

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



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 1.4×10^{-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.

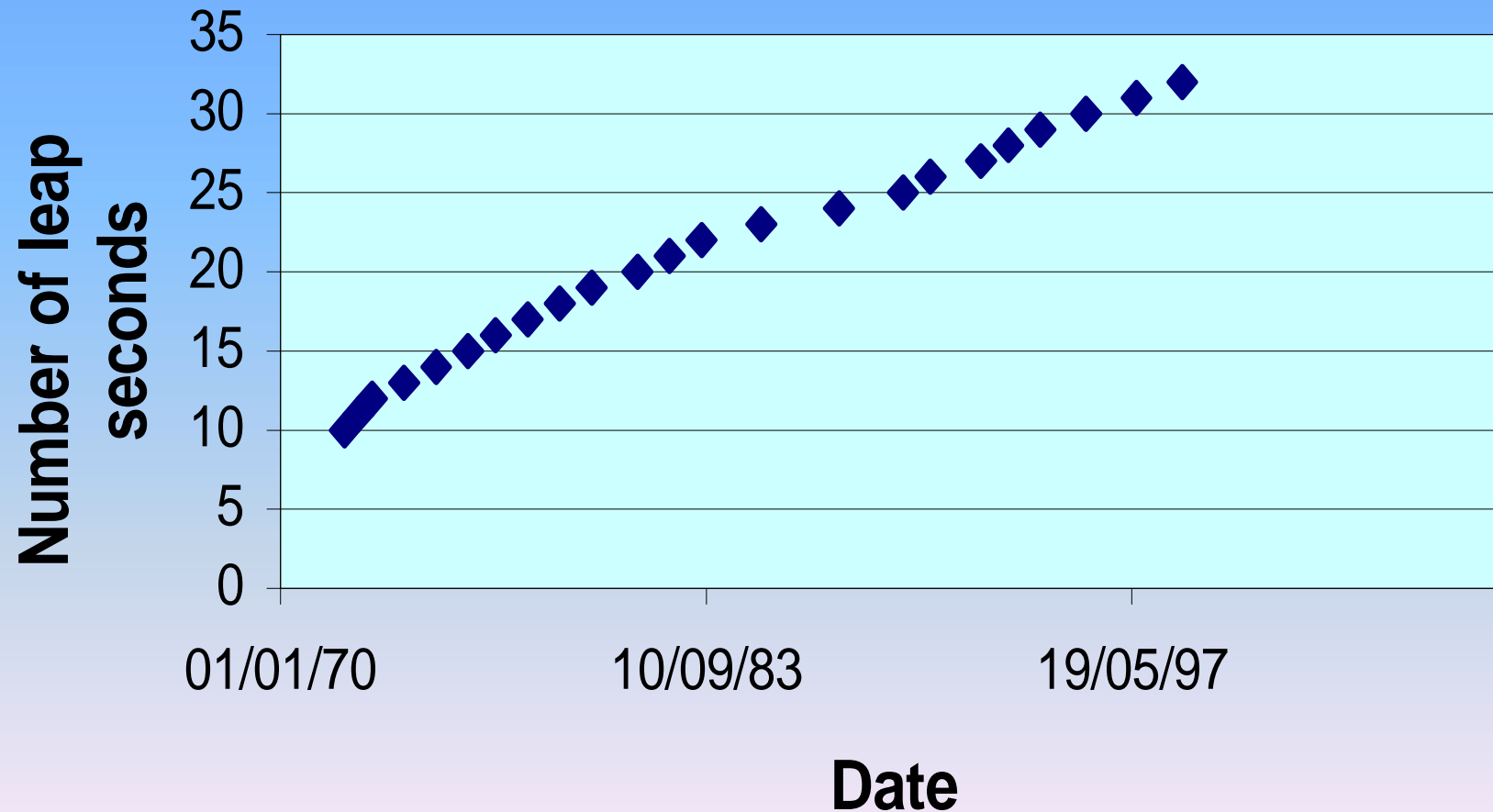


Coordinated Universal Time (UTC)

- 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 ($\text{TAI} - \text{UTC} = 32 \text{ s}$ today).



