26e CGPM
Versailles
13-16 novembre 2018

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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Needs for a reference atomic time scale

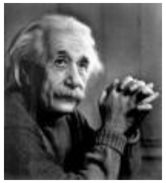
Synchronisation of a user clock to a common reference time scale:

- **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

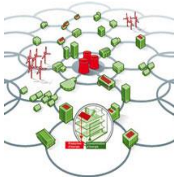
- **At various precision levels:**
  - from sub-nanosecond to second (1 nanosecond = 0,000 000 001 s)





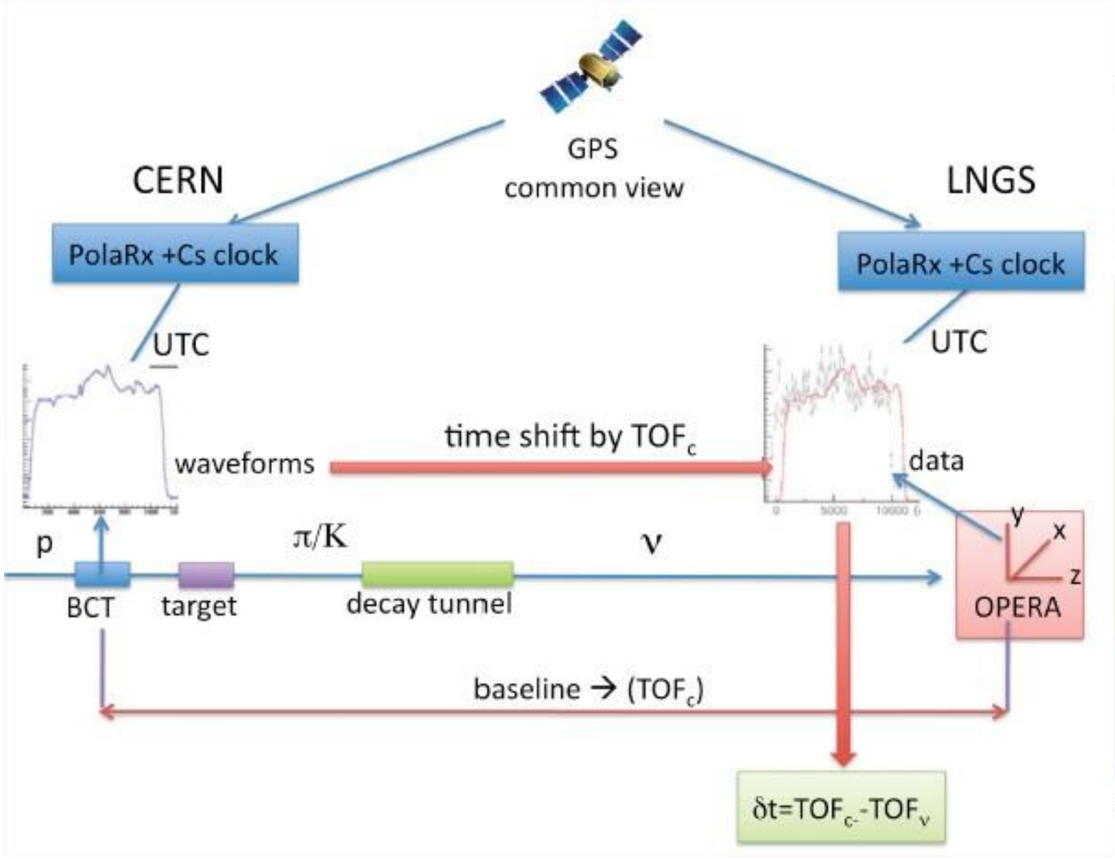


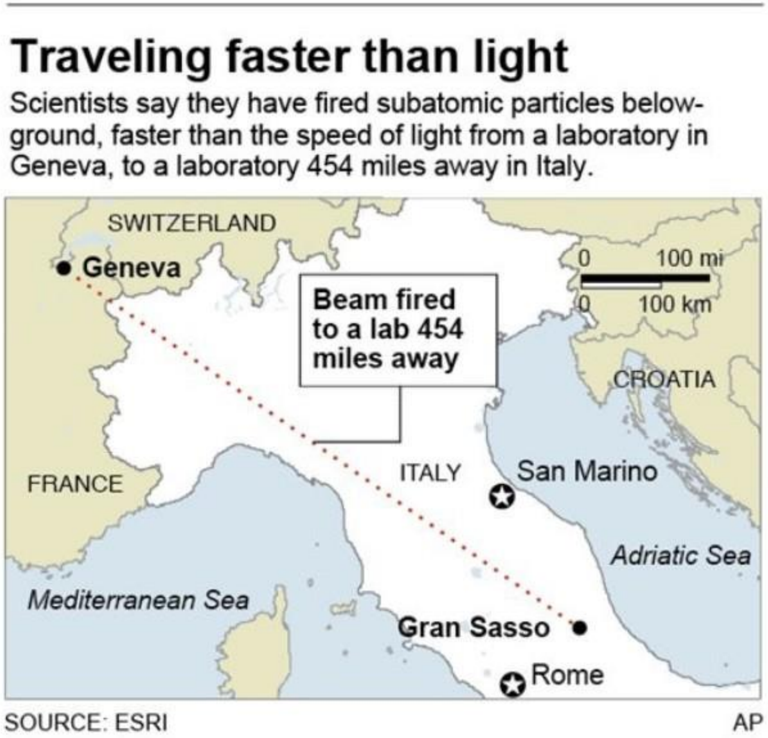




Example in science: Faster-than-light neutrino anomaly

(2011)





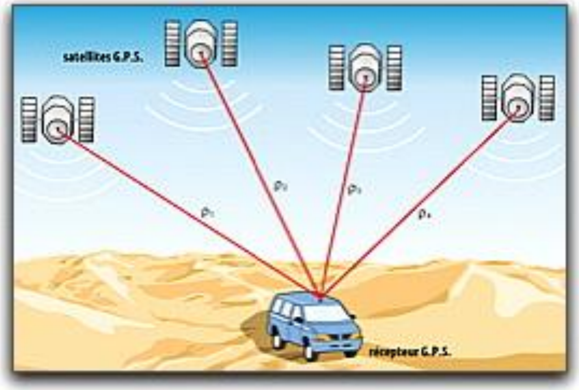
Observation of an unexpected effect: arrival of neutrinos before light (20 meters = 60 nanoseconds)

→ Not a scientific revolution (unfortunately) but a mistake in an instrument synchronisation

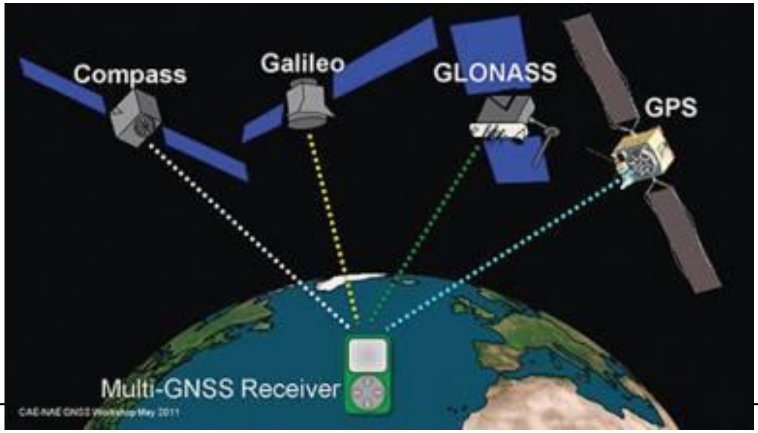
Example for the synchronization of networks: Global Navigation Satellite Systems (GNSS)

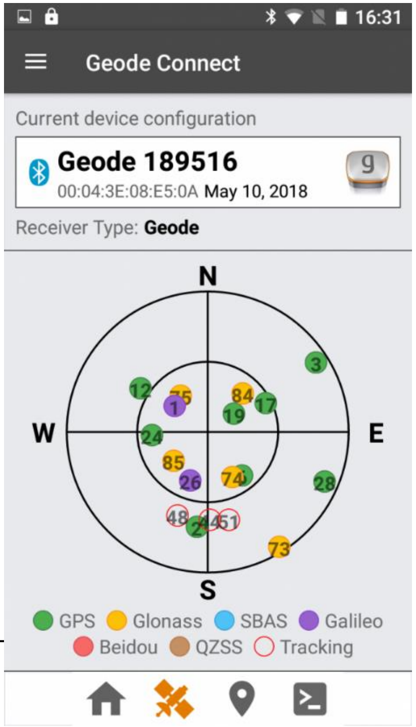
➢ Need to have synchronized clocks in satellites to get the user localization in space and in time

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

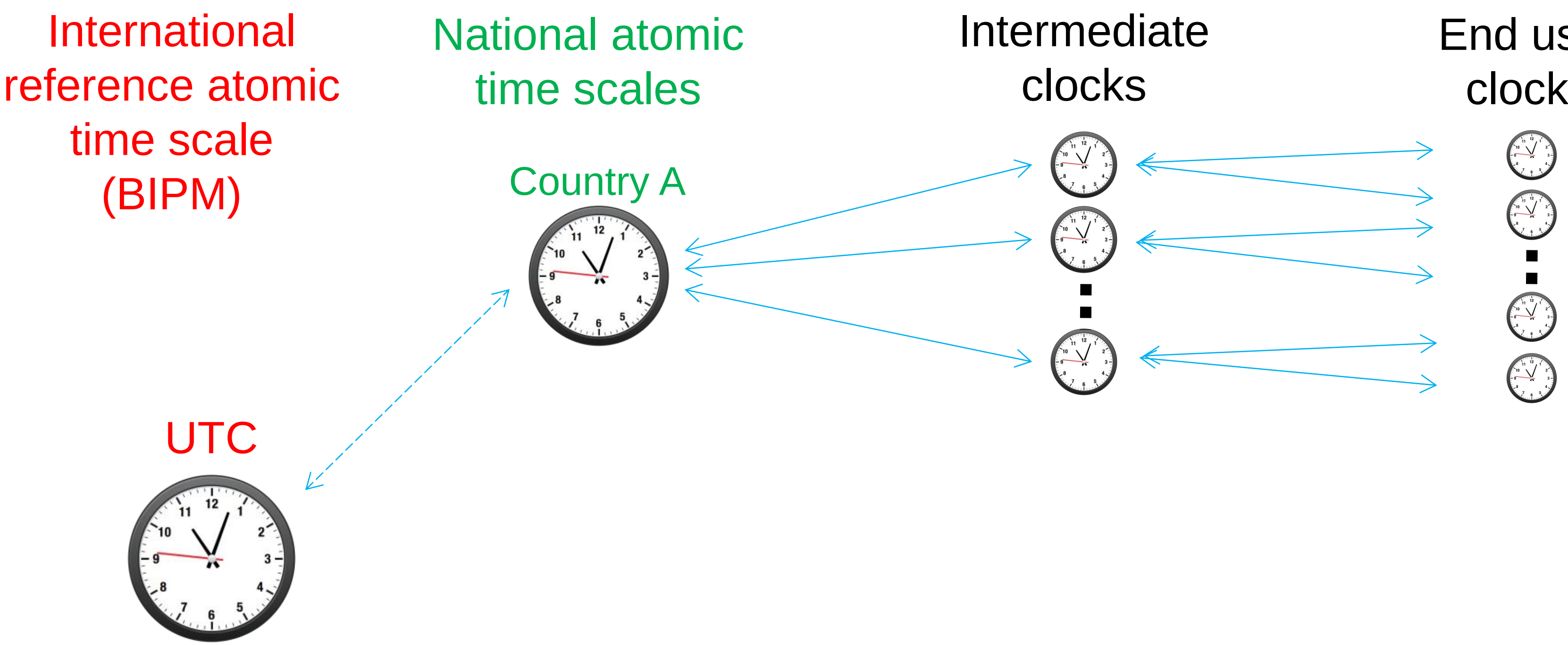
Example in the financial sector: Worldwide high frequency trading

