Considerations for International Timekeeping

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- International coordination in measurements
  - the BIPM and the Metre Convention
- Unification of time
- International time scales: TAI and UTC
- Establishment of the time scales at the BIPM
- Applications and impact

Why international coordination in measurements?

- benefits from international uniformity of measurement systems;
- non-uniformity in measurements has been recognized as one of the mayor barriers to trade;
- agreement on the definition and realization of units;
- establishment of national standards of demonstrable international equivalence;
- international harmonization of laws and regulations related to metrology.

Fields relying on metrology

- science
- communications and transportation
- surveying and navigation
- enforcement of government regulations
- generation and distribution of energy
- military services
- manufacturing and other industries
- trade and commerce
- health and safety
- environmental protection

BIPM

La Convention du Mètre
The Metre Convention

- Bureau International des Poids et Mesures
  - ensure world-wide unification of physical measurements
- 51 members states, 11 associates to the CGPM
- units
  - 1875 length, mass, time
  - 1946 electric current
  - 1948 thermodynamic temperature, luminous intensity
  - 1960 SI
  - 1971 amount of substance
- BIPM assists the NMIs to establish and maintain national standards which are reliably traceable to primary standards.

Time scales at the BIPM

- Definition of TAI (14th CGPM, 1971), established by the BIH.
- Legal time UTC, with approximations UTC(k) maintained at the national laboratories (15th CGPM, 1975).
- BIPM assumes the responsibility for TAI (1988).
- Linked international organizations
  - International Astronomical Union
  - International Telecommunications Union
  - International Earth Rotation and References Service
  - International Association of Geodesy
  - International Union of Geodesy and Geophysics

Unification of time

- 1884 Greenwich meridian, universal time
  - second: fraction of the rotational day
- 1948 IAU recommends the use of UT
- 1952 dynamical time scale (ET)
  - second: fraction of the tropical year for 1900 Jan. 0, 12h ET
- 1971 International Atomic Time (TAI)
  - second: 9 192 631 770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of Cs 133
- role of clocks

Atomic time (1971)

- Based on an atomic transition.
- Unit is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom.
- The second of atomic time (SI second) is shorter in 1.4 x 10^{-8} s than the second of ET (averaged for year 1960).
- Clocks have no more the solely role of time keepers, they also produce the frequency that realises the second of the SI.

Coordinated Universal Time (UTC)

