Distribution et transfert du temps

Paul-Eric Pottie

Crédits

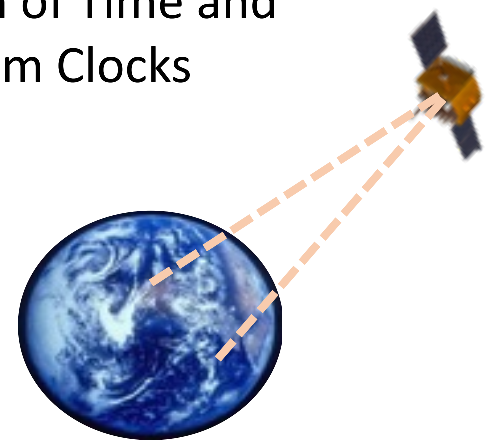
planches basées sur des apports substantiels de
Marie-Christine Angonin
Anne Amy-Klein (LPL/UP13-CNRS)
Noel Dimarcq
Giorgio Santarelli

Marc Weiss, Nathan Newbury (NIST)
Felicitas Arias (BIPM)
Ron Beard (USNO)
John Vig (IEEE)

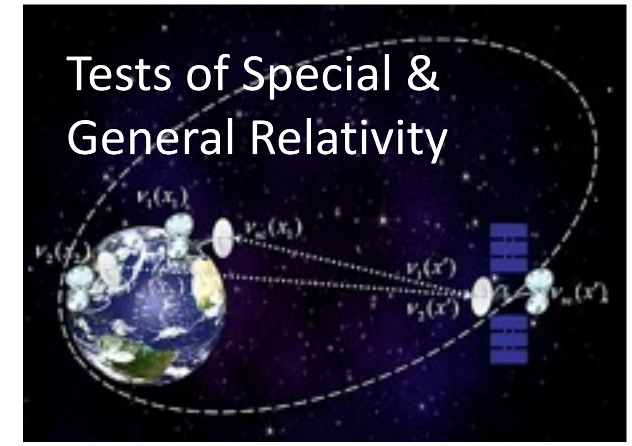
Introduction

Fundamental Scientific Applications

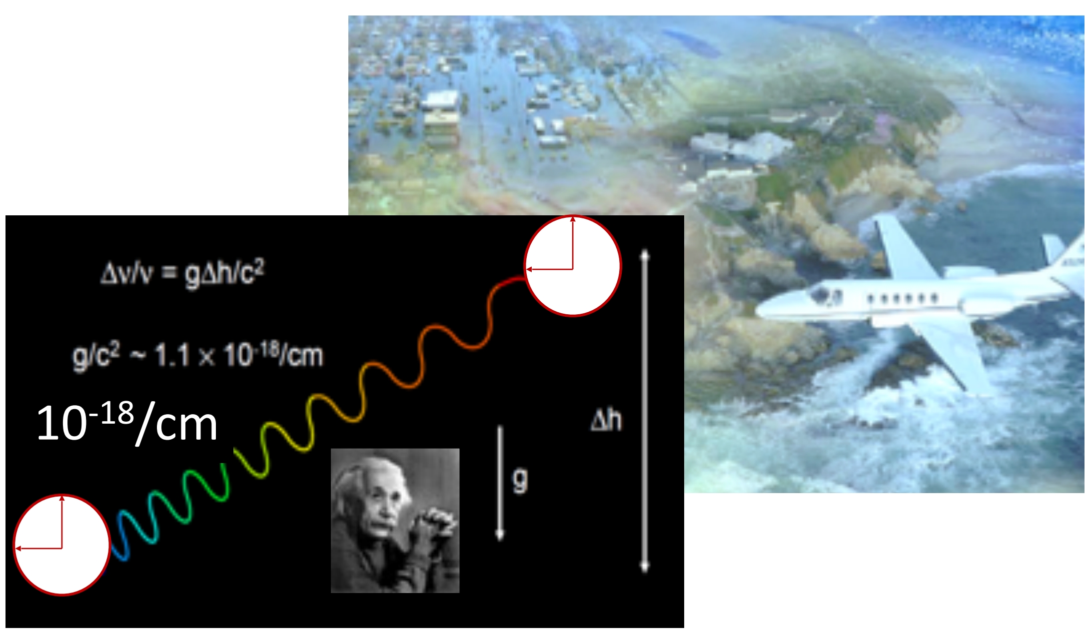
Dissemination of Time and Frequency from Clocks



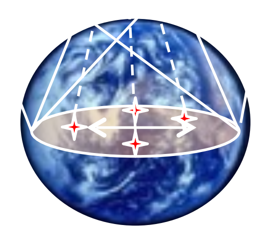
Definition & Variations in fundamental constants



Geodesy: Earth Science

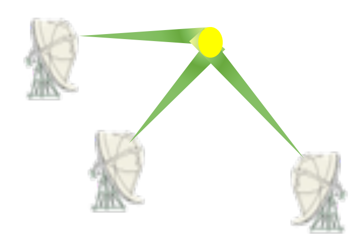


Sensing/Defense:
Positioning, Navigation and Timing



synthetic aperture global imaging

Large instruments, array of detectors



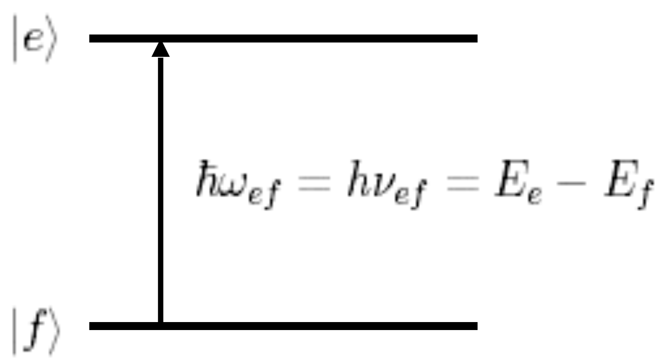
Courtesy of N . Newbury NIST

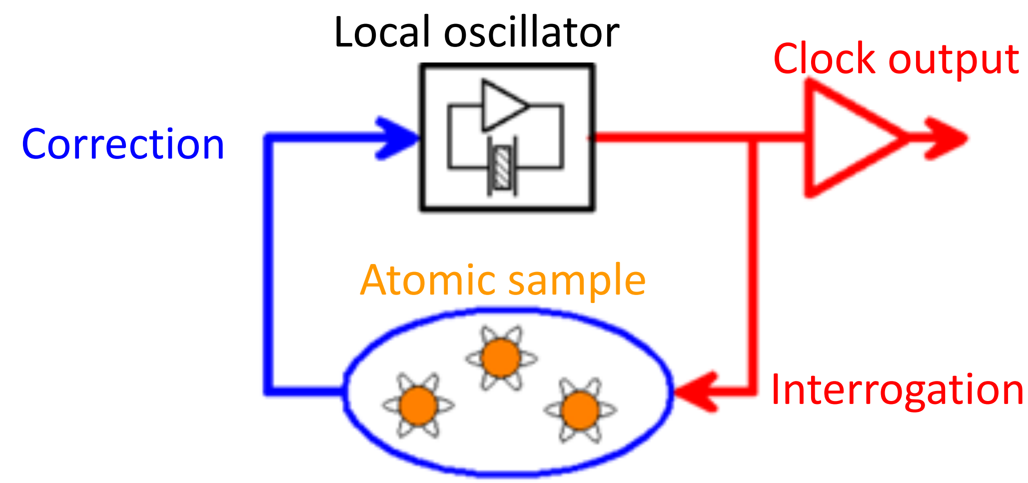
- T/F metrology
- Instruments
- Satellite T/F transfer
- Fiber links

part 1 : A tutorial to T/F metrology

- **Frequency standards**
- **Time scales**
- **What do metrologist measure ?**
- **Statistical tools: Allan deviation(s)**

Frequency standards : basic principles





$$Q_{at} = \frac{\nu_{ef}}{\Delta\nu} \propto \nu_{ef} T$$

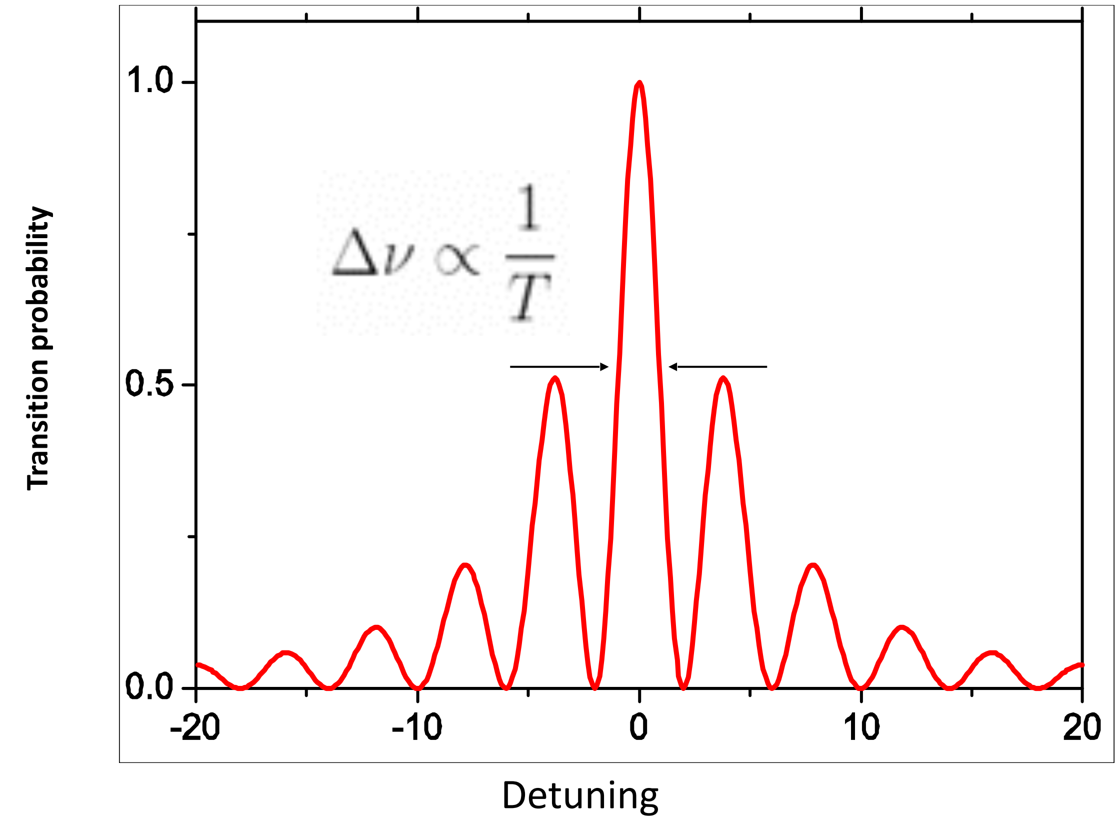
$\boxed{\text{Need high carrier frequency}}$

Relative frequency stability :

$$\sigma_y(\tau) \propto \frac{\sigma_{\delta P}}{Q_{at}} \sqrt{\frac{T_c}{\tau}}$$

tau = Integration time,

Tc = Cycle time



with T: Interrogation duration

Atomic clock : a frequency standard

Clock signal is

$$S(t) = A.\cos(2\pi.\nu(t).t) = A.\cos(\varphi(t))$$

Fréquence : $\boxed{\nu(t) = \nu_0 \times \left(1 + \varepsilon + y(t)\right)}$

Phase : $\boxed{\varphi(t) = 2\pi \int_0^t \nu(t')dt' = 2\pi.\nu_0 \left[(1+\varepsilon).t + \int_0^t y(t')dt' \right]}$

Temps : $\boxed{T(t) = \frac{1}{2\pi.\nu_0}\varphi(t) = \left(1 + \frac{\varepsilon}{\nu_0}\right).t + x(t)}$ $\boxed{y(t) = \frac{dx(t)}{dt}}$

Note : introduction of the integration time (or *observation time*)

Courtesy M.-C. Angonin

Mathematical model of a periodic signal

$$v(t)=\left[A_0+a(t)\right]\sin\left[2\pi\nu_0 t+\phi(t)\right]$$

$a(t) << A_0$ amplitude noise is negligible

$\phi(t)$ → Ergodic random process
wide sense stationary (WSS)

Ensemble averages ⟷ Time averages

$$\langle\phi\rangle=\overline{\phi}=\lim_{T\to\infty}\frac{1}{T}\int_0^T\phi(t)dt$$

Average value

$$\sigma_\phi^2=\lim_{T\to\infty}\frac{1}{T}\int_0^T\left[\phi(t)-\overline{\phi}\right]^2dt$$

Variance, (sqrt->standard deviation)

$$y=\frac{\Delta\nu(t)}{\nu_0}=\frac{\nu_0-\nu(t)}{\nu_0}=\frac{1}{\nu_0}\frac{\dot{\phi}(t)}{2\pi}$$

Relative frequency fluctuations

Power Spectral Density (PSD)

Single side power spectral density

$$S_\phi(f) = \begin{cases} 2\,S_\phi^{TS}(f) & f \geq 0 \\ 0 & f < 0 \end{cases} \qquad \left[\frac{rad^2}{Hz}\right]$$

$$\boxed{\varphi(t) = h(t) * \phi(t)}$$

Spectral density and linear systems

$$S_\varphi(f) = \left|H(j\,2\pi\,f)\right|^2 S_\phi(f)$$

Phase to frequency and related PSDs

Frequency fluctuations

$$\Delta\nu(t) = \nu_0 - \nu(t) = \frac{1}{2\pi}\frac{d\phi(t)}{dt}$$

$$S_{\Delta\nu}(f) = f^2 S_\phi(f) \quad \left[\frac{Hz^2}{Hz}\right]$$

Frequency fluctuations spectral density

Phase fluctuations

$$\phi(t) = 2\pi \int \Delta\nu(t)\,dt$$

$$S_\phi(f) = S_{\Delta\nu}(f) \big/ f^2$$

Phase fluctuations spectral density

Phase / Frequency : fractional fluctuations

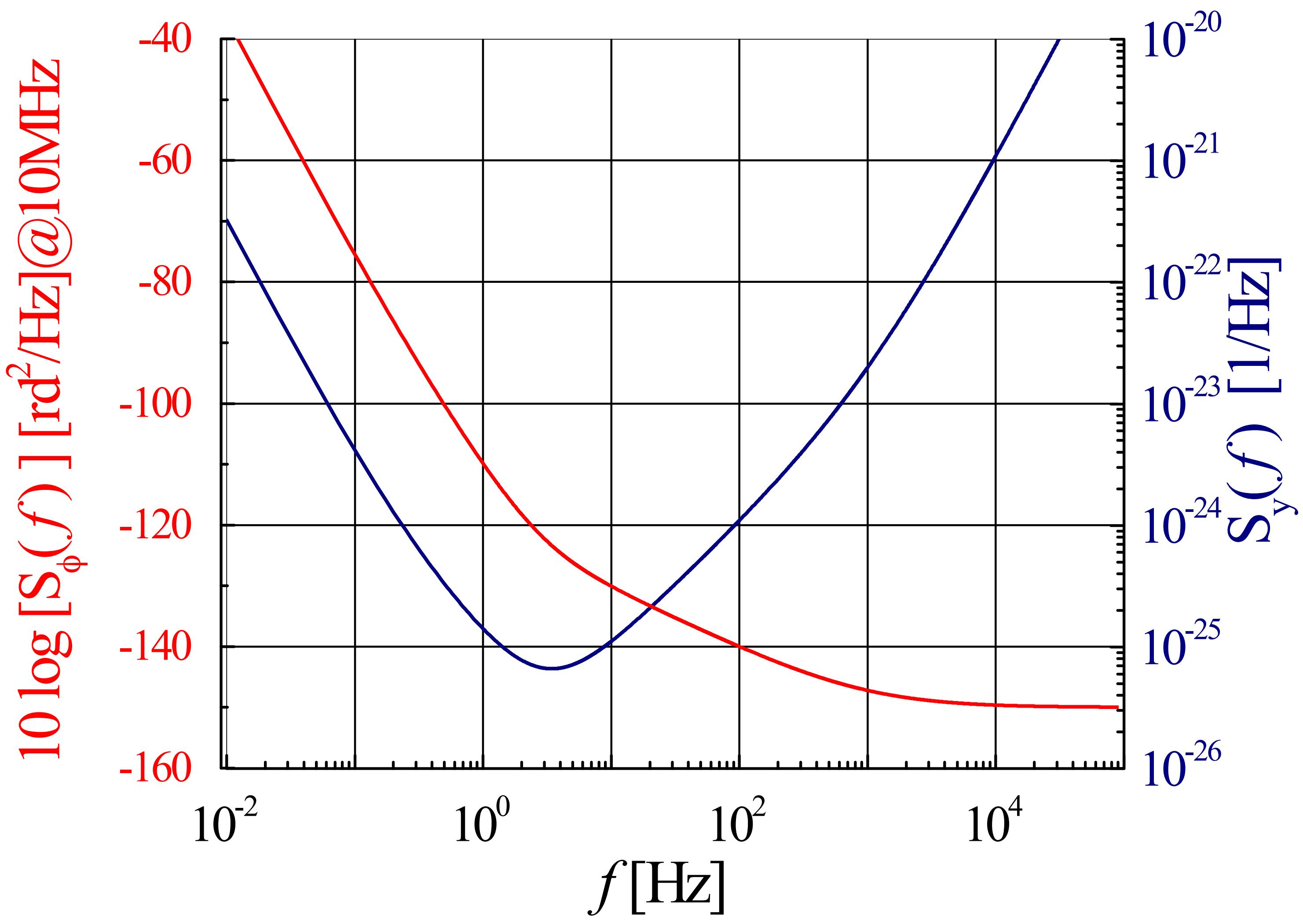
$$y = \frac{\Delta\nu(t)}{\nu_0} = \frac{\nu_0 - \nu(t)}{\nu_0} = \frac{1}{\nu_0}\frac{\dot{\phi}(t)}{2\pi}$$

Dimension less quantity

$$S_y(f) = \left(\frac{f}{\nu_0}\right)^2 S_\phi(f) \quad \left[\frac{1}{Hz}\right]$$

scales as the invert of the square of carrier frequency !
Advantages to work at the highest possible frequency

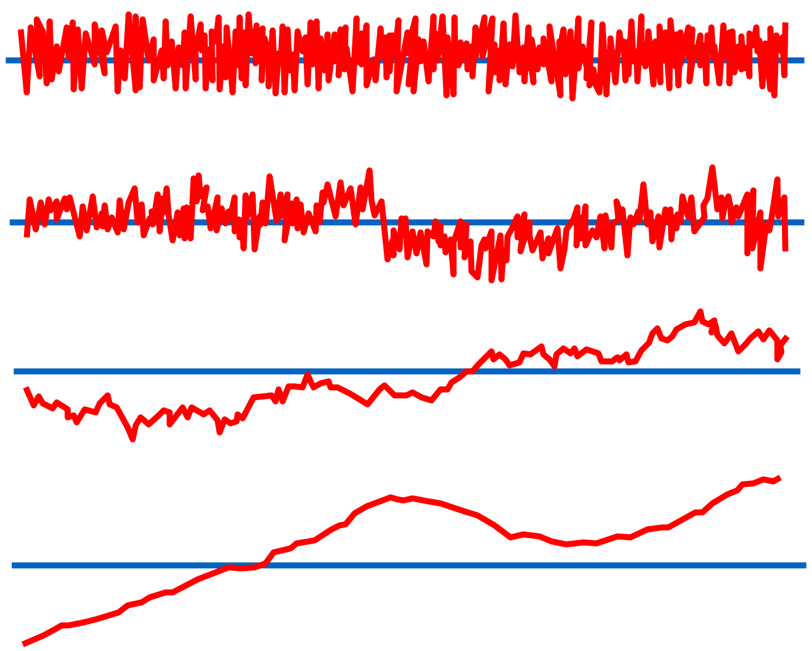
PSD Phase / Frequency noise : order of magnitudes



Power laws of Phase/Frequency noises

Type of noise	$S_\phi(f)$	$S_y(f)$
White phase	h_2	$h_2 f^2$
Flicker phase	h_1 / f	$h_2 f$
White freq./ random walk ph.	h_0 / f^2	h_0
Flicker frequency	h_{-1} / f^3	h_{-1} / f
Random walk freq.	h_{-2} / f^4	h_{-2} / f^2

Pictures of noise

Plot of z(t) vs. t	$S_z(f) = h_\alpha f^\alpha$	Noise name
	$\alpha = 0$	White
	$\alpha = -1$	Flicker
	$\alpha = -2$	Random walk
	$\alpha = -3$	

From John Vig IEEE

Plots show fluctuations of a quantity z(t), for instance :

output of a counter (Δf vs. t) ,

or output of a phase detector ($\phi[t]$ vs. t).

Simulated time-domain behaviors corresponding to the most common (power-law) spectral densities

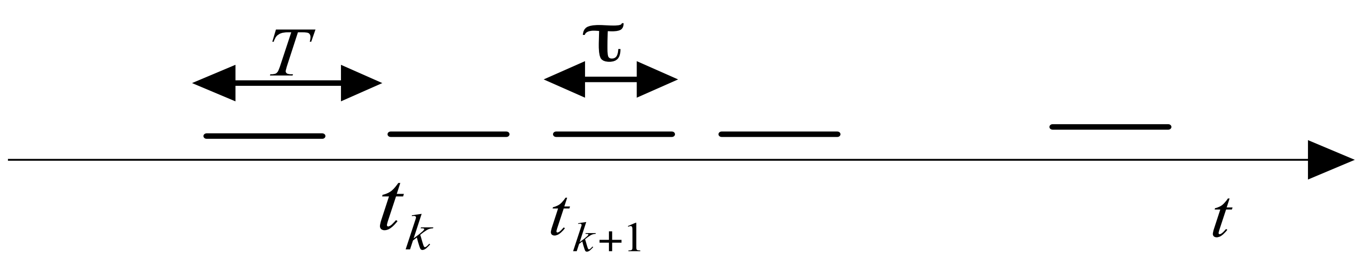
h_α is an amplitude coefficient.

Note: since $S_{\Delta f} = f^2 S_\phi$, e.g. white frequency noise and random walk of phase are equivalent.

Frequency measurement in the time domain

$$\overline{y}(t_k,\tau)=\frac{1}{\tau\nu_0}\int_{t_k}^{t_k+\tau}\nu(u)\,du$$

Average relative frequency fluctuations over a time τ



This is the quantity measured by a frequency counter

A counter produces M frequency measurements separated by a time T with a gate time of τ , the difference T-τ is called dead-time between measurements.

Frequency stability: The Allan Variance

Allan variance is the two sample variance with **zero dead time** between measurements

$$\boxed{N = 2 \quad T = \tau}$$

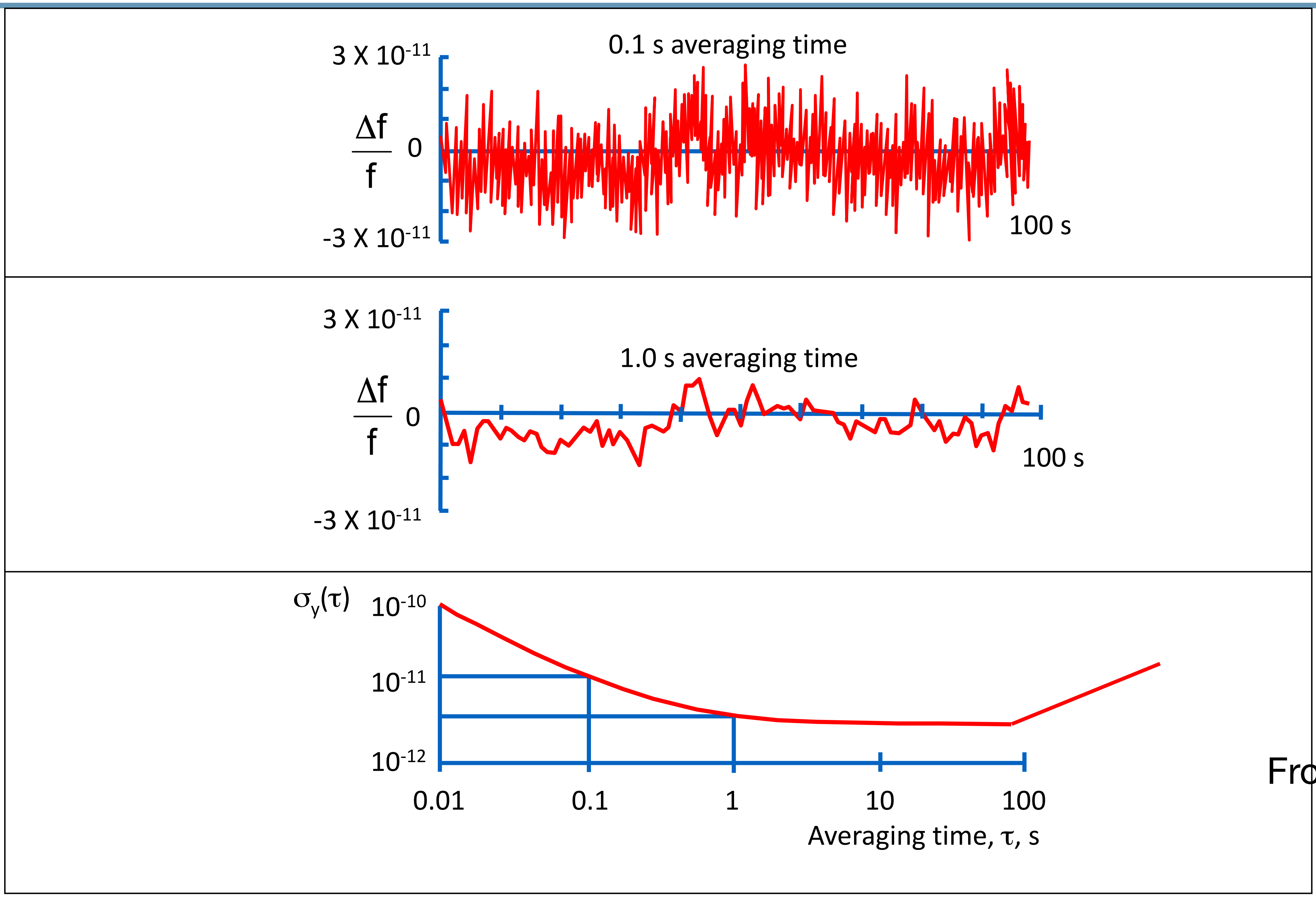
$$\sigma_y^2(2,\tau,\tau) = \frac{1}{2}\left\langle \overline{y}_1 - \overline{y}_2 \right\rangle^2$$

The Allan variance can be related to
power spectrum density of rel. frequency fluctuations or phase noise

$$\sigma_y^2(\tau) = \frac{1}{\pi\nu_0\tau}\int_0^\infty H(f,\tau)S_y(f)df = \frac{1}{\pi\nu_0\tau}\int_0^\infty H_1(f,\tau)S_\phi(f)df$$

D.W Allan, Proc. of the IEEE **54**, 221–230 (1966).
Riley, W. J. Handbook of Frequency Stability Analysis. 31, (1994).

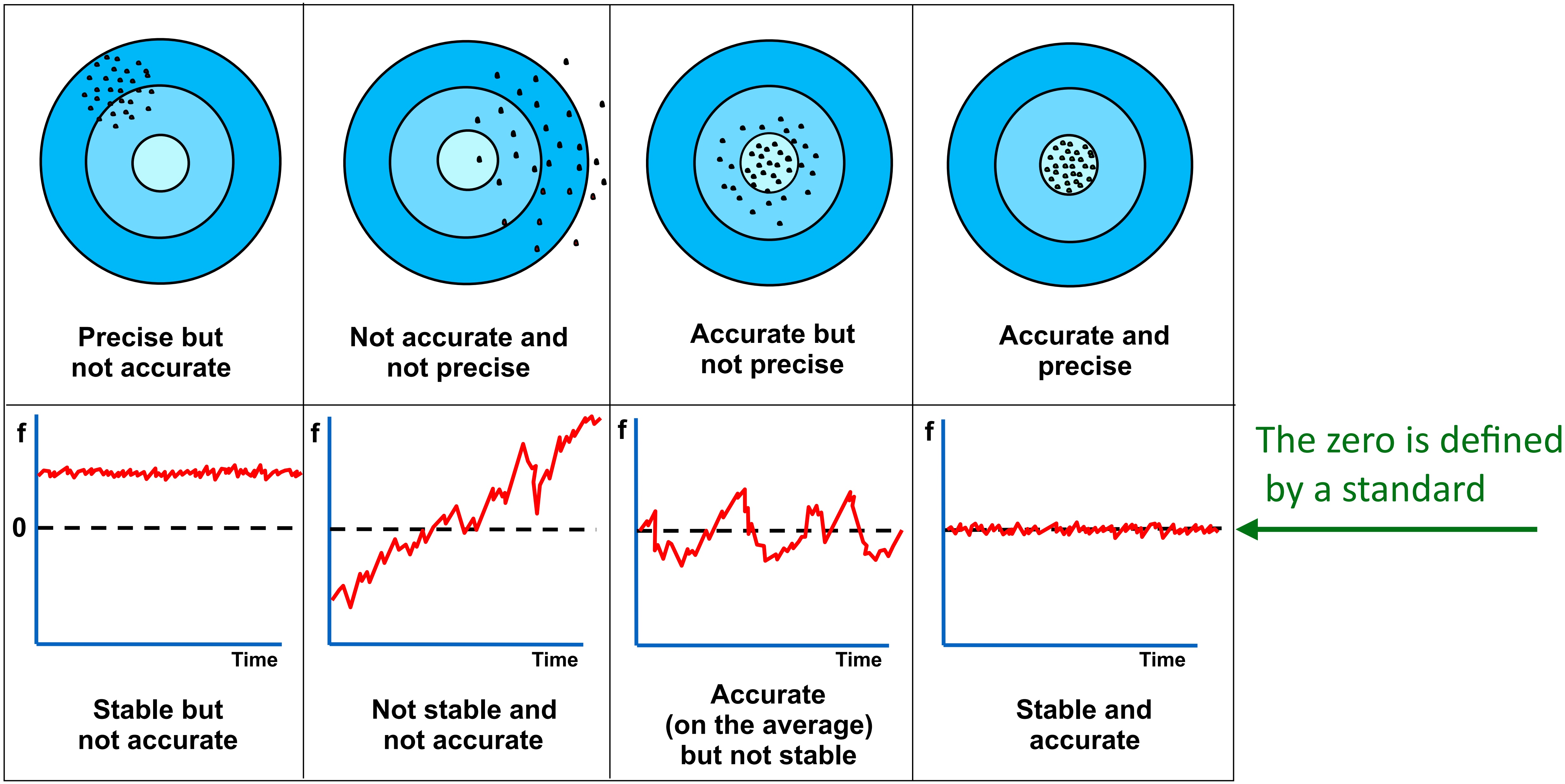
Frequency Noise and $\sigma_y(\tau)$



From John Vig IEEE

W. J. Riley, Handbook of Frequency Stability Analysis. **31**, (1994).
Interpretation of stability plots:
Howe, D. A. in Proc. IEEE IFCS 725–732 (2002). doi:10.1109/FREQ.2002.1075976

Stability and accuracy



From John Vig IEEE

Stability and accuracy : a summary

$$\nu = \nu_0\,[1 + \varepsilon + y(t)]$$

Fréquence délivrée par l'horloge

Fréquence de résonance idéale

Inexactitude

(Biais de fréquence inconnu)

B, E, collisions, effet Doppler résiduel, …

Instabilité

(bruit de fréquence)

<u>Stabilité :</u>

Amplitude des fluctuations y(t) (stabilité de fréquence) ou x(t) (stabilité en temps)

Estimée par un écart-type $\sigma_y(t)$ (sans dimension) ou $\sigma_x(t)$ (en seconde) : $\sigma_x(\tau) \propto \sigma_y(\tau).\tau$

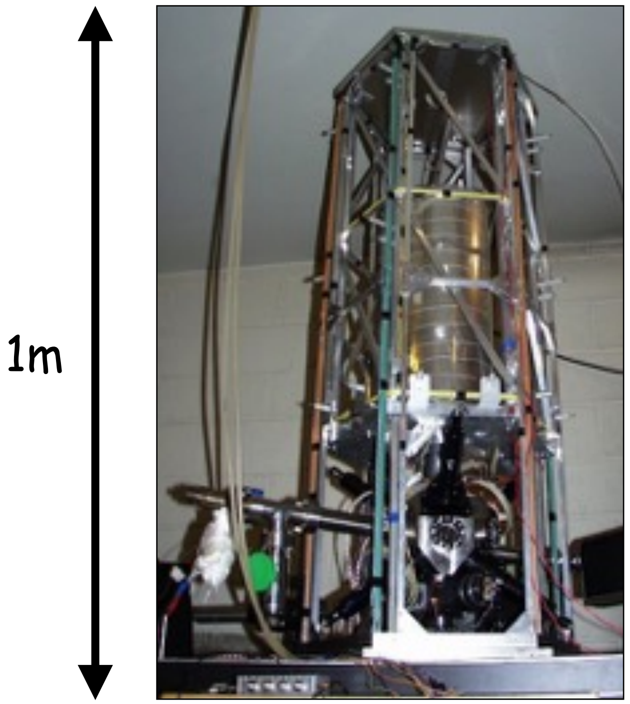
<u>Exactitude :</u>

Incertitude sur la valeur de ε

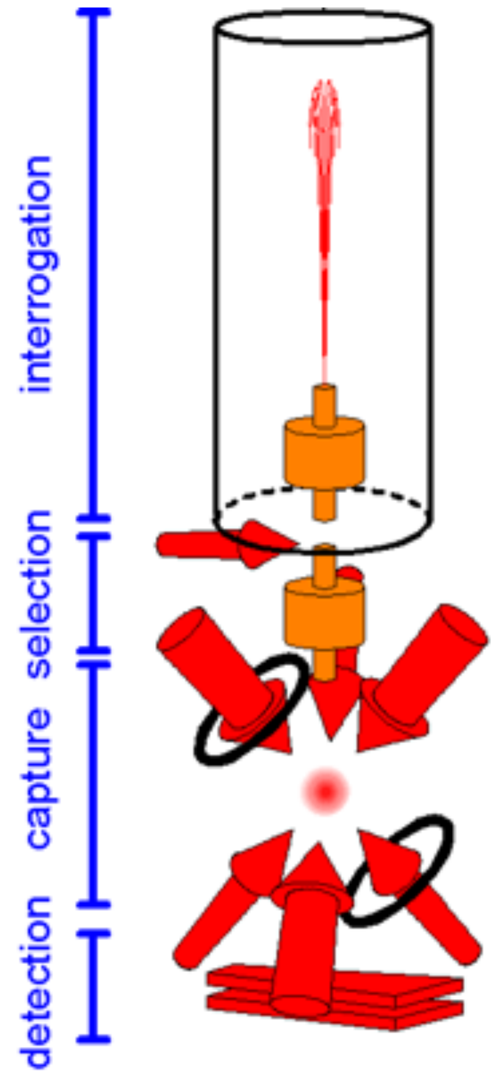
7

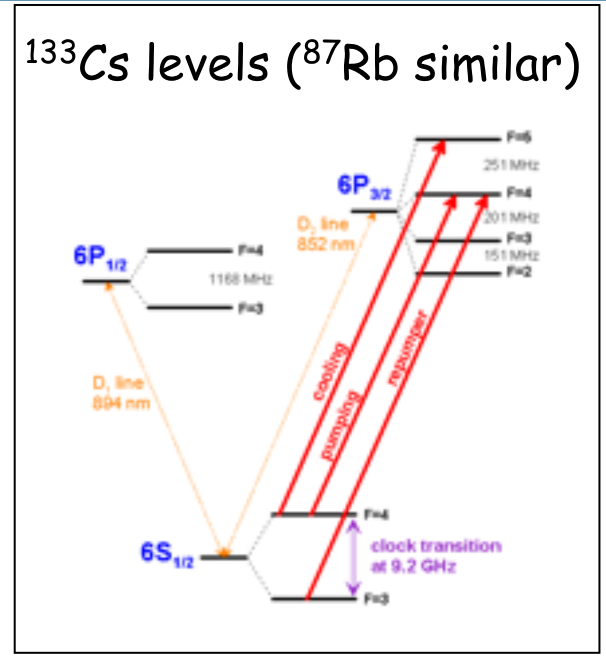
Courtesy N. Dimarcq

Atomic fountains: a frequency standard



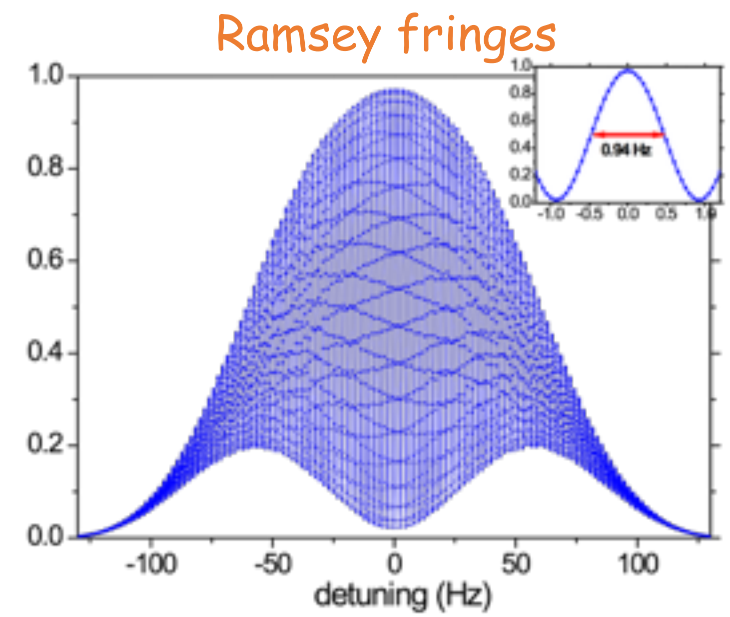
Best accuracy:
1-2x10^{-16}





Atomic quality factor:

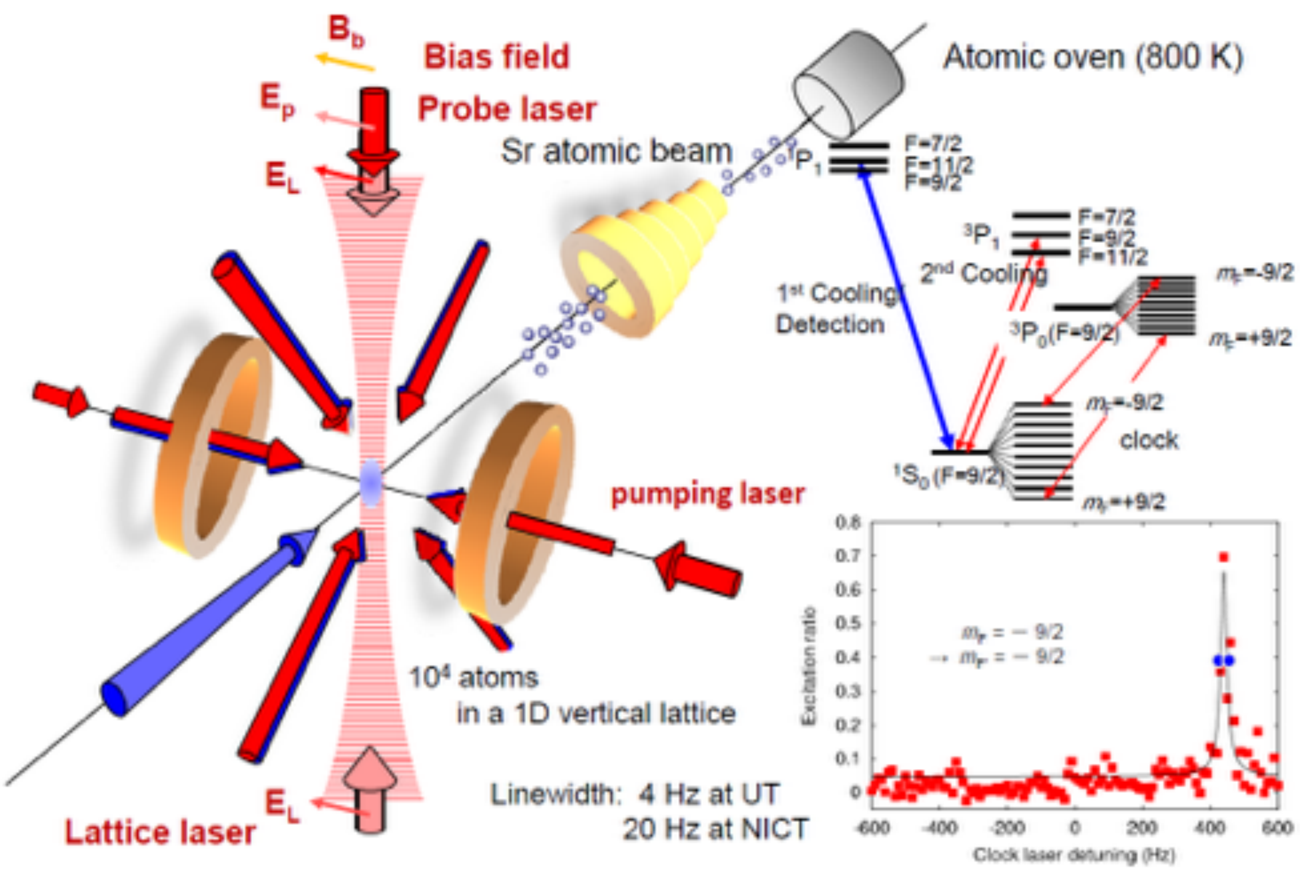
$$Q_{at} = \nu_{ef}/\Delta\nu \simeq 9.8 \times 10^9$$



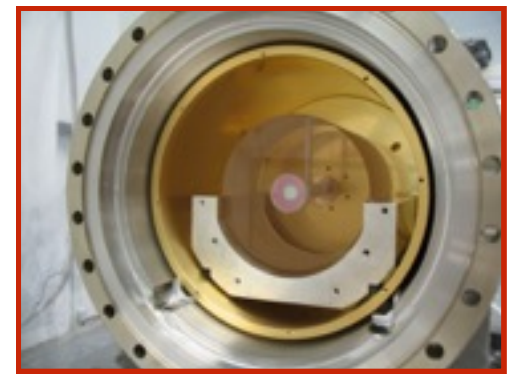
Best frequency stability (~ Quantum Projection Noise limited): 1.6x10^{-14} @1s

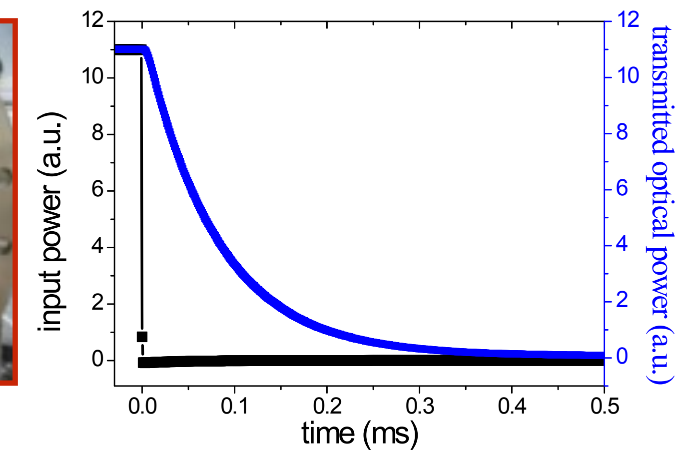
More than 10 fountains in operation (LNE-SYRTE, PTB, NIST, USNO, JPL, NICT, NMIJ, METAS, INRIM, NPL, NIM, USP,...)
with an accuracy a few 10^{-15} and <10^{-15} for a few of them.

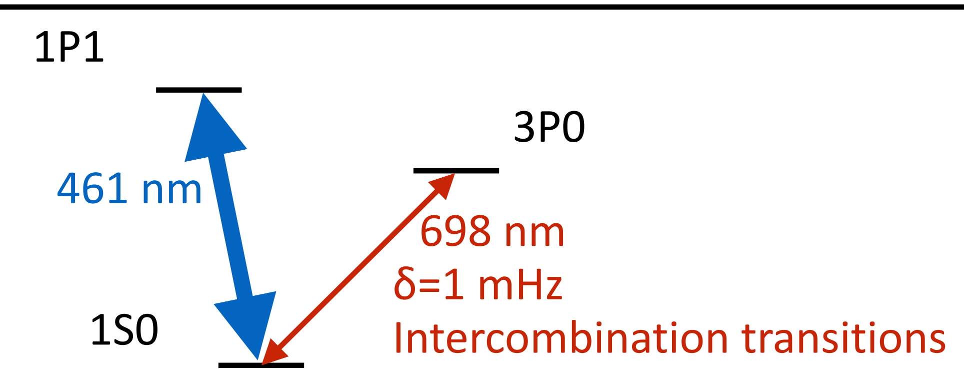
Optical clocks : (^{87}Sr) trapped in optical lattice



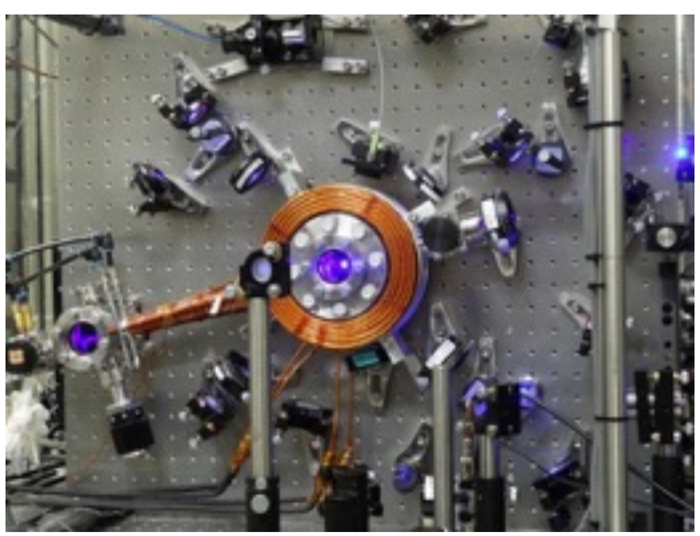
local oscillator = ultra-stable laser







^{87}Sr **Simplified level scheme**



Atomic quality factor:

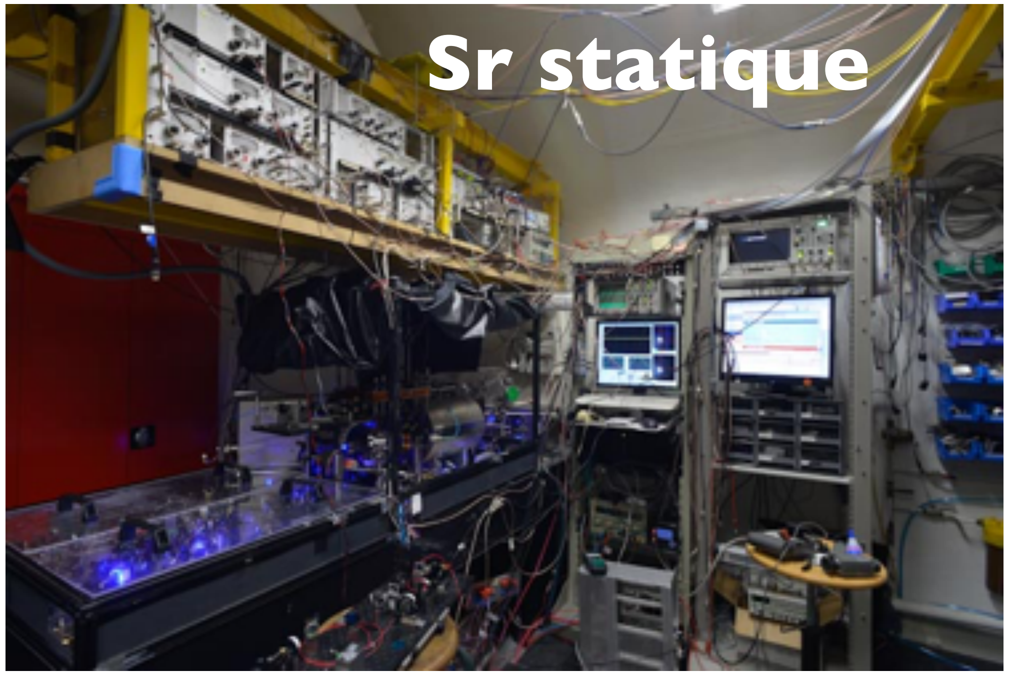
$Q \simeq 10^{14}$

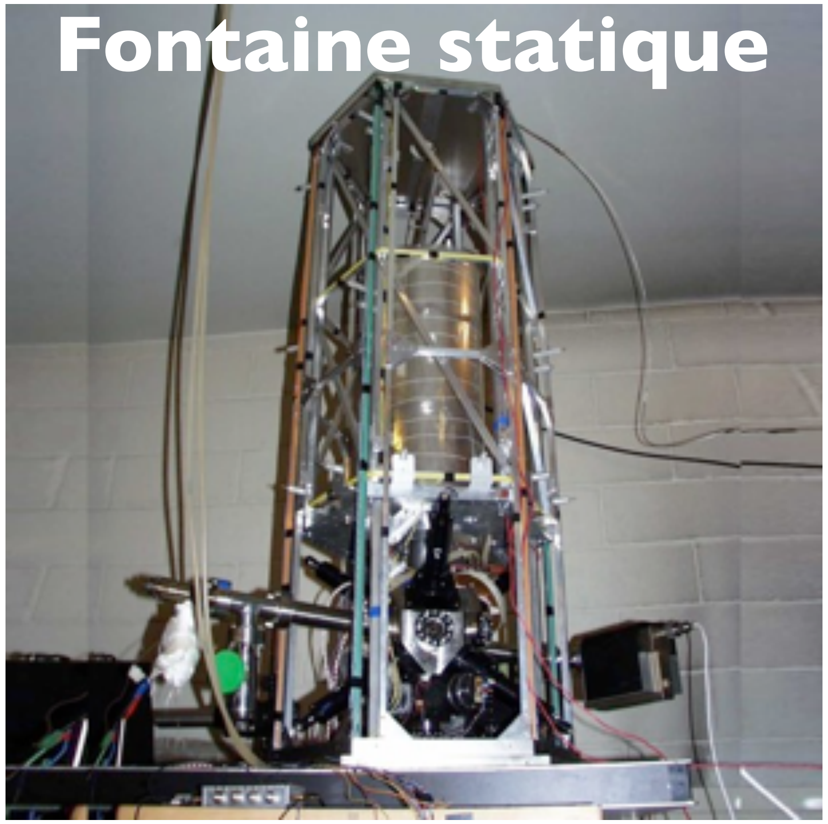
Sr (U. Tokyo, JILA, SYRTE, PTB, NPL, NMIJ, NICT…),
Yb (NIST, INRIM, U. Tokyo,…)
Hg (SYRTE, U. Tokyo),
Cd (U. Tokyo),

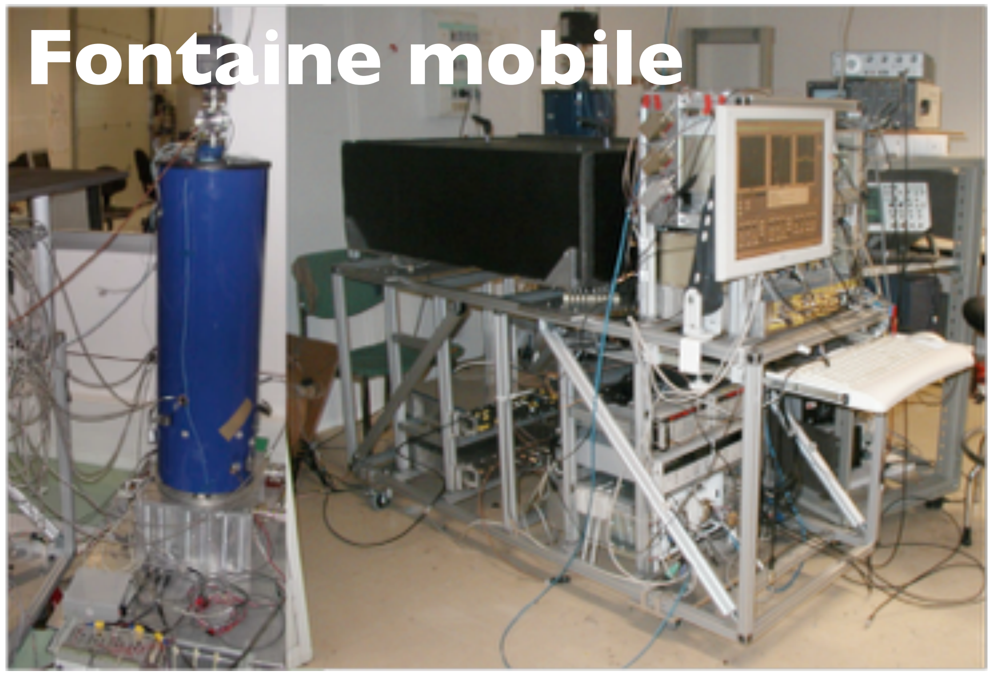
Accuracy $<10^{-16}$ and $<10^{-17}$ for a few of them.

Best frequency stability (Laser noise limited): **3x10^{-17} @150s** (Uni. Tokyo)

Pictures of frequency standards







Industrial clocks

Maser Hydrogène (oscillator)
Kvarz CH1-75A

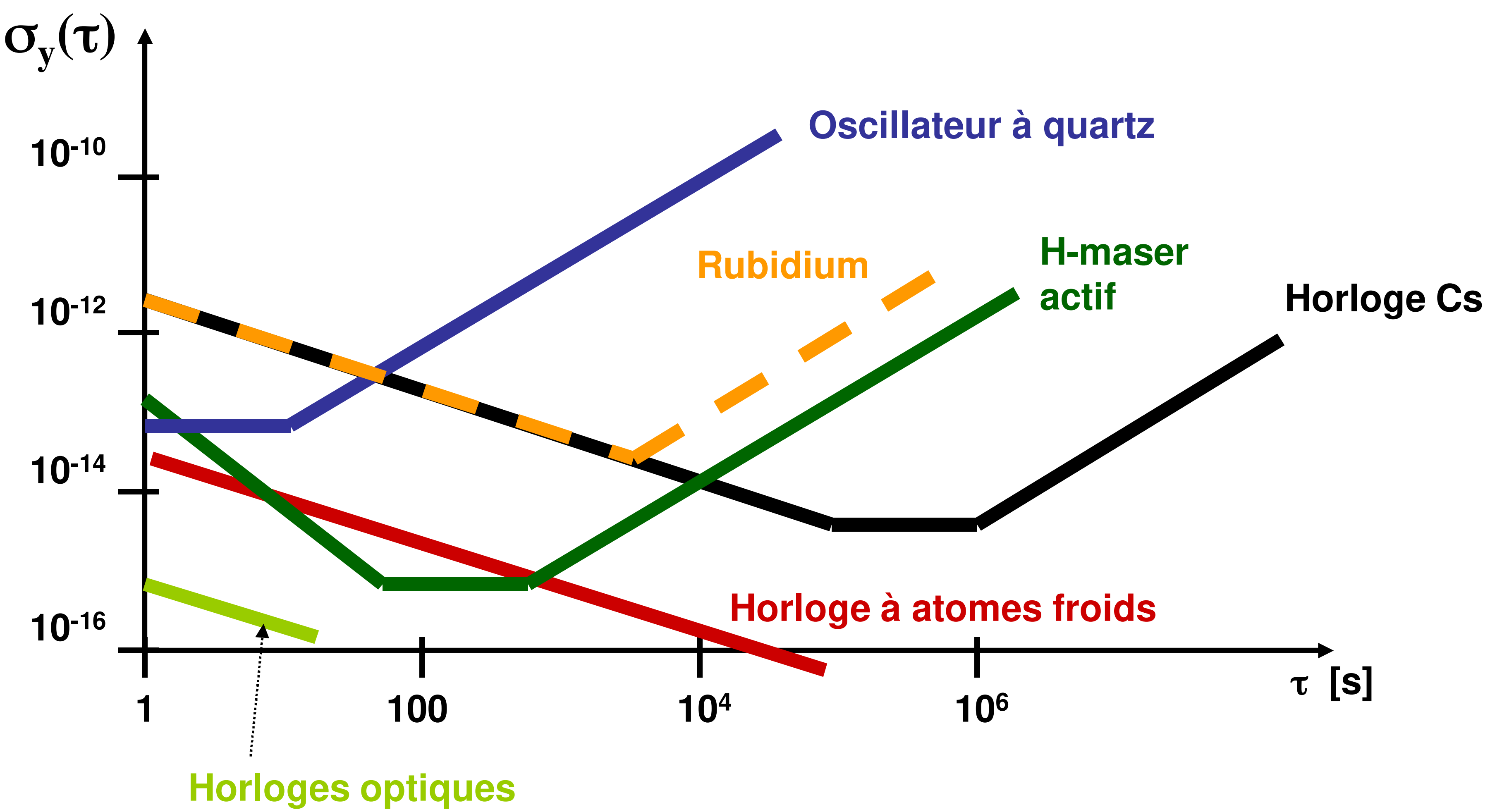
Cs 'chaud'
Micro semi HP5071 A

Rb chaud
Chip scale Atomic Clock

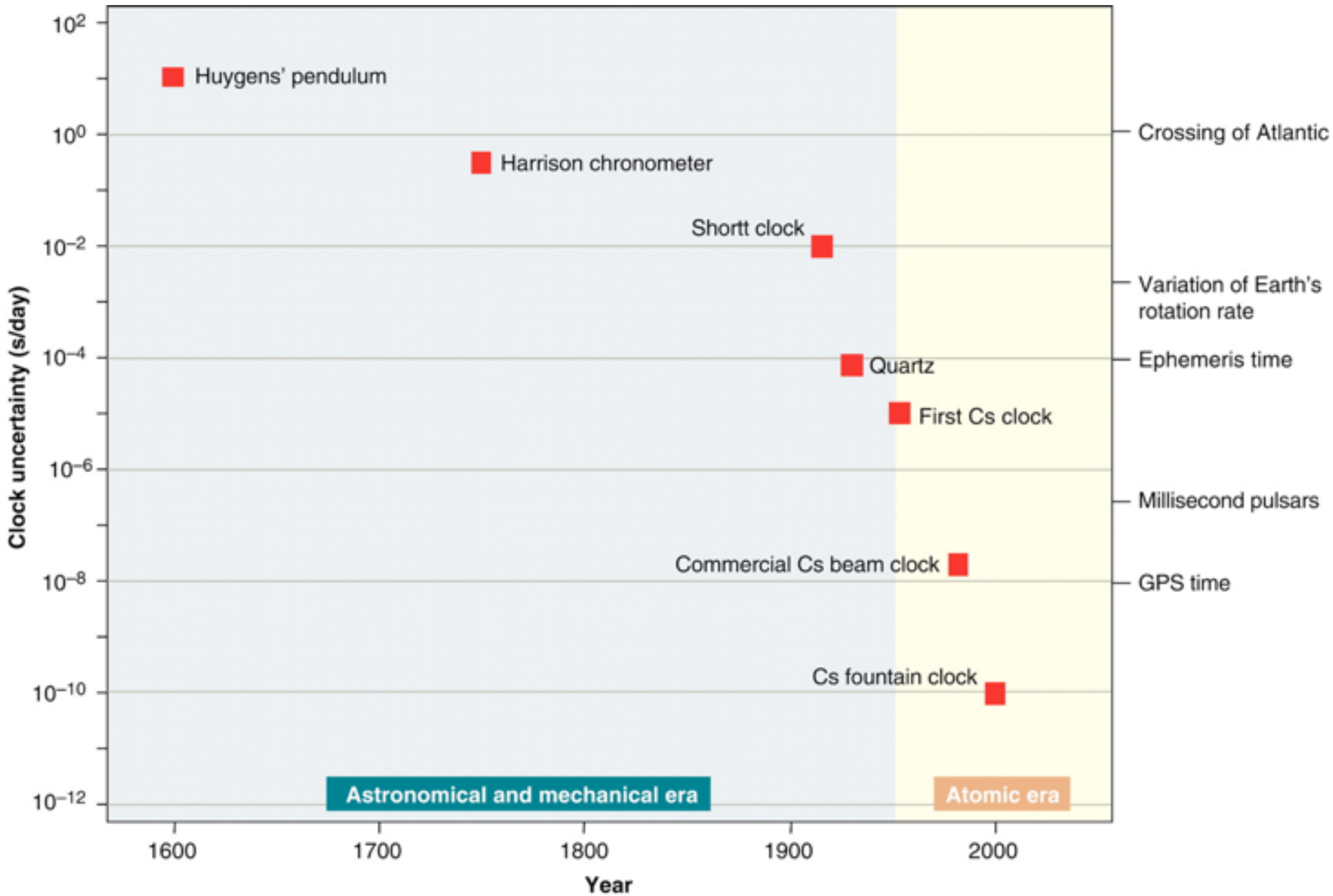
Rb chaud
Spectratime

Rb froid
MuQuans MuClock

Stabilités de fréquence typiques

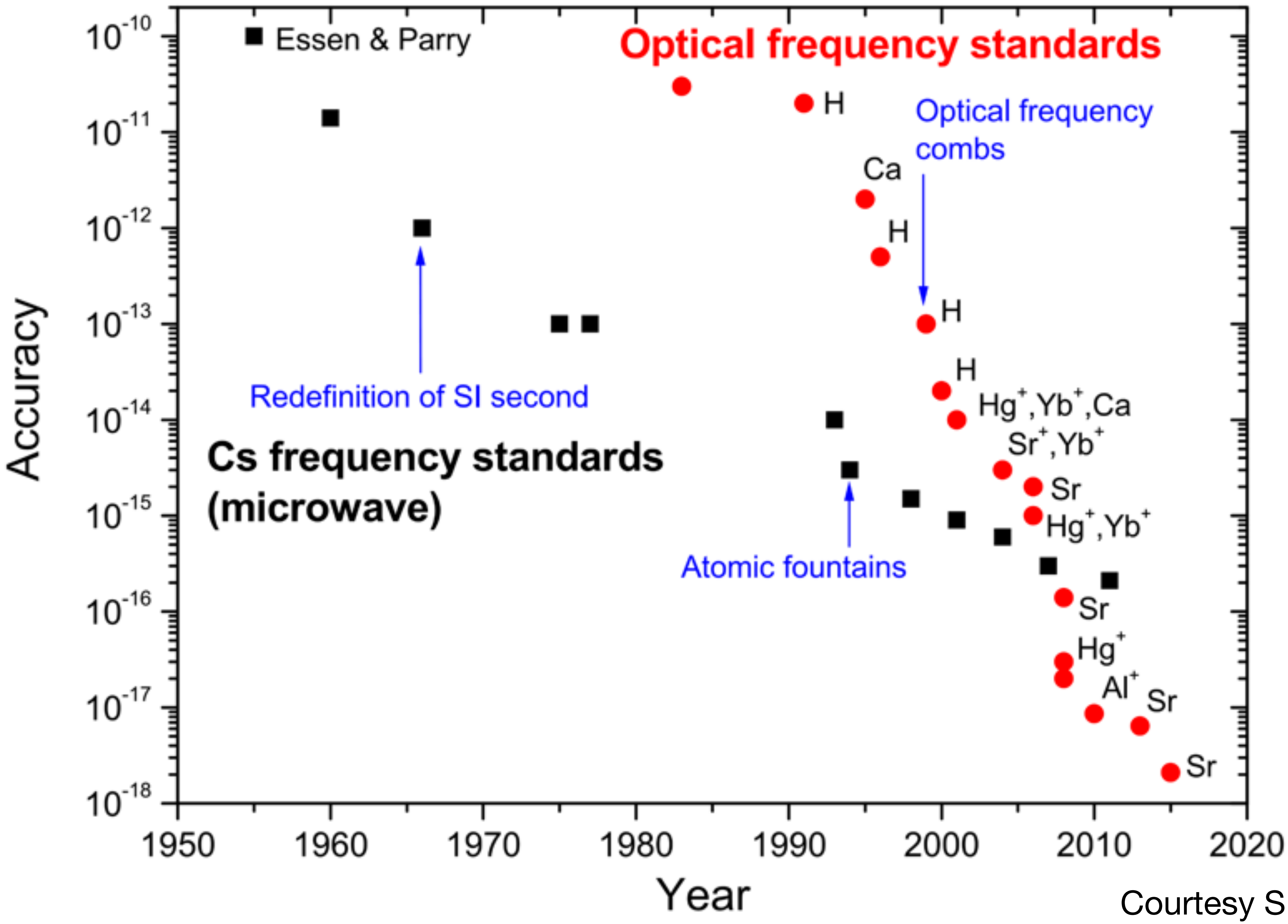


400 years of improvements...



S. A. Diddams et al., Science (2004) **306 (**5700), pp1318-1324
DOI: 10.1126/science.1102330

60 years of improvements…

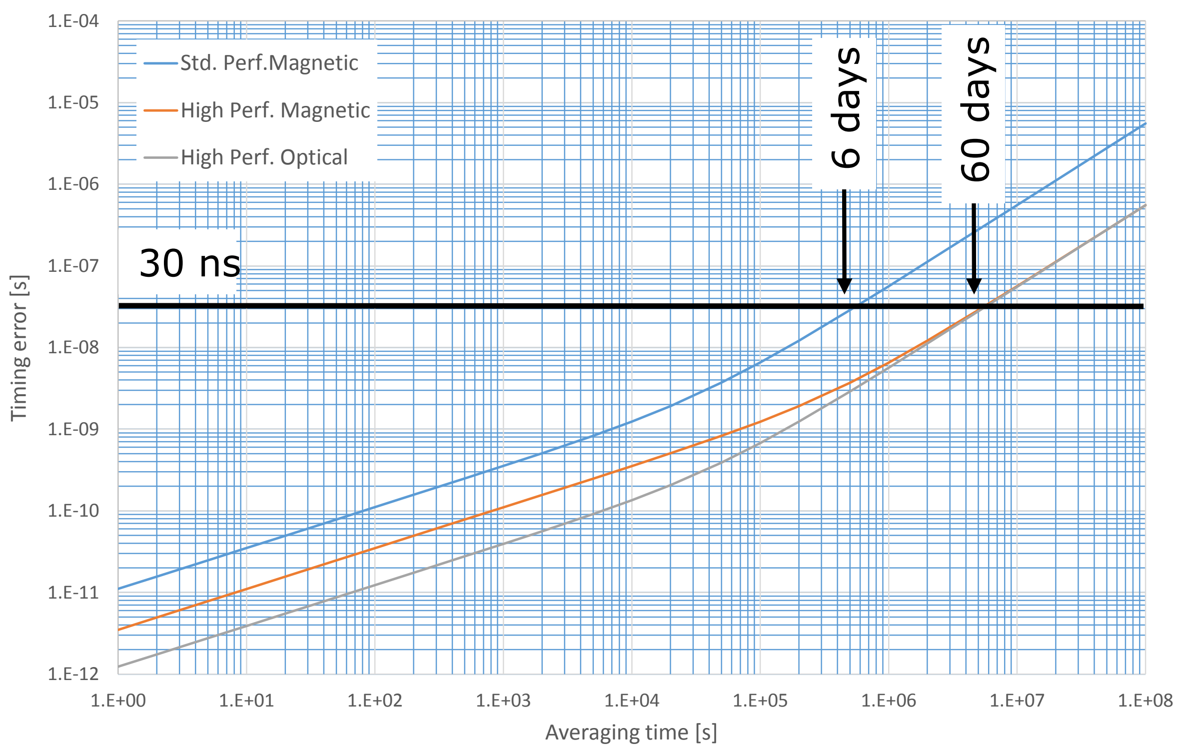


Courtesy S. Bize, C. Salomon

Time scale

A simplified vision:

Frequency standards (accurate time intervals)
+
continuous oscillator (continuous, phase keeper)
+
tick counter (display digits)
=
time scale



The issue :
1. inaccuracy * integration time
2. the absolute delay matters

Courtesy P. Berthoud
Oscilloquartz

Time scales

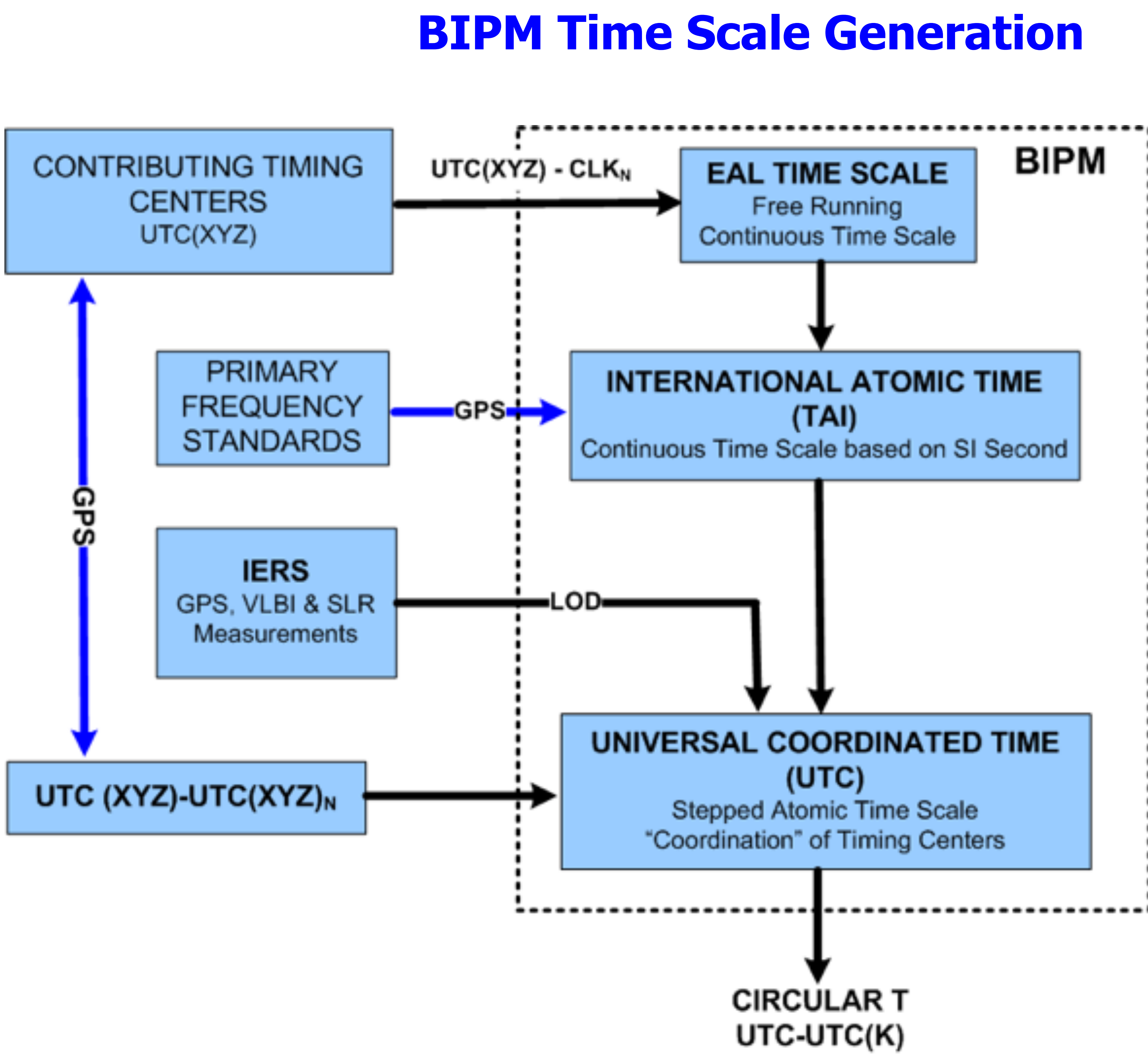
Timescales maintained at the BIPM

International Atomic Time (TAI)	✓ Continuous ✓ Interval unit is the SI second ✓ Calculated monthly at BIPM ✓ No clock representation, no broadcast
Coordinated Universal Time (UTC)	✓ 1-second discontinuities ✓ Interval unit is the SI second ✓ Calculated monthly at BIPM, derived from TAI ✓ Clock representations UTC(k), broadcast
Terrestrial Time (TT(BIPM))	✓ Continuous ✓ Interval unit is the SI second ✓ Calculated annually at BIPM ✓ Monthly predictions ✓ No clock representation, no broadcast

Courtesy F. Arias, BIPM

Bureau International des Poids et Mesures

Time scale generation



Courtesy R. Beard, USNO

Temps Atomique International (TAI)

Le Temps Atomique International TAI est la coordonnée de repérage temporel établie par le Bureau International de l'Heure (remplacé maintenant par le Bureau International des Poids et Mesures) sur la base des indications d'horloges atomiques fonctionnant dans divers établissements conformément à la définition de la seconde, unité de temps du Système International d'unités.
Il est défini par la seconde du SI réalisé sur un géoide en rotation.

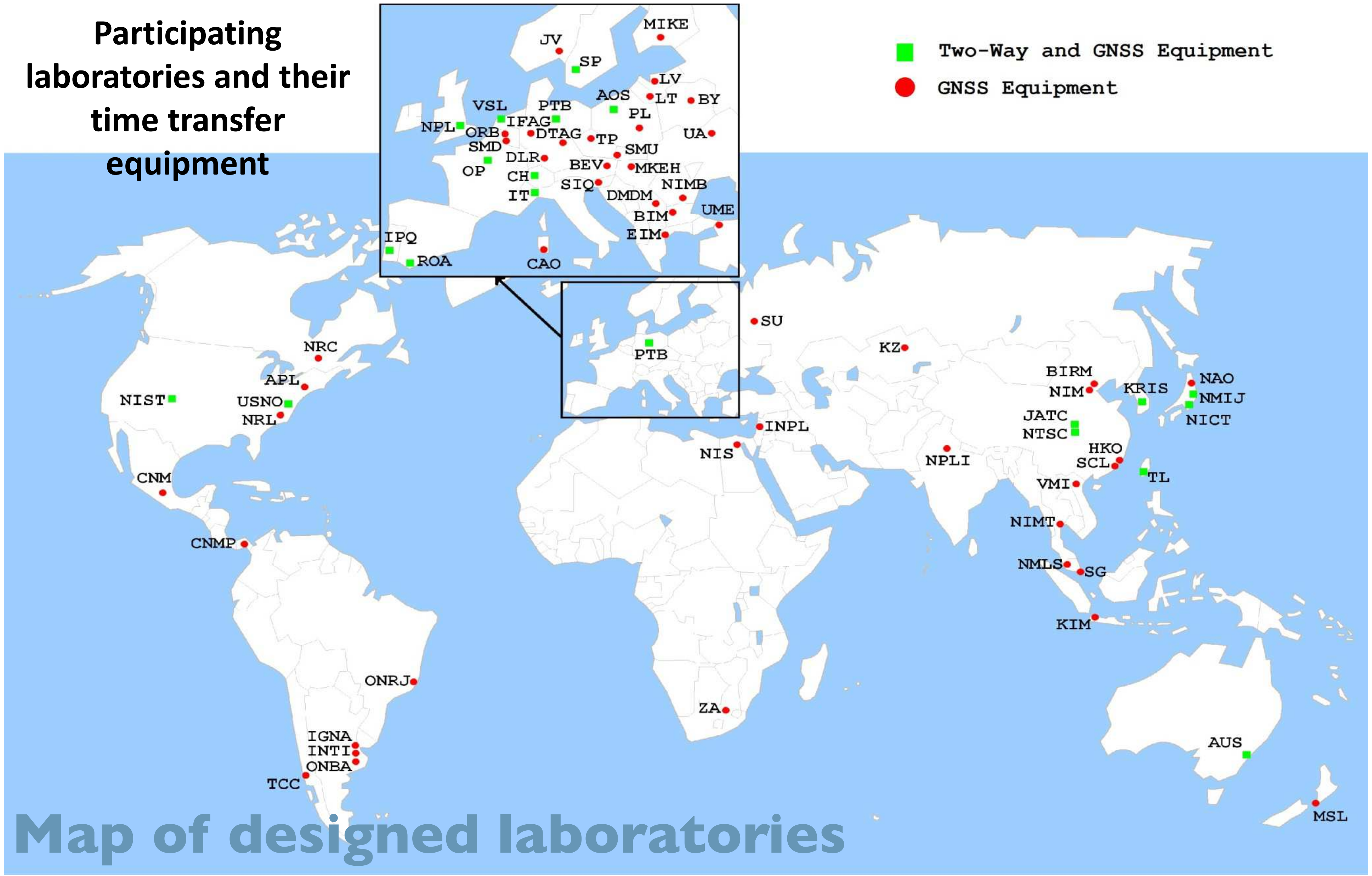
Echelle continue depuis 1958

Atomic time scales

TAI is built from 350 industrial clocks

Accuracy and long term stability is provided by the ultra-stable clocks operated by some designated laboratories

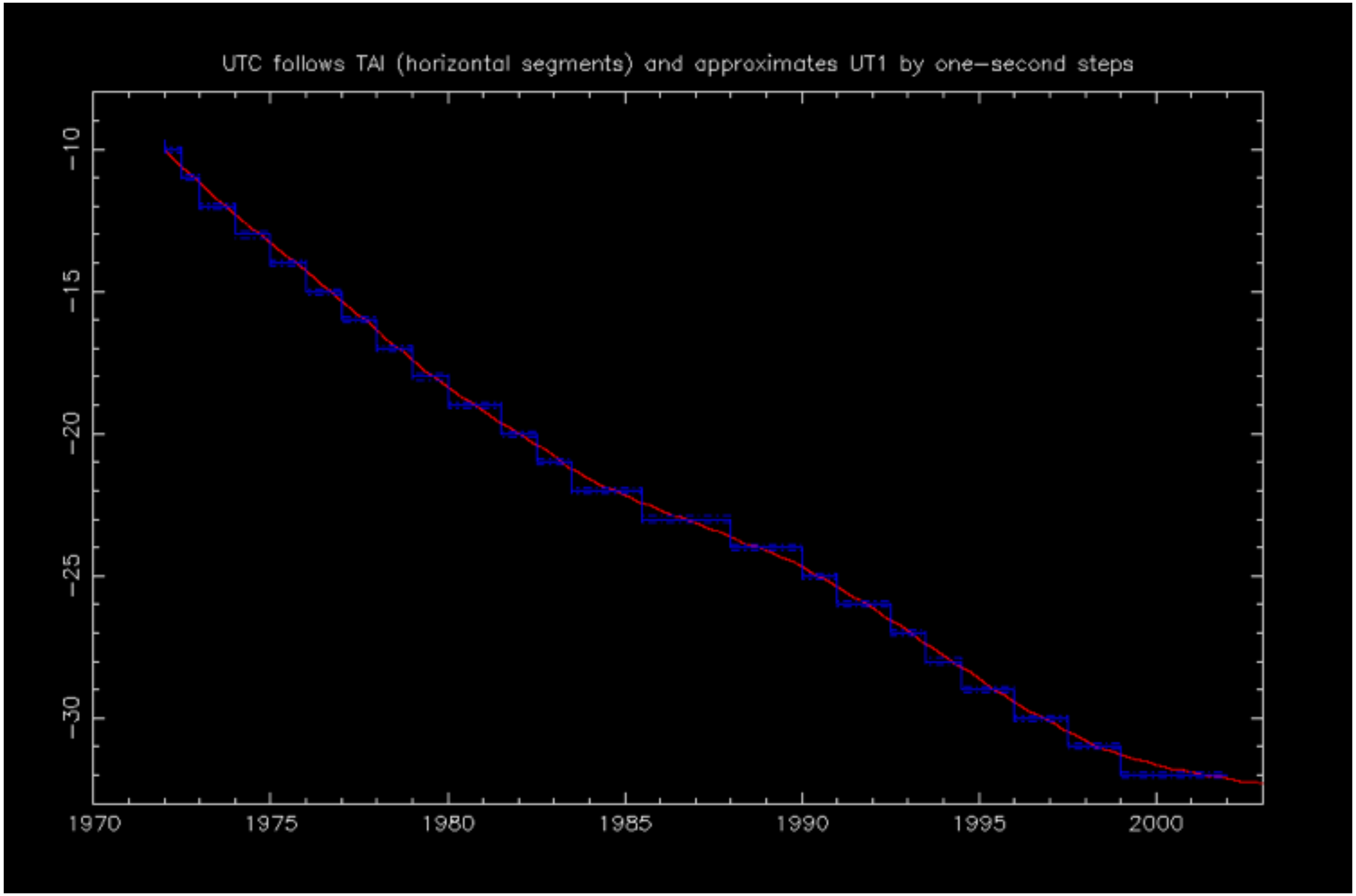
Participating laboratories and their time transfer equipment



Atomic time scales

Courtesy R. Beard, USNO

UTC follows TAI and approximates UT1



UTC

ITU-R TF.460-6 STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS (1970-1974-1978-1982-1986-1997-2002)

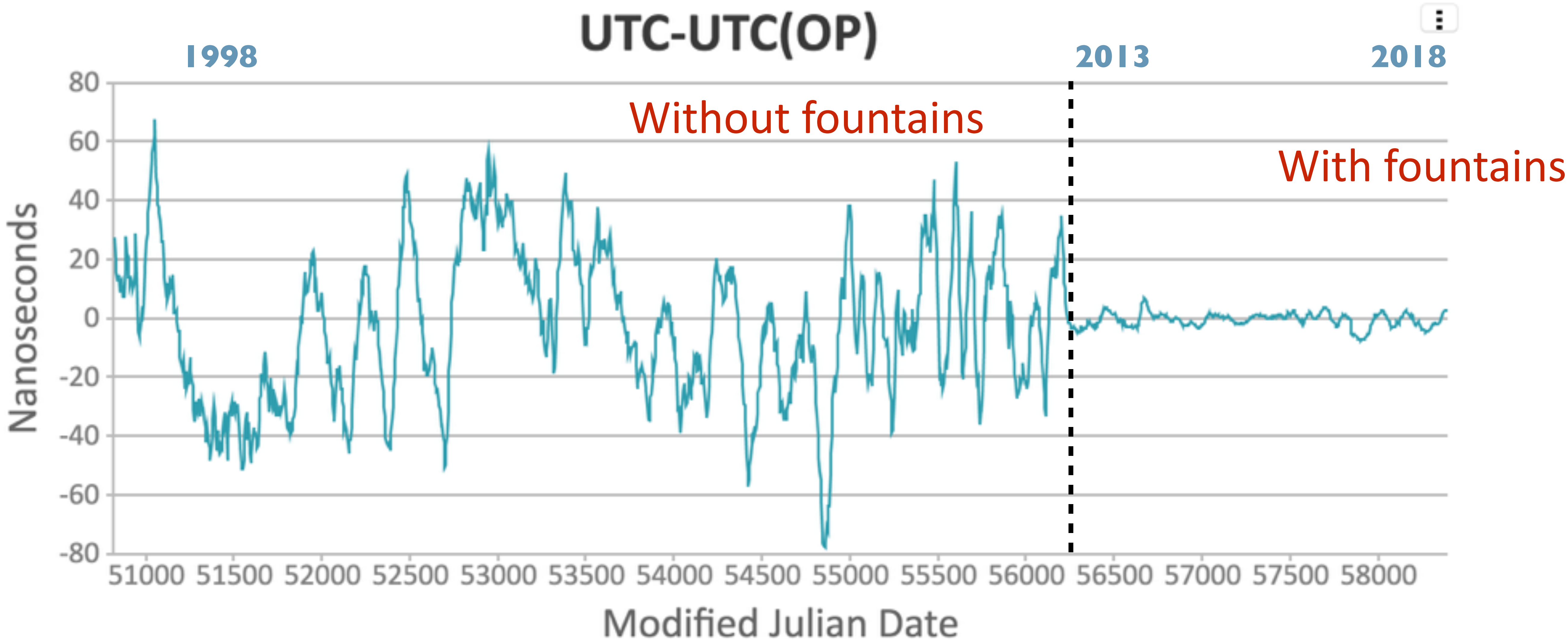
TAI - Echelle internationale de temps de référence à partir du temps atomique issue de la définition de la seconde et d'un géoïde en rotation.
Echelle continue dont l'origine est le 1er Jan 1958
TAI = UT1 le 1er janvier 1958, 0 h

UTC - Référence coordonnée sur laquelle se fonde les signaux standards de temps et de fréquence. Maintenue par le BIPM. Correspond exactement au TAI décalé d'un nombre entier de secondes afin d'assurer un accord avec UT1 inférieur à 0.9 s.
TAI – UTC = 37 s en 2018

Attention ! UTC est une échelle de temps papier diffusée par la circulaire T.
UTC(k) est une réalisation locale, c'est un signal physique.

Les secondes intercalaires peuvent être introduites comme dernière seconde de n'importe quel mois, préférentiellement décembre et juin, en deuxième choix mars et septembre.

A time scale over the years (continuous)



Last site modification : 30/07/2018

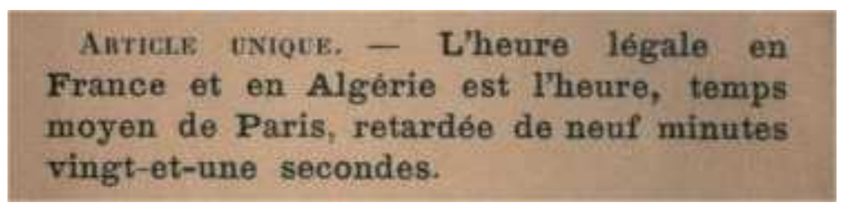
Legal time in France < March, 2017

Le temps légal et l'Observatoire de Paris

Courtesy M.-C. Angonin

1891 : Unification de l'heure – Méridien de Paris

1911 : Méridien de Greenwich (GMT)



ARTICLE UNIQUE. — L'heure légale en France et en Algérie est l'heure, temps moyen de Paris, retardée de neuf minutes vingt-et-une secondes.