- Synchronization errors led to major stock market disruption leading to a large trading loss for the company (15 ms error → 28 M$)

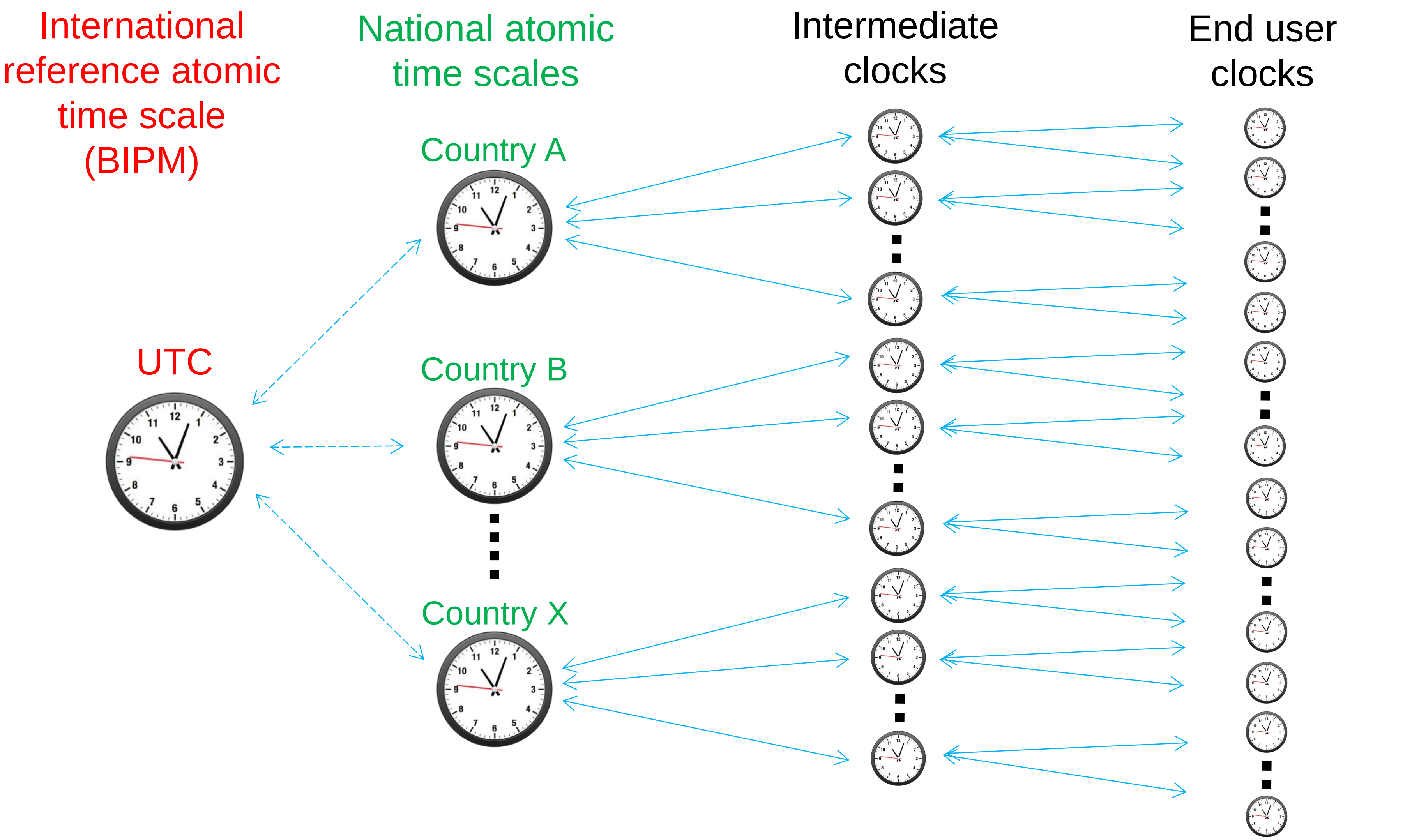
- Several misconducts were discovered as banks introduced a microsecond hold period between a customer order being received and it being executed. If markets moved in favour of the bank, the trade went through. If the client would have benefited, the trades were turned down (→ fine of 150 M$ to the bank)