Leap seconds in UTC since 1972



International Atomic Time (TAI)

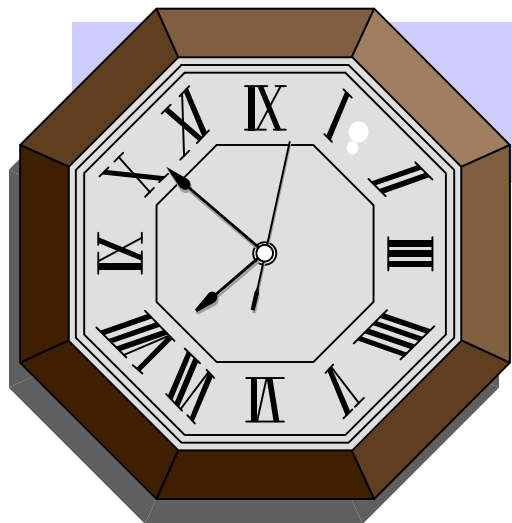
- Uniform time scale.
- High stability in the long term (0.6×10^{-15} , ~ 40 days).
- Accuracy conferred by using the reported measurements of the PFS.
- Calculated in differed time on the basis of monthly blocks of data.



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.





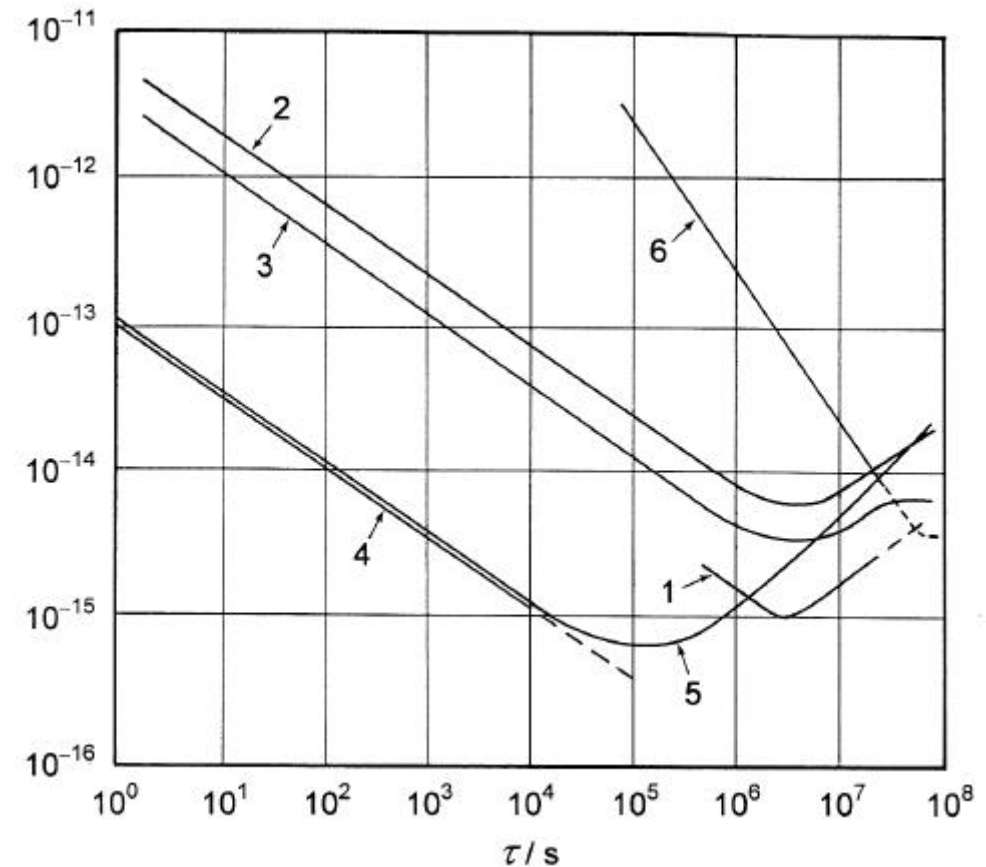
Clocks participating in TAI

- 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



Upper limit to relative clock weights

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

$w_{\text{MAX}} = A / N$ 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}



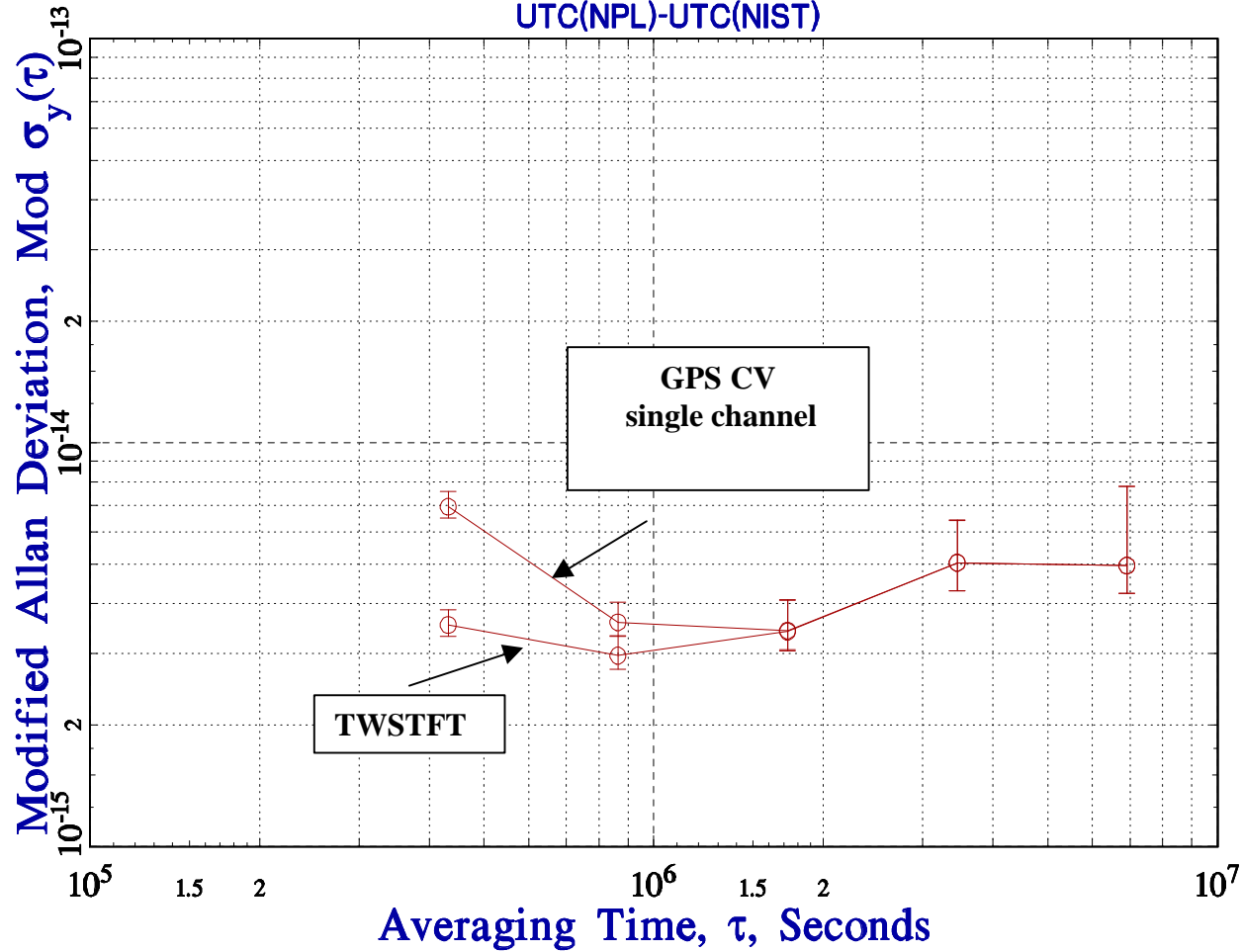
- Loran-C, TV links (before)
 - (several hundreds of ns uncertainty)
 - GPS C/A-code single-channel common-view
 - (3-10 ns uncertainty)
 - GPS C/A-code multi-channel common view
 - (ns uncertainty)
 - TWSTFT
 - GPSP3
 - GPS carrier phase
 - GLONASS P-code
- } ns uncertainty
or better





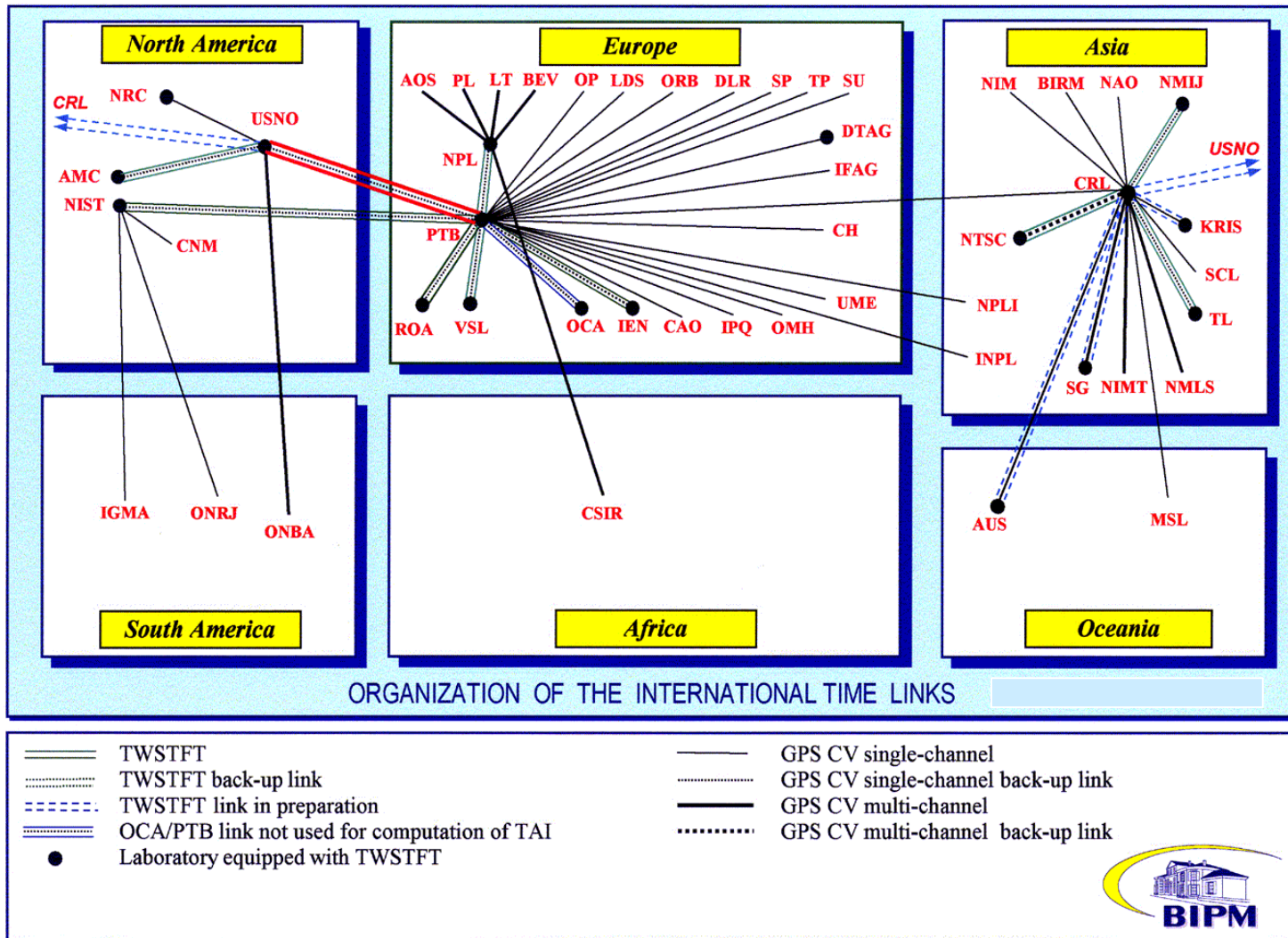
FREQUENCY STABILITY

UTC(NPL)-UTC(NIST)



Stable32

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



ORGANIZATION OF THE INTERNATIONAL TIME LINKS

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

**every 5 days at the
standard dates**



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
 - $u_{I/lab}$: uncertainty of the link PFS - clock in TAI
 - $u_{I/TAI}$: uncertainty in the link to TAI
- BIPM estimation of d , based on PFS measurements



