SIM
SISTEMA INTERAMERICANO DE METROLOGÍA

SIM METROLOGY SCHOOL

National Research Council Canada | Conseil national de recherches Canada

MWG5: Time and Frequency Metrology

SPEAKER

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National Research Council Canada (NRC)

Bogotá, Colombia | August 2024

Organized by
Instituto Nacional de Metrología de Colombia

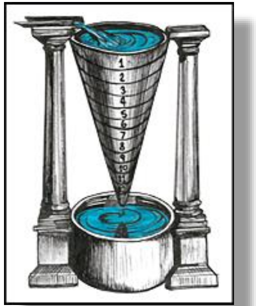
MEASUREMENT OF TIME

Measurement of Time

5000 years ago:

Babylonians and Egyptians began to measure time

- **solar day**
- **lunar month**
- **solar year**



Calendars

Aztec Calendar
https://www.calendar.com/history-of-the-calendar/

https://en.wikipedia.org/wiki/List_of_calendars

89 calendars:

- Solar (52)
- Lunar (2)
- Fixed (9)
- Lunisolar (23)
- Seasonal (2)

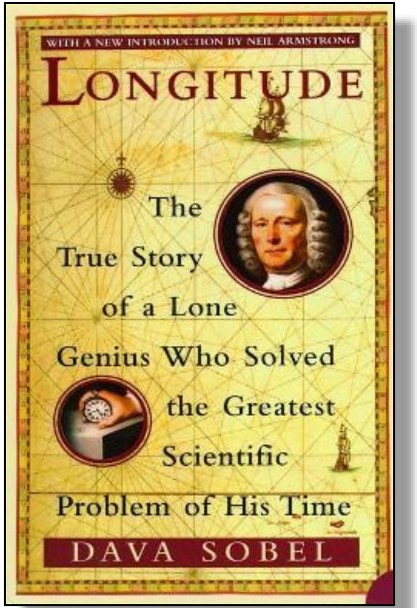
2024 in various calendars

Gregorian calendar	2024 *MMXXIV*
Ab urbe condita	2777
Armenian calendar	1473 ԹՎ ՌՆՀԳ
Assyrian calendar	6774
Bahá'í calendar	180–181
Balinese saka calendar	1945–1946
Bengali calendar	1431
Berber calendar	2974
British Regnal year	2 Cha. 3 – 3 Cha. 3
Buddhist calendar	2568
Burmese calendar	1386
Byzantine calendar	7532–7533
Chinese calendar	癸卯年 (Water Rabbit) 4721 or 4514 — *to* — 甲辰年 (Wood Dragon) 4722 or 4515
Coptic calendar	1740–1741
Discordian calendar	3190
Ethiopian calendar	2016–2017
Hebrew calendar	5784–5785
Hindu calendars	
- *Vikram Samvat*	2080–2081
- *Shaka Samvat*	1945–1946
- *Kali Yuga*	5124–5125
Holocene calendar	12024
Igbo calendar	1024–1025
Iranian calendar	1402–1403
Islamic calendar	1445–1446
Japanese calendar	Reiwa 6 (令和６年)
Javanese calendar	1957–1958
Juche calendar	113
Julian calendar	Gregorian minus 13 days
Korean calendar	4357
Minguo calendar	ROC 113 民国113年
Nanakshahi calendar	556
Thai solar calendar	2567
Tibetan calendar	阴水兔年 (female Water-Rabbit) 2150 or 1769 or 997 — *to* — 阳木龙年 (male Wood-Dragon) 2151 or 1770 or 998
Unix time	1704067200 – 1735689599

Measurement of Frequency

Pendulum clock:

- invented by Galileo in 16th century
- has two components:
    - **regular** natural process
    - counter



A book about John Harrison, an 18th-century clockmaker who created the first clock sufficiently accurate to be used to determine longitude at sea

Measurement of Time

-3000:

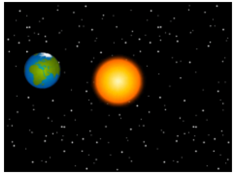
Babylonians and Egyptians began to measure time

- **solar day**
- **lunar month**
- **solar year**

1960:

CGPM resolution 9 (1960):

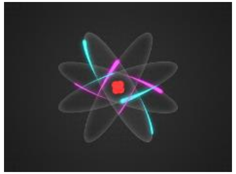
The second is the fraction 1/31 556 925.9747 of the **tropical year** for 1900 January 0 at 12 hours ephemeris time.



1967:

CGPM resolution 1 (1967):

The second 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



ATOMIC CLOCKS

SI second

CGPM resolution 9 (1960):

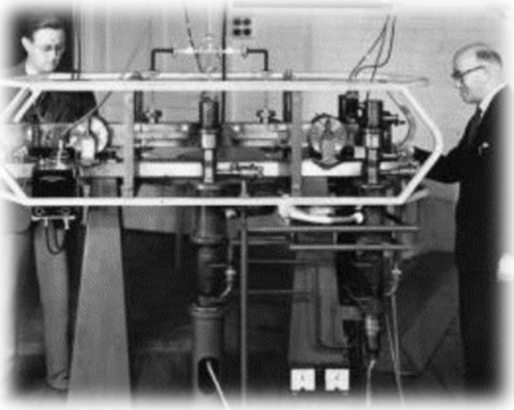
The second is the fraction 1/31 556 925.9747 of the tropical year for 1900 January 0 at 12 hours ephemeris time.

CGPM resolution 1 (1967):

The second 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

CGPM resolution 1 (2018):

The second, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{\mathrm{Cs}}$, the unperturbed ground-state hyperfine transition frequency of the caesium-133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}.

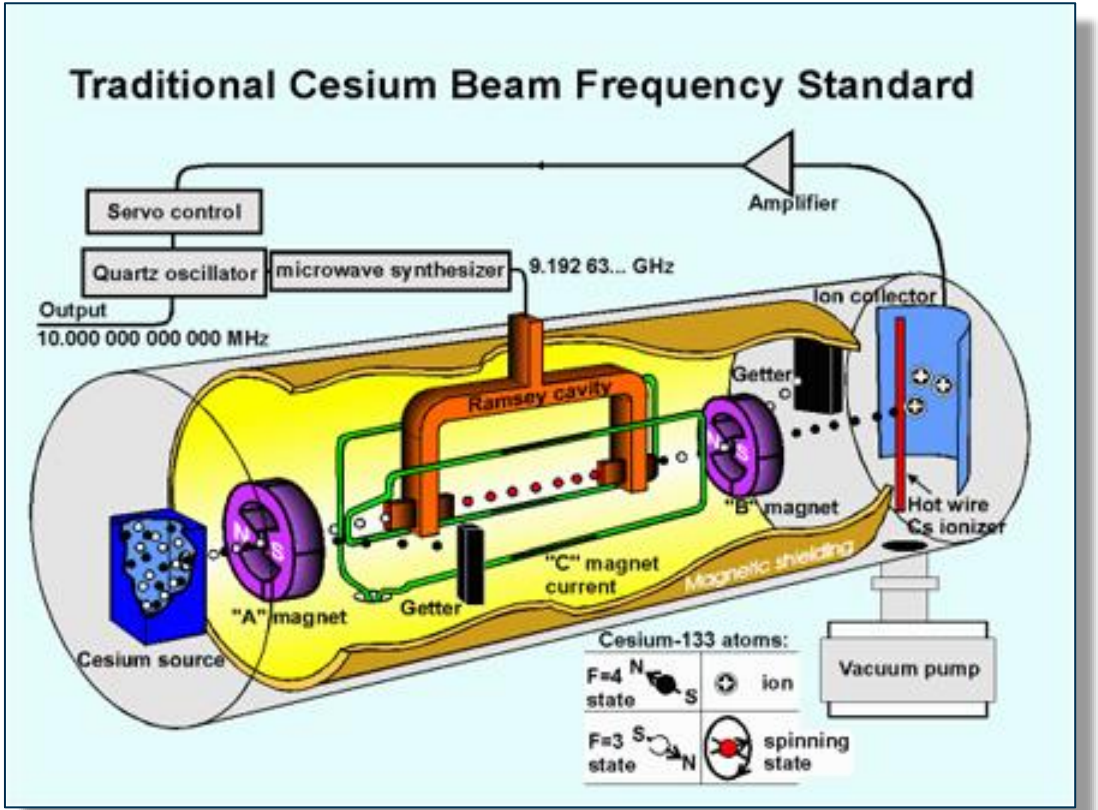


Essen & Parry (NPL, 1955)

Thermal beam Cs clock

Norman R. Ramsey

1989 Nobel Prize in Physics
or the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks

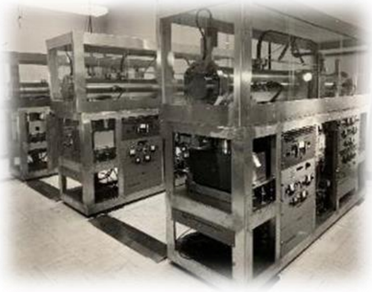


Cs beam clocks at NRC

NRC Cs-1
1950s-1960s

NRC Cs-3
1960s-1970s

NRC Cs-5
1970s-1980s



NRC Cs-6
1980s-1990s

1 / 86 400
of the mean solar day

1960

1 / 86 400
of the mean solar day
of the tropical year 1900

1967

9 192 631 770
periods of ^{133}Cs
ground state hyper-fine
transition

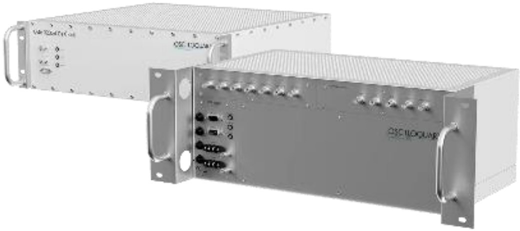
2018

$\Delta\nu_{Cs}$= 9 192 631 770 Hz

Commercial Atomic Clocks

caesium, rubidium, hydrogen



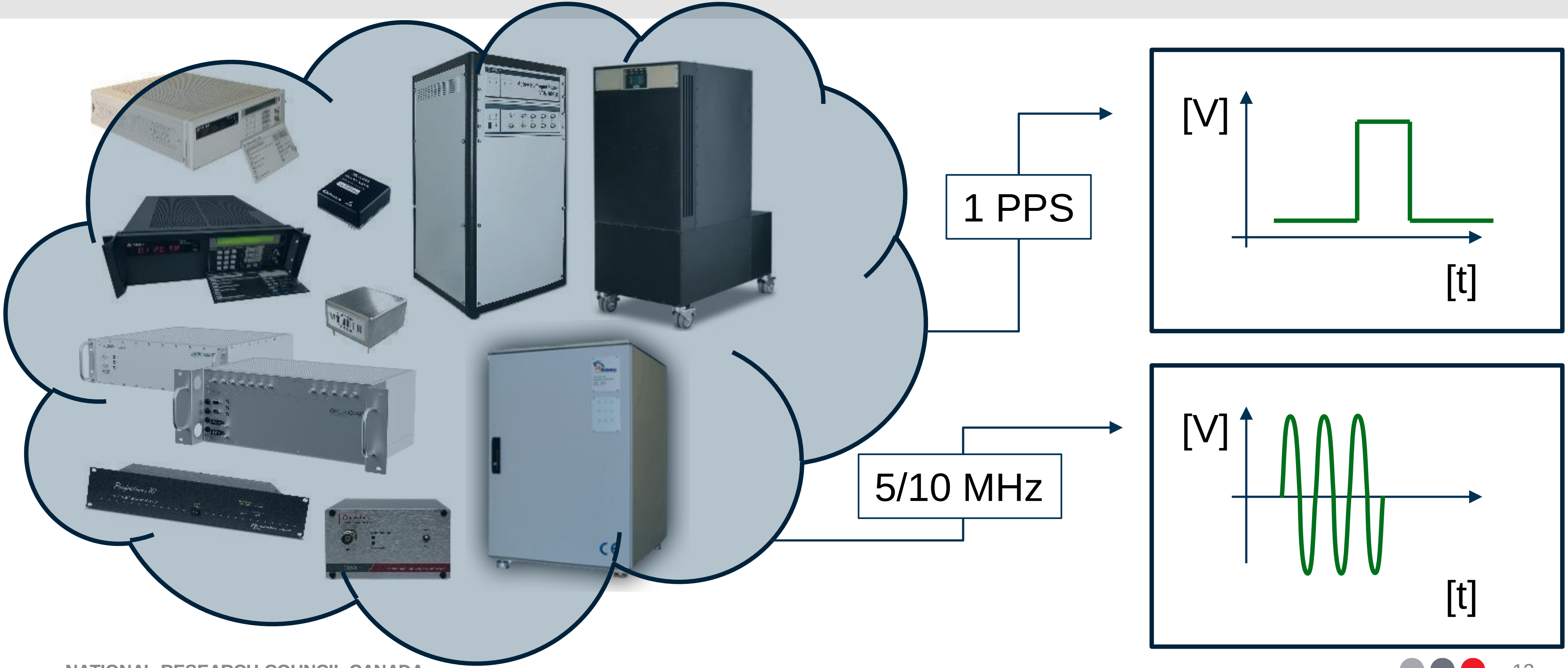




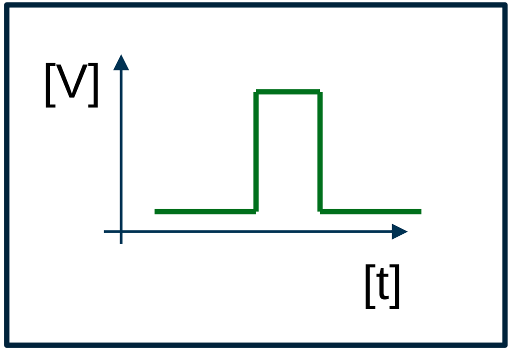


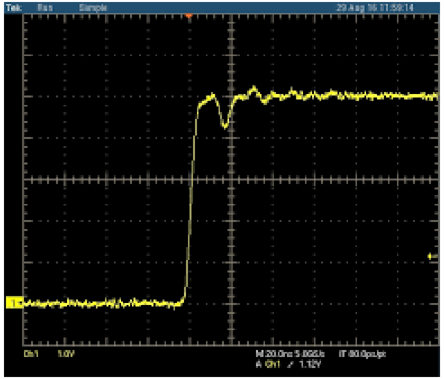

CLOCK DATA ANALYSIS

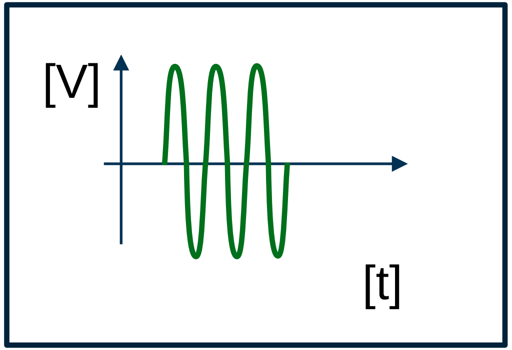
Atomic clock signals

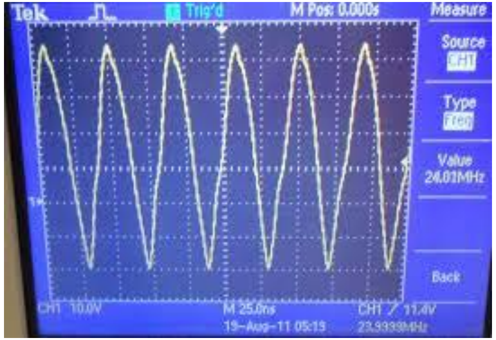


Time Metrology



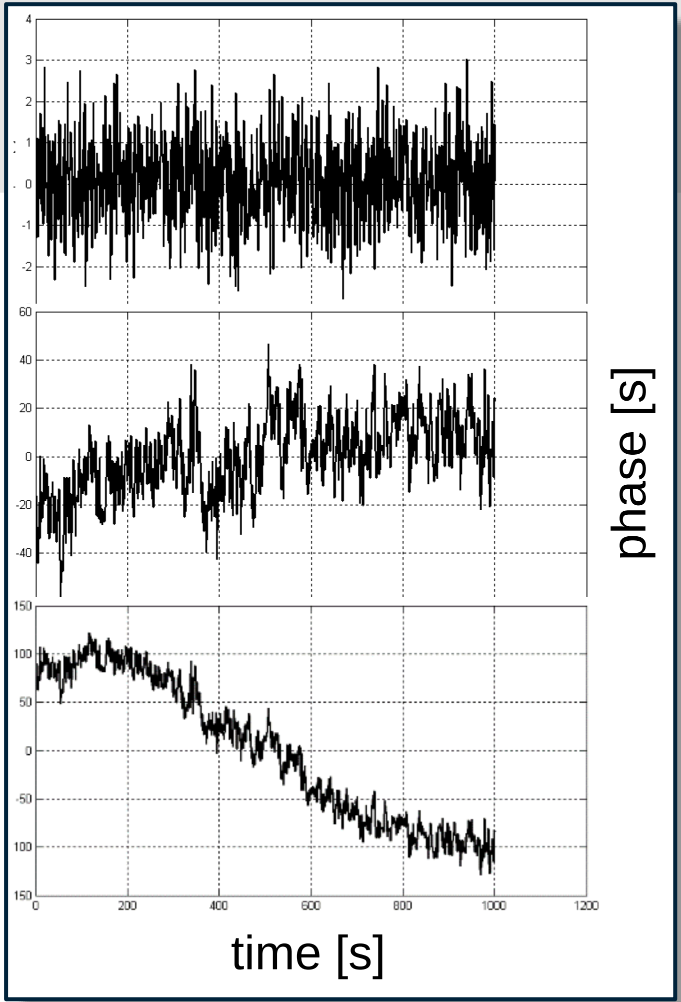






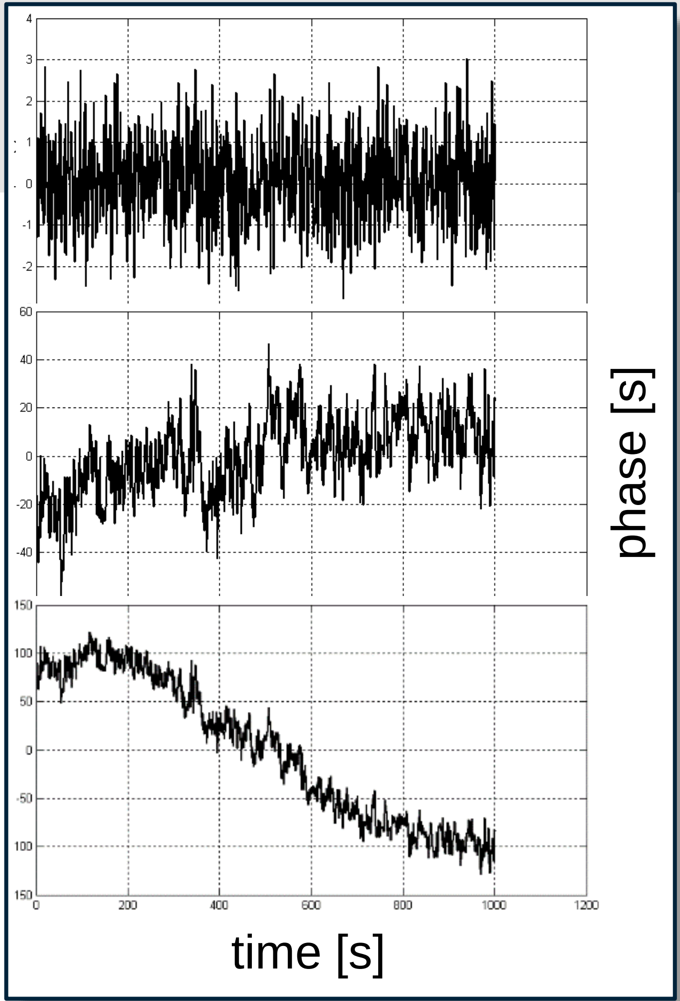
- rise time
- ringing
- voltage level
- DC offset
- amplitude
- skewing
- distortion

Statistical Analysis of Clocks Data



- How to analyze the data?
- How to assign uncertainties?