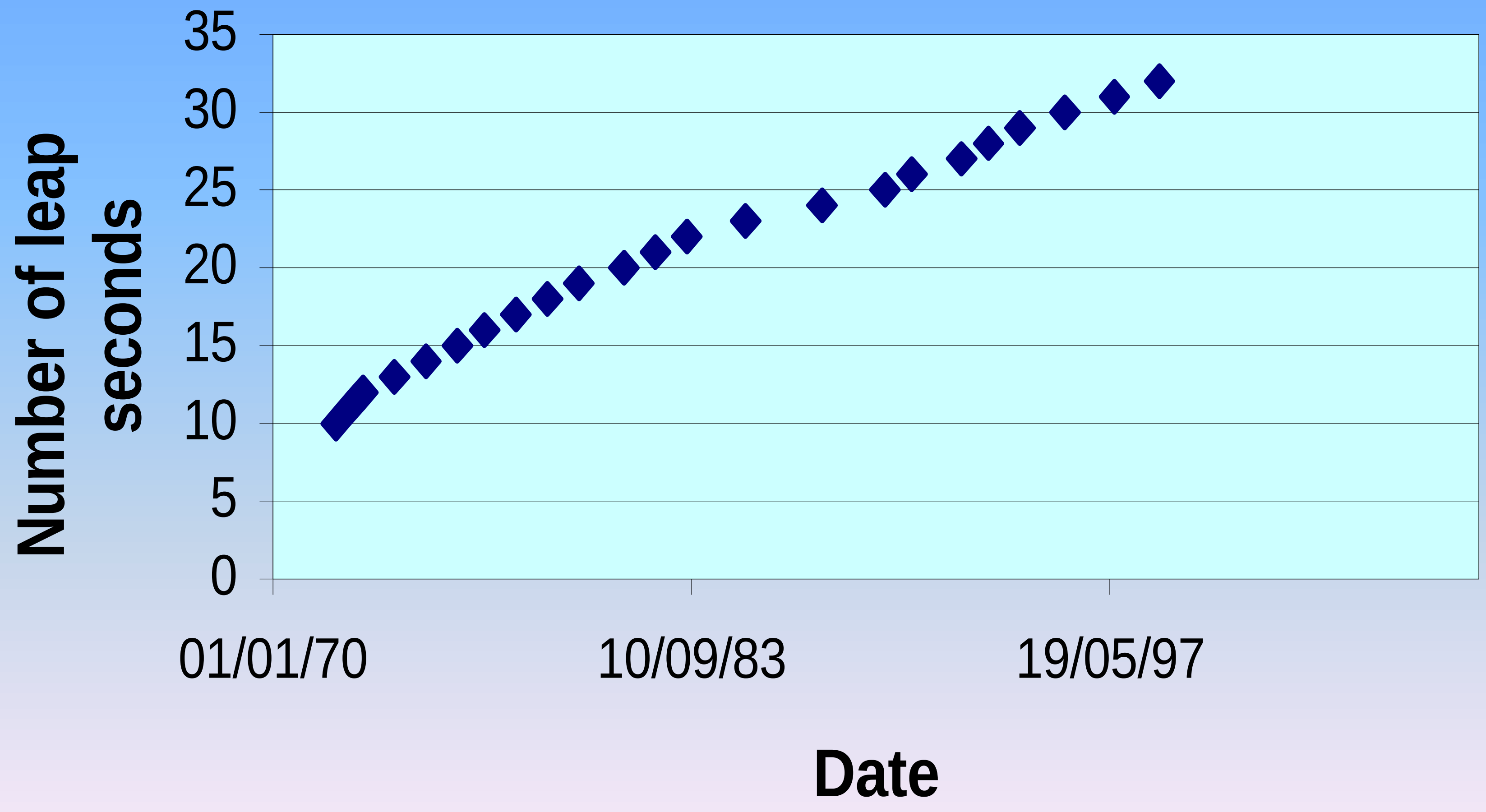
- UTC is the reference time scale for world wide time coordination.
- It serves as the basis of legal times in the different countries.
- UTC is calculated at the BIPM in concertation with the IERS on the basis of readings of clocks in the national laboratories.
- Local realizations of UTC named UTC(k) are broadcast by time signals.

Coordinated Universal Time (UTC)

- Defined to fulfil mainly the need of a time scale somehow related to the rotation of the earth.

- Conceptually identical to TAI but suffering from 1 second time steps (TAI - UTC = 32 s today).

Leap seconds in UTC since 1972

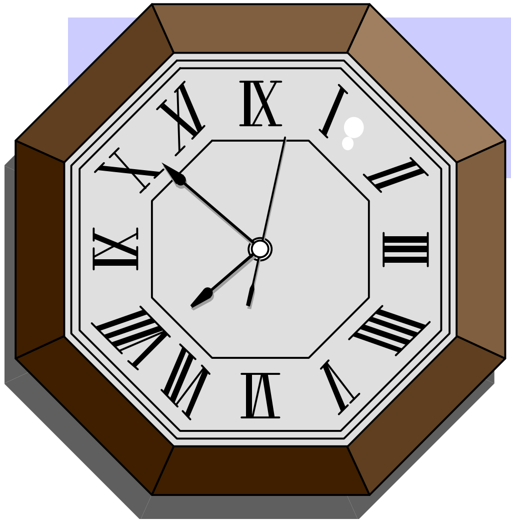


International Atomic Time (TAI)

- Uniform time scale.
- High stability in the long term (0.6×10^{-15}, ~ 40 days).
- Accuracy conferred by using the reported measurements of the PFS.
- Calculated in differed time on the basis of monthly blocks of data.