1978 : Temps atomique international

L'heure légale en France est déterminée par le décret du 9 aout 1978 : "le temps légal est obtenu en ajoutant ou en retranchant un nombre entier d'heures au temps universel coordonné", ce nombre entier d'heure étant fixé par décret. L'heure légale en France est fabriquée et diffusée par le SYRTE à l'Observatoire de Paris.

Legal time since March, 2017

Décret n° 2017-292 du 6 mars 2017 relatif au temps légal français

Le temps légal (ou heure légale) sur le territoire de la République française est fixé par référence au temps universel coordonné (UTC) établi par le Bureau international des poids et mesures (BIPM) dans le cadre de la conférence générale des poids et mesures.

II. - Dans le cadre de la coordination de la métrologie française et des règles fixées par le BIPM pour l'établissement du temps universel coordonné, l'Observatoire de Paris est chargé d'établir la valeur locale de l'UTC, dénommée « temps légal de base », et de la fournir aux utilisateurs.

III. - Le temps légal sur les différentes parties du territoire de la République française est défini à partir du temps légal de base auquel est ajouté ou retranché un nombre entier d'heures dans les conditions fixées aux articles 2 à 4 du présent décret.

- Frequency/Phase noise
- Delay
- Calibration methods and uncertainty

Frequency analysis

Phase noise characterization is a comparison process.

2 categories :

1. comparing with itself (delayed self-homodyne, delayed self-heterodyne, or Michelson interferometer).
2. comparing the laser under test with a much better source

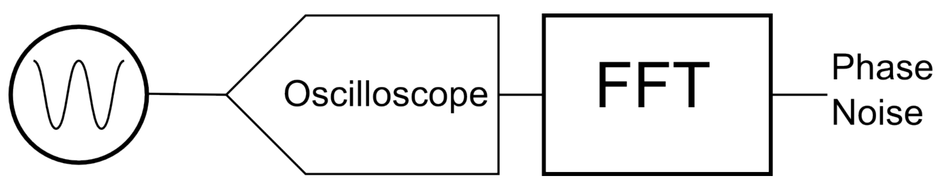
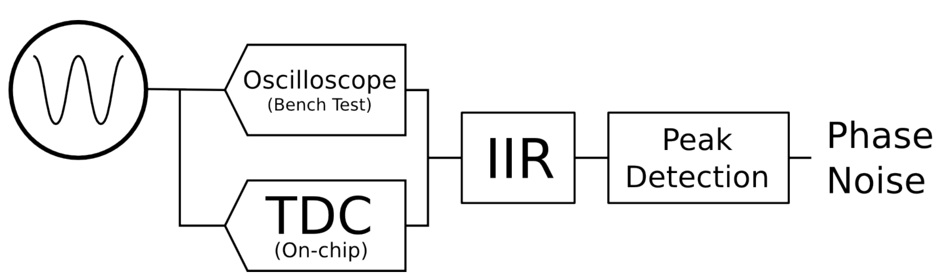


Figure 1.1: Conventional analog spectral analysis



Old way :
frequency mixing and low sampling rate

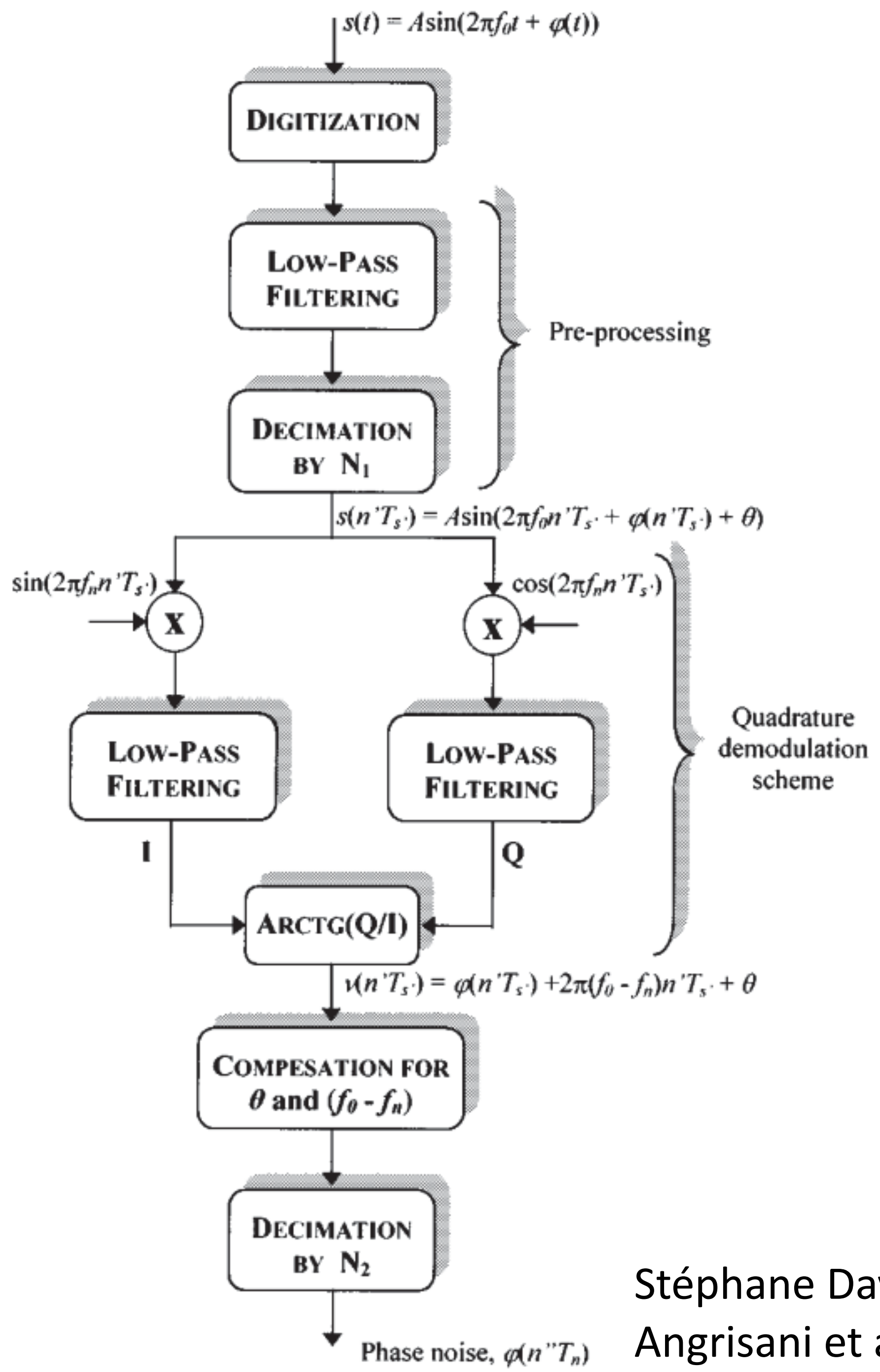
Nowadays :
High sampling rate
Data processing

heterodyne methods :
- Beat notes at low frequency (<50 MHz)
- Frequency counter

Cross correlation :

Reference paper : E. Rubiola and V. Giordanno https://doi.org/10.1063/1.1304871
In the optical domain : X. Xie, Opt. Lett. **42** (7) (2017) https://doi.org/10.1364/OL.42.001217

Phase noise analyzer



Stéphane David-Grignot, (hal) tel-01590614 (2015)

Angrisani et al., IEEE TIM **50** (4), 2001

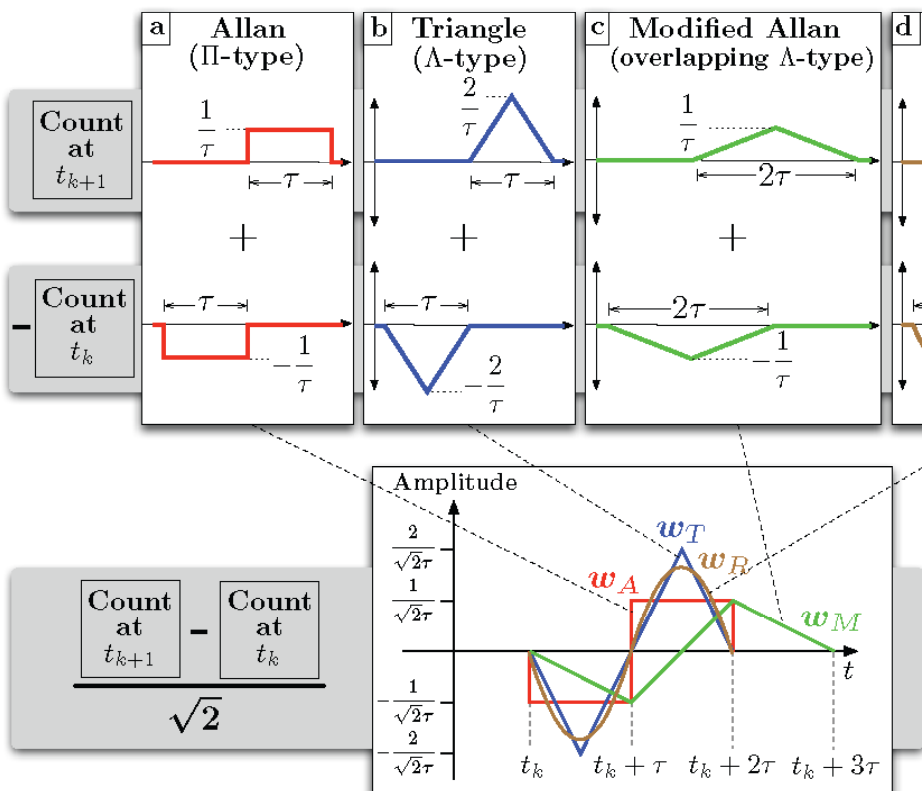
Holzworth

Noise XT

(Symmetricom) Microsemi

Frequency counter / Phase meter

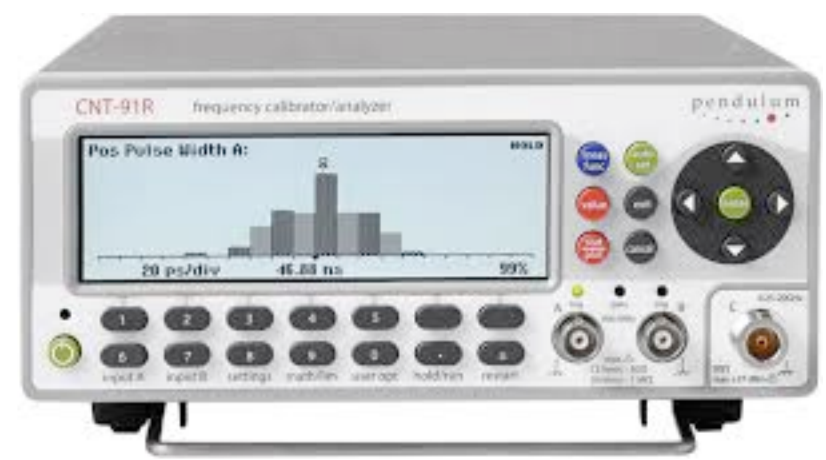
- Use only dead-time free frequency counter !
- Many operation possibilities :



E. Rubiola, RSI **76**, 054703 (2005)
Dawkins, IEEE T-UFFC **54**, 918–925 (2007)

Keysight 53230A

Pendulum CNR-91R



k+k Messtechnik

The Need for a Reference Plane

- With a need for true "time accuracy" the four dimensional space-time continuum is and engineering reality!

- We establish a plane of connectors with synchronized timing signals

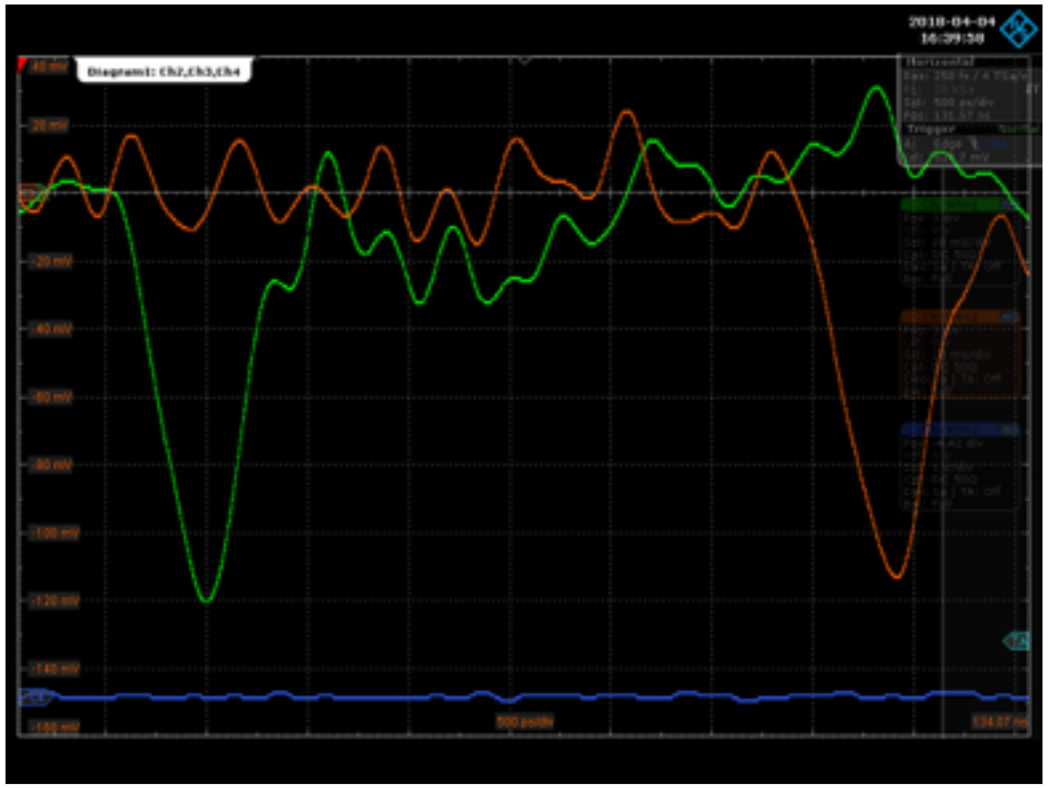
- A signal travelling away loses time at some fraction of the speed of light = 1 ft/ns = 30 cm/ns

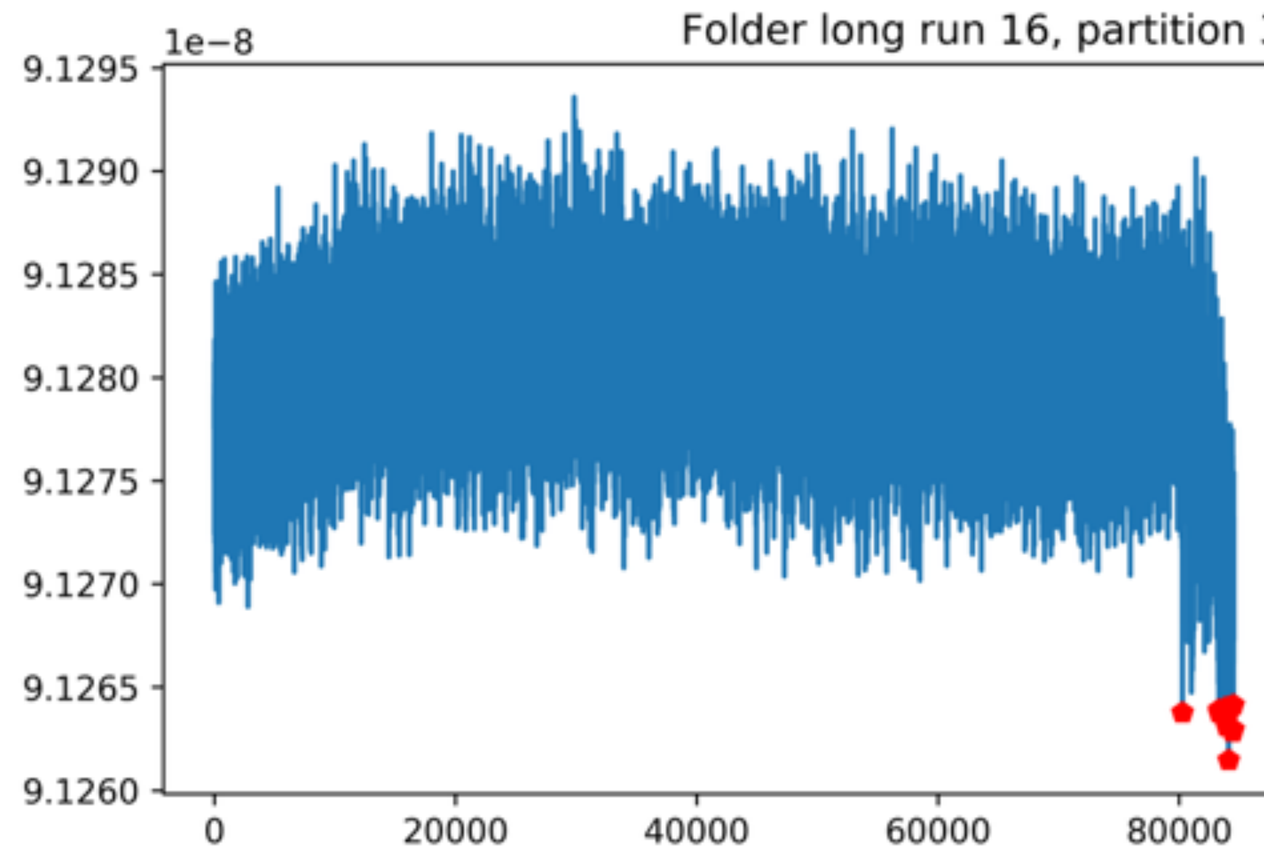
- For GPS receivers, calibration and measurements are relative to the reference point, and signals out are delayed relative to this

Time is marked by a 1 pulse per second (PPS) signal

Courtesy M. Weiss, NIST

Scope



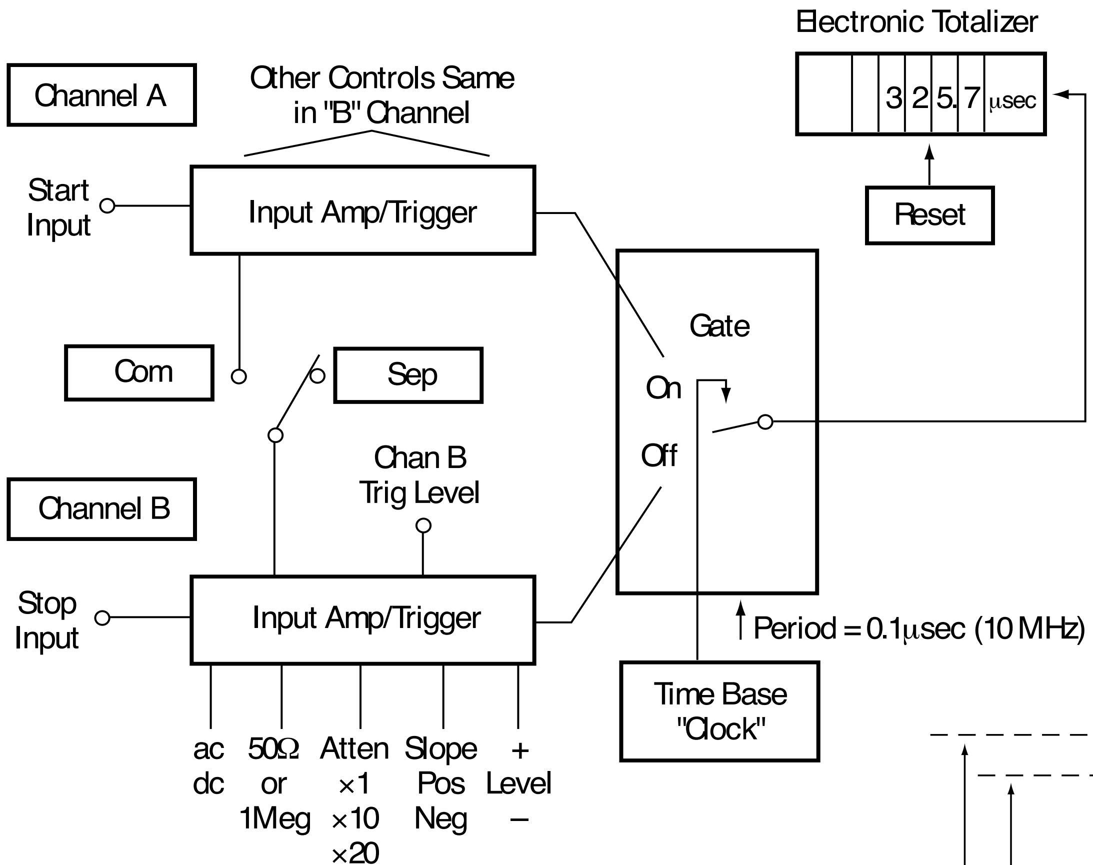


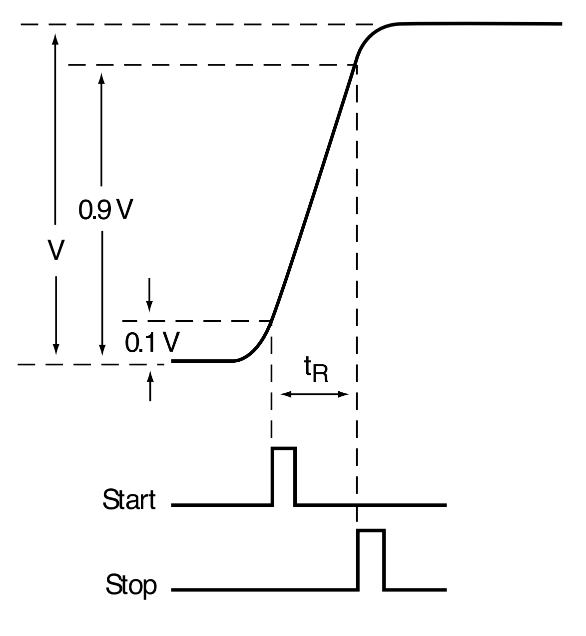
Modern scopes will provide you with a standard deviation based on gaussian assumptions in most cases

- Long run deviates from such simple approaches
- Issues with the outliers
- Trigger level

The best is to record data and to process yourself

Time interval counter





From Application Note 200-3
Agilent technologies

SRS 620

Carmel instruments (BI-200)

Guidetech GT9000R

Calibration methods

Les méthodes de calibration sont des méthodes variationnelles :

1. Installation du banc de mesure (*'Calibrator'*)
2. Réglage des offsets, mesure des stabilités
3. Insertion de l'élément à caractériser, et mesure du nouveau délai
4. Nouvelle mesure sans le nouvel élément (bouclage)

Contributions à l'incertitude systématique des délais instrumentaux par

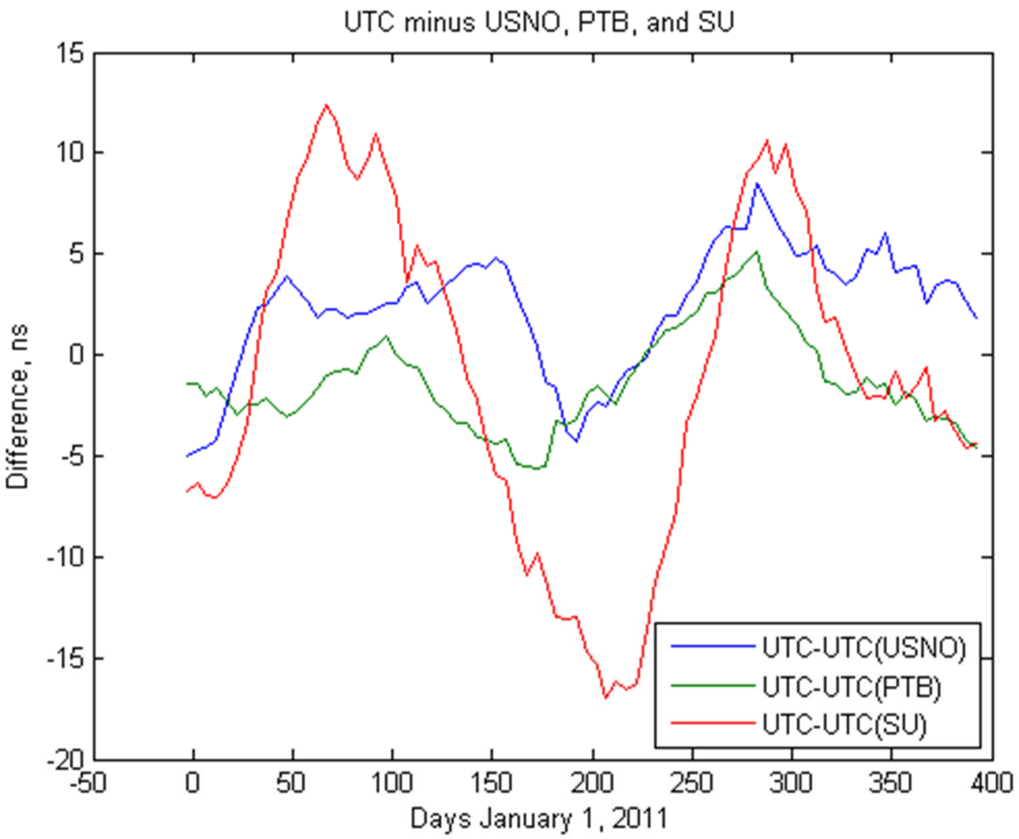
1. Effets liés à la température
2. Tensions de référence
3. Capacités parasites (connecteurs, cables…)
4. Maitrise des paramètres expérimentaux (AM/PM, forme des signaux…)
5. Problèmes de méthodologie (répétabilité…)

Délai de propagation

1. à portée local: même méthodes, même problèmes
2. à longue portée : mesure en pratique d'un aller-retour
    1. Hypothèse de chemin réciproques
    2. Modélisation de la propagation (multi-chemin…)
    3. Corrélations

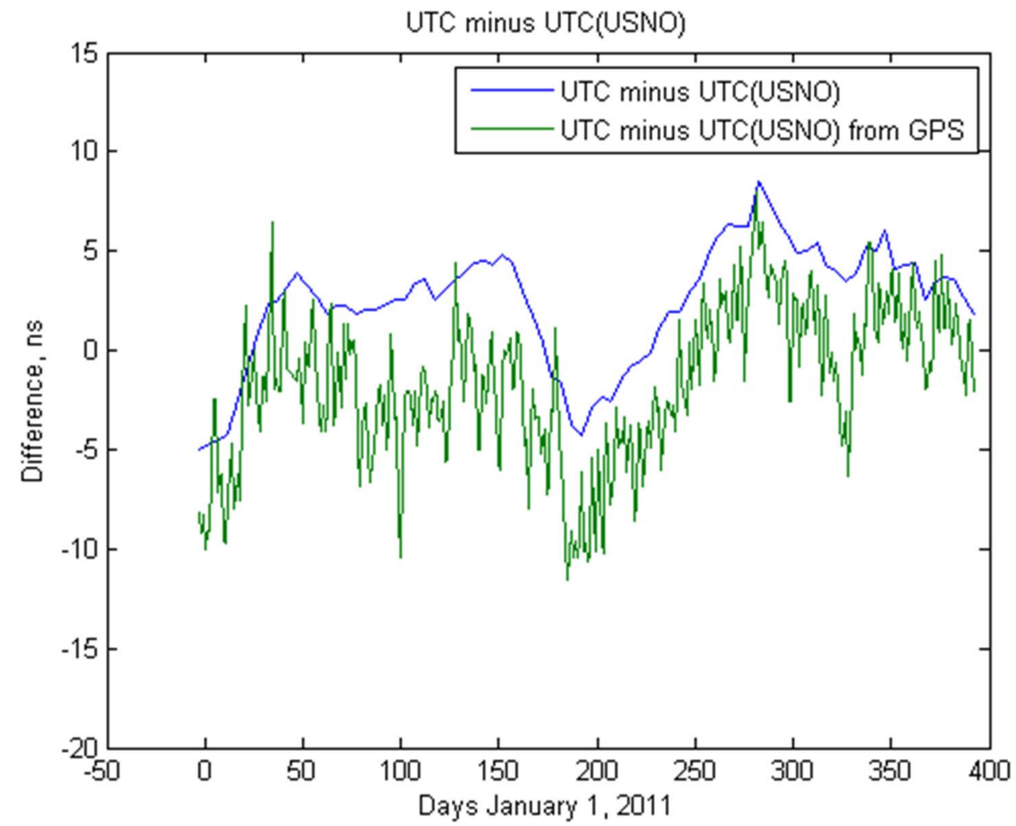
Error Sources

Differences for some UTC:



USNO = the US reference for GPS,
PTB = the German lab, possible for Galileo,
SU = the reference for GLONASS

UTC(USNO) vs. UTC(USNO) from GPS

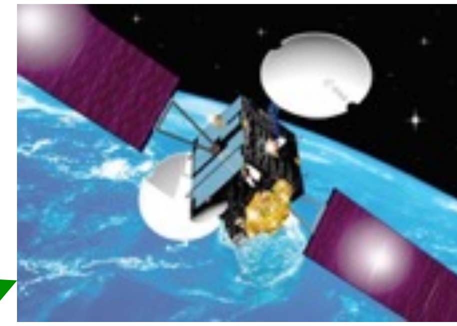


Courtesy M. Weiss, NIST

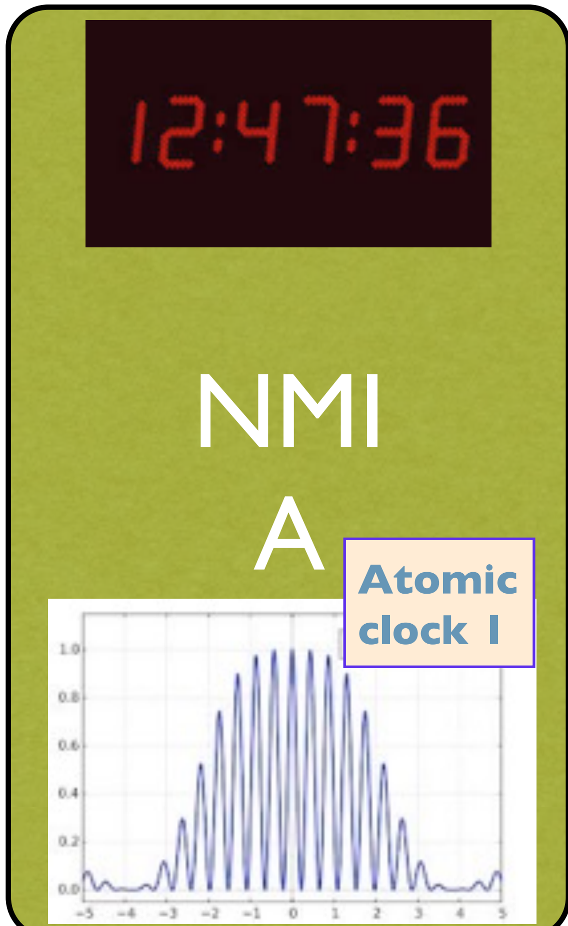
- Basic ideas
- Satellite
- Fibre

Means to compare/disseminate clocks

Radio signals and
Satellite Link
10^{-11}(1s)
$2\text{x}10^{-15}$(1d)



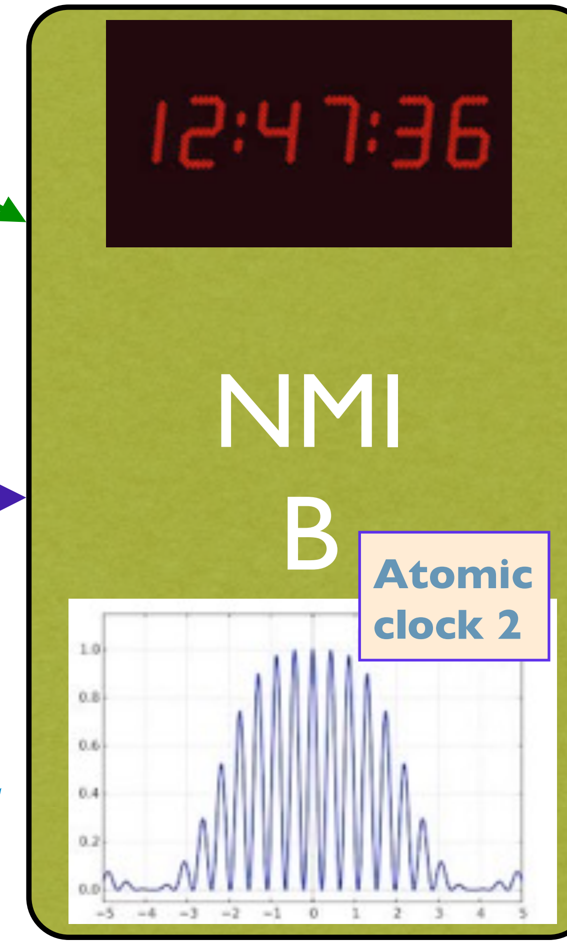
Nobel prize 1909
Guglielmo Marconi,
for the 1st trans-atlantic
radio transmission



Stability(1s) <10^{-13}
Accuracy <10^{-16}

in Europe
800< distance <1500 km

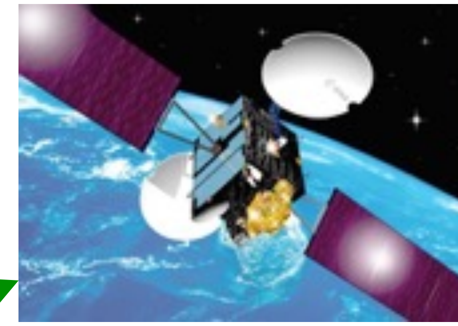
(cf. Belville and *The Greenwich time lady*)



Transportable clock
(Cs, Sr)
Cs : 10^{-13}(1s), $4\text{x}10^{-16}$(1d)
Sr : 10^{-15}(1s), 10^{-17}(3h)

Means to compare/disseminate clocks

Radio signals and
Satellite Link
10^{-11}(1s)
$2\text{x}10^{-15}$(1d)

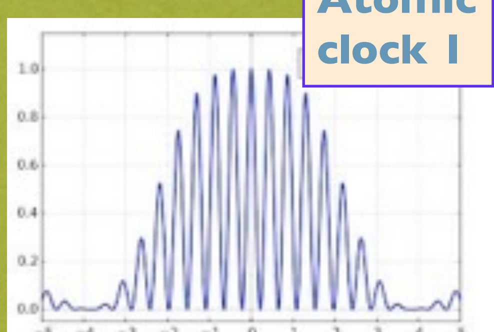


Nobel prize 1909
Guglielmo Marconi,
for the 1st trans-atlantic
radio transmission

12:47:36

NMI
A

Atomic clock 1



Optical Fiber Link

in Europe
800< distance <1500 km

12:47:36

NMI
B

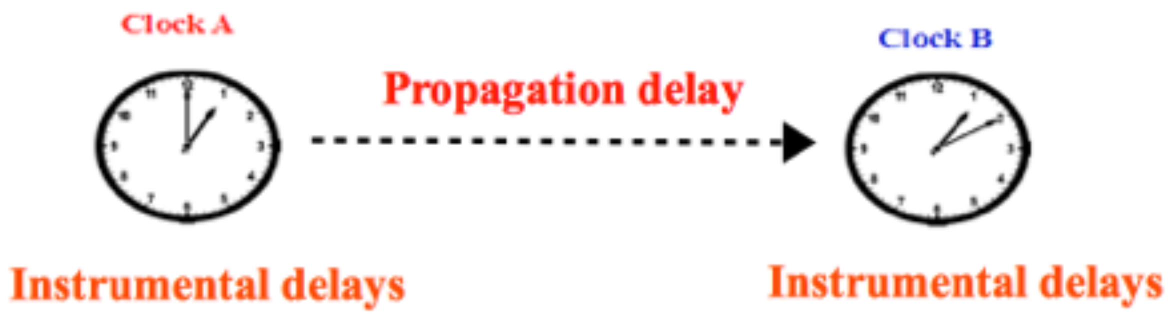
Atomic clock 2

Stability(1s) <10^{-13}
Accuracy <10^{-16}

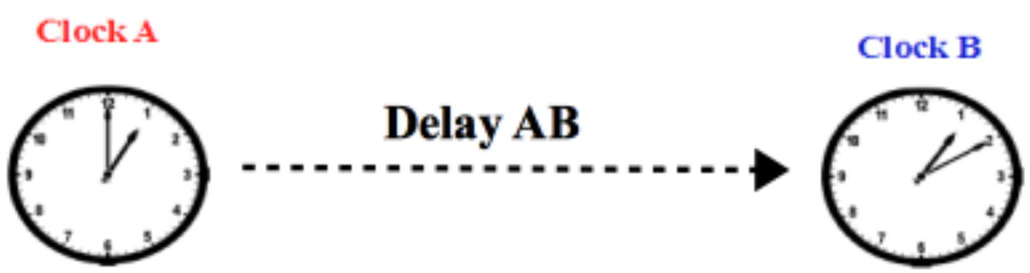
(cf. Belville and *The Greenwich time lady*)

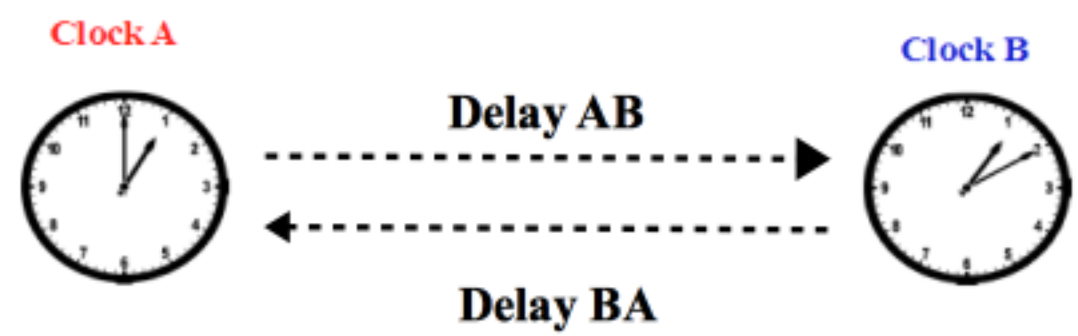
Transportable clock
(Cs, Sr)
Cs : 10^{-13}(1s), $4\text{x}10^{-16}$(1d)
Sr : 10^{-15}(1s), 10^{-17}(3h)

Time/Frequency transfer : basic ideas



Time transfer = mastering delays
Instrumental delays
Propagation delays
Other… (Sagnac effect)





The path delay AB needs to be determined.
Hypothesis
- Celerity of the waves
- Propagation modeling
- Spatial coordinates
- Measure a time interval at B side

Applied in GPS time transfer method

Both clocks must transmit signals.
Measure the Round trip time (RTT).
- One way delay is estimated as half of the round tr value.
- Hypothesis of reciprocity.

Applied in : Two-Way satellite T&F transfer, T&F over optical fiber links, NTP, PTP...

