IMPACT OF NEW FREQUENCY STANDARDS ON THE INTERNATIONAL TIME SCALES

E. F. Arias, G. Panfilo

JD 6 – Commission 31

XXVII IAU General Assembly

Rio de Janeiro (Brazil), 7 August 2009

Elements of a time scale

Minimum requisite: 1 clock

Reliable

Stable and accurate in frequency

Accessible

Algorithm

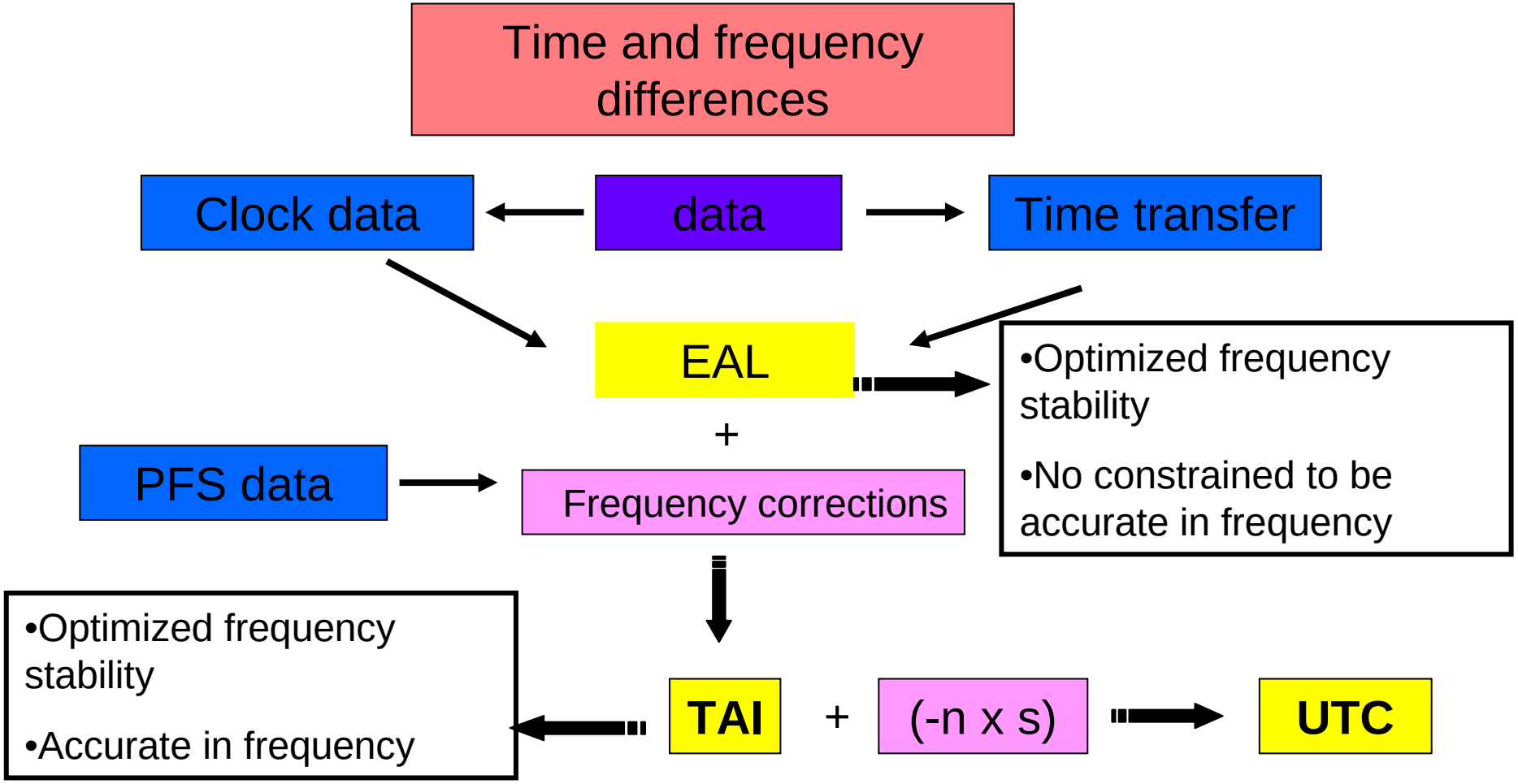
Atomic standards performances

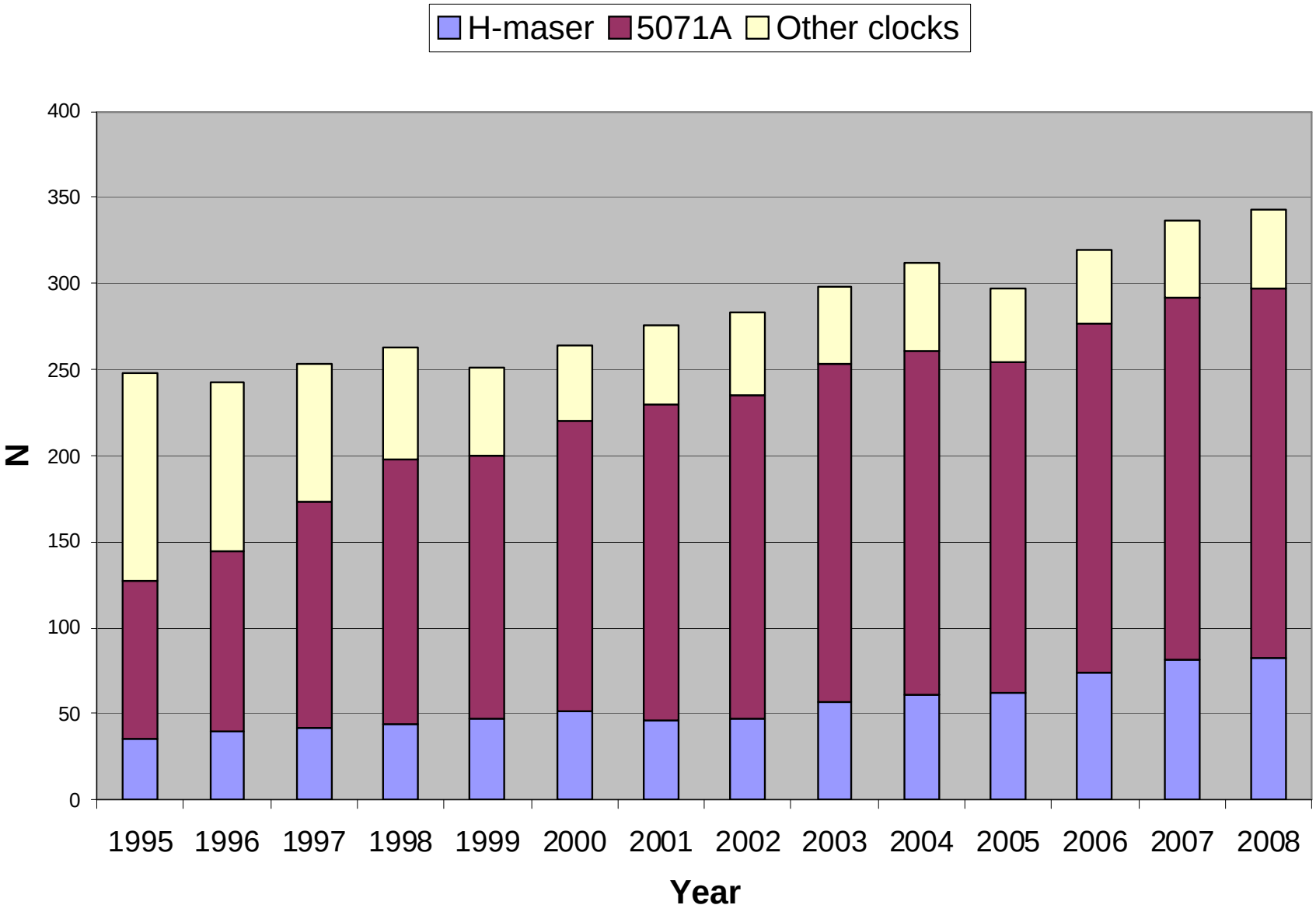
- Secondary standards

	Stability	Accuracy
Cs standard (st. tube)	5×10^{-14} @ 5 days	1×10^{-12}
Cs standard (high perf.)	1×10^{-14} @ 5 days	5×10^{-13}
H- maser (active)	$< 2 \times 10^{-16}$ @ 1 day	