Statistical Analysis of Clocks Data



Overlapping **Allan Deviation**:

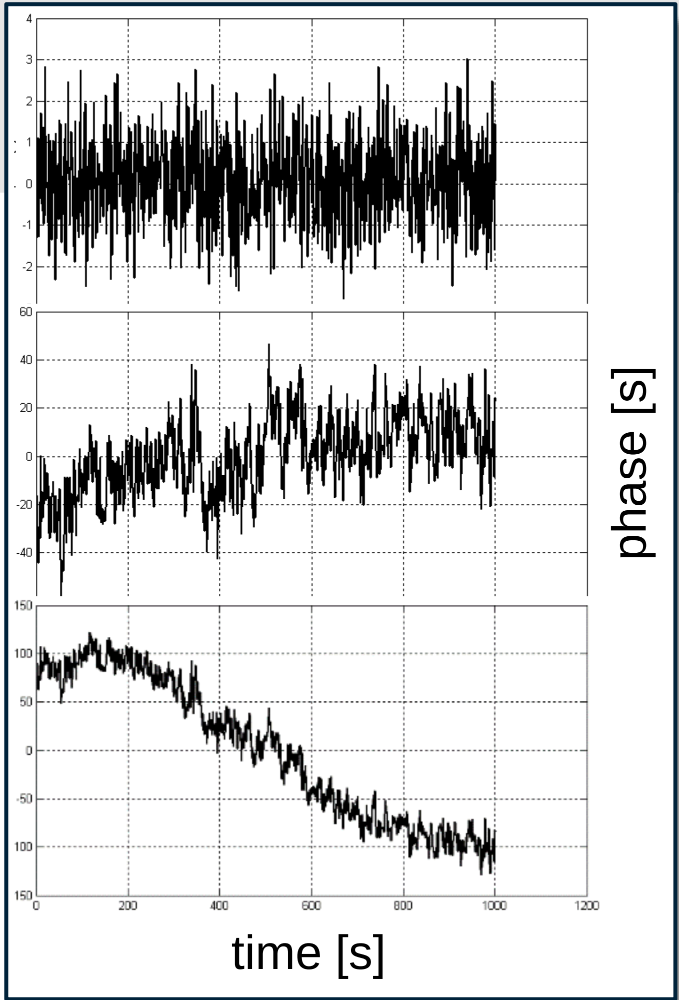
$$\sigma_y(\tau) = \sqrt{\left\langle \frac{1}{2\tau^2}\left[x_{i+2} - 2x_{i+1} + x_i\right]^2 \right\rangle} = \sqrt{\frac{1}{2}\left\langle \left(\overline{y}_{i+1} - \overline{y}_i\right)^2 \right\rangle}$$

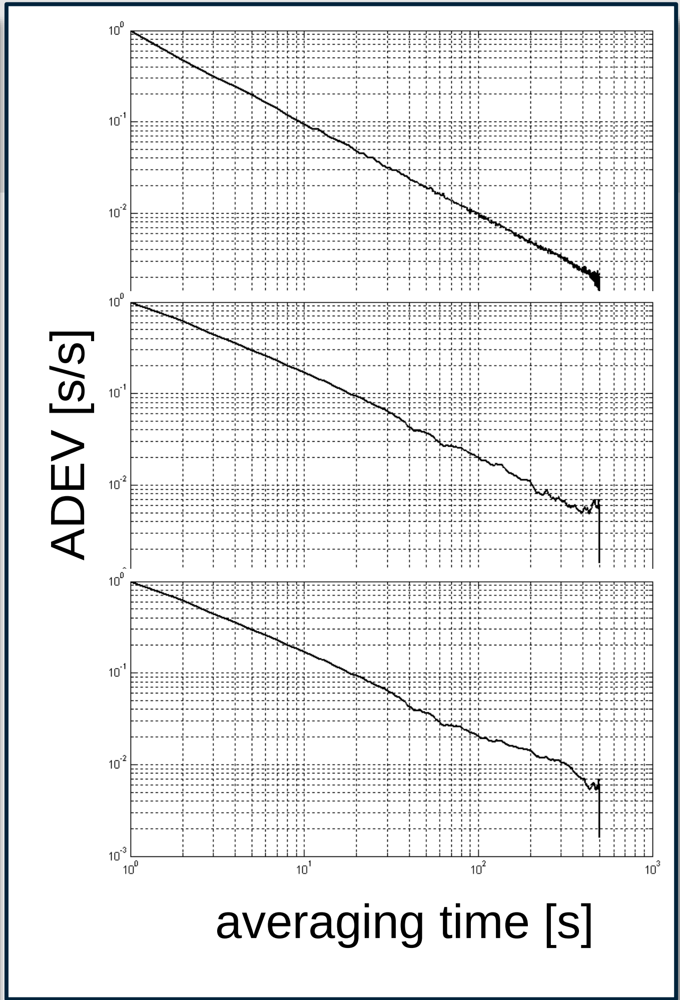
Modified Allan Deviation:

$$\operatorname{mod}\sigma_y(\tau) = \sqrt{\frac{1}{2}\left\langle \left[\frac{1}{n}\sum_{i=0}^{n-1}\overline{y}_{i+n} - \overline{y}_i\right]^2 \right\rangle}$$

x – phase difference [s]
y – fractional frequency offset [s/s]

Allan Deviation





Standard uncertainty:

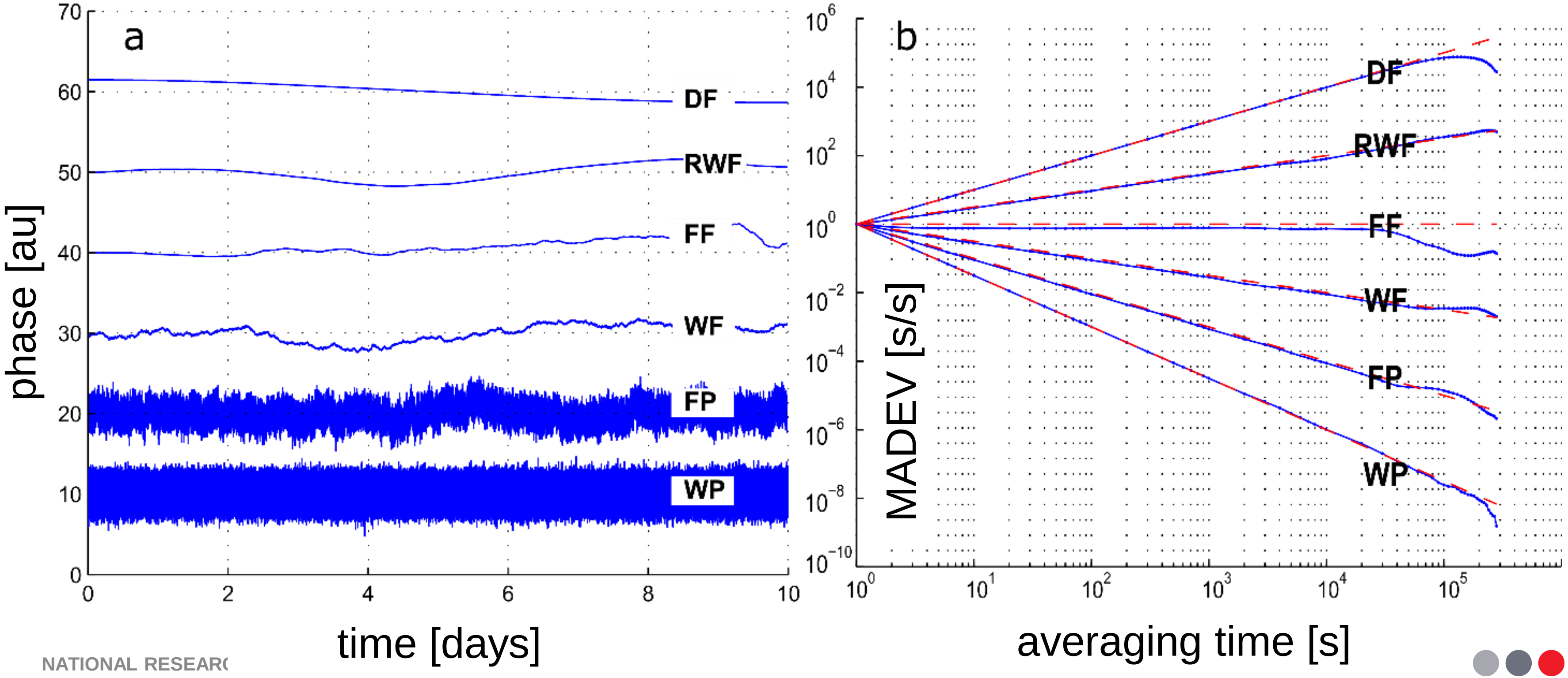
$$u_C = \sigma_y(\tau)$$

Allan Deviation for different noise types

- Noise types defined based on characteristic Fourier frequency power law: $S_y \sim f^n$
- Allan Deviation (**ADEV**) power law: $\sigma_y \sim \tau^\alpha$
- Modified Allan Deviation (**MADEV**) power law: $\sigma_y \sim \tau^b$

noise type	n	α	β
white phase, WP	2	-1	-3/2
flicker phase, FP	1	-1	-1
white frequency, WF	0	-1/2	-1/2
flicker frequency, FF	-1	0	0
frequency random walk, RWF	-2	1/2	1/2
frequency drift, DF	-3	1	1

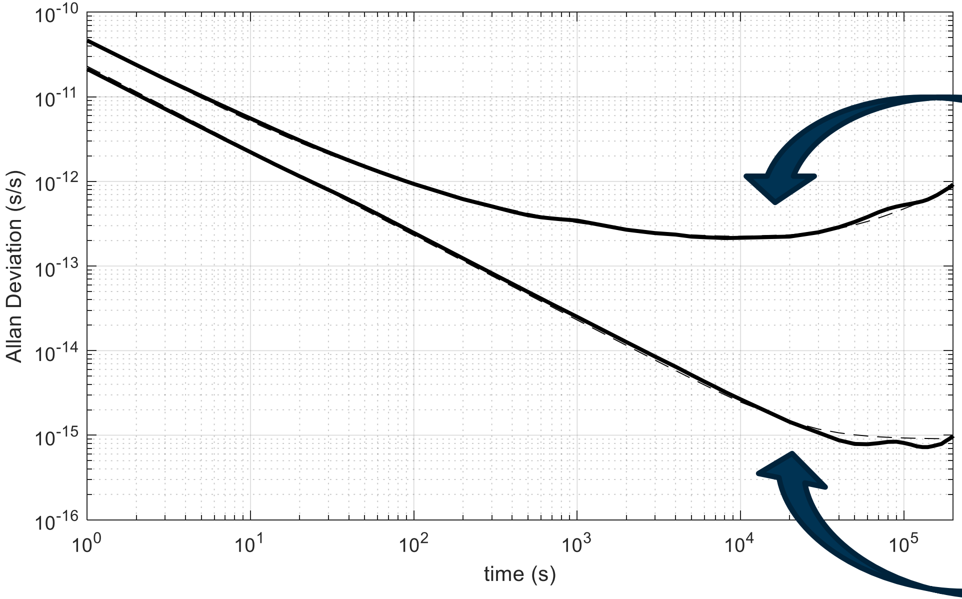
Noise Types


a
DF
RWF
FF
WF
FP
WP
phase [au]
time [days]
b
MADEV [s/s]
averaging time [s]

Example

Measurements with the Time Interval Counter

$$\sigma_y(\tau) = \sqrt{\sum_{i=-3}^{2} \sigma_{y,i}^2 \times \tau^i}$$



Rubidium Frequency Standard Model RFK:

WP $\sigma_{y,-2} = 4.5 \times 10^{-11} s^1$

WF $\sigma_{y,-1} = 8.0 \times 10^{-12} s^{1/2}$

FF $\sigma_{y,0} = 2.0 \times 10^{-13} s^0$

RWF $\sigma_{y,1} = 5.0 \times 10^{-16} s^{-1/2}$

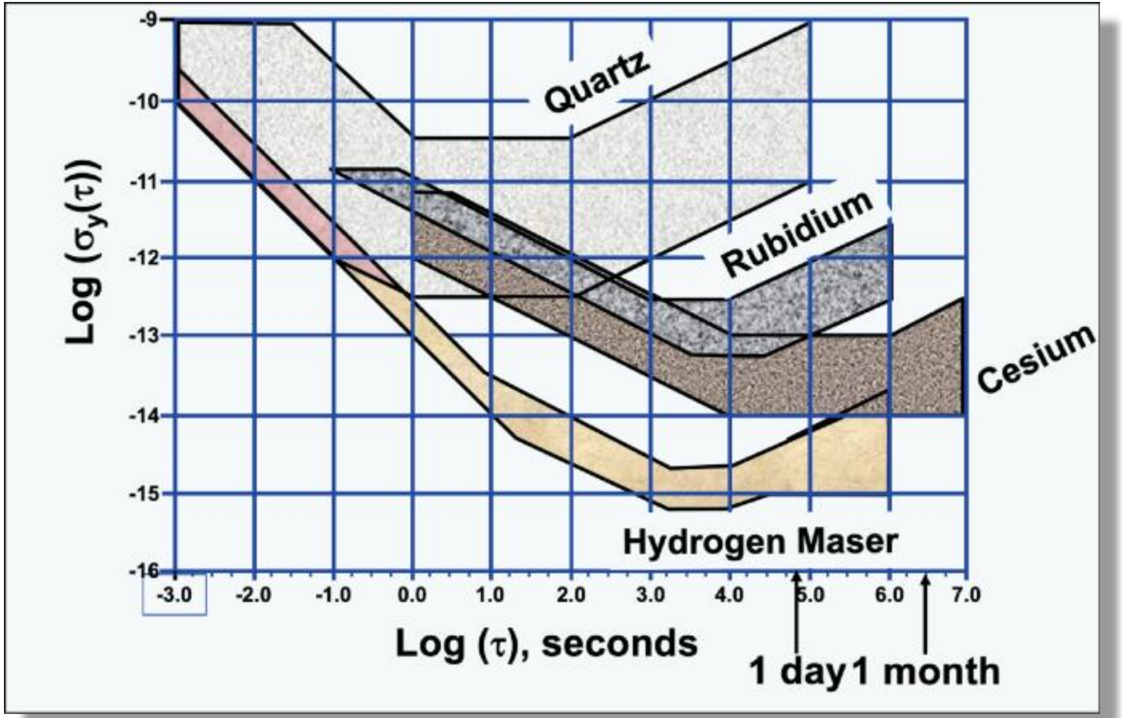
DF $\sigma_{y,2} = 4.0 \times 10^{-18} s^{-1}$

Hydrogen Maser:

WP $\sigma_{y,-2} = 2.3 \times 10^{-11} s^1$

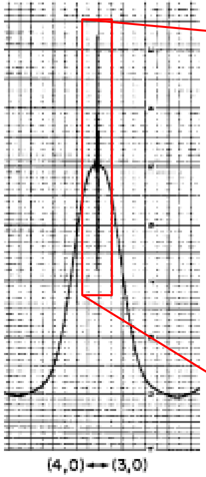
FF $\sigma_{y,0} = 9.0 \times 10^{-16} s^0$

Comparative clocks performance

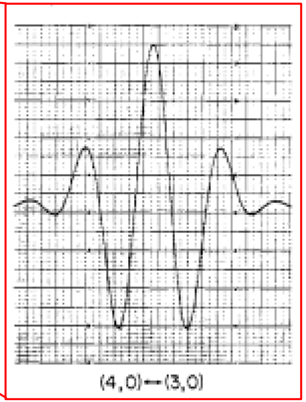


COLD ATOMS CLOCKS

Thermal beam Cs clock

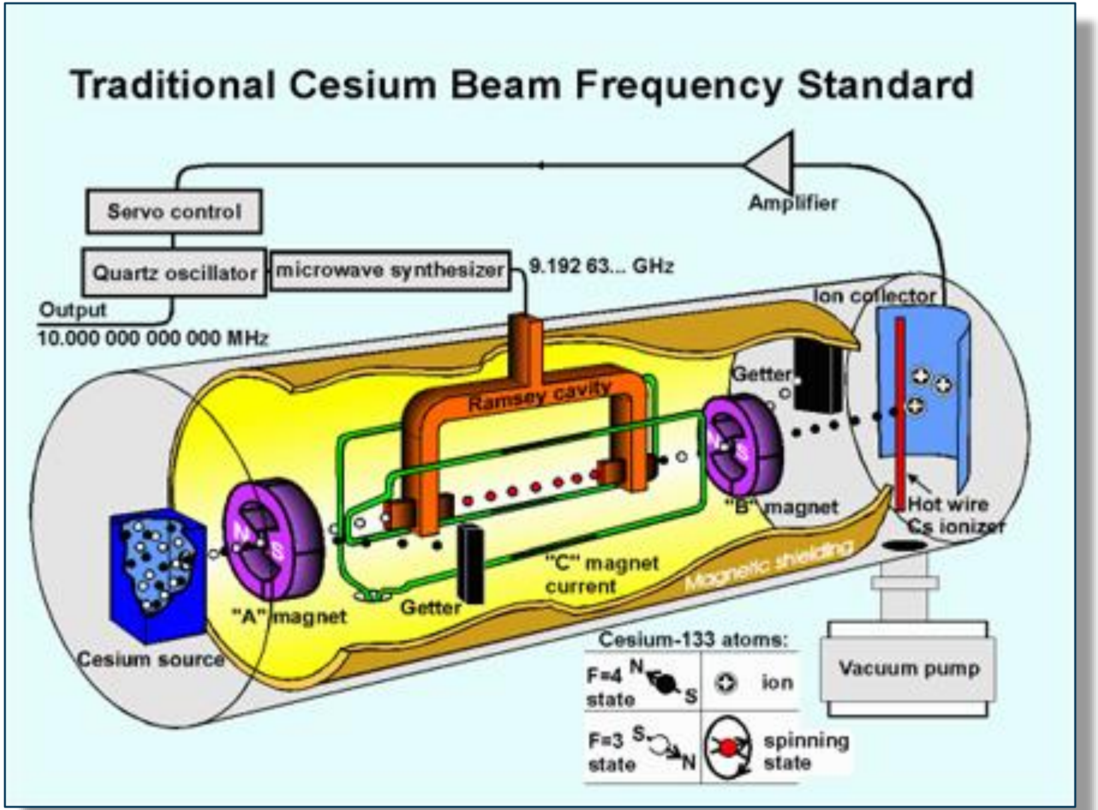


Mungall, A. G., *et al*, Metrologia 17.4 (1981)



FWHM ~ 100 Hz

$$p_g = \frac{1}{2}(1 - \cos\Delta\varphi),\, \Delta\varphi = \Delta\omega\Delta t$$



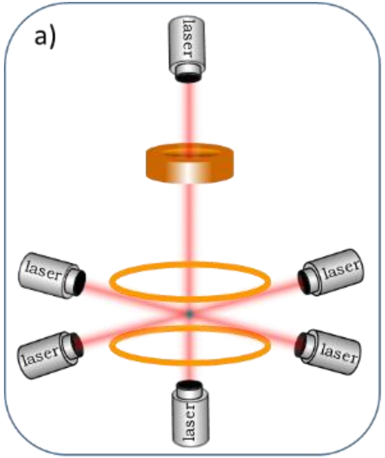
Cs Fountain clock

Claude Cohen-Tannoudji

Steven Chu

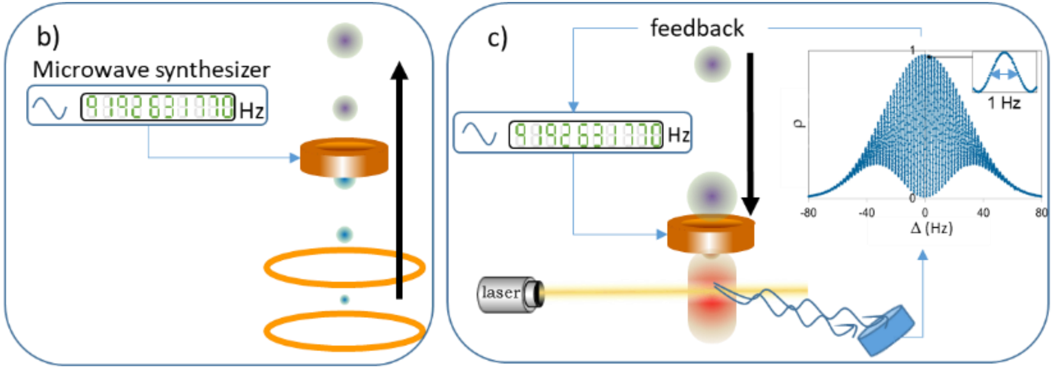
William D. Phillips

1997 Nobel Prize in Physics
for development of methods to cool and trap atoms with laser light

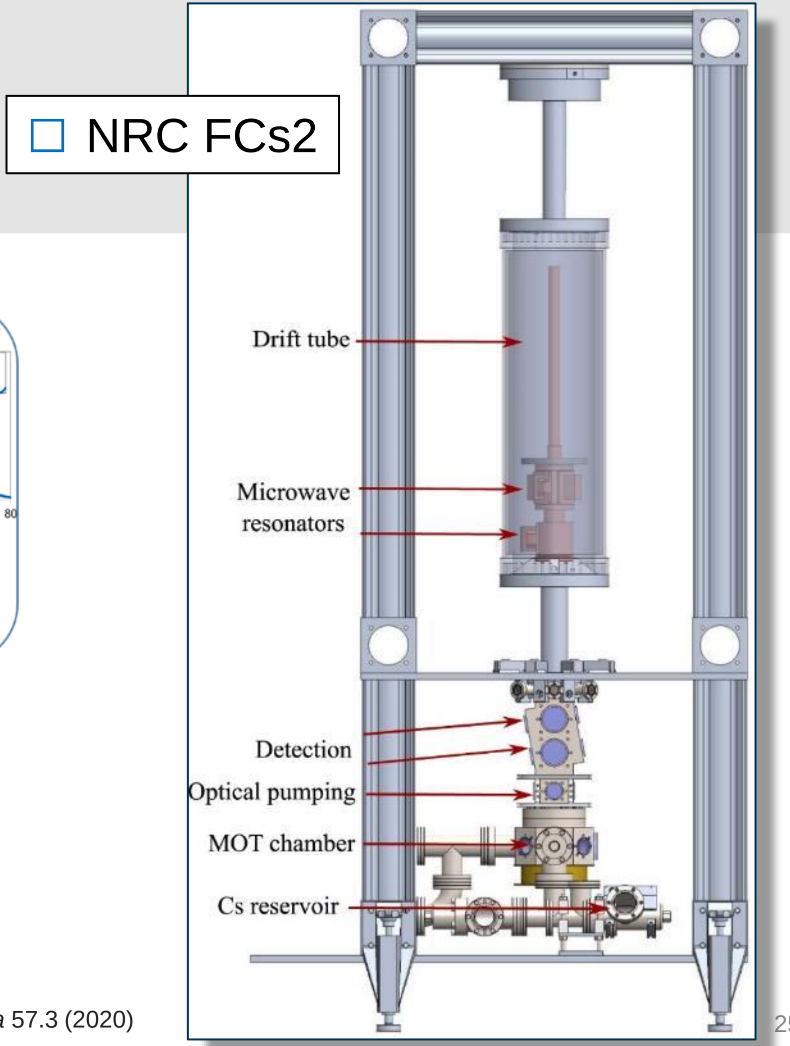


Laser cooling down to $T \sim 1\ \mu K$

Cs Fountain clock



FWHM ~ 1 Hz



Beattie, S., et al. *Metrologia* 57.3 (2020)

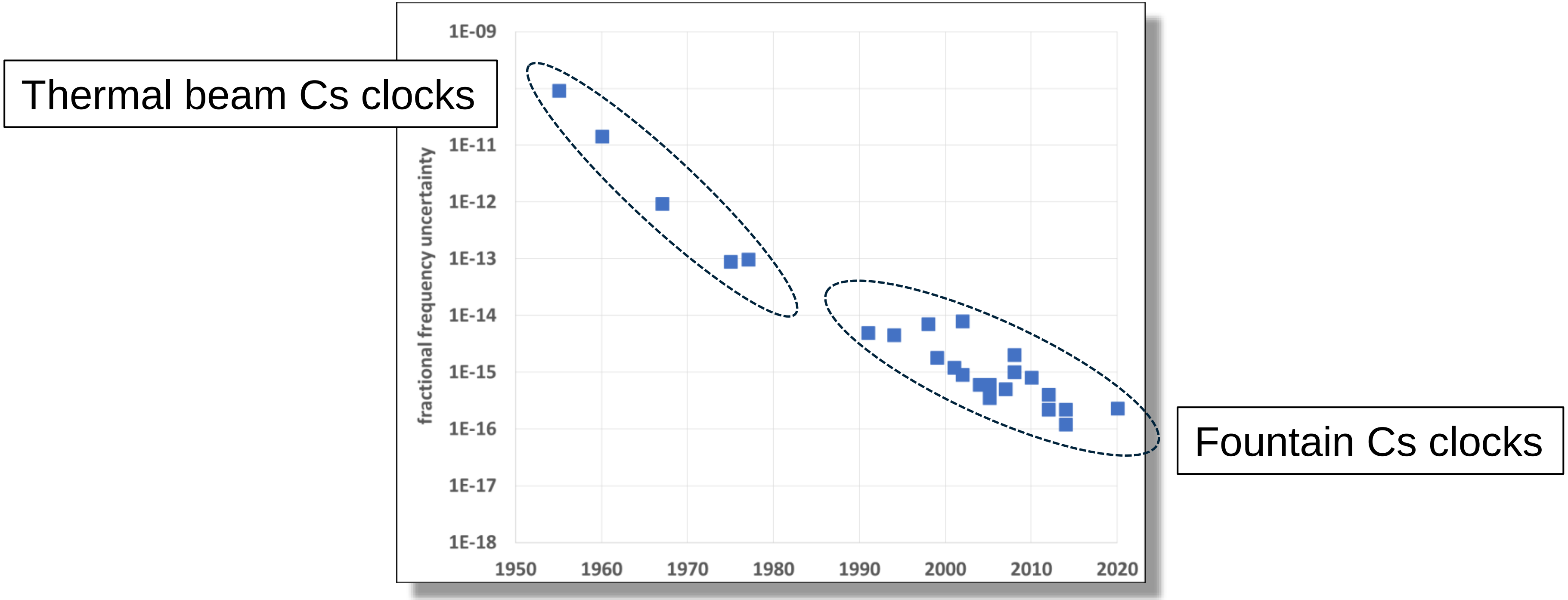
NRC Caesium Fountain Uncertainty budget

Effect	Uncertainty $[1 \times 10^{-16}]$	Uncertainty $[1 \times 10^{-16}]$
Zeeman effect	0.2	0.2
BBR	0.7	0.7
Gravitational redshift	0.03	0.03
Cold collisions	1.0	0.3
MW leakage	1.0	0.2
MW phase transients	0.8	0.5
DCP m=0	0.2	0.2
DCP m=1	1.3	1.0
DCP m=2	0.2	0.2
MW lensing	0.2	0.2
Total	**2.3**	**1.4**
year	2020	2023

reported expected

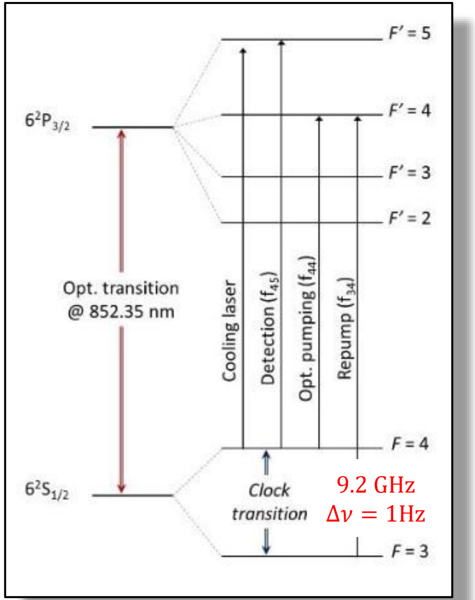
S. Beattie, *et al*, *Metrologia* 57.3 (2020)
S. Beattie, *et al*, *Metrologia* 60.4 (2023)
S. Beattie, *et al*, EFTF-IFCS 2023
S. Beattie, *et al*, 9SFSM 2023

Caesium Clocks Accuracy



From Microwave to Optical clocks

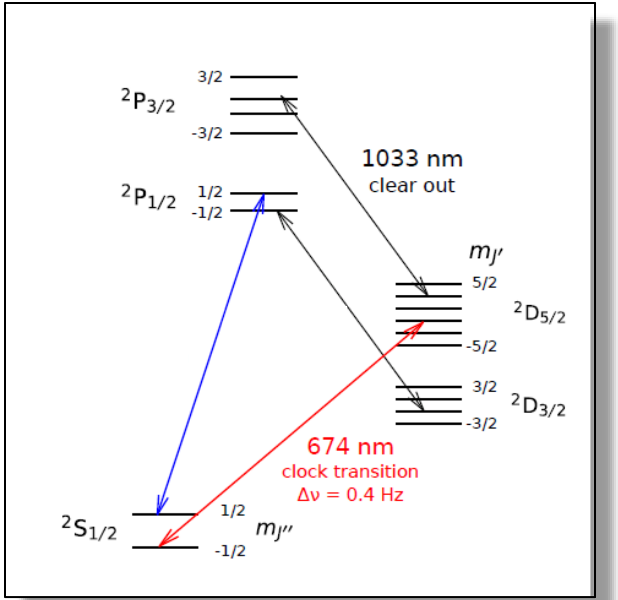
^{133}Cs



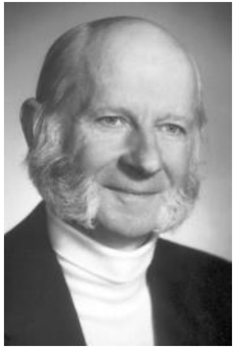
$$\frac{1}{9.2 \times 10^9} \approx \mathbf{1 \times 10^{-10}}$$

$$\frac{0.4}{445 \times 10^{12}} \approx \mathbf{1 \times 10^{-15}}$$

$^{88}Sr^{+}$

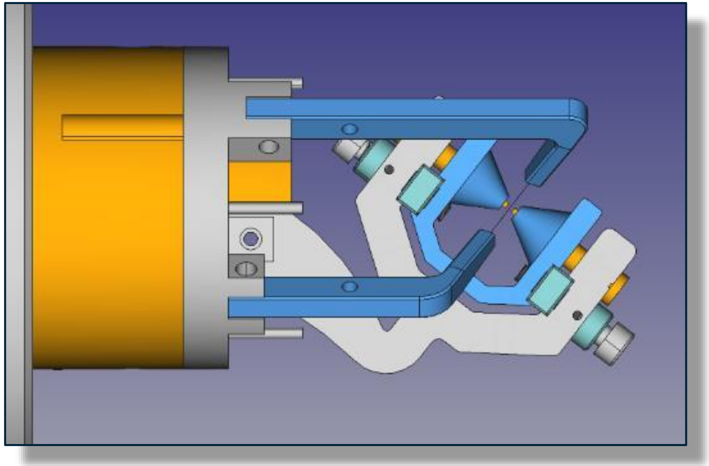


Ion Traps



Wolfgang Paul **Hans G. Dehmelt**

1989 Nobel Prize in Physics
for the development of the ion trap technique



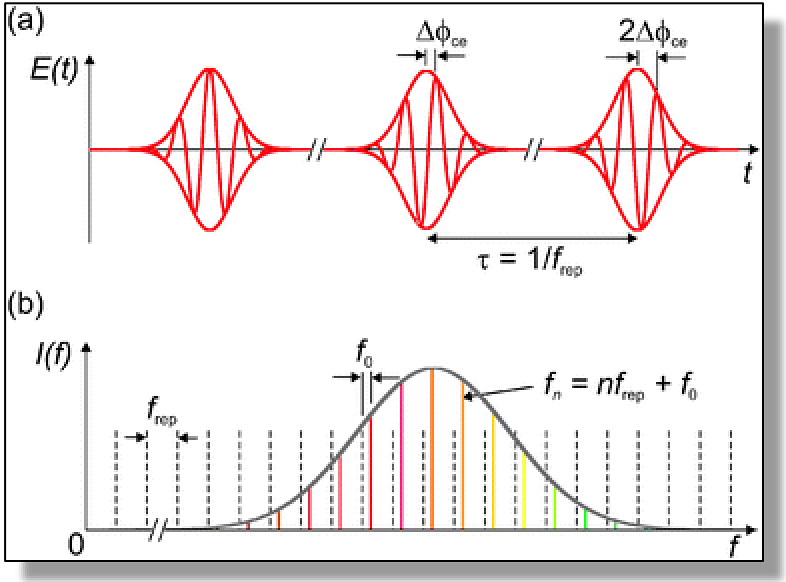
NRC $^{88}Sr^{+}$ POC trap

Ultrastable Lasers and Frequency Combs

John L. Hall

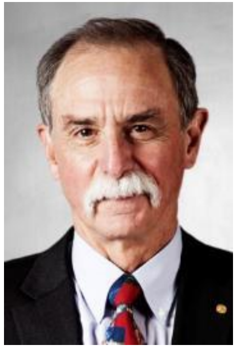
Theodor W. Hansch

2012 Nobel Prize in Physics
for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique.



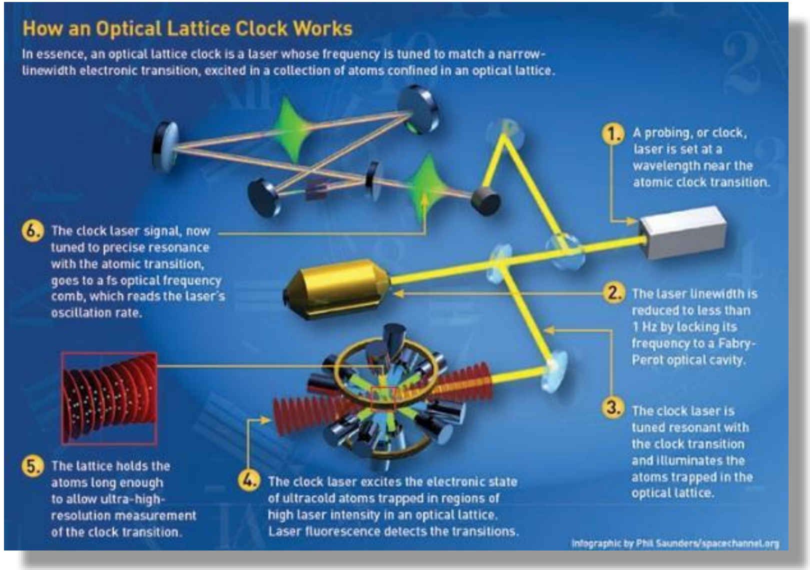
adapted from Margolis H., *Chem. Soc. Rev.*, 41 (2012)

Optical Clocks



David Wineland

2012 Nobel Prize in Physics
for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems



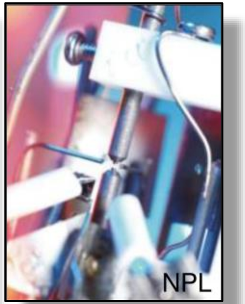
adapted from Oates. C. W. et. al., *Optics and Photonics News* 26.1 (2015)

Optical clocks - an incomplete list

Species	Transition	Clock transition
^{87}Sr	$^1S_0 - {}^3P_0$	698 nm
^{171}Yb	$^1S_0 - {}^3P_0$	578 nm
$^{27}Al^+$	$^1S_0 - {}^3P_0$	267 nm
$^{10}B^+$	$^1S_0 - {}^3P_0$	268 nm
$^{138}Ba^+$	$^2S_{1/2} - {}^2D_{5/2}$	1760 nm
$^{40}Ca^+$	$^2S_{1/2} - {}^2D_{5/2}$	729 nm
$^{199}Hg^+$	$^2S_{1/2} - {}^2D_{5/2}$	282 nm
$^{115}In^+$		237 nm
$^{171}Yb^+$	$^2S_{1/2} - {}^2F_{7/2}$	467 nm
$^{171}Yb^+$	$^2S_{1/2} - {}^2D_{3/2}$	436 nm
$^{88}Sr^+$	$^2S_{1/2} - {}^2D_{5/2}$	674 nm

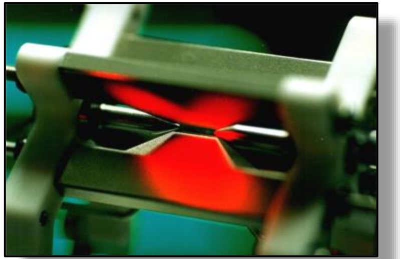
Yb^+ @ PTB

Hg^+ @ NIST



Sr^+ @ NPL

Sr^+ @ NRC

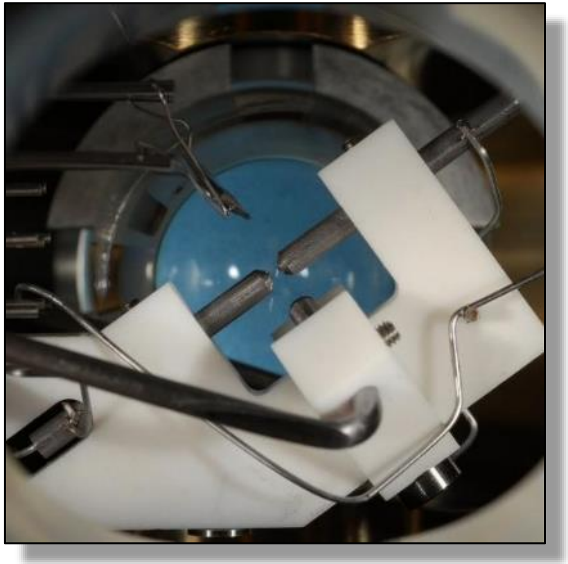


Ca^+ @ Innsbruck

adapted from P. Dubé course on Ion Optical Clocks, 2015

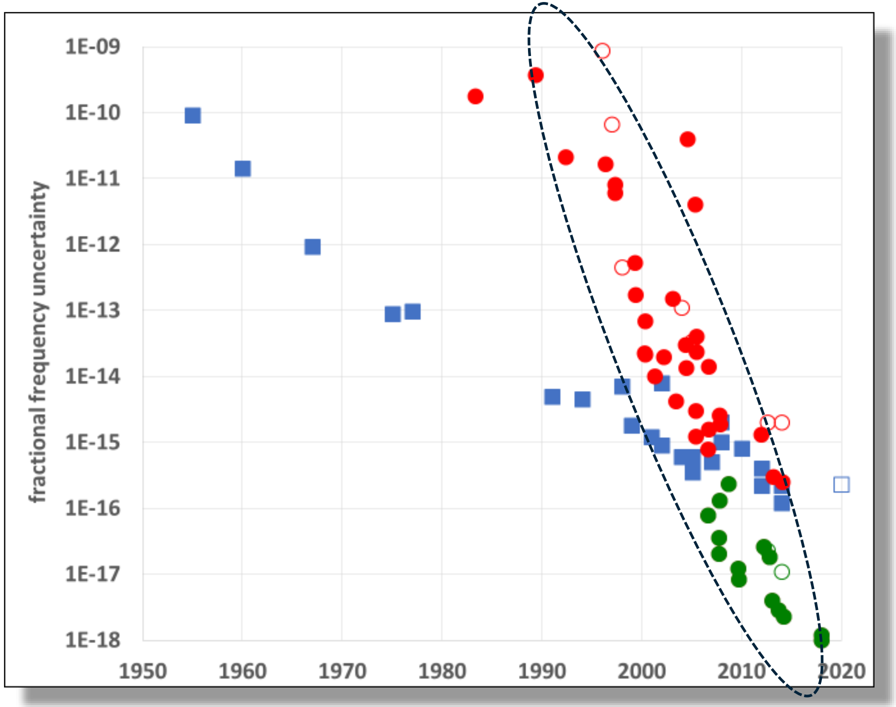
NRC Sr+ ion Uncertainty Budget

Effect	**Uncertainty** $[1 \times 10^{-18}]$	**Uncertainty** $[1 \times 10^{-18}]$
BBR	11	11
Gravitational redshift	2.0	2.6
Collisional shift (with background gas)	2.0	2.6
AC Stark shift	2.0	0.07
Micromotion shifts	0.1	0.2
Doppler Shift (2^{nd} order, thermal)	0.8	0.8
AOM frequency error	10	0.2
Total	**15**	**11.7**
Link uncertainty	1700	432
year	2017	2023