- 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

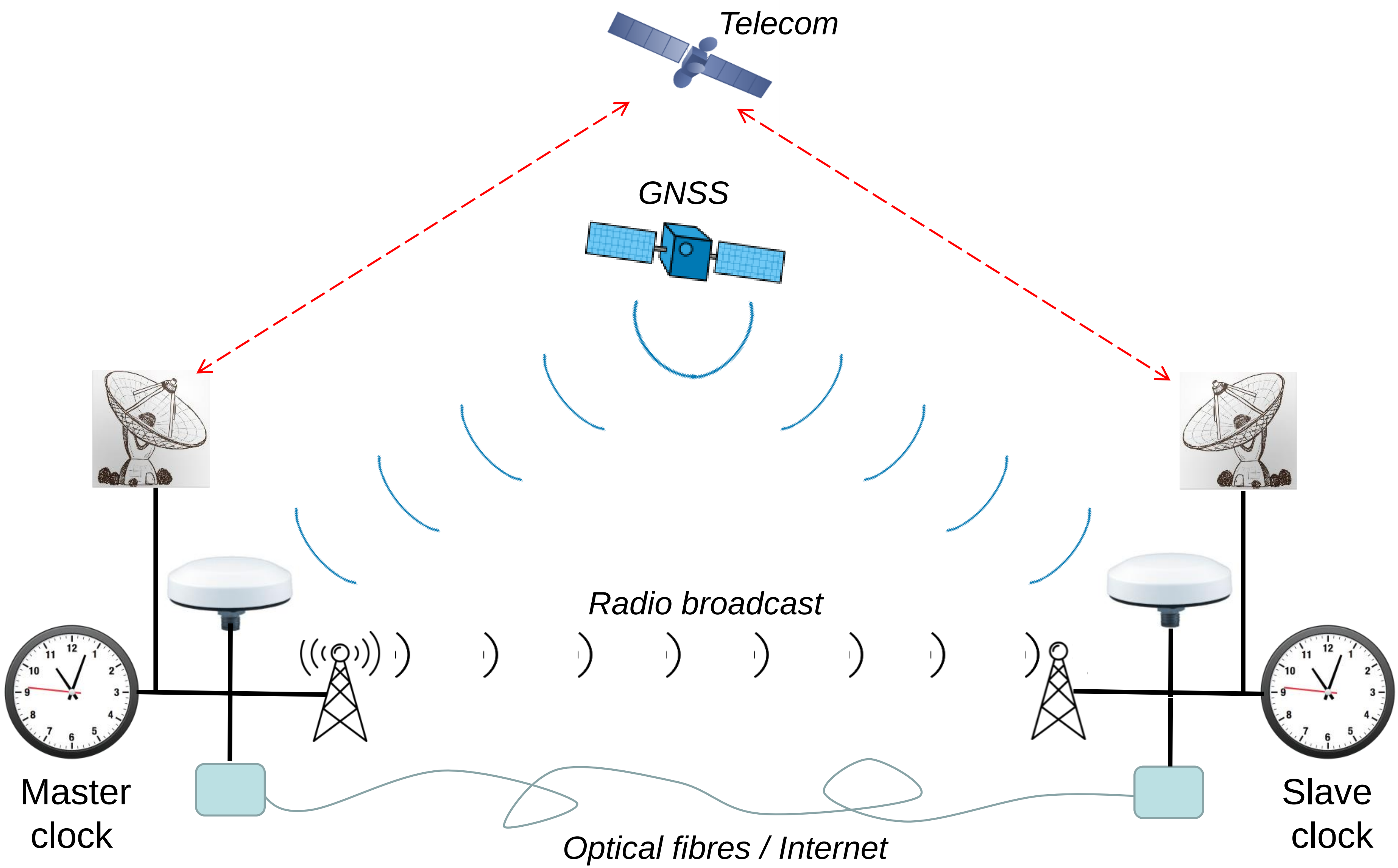
Synchronization method



Synchronization method



Synchronization techniques



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 rythm 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 !)

On the importance of a reference time scale for metrology

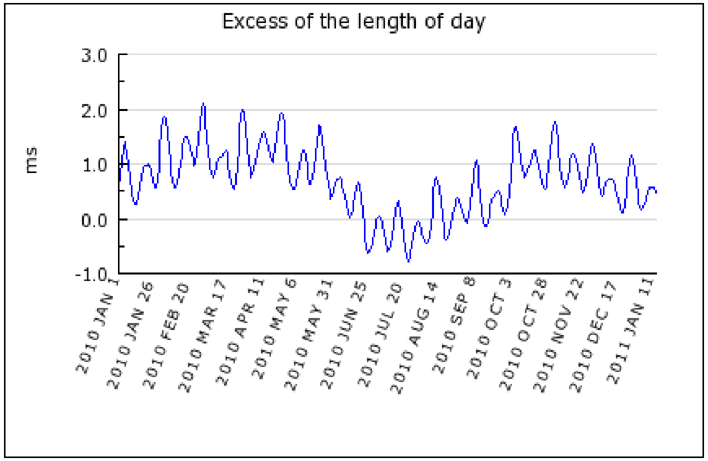
<u>Outline</u>:

- Needs for a reference time scale UTC
- **Construction of UTC**
- Conclusions and prospects

Construction of the reference atomic time scale

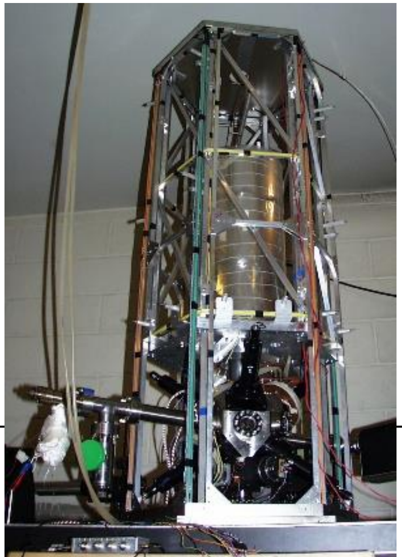
Need to have a time scale related to the SI definition of the time unit

fluctuations of the Earth rotation rate

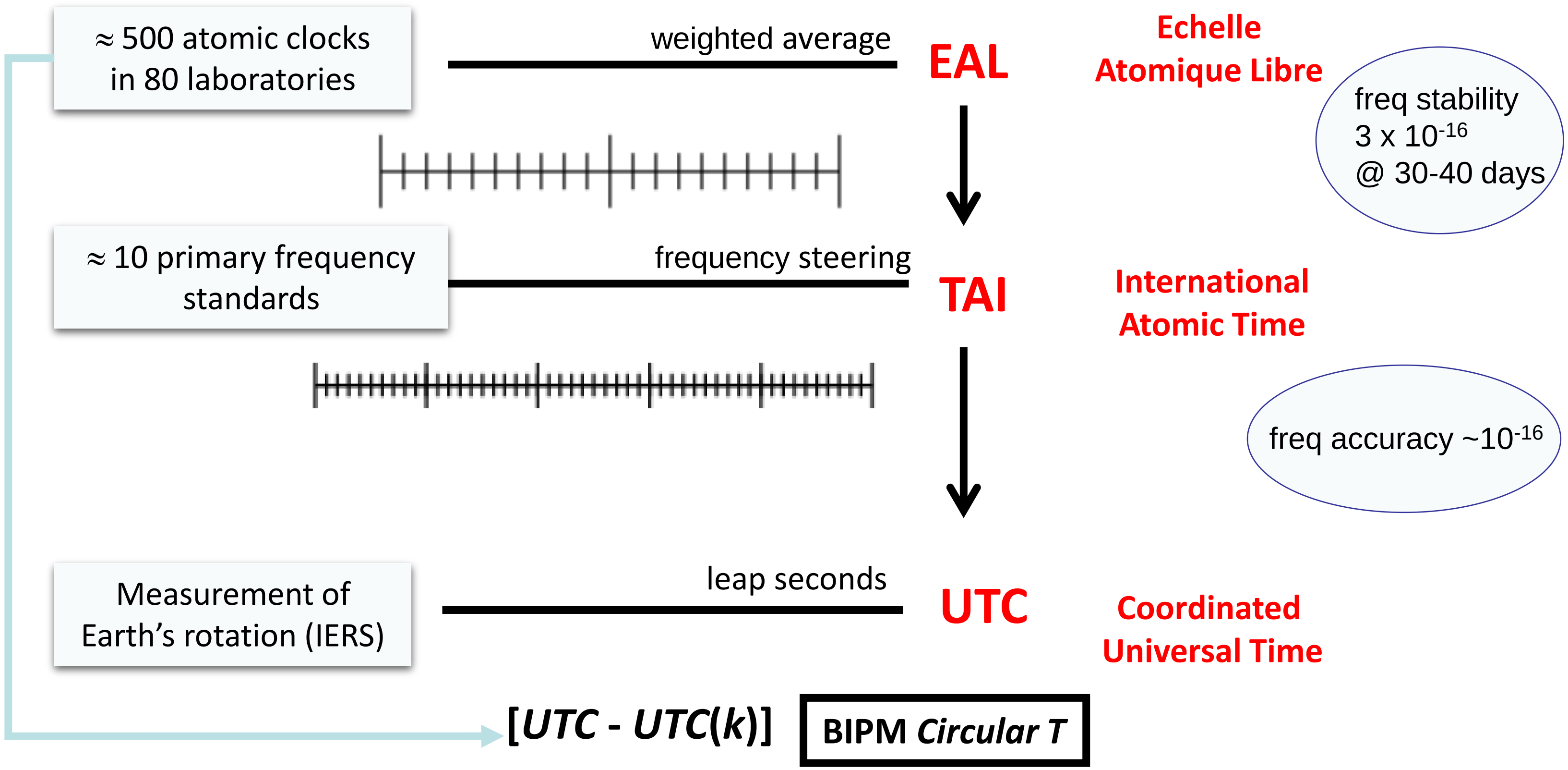


➢ **Before 1967:**
- provided by Earth rotation
- realization of the unit with astronomical observations

➢ **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 ~ 10^{-16})

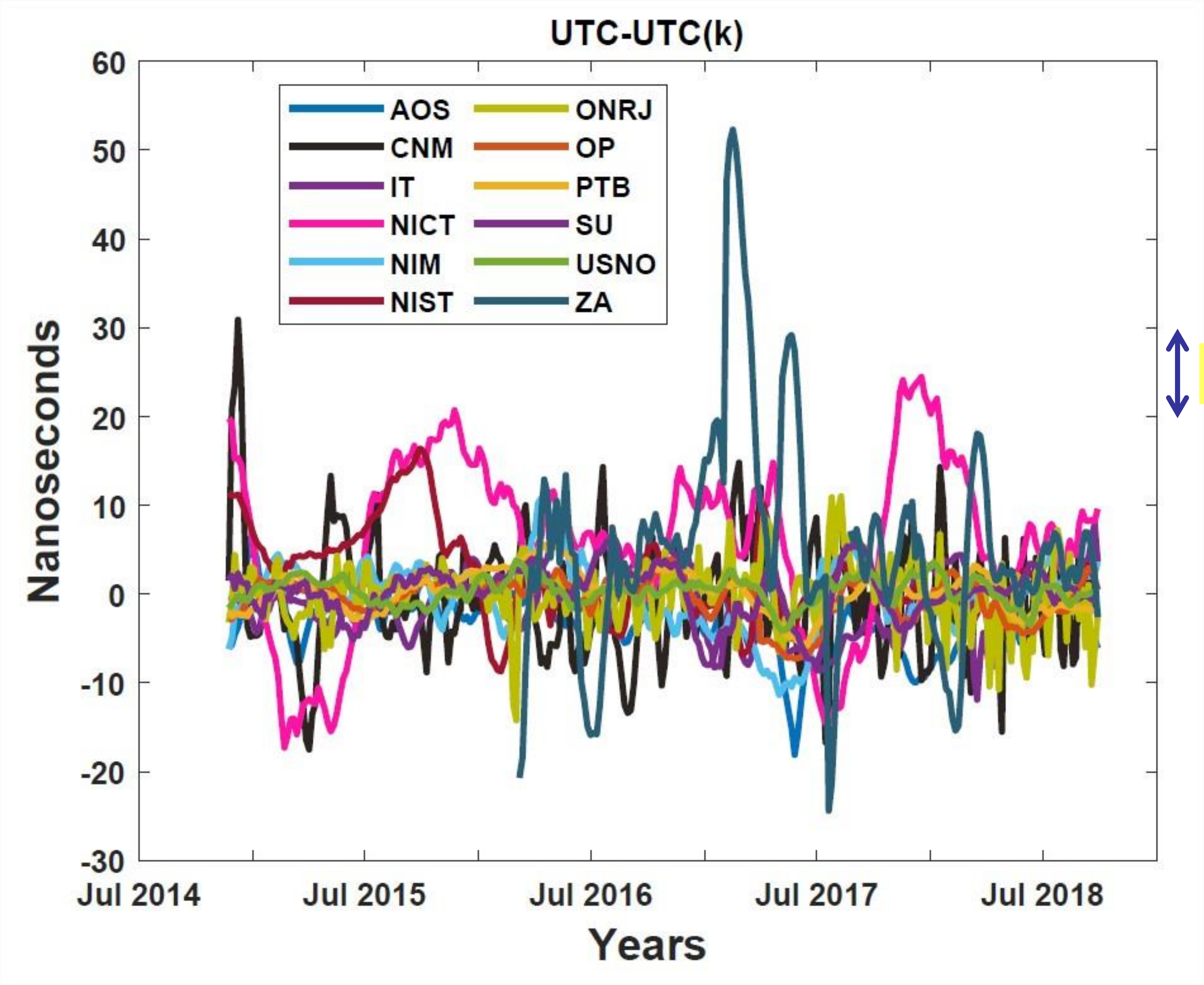


Construction of the reference atomic time scale by BIPM



- 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

Traceability of UTC(k) to UTC



10 nanoseconds

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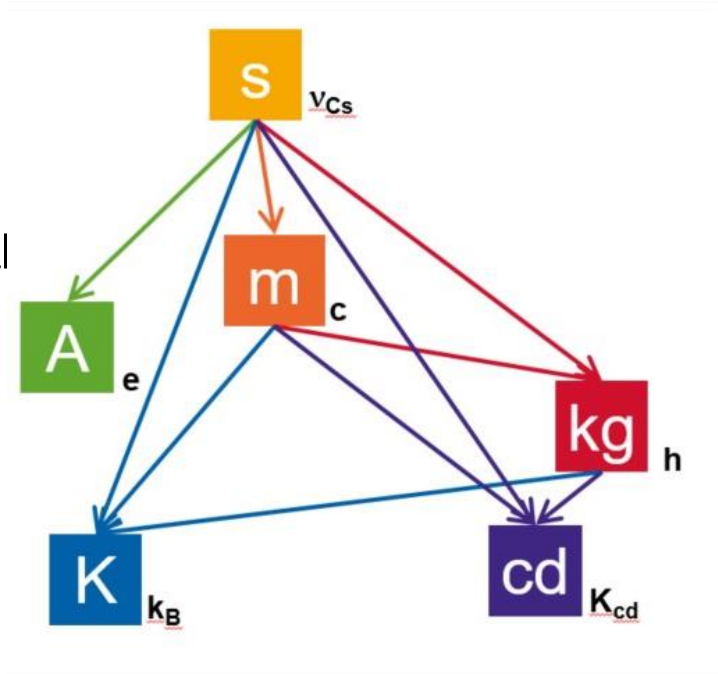
Conclusions

- 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

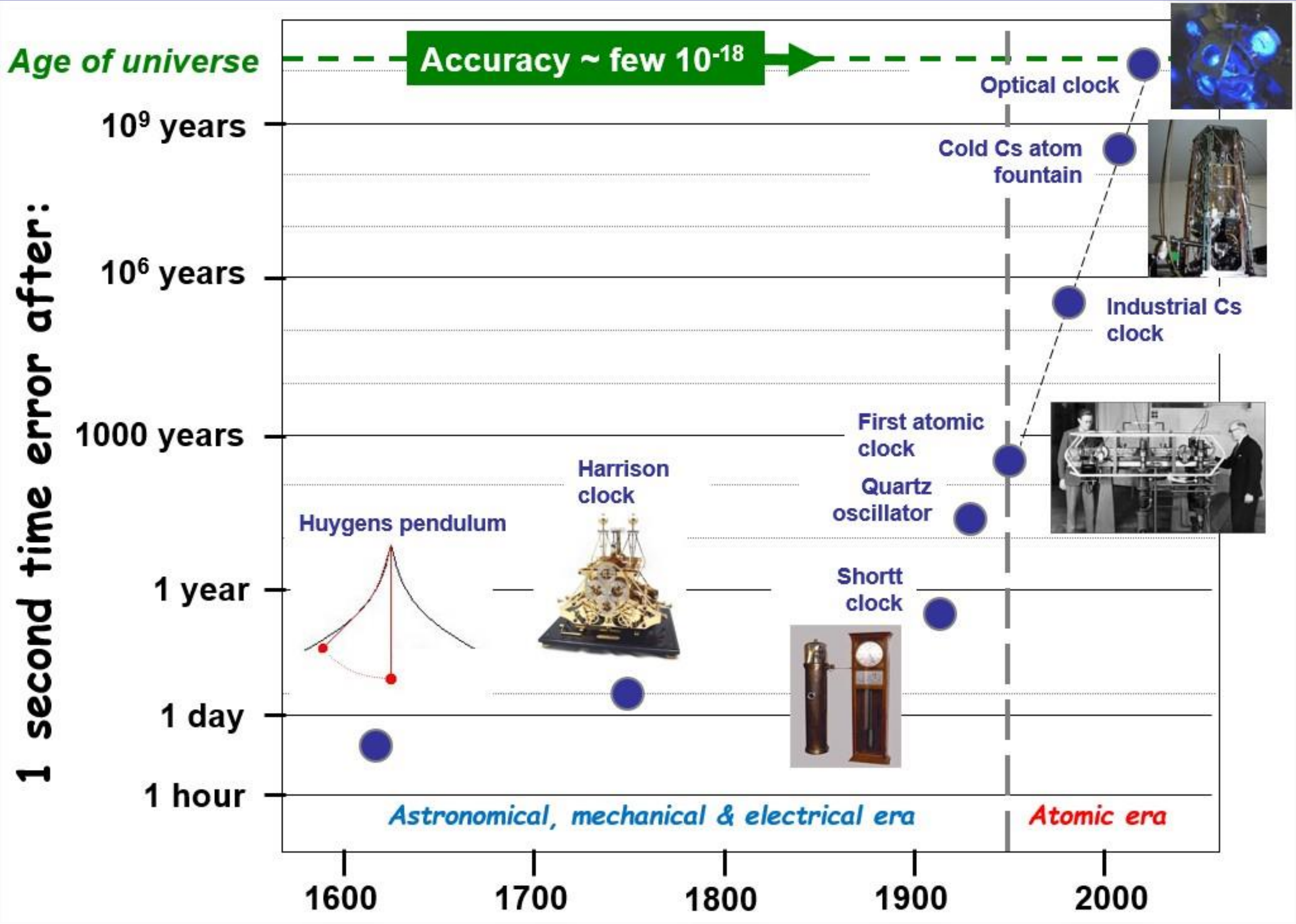
- Central role played by BIPM for the construction of UTC within an international coordination



- 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 ?

UTC-UTC(k) provided by BIPM Circular T

Bureau International des Poids et Mesures

CIRCULAR T 370

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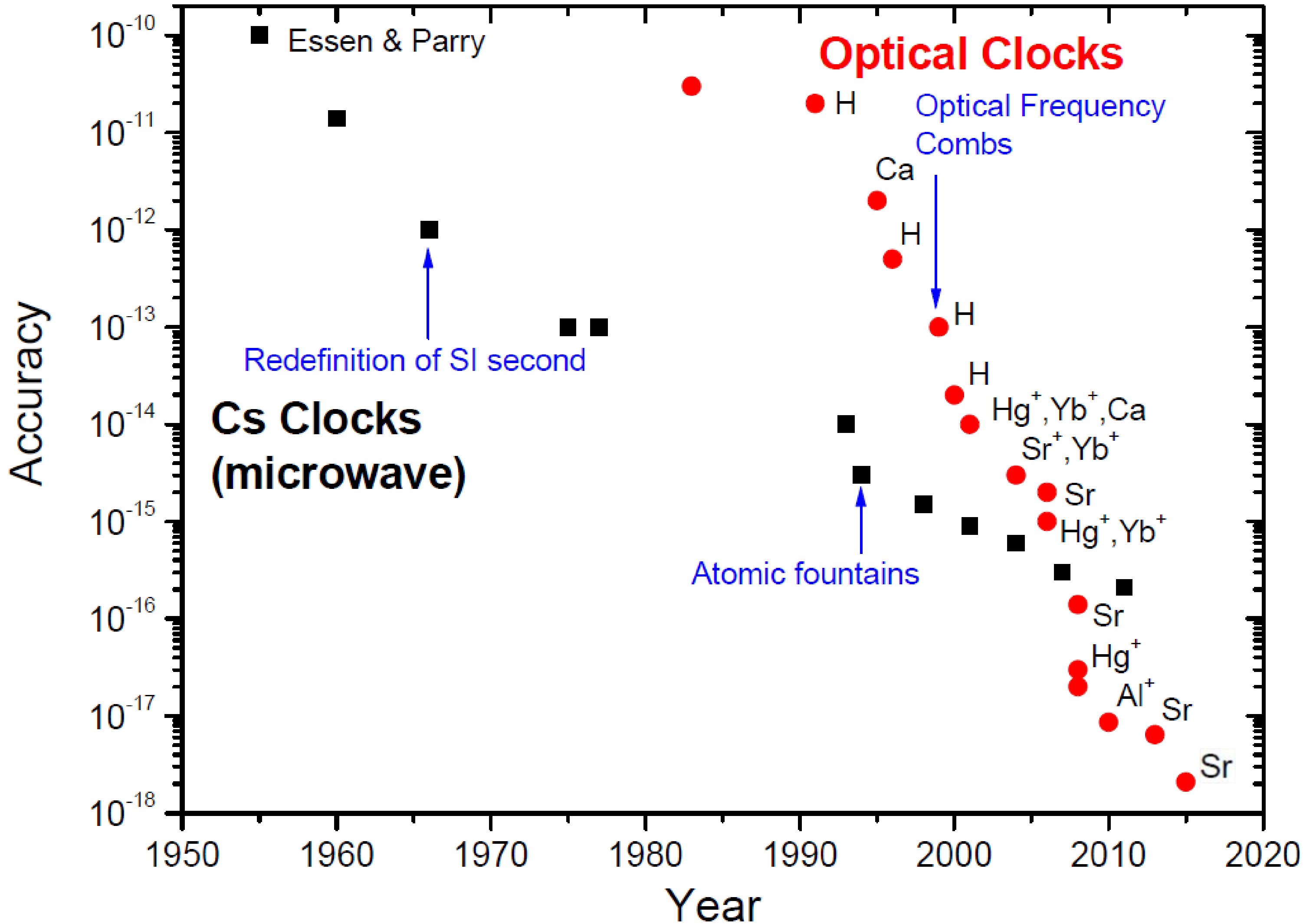
BUREAU INTERNATIONAL DES POIDS ET MESURES
THE INTERGOVERNMENTAL ORGANIZATION ESTABLISHED BY THE METRE CONVENTION
PAVILLON DE BRETEUIL F-92312 SEVRES CEDEX TEL. +33 1 45 07 70 70 tai@bipm.org