- Primary standards — few 10^{-16}

Principles of calculation of UTC/TAI with the algorithm ALGOS




H-maser
5071A
Other clocks
400
350
300
250
200
150
100
50
0
N
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
Year

EAL

Weighting algorithm

Prediction algorithm

$$EAL(t) = \sum_{i=1}^{N} w_i \left[h_i(t) + h_i'(t) \right]$$

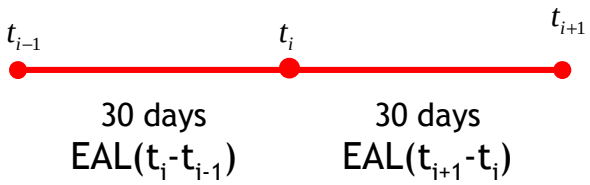
- ***N*** is the number of atomic clocks
- w_i the relative weight of the clock H_i.
- $h_i(t)$ is the reading of clock H_i at time t
- $h_i'(t)$ is the prediction of the reading of clock H_i

The weights of the clocks obey the relation:

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

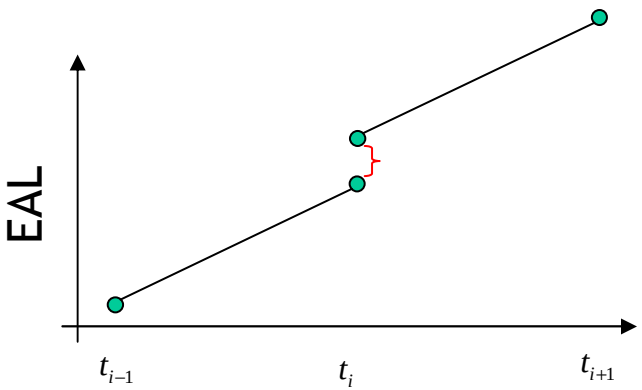
w_{max}= 2.5/N

Prediction Algorithm

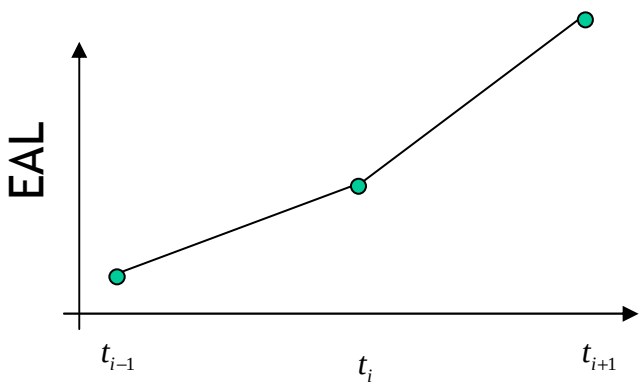


In two different intervals the clock ensemble can change

The consequences:



Time step



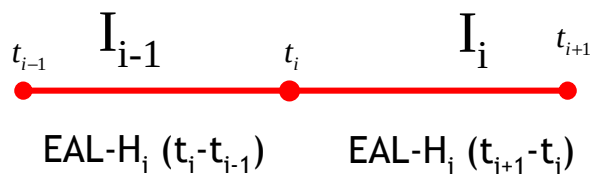
Frequency step

Prediction Algorithm on EAL

The prediction term $h_i'(t)$ for clock H_i is the sum of two terms:

Term to avoid time steps Term to avoid frequency steps

$$h_i'(t) = a_{i,I_i} + B_{ip,I_i}(t - t_i)$$

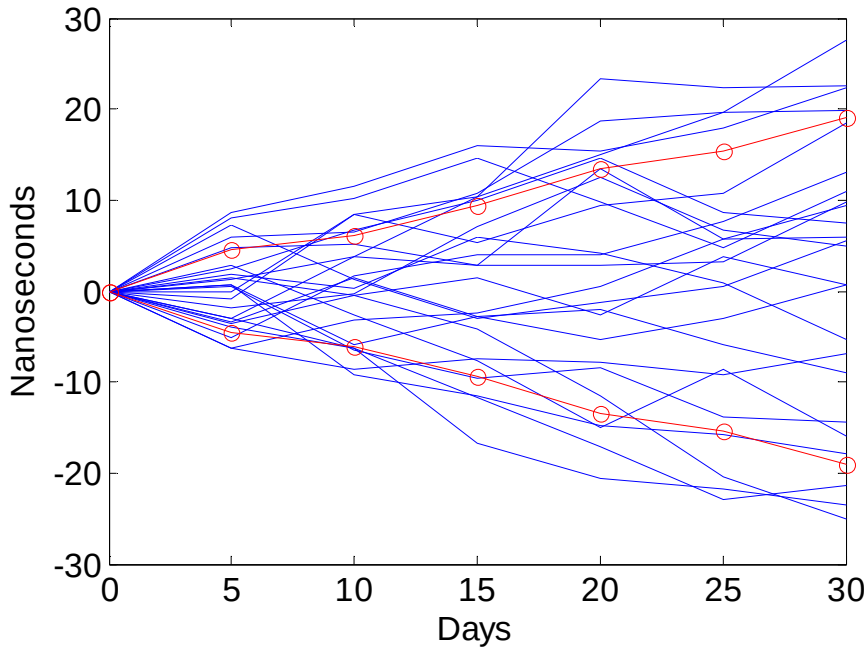


- a_{i,I_i} is the time correction relative to EAL of clock H_i at date t_i
- B_{ip,I_i} is the frequency of clock H_i, relative to EAL, predicted for the period [t_i, t]

Linear model: the frequency is considered constant during the month

Prediction Analysis – Cesium Clock

3-year test period (2006-2008)



The difference (prediction-reality) of the EAL-CS Clock with standard deviation (red lines).

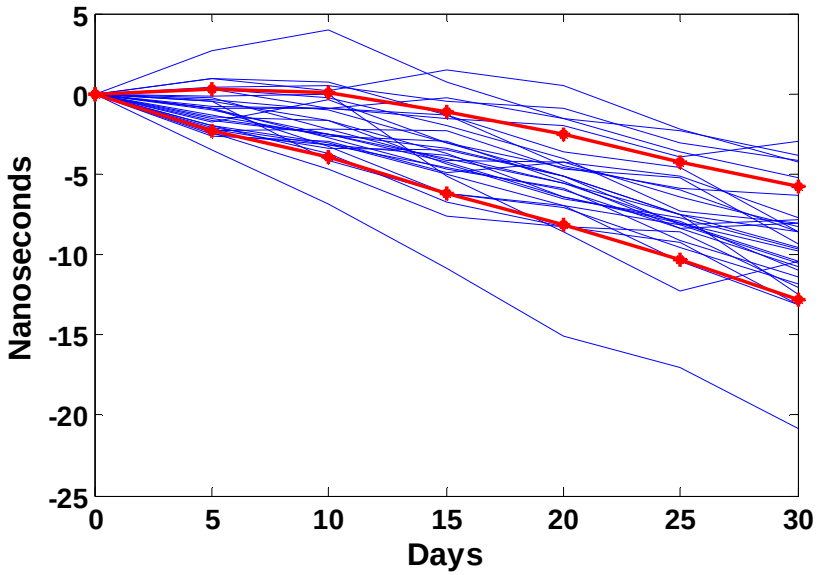
Considering 100 Cesium Clocks

The mean value of the difference (prediction-reality) for 100 EAL-CS Clock at 30 days is about **0.2** ns and the standard deviation is about **21** ns

Prediction Analysis - H-maser

3-year test period (2006-2008)