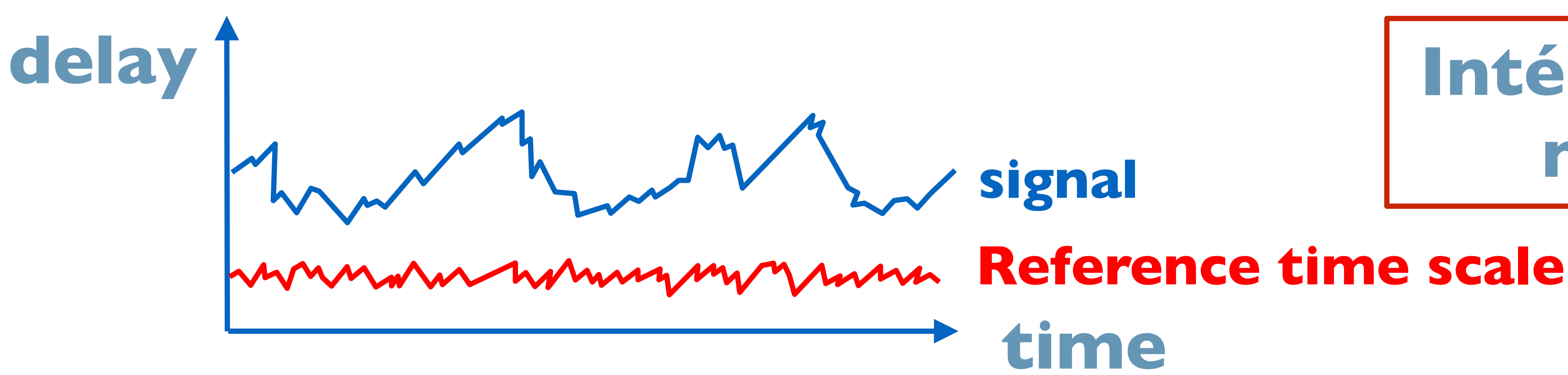
Time accuracy : basic ideas

Temps : la coordonnée de temps d'un repère espace-temps
Mais le plus souvent
temps = délai à une échelle de temps de référence

Transfert de temps = transfert d'un signal de référence, où le signal reçu en un point B à l'instant t a un délai connu par rapport à l'échelle de temps de référence localisée en A à l'instant t

Délai = Instrumental + propagation
(+ effet physique lié aux différences de coordonnées)

Délai instrumental : mesuré ('*mal*' modélisé)
Délai propagation : mesuré et/ou modélisé (avec ajout(s) de nouvelles données)

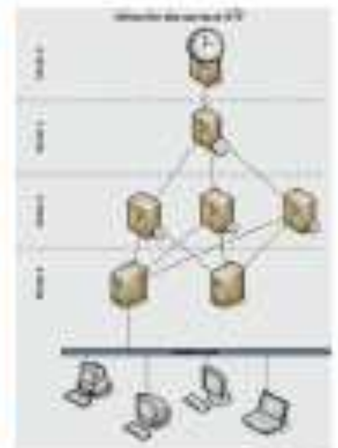
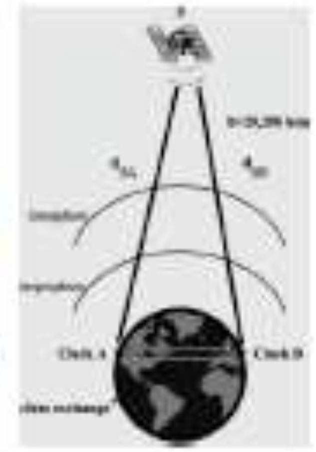
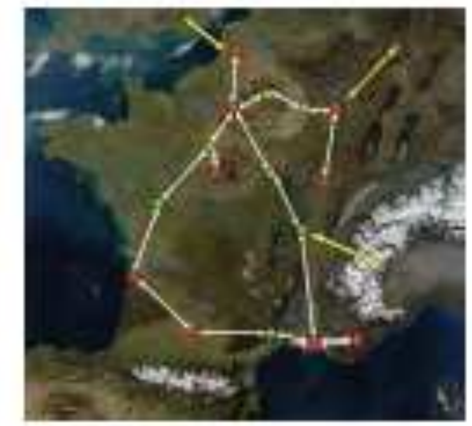


Intérêt des méthodes mode commun

Time/Frequency dissemination nowadays

ntp-p1.obspm.fr

Horloge parlante	Réseau hertzien	Internet (NTP)	Satellites	Lien laser fibré

Précision : 1 - 50 ms | 1 ns | < 100 ps

PROJET REFIMEVE

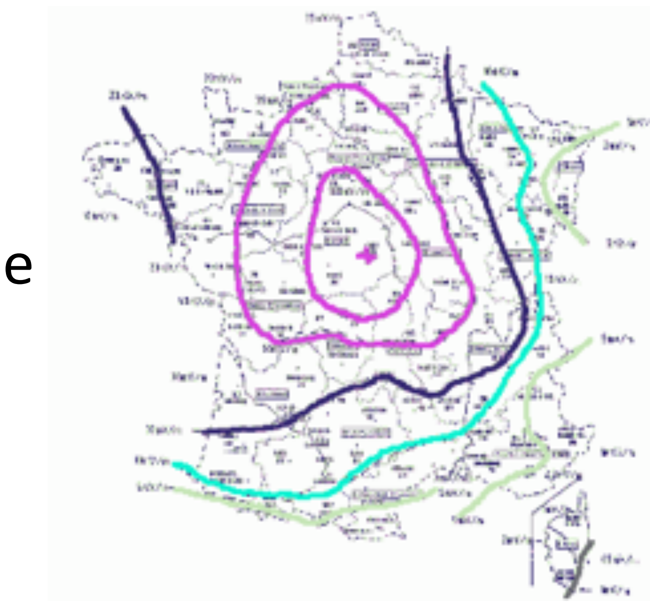
Courtesy M.-C. Angonin

part 3 : Free space methods

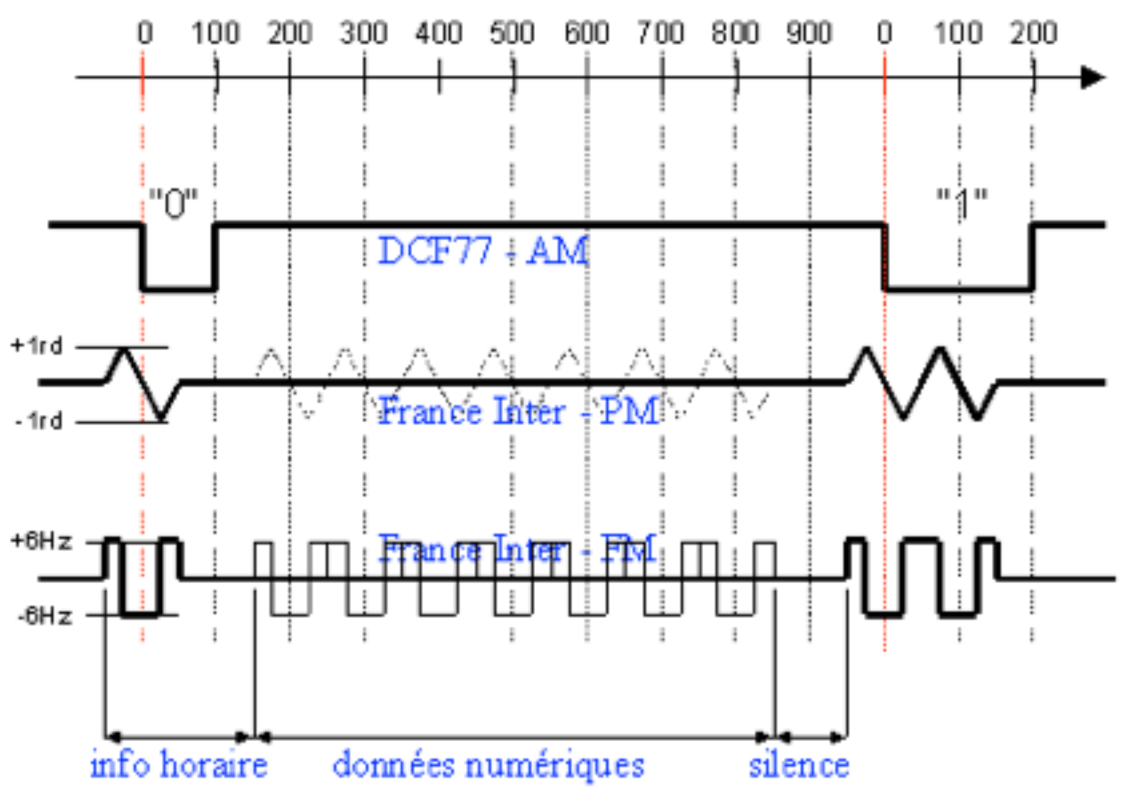
- Radio broadcast
- GNSS
- Advanced methods
- TWSTFT
- T2L2
- Optical methods

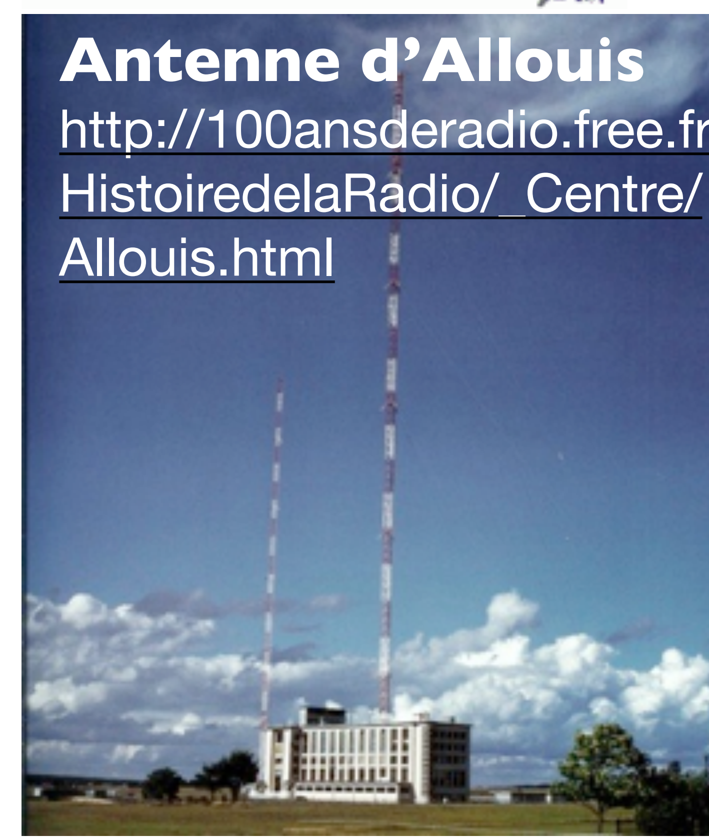
France Inter

Depuis 1977, la fréquence 162 kHz transmet un signal horaire de référence élaboré à partir d’horloges atomiques et fournit l’heure légale française.
Ce service est largement utilisé dans des secteurs clés de l’industrie française pour synchroniser plus de 200 000 horloges.



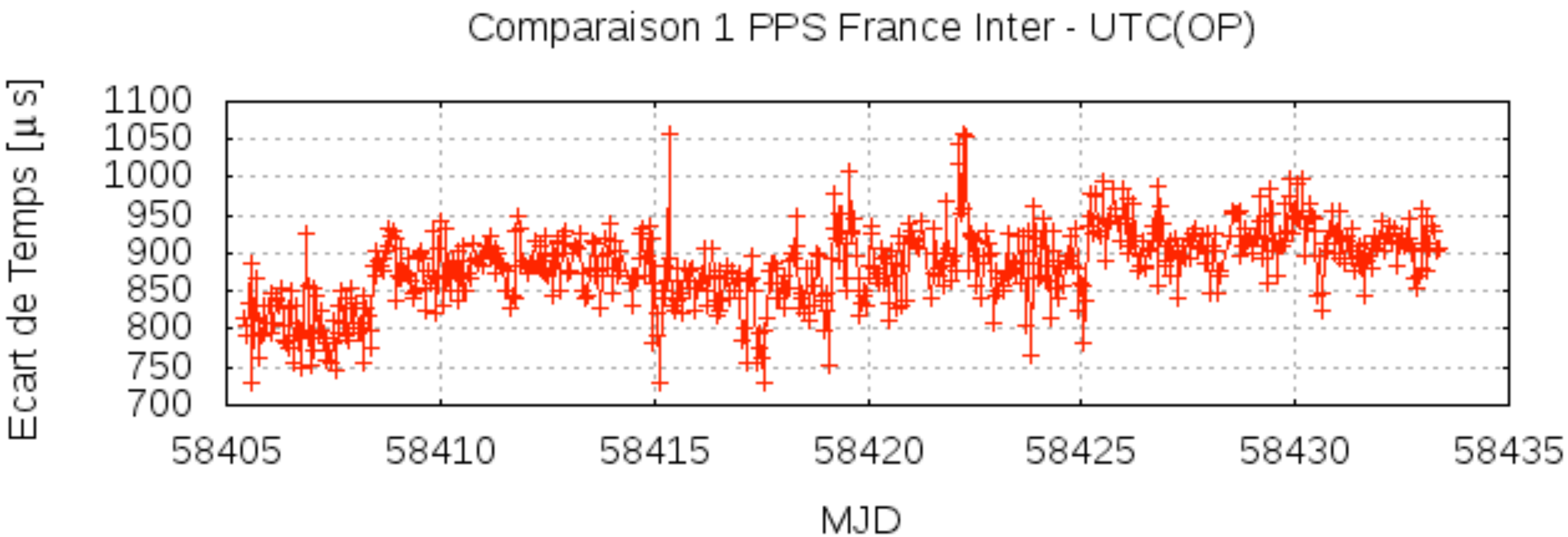
D : DCF77 (77.5 kHz), depuis 1959
F : France-Inter (162 kHz) depuis juillet 1980





http://www.datelec.fr/signaux_horaires/p0.htm

France Inter



Satellite methods

Measure with each clock a common external signal: GNSS

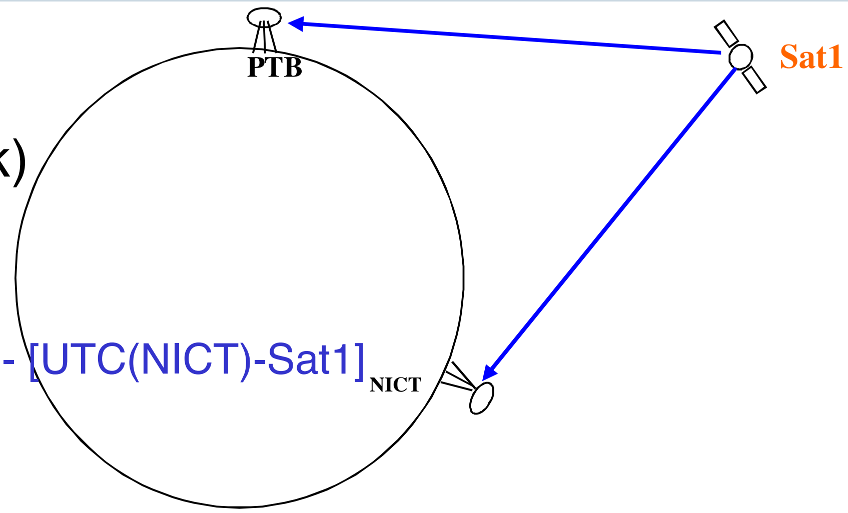
Each station measures

- (Local clock – Satellite clock)

Then two solutions

- Common-view

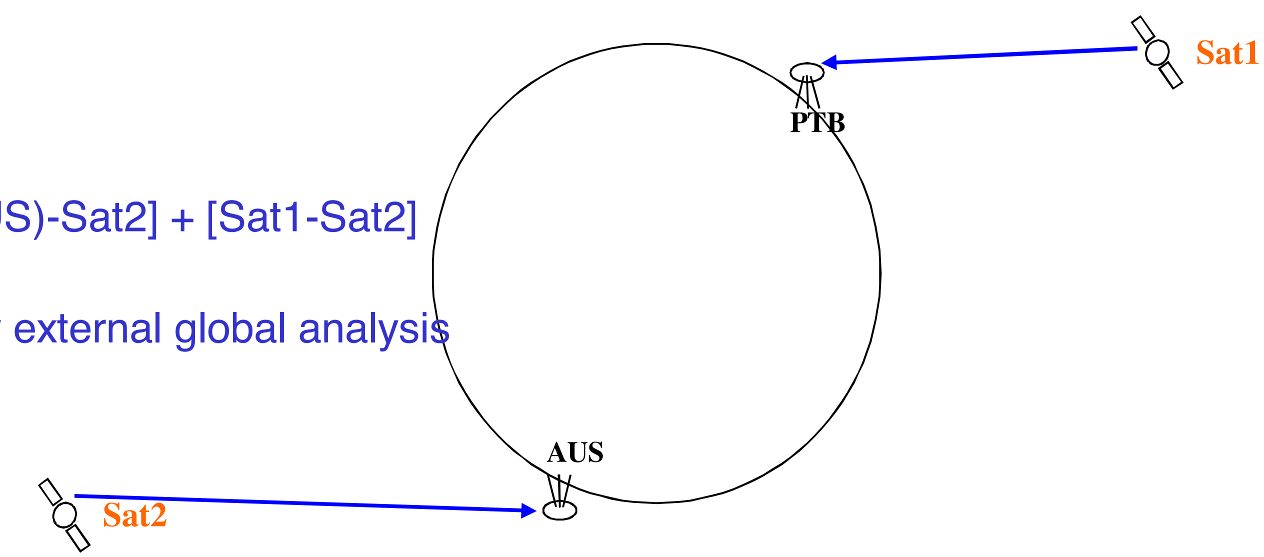
UTC(PTB)-UTC(NICT) = [UTC(PTB)-Sat1] - [UTC(NICT)-Sat1]

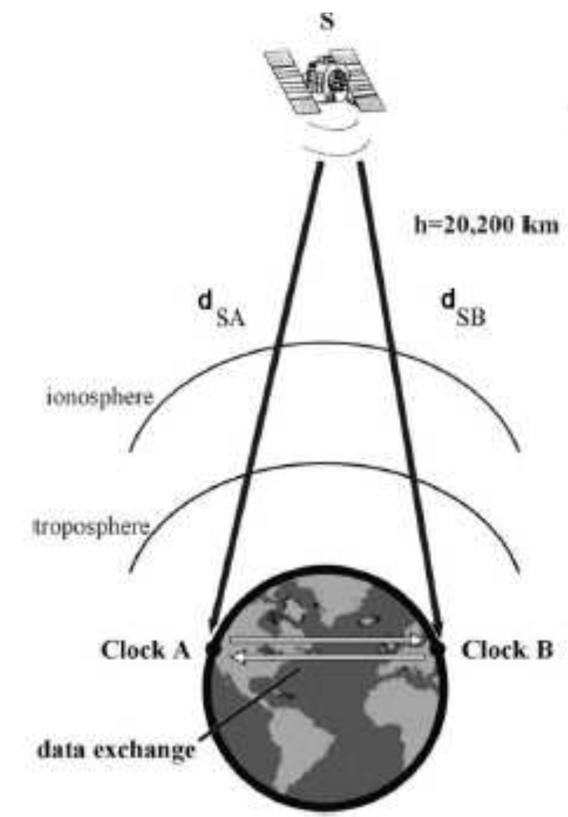


- All-in-view

UTC(PTB)-UTC(AUS) =
[UTC(PTB)-Sat1] - [UTC(AUS)-Sat2] + [Sat1-Sat2]

with [Sat1-Sat2] provided by external global analysis





Bureau International des Poids et Mesures

BIPM

Multi-satellite constellation

GPS

Galileo

Glonass

GPS : C/A, CV, all-in-view, CP, PPP…

Courtesy F. Arias, BIPM

Satellite methods : corrections

Equation de mesure GPS

$$P(f_i)=c(\tau_{geom}+\tau_{iono}(f_i)+\tau_{tropo}+\tau_{relat})+c\Delta t_r-c\Delta t_e+\sigma_P$$

A chaque terme son intérêt...

τ_{geom} : **Géodésie (positionnement / Rotation terrestre / Orbitographie)**

Δt_r : Transfert de temps

$\tau_{iono}(f_i)$: Détermination du contenu électronique de la ionosphère

τ_{tropo} : Etude de l'atmosphère

Relativistic corrections

- Relation temps propre / temps coordonnée

$$\mathrm{d}\tau \simeq \left(1 - \frac{GM}{c^2 r} - \frac{v^2}{2c^2}\right)\mathrm{d}t$$

- Alors on a un décalage en fréquence :

$$\frac{\Delta f}{f} \simeq \underbrace{\frac{GM}{c^2}\left(\frac{1}{r_g} - \frac{1}{r_s}\right)}_{528.3 \times 10^{-12}} + \underbrace{\frac{1}{2c^2}\left(v_g^2 - v_s^2\right)}_{-82.24 \times 10^{-12}}$$

$$= 446.1 \times 10^{-12}$$

Relativistic corrections seen by Navstar GPS TS-2 (1977)

Buisson et al., *Initial results of the NAVSTAR GPS NTS-2 satellite*, PTTI proceedings

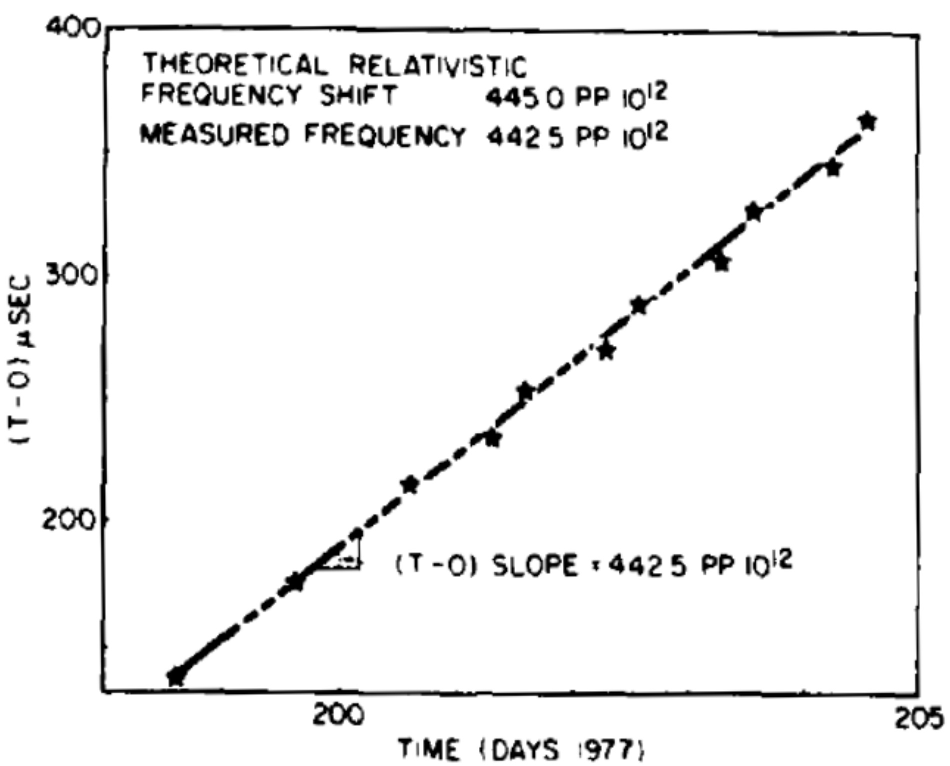


Fig. 20 - Cesium frequency via (T-O) slope

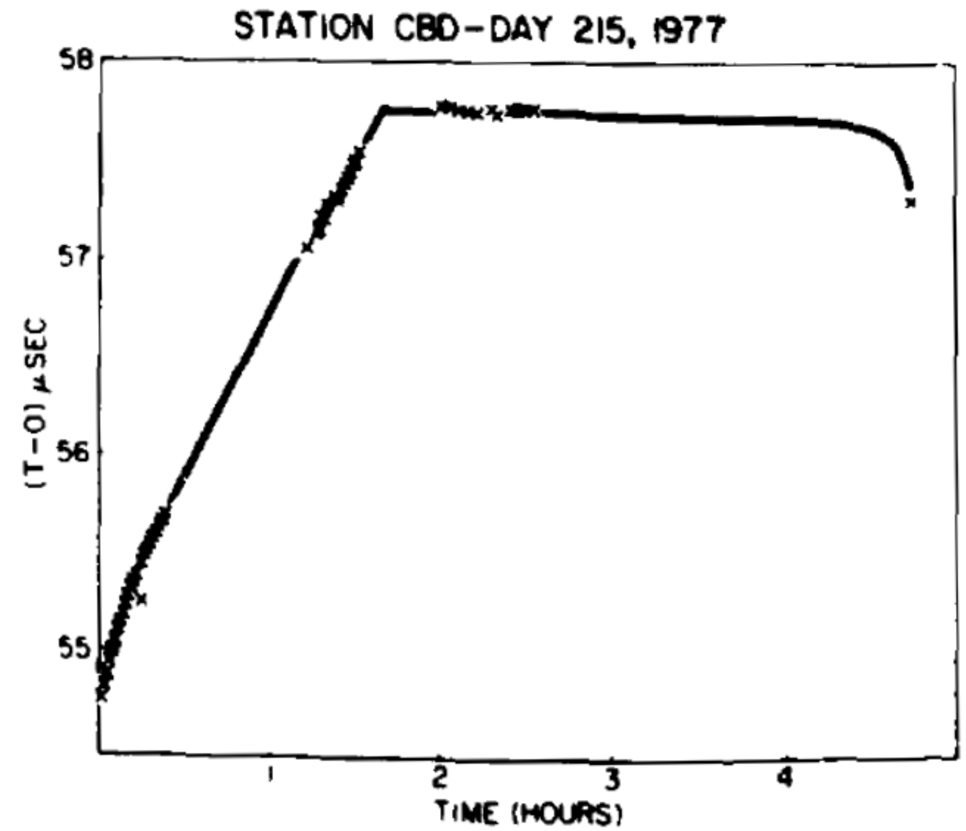


Fig. 21 - Effect of relativity correction

- effet relativiste = **décalage gravitationel** (« redshift ») + **effet Doppler du second ordre** = 38,5 µs @ 1d = 11,6 km @ 1d

GPS commercial receivers

MJD

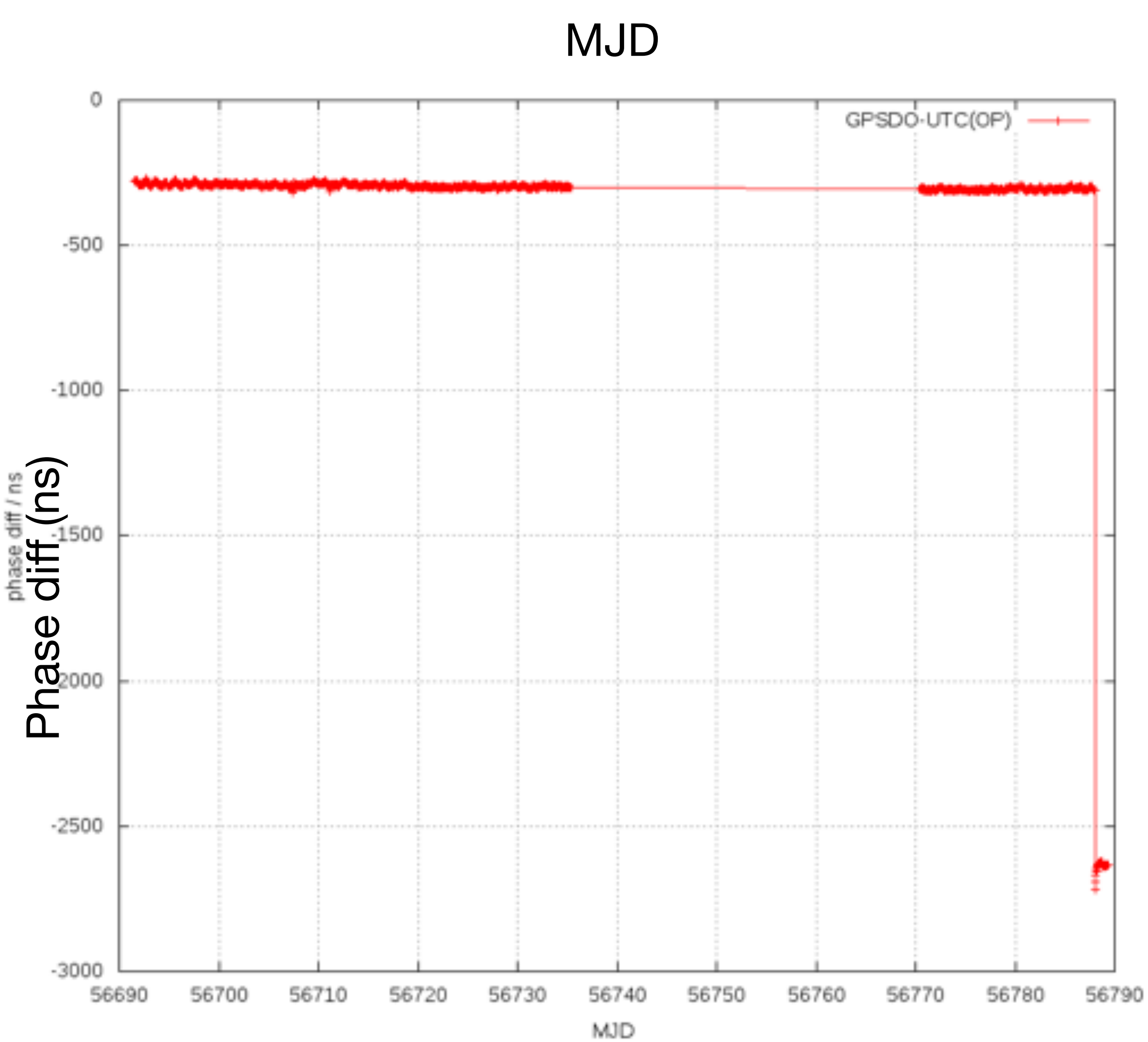
Oscilloquartz 5201 (ADVA)

Jackson Labs. Fury

Quartzlock

Septentrio

GPS commercial receivers



Oscilloquartz 5201 (ADVA)

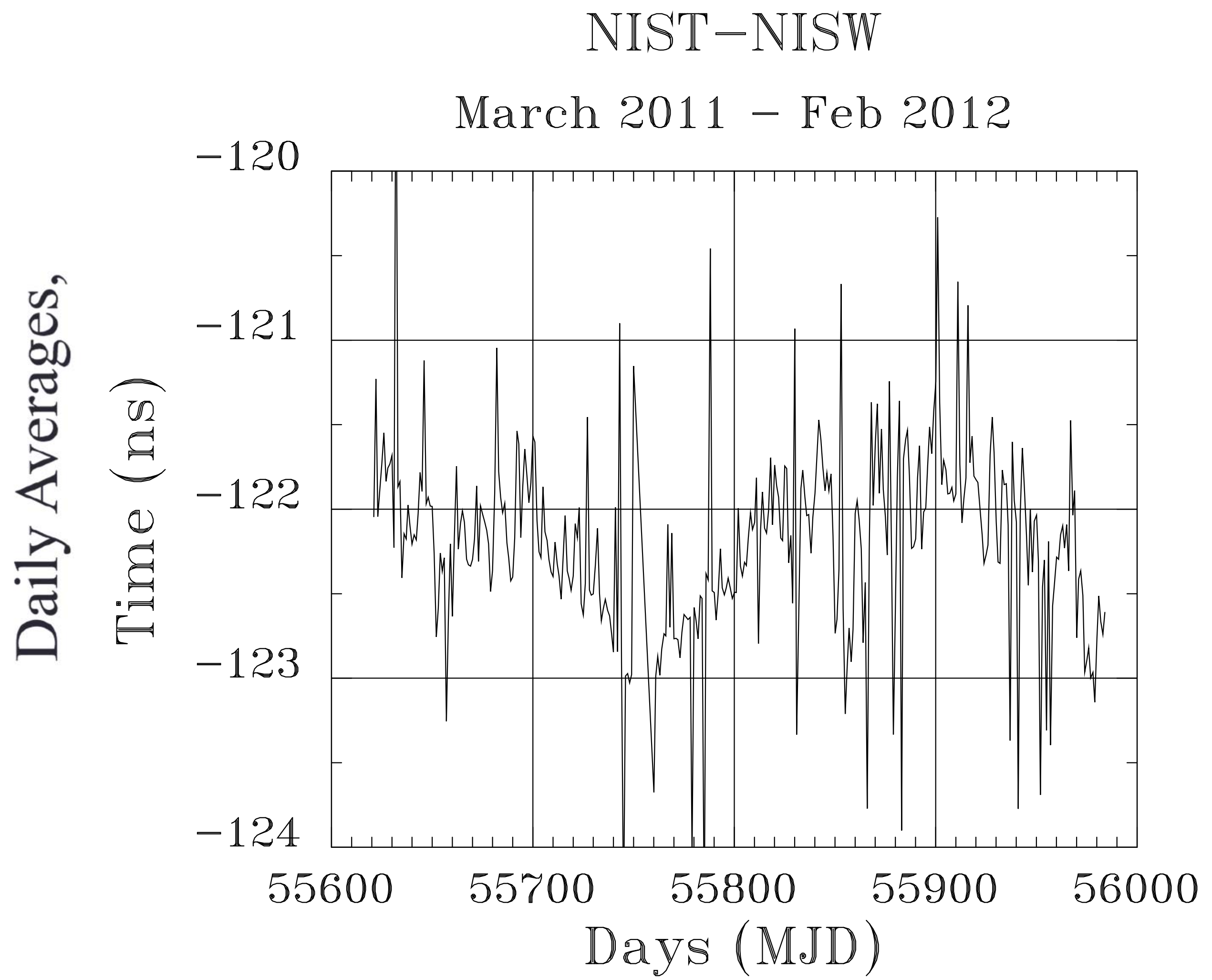
Jackson Labs. Fury

Quartzlock

Septentrio

Satellite methods : what could limit the uncertainty ?

Annual Differential Delay Between Two Different Models, Same Manufacturer



Courtesy M. Weiss, NIST

"Best" Error Budget
Peak Values

- UTC as the reference source – if multiple constellations are allowed
  - Different labs produce different real-time UTC_i …………… 30 ns
  - Note this value can be reduced if differences are transmitted as in the GPS-Gallileo Time Offset (GGTO) ……………………………….. 5 ns
  - UTC from GPS minus UTC(USNO) ……………………….. 10 ns

- System calibration by manufacturer
  - Total change …………………………………………………. 5 ns/4 years

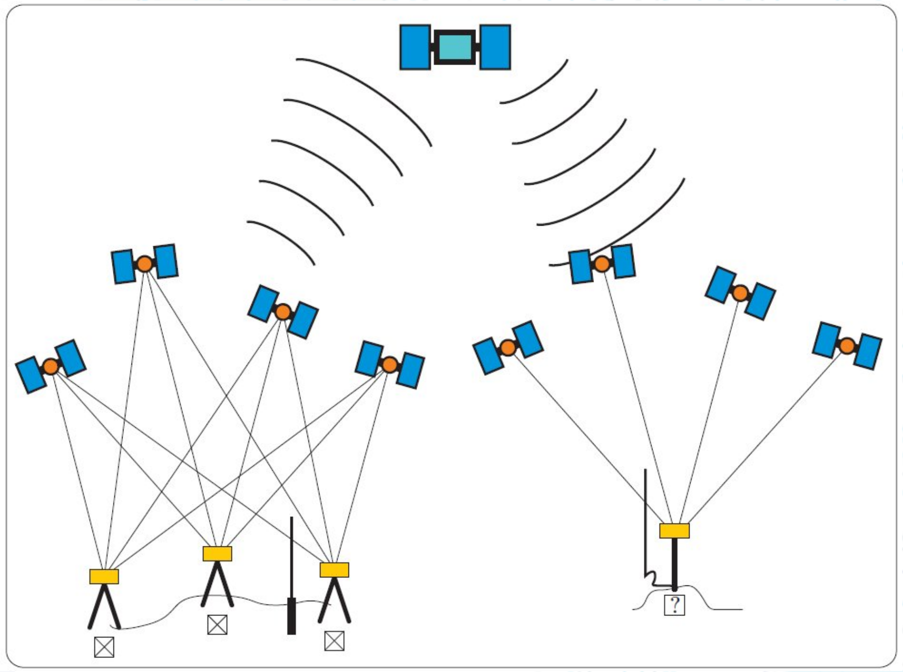
- User calibration issues
  - All of these are < 1 ns if done well
    - Antenna coordinates
    - User time reference delay
    - Possible change of antenna cable
    - Disciplining oscillator
  - Multipath …………………………………………………….. 5 ns

Courtesy M. Weiss, NIST

Ways to improve further

Les systèmes d'augmentation SBAS (Satellite Based Augmentation System)

- Amélioration du système de positionnement par l'utilisation d'informations complémentaires aux observations classiques:
  - **Performance** → ~ 1 - 2 m
  - **Disponibilité** → échelle d'un continent ou d'un pays
  - **Fiabilité** → message d'intégrité

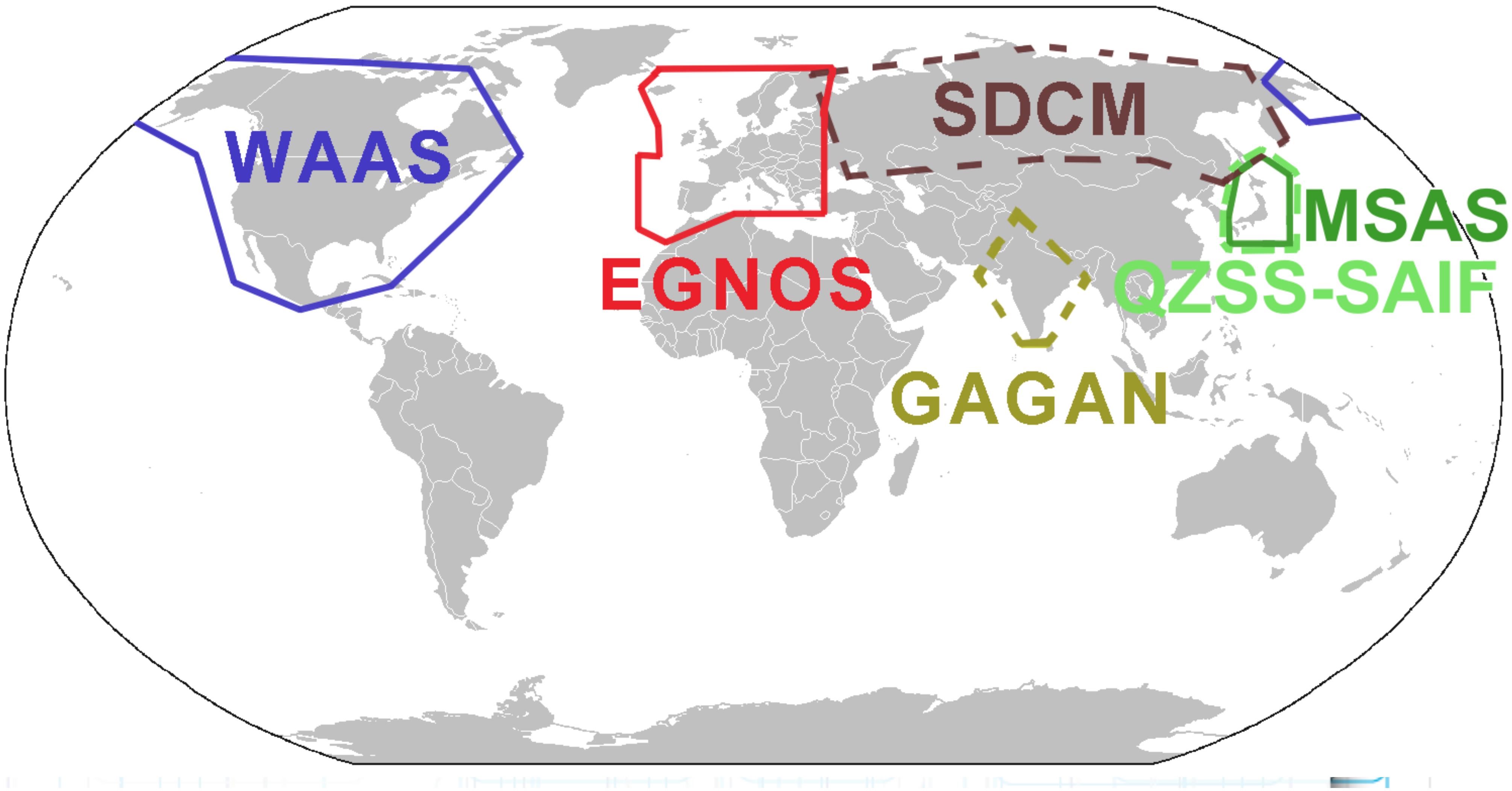


© P. Bosser, GNSS

Principe de fonctionnement:
WADGNNS (*Wide Area Differential GNSS*) → voir cours sur les signaux

- réseau de stations GNSS au sol
- corrections transmises à un satellite (souvent géostationnaire)
- puis retransmises aux utilisateurs aux sol

SBAS



Satellite methods

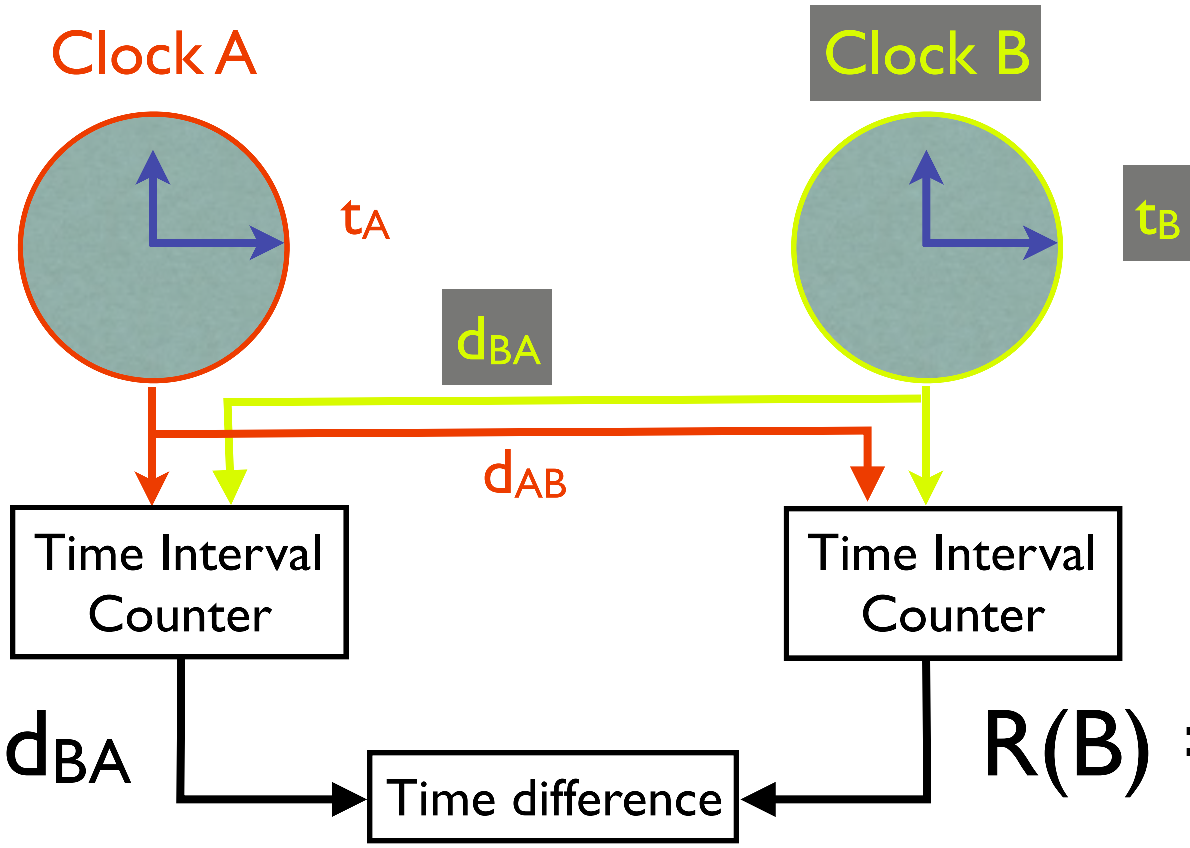
Moyens de transfert de T&F existants ou en développement

LIEN	Type de comparaison	Technique	PERFORMANCE
GPS, GALILEO	Espace → Sol Sol → Sol en vue commune (pas de mesure dans l'espace)	Down link Phase porteuse + phase code 2 fréquences bande L	Stabilité : 100 ps – 1 ns sur 1 jour Exactitude : 1 ns
TWSTFT	Sol → Sol Via un satellite géostationnaire (pas de mesure dans l'espace)	Up et down links Phase code 2 fréquences bande Ku	Stabilité : 100 ps – 1 ns sur 1 jour Exactitude : 1 ns
ACES MWL	Sol → Espace Sol → Sol en vue commune ou non (mesures sol et espace)	Up and Down links phase code + phase porteuse 3 fréquences bande S et Ku	Stabilité : 0.3 ps sur 300 s < 10 ps sur 1 jour Exactitude ≈ 100 ps
T2L2	Sol → Espace Sol → Sol en vue commune ou non (mesures sol et espace)	Up and Down links Datation d'impulsions 1 voire 2 fréquences optiques	Stabilité : 0.3 ps sur 1000 s < 5 ps sur 1 jour Exactitude : 50 ps

existants

en développement

Satellite methods : more advanced methods



$$R(A) = t_A - t_B + d_{BA}$$

$$R(B) = t_B - t_A + d_{AB}$$

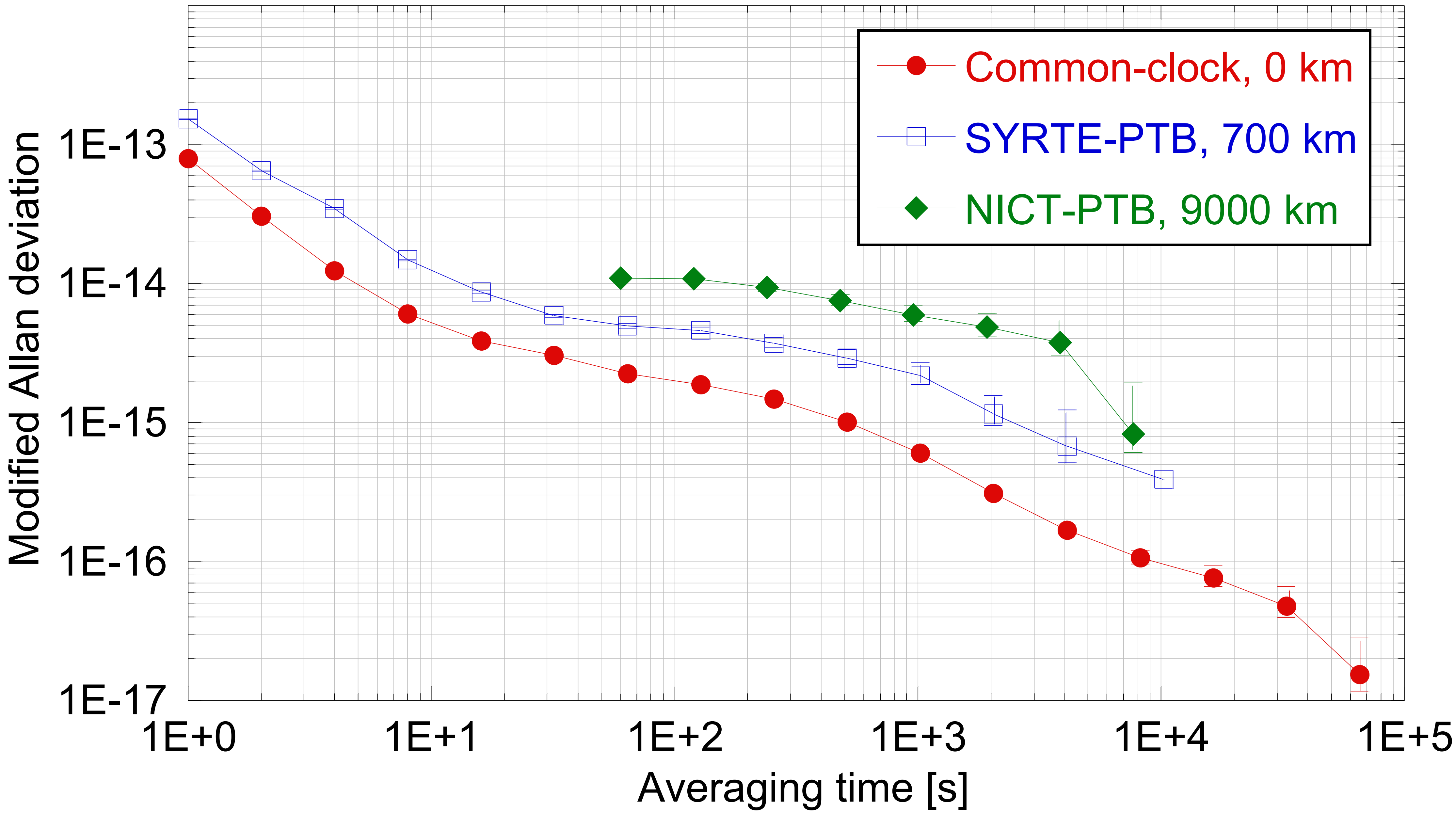
$$R(A)-R(B) = 2\,(t_A - t_B) + (d_{BA} - d_{AB})$$

Delay d_{ba}-d_{ab} = propagation delay + instrumental delay + Sagnac

Calibrated/Calc Calibrated Calculated

From D. W. Hanson, 43rd Annual Frequency Control Symposium, pp. 174-178, 1989

Two way satellite time transfer: Carrier Phase (state-of-the-art)



Fujieda, M. et al., Metrologia **51**, 253–262 (2014).

