On the importance of a reference time scale for metrology

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On the importance of a reference time scale for metrology

Outline:

• Needs for a reference time scale UTC

• Construction of UTC

• Conclusions and prospects
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• Conclusions and prospects
Needs for a reference atomic time scale

Synchronisation of a user clock to a common reference time scale:

- **For various application fields:**
  - society: appointment times, transportation
  - networks: telecommunications, energy distribution and smart grids, global satellite positioning systems, solar system probe tracking, …
  - economy and financial sector
  - science (astronomy, fundamental physics, …)

- **At various scales:**
  - local, regional, international, on Earth or in space

- **At various precision levels:**
  - from sub-nanosecond to second (1 nanosecond = 0,000 000 001 s)
Example in science: Faster-than-light neutrino anomaly (2011)

Observation of an unexpected effect: arrival of neutrinos before light (20 meters = 60 nanoseconds)

→ Not a scientific revolution (unfortunately) but a mistake in an instrument synchronisation
Example for the synchronization of networks: Global Navigation Satellite Systems (GNSS)

- Need to have synchronized clocks in satellites to get the user localization in space and in time.
  
  1 nanosecond time error = 30 cm position error

- Need to synchronize GNSS time scales (GPS, GALILEO, GLONASS, Beidou, ...) to the same reference time scale (UTC) to ensure the interoperability of these systems.
Example in the financial sector: Worldwide high frequency trading

- Need to have fast response trading systems to minimize latency
- Have to be sure that operations and orders are correctly time stamped, to avoid mistakes or volunteer misconducts in the treatment of trade orders
- Synchronization errors led to major stock market disruption leading to a large trading loss for the company (15 ms error → 28 M$)

- Several misconducts were discovered as banks introduced a microsecond hold period between a customer order being received and it being executed. If markets moved in favour of the bank, the trade went through. If the client would have benefited, the trades were turned down (→ fine of 150 M$ to the bank)

- Due to these misconducts, the different regulation bodies in the world are now asking a precise and traceable time tagging to UTC to avoid fictitious delays
Synchronization method

International reference atomic time scale (BIPM)

National atomic time scales

Country A

Intermediate clocks

End user clocks

UTC
Synchronization method

International reference atomic time scale (BIPM)

National atomic time scales

UTC

Intermediate clocks

End user clocks

Country A

Country B

Country X

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Synchronization techniques

Telecom

GNSS

Radio broadcast

Optical fibres / Internet

Master clock

Slave clock
Synchronization limitations

- **Knowledge of the propagation time and mitigation of its fluctuations**
  - State of the art ~ 1 nanosecond for intercontinental synchronization
  - Expected improvements with upgraded satellite and fibre techniques

- **Correction of relativistic effects**
  - Two identical clocks at different locations do not beat at the same rhythm due to Einstein relativistic effects
  - These effects must be corrected (if not, error of 40 000 nanoseconds after 1 day for GNSS satellites = 12 km error for positioning !)
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Construction of the reference atomic time scale

Need to have a time scale related to the SI definition of the time unit

- Before 1967:
  - provided by Earth rotation
  - realization of the unit with astronomical observations

- Since 1967:
  - provided by the Cs atom transition frequency
  - realization of the unit with primary Cs clocks
    - (ultra stable laser cooled Cs clocks with accuracy $\sim 10^{-16}$)
Each country provides its legal time relying on a «real time» realization of UTC (called «UTC(k)») which can be distributed towards users.

The time differences between UTC(k) and UTC are provided monthly by BIPM.

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Traceability of UTC(k) to UTC

UTC-UTC(k)

Nanoseconds

AOS
ONRJ
CNM
OP
IT
PTB
NICT
SU
NIM
USNO
NIST
ZA

10 nanoseconds

Years

Jul 2014
Jul 2015
Jul 2016
Jul 2017
Jul 2018
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• Conclusions and prospects
Conclusions

- Importance to have a unique international reference time scale (linked to the SI second) for strategic applications in a wide range of fields

- Need to ensure the traceability to UTC of all national time scales distributed to end-users

- Central role played by BIPM for the construction of UTC within an international coordination

- UTC relies on the SI definition of the time unit, the second, which will have a specific position with respect to other SI units (provided the redefinition is accepted)

- Outstanding quality of the realization of the SI second (and of UTC) thanks to ultrastable atomic clocks
Prospects

→ Cs clocks are now surpassed by optical clocks
→ Possible redefinition of the SI second at a next CGPM?

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### UTC-UTC(k) provided by BIPM Circular T

**CIRCULAR T 370**  
2018 NOVEMBER 08, 14h UTC

**BUREAU INTERNATIONAL DES POIDS ET MESURES**  
THE INTERGOVERNMENTAL ORGANIZATION ESTABLISHED BY THE METRE CONVENTION  
PAVILLON DE BRETEUIL F-92312 SEVRES CEDEX TEL. +33 1 45 07 70 70 tai@bipm.org

The contents of the sections of BIPM Circular T are fully described in the document "Explanatory supplement to BIPM Circular T " available at ftp://ftp2.bipm.org/pub/tai/publication/notes/explanatory_supplement_v0.1.pdf

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Improvement of atomic frequency standards

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Accuracy ~ few $10^{-18}$

Age of universe

- $10^9$ years
- $10^6$ years
- 1000 years
- 1 year
- 1 day
- 1 hour

1 second time error after:

- Huygens pendulum
- Harrison clock
- Quartz oscillator
- First atomic clock
- Cold Cs atom fountain
- Industrial Cs clock
- Optical clock

Astronomical, mechanical & electrical era

Atomic era
Useful illustrations: