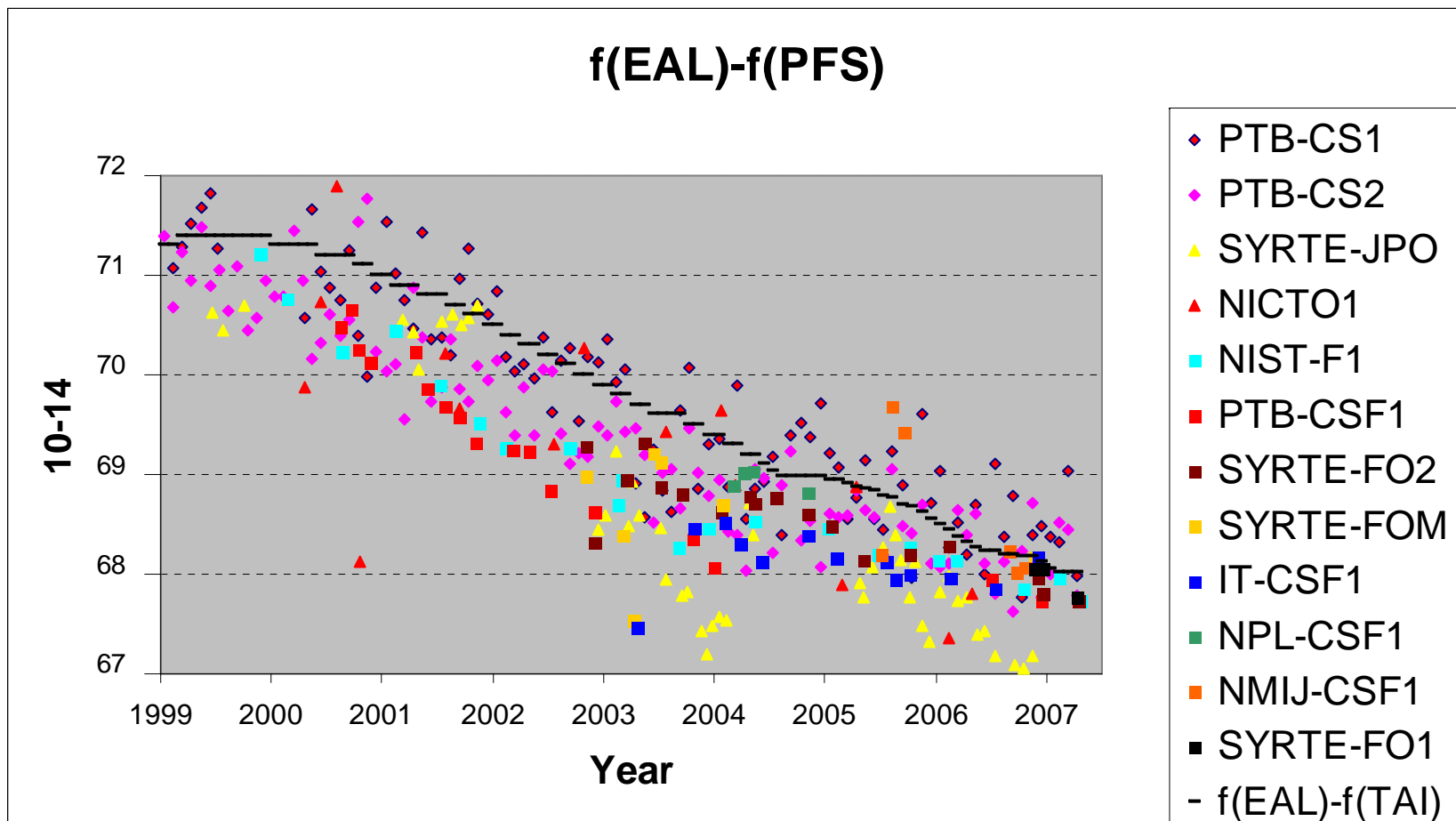
$$u_{l/TAI} = \left( \frac{\sqrt{u_A(k)_1^2 + u_A(k)_2^2}}{86400 \cdot \tau_0} \right) / \left( \frac{\tau}{\tau_0} \right)^x$$



●	Laboratory equipped with TWSTFT (not yet used)			 <b>BIPM</b>
— (blue)	TWSTFT by Ku band with X band back-up	— (orange)	GPS AV multi-channel link	
— (green)	TWSTFT link	- - - (orange)	GPS AV multi-channel back-up link	
— (black)	GPS AV single-channel link	— (red)	GPS AV dual frequency link	
- - - (black)	GPS AV single-channel back-up link	- - - (red)	GPS AV dual frequency back-up link	

# Intervals of evaluation of PFS reported for TAI since January 2003





# 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.