TAI accuracy improvement

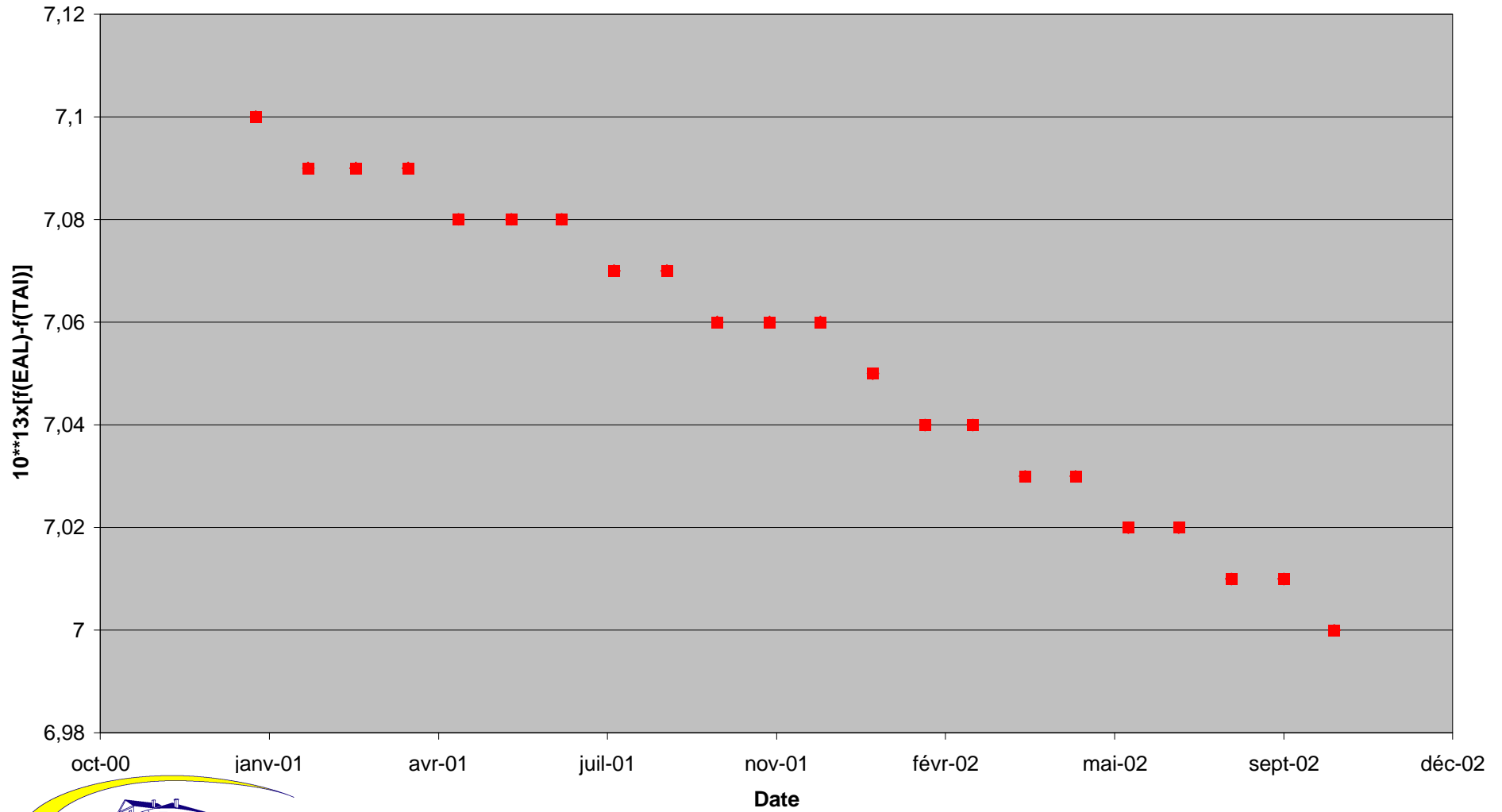
- External to the main algorithm
- Frequency steering of EAL

$$f(\text{TAI}) = f(\text{EAL}) + \text{frequency steering correction}$$

- 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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