The difference (prediction-reality) of the EAL- H Maser



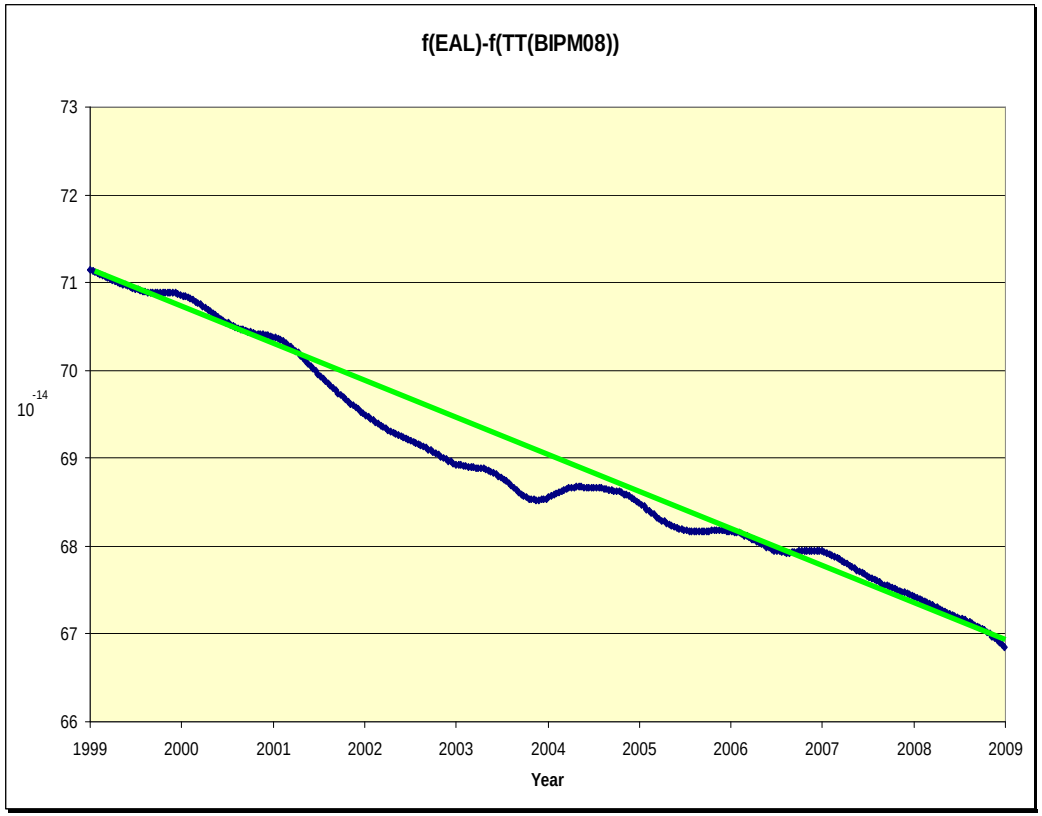
Considering 20 H-masers

The mean value of the difference (prediction-reality) after 30 days is about **-30** ns and the standard deviation at 30 days is about **40** ns

As expected, linear model does not take care of the H-maser frequency drift

EAL compared to TT(BIPM)

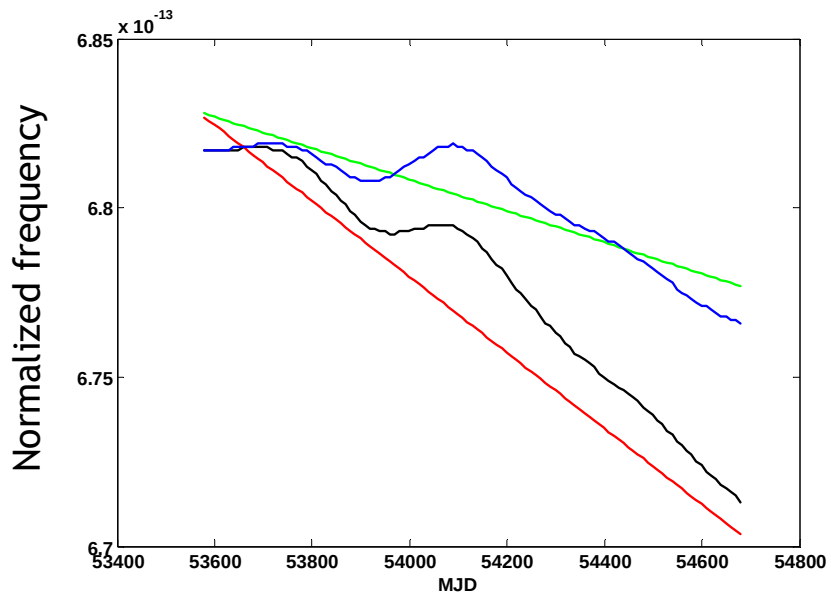
EAL shows a frequency drift w.r.t. TT



$$4\times10^{-16}\ /\ month$$

EAL-TT

To show the influence of H-masers on EAL drift we consider TT as an independent reference:



— $f(EAL_{without\ Hmaser})$-f(TT)

— f(EAL)-f(TT)