In the elaboration of TAI/UTC:

- Clock data provided by the participating laboratories.
- Organisation of international time links for clock comparison.
- Appropriate methods of time transfer.
- Primary frequency standards measurements.
- Algorithm to elaborate a time scale which fulfils the required characteristics: stability in the long term and frequency accuracy.
- Fluid communication between the BIPM and the time laboratories.



Clocks participating in TAI

- HP5071A 68%
- H masers 16%
- Other 16%

Relative frequency stability
(Allan deviation)
vs. averaging duration t for

(1) TAI

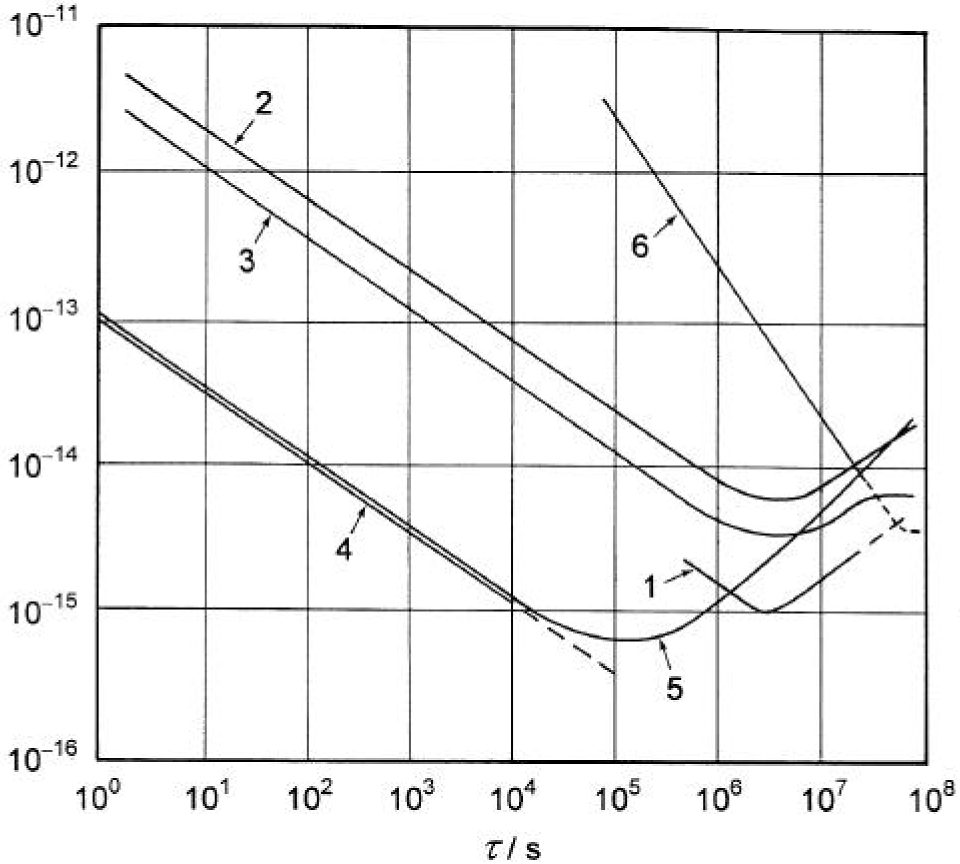
(2) commercial caesium clock

(3) primary clock PTB-CS1 (Braunschweig)

(4) caesium fountain LPTF-FO1 (Paris)

(5) commercial hydrogen maser

(6) rotation of a *best-case* millisecond pulsar



Clock weighting → stability

- independent clocks,
- relative weights,
- upper limit to clock weights,
- weight of a clock remains constant on the 30 days of the interval of computation,
- iterative process based on the previous interval to predict the clock frequencies on the following interval (random walk frequency modulation…),
- weight determination based on 12 intervals of computation (one year)
  - deweighting (annual frequency variations, long term drifts),
  - detection of abnormal behavior