P. Dube, *et al*, *Metrologia* 54.3 (2017)
B. Jian, *et al*, *Metrologia* 60.1 (2023)

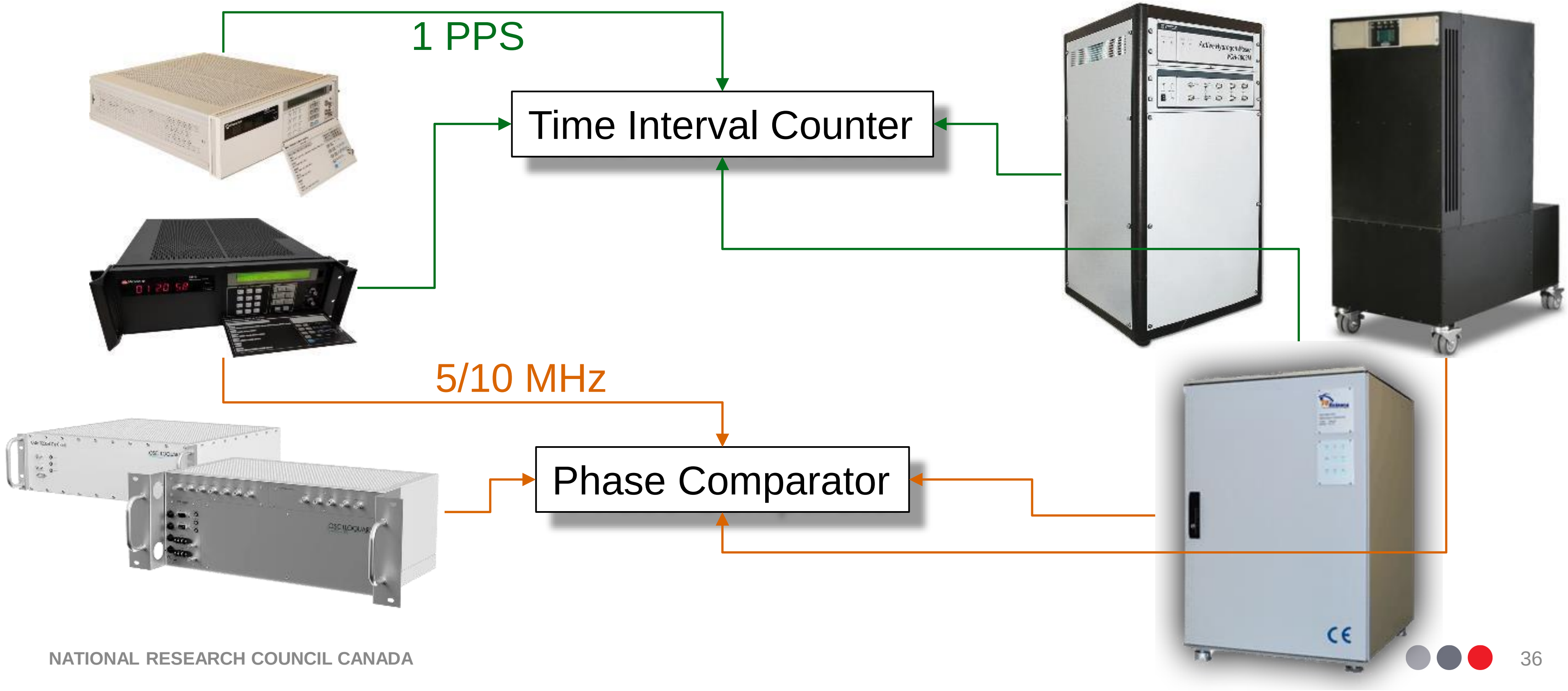
Optical Clocks Accuracy



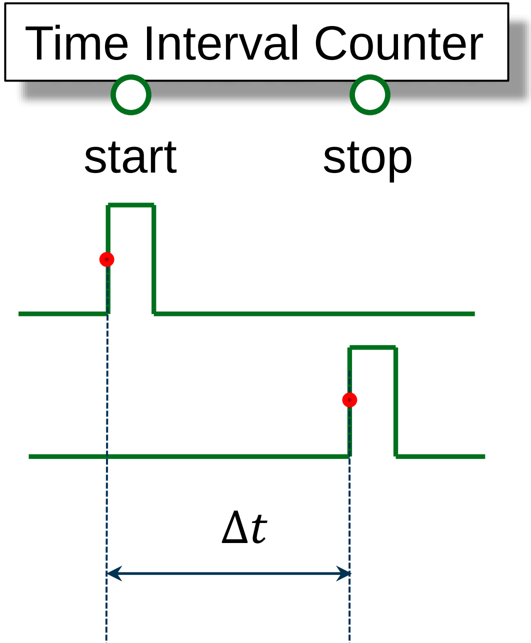
Optical clocks

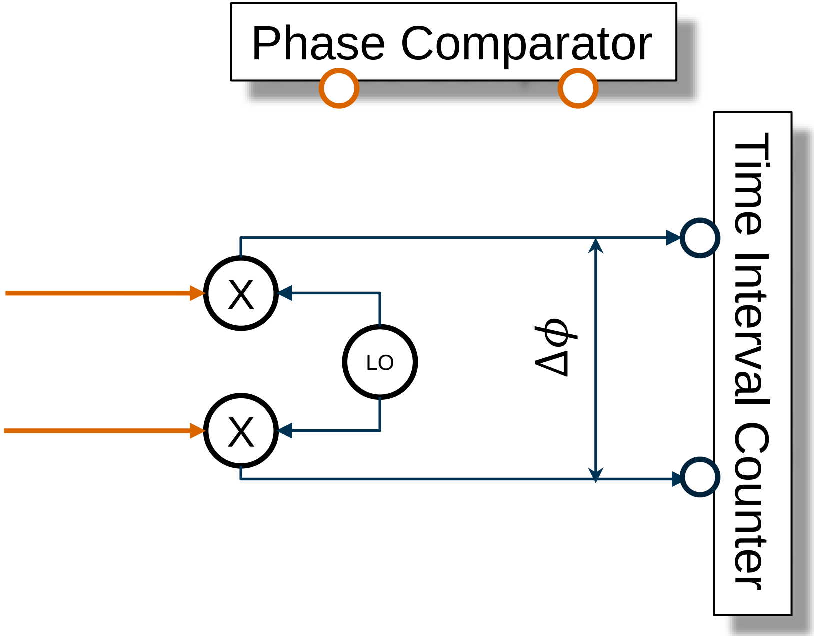
TIME AND FREQUENCY TRANSFER

Clocks Comparisons – in the laboratory

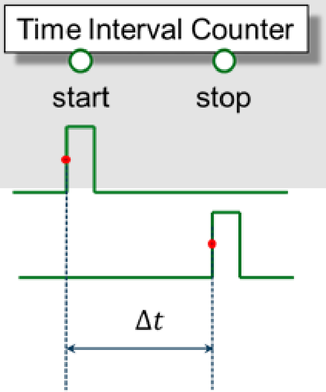


Time Interval Counter and Phase Comparator

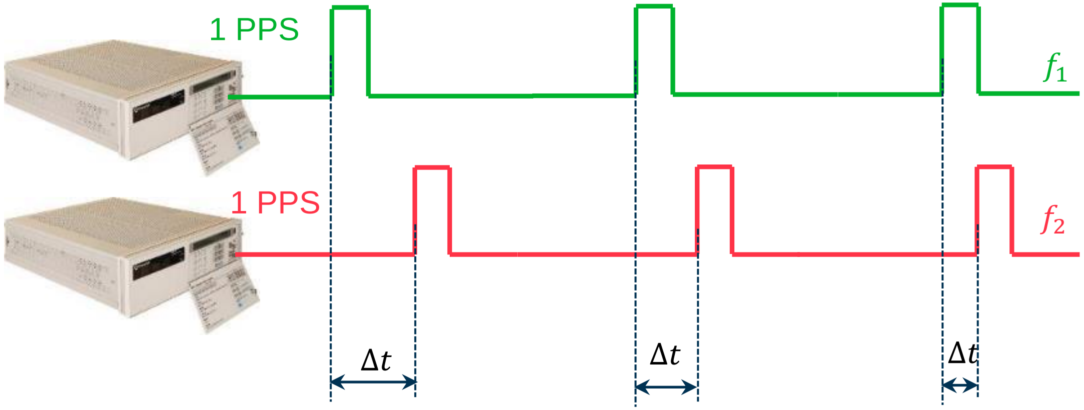




Time Interval Counter

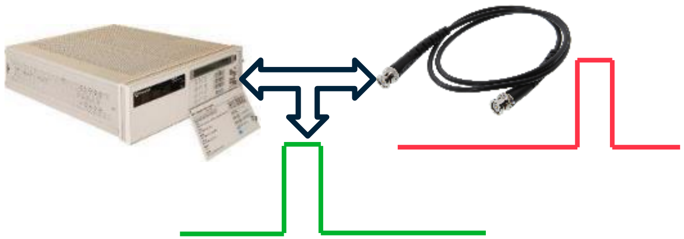


- Time offset measurements
- Frequency offset measurements



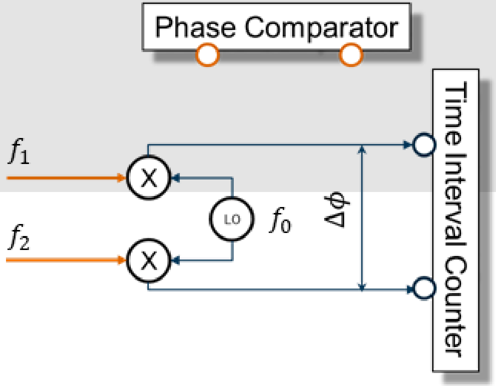
$$f_1 - f_2 = \frac{\partial \Delta t(t)}{\partial t}$$

- Time delay measurements



$1 \text{ ft in the vacuum} \cong 1\ ns$

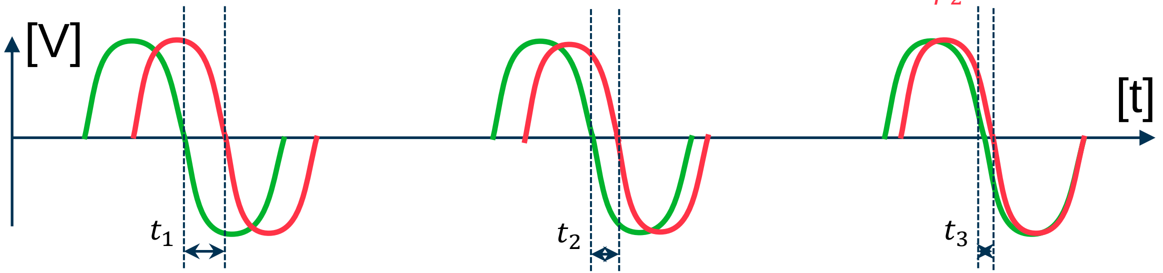
Phase Comparator



- Frequency offset measurements

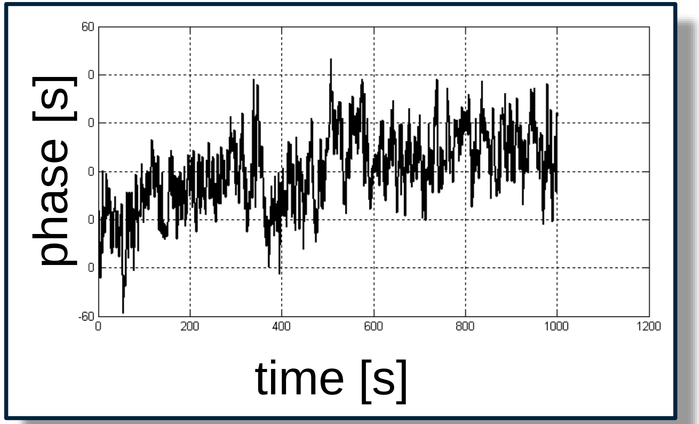
$$\cos(2\pi f_1 t) \times \cos(2\pi f_0 t) = \frac{1}{2}\cos(2\pi[f_1 + f_0]t) + \frac{1}{2}\cos\overbrace{(2\pi[f_1 - f_0]t)}^{\phi_1}$$

$$\cos(2\pi f_2 t) \times \cos(2\pi f_0 t) = \frac{1}{2}\cos(2\pi[f_2 + f_0]t) + \frac{1}{2}\cos\underbrace{(2\pi[f_2 - f_0]t)}_{\phi_2}$$



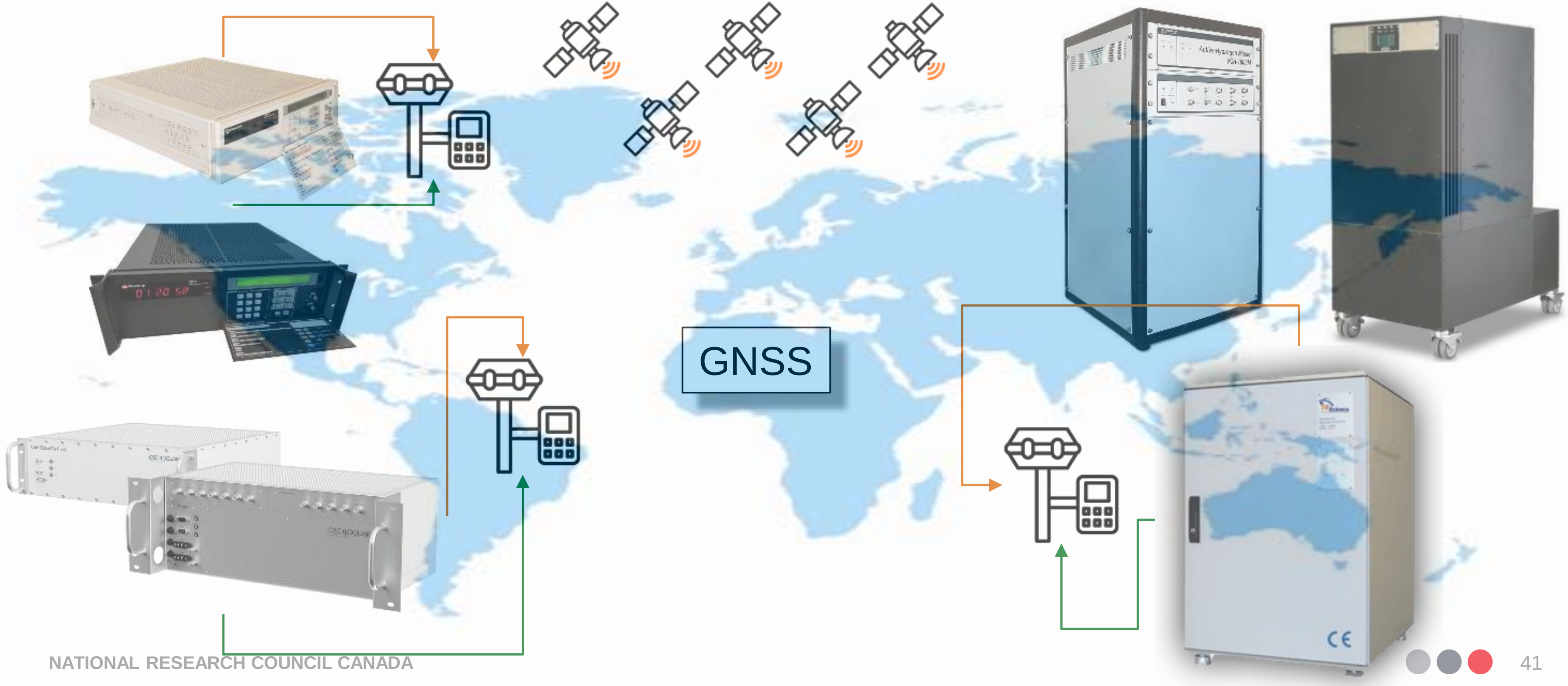
$\Delta\phi(t_1) = 2\pi[f_1 - f_2]t_1$ $\Delta\phi(t_2)$ $\Delta\phi(t_3)$

$$f_1 - f_2 = \frac{\partial \Delta\phi(t)}{\partial t}$$



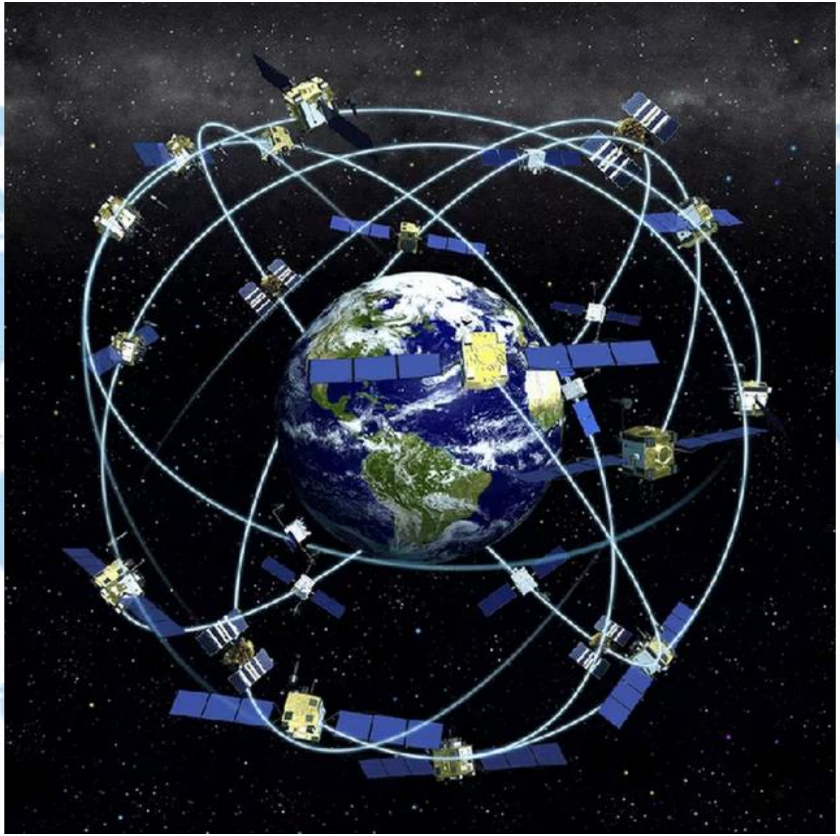
Clocks Comparisons – between the laboratories

Clocks Comparisons – between the laboratories



GNSS: Global Navigation Satellite Systems

USNO

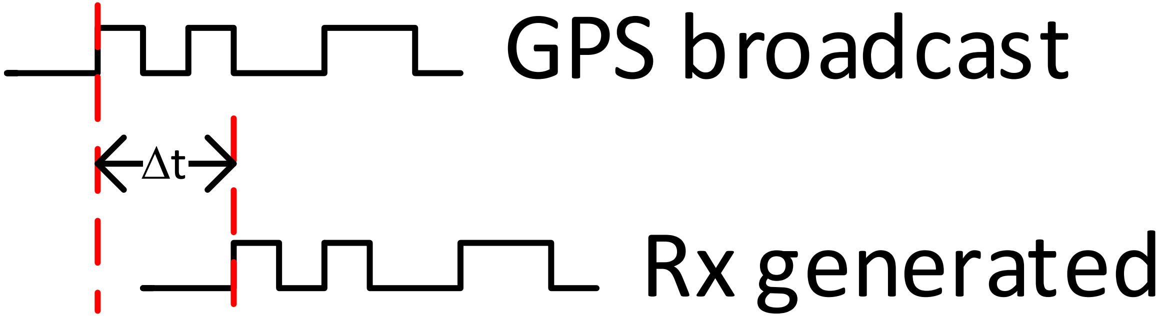


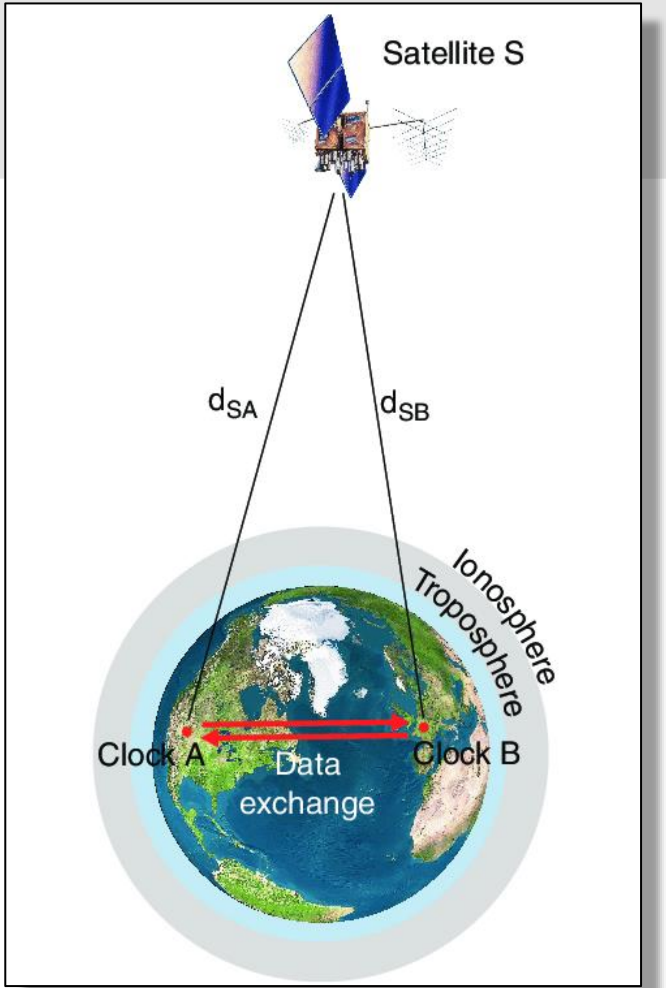
SU

EU

NIM

Common View GPS



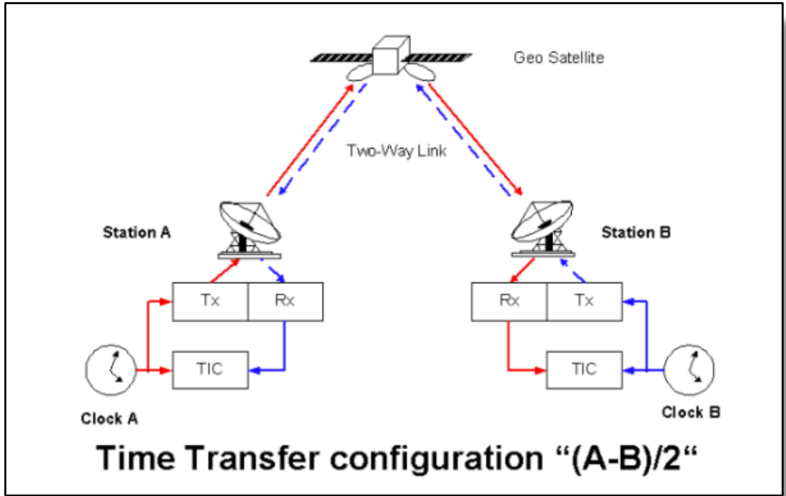


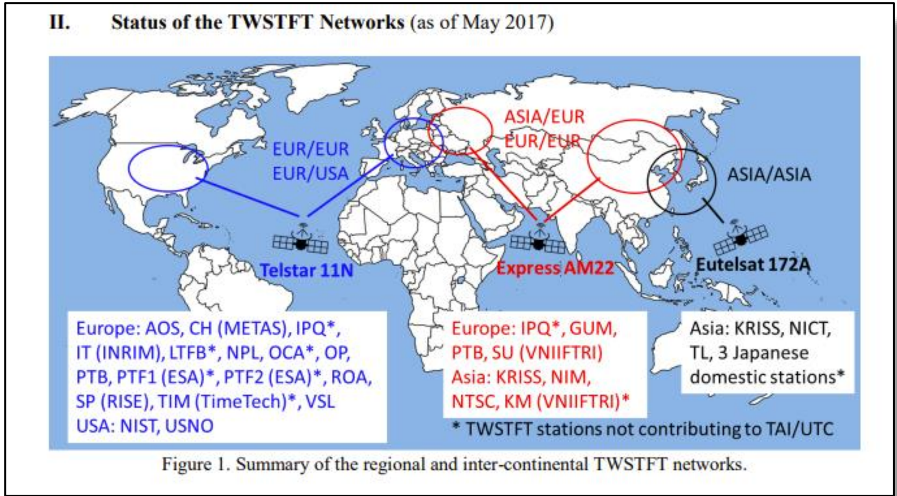
$$(\text{Clock A} - S) - (\text{Clock B} - S) = (T_A - T_B) + (d_{SA} - d_{SB})$$

Clock Comparisons Techniques

Link type	Typical Uncertainty
Global Navigation Satellite System	$1 \times 10^{-15}/\mathrm{T[d]}$
Two Way Satellite Time and Frequency Transfer	1×10^{-17}@ 100s d
Optical Fiber Links	$< 1 \times 10^{-18}$
Transportable Clocks	1×10^{-17}
Free Space Optical Links	1×10^{-18}@ 5 min
Optical Satellite Links	1×10^{-18}@ 5 min

Two Way Satellite Time and Frequency Transfer

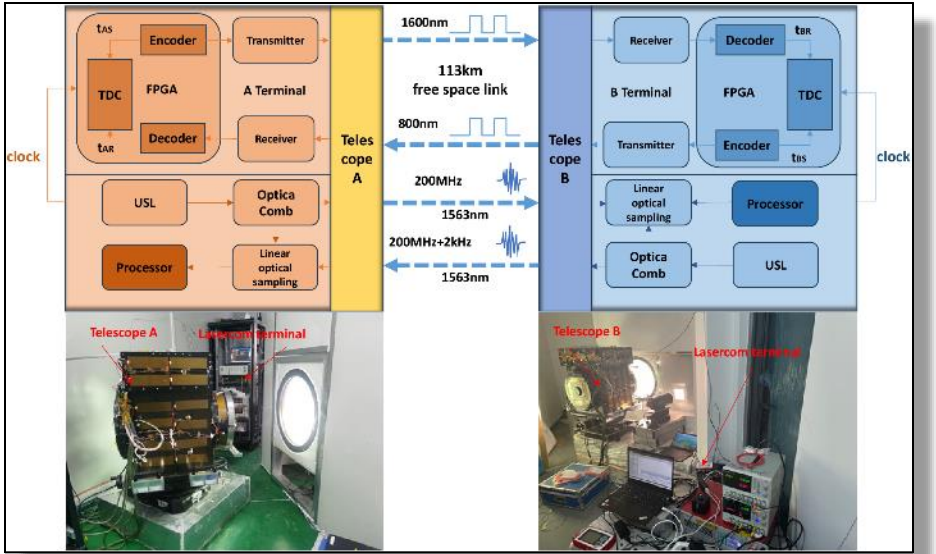


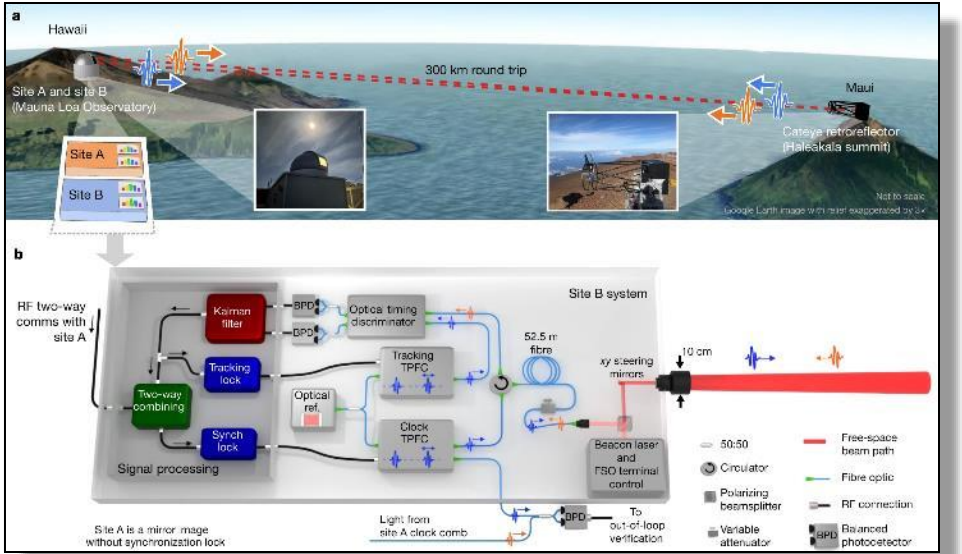


W. Schäfer, T. Feldmann, 8SFTSM, 2015

CCTF WG-TWSTF Report, May 2017

Free Space Optical Time and Frequency Transfer





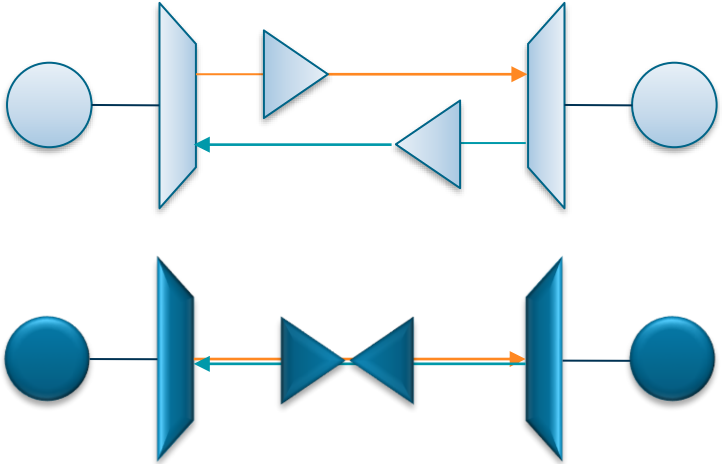
Yu-Xiang Cheng, et. al., Opt. Express 32, (2024)
Time transfer over 113 km free space laser communication channel

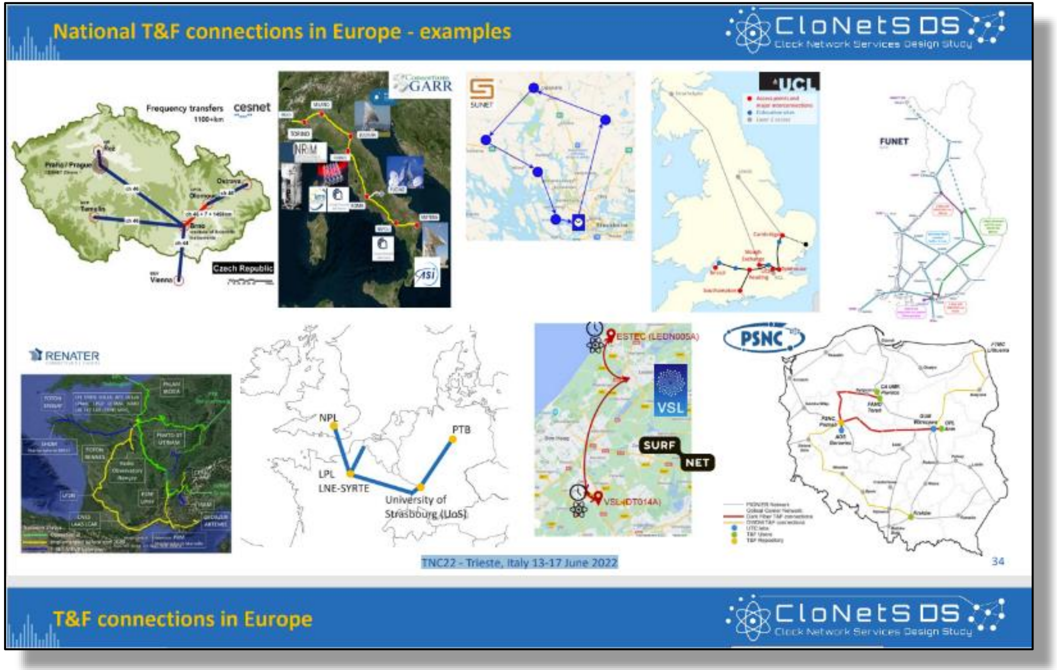
Caldwell, E.D., et al. Nature 618, (2023)
Quantum-limited optical time transfer for future geosynchronous links

Fibre Time and Frequency Transfer

EndRun

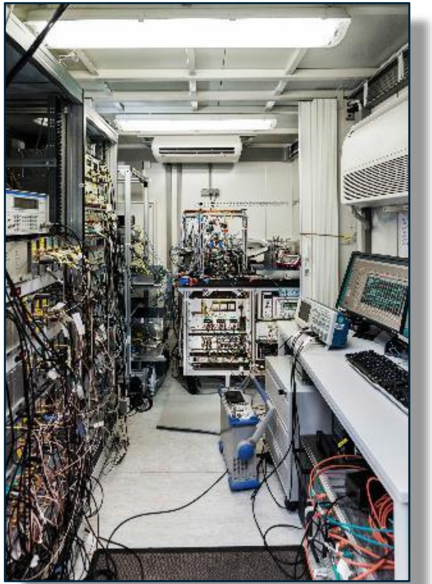
Safran



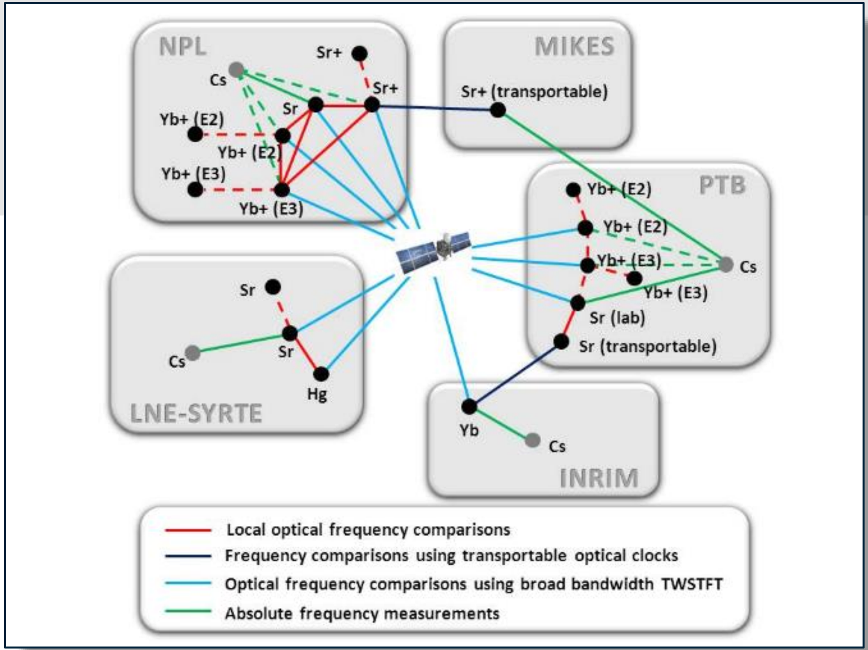


https://www.netnod.se/sites/default/files/2023-03/Nr.6_Sven-Christian%20Ebenhag.pdf

Transportable clocks (Frequency Comparisons)

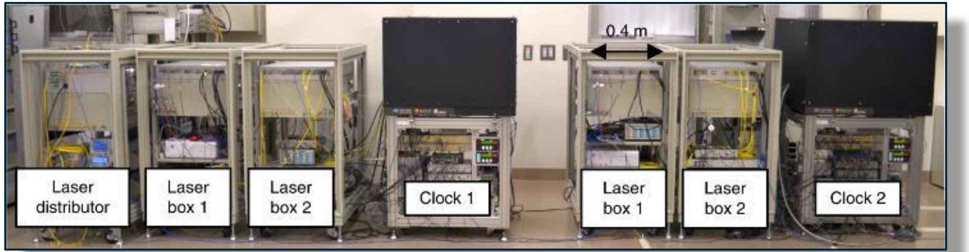


PTB
Sr Lattice Clock



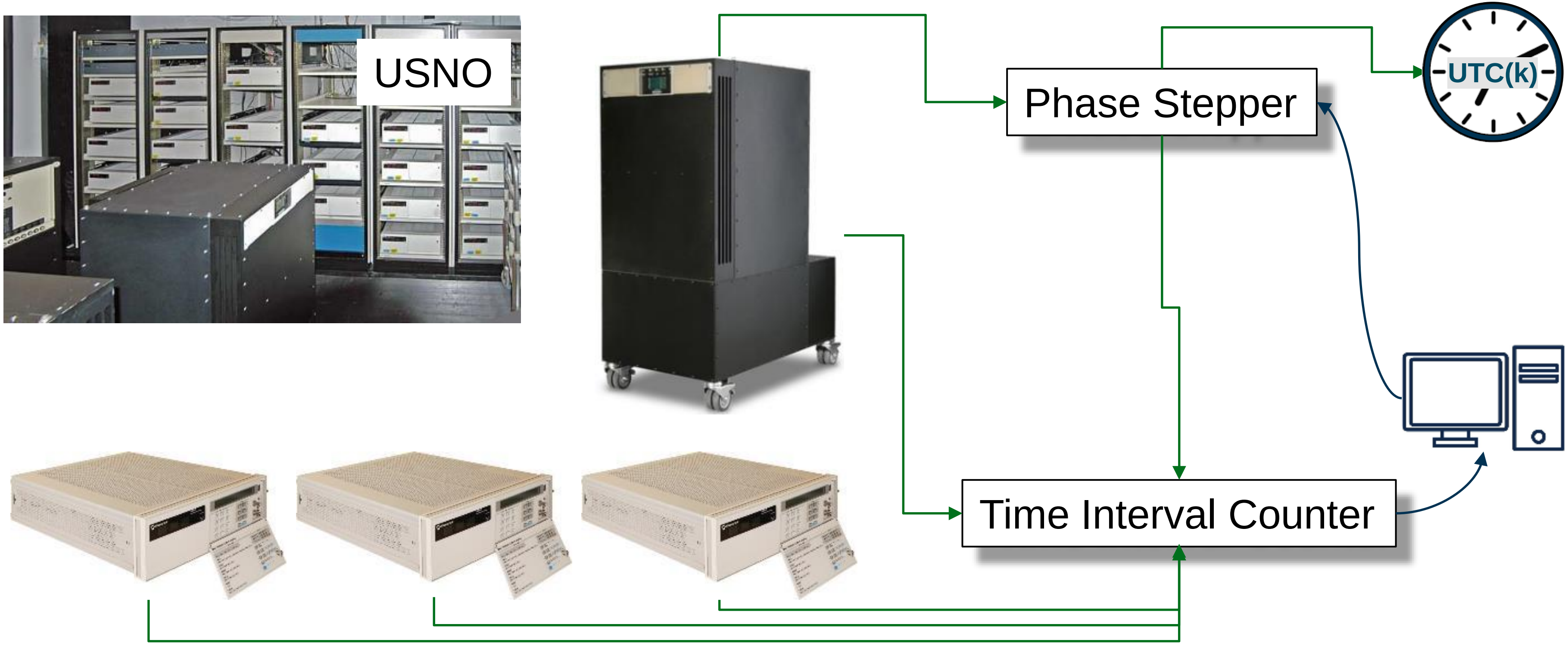
http://projects.npl.co.uk/itoc/assets/images/image.jpg

RIKEN
Sr Lattice Clock (x2)



TIME SCALES

Time Scales



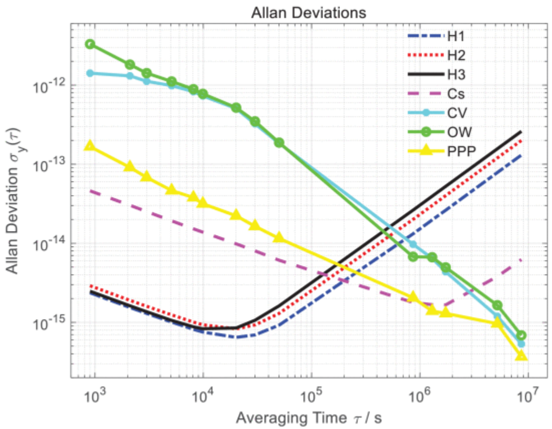
Time Scale Algorithms

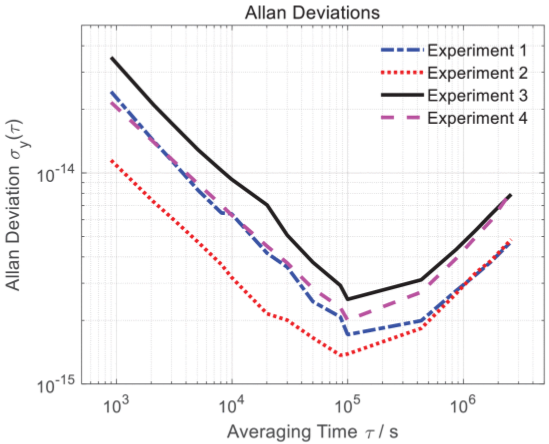
Clock model:

$$x(t) = x_0 + y_o(t - t_0) + \frac{1}{2}d_0(t - t_0)^2 + \varepsilon$$

Clock weight:

$$\omega_i \sim \sigma_y(\tau)$$



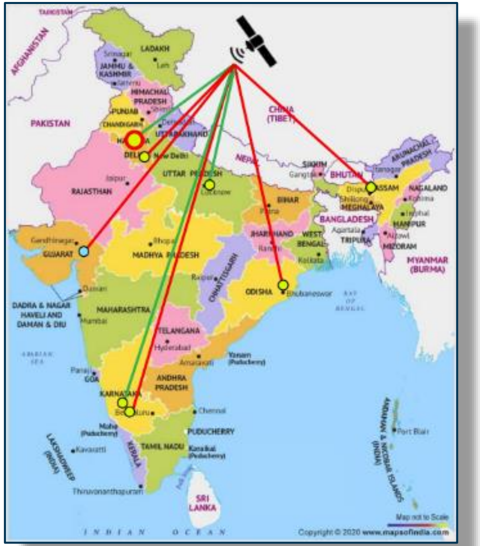


Y. Liu, et al, IEEE TIM, vol. 71, 2022

UTC(k) Time Scale Requirements

- Best noise performance – better than 1 individual clock
- Reliability – continuously running
- Redundancy – resilience to equipment failure
- AC/DC Power stability
- Network availability
- Geographical distribution
- …