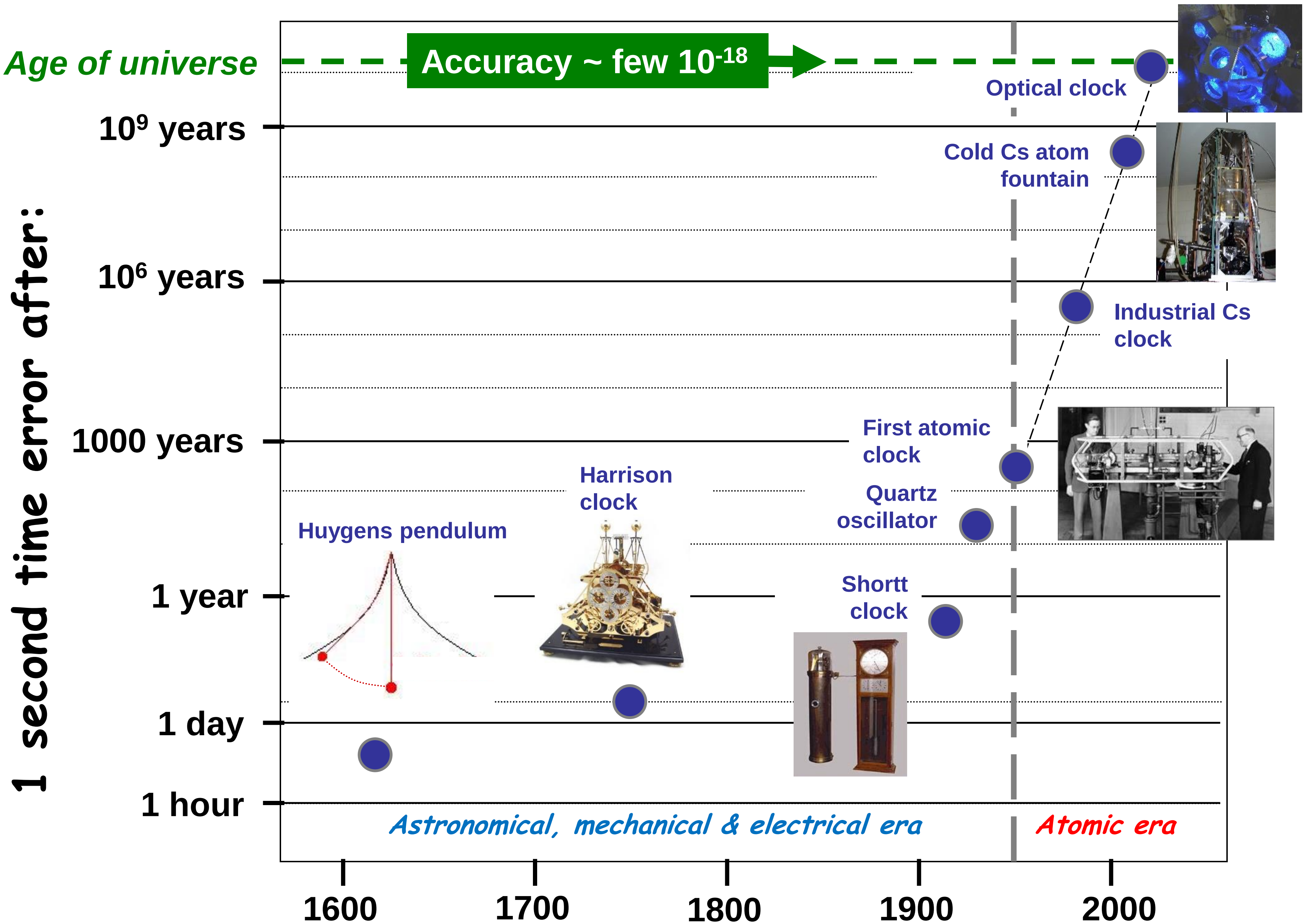
The contents of the sections of BIPM *Circular T* are fully described in the document " Explanatory supplement to BIPM Circular T " available at ftp://ftp2.bipm.org/pub/tai/publication/notes/explanatory_supplement_v0.1.pdf

1 - Difference between UTC and its local realizations UTC(k) and corresponding uncertainties. From 2017 January 1, 0h UTC, *TAI-UTC* = 37 s.

Date 2018 0h UTC		SEP 28	OCT 3	OCT 8	OCT 13	OCT 18	OCT 23	OCT 28	Uncertainty/ns			Notes
	MJD	58389	58394	58399	58404	58409	58414	58419	u_A	u_B	u	
Laboratory *k*		[*UTC-UTC*(*k*)]/ns										
AOS	(Borowiec)	-6.1	-6.4	-6.1	-6.2	-6.4	-6.8	-6.8	0.4	4.1	4.1	
APL	(Laurel)	1.0	1.0	1.2	1.1	-5.0	-6.5	0.9	0.4	11.3	11.3	(1)
AUS	(Sydney)	-47.0	-40.1	-25.1	-24.6	-25.7	-28.9	-28.8	0.4	6.4	6.4	
BEV	(Wien)	18.6	18.7	18.3	17.0	14.9	13.5	18.0	0.4	3.2	3.2	
BIM	(Sofiya)	-	-	-	-	-	-	-				
BIRM	(Beijing)	15.0	12.9	12.9	14.1	12.0	8.0	7.6	0.5	3.1	3.2	
BOM	(Skopje)	-821.1	-855.4	-885.9	-907.3	-936.4	-958.3	-977.1	1.5	8.2	8.3	
BY	(Minsk)	-3.0	-3.4	-3.6	-2.0	-2.5	-2.2	-1.1	1.5	12.2	12.3	
CAO	(Cagliari)	-6944.9	-7045.6	-7148.4	-7252.2	-7356.4	-7456.2	-7562.0	1.5	20.0	20.1	
CH	(Bern-Wabern)	-5.4	-5.6	-5.7	-4.9	-4.3	-4.8	-4.0	0.4	2.2	2.3	
CNES	(Toulouse)	22.3	20.7	13.9	15.9	15.3	16.8	13.4	0.4	4.6	4.6	
CNM	(Queretaro)	-2.2	-7.3	-5.1	0.4	1.3	0.3	-0.2	2.5	11.2	11.5	
CNMP	(Panama)	-7.5	-3.6	-7.8	7.2	-15.2	-15.9	-7.2	0.7	7.4	7.4	
DFNT	(Tunis)	1694.9	192.6	377.2	595.6	785.8	979.6	1187.3	0.7	20.0	20.0	(2)

Improvement of atomic frequency standards





1 second time error after:
Age of universe
Accuracy ~ few 10^{-18}
10^9 years
10^6 years
1000 years
1 year
1 day
1 hour
Optical clock
Cold Cs atom fountain
Industrial Cs clock
First atomic clock
Quartz oscillator
Harrison clock
Huygens pendulum
Shortt clock
Astronomical, mechanical & electrical era
Atomic era
1600
1700
1800
1900
2000

Useful illustrations :