Stablishment of the SIM time scale

J. M. Lopez-Romero[1], N. Diaz- Muñoz[1] and M.A. Lombardi[2]

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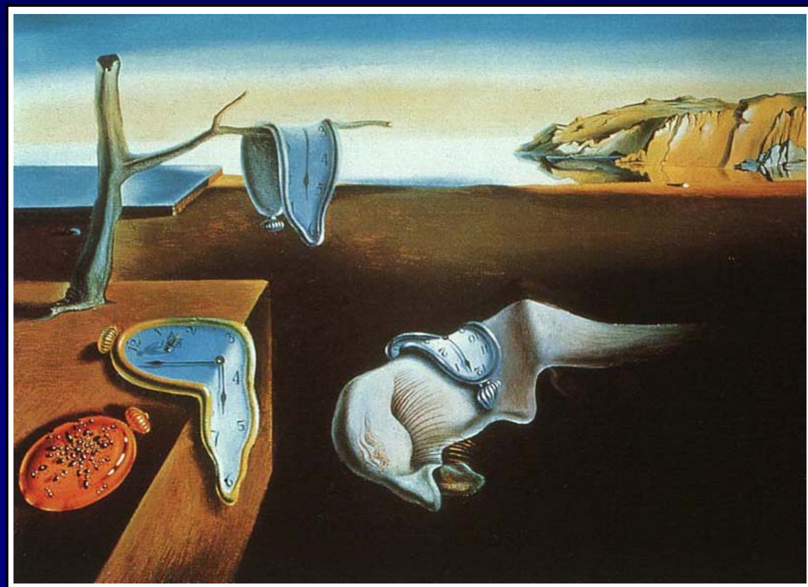

Salvador Dalí

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Outline

1. Motivation
2. Time scales
3. The SIM time and frequency comparison network
4. Preliminary results
5. Conclusions

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1. Motivation

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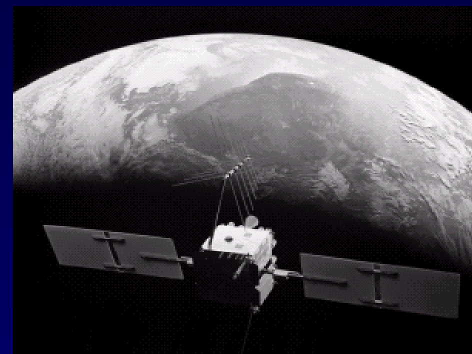
Time scales