T2L2 (optical method)

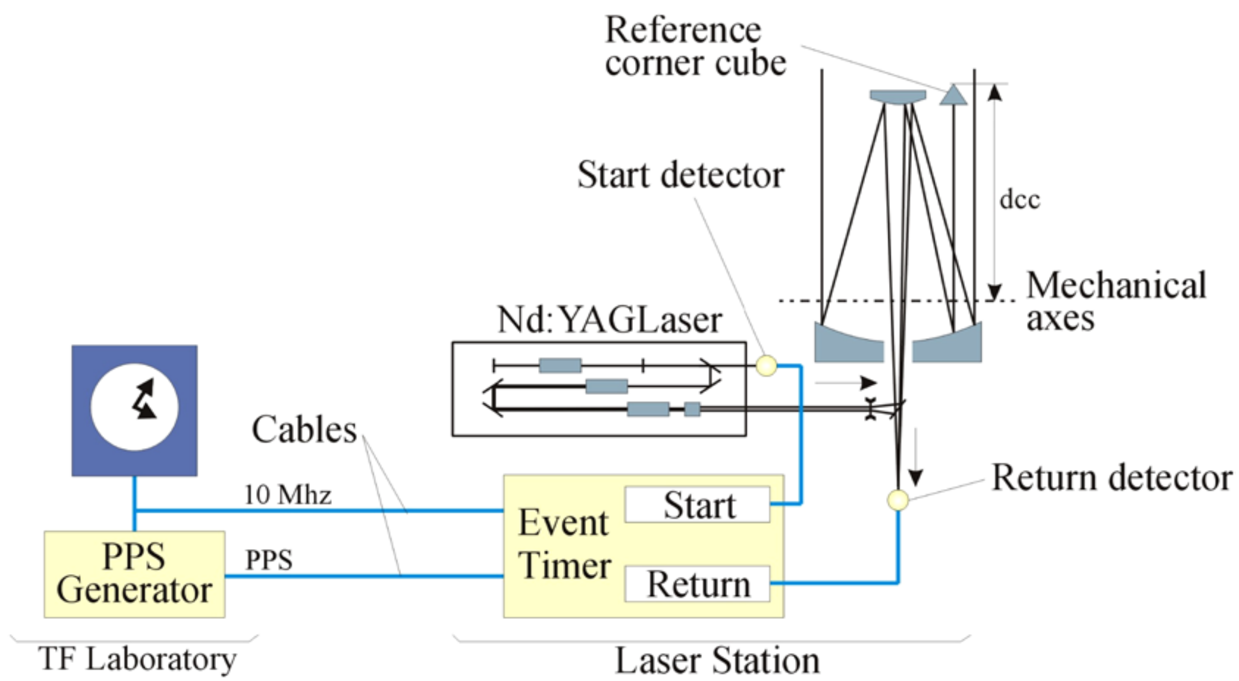
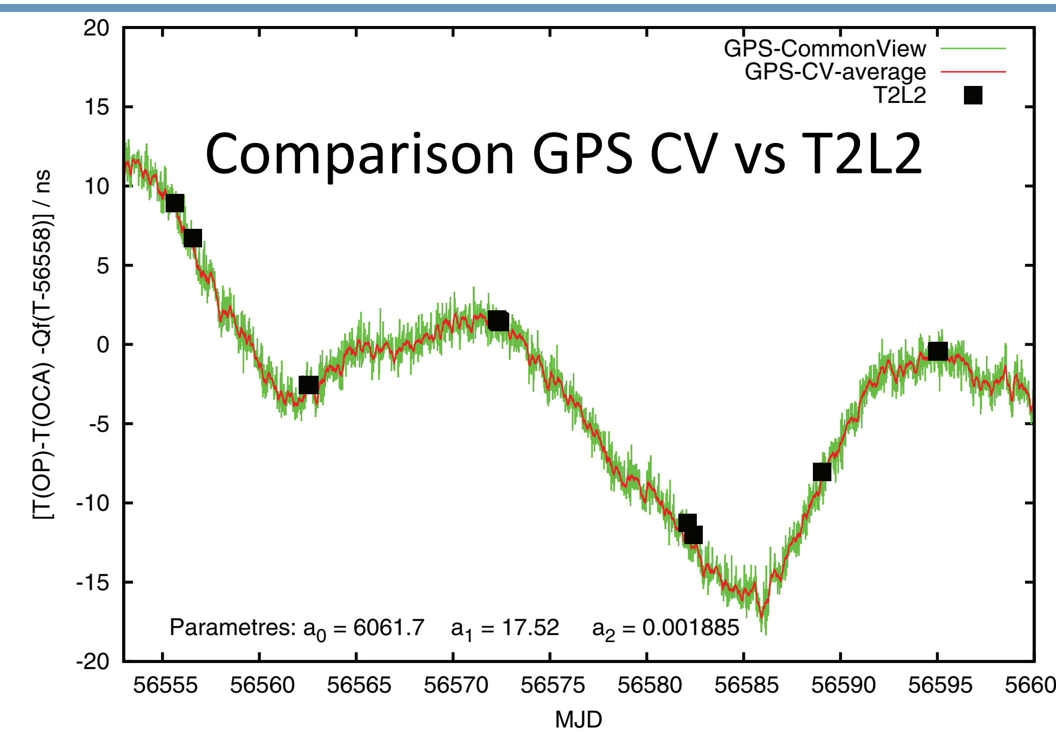
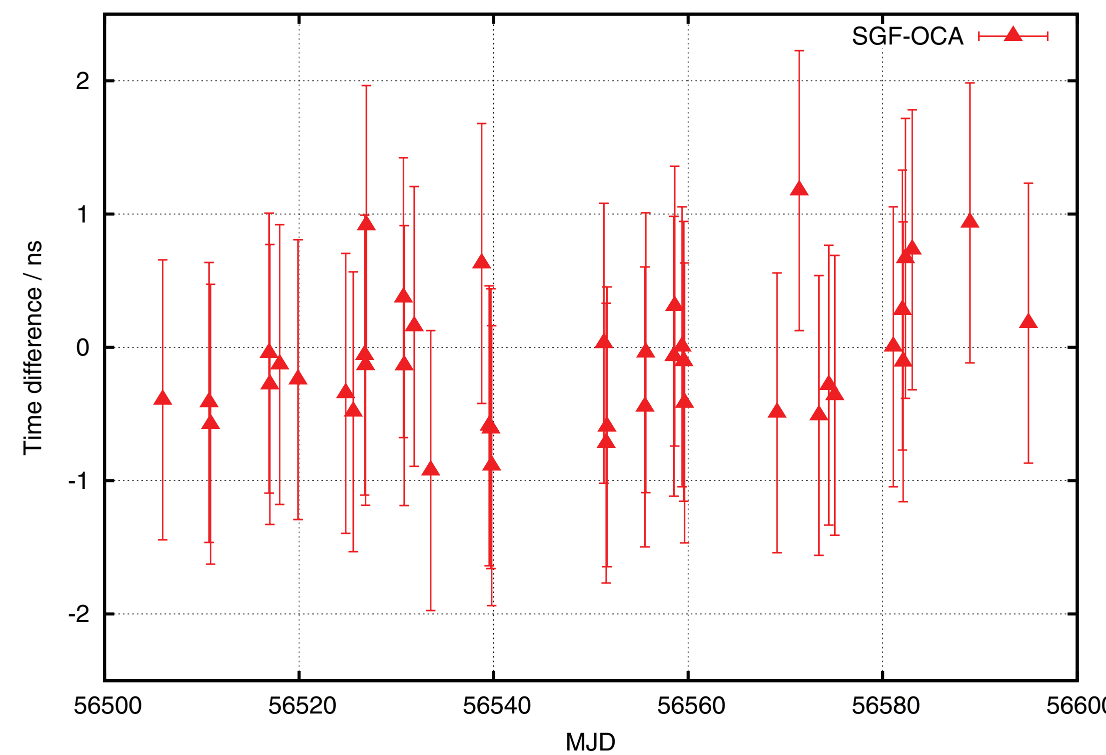


Table 2. Mean values of the time differences between GPS CV and T2L2.

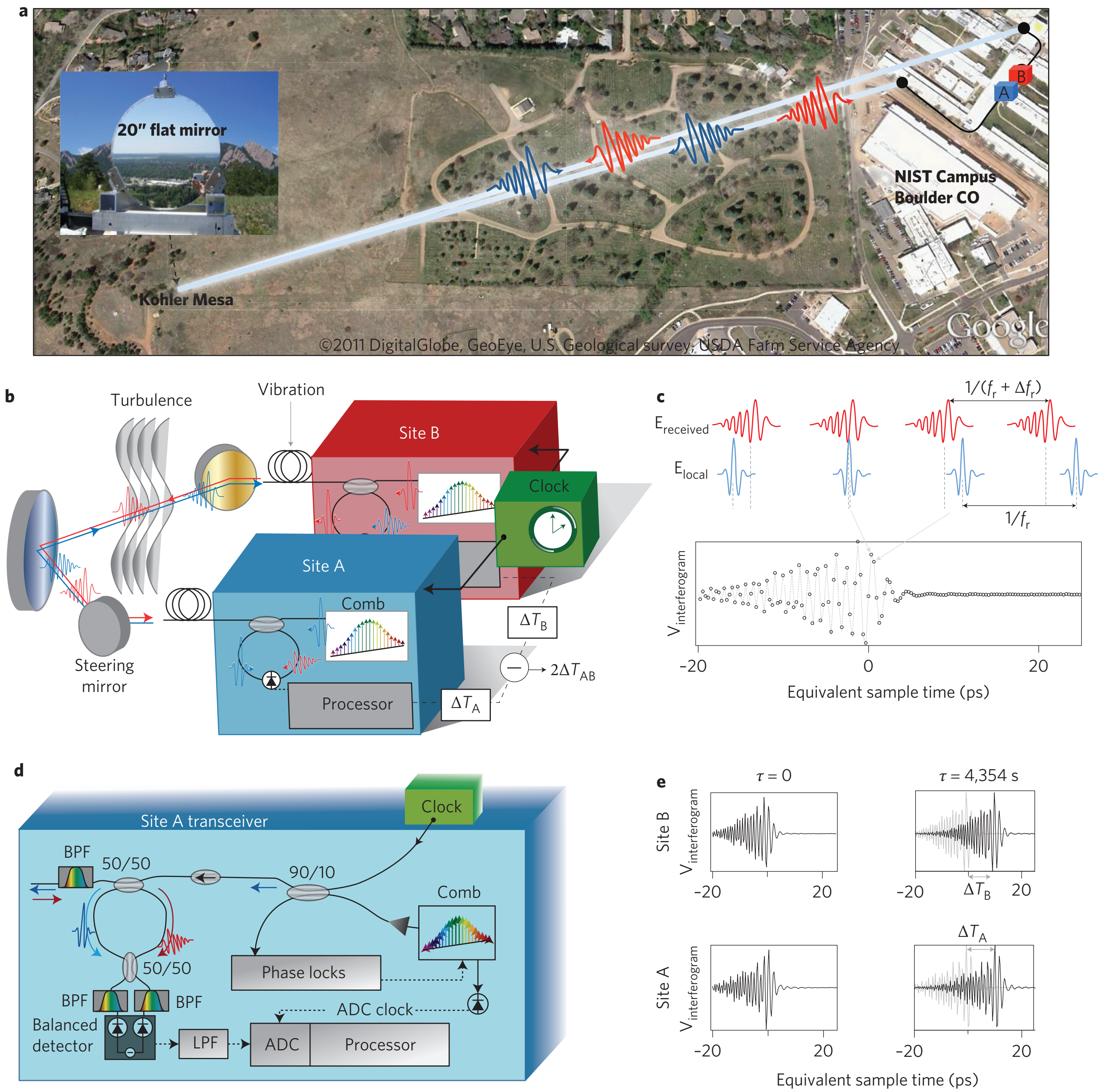
Link	Number of points	Mean values (ns)	Std deviations (ns) Raw GPS CV	Std deviations (ns) Filtered	Combined uncertainty (ns)
OCA–OP	12	0.24	0.48	0.25	1.1
OCA–SGF	42	0.09	0.49	0.37	1.1
OP–SGF	5	0.10	0.32	0.32	0.8





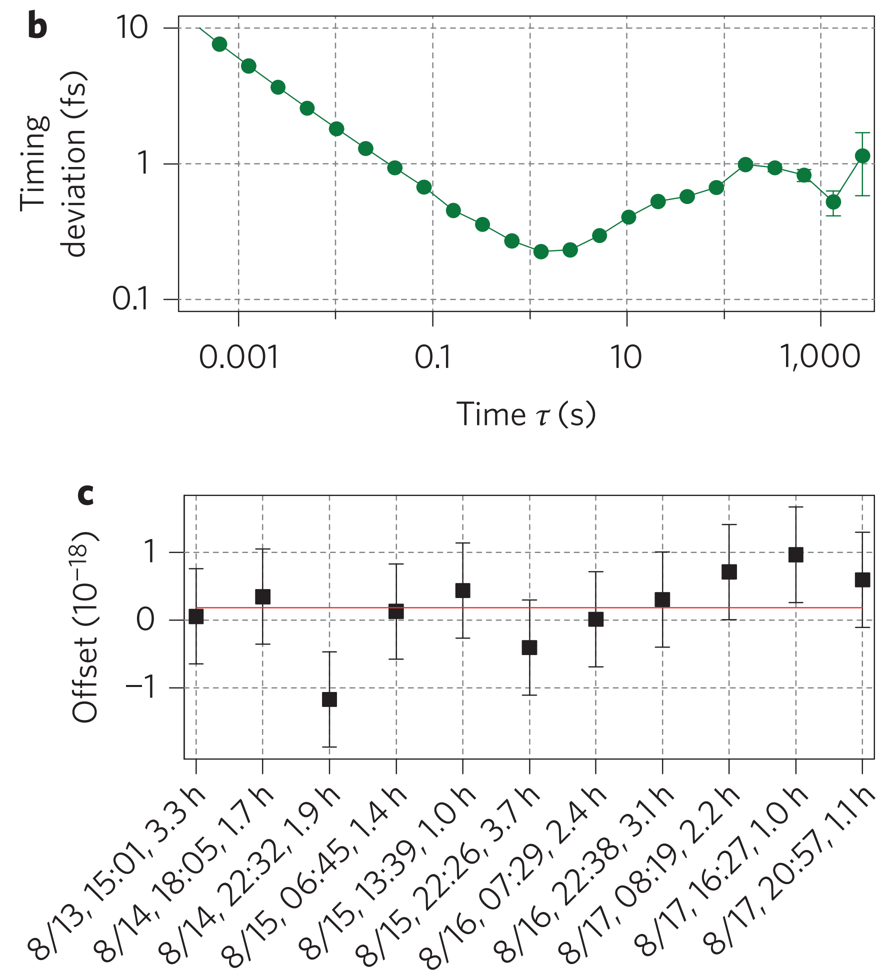
P. Exertier et al. Metrologia **53** (2016) 1395–1401 doi: 10.1088/0026-1394/53/6/1395

Optical combs

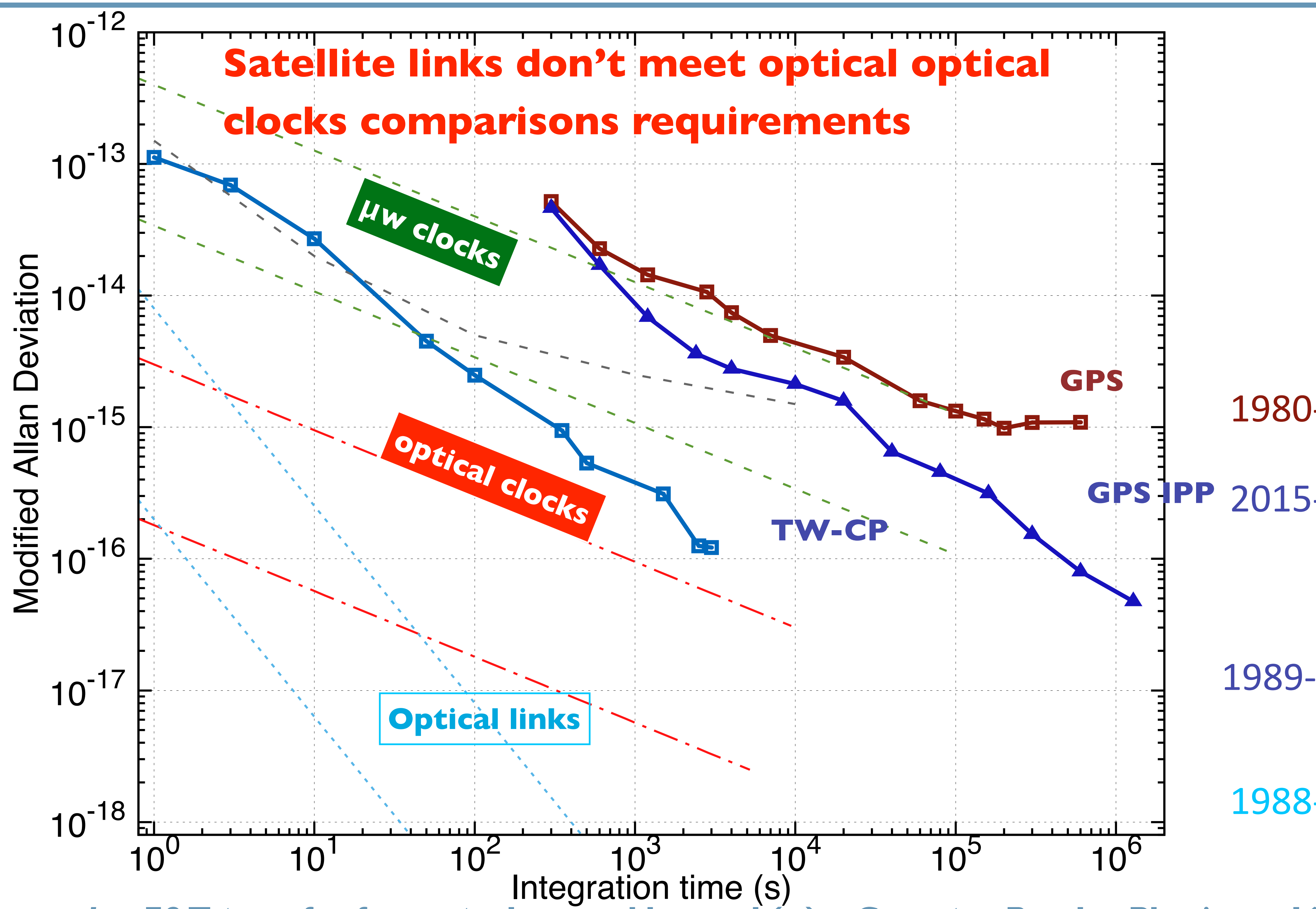


F. Giorgetta et al., Nat. Phot. **7**, 2013

4 km link
Works also with drones !



30 years of improvements



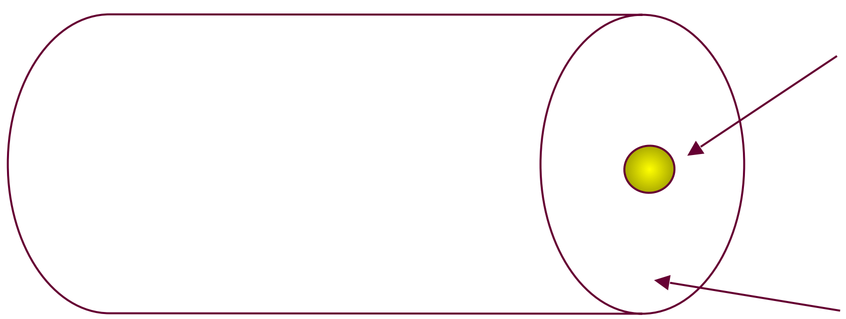
O. Lopez *et al.*, «F&T transfer for metrology and beyond (...)», Comptes Rendus Physique, 16 (5), pp. 459-586 (2015) (2015)

- Introduction
- Classification of links
- Review of methods
  - PTP, WR-PTP
  - ELSTAB
  - ‘Pure’ Optical
- Fundamental and technical limits

- Introduction
- Classification of links
- Review of methods
  - PTP, WR-PTP
  - ELSTAB
  - ‘Pure’ Optical
- Fundamental and technical limits

Review article
O. Lopez *et al.*, Comptes Rendus Physique, 16 (5), pp. 459-586 (2015)
Suggested focus on :
P. Krehlik, et al.; Metrologia, 52 , pp. 82-88, (2015)
Parker et al., **53**,(35),8157-8166 (2014)
G. Marra et al., **20** (2),1775-1782 (2012)

Optical fiber



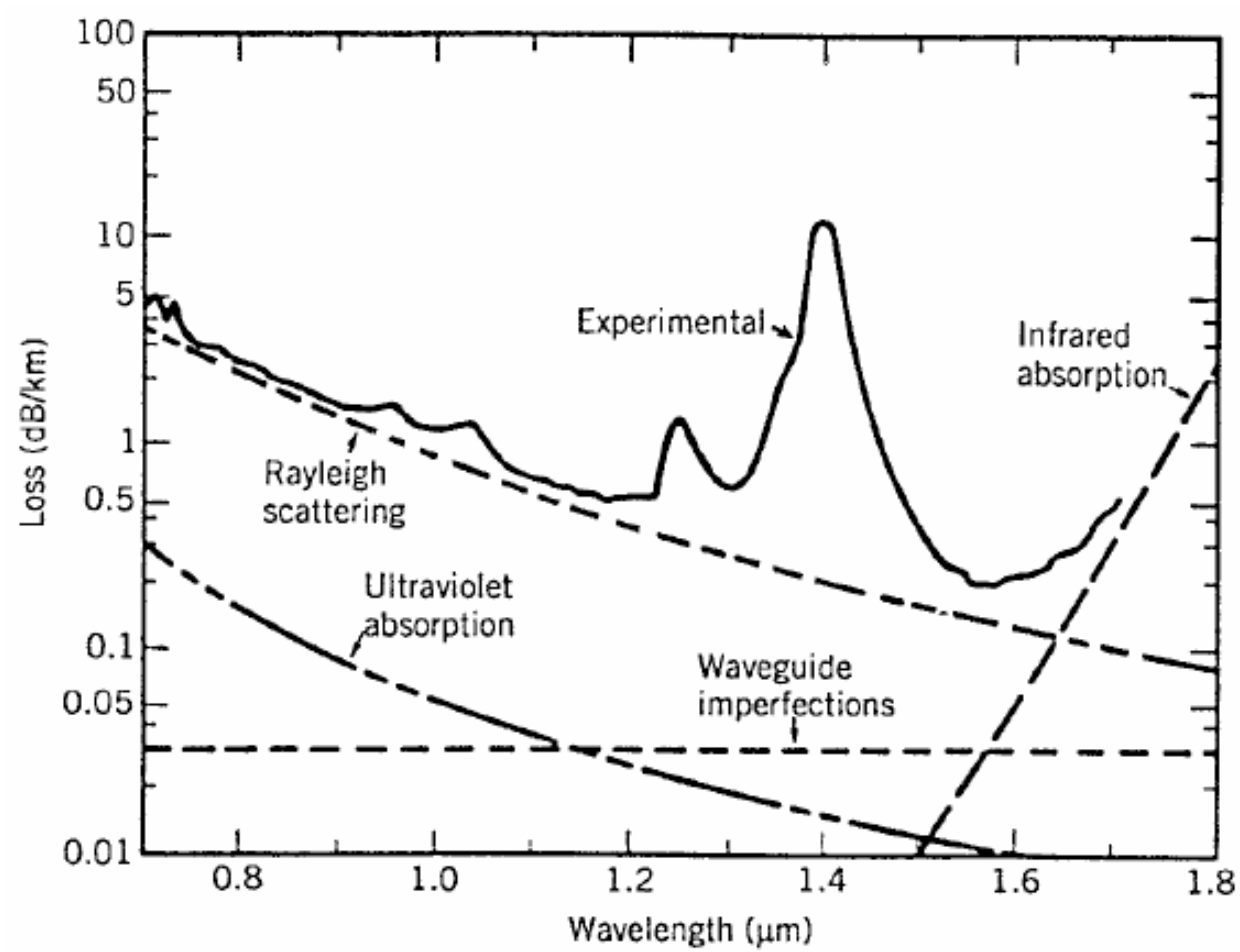
Core (glass) : central zone with higher optical index n_1, where most of the light propagates, diameter 2a ≤10µm

Cladding (glass): surrounding zone with (a little) lower index n_2, typical diameter 125 µm

Also : jacket to protect the fiber

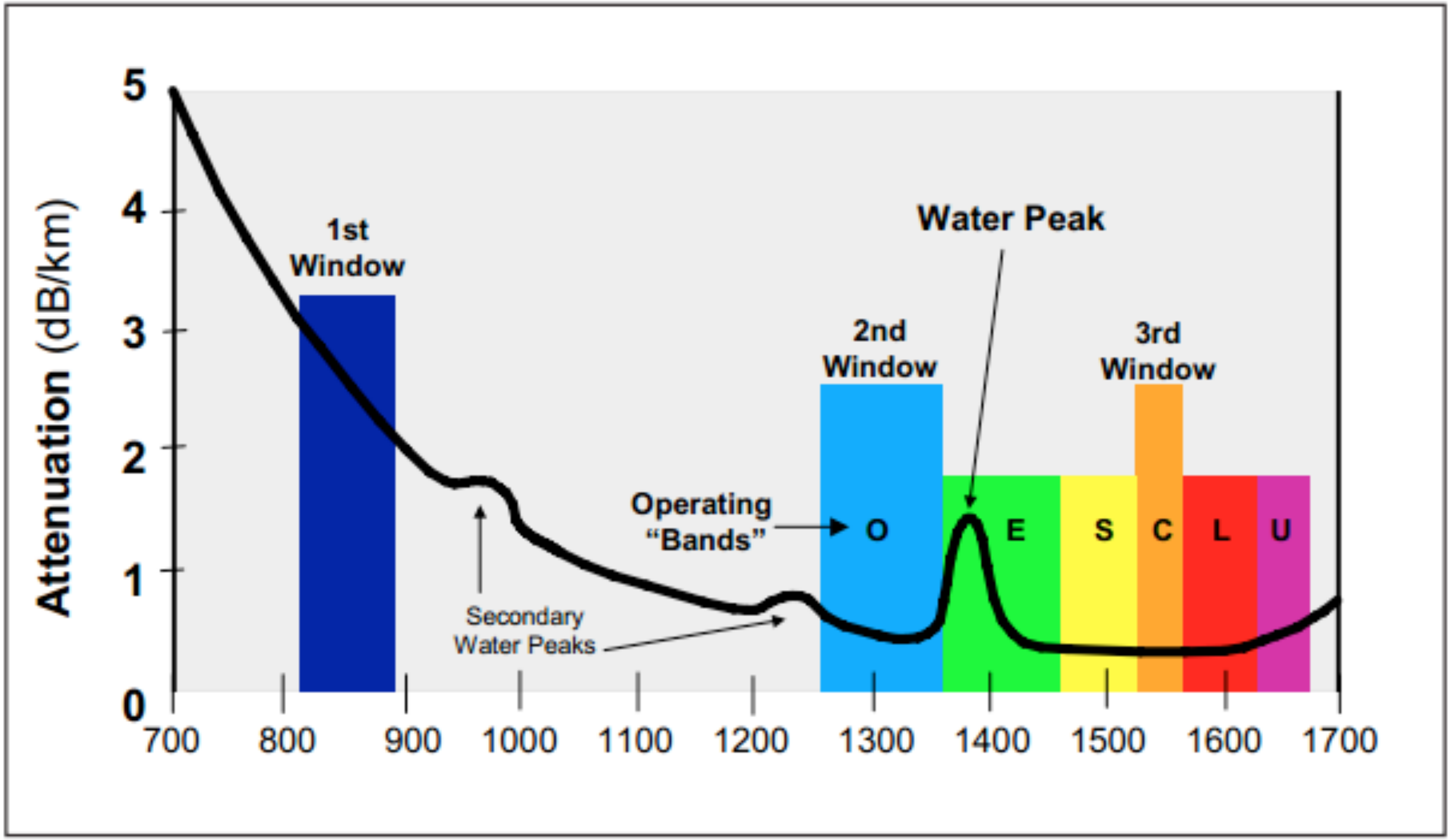
- Widely used for telecommunications since 30 years
- Optical waves are guided inside the optical fibers (velocity ~c/n)
- Monomode propagation if $V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} < 2.4$
- Very low losses, minimum attenuation 0.2 dB/km at 1.55 µm
- Very low dispersion : 17 ps/(km.nm) at 1.55 µm

Attenuation



https://www.fiberoptics4sale.com/blogs/archive-posts/95052294-optical-fiber-attenuation

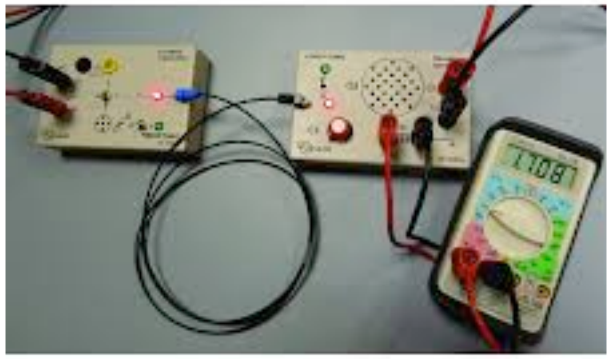
Spectral sharing



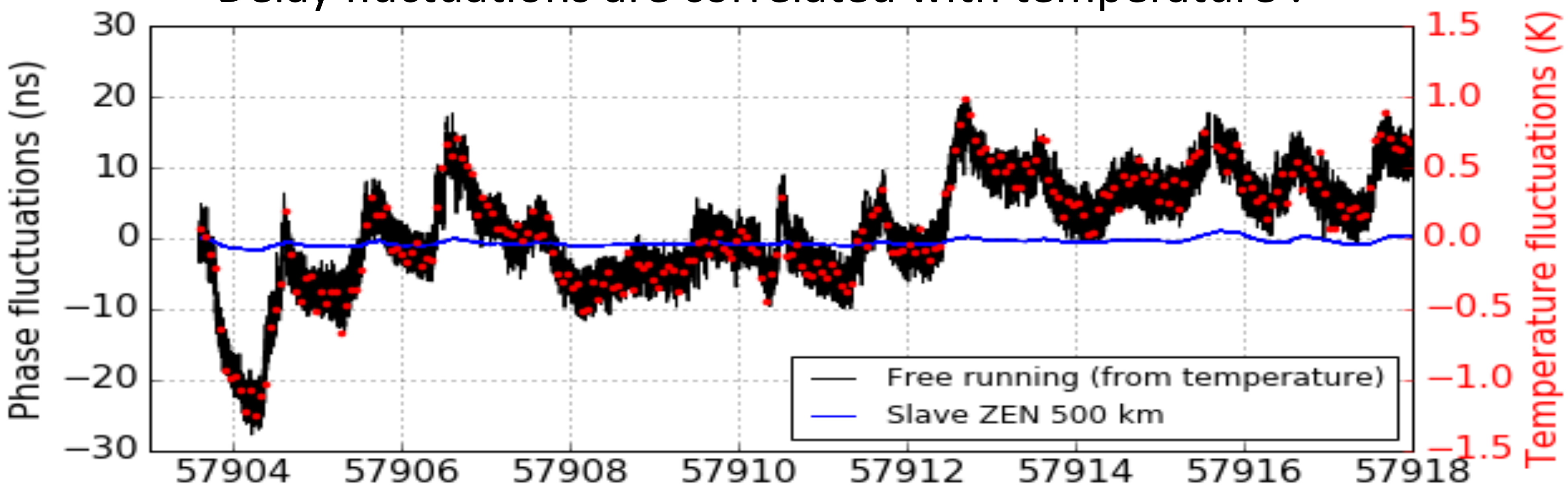
http://www.fowiki.com/b/understand-fiber-attenuation/

Noise

- Propagation noise (also for RF transfer)
  - Fiber optical length **n L** (index x length) varies with acoustical and thermal fluctuations
  - This induces phase fluctuations and therefore frequency fluctuations
  - This propagation noise is quite low but has to be corrected for metrological applications



Delay fluctuations are correlated with temperature :



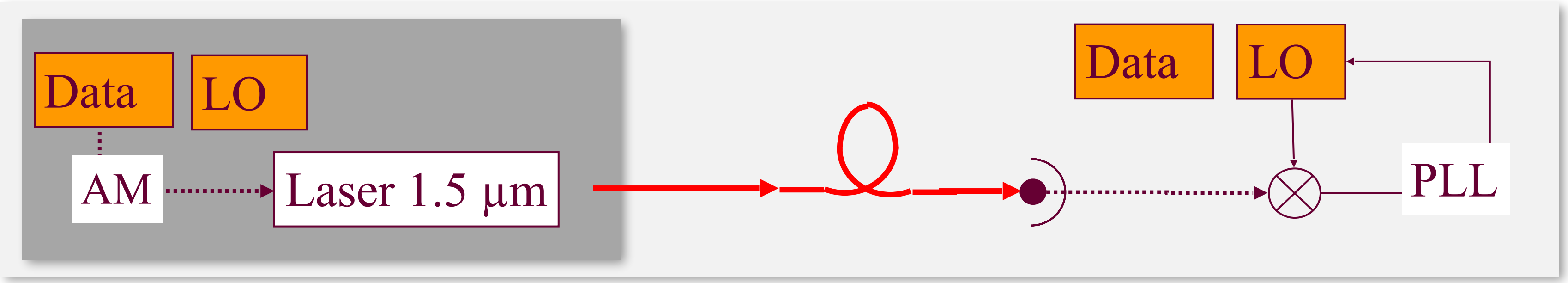
Classes of fiber links

- Two-way : Stabilized / Post-processed
  - Post-processed techniques used for comparison purposes
- One way: Unstabilized (affects stability and accuracy)

- Bi-directional or uni-directional (affects the correlations)
- Analog or digital (affect the scalability)

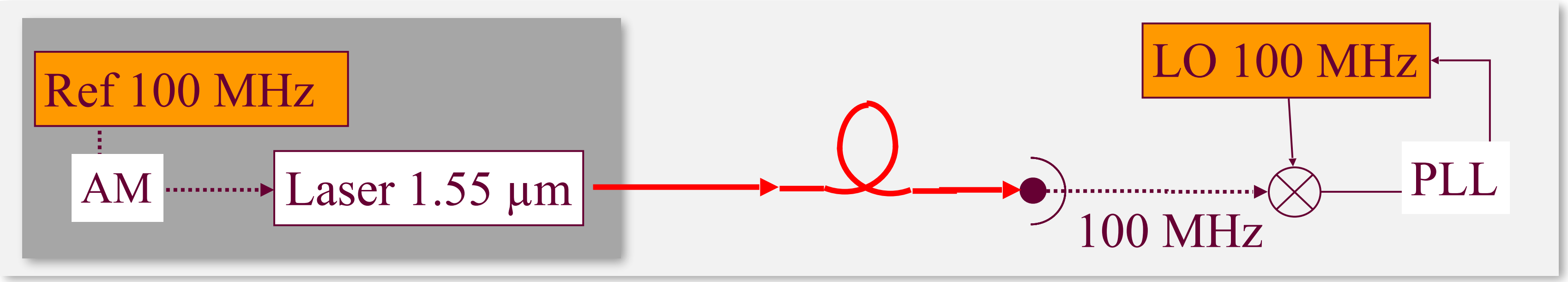
2 classes of experiments

Digital

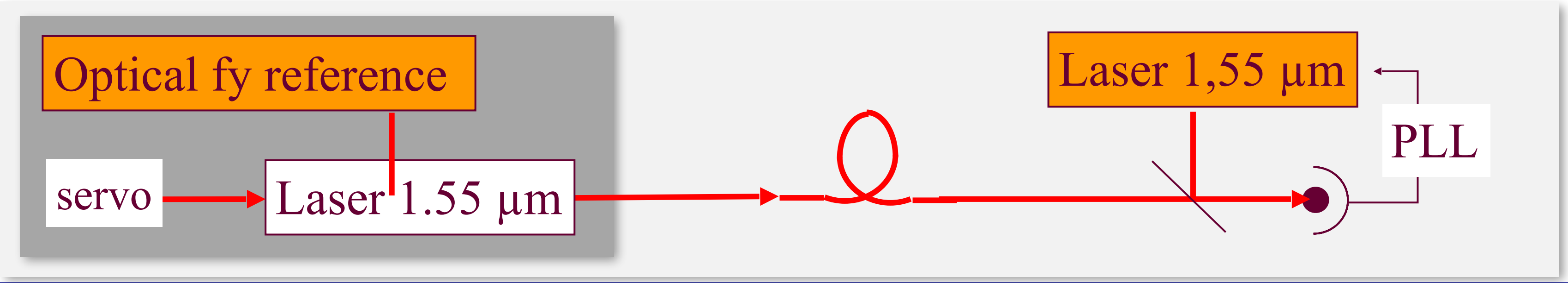


Analog

- RF or MW transfer (100 MHz to 10 GHz)
  - Amplitude modulation of the optical carrier



- Direct transfer of an optical frequency
  - Well-suited to optical clocks comparison



Fiber links : seminal works (Primas et al., 1988)

STABILIZED FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM*

Lori E. Primas
George F. Lutes
Richard L. Sydnor
Jet Propulsion Laboratory
Pasadena, California 91109

Passive stabilization of fiber optic transmission links, such as burial of the cable, is not sufficient for maintaining stabilities in the range required for many applications. When stabilities higher than a part in 10^{15} are required the link must be actively stabilized.