Timescales around the world



Colombia

C. Rodriguez, CCTF TE 22-05-2024

India

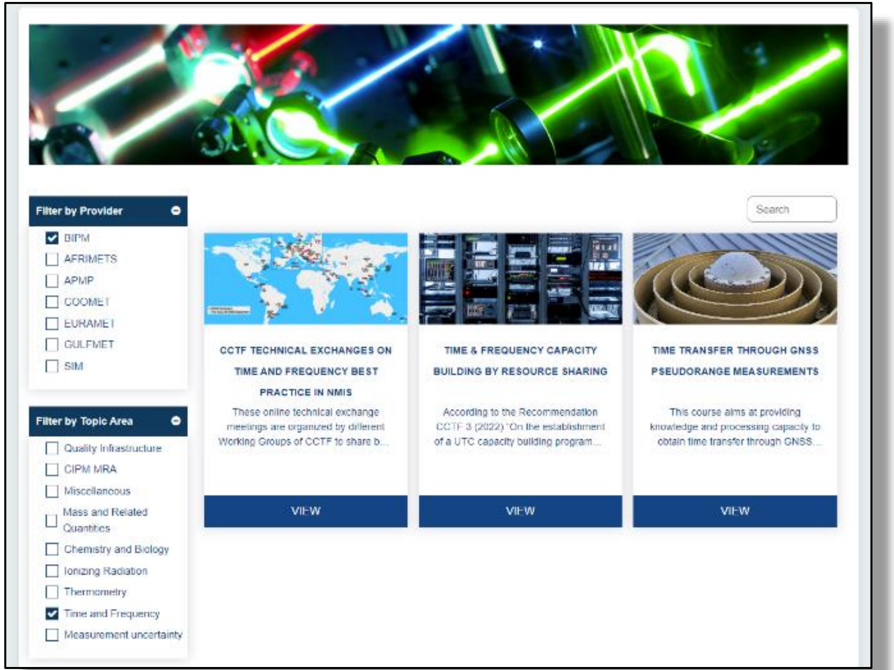
A. Agrawal, CCTF TE 22-05-2024

Uzbekistan

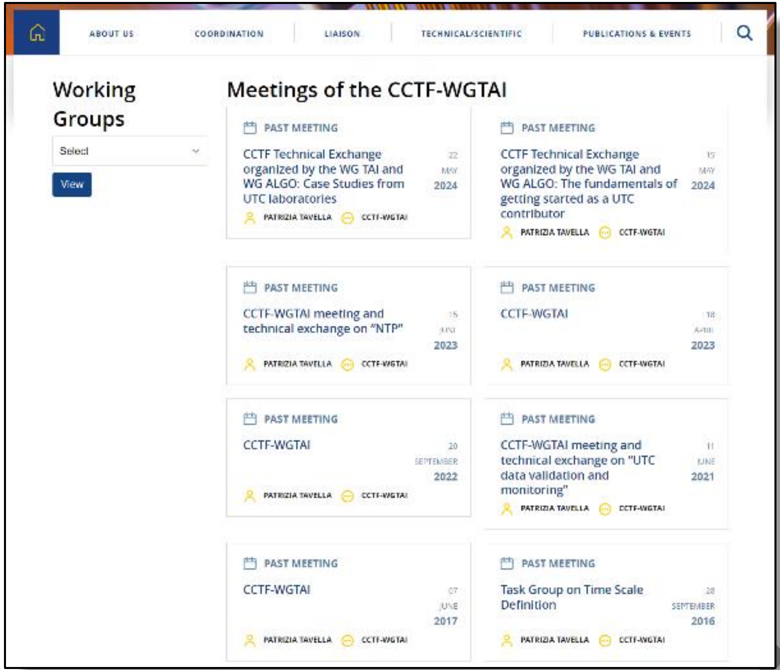
V. Nishonov, CCTF TE 22-05-2024

BIPM Resources

BIPM e-Learning Platform



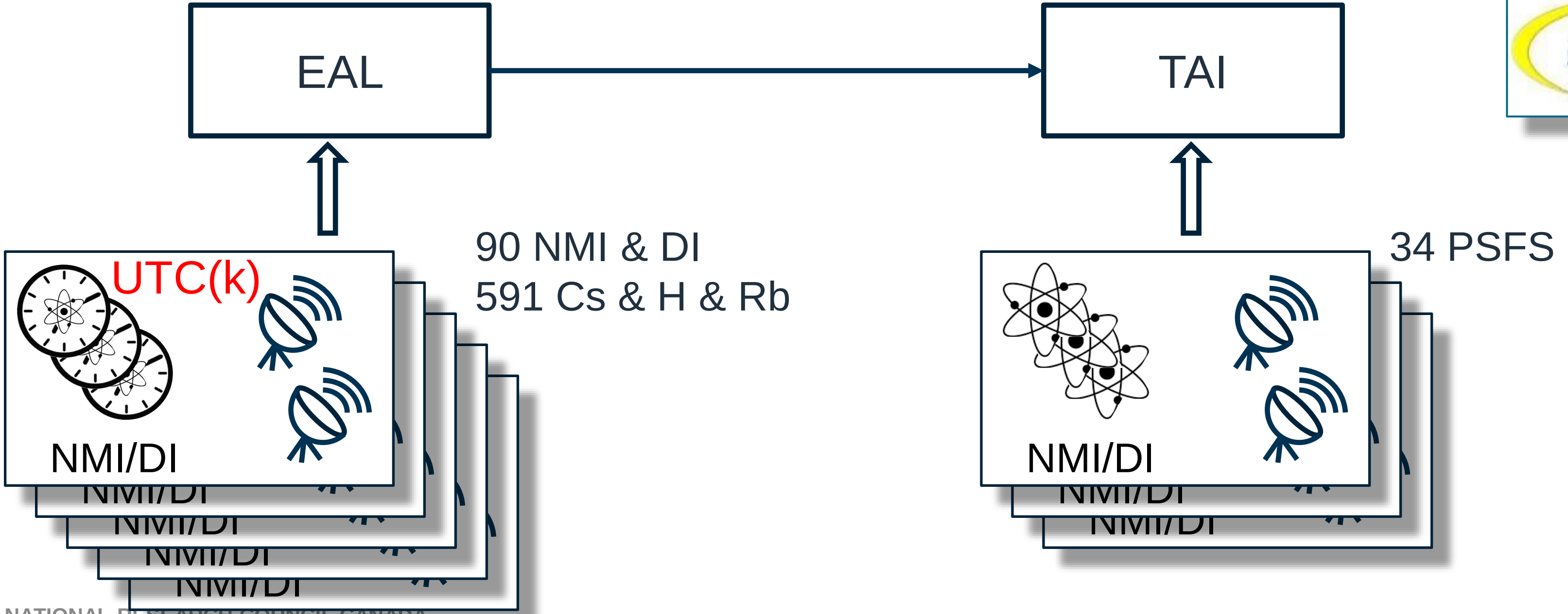
WG TAI meetings archive



CCTF & BIPM

Coordinated Universal Time - UTC

Coordinated Universal Time (UTC), is the international reference time scale that forms the basis for the coordinated dissemination of standard frequencies and time signals



Coordinated Universal Time - UTC

Coordinated Universal Time (UTC), is the international reference time scale that forms the basis for the coordinated dissemination of standard frequencies and time signals

EAL → TAI

90 NMI & DI
591 Cs & H & Rb

34 PSFS

- clock files:
  - UTC(k)-Clock$_i$
    - 1 point / day
    - submitted daily
- GNSS observations:
  - CGGTTS files
  - RINEX files
    - submitted daily

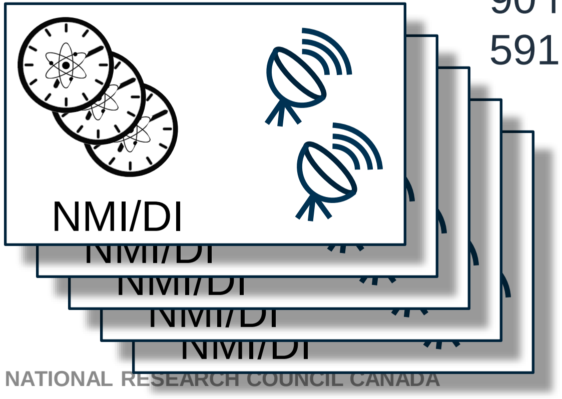
- PSFS files:
  - *y*(UTC(k)- PSFS$_i$)
    - 1 point / 5 days
    - submitted monthly

Coordinated Universal Time - UTC

Coordinated Universal Time (UTC), is the international reference time scale that forms the basis for the coordinated dissemination of standard frequencies and time signals

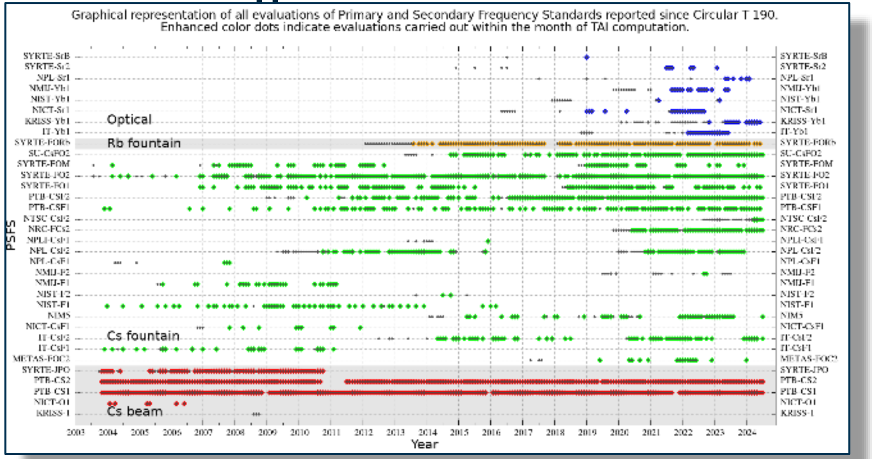
EAL

TAI

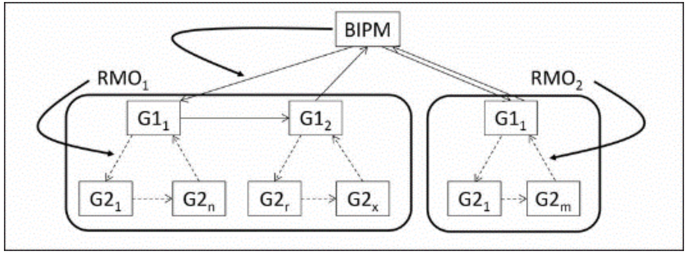


90 NMI & DI
591 Cs & H & Rb

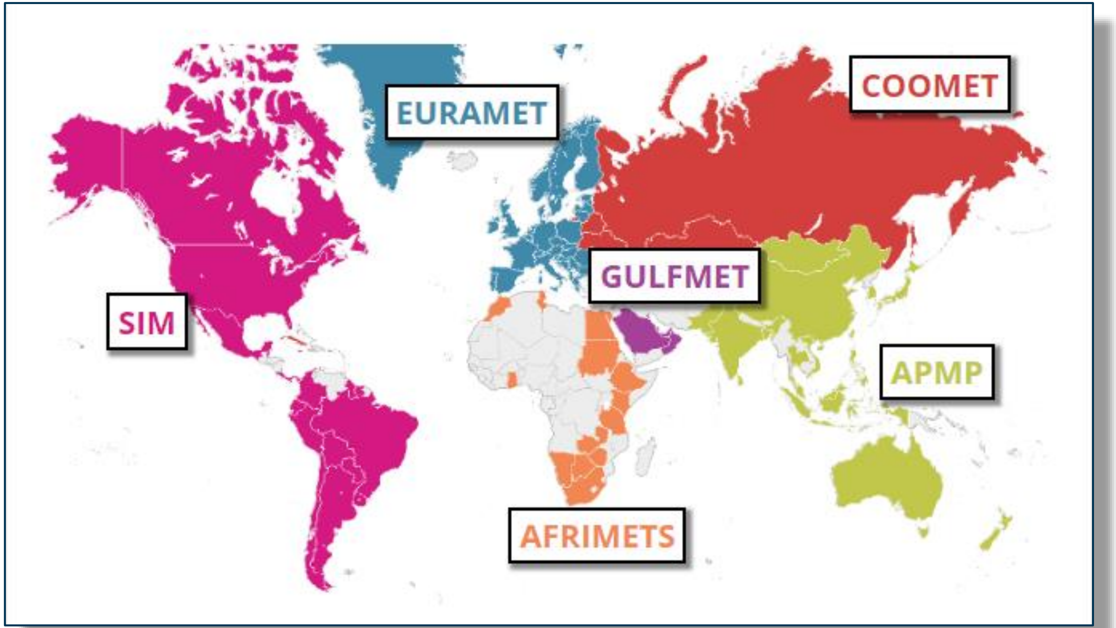
https://webtai.bipm.org/database/show_psfs.html



UTC(k) Calibration



SIM:
G1: NIST, USNO
New: **SIM traveling system**



https://www.bipm.org/kcdb/

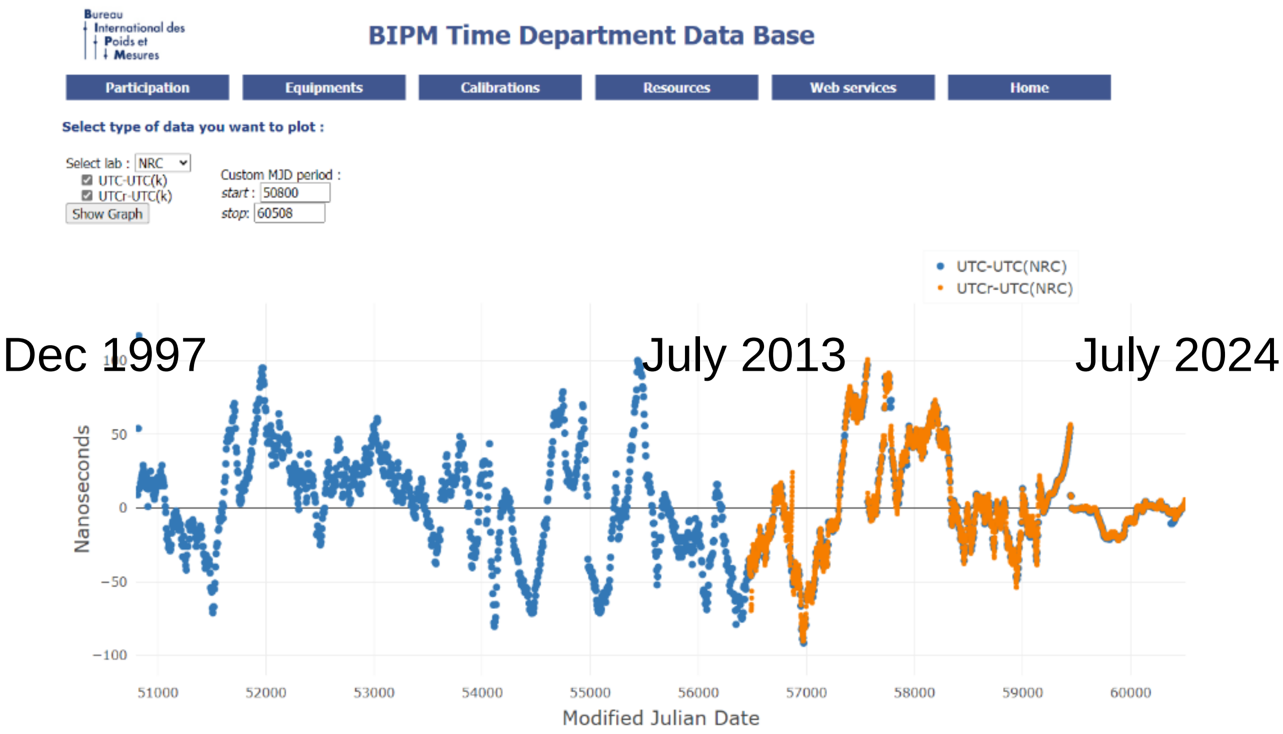
Circular T

https://webtai.bipm.org/ftp/pub/tai/Circular-T/cirthtm/cirt.437.html

```
CIRCULAR T 437                                                                       ISSN 1143-1393
2024 JUNE 10, 16h 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 https://webtai.bipm.org/ftp/pub/tai/other-products/notes/explanatory_supplement_v0.7.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 2024    0h UTC          APR 29    MAY  4    MAY  9    MAY 14    MAY 19    MAY 24    MAY 29     Uncertainty/ns Notes
        MJD                   60429     60434     60439     60444     60449     60454     60459      uA     uB     u
Laboratory k                                          [UTC-UTC(k)]/ns

AGGO (La Plata)               693.8     697.1     677.3     685.1     659.0     645.8     633.3     0.7    2.9    3.0
AOS  (Borowiec)               -20.0     -20.9     -22.8     -24.7     -26.4     -27.5     -27.3     0.2    3.4    3.4
APL  (Laurel)                  -0.4       0.4       1.6       3.0       1.2       0.7      -0.2     0.2    NC      -
AUS  (Sydney)                -243.6    -238.0    -233.9    -203.4    -203.0    -190.2    -173.6     0.2    2.9    2.9
```

NC – Not Calibrated

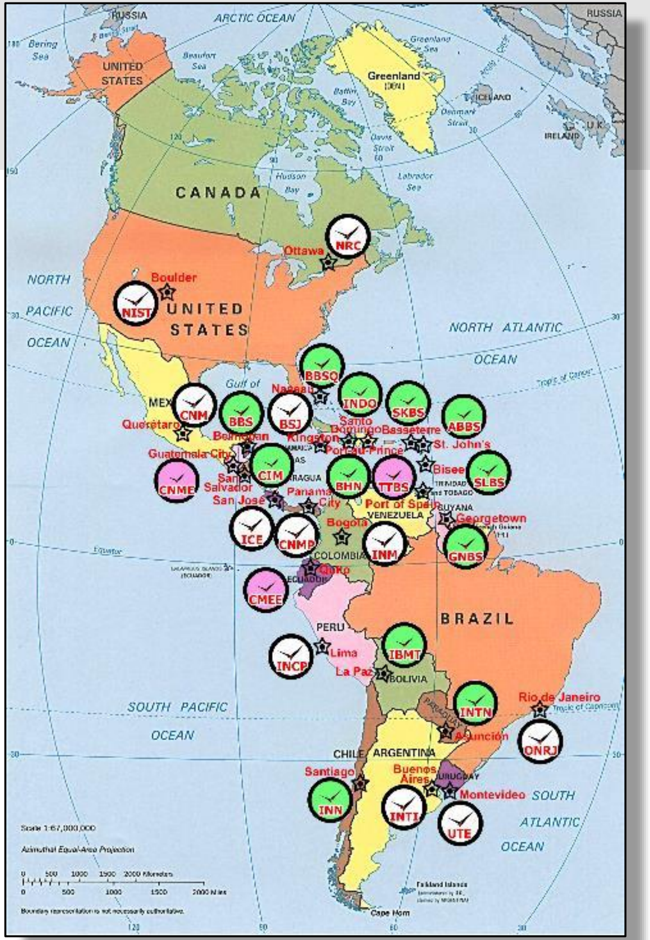
UTC(NRC)



Bureau International des Poids et Mesures
BIPM Time Department Data Base
Participation
Equipments
Calibrations
Resources
Web services
Home
Select type of data you want to plot :
Select lab : NRC
UTC-UTC(k)
UTCr-UTC(k)
Show Graph
Custom MJD period :
start : 50800
stop: 60508
UTC-UTC(NRC)
UTCr-UTC(NRC)
Dec 1997
July 2013
July 2024
Nanoseconds
Modified Julian Date

SIM TIME NETWORK

SIM Time Network



staring in 2005…

https://sim.nist.gov/scripts/sim_rx_grid.exe

SIMTN

- data updated every 10 minutes
- CGGTTS data format available for BIPM submissions
- new system with dual frequency receiver is under development at NIST

SIM Time Network

(real-time measurement results for the 10-minute period ending on 07-09-2024 at 1810 UTC)

	United States SIMT(NIST)	Mexico SIMT(CNM)	Canada SIMT(NRC)	Panama SIMT(CNMP)	Brazil SIMT(ONRJ)	Costa Rica SIMT(ICE)	Colombia SIMT(INM)	Argentina SIMT(INTI)	Guatemala SIMT(CNME)	Jamaica SIMT(BSJ)	Uruguay SIMT(UTE)	Paraguay SIMT(INTN)	Peru SIMT(INCP)	Trinidad SIMT(TTBS)	St. Lucia SIMT(SLBS)	Chile SIMT(INN)	Antigua SIMT(ABBS)	Ecuador SIMT(CMEE)	Bolivia SIMT(IBMET)	St. Kitts SIMT(SKBS)	Guyana SIMT(GNBS)	El Salvador SIMT(CIM)	Dominican Rep. SIMT(INDO)	Bahamas SIMT(BBSQ)	Haiti SIMT(BHN)	Belize SIMT(BBS)
United States SIMT(NIST)		3.4	-17.0	17.0	7.9	-49.1	139.3	-176.1	31.9	-10.2					14921.3			-124.4				49.0				
Mexico SIMT(CNM)	-3.4		-20.3	14.3	6.3	-50.0	137.6	-171.7	27.0	-13.5					14919.2			-127.2				46.2				
Canada SIMT(NRC)	17.0	20.3		35.5	28.6	-29.7	156.1	-157.6	52.6	6.8					14938.8			-107.8				92.0				
Panama SIMT(CNMP)	-17.0	-14.3	-35.5		-7.5	-64.9	114.5	-196.3	15.3	-28.6					14900.9			-146.7				58.0				
Brazil SIMT(ONRJ)	-7.9	-6.3	-28.6	7.5		-53.4	128.2	-185.0	26.3	-18.9					14911.2			-136.9				64.0				
Costa Rica SIMT(ICE)	49.1	50.0	29.7	64.9	53.4		170.2	-133.1	80.8	36.0					14965.5			-84.4				112.3				
Colombia SIMT(INM)	-139.3	-137.6	-156.1	-114.5	-128.2	-170.2		-311.4	-106.9	-145.8					14783.4			-265.3				-63.9				
Argentina SIMT(INTI)	176.1	177.7	157.6	196.3	185.0	133.1	311.4		210.3	167.2					15096.0			44.7				235.9				
Guatemala SIMT(CNME)	-31.9	-27.0	-52.6	-15.3	-26.3	-80.8	106.9	-210.3		-47.0					14890.8			-155.8				10.5				
Jamaica SIMT(BSJ)	10.2	13.5	-6.8	28.6	18.9	-36.0	145.8	-167.2	47.0						14922.5			-117.4				76.3				
Uruguay SIMT(UTE)																										
Paraguay SIMT(INTN)																										
Peru SIMT(INCP)																										
Trinidad SIMT(TTBS)																										
St. Lucia SIMT(SLBS)	-14921.3	-14919.2	-14938.8	-14900.9	-14911.2	-14965.5	-14783.4	-15096.0	-14890.8	-14922.5								-15047.6				-14846.8				
Chile SIMT(INN)																										
Antigua SIMT(ABBS)																										
Ecuador SIMT(CMEE)	124.4	127.2	107.8	146.7	136.9	84.4	265.3	-44.7	155.8	117.4					15047.6							181.0				
Bolivia SIMT(IBMET)																										
St. Kitts SIMT(SKBS)																										
Guyana SIMT(GNBS)																										
El Salvador SIMT(CIM)	-49.0	-46.2	-92.0	-58.0	-64.0	-112.3	63.9	-235.9	-10.5	-76.3					14846.8			-181.0								
Dominican Rep. SIMT(INDO)																										
Bahamas SIMT(BBSQ)																										
Haiti SIMT(BHN)																										
Belize SIMT(BBS)																										
Last Update (HHMM)	1810	1810	1810	1810	1810	1810	1810	1810	1810	1810			1810		1810		1810	1810				1810				