BIPM

Upper limit to relative clock weights

$w_{\mathrm{MAX}} = 0.700\ \%$ until December 2000

$w_{\mathrm{MAX}} = A / N$ since January 2001

A : empirical constant

N : number of clocks that contributes to TAI

Clock weights (mean %)

- 2000
- 55% of clocks at ω_{max}
  - 14%are H-masers
  - 74% are HP5071A

- Over the H-masers
  - 42% are at ω_{max}

- Over the HP5071A
  - 65% are at ω_{max}

- Jul-Dec 2002
- 11% of clocks at ω_{max}
  - 14% are H-masers
  - 76% are HP5071A

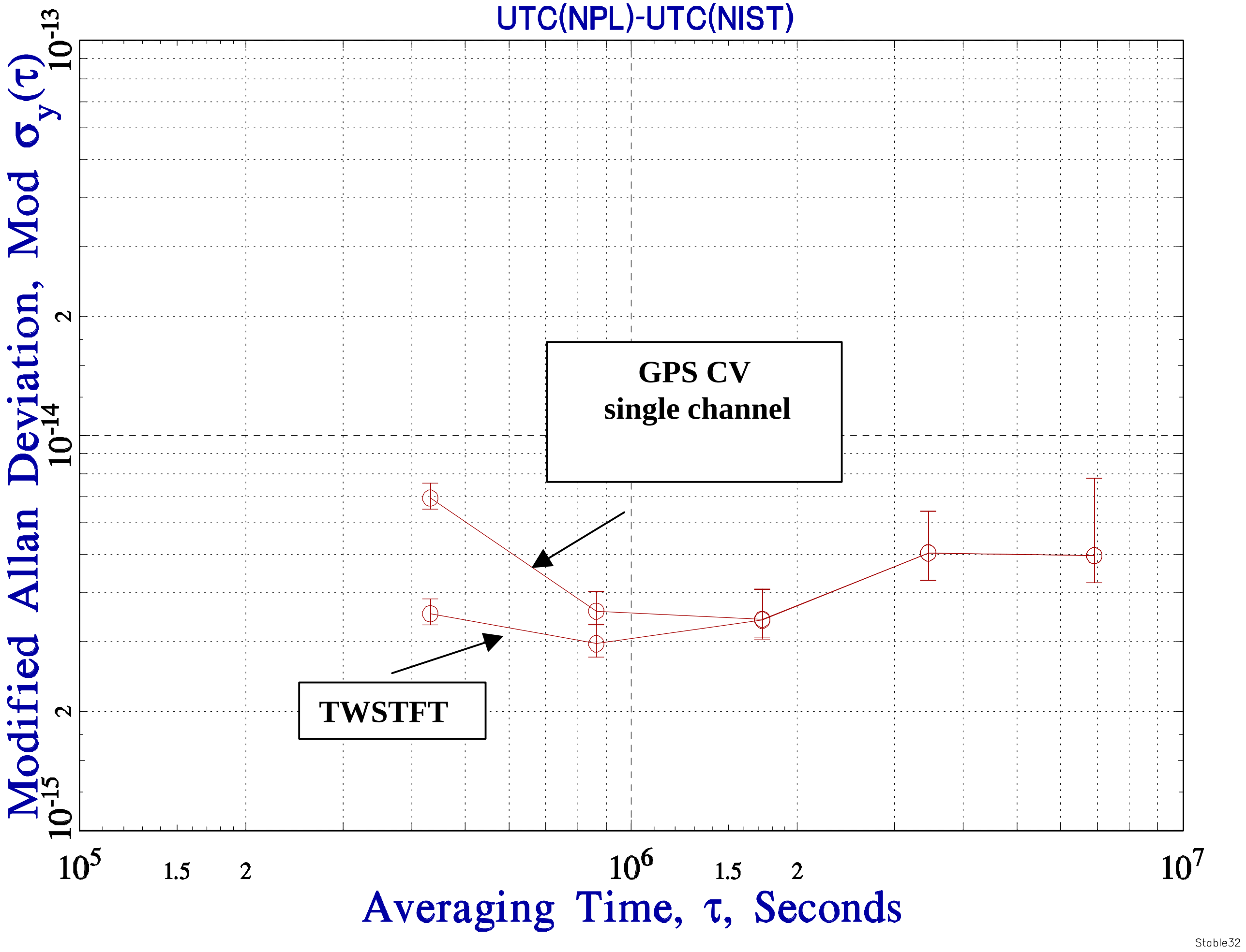
- Over the H-masers
  - 10% are at ω_{max}