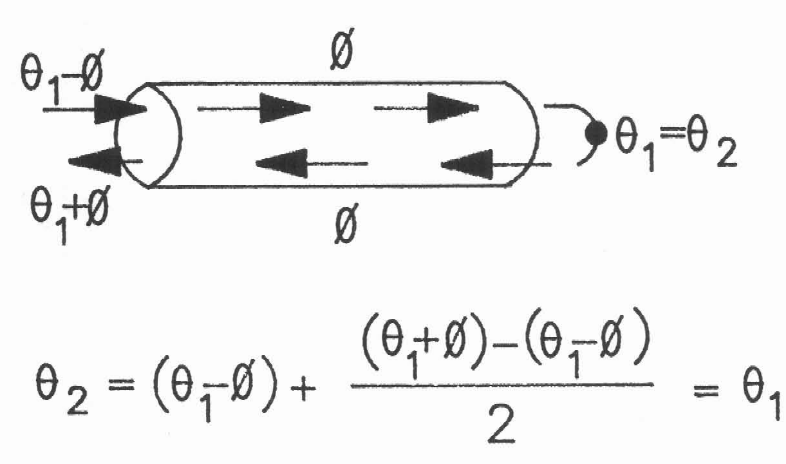


FIGURE 1. PHASE CONJUGATION AT INPUT TO OPTICAL FIBER

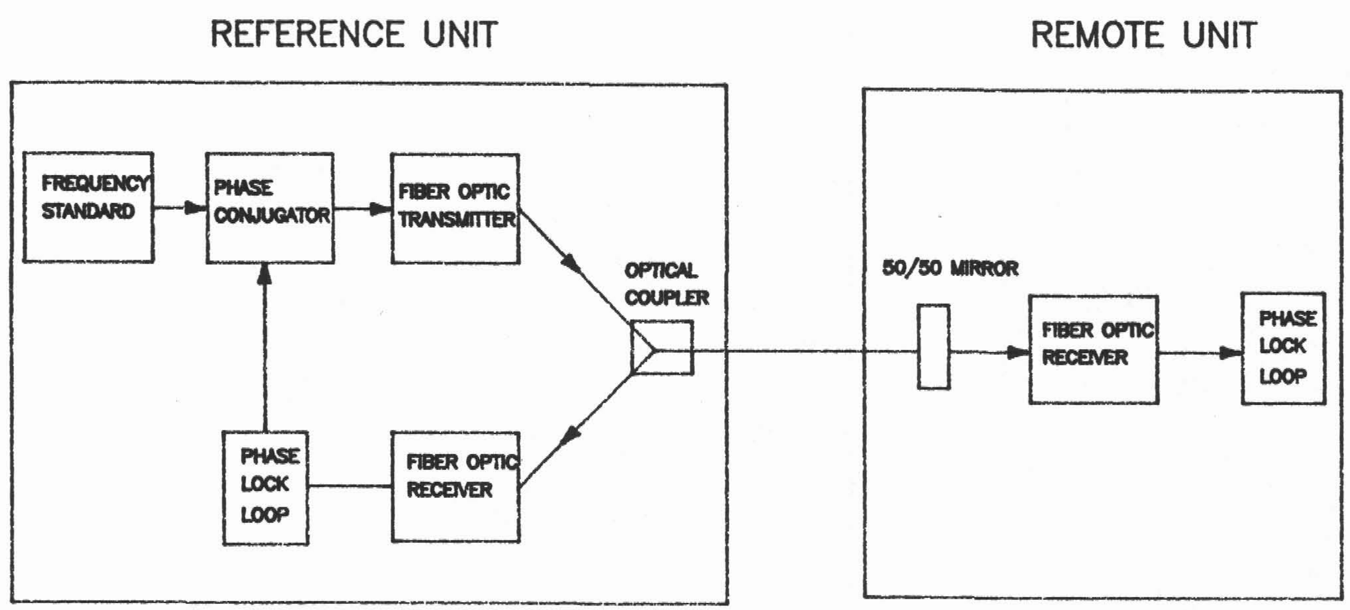


FIGURE 3. FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM

L. E. Primas *et al.*, Proc. 20th PTTI, Vienna, VA, 29 Nov - 1 Dec 1988(1988)

Fiber links : seminal works (Primas et al., 1988)

STABILIZED FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM*

- **Active noise compensation after one round-trip**
- **Strong hypothesis : noise forth and back are the same**
- **2 ends at the same place (for link stability measurements)**
- **RF, hF or optical signals**
-

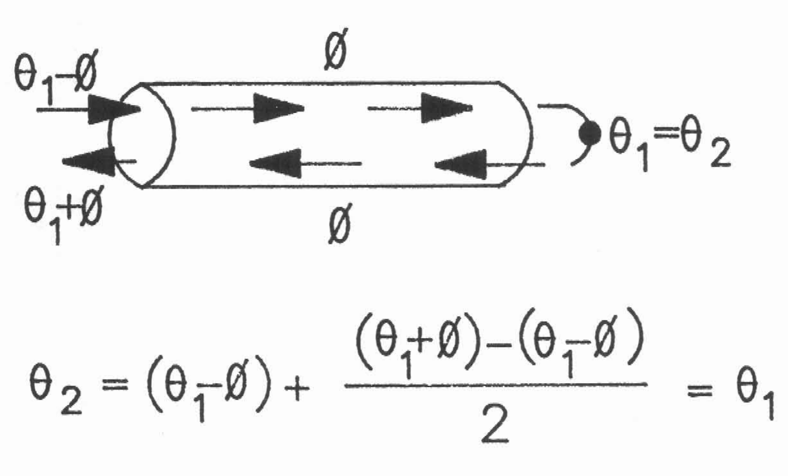


FIGURE 1. PHASE CONJUGATION AT INPUT TO OPTICAL FIBER

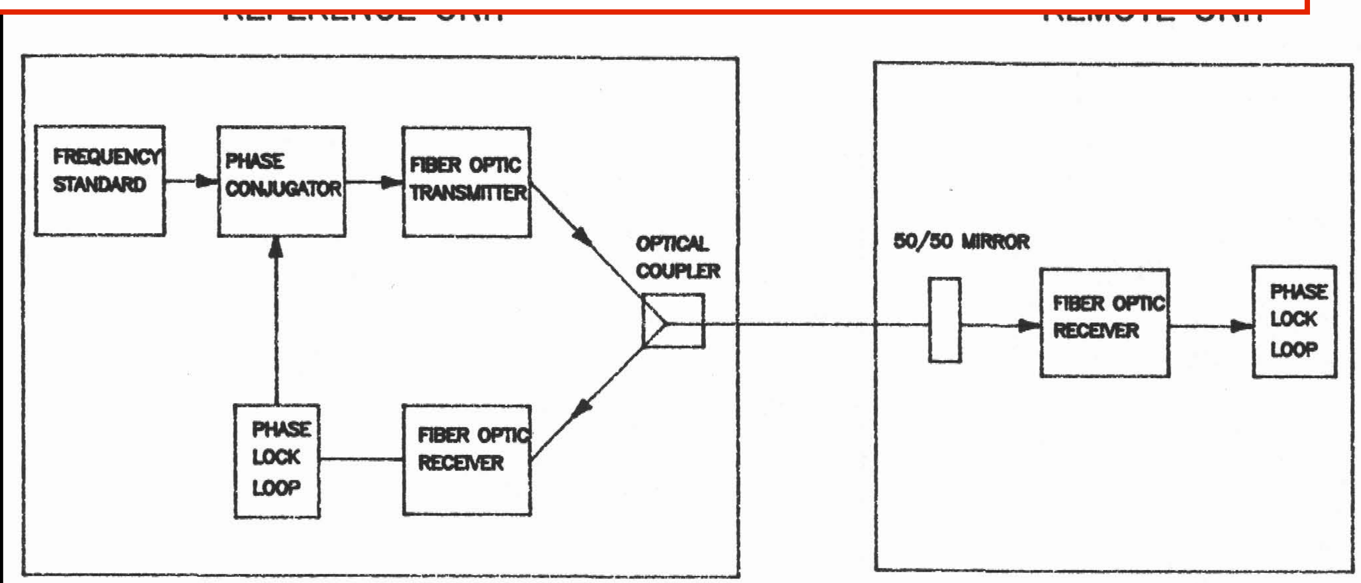
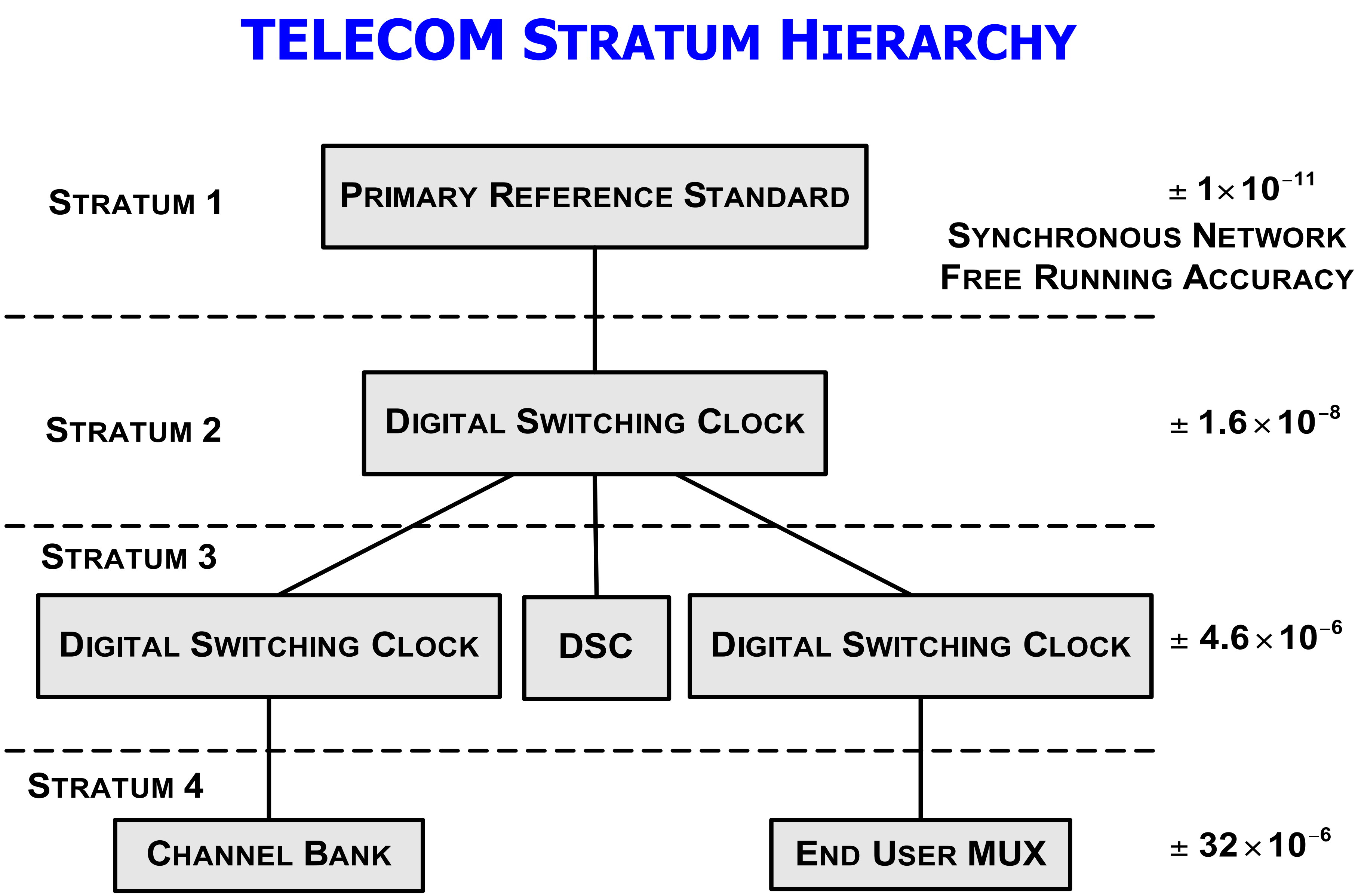


FIGURE 3. FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM

L. E. Primas *et al.*, Proc. 20th PTTI, Vienna, VA, 29 Nov - 1 Dec 1988(1988)

Massive multi-user : hierarchical links



PTP

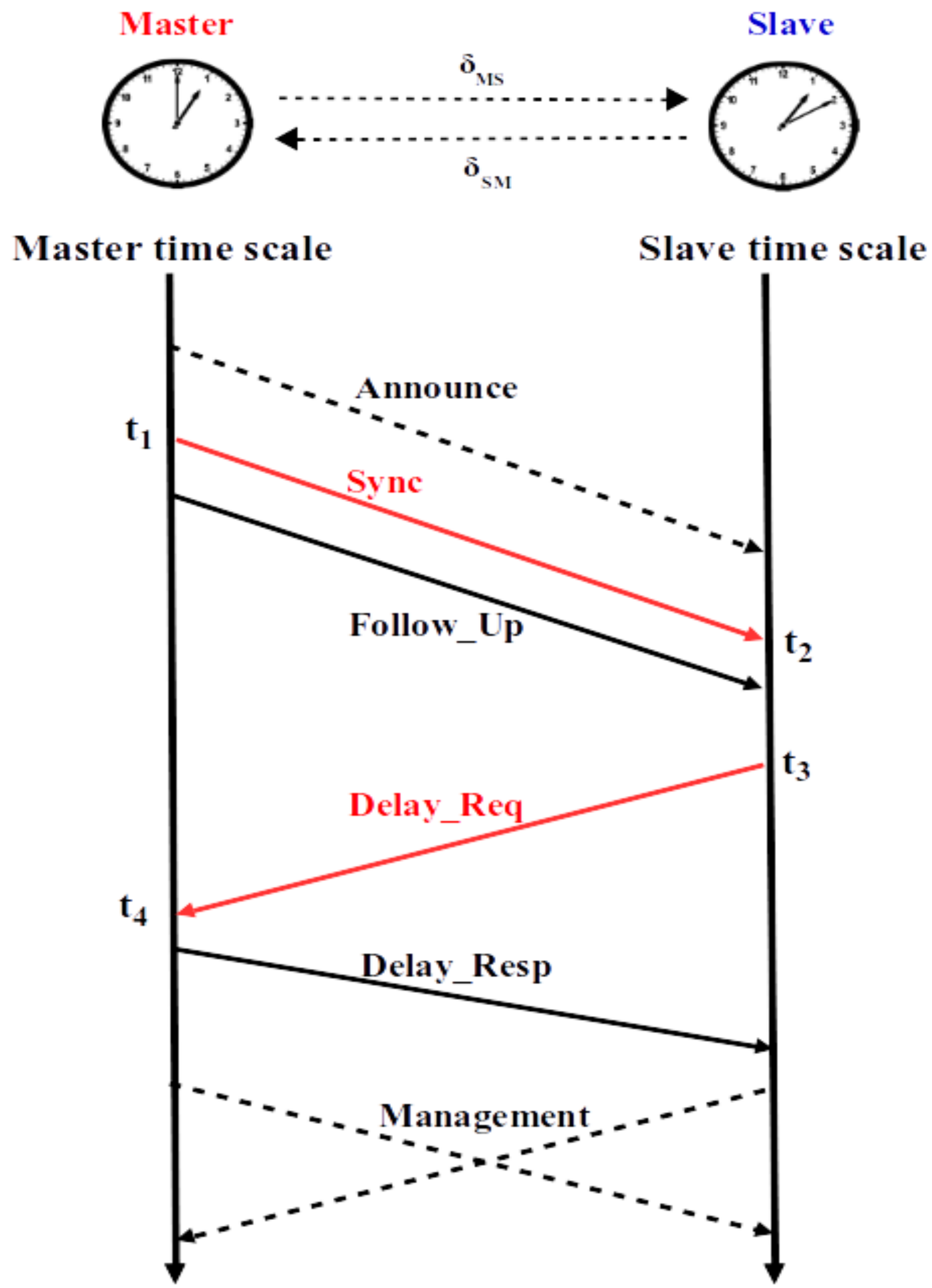


FIGURE 2.1: PTP two way messsage exchange mechanism [36].

PTP accounts for instrumental asymmetries.

Round trip time (RTT) = (t2−t1) + (t4−t3)

Clock offset = t2 − t1 + δMS

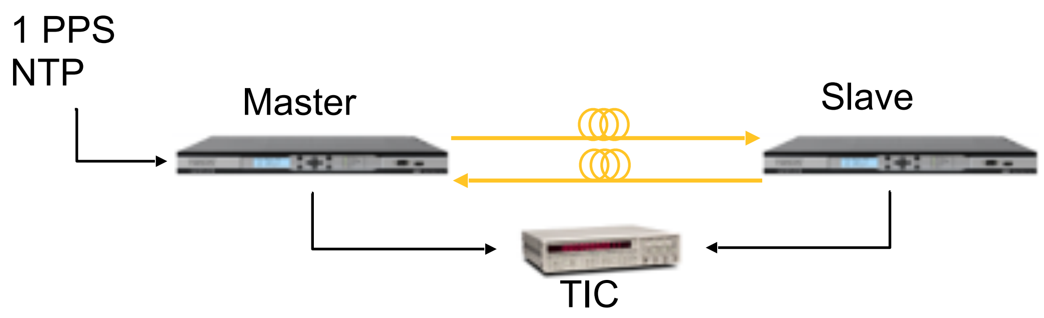
In case of asymmtery (δMS ≠ δSM):

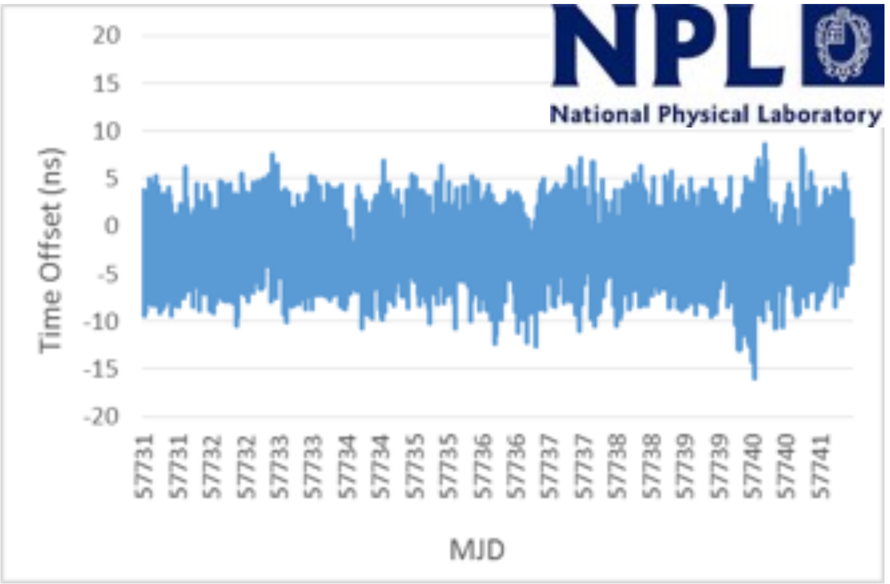
error = (δMS −δSM) /2

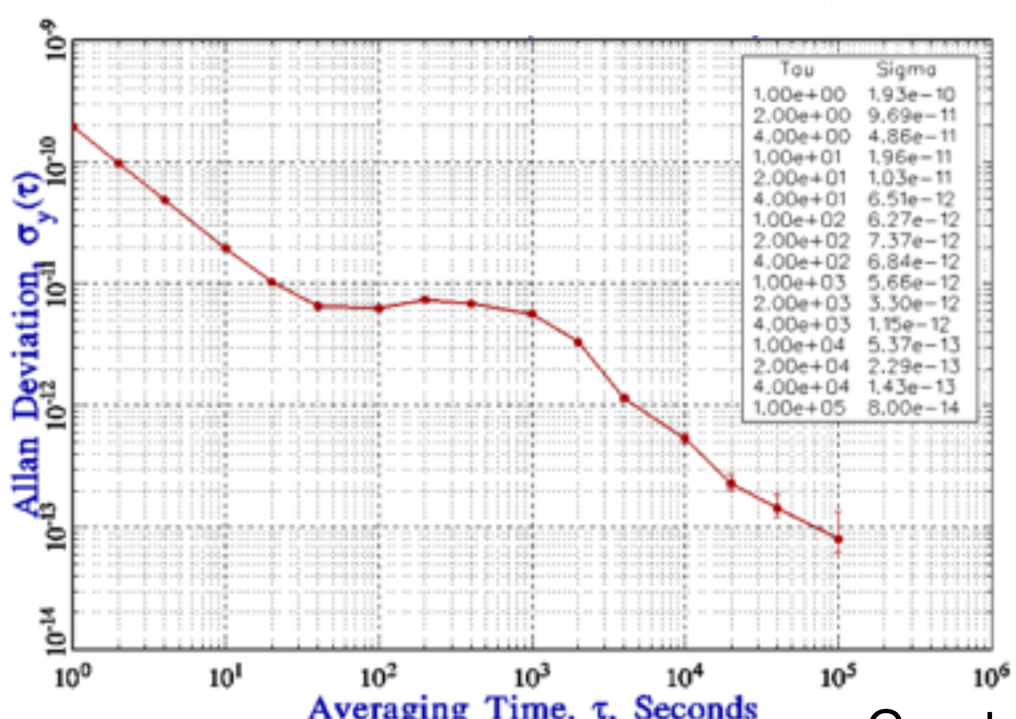
PTP

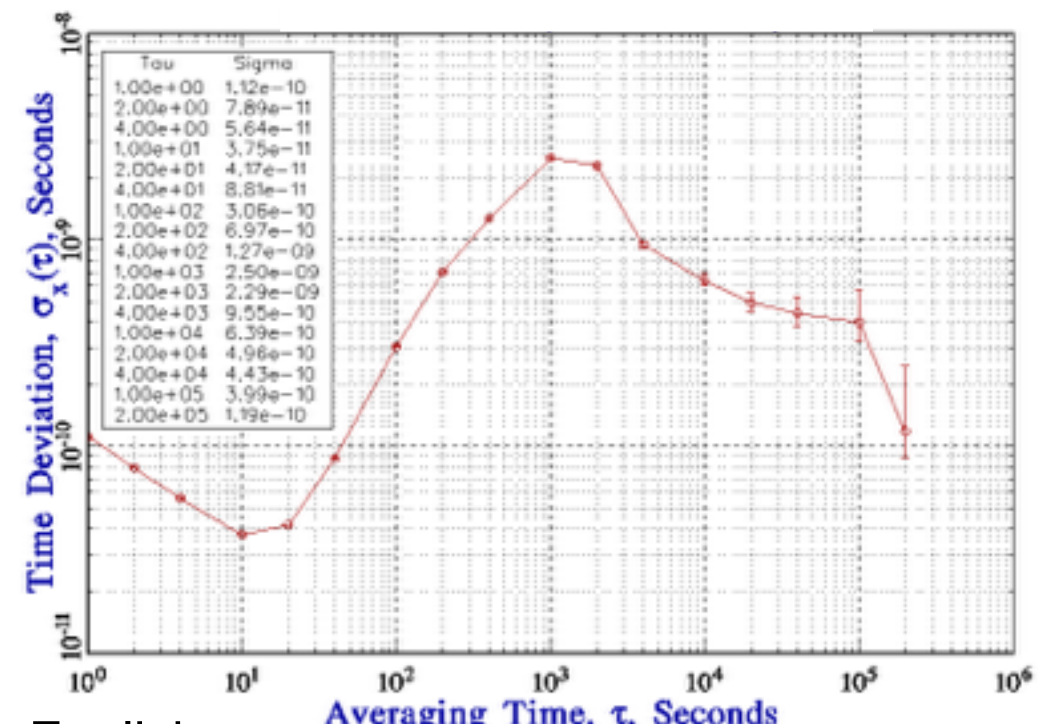
Results from test set-up using M1000 units

Test set-up: A master M1000 unit with a 1PPS and NTP reference from UTC(NPL) transmitting PTP to a slave M1000 unit over two 50km fibre spools with long range SFPs.









Courtesy E. Laier-English

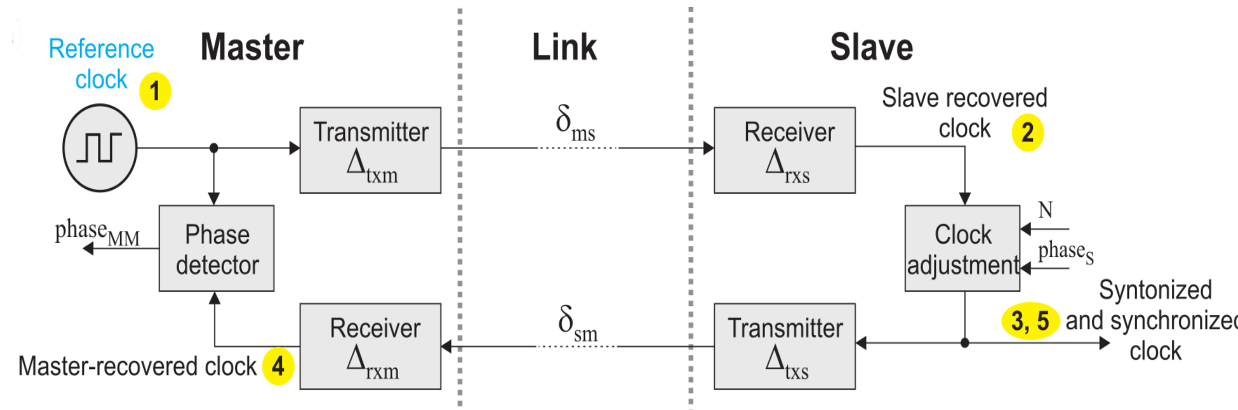
WR-PTP

Synchronous Ethernet (SyncE)

Layer-1 syntonization

A common frequency reference for the entire network

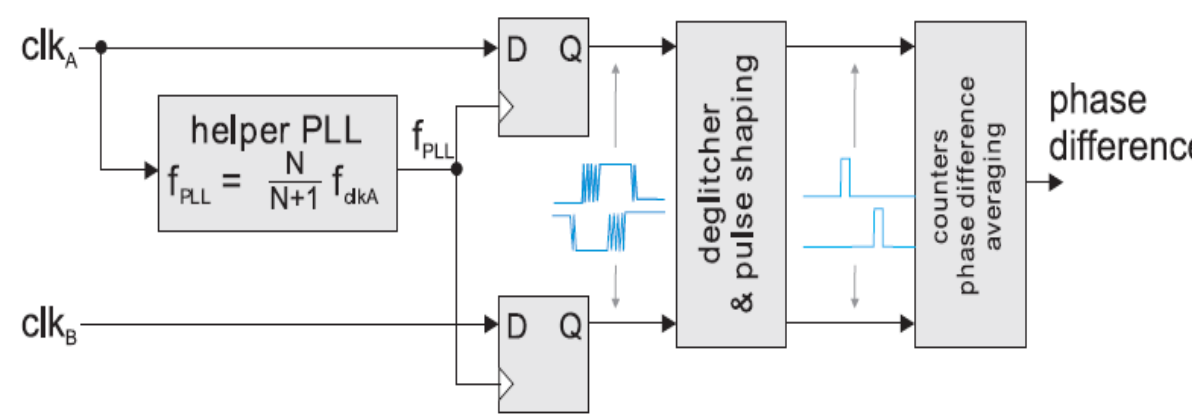
All nodes of the network are locked to the frequency of the System timing master



Digital Dual Mixer Time Difference (DDMTD)

Precise phase measurement

A phase compensated clock signal for the slave



Asymmetry compensation

Sources of propagation asymmetry in a White Rabbit link:

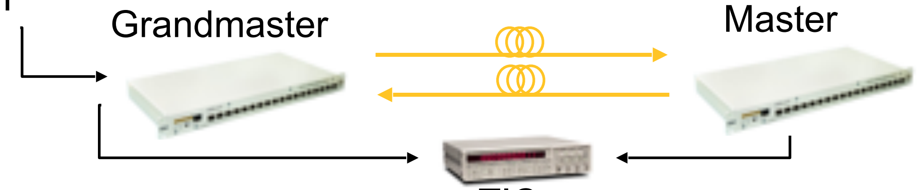
- Chromatic dispersion
- Unequal fiber lengths

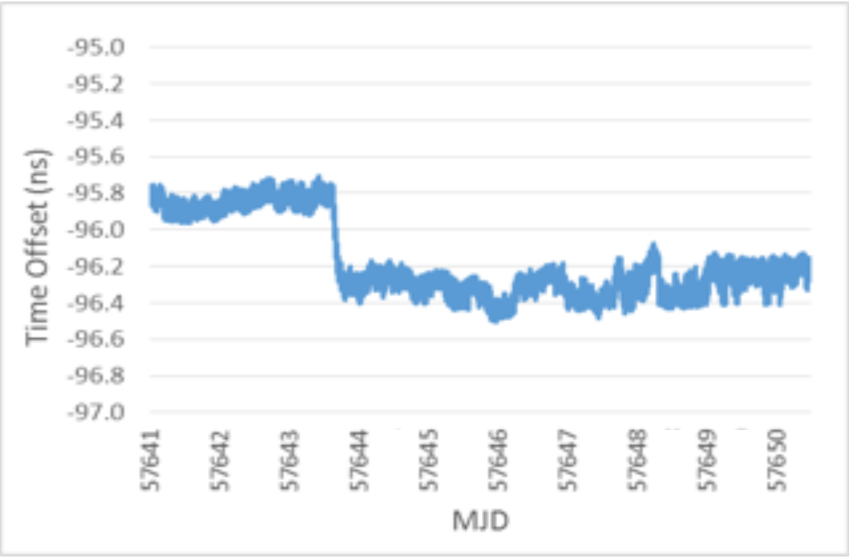
'Static' correction of propagation asymmetry possible with WR.

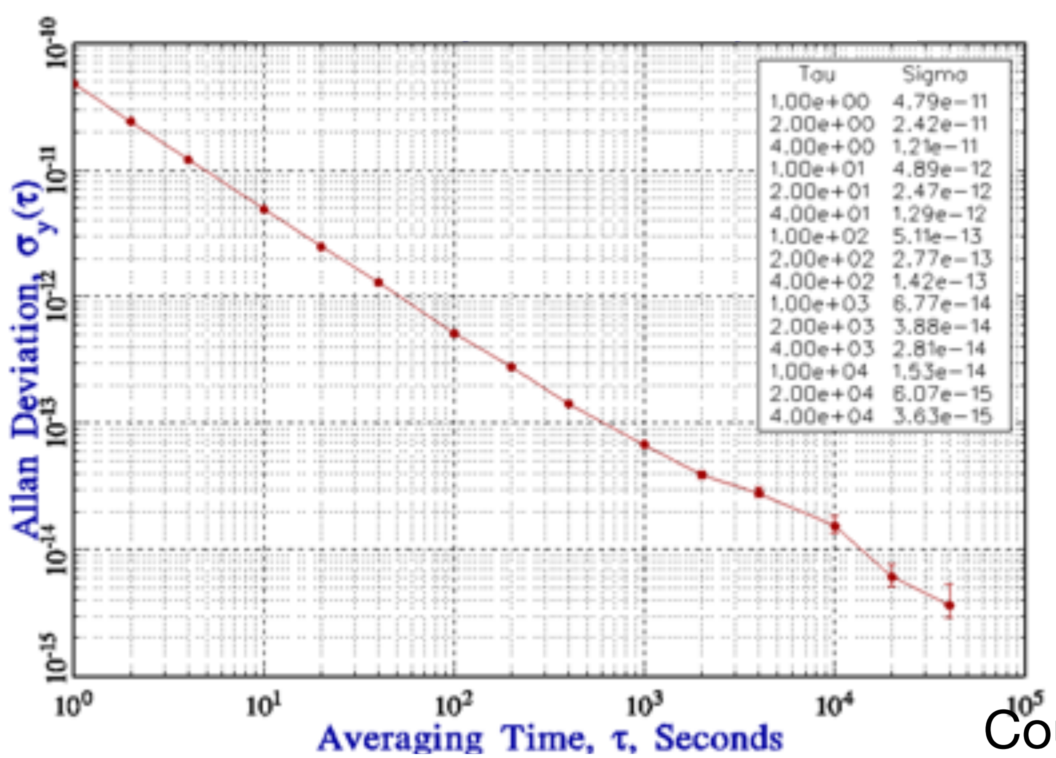
G. Daniluk,(CERN). Nuclear Instruments and Methods in Physics Research **725**, 187–190 (2013).

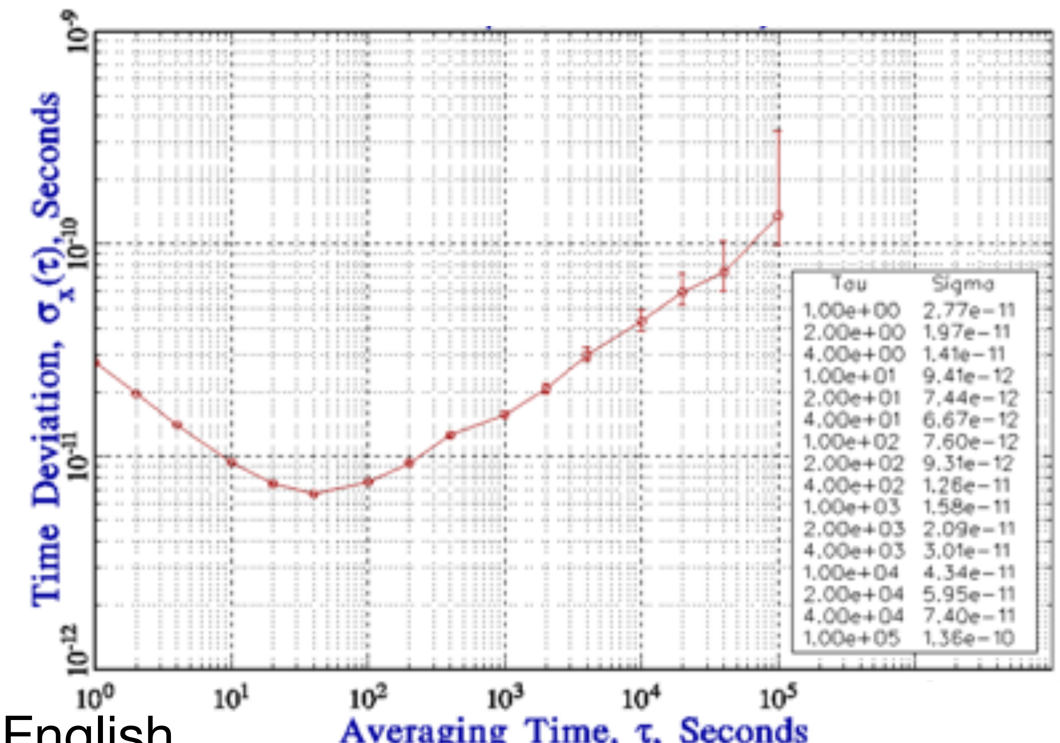
Results from test set-up using White Rabbit

Test set-up: A grandmaster WRS unit with a 1PPS and 10 MHz reference from UTC(NPL) transmitting WR to a master WRS unit over two 50km fibre spools with long range SFPs.



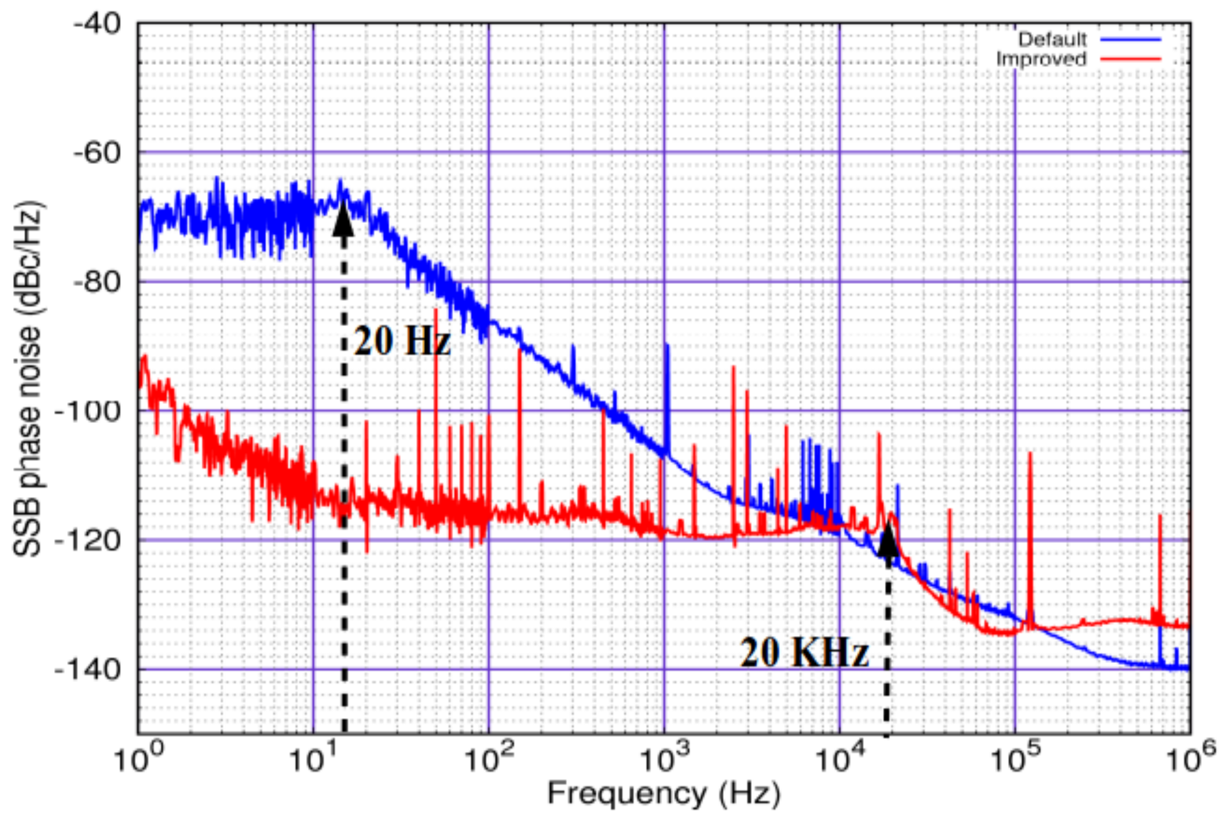


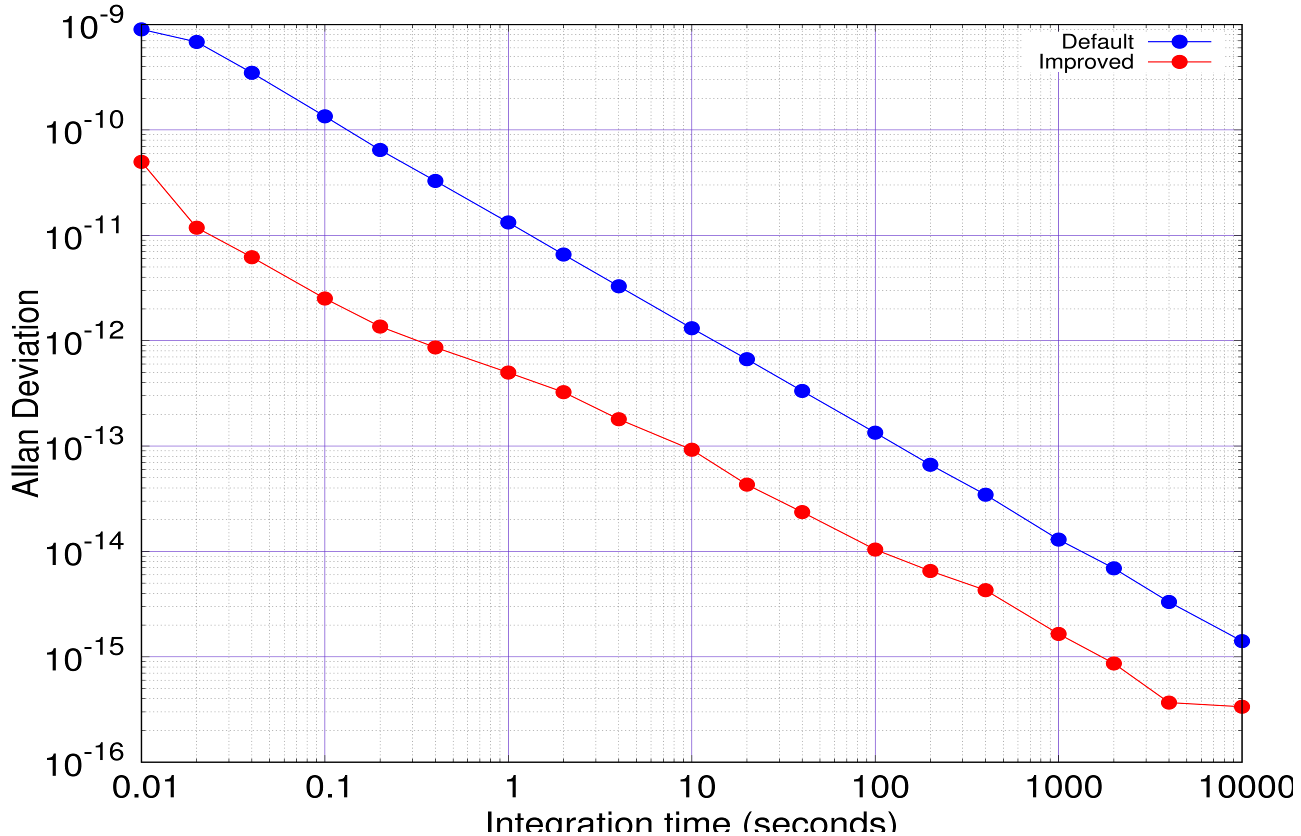




Courtesy E. Laier-English

Ways to improved WR





Trick : increased PLL bandwidth of the GM L.O. to a good quality reference signal (H-Maser) (M. Rizzy)

NB : Many other work to improve performances of WR (better clocking scheme, better choice of components (clock fan out), etc

WR community os very active !