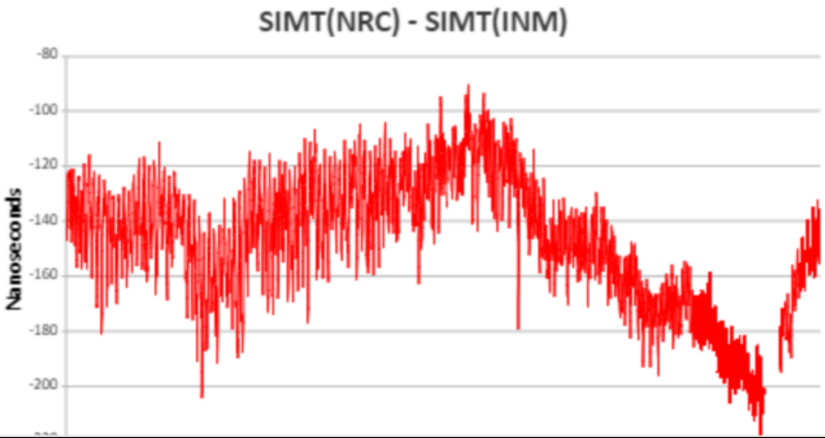
SIMTN

SIMT(NRC) versus SIMT(INM) via Common-View GPS

1 Day Averages | 1 Hour Averages | 10 Minute Averages | Next Date | Last Date | Flip

Laboratory 1	National Research Council	**ID Number**	008	**End Date**	2024-07-09
Latitude	45° 27 min 14.853 s N	**Counter Delay**	0.53 ns	**Reference Source**	SIMT(NRC)
Longitude	75° 37 min 25.777 s W	**REF Delay**	38 ns	**Mask Angle**	10°
Altitude	82.59 m	**Receiver Delay**	229.3 ns	**Receiver Temp.**	34 °C
Laboratory 2	Instituto Nacional de Metrologia (INM)	**ID Number**	012	**Baseline**	4430.241 km
Latitude	4° 38 min 34.643 s N	**Counter Delay**	0.24 ns	**Reference Source**	SIMT(INM)
Longitude	74° 5 min 32.593 s W	**REF Delay**	60.9 ns	**Mask Angle**	10°
Altitude	2611.11 m	**Receiver Delay**	128.2 ns	**Receiver Temp.**	27 °C

Hours in Common-View	Mean Time Offset (ns)	Range (ns)	Frequency Offset	Confidence (r)
3509	-146.81	129.23	-2.90×10^{-15}	-0.46



https://tf.nist.gov/sim/index.htm

SIM Time and Frequency Metrology Working Group

Select a Menu Item

- Home
- CMCs
- Comparisons
- Meetings
- Publications
- SIM Time Network (USA)
- SIM Time Network (Mexico)
- SIM Time Network (Canada)
- SIM Time Scale (USA)
- SIM Time Scale (Mexico)
- SIM Time Scale (Canada)
- SIM NTP Comparisons
- SIMT/UTC/TAI/GPS Clock
- Video of 2016 Leap Second

Related Web Sites

- SIM Web Site
- OAS Web Site
- BIPM Web Site
- TIME.IS Web Site

Time and Frequency Groups

- CENAM
- NIST
- NRC
- ONRJ

National Web Clocks (SIM region)

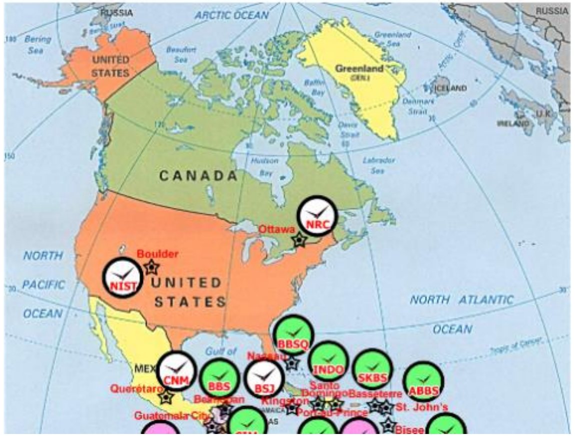
- Argentina
- Bolivia

Welcome

Welcome to the home of the Time and Frequency Metrology Working Group (TFMWG) of the Sistema Interamericano de Metrologia (SIM). The SIM region covers North, Central, and South America, and the Caribbean Islands. The members of the SIM TFMWG are timing laboratories located at national metrology institutes and other designated institutions in the 34 member nations of the Organization of American States (OAS). In most cases, these timing laboratories are responsible for keeping the official time in their respective nations.

SIM Time (SIMT)	2024/07/09 20:17:34
Coordinated Universal Time (UTC)	2024/07/09 20:17:34
Local Time	2024/07/09 16:17:34
This Device's Clock	2024/07/09 16:17:34
Device Clock Compared to Local SIMT	0.182 s slow

To support time and frequency metrology throughout the Americas, the SIM TFMWG maintains the SIM time scale (SIMT), the first continuously maintained multi-national ensemble time scale that is generated and published in real time (updated every hour). SIMT complements the world's official time scale, Coordinated Universal Time (UTC), by providing real time support to operational timing and calibration systems in the SIM region. The stability of SIMT is superior to most SIM local time scales and SIMT also provides a good approximation of UTC timing accuracy (±15 ns). The clock above displays SIMT, UTC, and your local time. It also shows the difference between local SIMT and the clock in the device you are using to view this site.



CCTF WORKING GROUPS

CCTF Structure

CCTF

WG SP

WG TAI

WG ALGO

WG PSFS

WG GNSS

WG TWSTFT

WG ATFT

WG MRA

CCL-CCTF FSWG

TG Roadmap towards the **redefinition of the second**

TG Promotion of the **mutual benefit of UTC and GNSS**

TG **Sharing of resources** to improve international timekeeping

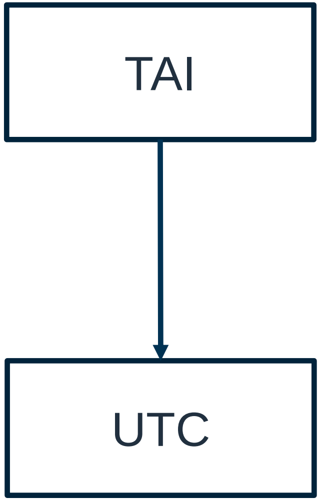
TG **Leap seconds** in UTC and building a consensus for a continuous timescale

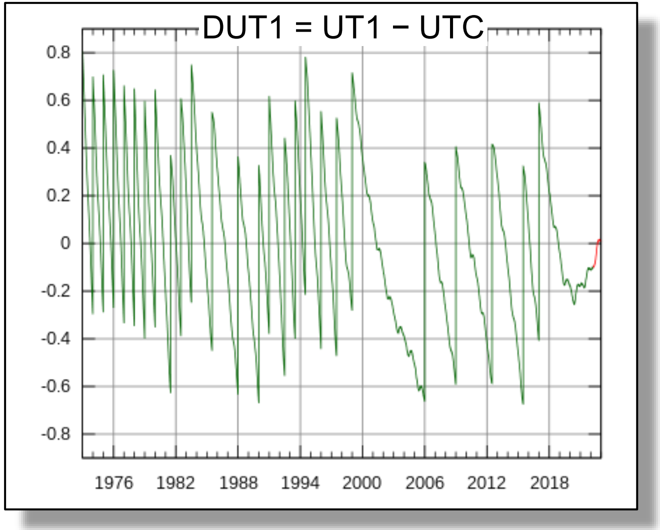
CCTF established in 1956 (before 1997 called CCDS)

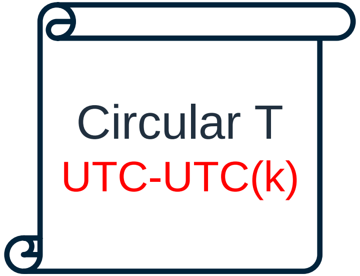
LEAP SECONDS

Coordinated Universal Time - UTC

UTC is obtained from International Atomic Time (TAI) by the insertion of leap seconds according to the advice of the International Earth Rotation and Reference Systems Service (IERS) to ensure approximate agreement with the time derived from the rotation of the Earth.

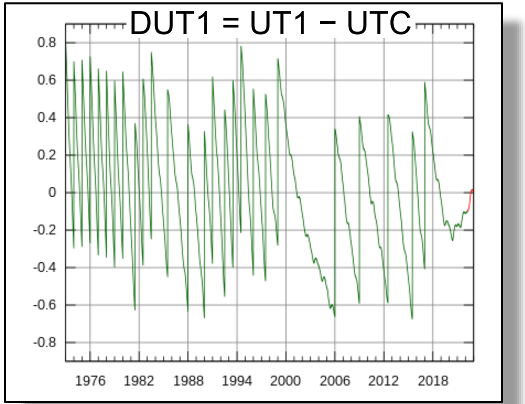






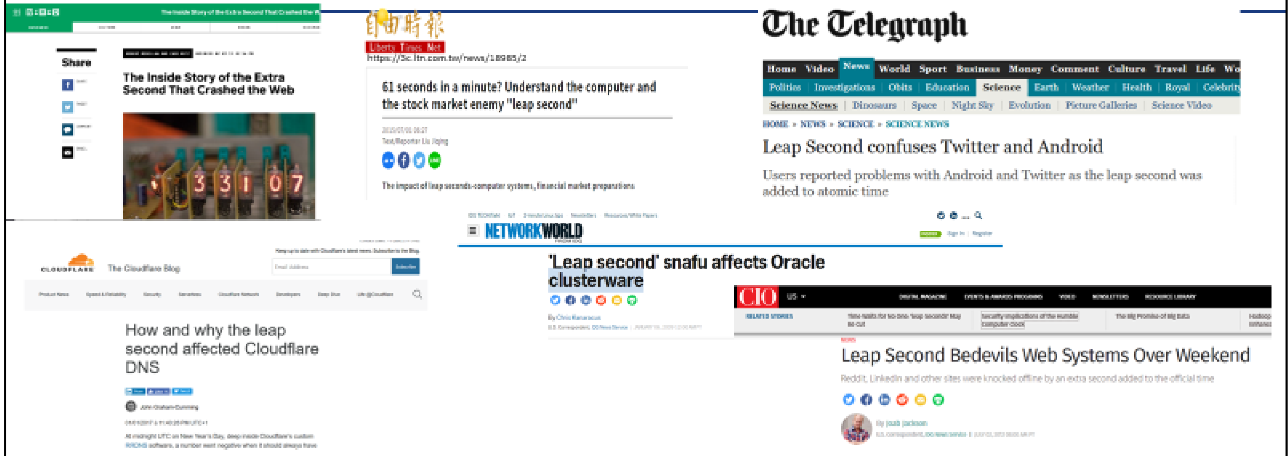
https://www.bipm.org/en/time-ftp/circular-t

Need for Continuous UTC



- proliferation of alternative timescales
- possible negative leap second

The digital networks cannot cope with unpredictable leap seconds



Time travels on the network

Computer operating systems are not easily able to handle a minute with 61 seconds

Consultative Committee on Time and Frequency User Survey (2021)

- > 200 answers
- The large majority asks to get rid of discontinuities in UTC
- Other time scales are used, instead of UTC, as continuous time scales

P. Tavella, CPEM, 2022

Continuous UTC and the future of UT1-UTC

- 26th CGPM (2022) Resolution 2: "On the definition of time scales“
    - https://www.bipm.org/en/committees/cg/cgpm/26-2018/resolution-2
    - confirms UTC is a time scale produced by the BIPM with the same rate as TAI, but differing from TAI only by an integral number of seconds,
    - recommends that all relevant unions and organizations work together to develop a common understanding
- 2020: the BIPM and ITU-R signed an MoU for mutual assistance
    - to the ITU-R in its role to set standards concerning time signals and frequency standard emissions, protocols, and dissemination procedure,
    - to the BIPM in its role of defining and realizing measurement standards and reference time-scales
- 27th CGPM (2022) Resolution 4: “On the use and future development of Coordinated Universal Time (UTC)”
    - https://www.bipm.org/en/cgpm-2022/resolution-4
    - Decides that the maximum value for the difference (UT1-UTC) will be increased in, or before, 2035
- 2023: ITU WRC - **endorsed the CGPM 2022 resolution**

Next Steps

- Define **new tolerance** for UT1-UTC
  - 100 s, 1 h, 1 d, …
- Define **new rules** for applying “leap offset”
  - Phase step, frequency slew, regular or on demand, …
- Define **implementation date** for the new rules
  - 2025, 2030, 2035,…

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Establishment of a CCTF Task Group to address progress towards a continuous UTC

The 27th meeting of the CGPM (2022) adopted Resolution 4 *On the use and further development of UTC*. Subsequently, the CCTF Working Group on Strategic Planning established a task group (TG) in May 2023 to address the progress towards a continuous UTC.

The TG shall work together with the CCTF, laboratories that contribute to UTC, GNSS providers, International Organizations - such as the International Astronomical Union, the International Telecommunication Union (ITU), the International Earth Rotation and Reference Systems Service (IERS) - and other stakeholders to prepare a draft resolution for the 28th meeting of the CGPM (2026) including:

- the extended tolerance value of UT1 UTC*
- the procedure to align UTC to UT1 when the new tolerance is reached
- the revision periodicity of this decision by the CGPM
- the exact implementation date.

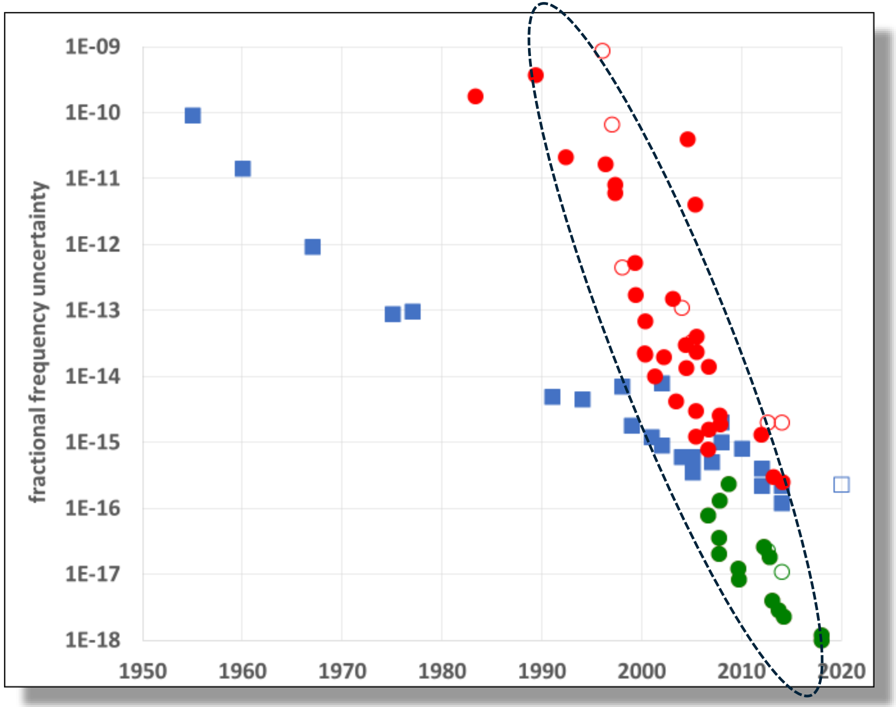
The TG aims to provide support to ITU delegations so that they are well prepared for the 2023 ITU World Radiocommunication Conference, where the update on UTC will be considered. Finally, the TG will foster communication efforts to increase awareness about this initiative, which will have profound implications for the future of reference time scales. Educational materials and promotional initiatives will be developed and shared over the coming years.

The TG looks forward to submitting a proposal to the 28th meeting of the CGPM that takes into account the requests and constraints of the different communities, while enabling UTC to be universally accepted, robust and useful.

TG **Leap seconds** in UTC and building a consensus for a continuous timescale

REDEFINITION OF THE SECOND

Optical Clocks Accuracy



Optical clocks

CGPM 2022 Resolution 5 - On the future redefinition of the second

encourages the International Committee for Weights and Measures (CIPM)

- to promote the importance of achieving the objectives in the roadmap for the redefinition of the second,
- to bring proposals to the 28th meeting of the CGPM (2026) for the choice of the preferred species, or ensemble of species for a new definition of the second, and for the further steps that must be taken for a new definition to be adopted at the 29th meeting of the CGPM (2030),

and **invites** Member States to support research activities, and the development of national and international infrastructures, to allow progress towards the adoption of a new definition of the second.

TG Roadmap towards the **redefinition of the second**

https://www.bipm.org/documents/20126/64811223/Resolutions-2022.pdf

CCTF: Roadmap towards a redefinition of the second

N Dimarcq et al 2024 Metrologia 61 012001

Table 4. Mandatory criteria and ancillary conditions to ensure the benefit and the acceptability of a new definition.

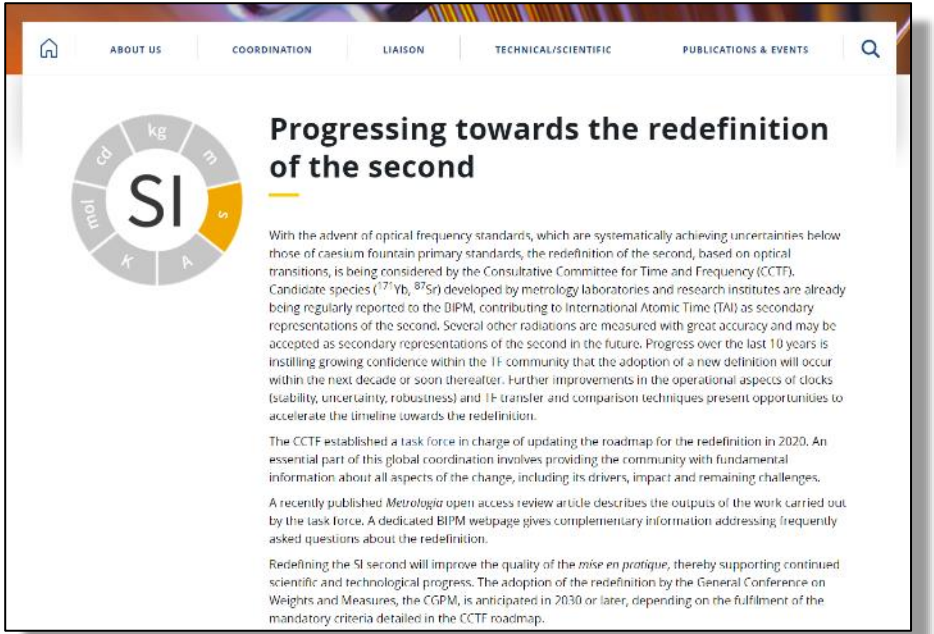
	Mandatory criteria	Ancillary conditions	Criteria and conditions
Frequency standards, including the contribution of OFS to time scales	X		I.1—Accuracy budgets of optical frequency standards
	X		I.2—Validation of Optical Frequency Standard accuracy budgets—Frequency ratios
	X		I.3—Continuity with the definition based on Cs
	X		I.4—Regular contributions of optical frequency standards to TAI (as secondary representations of the second)
		X	I.5—High reliability of OFS
		X	I.6—Regular contributions of optical frequency standards to UTC(k)
TF links for comparison or dissemination	X		II.1—Availability of sustainable techniques for Optical Frequency Standards comparisons
	X		II.2—Knowledge of the local geopotential with an adequate uncertainty level
		X	II.3—High reliability of ultra-high stability TF links
Acceptability of the new definition	X		III.1—Definition allowing more accurate realizations in the future
	X		III.2—Access to the realization of the new definition
		X	III-3—Continuous improvement of the realization and of time scales after redefinition
		X	III.4—Availability of commercial optical frequency standards
		X	III.5—Improved quality of the dissemination towards users

CCTF Task Force on the Redefinition

SG1	SG2	SG3
Option	Criteria	Education

TFU

Task Force on Updating the Roadmap for the redefinition of second



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Progressing towards the redefinition of the second

With the advent of optical frequency standards, which are systematically achieving uncertainties below those of caesium fountain primary standards, the redefinition of the second, based on optical transitions, is being considered by the Consultative Committee for Time and Frequency (CCTF). Candidate species (^{171}Yb, ^{87}Sr) developed by metrology laboratories and research institutes are already being regularly reported to the BIPM, contributing to International Atomic Time (TAI) as secondary representations of the second. Several other radiations are measured with great accuracy and may be accepted as secondary representations of the second in the future. Progress over the last 10 years is instilling growing confidence within the TF community that the adoption of a new definition will occur within the next decade or soon thereafter. Further improvements in the operational aspects of clocks (stability, uncertainty, robustness) and TF transfer and comparison techniques present opportunities to accelerate the timeline towards the redefinition.

The CCTF established a task force in charge of updating the roadmap for the redefinition in 2020. An essential part of this global coordination involves providing the community with fundamental information about all aspects of the change, including its drivers, impact and remaining challenges.

A recently published *Metrologia* open access review article describes the outputs of the work carried out by the task force. A dedicated BIPM webpage gives complementary information addressing frequently asked questions about the redefinition.

Redefining the SI second will improve the quality of the *mise en pratique*, thereby supporting continued scientific and technological progress. The adoption of the redefinition by the General Conference on Weights and Measures, the CGPM, is anticipated in 2030 or later, depending on the fulfilment of the mandatory criteria detailed in the CCTF roadmap.

CCTF Task Force on the Redefinition – SG1

SG1
Option

Option 1	Option 2	Option 3
choosing one single atomic transition in lieu of the Cs hyperfine transition and to fix the numerical value of the frequency of this transition υ_{Xy} $\upsilon_{\mathrm{Xy}} = N$ Hz, where N is the defining value.	consists of creating a defining constant based on several transitions rather than just a single one, as described in. The quantity whose numerical value is used in the definition is a weighted geometrical mean of the frequency of an ensemble of chosen transitions. The unit of time is set by the relation: $\prod_i \upsilon_i^{w_i} = N$ Hz, where w_i and N are the defining values. J. Lodewyck, Metrologia 56 (2019)	consists in fixing the numerical value of one more fundamental constant, in addition to *c*, *h and e*. From the fundamental standpoint, a good choice for this constant is the electron mass m_e, in which case the system of unit is set by the relations: m_e=M kg, where M is the defining value, completed by the other defining relations for *c*, *h*, *e*, k_B, N_A and K_{cd}.
$\upsilon_{\mathrm{Xy}} = N\ \mathrm{Hz}$	$\prod_i \upsilon_i^{w_i} = N\ \mathrm{Hz}$	$m_{\mathrm{e}} = M\ \mathrm{kg}$
• Familiar and practical • Uncertainty lower × 10^2 than for the current definition with Cs • … • The new definition might rapidly become obsolete • …	• Uncertainty lower × 10^2 than for the current definition with Cs • Flexible scheme • … • Conceptual deviation from the principle of applying fixed defining constants for the SI units • …	• Consistent with other SI units • … • Uncertainty higher × 10^4 than for the current definition with Cs • … *N Dimarcq et al 2024 Metrologia 61 012001*

CCTF Task Force on the Redefinition – SG2

N Dimarcq et al 2024 Metrologia 61 012001

SG2

Criteria

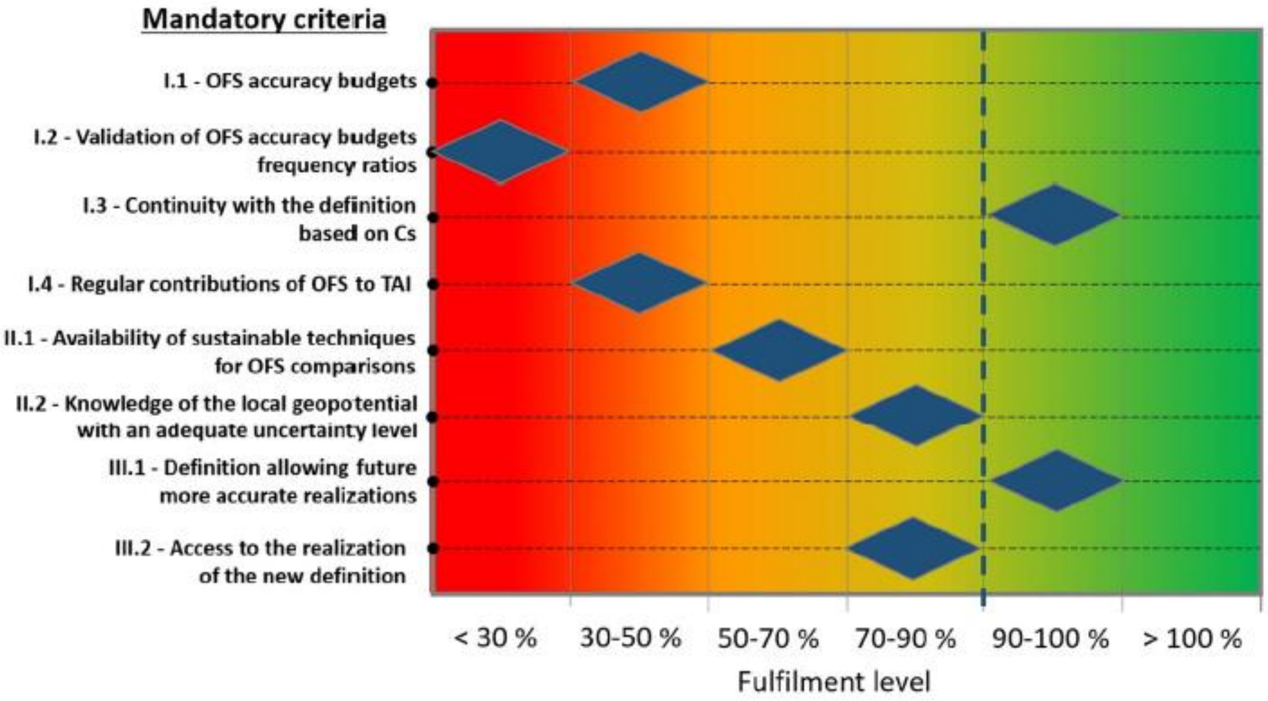


Figure 5. Fulfilment levels of mandatory criteria in 2022.

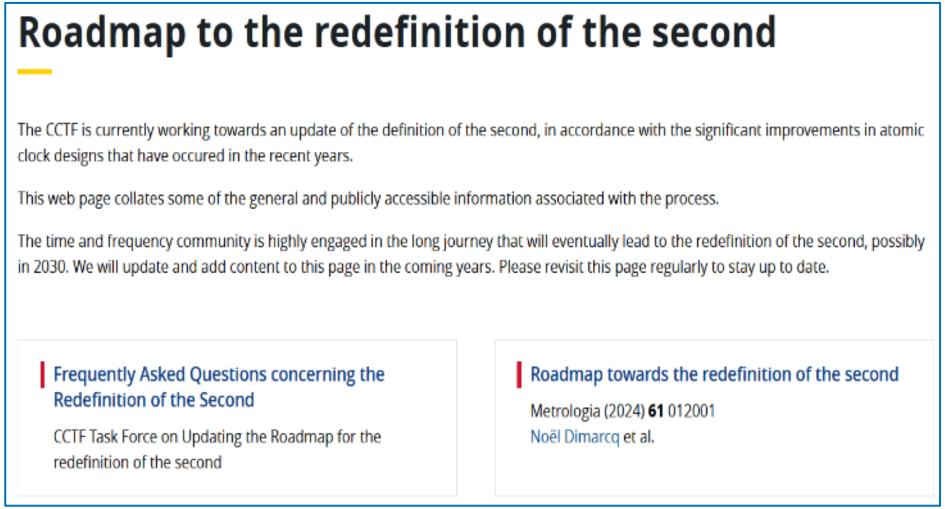
CCTF Task Force on the Redefinition – SG3

SG3

Education

FAQ – Frequency Asked Questions:

- What is the timeline for redefinition?
- Why does the community want to redefine the second?
- What are the options to redefine the second?
- What will happen to the caesium standards after the redefinition?
- What actions might I need to take prior to the redefinition?
- Will I need to replace my caesium standards after the redefinition?
- Will caesium standards still be accepted into UTC after the redefinition?
- What are the criteria for deciding if we are ready for the redefinition?



Roadmap to the redefinition of the second

The CCTF is currently working towards an update of the definition of the second, in accordance with the significant improvements in atomic clock designs that have occured in the recent years.

This web page collates some of the general and publicly accessible information associated with the process.

The time and frequency community is highly engaged in the long journey that will eventually lead to the redefinition of the second, possibly in 2030. We will update and add content to this page in the coming years. Please revisit this page regularly to stay up to date.

Frequently Asked Questions concerning the Redefinition of the Second

CCTF Task Force on Updating the Roadmap for the redefinition of the second

Roadmap towards the redefinition of the second

Metrologia (2024) **61** 012001

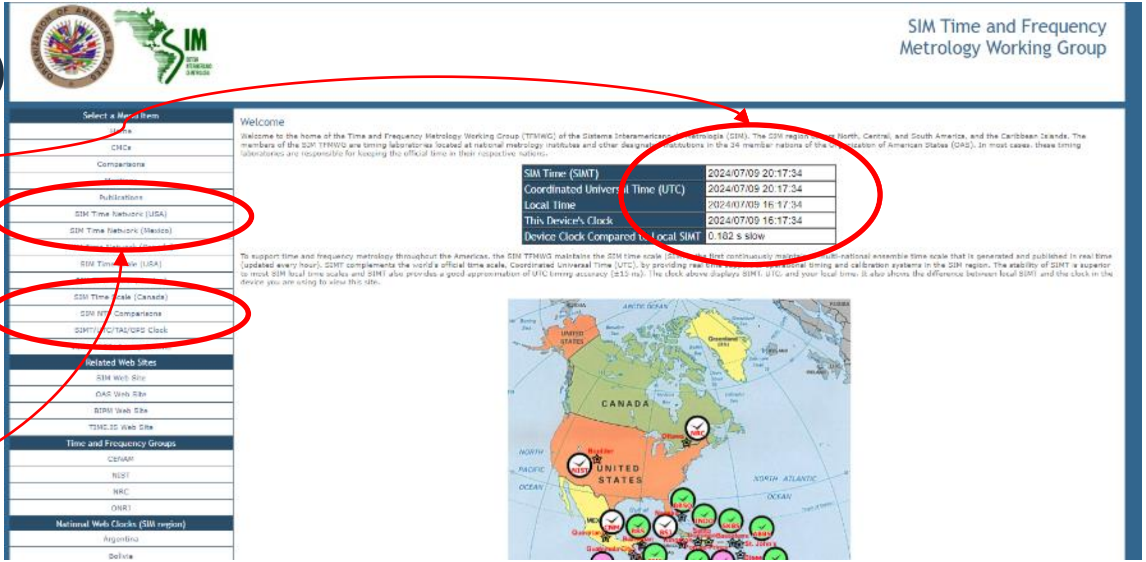
Noël Dimarcq et al.

https://www.bipm.org/en/redefinition-second

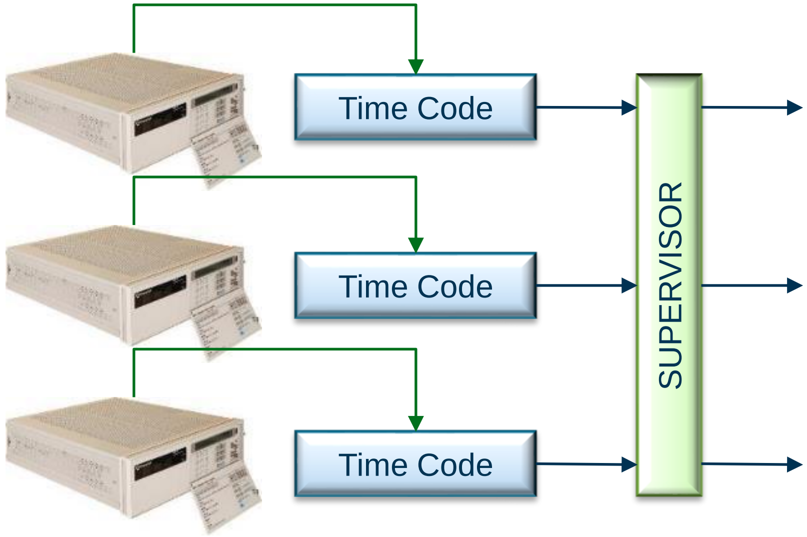
UTC(K) DISSEMINATION

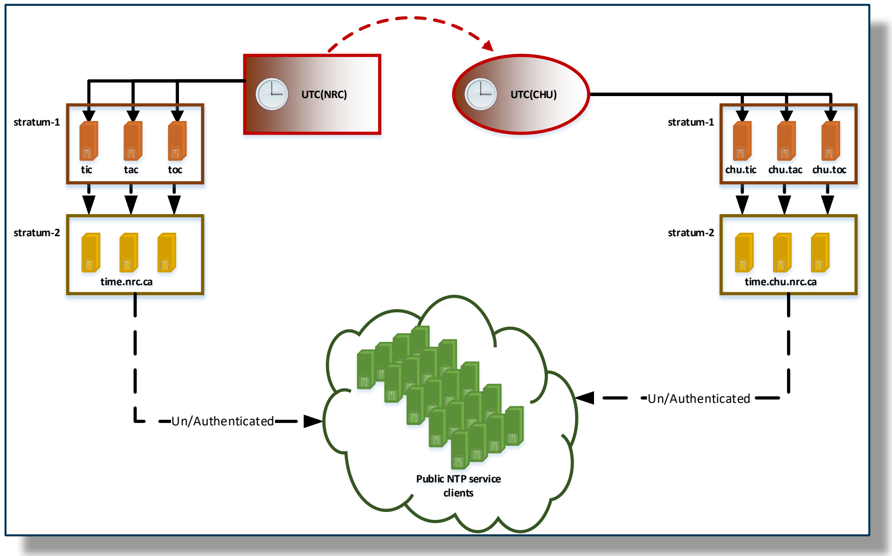
UTC(k) Dissemination methods

- Network Time Protocol (NTP)
- Web clock
- Telephone Talking Clock
- Short Wave Broadcasts
- Common View GNSS
- Calibration Services



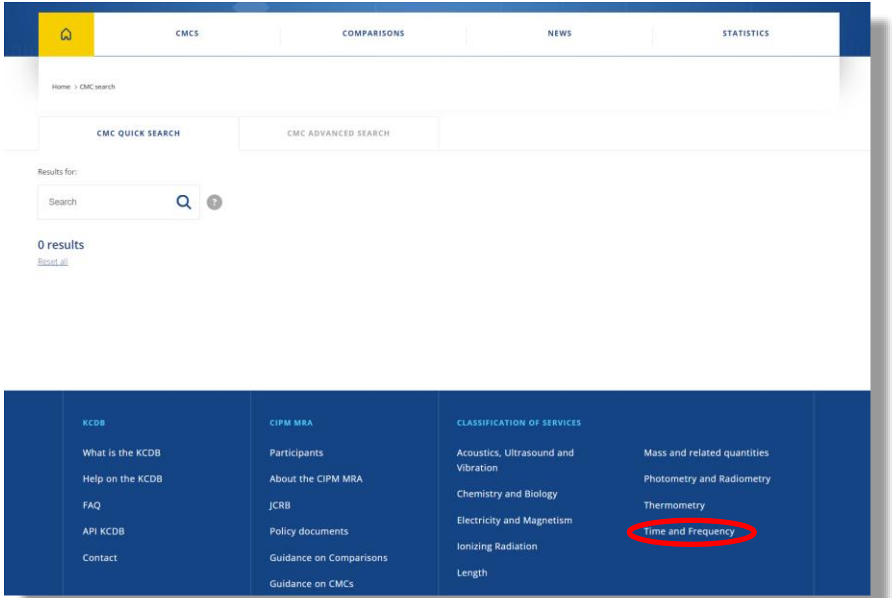
Have redundancy!





Calibration Capabilities

https://www.bipm.org/kcdb/cmc/quick-search



Classification of services in Time and Frequency

Version 1.1 (September 2013)

Metrology Area: Time and Frequency
Branch: Time scale difference

1 Time scale difference
- 1.1 Local clock
  - 1.1.1 Local clock vs. UTC(NMI)
  - 1.1.2 Local clock vs. UTC
- 1.2 Remote clocks
  - 1.2.1 Remote clock vs. UTC(NMI)
  - 1.2.2 Remote clock vs. UTC

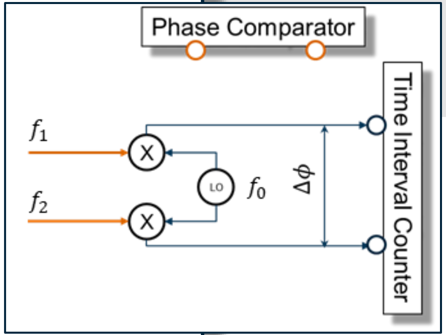
Branch: Frequency

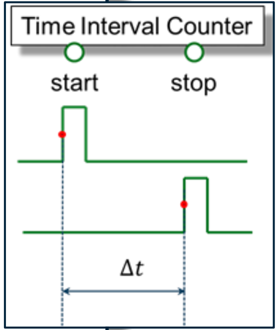
2 Frequency
- 2.1 Standard frequency source
  - 2.1.1 Local frequency standard
  - 2.1.2 Remote frequency standard
- 2.2 General frequency source
  - 2.2.1 General frequency source
- 2.3 Frequency meter
  - 2.3.1 Frequency counter
  - 2.3.2 Frequency meter

Branch: Time interval

3 Time Interval
- 3.1 Period source
  - 3.1.1 Period source
- 3.2 Time Interval source
  - 3.2.1 Rise/fall time source
  - 3.2.2 Pulse width source
  - 3.2.3 Time difference source
  - 3.2.4 Delay source
- 3.3 Period meter
  - 3.3.1 Period meter
- 3.4 Time Interval meter
  - 3.4.1 Rise/fall time meter
  - 3.4.2 Pulse width meter
  - 3.4.3 Time difference meter
  - 3.4.4 Delay meter

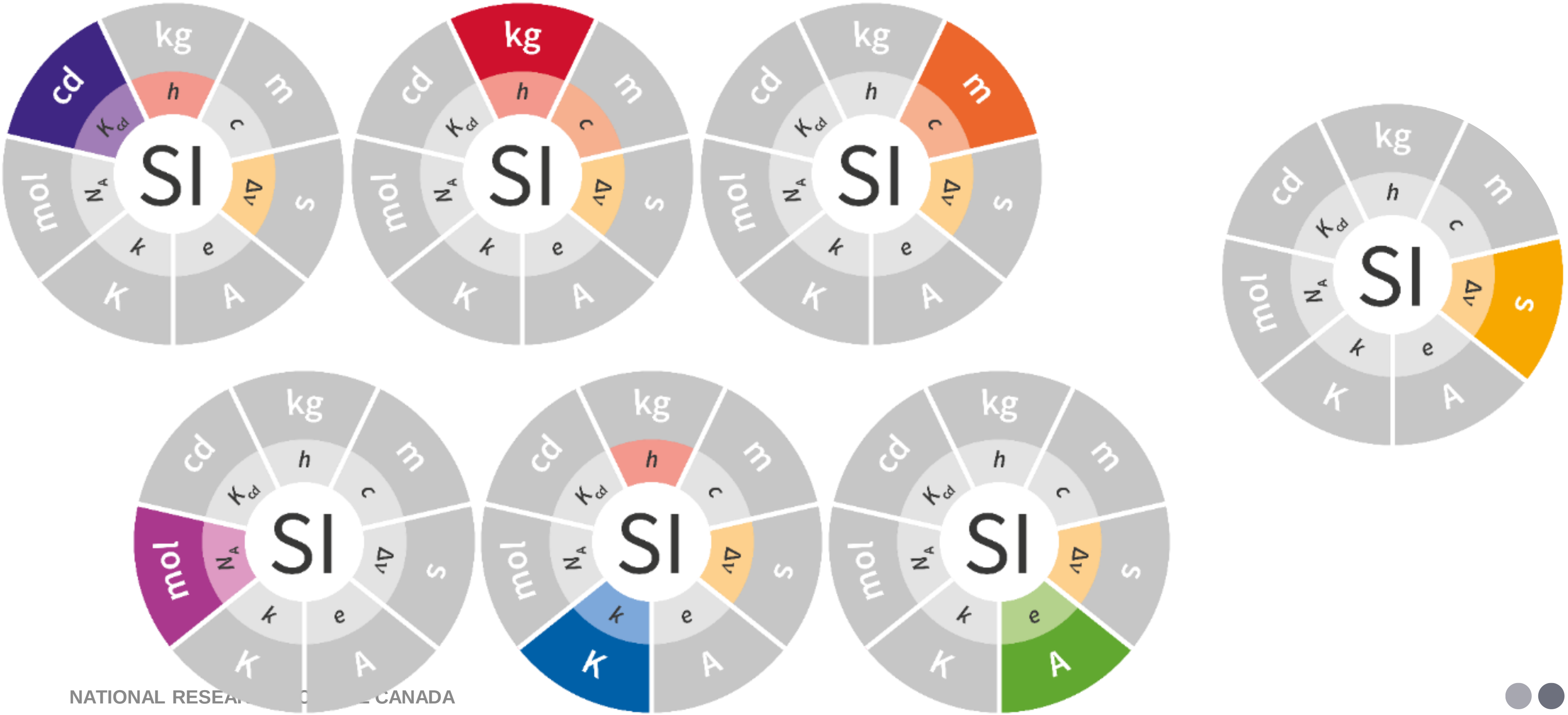
Note: Only the second sub-level items presented as "a.b.c", where "a", "b", and "c" are integers, should be selected for the column "Service category" (for instance "1.1.1") and "Instrument or Artifact" (for instance "Local clock vs. UTC(NMI)") of the CMC table.





CONCLUSION

SI Second



Accurate Time for the functioning of our lives

Power grids
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Finance
Transportation
Agriculture
Manufacturing
Scientific research
…

https://www.space.com/time-how-it-works

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Thank You

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