- Over the HP5071A
  - 12% are at ω_{max}

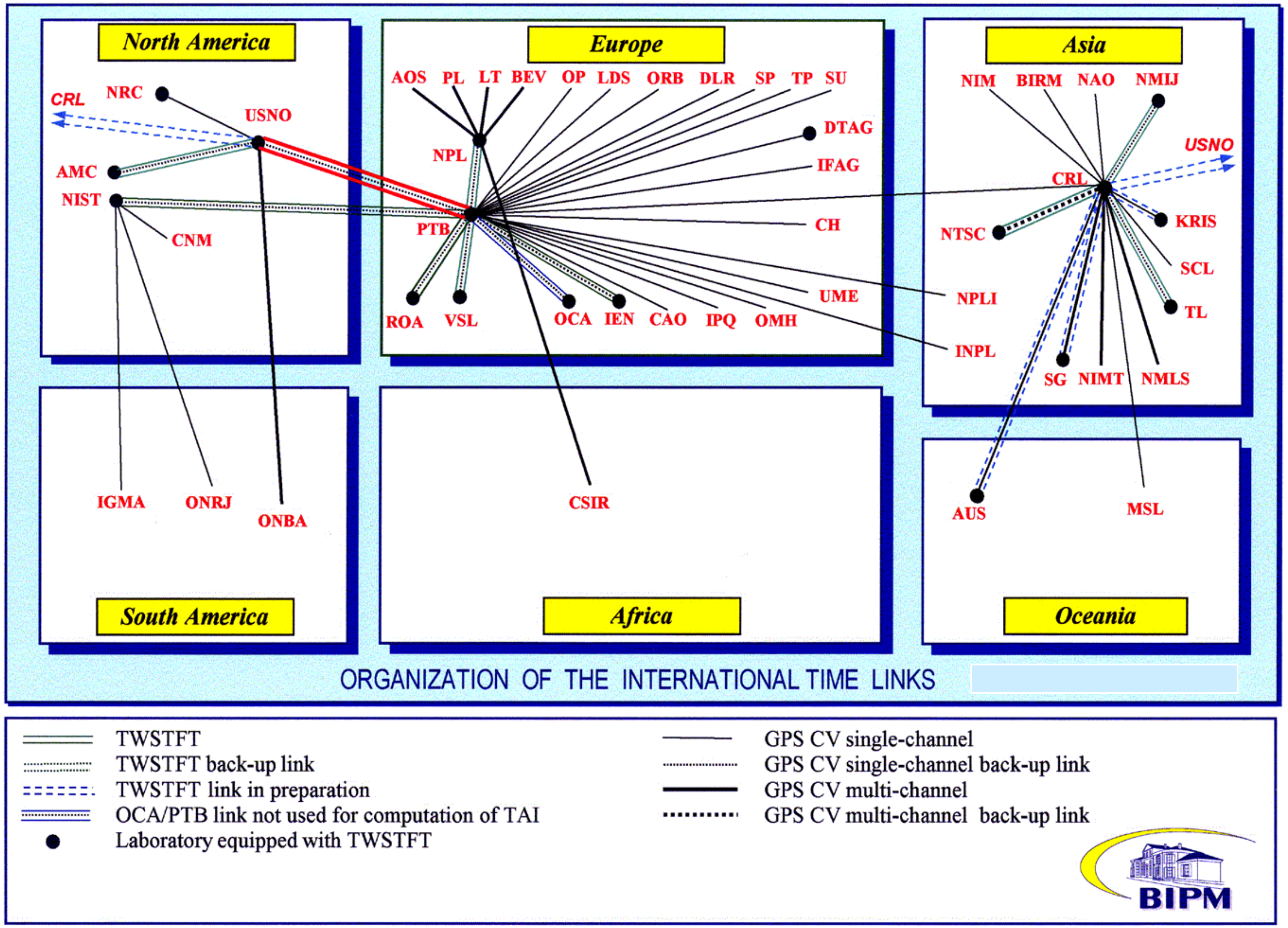
- Loran-C, TV links (before)
  - (several hundreds of ns uncertainty)
- GPS C/A-code single-channel common-view
  - (3-10 ns uncertainty)
- GPS C/A-code multi-channel common view
  - (ns uncertainty)
- TWSTFT
- GPSP3
- GPS carrier phase
- GLONASS P-code

} ns uncertainty or better

FREQUENCY STABILITY



Frequency stability of [*UTC(NPL) – UTC(NIST)*] by GPS CV single channel and by TWSTFT


North America
CRL
NRC
USNO
AMC
NIST
CNM
Europe
AOS PL LT BEV OP LDS ORB DLR SP TP SU
NPL
DTAG
IFAG
PTB
CH
UME
ROA VSL OCA IEN CAO IPQ OMH
Asia
NIM BIRM NAO NMIJ
USNO
CRL
NTSC
KRIS
SCL
NPLI
TL
INPL
SG NIMT NMLS
IGMA ONRJ ONBA
South America
CSIR
Africa
AUS
MSL
Oceania
ORGANIZATION OF THE INTERNATIONAL TIME LINKS
TWSTFT
TWSTFT back-up link
TWSTFT link in preparation
OCA/PTB link not used for computation of TAI
Laboratory equipped with TWSTFT
GPS CV single-channel
GPS CV single-channel back-up link
GPS CV multi-channel
GPS CV multi-channel back-up link
BIPM

ALGOS (algorithm for the calculation of TAI/UTC)

- Step-by-step algorithm.
- Designed to build a time scale
  - stable on the medium / long term
  - accurate in frequency
- Blocks of one month clock and clock comparison data
  - UTC - UTC(k)
  - TAI - TA(k)

  } **every 5 days at the standard dates**

  - BIPM estimation of the relative duration of the scale unit of TAI by using PFS measurements over 1 year.

ALGOS

- Calculation of time links.
  - GPS common views
  - TWSTFT links
- Clock weighting.
- Atomic free scale, Echelle Atomique Libre (EAL).
- Duration of the scale unit of TAI; steering.
- BIPM Circular T.

- EAL, atomic free scale
(its unit is not constrained to be the second of SI)
- EAL stability given by the Allan deviation is 0.6×10^{-15} for averaging times between 30-40 days.

- Clock weights and rates derived from [EAL - clock] over the last 11+1 months

- EAL stability model
  - white frequency noise $6 \times 10^{-15} / \ t$
  - flicker frequency noise 0.6×10^{-15}
  - random walk frequency noise $1.6 \times 10^{-16} \ t$

TAI accuracy

- Fractional deviation *d* of the scale interval of TAI from that of TT.

- PFS reporting measurements:
  PTB, CRL, NIST, SYRTE

- Uncertainty expressed by four components:
  - u_B : systematic effects
  - u_A : instability of the PFS
  - $u_{l/lab}$: uncertainty of the link PFS - clock in TAI
  - $u_{l/TAI}$: uncertainty in the link to TAI