WR-PTP short range

- 2 architectures possible
  - 2 similar wavelength, 2 fibers
  - 2 wavelengths (1310/1490), 1 fiber
- Similar performances for frequency transfer (time stability)
- Time calibration :
  - Input refraction index difference
    - < 10 ns (conservative)
    - <1 ns doable with proper calibration (including instruments…)
  - On LAN : fiber swapping technique
  - Fiber delay calibration

accuracy < 10 ns doable

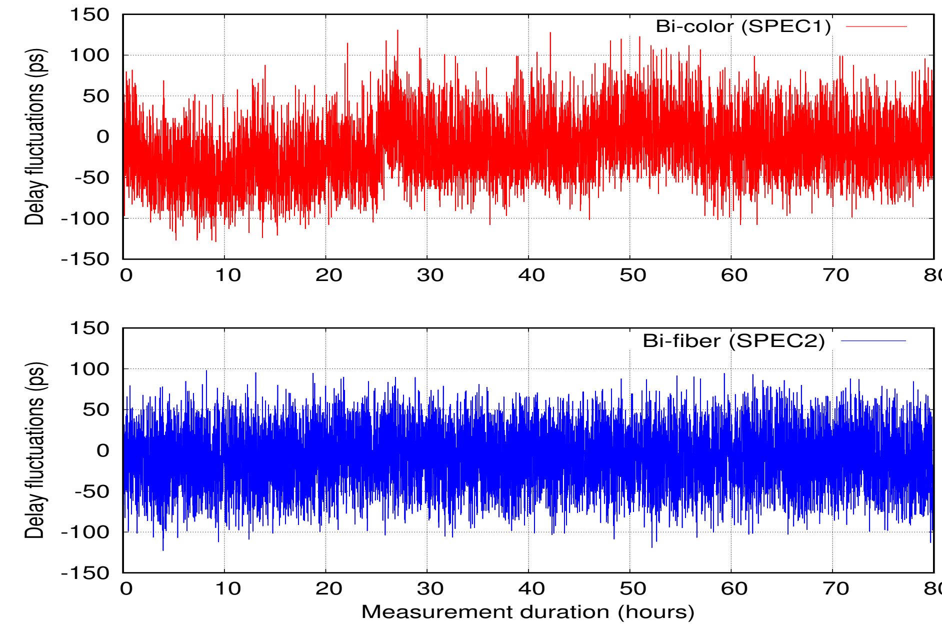
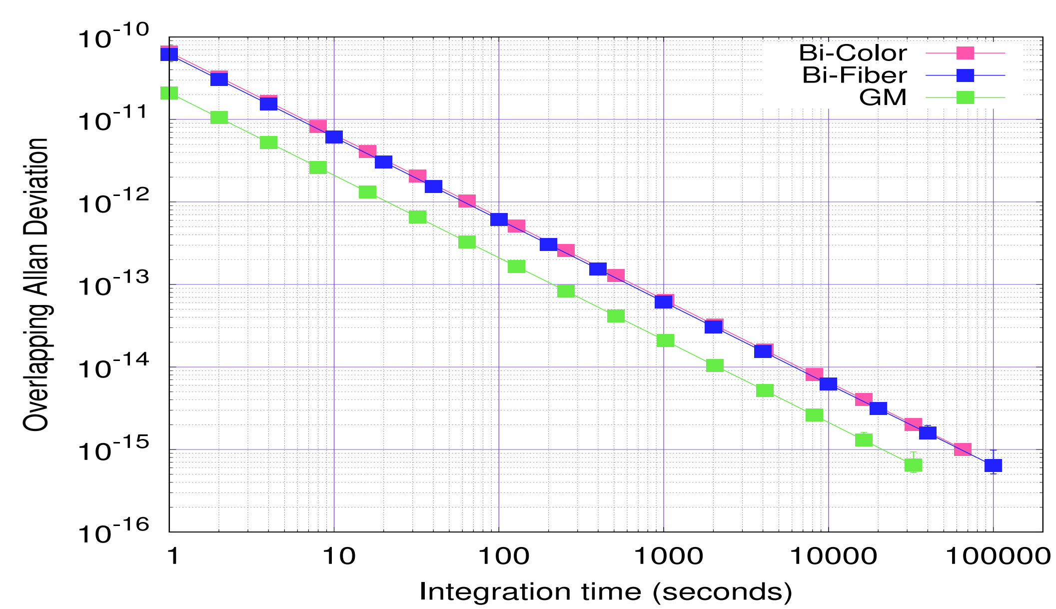
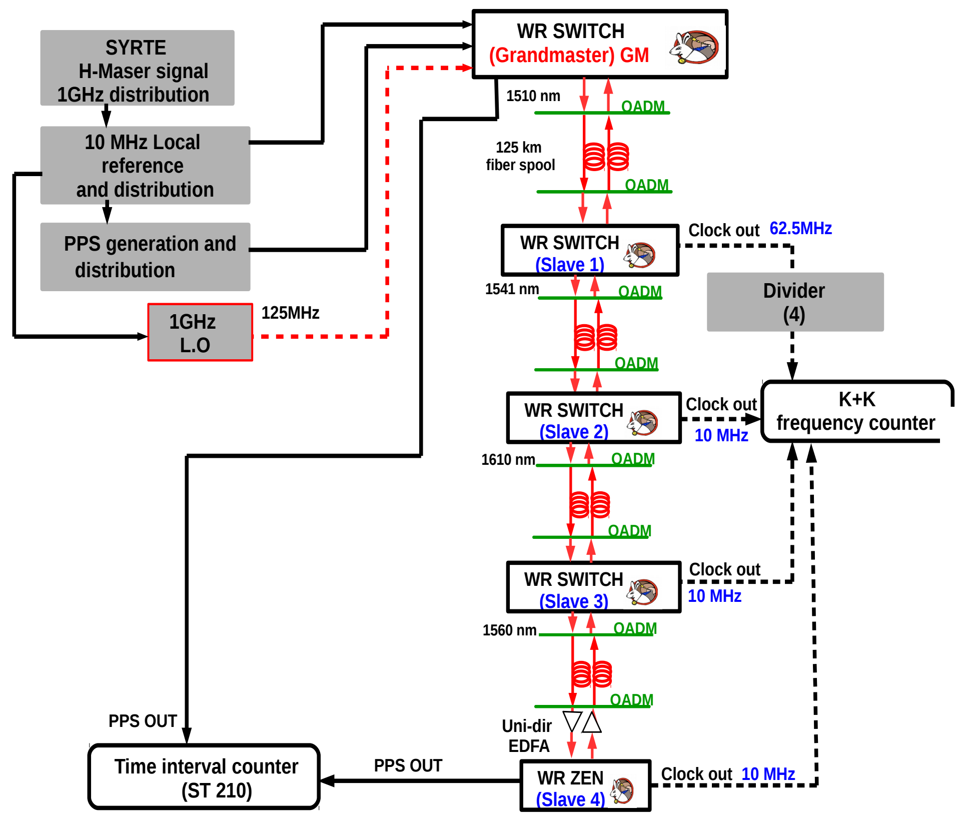
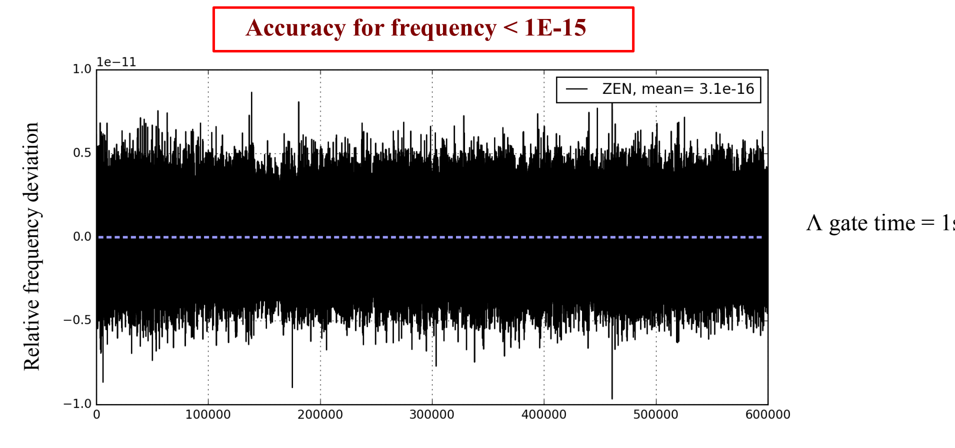


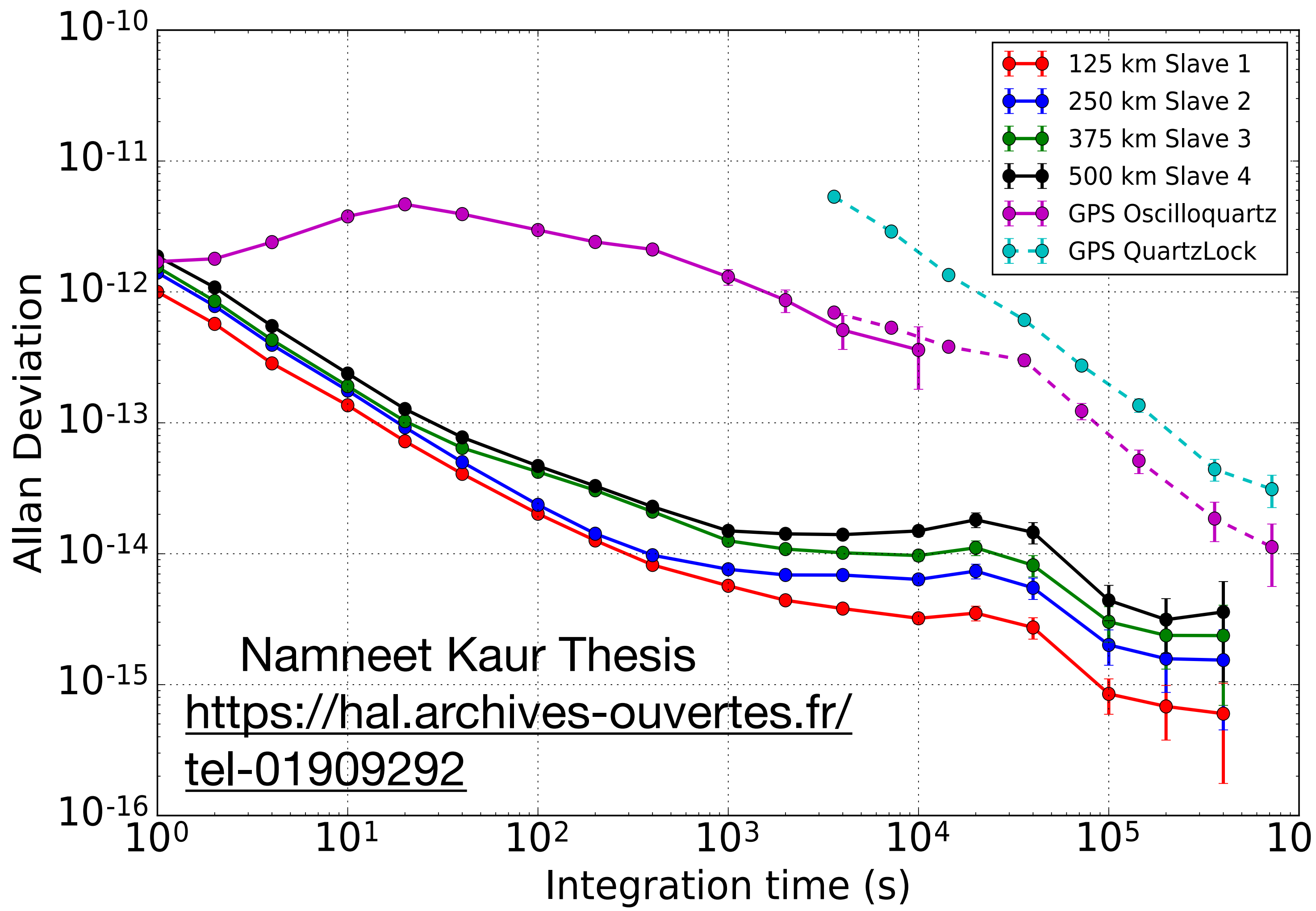
FIGURE 3.15: Phase data for the uni-directional (Bi-fiber) and bi-directional (Bi-color) setups.



WR-PTP long range : experiments with spools

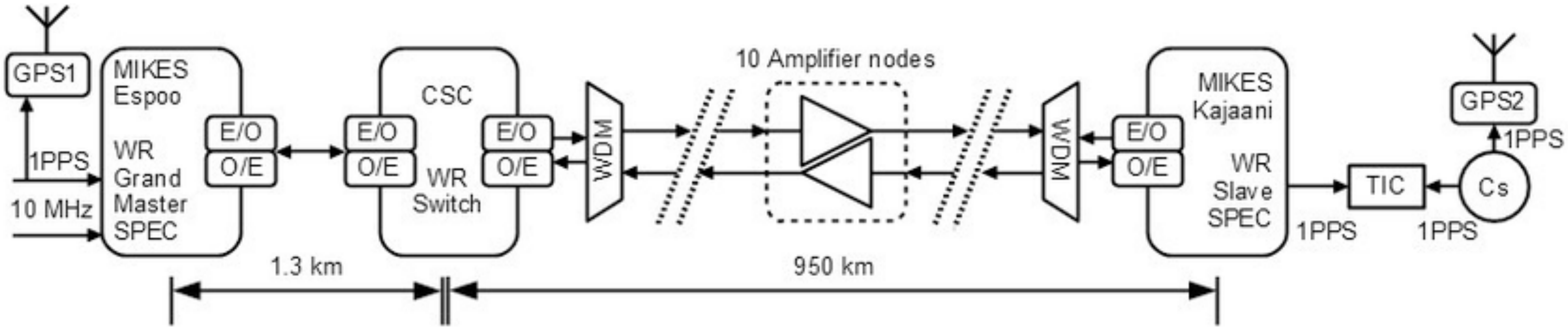




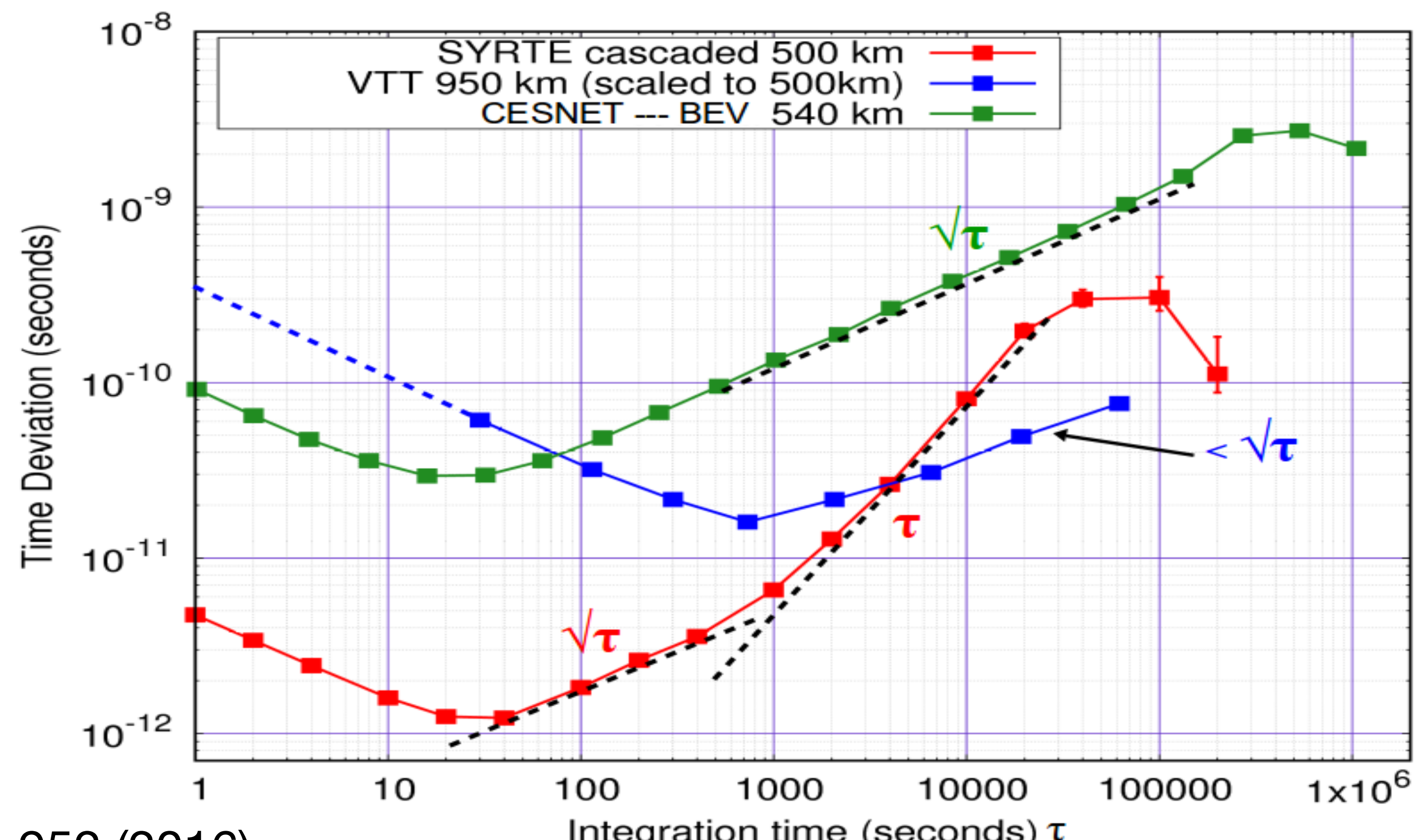


- 4-span cascaded
- Uni-dir
- Multi wavelength
- Better than Oscilloquartz GPS receiver

WR-PTP long range : MIKES



- CESNET limited by the Cs clocks instabilities
- WR@VTT < 100 ps @ 4 days



E.F. Dierikx, et al. IEEE T-UFFC 63, 945–952 (2016).

Analog methods

A non-exhaustive review:

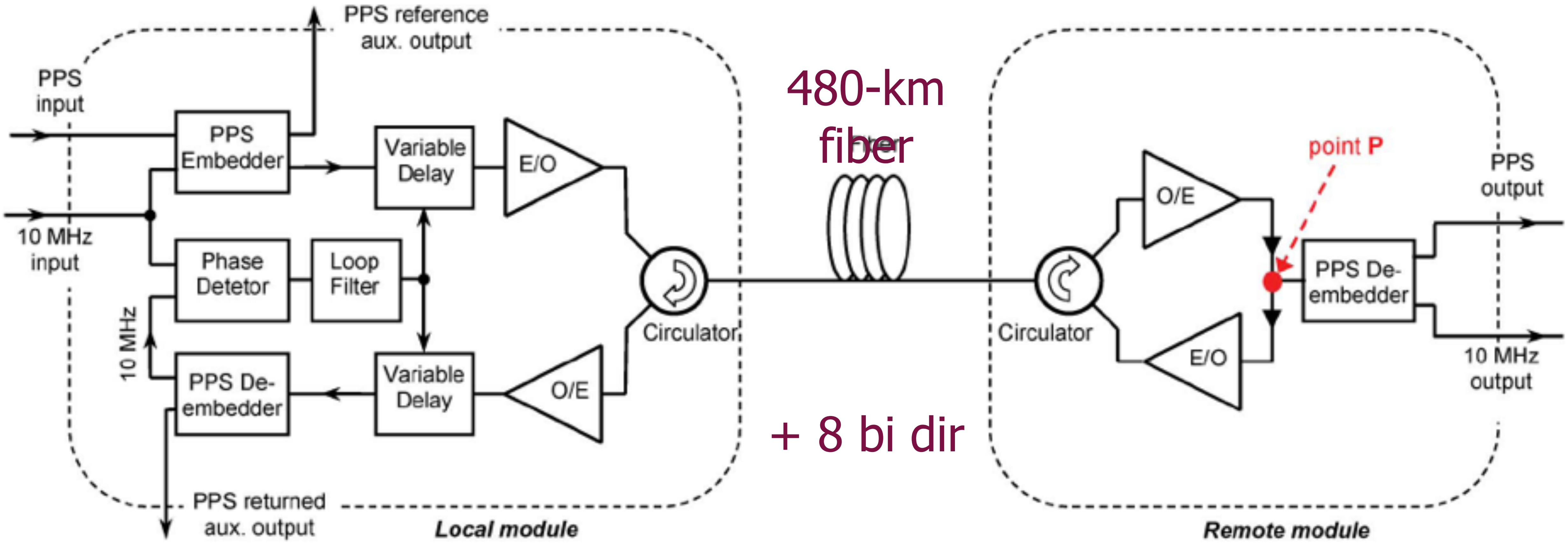
Hyper-frequency:

O. Lopez, et al. Applied Physics B **98**, 723–727 (2010).
F. Yin, F. et al. Optics Express 22, 878 (2014).
X. Chen, X. et al. Optics Letters 40, 371 (2015).
S. Schediwy, Optics Letters 42, 1648 (2017).

Radio-frequency:

C. Daussy et al. Physical Review Letters **94**, (2005).
J.-F. Cliche et al. IEEE Control Systems Magazine **26**, 19–26 (2006).
M. Fujieda et al., IEEE T-IM **58**, 1223–1228 (2009).
R.Wilcox, Optics Letters **34**, 3050 (2009).
Y.He, et al. Optics Express **21**, 18754 (2013).
P. Krehlik, IEEE T-UFFC **63**, 993–1004 (2016).
D. Gozzard, IEEE Photonics Technology Letters **30**, 258–261 (2018).

ELSTAB

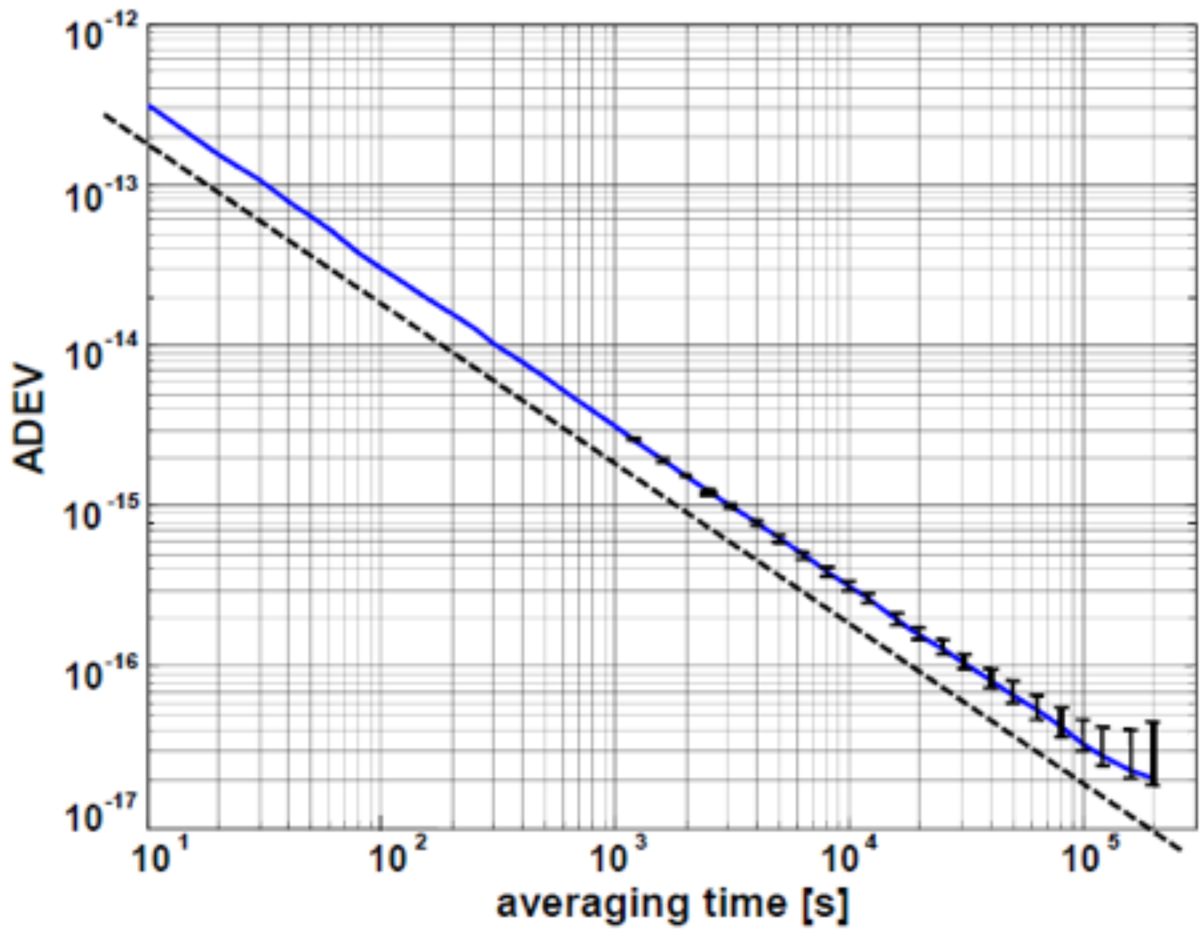


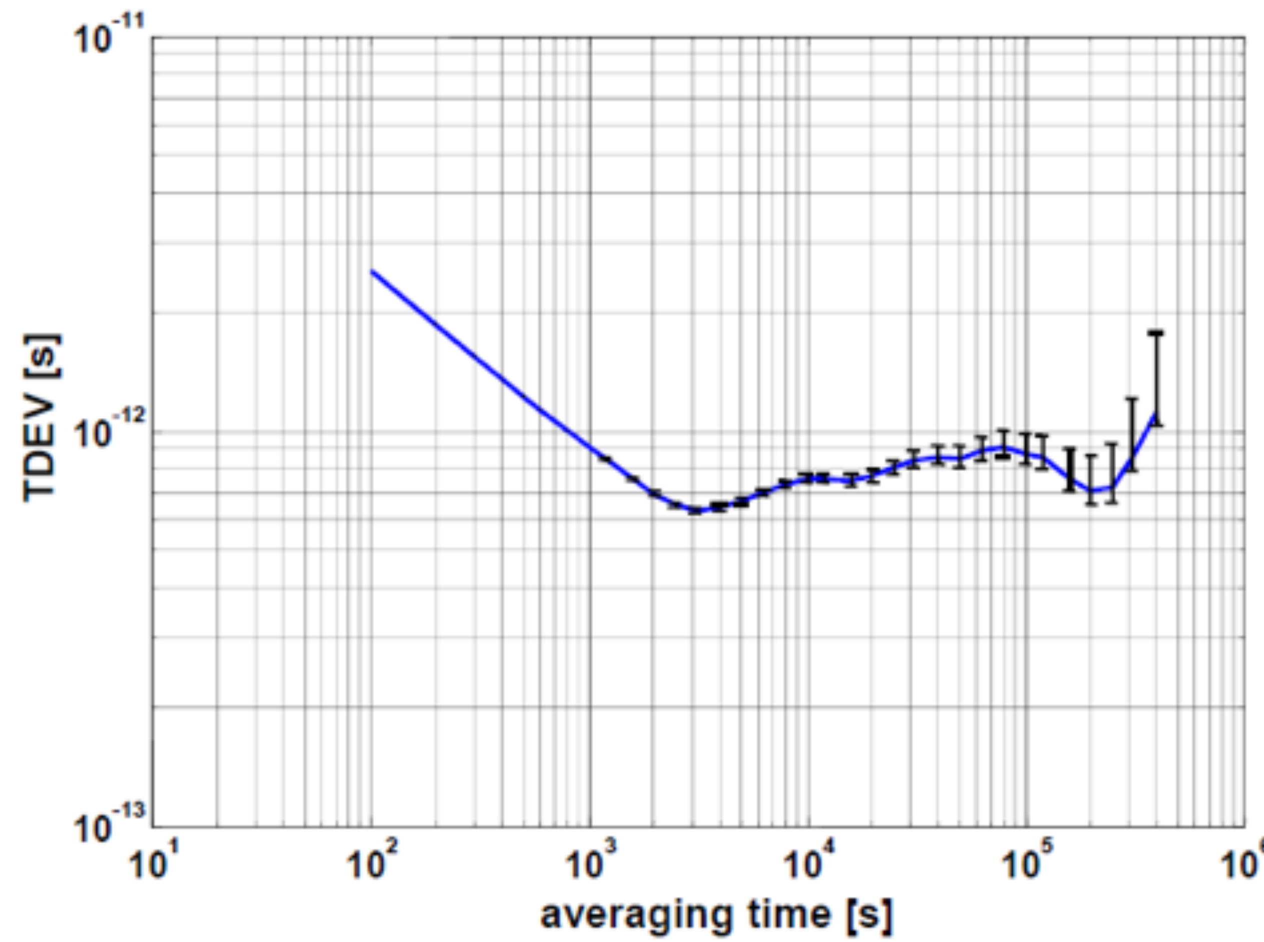
- 10-MHz + 1pps joint transfer through intensity modulation of the optical carrier; stabilized laser
- Roundtrip propagation in the same fiber for noise correction
- Active stabilization of the propagation delay through a variable delay module (DLL)

Commercially available by PikTime

Delay-stabilized time transfer

- 420-km loop fiber (Polish Telecom -Krakow-Skawina and back)
  - Full bi-directional (1 fiber, 1 wavelength)
    - Accuracy 100 ps, Stability (1d) : 0.3 ps





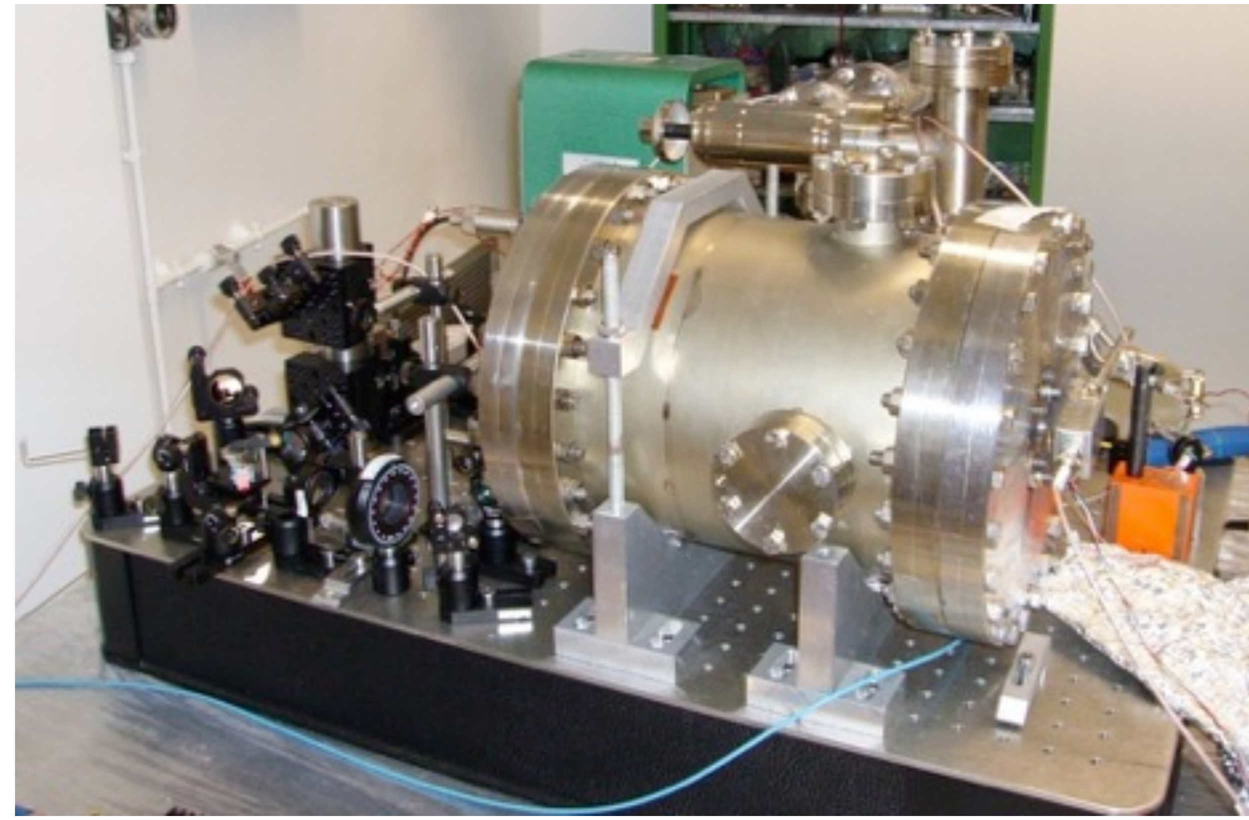
P. Krehlik, Ł. Śliwczyński, Ł. Buczek, M. Lipiński, AGH University of Science and Technology, Institute of Electronics, Kraków, Poland, IEEE Trans. on Instr. and Meas. (2012).

Optical methods

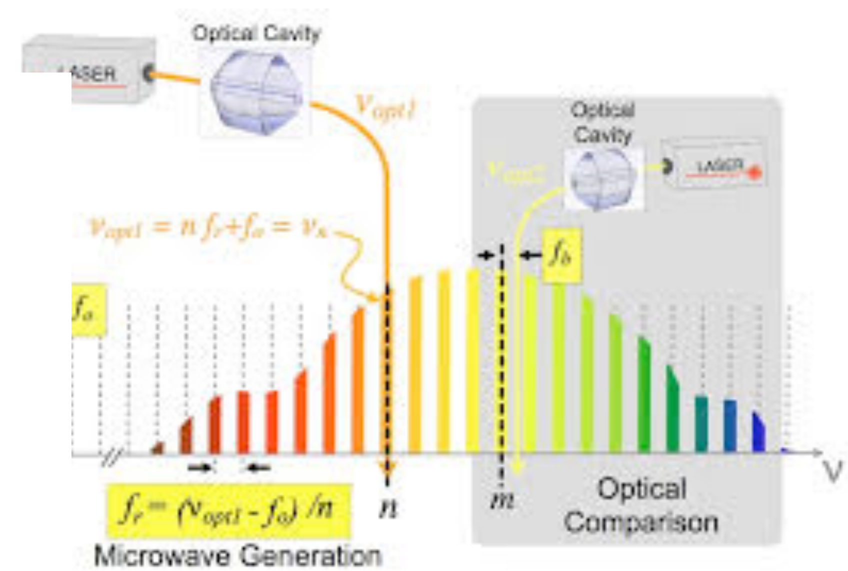
- For long range frequency transfer
- Optical frequency metrology
- Spectroscopy, high precision measurements

- Ultra-stable laser @ 1,55 µm using ultra-stable cavity
  - Rel. frequency stability ~ 10^{-15} @ 1 s
  - Uncertainty none by itself
  - Optical frequency is measured with optical frequency combs≤ 10^{-14} as compared to optical clocks or fountains clocks
  - **Basically sub-Hz laser**

- Optical frequency comb
  - Spectral purity transfer
  - Frequency ratio

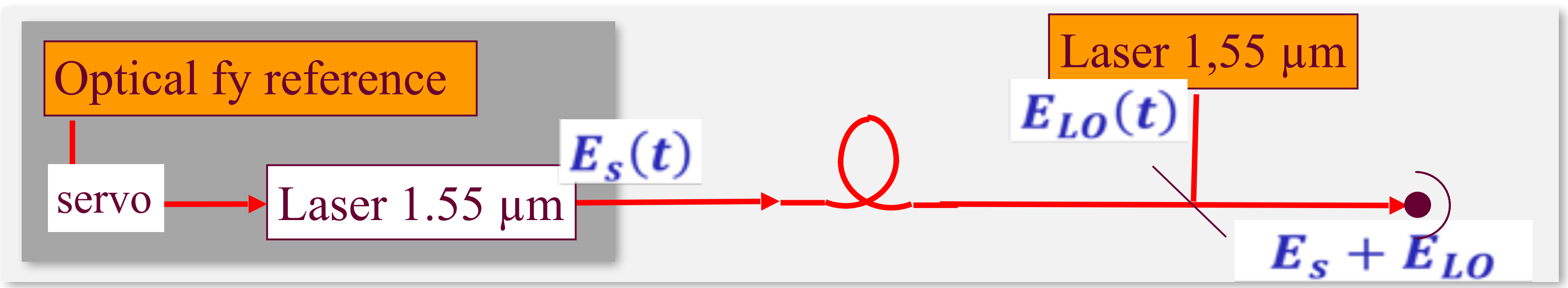


Menlo



Courtesy J. Ye, JILA

Advantages of the full optical method



- Heterodyne detection at remote end
- Signal $S(t) = |E_s + E_{LO}|^2$

  with $E_S(t) = \sqrt{P_S} e^{j(\omega_s t + \phi_s(t))}$ and $E_{LO}(t) = \sqrt{P_{LO}} e^{j(\omega_{LO} t + \phi_{LO}(t))}$

  After AC filter: $S(t) \propto \sqrt{P_{LO} P_S} \, cos\big((\omega_s - \omega_{LO})t + \phi_s(t) - \phi_{LO}(t)\big)$

$\longrightarrow$ detection of the transmitted field (not intensity)

$\longrightarrow$ fiber losses of X dB reduce the detected signal by X/2 dB

The optical way : Seminal works (Ma et al., 1994)

November 1, 1994 / Vol. 19, No. 21 / OPTICS LETTERS 1777

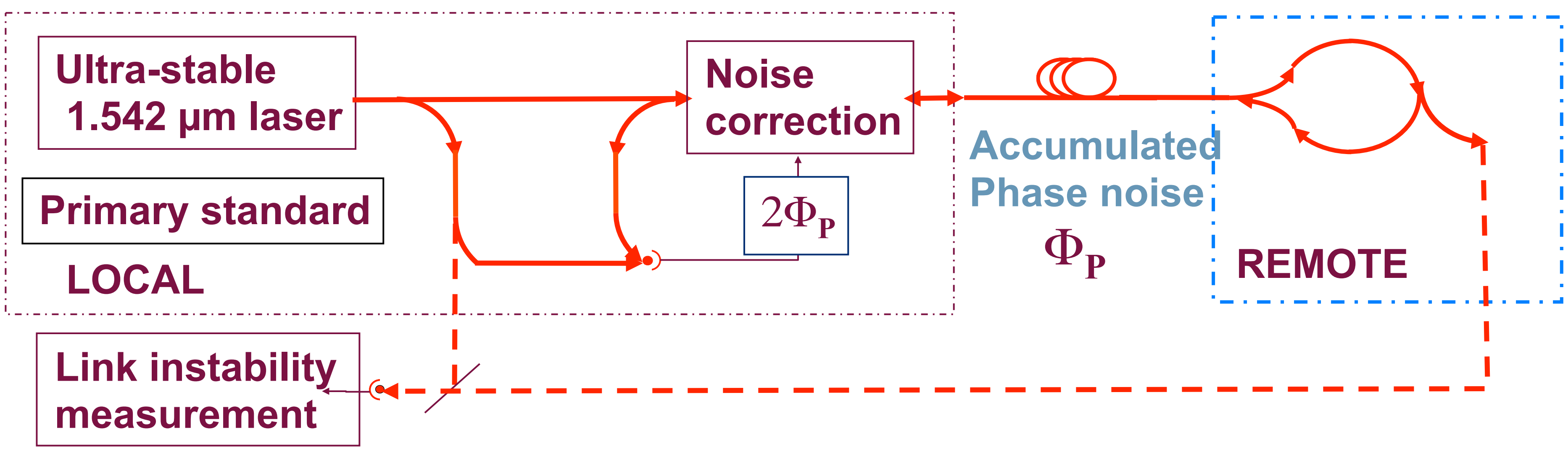
Delivering the same optical frequency at two places: accurate cancellation of phase noise introduced by an optical fiber or other time-varying path

Long-Sheng Ma,* Peter Jungner,† Jun Ye, and John L. Hall‡

Joint Institute for Laboratory Astrophysics, University of Colorado and National Institute of Standards and Technology, Boulder, Colorado 80309-0440

Received May 12, 1994

Although a single-mode optical fiber is a convenient and efficient interface/connecting medium, it introduces phase-noise modulation, which corrupts high-precision frequency-based applications by broadening the spectrum toward the kilohertz domain. We describe a simple double-pass fiber noise measurement and control system, which is demonstrated to provide millihertz accuracy of noise cancellation.



The optical way : Seminal works (Ma et al., 1994)

November 1, 1994 / Vol. 19, No. 21 / OPTICS LETTERS 1777

Delivering the same optical frequency at two places: accurate cancellation of phase noise introduced by an optical fiber or other time-varying path

Long-Sheng Ma,* Peter Jungner,† Jun Ye, and John L. Hall‡

Joint Institute for Laboratory Astrophysics, University of Colorado and National Institute of Standards and Technology, Boulder, Colorado 80309-0440

Received May 12, 1994

Although a single-mode optical fiber is a convenient and efficient interface/connecting medium, it introduces phase-noise modulation, which corrupts high-precision frequency-based applications by broadening the spectrum toward the kilohertz domain. We describe a simple double-pass fiber noise measurement and control system, which is demonstrated to provide millihertz accuracy of noise cancellation.

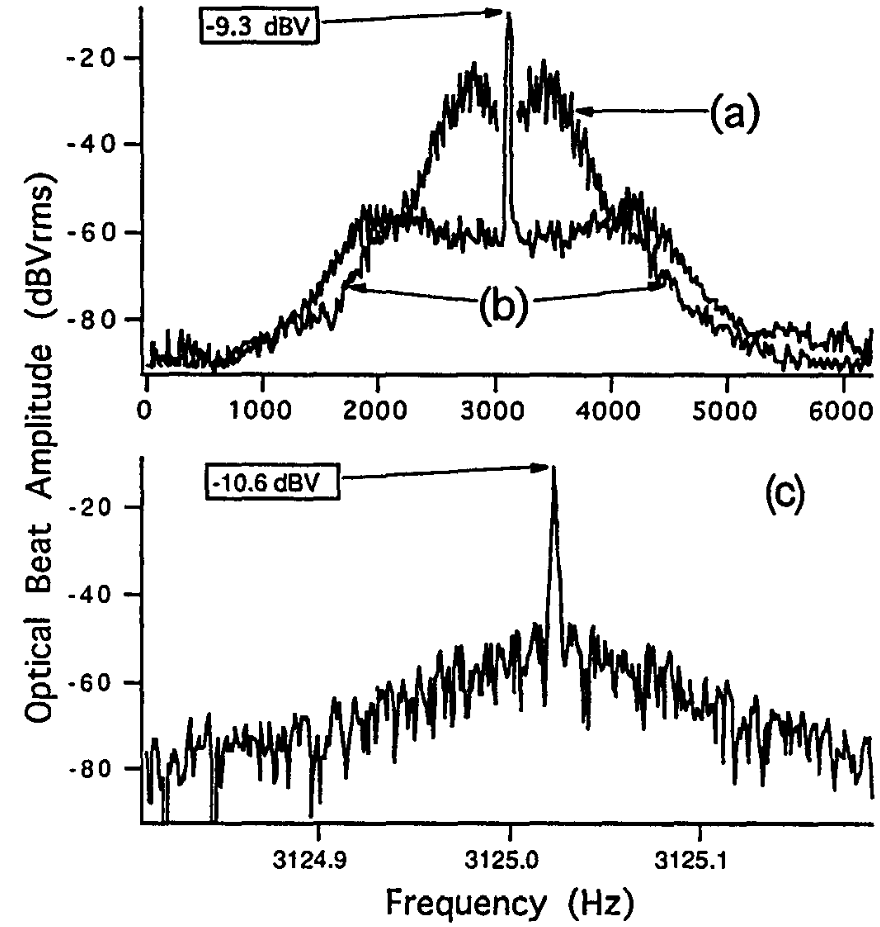
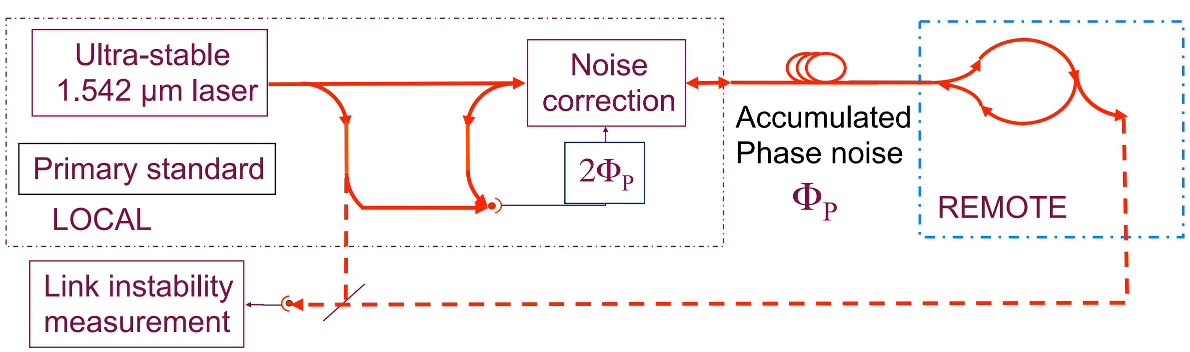
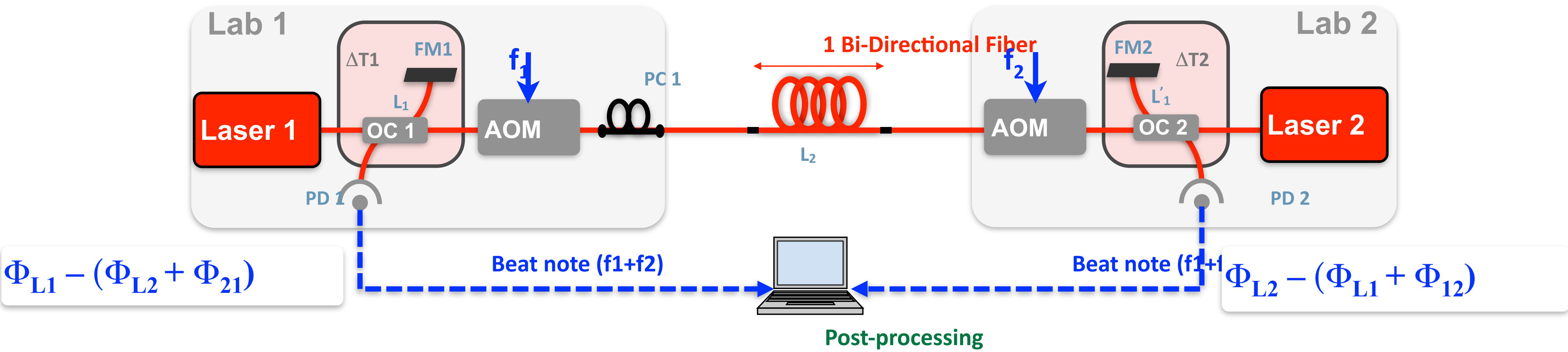


Fig. 2. Optical field spectrum at the output of a 25-m fiber. The input optical signal approximates a delta function. The signal arrives at the far end with a 1.2-kHz width, shown in (a). In (b) the phase-noise compensation system is operational, and one regains 99.6% of the power in the sharp spectral feature. The resolution bandwidth is 15.6 Hz. In (c) the resolution bandwidth is 0.95 mHz. The carrier is reduced by only 1.3 dB from (b) to (c) because of noise near the carrier.