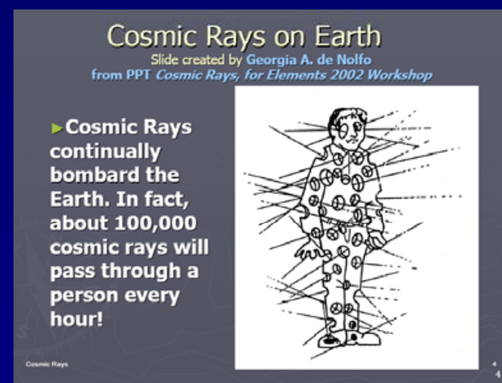
Demanding applications

Time keeping



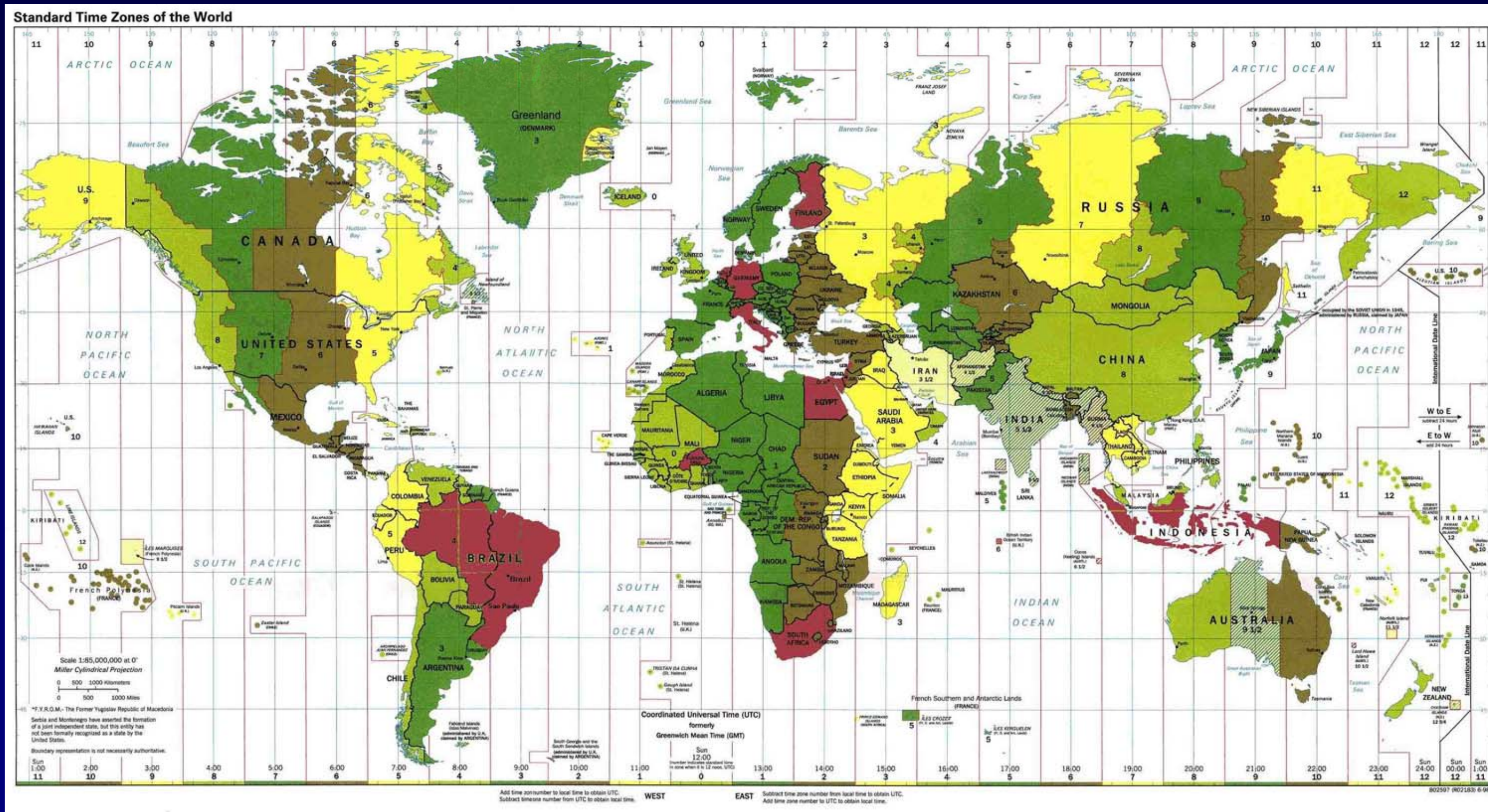
Satellite navigation systems

Telecomunications systems

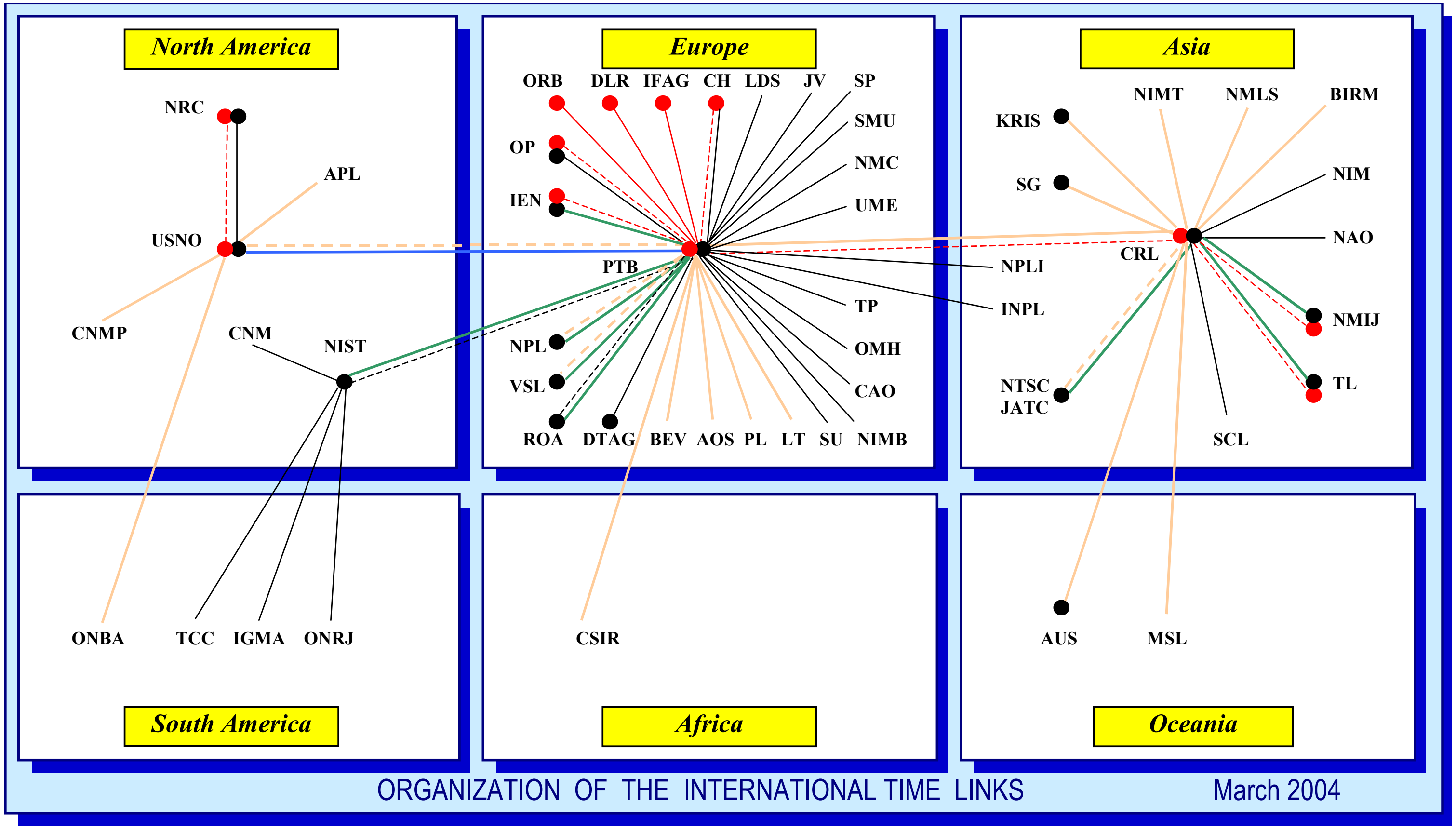


Fundamental Physics

The BIPM UTC time scale



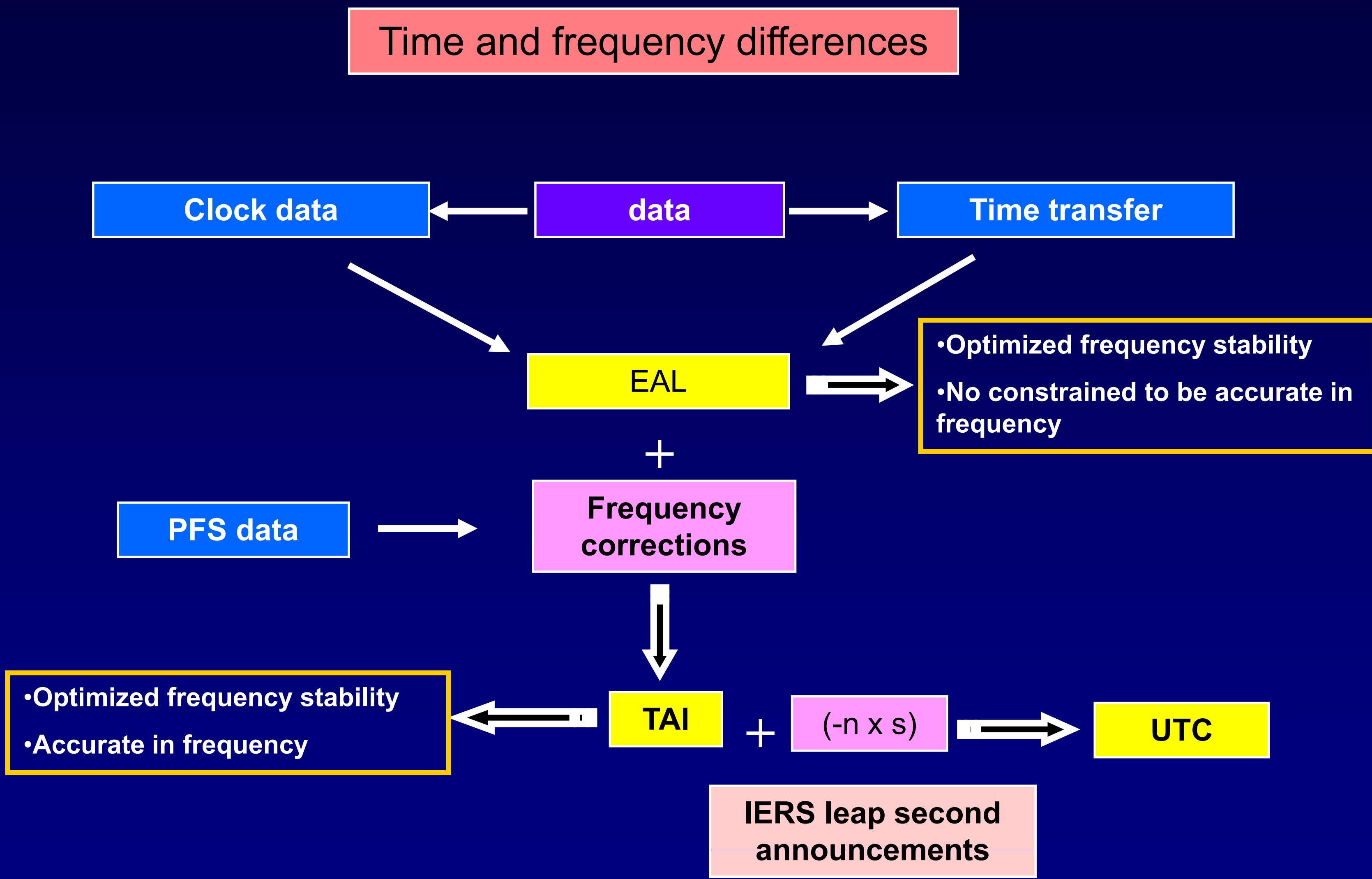
International links



Laboratory equipped with TWSTFT
TWSTFT
TWSTFT by Ku band with X band back-up
Laboratory equipped with dual frequency reception
GPS CV dual frequency link
GPS CV dual frequency back-up link
GPS CV single-channel link
GPS CV single-channel back-up link
GPS CV multi-channel link
GPS CV multi-channel back-up link

BIPM

TAI/UTC ALGOS (algorithm for calculation)



BIPM UTC time scale facts

- 56 participating laboratories
- Around 260 atomic cloks envolved
- 10 primary frequency standards (5 Cs)
- Stablility: 0.6×10^{-15} (de 20 a 40 días)
- Uncertainty $< 3 \times 10^{-15}$

The SIM region

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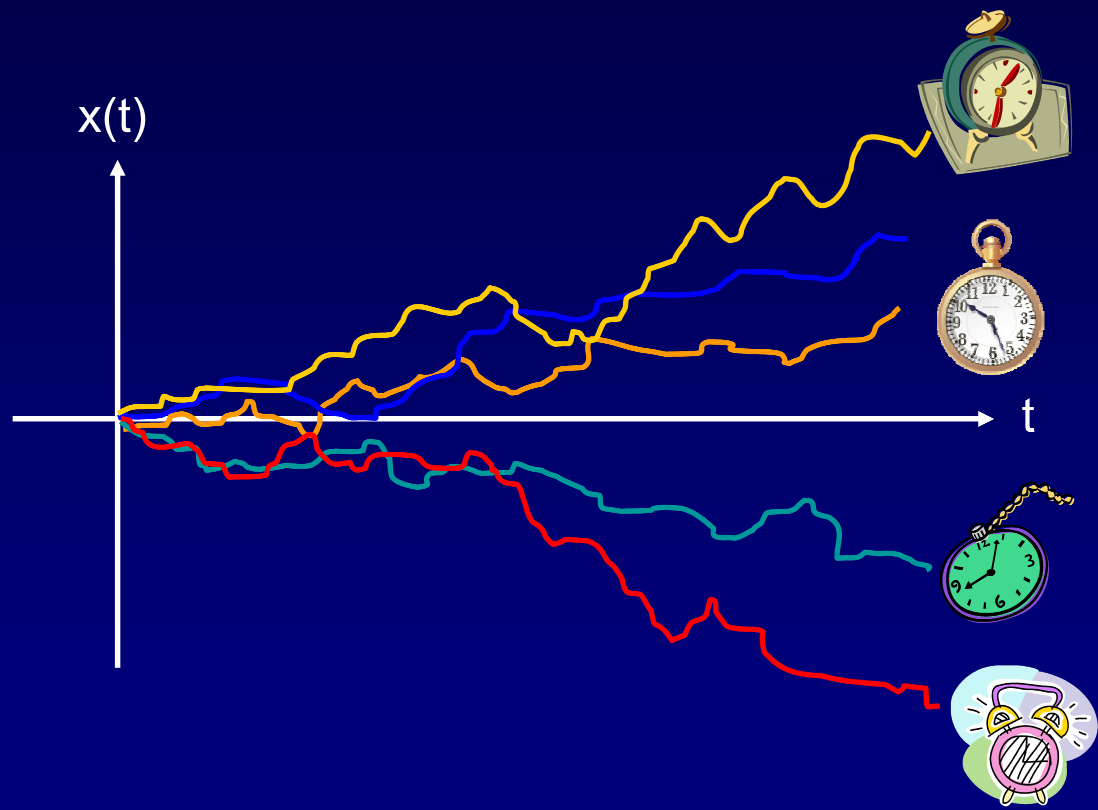
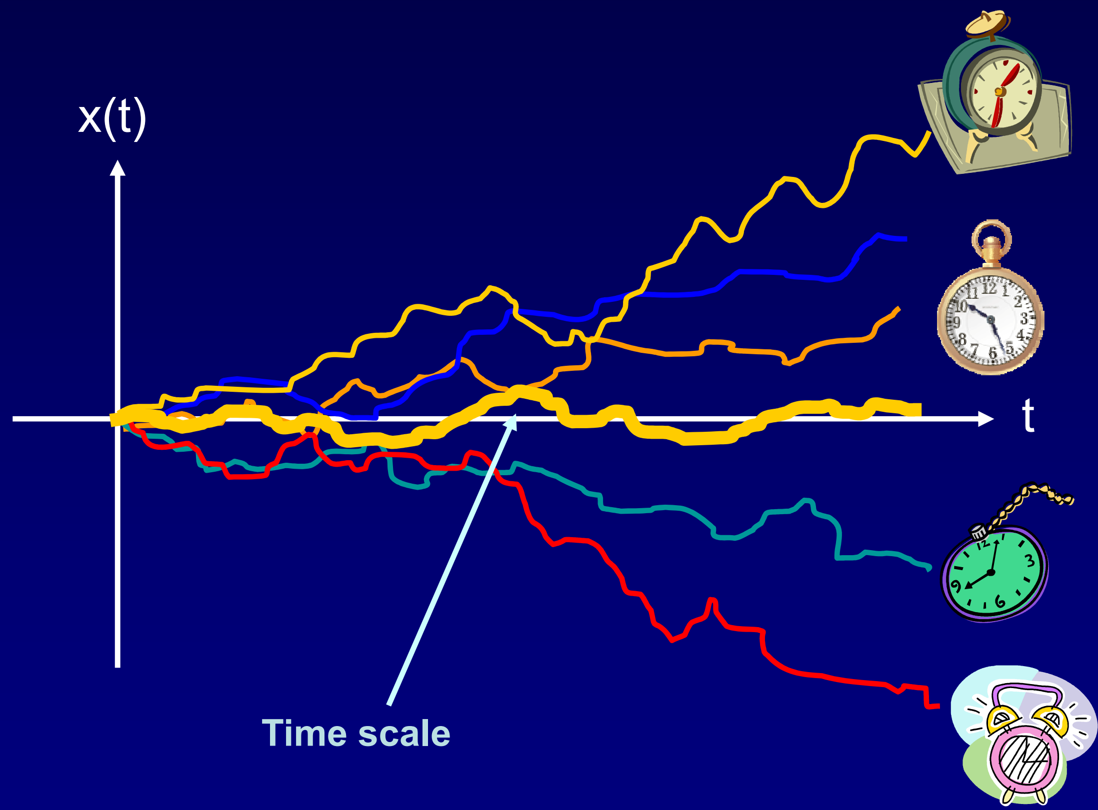
¿How to define a time scale in terms of a set (ensamble) of clocks?