- BIPM estimation of *d*, based on PFS measurements

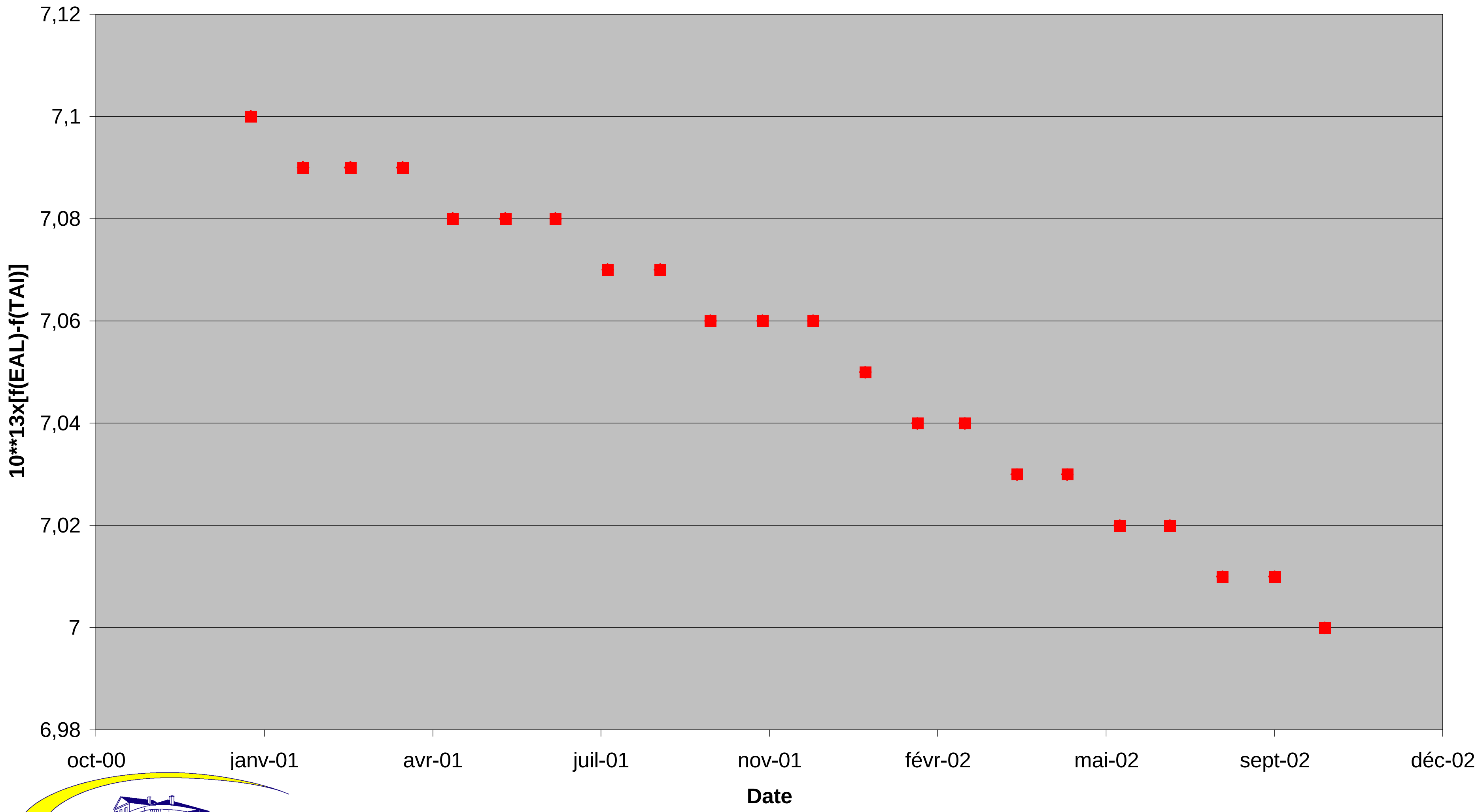
TAI accuracy improvement

- External to the main algorithm
- Frequency steering of EAL

f(TAI) = f(EAL) + frequency steering correction

- Frequency corrections of 1×10^{-15} (smaller than the frequency fluctuations)

Frequency steering of TAI



Dissemination of the time scales

- BIPM Time Section Circular T
- TWSTFT reports
- BIPM Time Section Annual Report

- all data and information linked to the time scales on the internet (web, ftp)

- Scientific publications of the staff members

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