25-m optical fiber link

Optical frequency comparison with two-way



$$(\Phi_1 - \Phi_2)/2 = (\Phi_{L1} - \Phi_{L2}) + (\Phi_{12} - \Phi_{21})/2$$

- Laser Lights propagate from the two sides.
- Noise rejection can be 6 dB better (with post-processing).
- No active compensation. But it's the same signal processing.

Calosso et al., Opt. Lett. **39**, 1177- 1180 (2014)
A. Bercy et al., Phys. Rev. A 90, 061802(R) (2014) : Two-way set-ups
F. Stefani *et al*, «Tackling the limits of optical fiber links», JOSA B 32, 787-797 (2015)

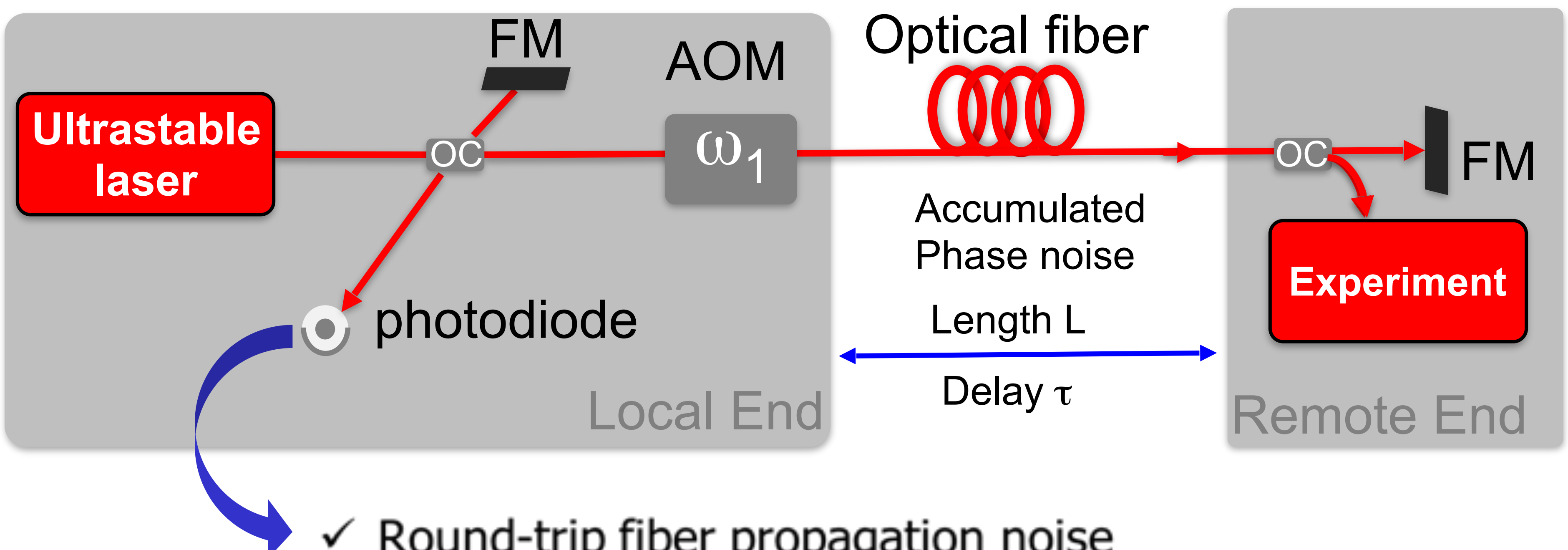
Optical frequency comparison with two-way

- Laser Lights propagate from the two sides.
- Noise rejection can be 6 dB better (with post-processing).
- No active compensation. But it's the same signal processing.

Calosso et al., Opt. Lett. **39**, 1177- 1180 (2014)
A. Bercy et al., Phys. Rev. A 90, 061802(R) (2014) : Two-way set-ups
F. Stefani *et al*, «Tackling the limits of optical fiber links», JOSA B 32, 787-797 (2015)

Detection of round-trip noise

- Strongly unbalanced Michelson interferometer
- Frequency shifter $\omega_1 \rightarrow$ heterodyne detection at $2\omega_1$
- Using Faraday mirrors automatically aligns polarisations at detection



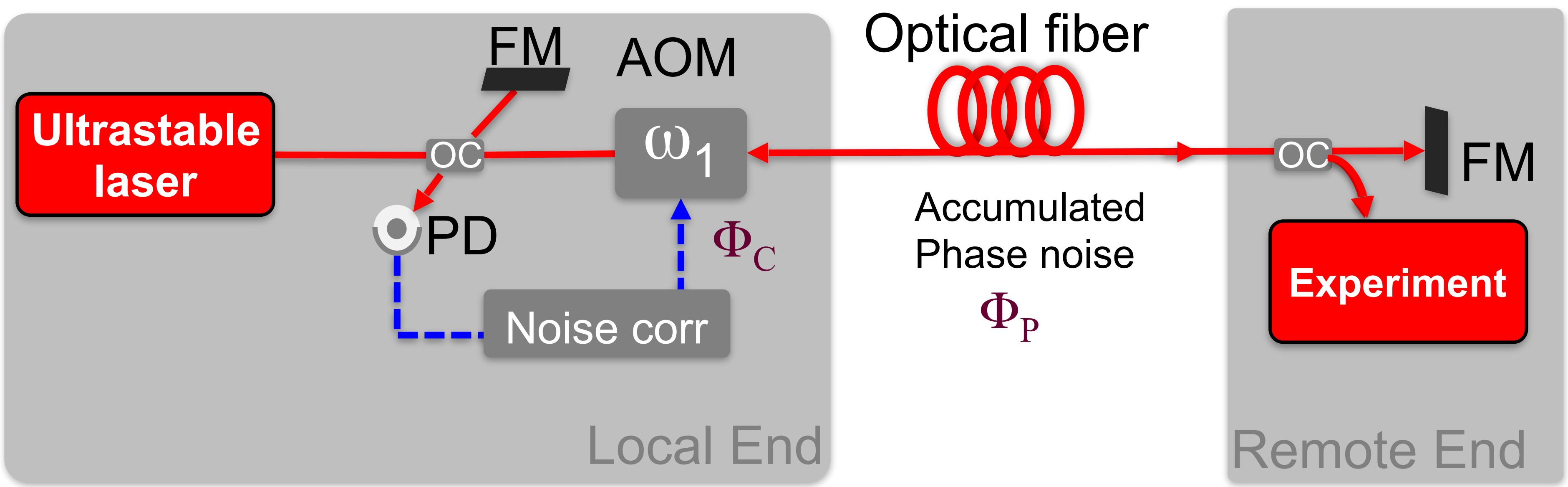
✓ Round-trip fiber propagation noise

✓ + Laser autocorrelation noise $\phi_{laser}(t) - \phi_{laser}(t - 2\tau)$

→ Ultrastable laser are needed with coherence length > 2L to keep the coherent regime

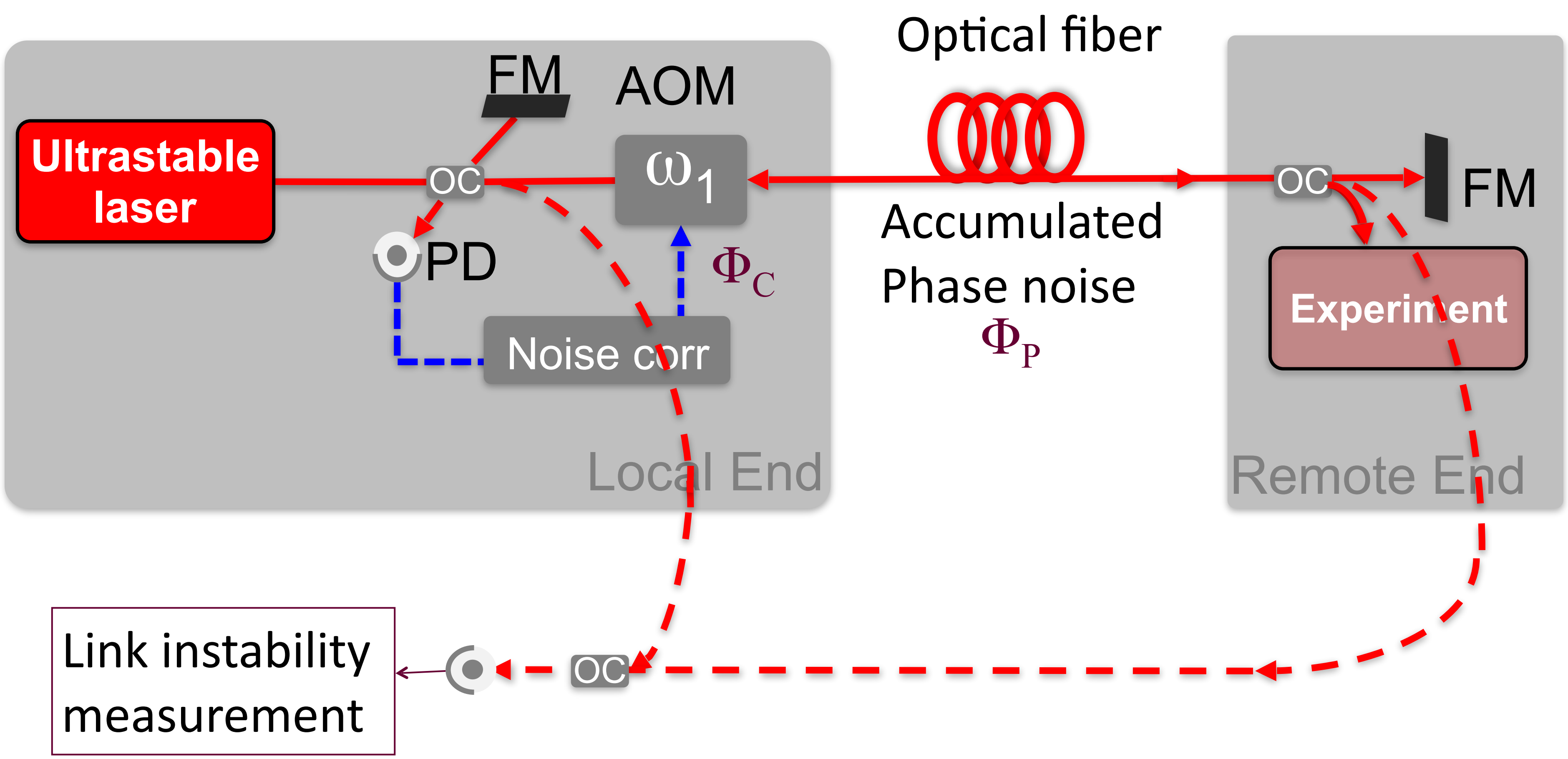
Active noise compensation in an optical fiber link

- Doppler noise compensation or active noise compensation



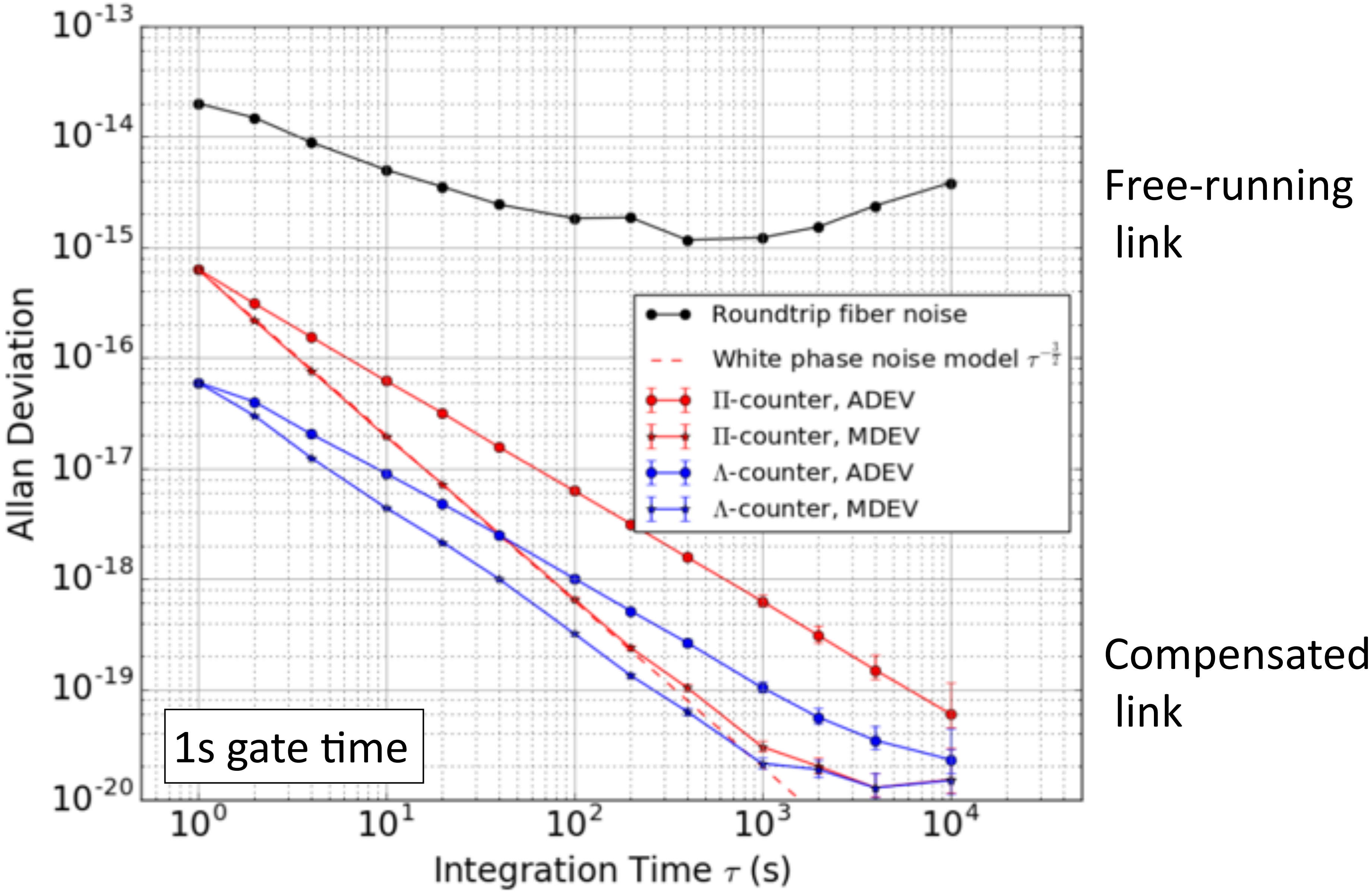
- Noise correction Φ_c applied at the link input : $2(\Phi_C + \Phi_P) = 0$
- Assumption : Forward noise = ½ Round-trip noise
  → corrects only reciprocal noise

Evaluation of noise compensation



- So-called “End-to-end” instability measurement
- Demonstration with 2 parallel fibers or one loop fiber: two ends at the same place

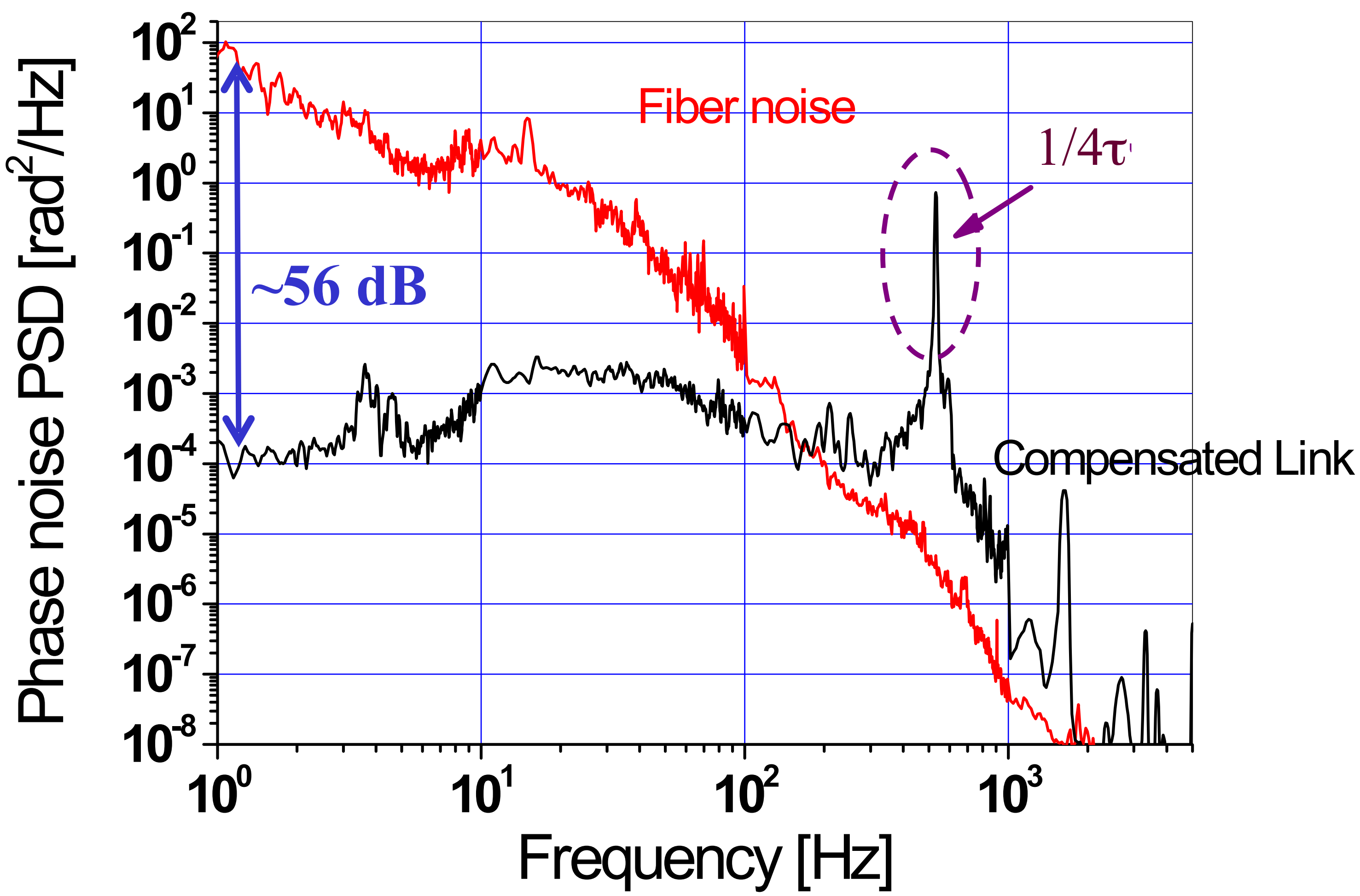
Example: optical link stability – 2x43 km



Xu et al, Opt. Exp. 2018

Example: phase noise of a 86 km optical link

Carrier = 200 THz



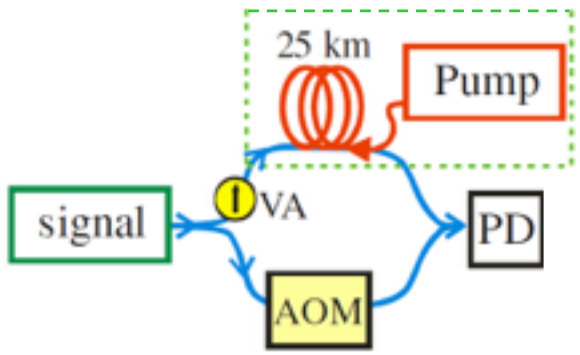
Jiang et al, JosaB 2008

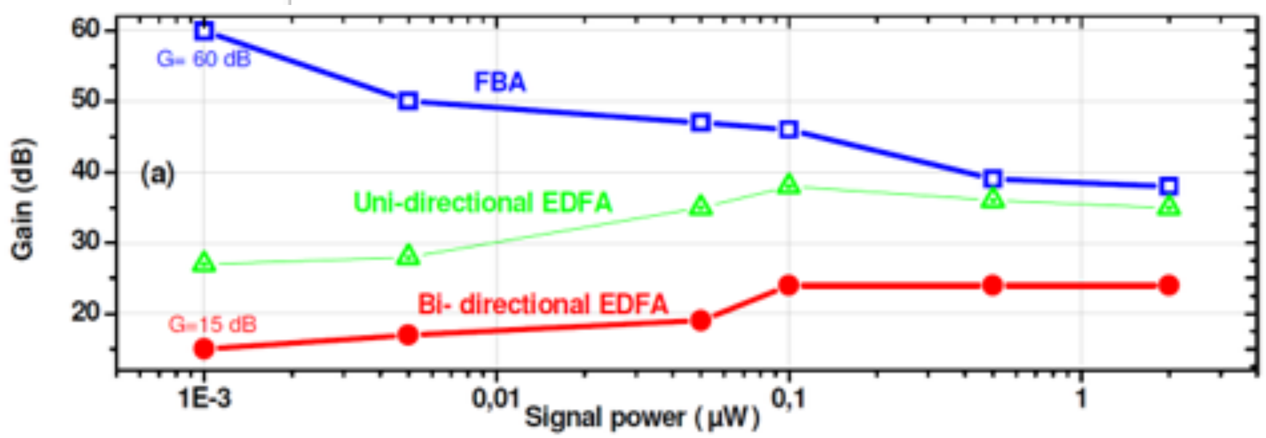
Bidirectional amplification

- Erbium-doped fiber amplifier (10<G<20 dB)
  - Wide bandwidth (40 nm)
  - Gain should be limited to avoid self-oscillation
  - Widely used, commercially available with remote gain control
- Fiber Brillouin amplifier (<60 dB)
  - Narrow bandwidth (10 MHz)
  - Very selective, enabling high gain
- Raman amplifier (20-25 dB)
  - Intermediate bandwidth (1THz)
  - High pump power, intermediate gain

- Optical regeneration (repeater laser station, 2dBm output)

Fiber Brillouin amplifier



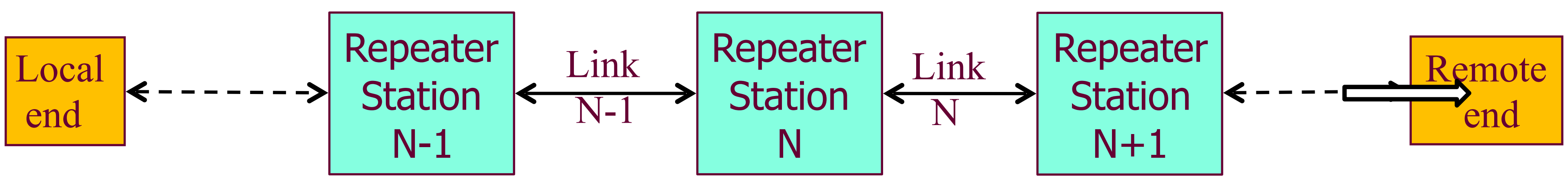


- Amplify opposite to pump with narrow bandwidth (10 MHz)
- Small signal gains up to 60 dB
- Amplifier spacing up to 250 km: demonstration of a 480-km link with one FBA
- Brillouin amplification supports 1×10^{-20} uncertainty (demonstration over 1400 km of underground fiber)

Raupach et al, PRA2015, Raupach et al, OE 2014, Terra et al, OE 2010

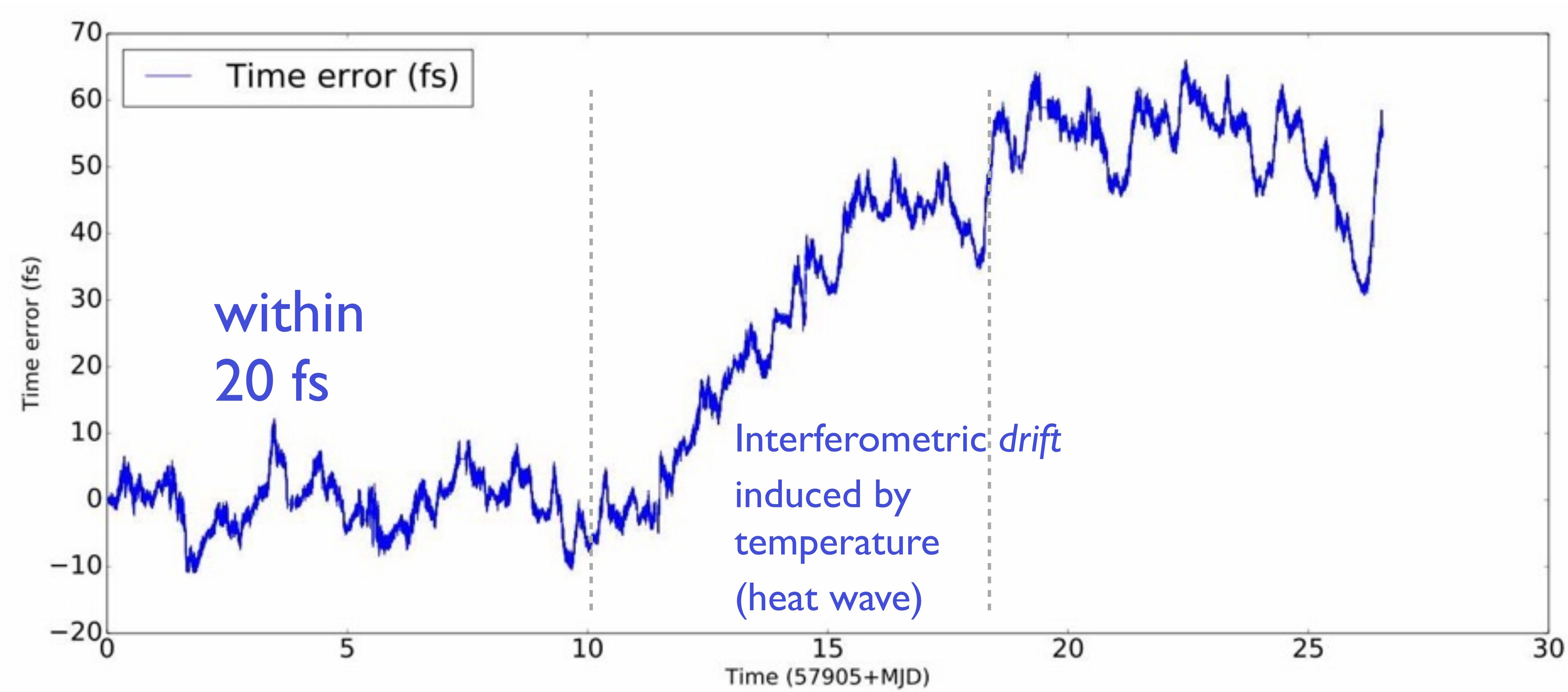
Cascaded links

- Multi-segments approach :
  - Link is divided into a few segments, depending on noise and losses
  - → shorter delay
  - → larger bandwidth and better noise rejection
- Repeater stations are needed :
  - Repeater station N : send back signal to station N-1, amplify and filter, correct the noise of next link N



Repeater laser station commercially available
F.Guillou-Camargo et al, Appl. Opt., AO 57, 7203–7210 (2018).

Last results with cascaded links (1420 km, 4 cascades)

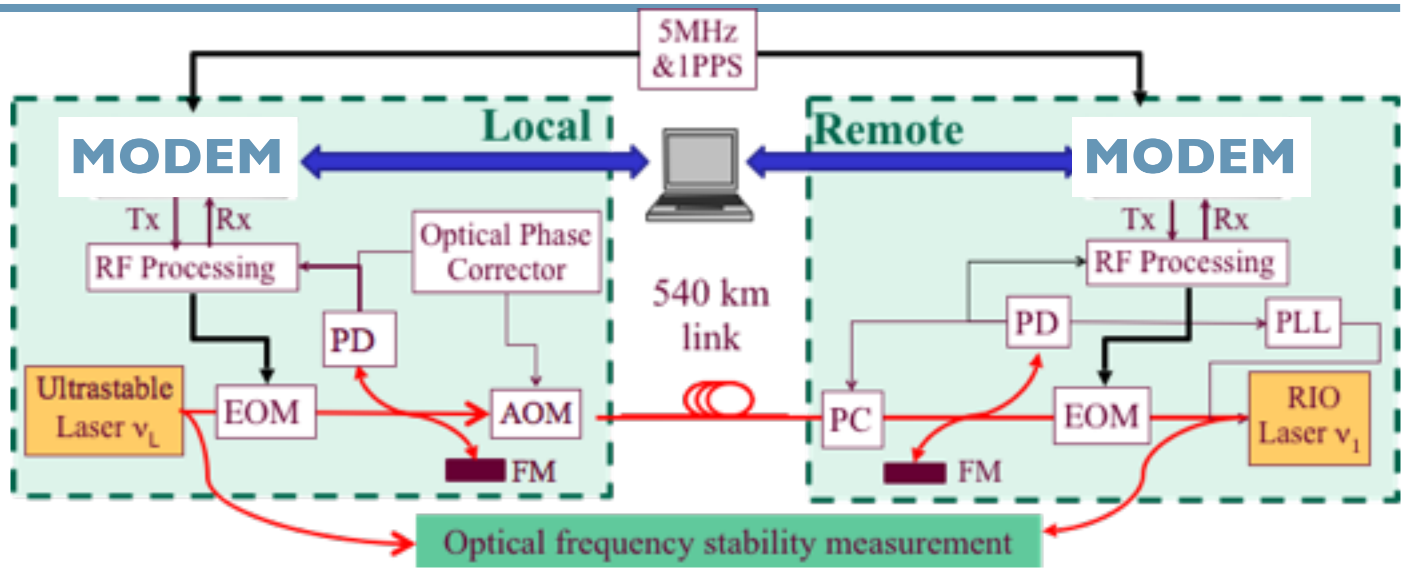


Corresponds to 5 10^{-20} @ 500 000 s integration time

Optical time transfer

Amplitude or Phase modulation of the optical carrier

O.Lopez, et al. Applied Physics B 110, 3–6 (2013).

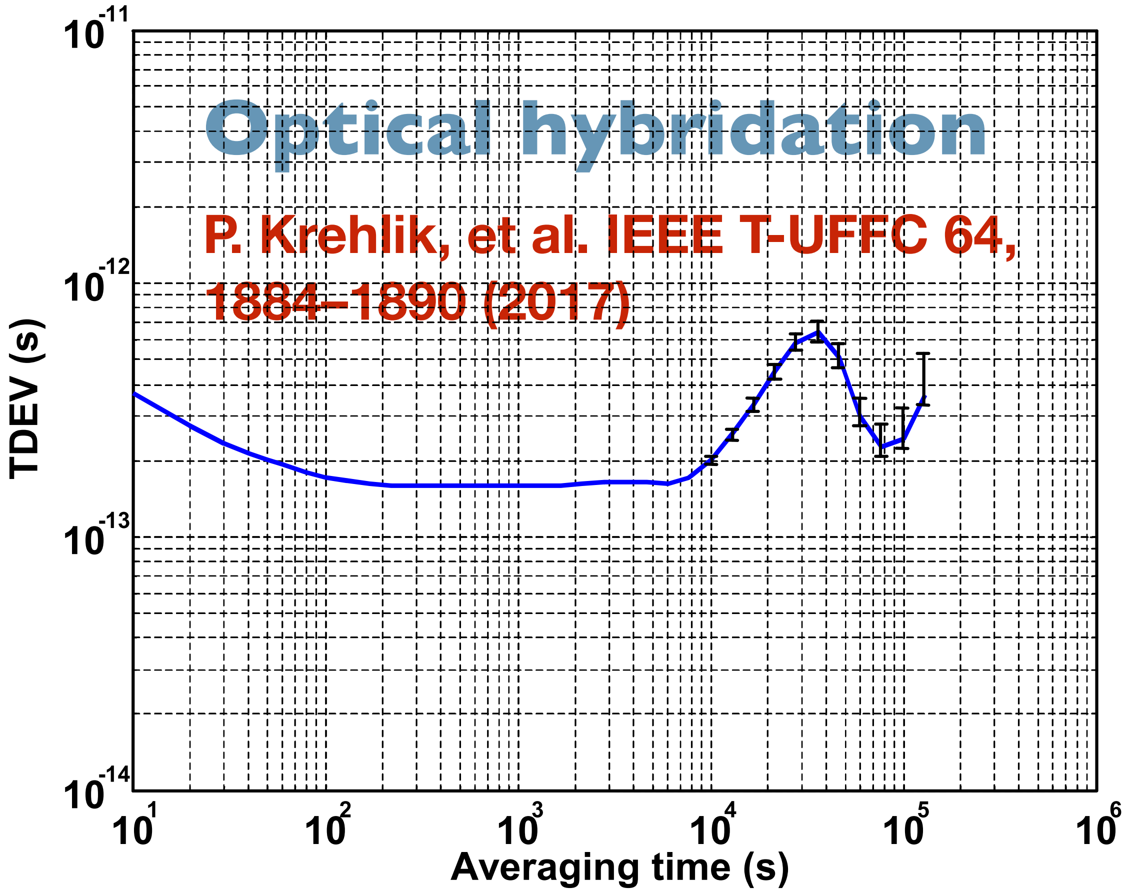


Optical demodulation

F. Frank, et al. IEEE T-UFFC 1–1 (2018)

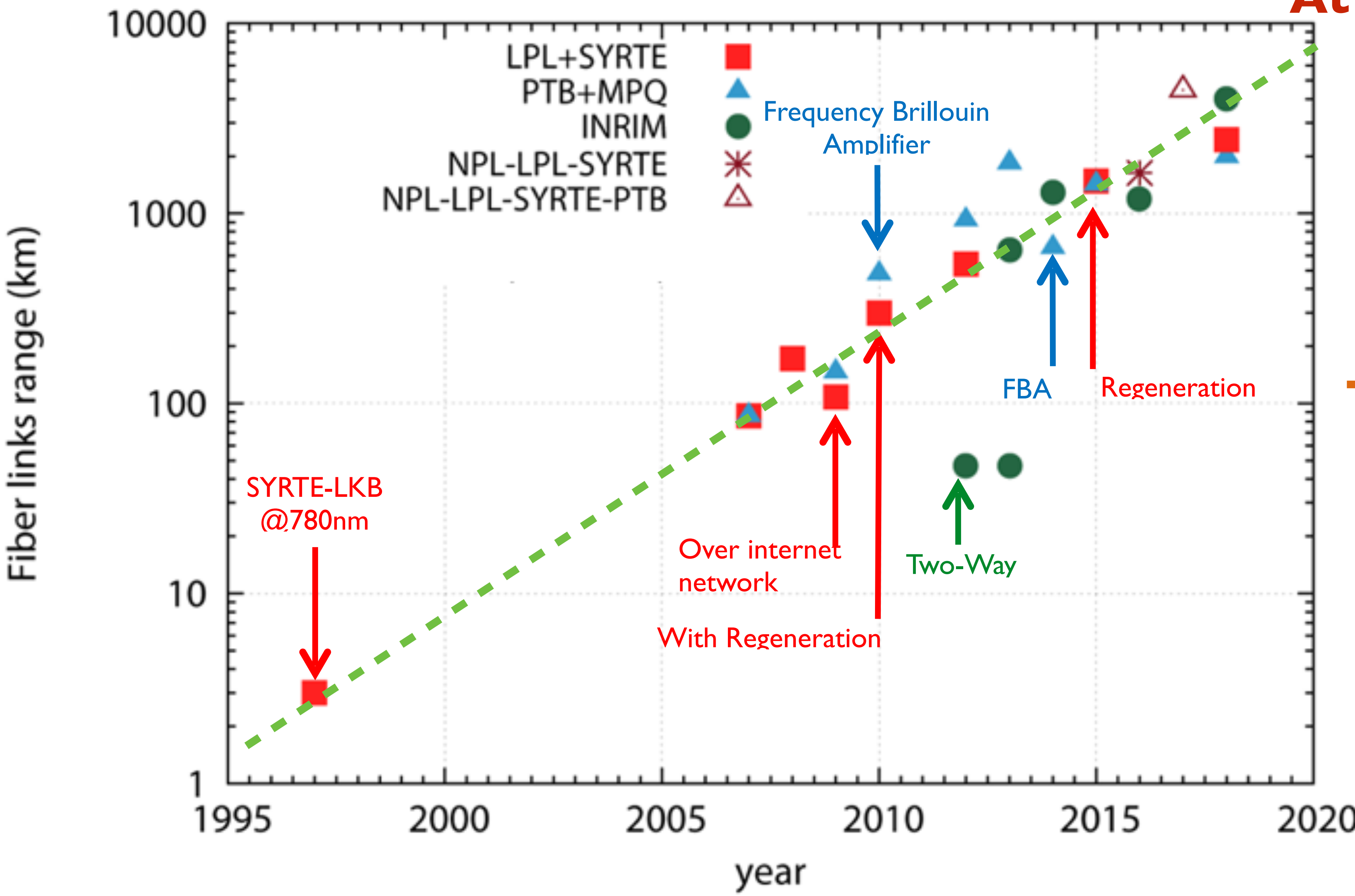
Optical hybridation

P. Krehlik, et al. IEEE T-UFFC 64, 1884–1890 (2017)



Techniques not yet as mature as frequency transfer

25 years of range improvement



At horizon 2020 : 8000 km

GÉANT
connect • communicate • collaborate

Towards a large research infrastructure ?

RENATER, CESNET, PSNC, GARR JISC/JANET, DFN, SURFNET, NORDUNET…

Future prospects

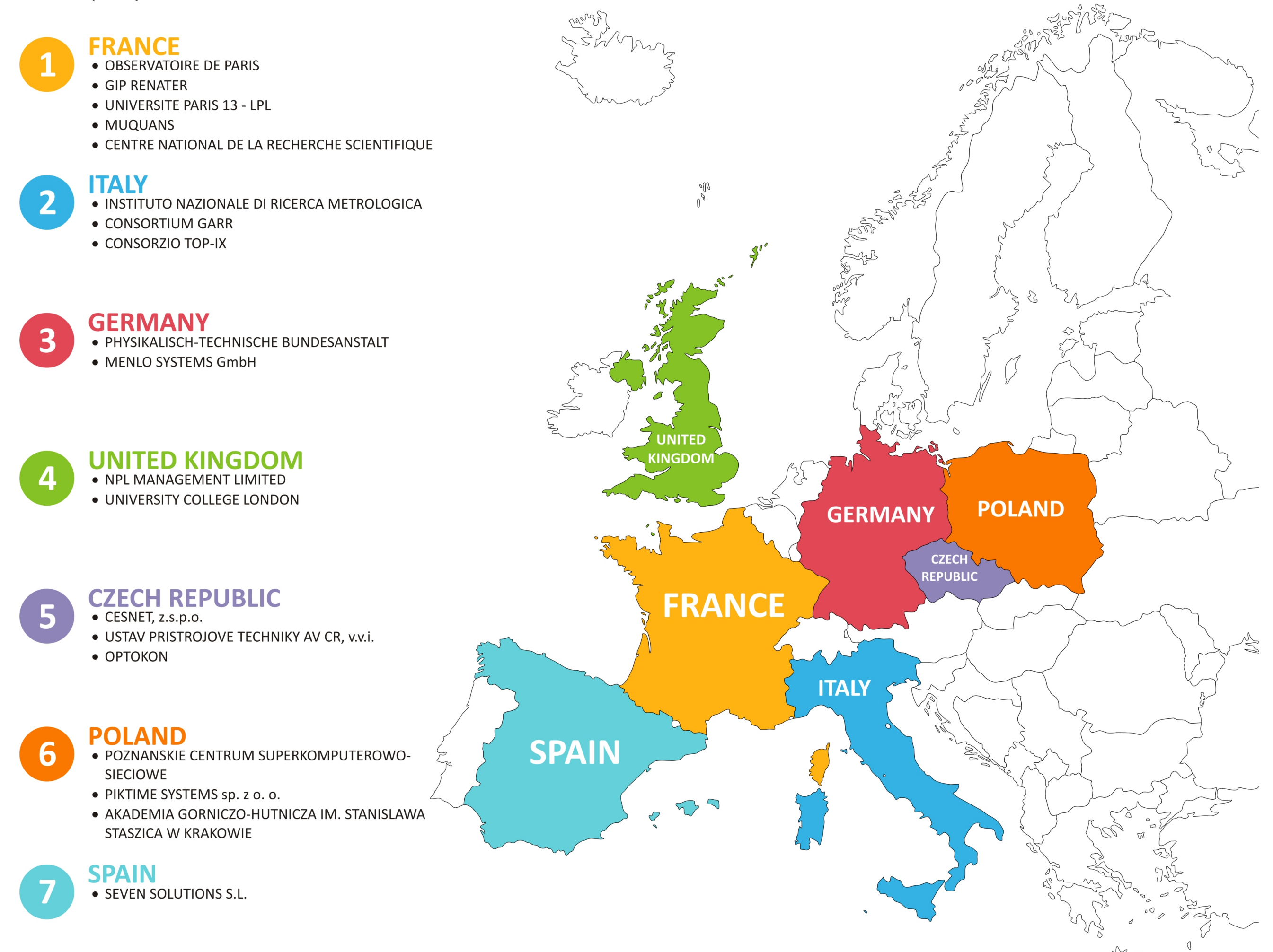
Project CLONETS involved 16 partners from 7 European countries. Partners represent 4 main areas:

- National Measurement Institutes: OBS PARIS (FR), NPL (UK), PTB (DE), INRIM (IT)
- National Research and Education Network: RENATER (FR), CESNET (CZ), PSNC (PL), GARR* (IT),
- Academic Laboratories: AGH (PL), UP13 (FR), UCL (UK), ISI (CZ), CNRS* (FR)
- Industrial: MUQUANS (FR), MENLO (DE), PIKTIME (PL), SEVEN SOL (SP), OPTOKON (CZ), TOP-IX* (IT)

Towards Research Infrastructure

- Work with Network for Education and Research Industry to make the technology available
- Ways to access the network
- Compatibility with TelCo

* Third-party member



Take away messages

- Clocks and time scales were improved by order of magnitude
- Many ways to disseminate T/F
- GNSS methods are the most widely used
- Fiber links improve by order of magnitude capabilities