Averaged time scale concept



Averaged time scale concept



Mathematical model for a clock

Frequency output of a clock: $V(t) = \left[V_0 + \varepsilon(t)\right]\sin\left[2\pi\upsilon_0 t + \phi(t)\right]$

Noise

Where

$$\left|\frac{\varepsilon(t)}{V_0}\right| << 1$$

$$\upsilon(t) = \upsilon_0 + \frac{1}{2\pi}\frac{d}{dt}\phi(t)$$

$$\left|\frac{1}{2\pi\upsilon_0}\frac{d}{dt}\phi(t)\right| << 1$$

Mathematical model for a clock

$$V(t) = \left[V_0 + \varepsilon(t)\right]\sin\left[2\pi\upsilon_0 t + \phi(t)\right]$$

Fractional frequency deviation

$$y(t) = \frac{\upsilon(t) - \upsilon_0}{\upsilon_0} = \frac{1}{2\pi}\frac{d}{dt}\phi(t)$$

Time deviation

$$x(t) = \frac{\phi(t)}{2\pi\upsilon_0}$$

$$y(t) = \frac{d}{dt}x(t)$$

$$\overline{y_i} = \frac{1}{\tau}\int_{t_i}^{t_i+\tau} y(t)dt = \frac{1}{\tau}\left[x(t_i + \tau) - x(t_i)\right]$$

Mathematical model for a clock

Frequency prediction

$$y(t) = y(t_0) + d_0(t - t_0) + \varepsilon(t)$$

Time prediction

$$x(t) = x(t_0) + y(t_0) \times (t - t_0) + \frac{1}{2} d_0 (t - t_0)^2 + \psi(t)$$

Mathematical model for a time scale

1 clock case

If h(t) is the reading of a clock at the time t then the most simple time scale *TA* can be defined by the relation

$$TA(t) = h(t)$$

$$\Downarrow$$

$$TA(t) - h(t) = 0$$

Mathematical model for a time scale

2 clocks case

$$TA(t) = \frac{1}{2}\left(h_1(t) + h_2(t)\right)$$

$$\Downarrow$$

$$TA(t) - \left[\frac{1}{2}\left(h_1(t) + h_2(t)\right)\right] = 0$$

$$\Downarrow$$

$$\sum_{i=1}^{2}\left[TA(t) - h_i(t)\right] = 0$$

Mathematical model for a time scale

N clocks case

$$TA(t) = \frac{1}{N}\sum_{i=1}^{N} h_i(t)$$

$$TA(t) - \frac{1}{N}\sum_{i=1}^{N} h_i(t) = 0$$

$$\sum_{i=1}^{N}\left[TA(t) - h_i(t)\right] = 0$$

Mathematical model for a time scale

N clocks with different weights

$$TA(t) = \frac{1}{N}\sum_{i=1}^{N}\omega_i h_i(t) \Rightarrow TA(t) - \frac{1}{N}\sum_{i=1}^{N}\omega_i h_i(t) = 0$$

$$\sum_{i=1}^{N}\omega_i\left[TA(t) - h_i(t)\right] = 0$$

With the restriction

$$\sum_{i=1}^{N}\omega_i = 1$$

Mathematical model for a time scale

N clocks with different weights

$$TA(t) = \frac{1}{N}\sum_{i=1}^{N}\omega_i h_i(t) \quad \Rightarrow \quad TA(t) - \frac{1}{N}\sum_{i=1}^{N}\omega_i h_i(t) = 0$$

$$\sum_{i=1}^{N}\omega_i\left[TA(t) - h_i(t)\right] = 0$$

With the restriction

$$\sum_{i=1}^{N}\omega_i = 1$$

Not a physical observable!!

Mathematical model for a time scale

$$TA(t) = \frac{\sum_{i=1}^{N} \omega_i h_i(t)}{\sum_{i=1}^{N} \omega_i} = \frac{\sum_{i=1}^{N} \frac{1}{\sigma_i(\tau)} h_i(t)}{\sum_{i=1}^{N} \frac{1}{\sigma_i(\tau)}}$$

Mathematical model for a time scale

$$TA(t) = \frac{\sum_{i=1}^{N} \omega_i h_i(t)}{\sum_{i=1}^{N} \omega_i} = \frac{\sum_{i=1}^{N} \frac{1}{\sigma_i(\tau)} h_i(t)}{\sum_{i=1}^{N} \frac{1}{\sigma_i(\tau)}}$$

!!??

Mathematical model for a time scale

$$TA(t) = \frac{\sum_{i=1}^{N} \omega_i h_i(t)}{\sum_{i=1}^{N} \omega_i} = \frac{\sum_{i=1}^{N} \frac{1}{\sigma_i(\tau)} h_i(t)}{\sum_{i=1}^{N} \frac{1}{\sigma_i(\tau)}}$$

Only time difference between clocks is an physical observable

$$x_{ij}(t) = h_j(t) - h_i(t) \longleftarrow \text{Time difference between clock j and clock i}$$

Clock k and *TA* time scale difference is given by the relation:

$$x_k(t) = TA(t) - h_k(t)$$

Mathematical model for a time scale

$$TA(t) = \frac{\sum_{i=1}^{N} \omega_i h_i(t)}{\sum_{i=1}^{N} \omega_i}$$

$$TA(t) - h_k = \frac{\sum_{i=1}^{N} \omega_i \left[h_i(t) - h_k(t)\right]}{\sum_{i=1}^{N} \omega_i}$$

$$x_k(t) = \frac{\sum_{i=1}^{N} \omega_i x_{ki}(t)}{\sum_{i=1}^{N} \omega_i}$$

$$x_k(t) = \sum_{i=1}^{N} \omega_i x_{ki}(t)$$

Mathematical model for a time scale

$$x_k(t) = \sum_{i=1}^{N} \omega_i x_{ki}(t)$$

$$\hat{X}_k(t+\tau) = X_k(t) + \left[Y_k(t) + \frac{D_k \tau}{2} \right] \tau$$

$$X_k(t+\tau) = \sum_{j=1}^{N} w_j \left[\hat{X}_j(t+\tau) - X_{jk}(t+\tau) \right]$$

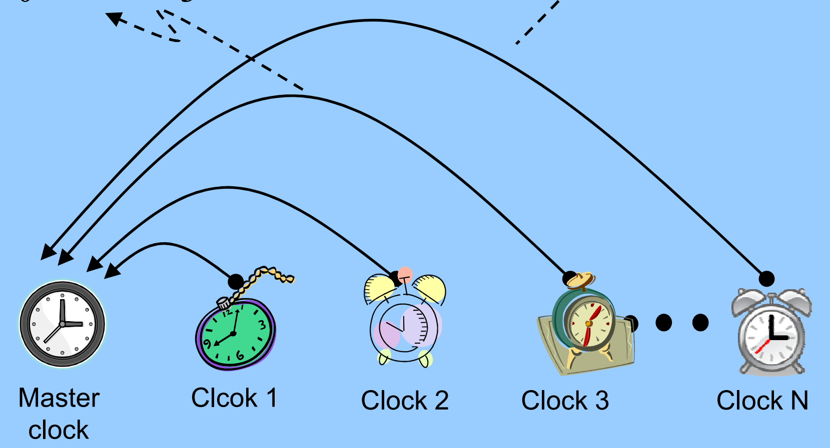
$$\hat{Y}_k(t+\tau) = \frac{X_k(t+\tau) - X_k(t)}{\tau}$$

$$Y_k(t+\tau) = \frac{\hat{Y}_k(t+\tau) + m_k Y_k(t)}{1 + m_k}$$

Experimental set up

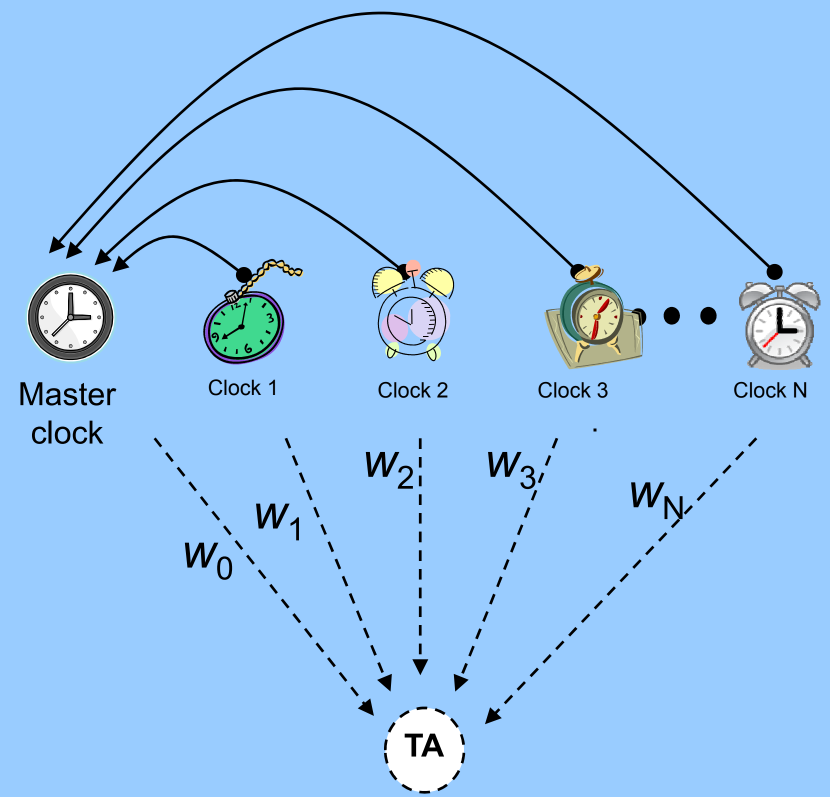
$$x_{N0}(t) = h_0(t) - h_N(t)$$

$$x_{30}(t) = h_0(t) - h_3(t)$$



$$x_{ij}(t) = h_j(t) - h_i(t) = \left[h_0(t) - h_i(t)\right] - \left[h_0(t) - h_j(t)\right]$$

Experimental set up



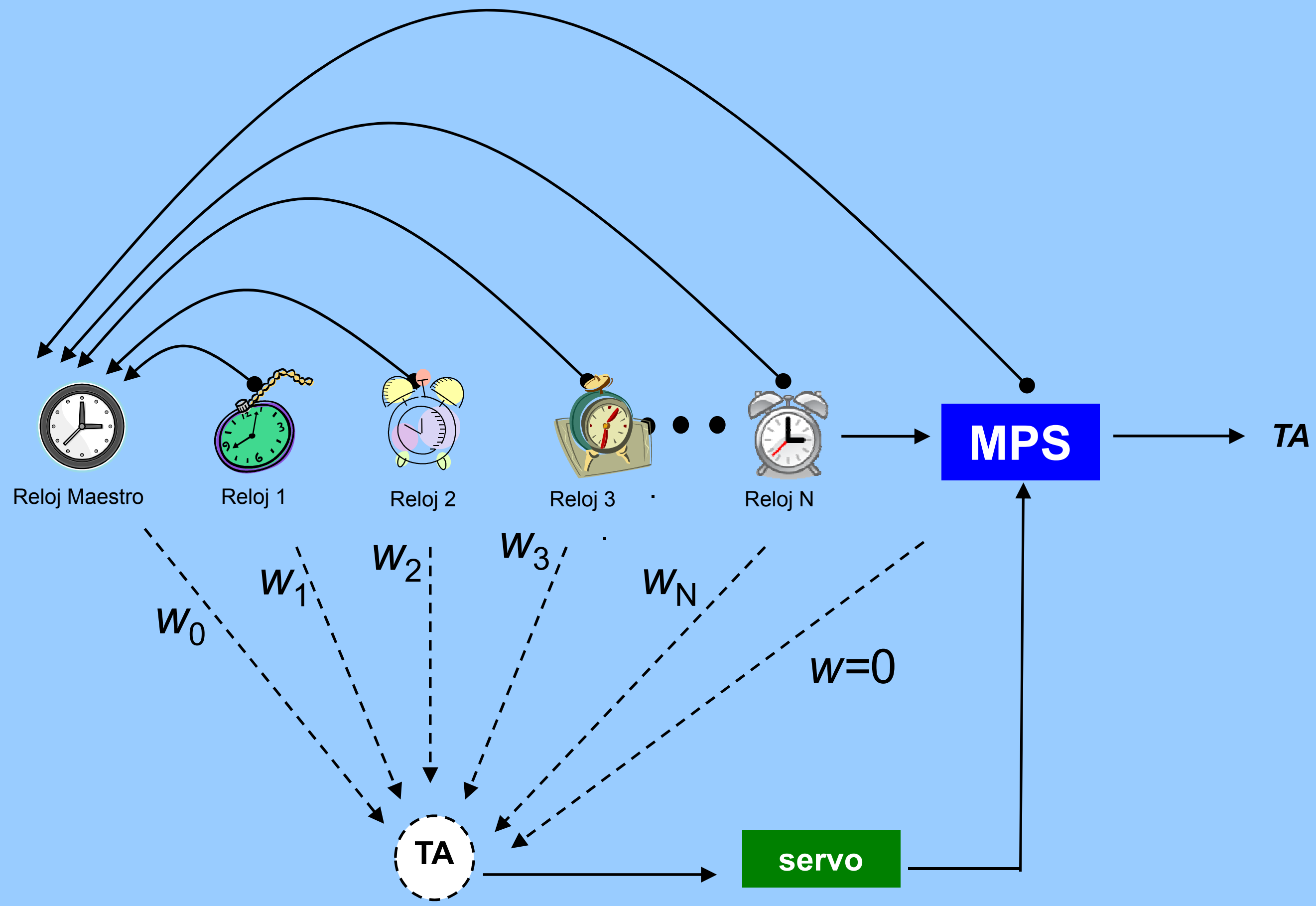
$$\hat{X}_i(t+\tau) = X_i(t) + \left[Y_i(t) + \frac{D_i\tau}{2}\right]\tau$$

$$X_i(t+\tau) = \sum_{j=1}^{N} w_j\left[\hat{X}_j(t+\tau) - X_{ji}(t+\tau)\right]$$

$$\hat{Y}_i(t+\tau) = \frac{X_i(t+\tau) - X_i(t)}{\tau}$$

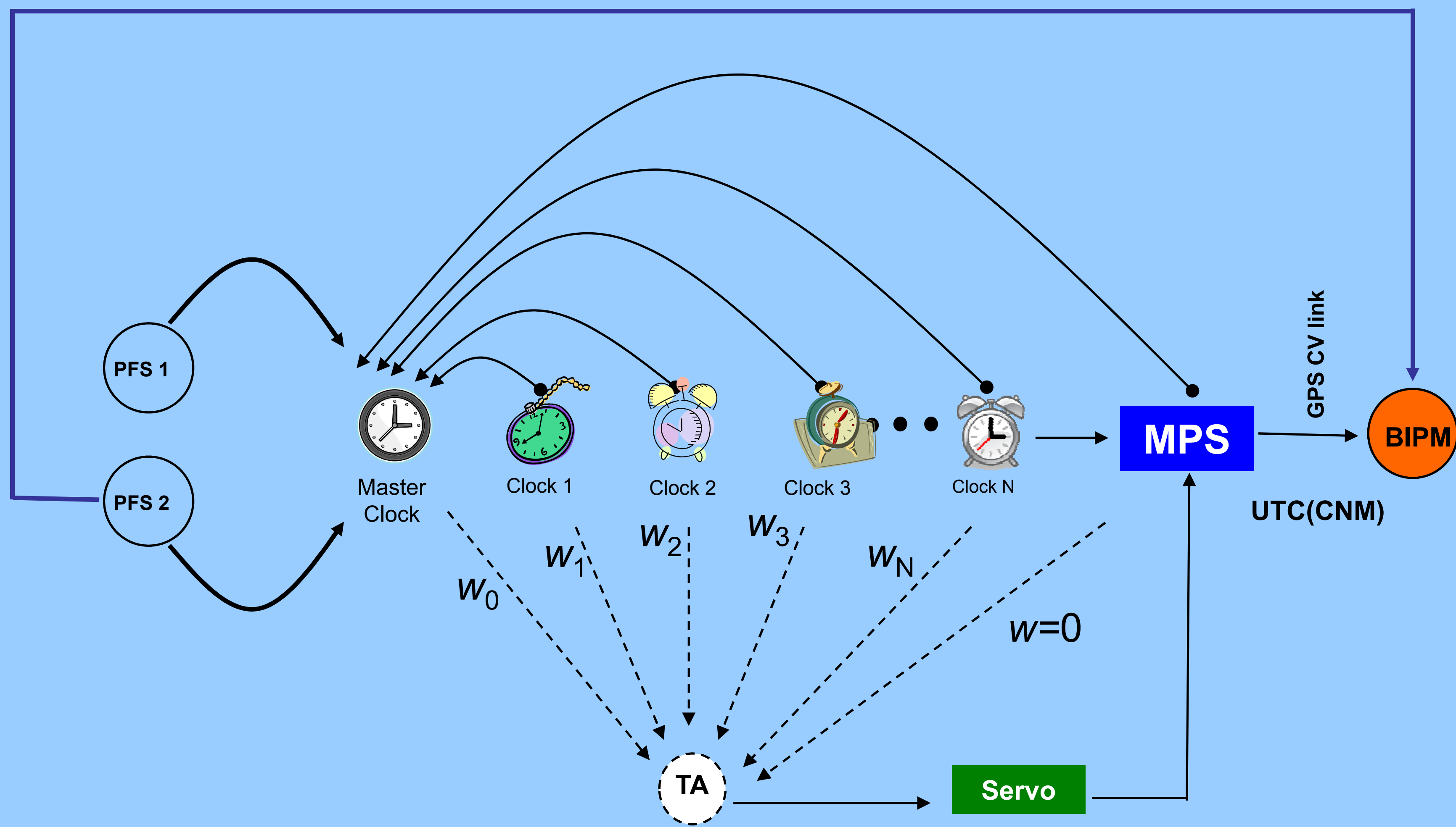
$$Y_i(t+\tau) = \frac{\hat{Y}_i(t+\tau) + m_i Y_i(t)}{1+m_i}$$

Experimental set up



Experimental set up to transform a virtual *TA* time scale into a real *TA* time scale

Esquema completo de generación del UTC(CNM)



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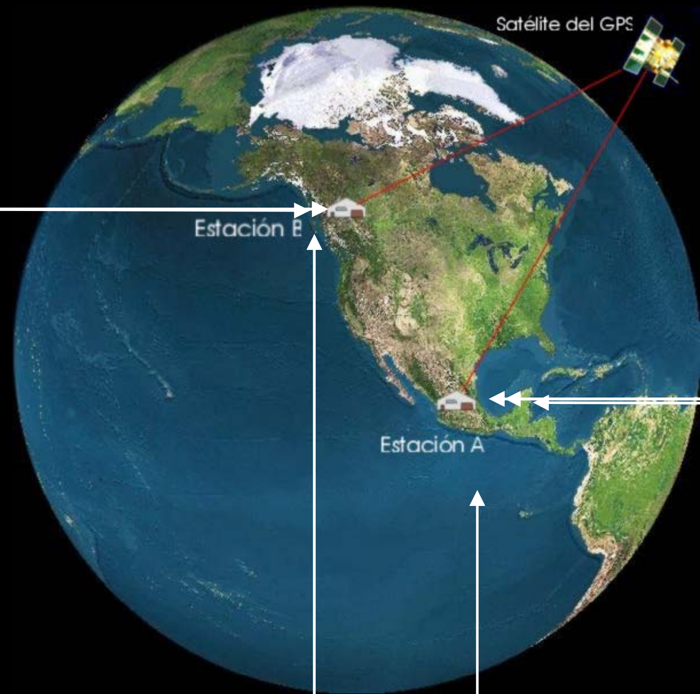
Common view method of the GPS

GPS-B receiver

Clock B

$\Delta t_B = t_B - t_{GPS} \pm \varepsilon_B$



GPS-A receiver

Clock A

$\Delta t_A = t_A - t_{GPS} \pm \varepsilon_A$

Common agenda to view GPS satellites

$$\Delta t_{BA} = \Delta t_B - \Delta t_A = (t_B - t_{GPS} + \varepsilon_B) - (t_A - t_{GPS} + \varepsilon_A) = t_B - t_A \pm (\varepsilon_B + \varepsilon_A)$$

NRC

NIST

CENAM

ICE

CENAMEP

SIC

ONRJ

INTI

- Around 30 Cs clocks at SIM (without the USNO)

- 10 Hydrogen Masers at SIM (without the USNO)

-12 SIM laboratories participating on the SIM TF Network (Paraguay, Uruguay the latest)

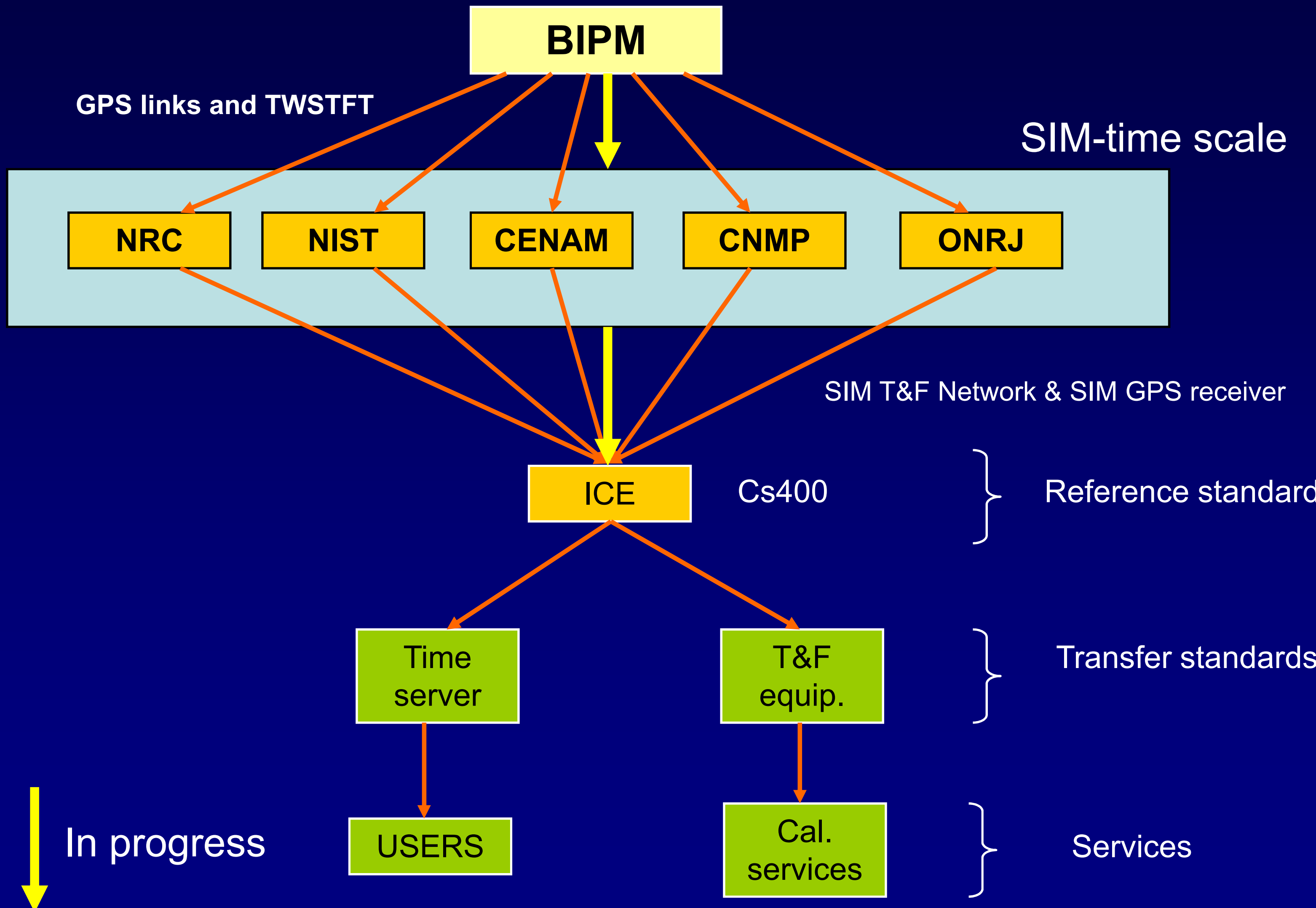
- INDECOPI (Peru) will be hopefylly added soon to the SIM TF Network

- Probably two or three more labs during 2009

Current and Future SIM Network Members.

Country	NMI	Member of SIM Network	National Standard
Argentina	INTI	Yes	Cesium
Brazil	ONRJ	Yes	Time Scale
Canada	NRC	Yes	Time Scale
Chile	INN	Future	Rubidium
Colombia	SIC	Yes	Cesium
Costa Rica	ICE	Yes	Cesium
Guatemala	LNM	Yes	Rubidium
Jamaica	BSJ	Yes	Cesium
Mexico	CENAM	Yes	Time Scale
Panama	CENAMEP	Yes	Cesium
Paraguay	INTN	Future	Rubidium
Peru	INDECOPI	Future	Rubidium
St. Lucia	SLBS	Future	Rubidium
Trinidad / Tobago	TTBS	Future	Rubidium
United States	NIST	Yes	Time Scale
Uruguay	UTE	Future	Rubidium

Obtaining traceability to the second of the SI though the SIM TF network



SIM GPS system

- Multichannel (8) GPS receiver

- SIM receiver sends data automatically to the SIM server every 10 minutes

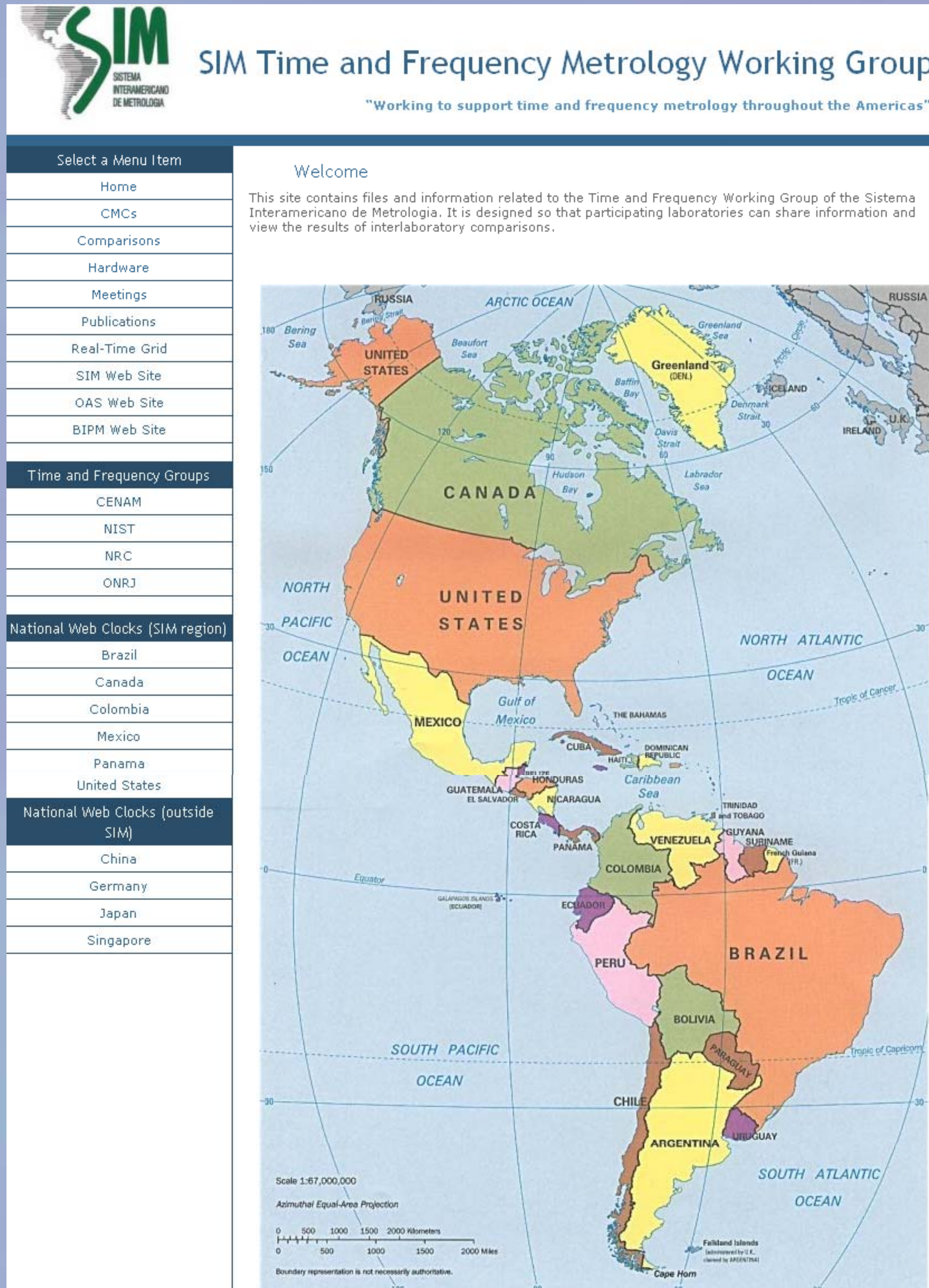
- includes SIM's own software (developed by NIST)

- Includes a PC. It is able to show common view results in near real time among participating laboratories

SIM GPS antenna

Novatel antenna

Rejects multiple reflections of the GPS signal



http://tf.nist.gov/sim/

TIME AND FREQUENCY METROLOGY WORKING GROUP

Working to support time and frequency metrology throughout the Americas

SIM Time and Frequency comparison network

SIM Time Scale Comparisons via GPS Common-View

(Table shows results for the 10-minute period ending on 07-24-2007 at 2340 UTC)

SISTEMA INTERAMERICANO DE METROLOGIA		UTC(NIST)	UTC(CNM)	UTC(NRC)	UTC(CNMP)	UTC(ONRJ)	UTC(ICE)	UTC(SIC)
	UTC(NIST)		-18.88	38.48	-122.13	-36.67	-377534824.10	-216367.87
	UTC(CNM)	18.88		57.71	-106.31	-22.83	-377534808.93	-216351.58
	UTC(NRC)	-38.48	-57.71		-161.76	-76.88	-377534863.94	-216407.26
	UTC(CNMP)	122.13	106.31	161.76		06.60	-377534703.62	-216245.04
	UTC(ONRJ)	36.67	22.83	76.88	-86.60		-377534785.42	-216334.37
	UTC(ICE)	377534824.10	377534808.93	377534863.94	377534703.62	377534785.42		377318454.63
	UTC(SIC)	216367.87	216351.58	216407.26	216245.84	216334.37	-377318454.63	
Last Update (HHMM UTC)		2340	2340	2340	2340	2340	2340	2340

This table was created at 07-24-2007 (MJD 54305) 23:45:47 UTC and will automatically refresh every five minutes.

Comparison between NIST and CENAM

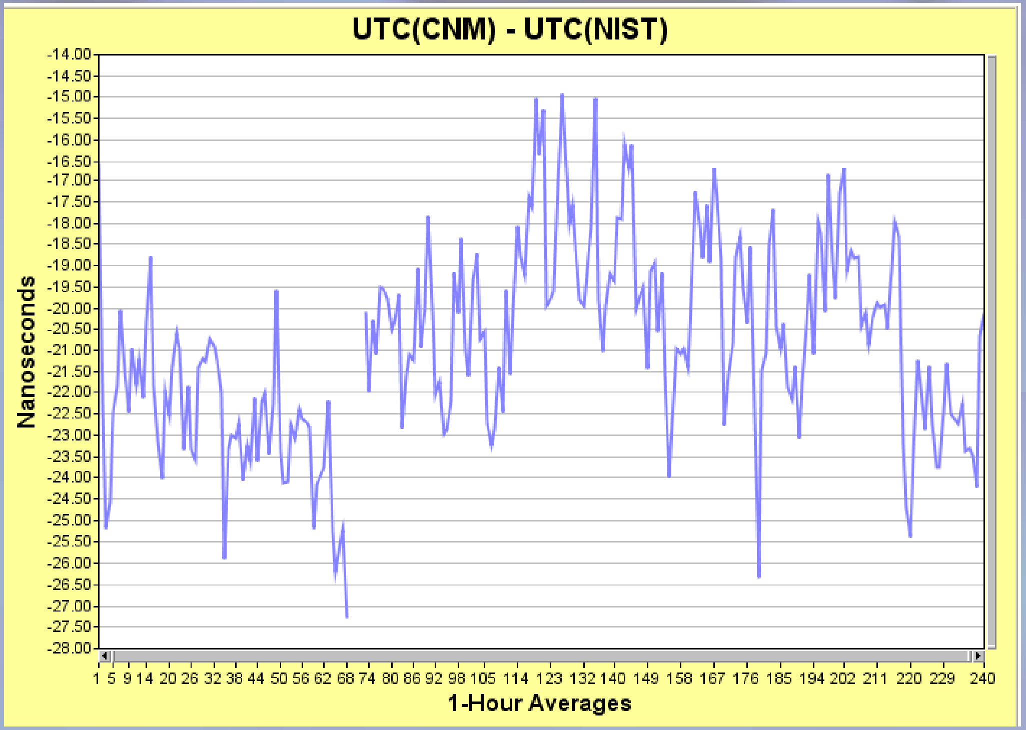
UTC(CNM) versus UTC(NIST) via Common-View GPS

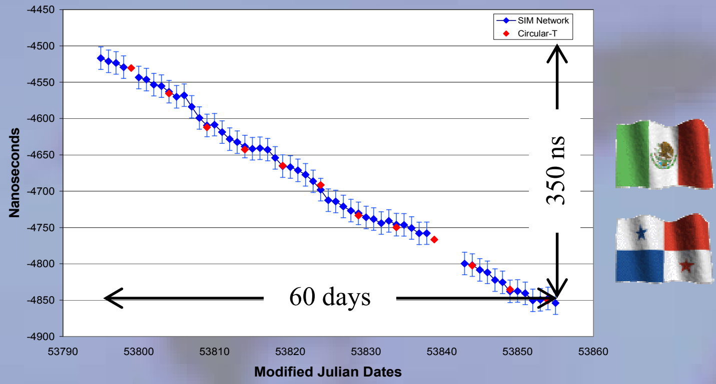
1 Day Averages | 1 Hour Averages | 10 Minute Averages | Next Date | Last Date | Flip

Laboratory 1	Centro Nacional de Metrologia	**ID Number**	007	**End Date**	2007-07-24
Latitude	20° 32 min 13.373 s N	**Counter Delay**	-0.15 ns	**Reference Source**	UTC(CNM)
Longitude	100° 15 min 17.204 s W	**REF Delay**	12.9 ns	**Mask Angle**	10°
Altitude	1917.16 m	**Receiver Delay**	55.2 ns	**Receiver Temp.**	25° C
Laboratory 2	National Institute of Standards and Technology	**ID Number**	006	**Baseline**	2198.851 km
Latitude	39° 59 min 44.494 s N	**Counter Delay**	-0.10 ns	**Reference Source**	UTC(NIST)
Longitude	105° 15 min 43.409 s W	**REF Delay**	435.4 ns	**Mask Angle**	10°
Altitude	1645.60 m	**Receiver Delay**	1.5 ns	**Receiver Temp.**	29° C

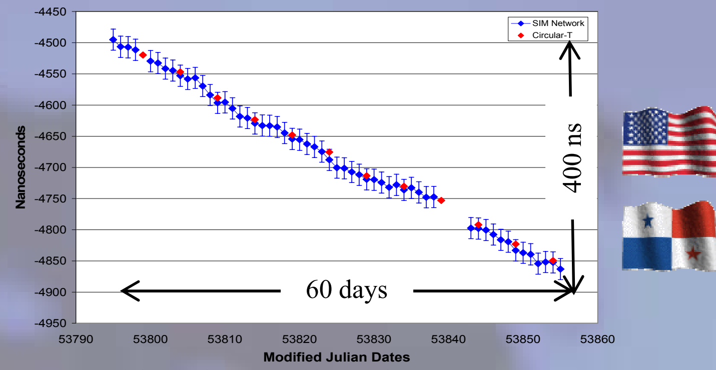
Hours in Common-View	Mean Time Offset (ns)	Range (ns)	Frequency Offset	Confidence (r)
236	-20.87	12.35	$+2.38 \times 10^{-15}$	+0.26

Comparison between NIST and CENAM

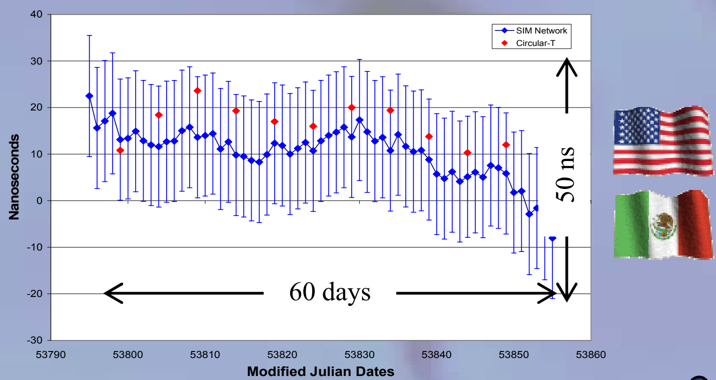




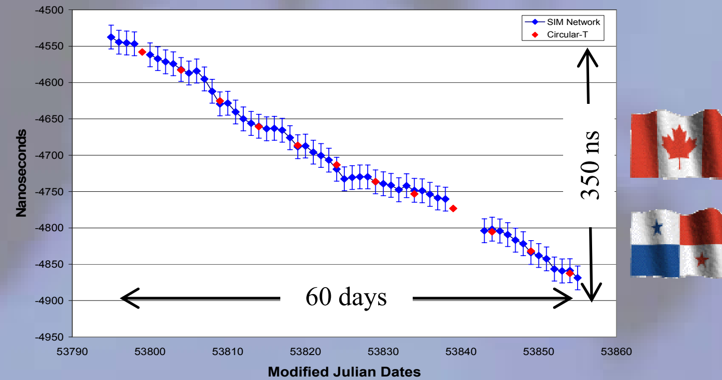
UTC(CNM) – UTC(CNMP).



UTC(NIST) – UTC(CNMP).



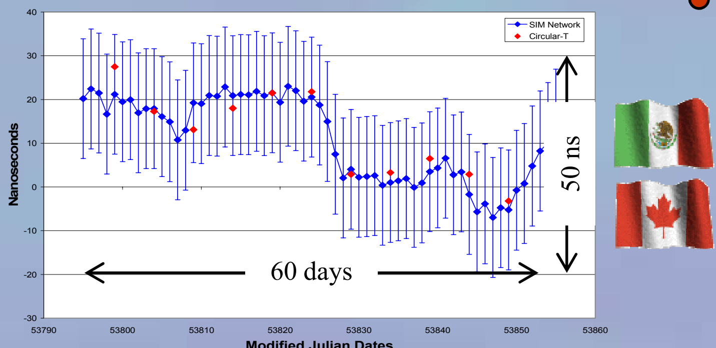
UTC(NIST) – UTC(CNM).



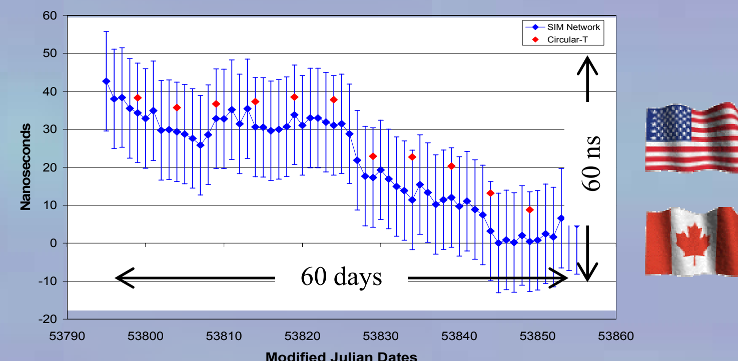
UTC(NRC) – UTC(CNMP).

● **SIM**

● **BIPM**



UTC(CNM) – UTC(NRC).



UTC(NIST) – UTC(NRC).

Summary of uncertainties (in nanoseconds) for all six comparisons (March-April 2006)

	CNM – CNMP	NIST – CNM	CNM – NRC	NIST – CNMP	NRC – CNMP	NIST – NRC
Baseline (km)	2544.0	2198.9	3520.7	4194.9	3989.0	2471.3
Mean Freq. Offset	-6.7×10^{-14}	-2.8×10^{-15}	-4.8×10^{-15}	-7.0×10^{-14}	-6.3×10^{-14}	-7.7×10^{-15}
Mean Time Offset	–4690.4	+10.3	+11.0	–4680.7	–4702.8	+21.2
U_A, $\sigma_x(\tau)$	1.8	1.2	1.4	1.5	1.5	1
U_B, Calibration	4	4	4	4	4	4
U_B, Coordinates	3	3	3	3	3	3
U_B, Environment	3	3	3	3	3	3
U_B, Multipath	2	2	2	2	2	2
U_B, Ionosphere	2	1.5	2.5	3	3	1.5
U_B, Ref. delay	0.5	0.5	0.5	0.5	0.5	0.5
U_B, Resolution	0.05	0.05	0.05	0.05	0.05	0.05
U_C, $k = 2$	*13.5*	*13.1*	*13.5*	*14.0*	*14.0*	*12.9*

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SIM Time and Frequency comparison network and SIM-time scale generation

Time scale Algorithm

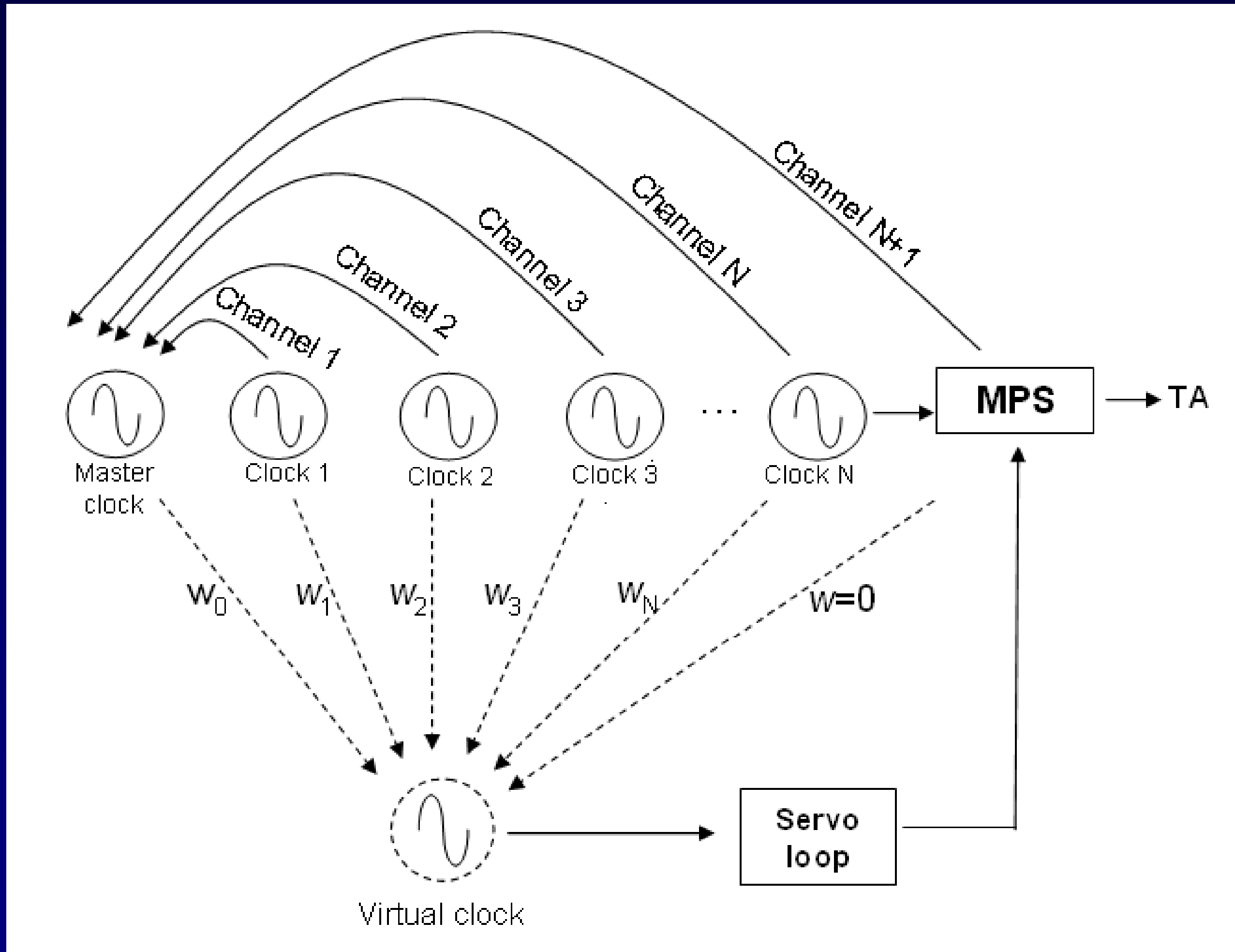
$$\hat{X}_i(t+\tau) = X_i(t) + \left[Y_i(t) + \frac{D_i\tau}{2}\right]\tau$$

$$X_i(t+\tau) = \sum_{j=1}^{N} w_j \left[\hat{X}_j(t+\tau) - X_{ji}(t+\tau)\right]$$

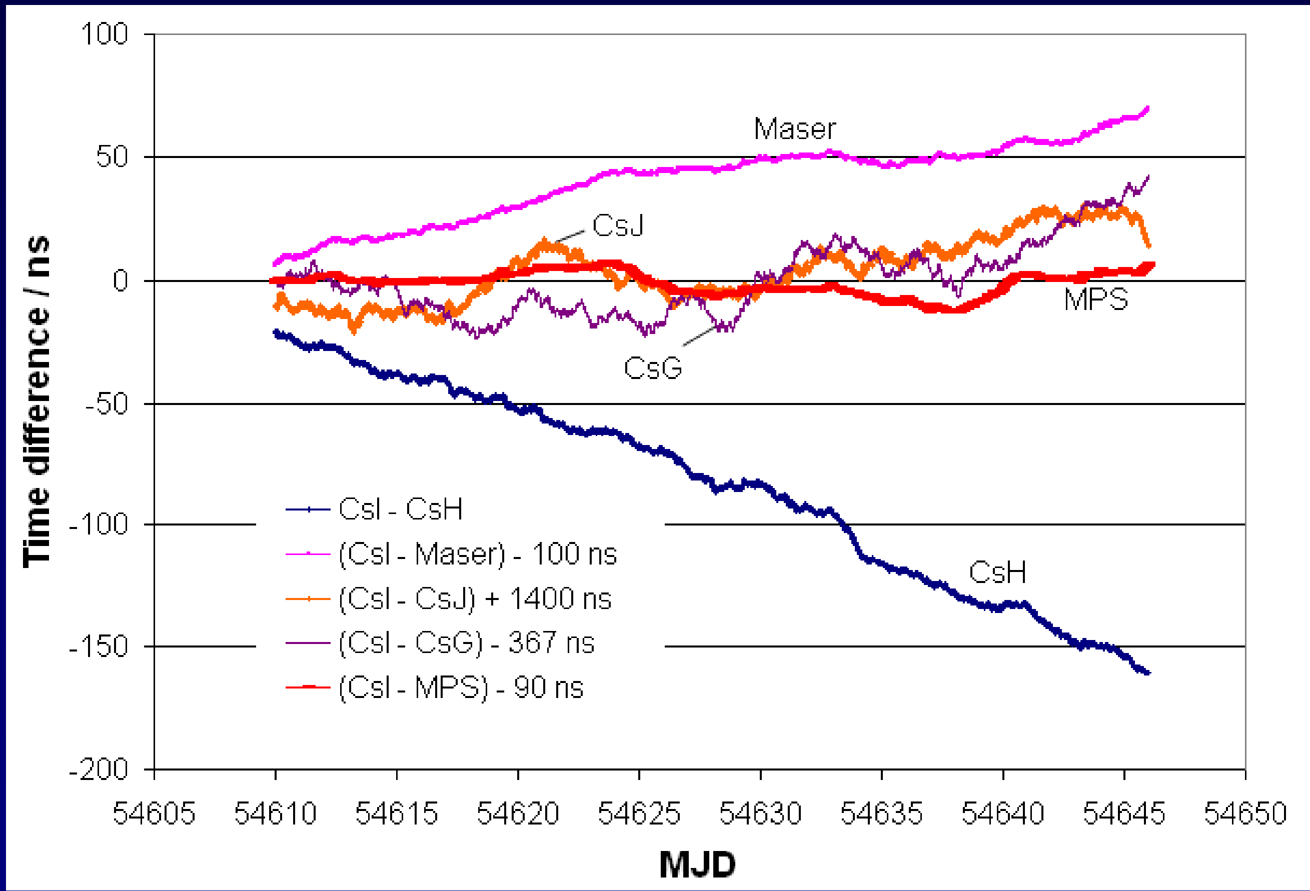
$$\hat{Y}_i(t+\tau) = \frac{X_i(t+\tau) - X_i(t)}{\tau}$$

$$Y_i(t+\tau) = \frac{\hat{Y}_i(t+\tau) + m_i Y_i(t)}{1+m_i}$$

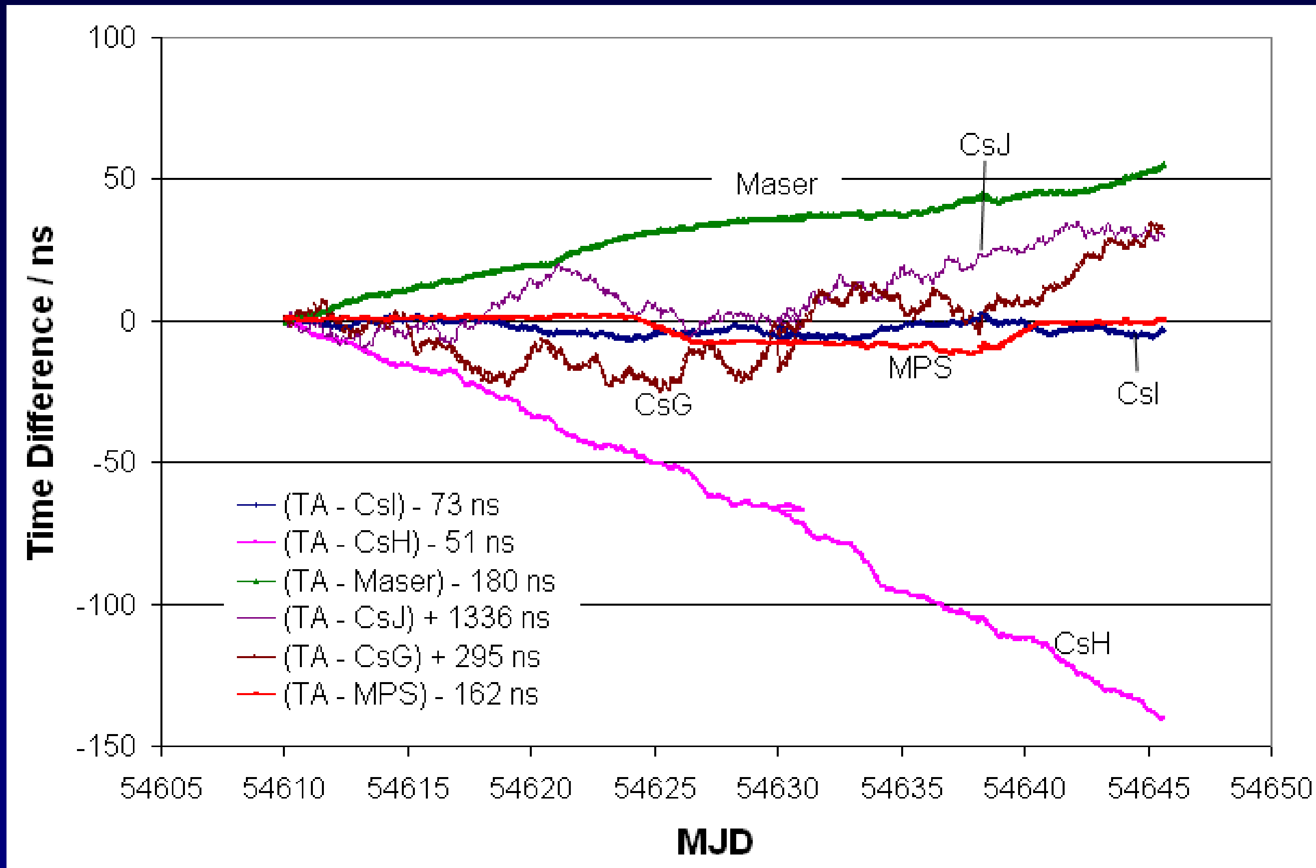
SIM-time scale generation: Preliminary results



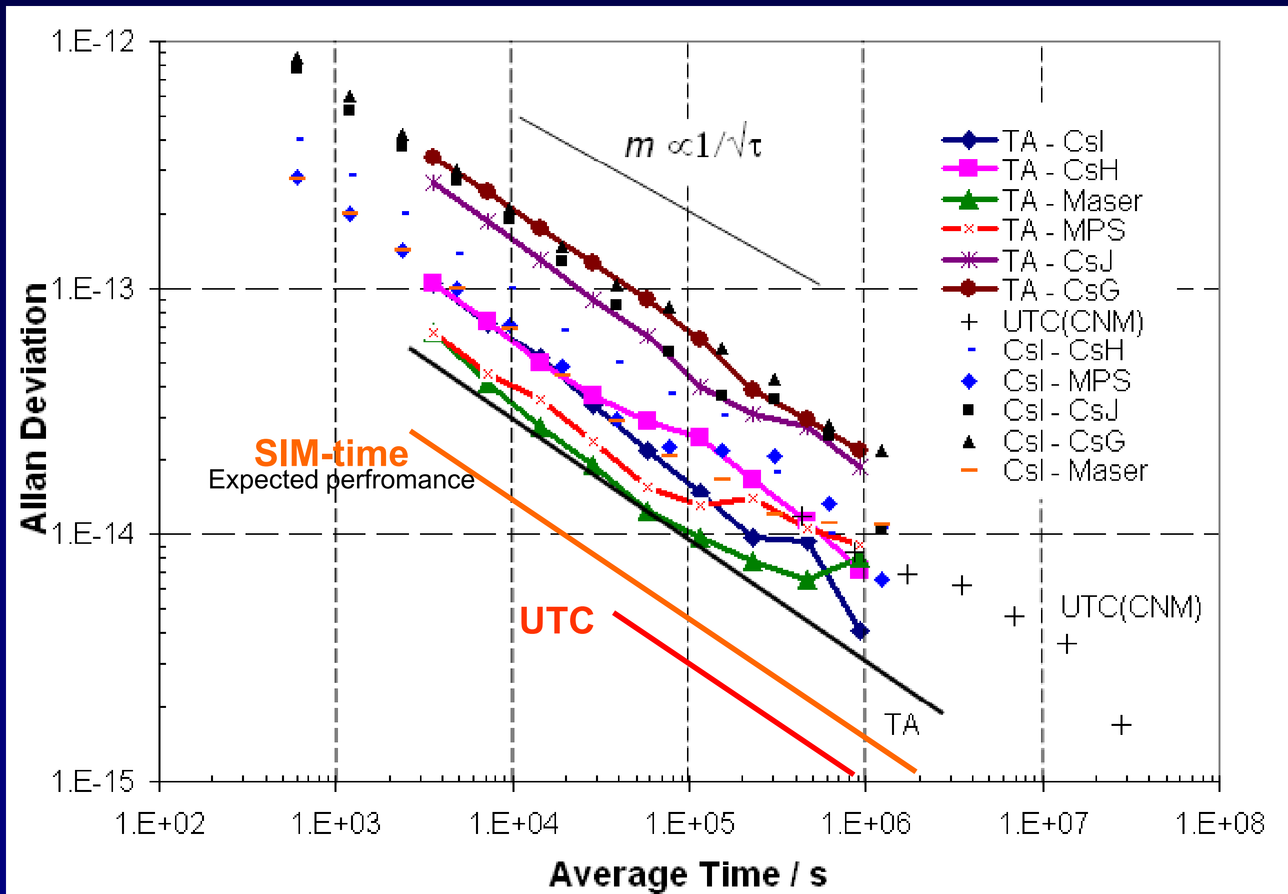
SIM-time scale generation: Preliminary results



SIM-time scale generation: Preliminary results



SIM-time scale: first time scale in the world generated with the contribution of several nations in real time



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Conclusions

1. The SIM Time and frequency comparison network has currently 11 SIM laboratories under continuous comparison in real time

2. CENAM has developed a time scale algorithm and generating a averaged time scale since march 2008. Results are in agreement with the expected performance

3. The SIM time scale algorithm will be tested by first time in January 2009 using real time data from the SIM time and frequency network

4. The SIM time scale will be the first time scale in the world generated in real time with the contribution of several nations

5. SIM probably will run 3 copies of the SIM time scale: NRC, NIST and CENAM

Thanks for your attention

Stablishment of the SIM time scale

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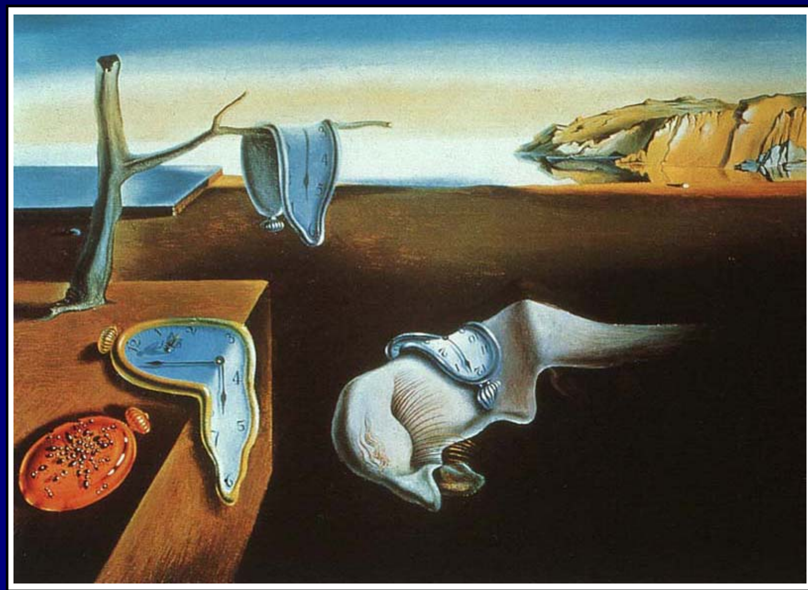

Salvador Dalí