About 40% of EAL frequency drift is due to the H-masers

Frequency drift on f(EAL)-f(TT) is: **$4x10^{-16}$/ month**

Frequency drift on $f(EAL_{without\ Hmaser})$-f(TT) is: **$2.4x10^{-16}$/ month**

New prediction algorithm for the H-masers

The obtained relation for the prediction algorithm:

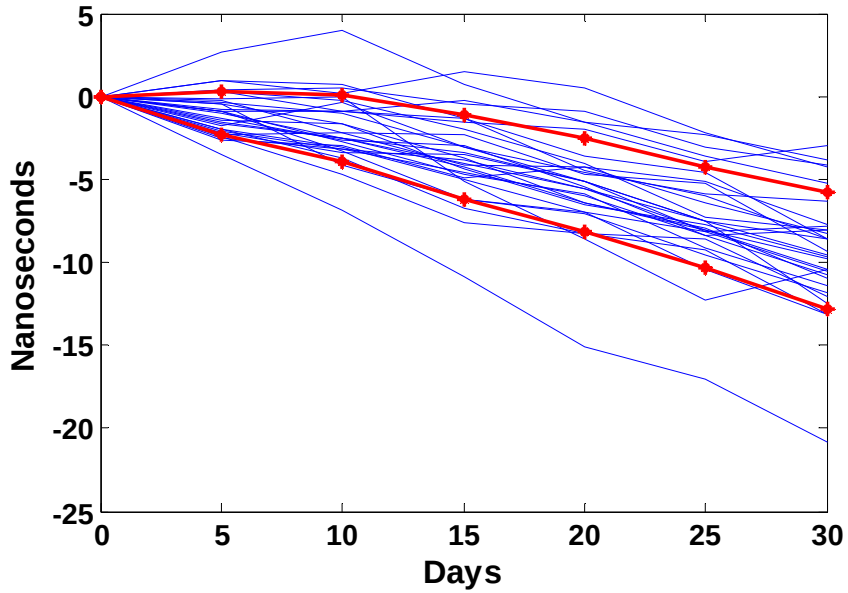
$$h_i^{'}(t) = a_{i,I_i} + B_{ip,I_i}(t - t_i) + \frac{1}{2} C_{ip,I_{i-1}}(t_i - t_{i-1})(t - t_i) + \frac{1}{2} C_{ip,I_i}(t - t_i)^2$$

Now the frequency is not constant on the interval!

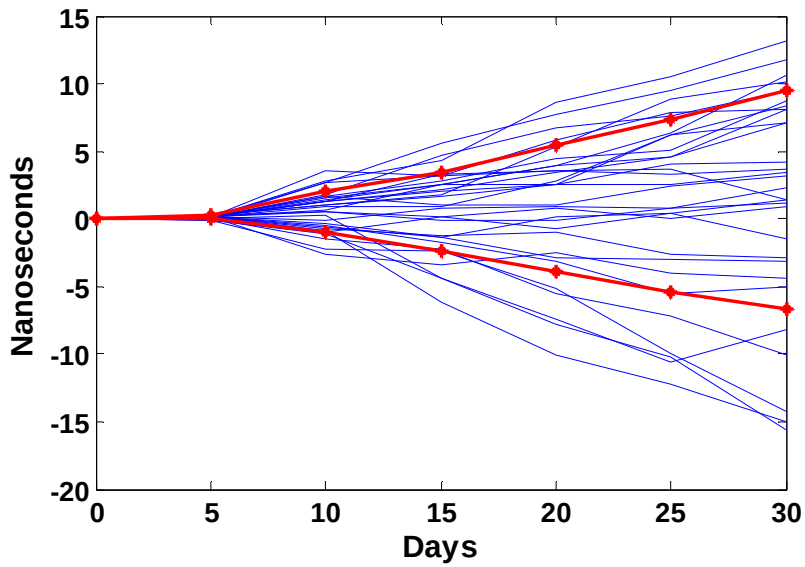
- a_{i,I_i} is the time correction relative to EAL of clock H_i at date t_i
- B_{ip,I_i} is the frequency of clock H_i, relative to EAL, predicted for the period [t_i, t]
- C_{ip,I_i} is the frequency drift of the clock Hi, relative to EAL, predicted for the period [t_i, t]
- $C_{ip,I_{i-1}}$ is the frequency drift of the clock Hi, relative to EAL, predicted for the period [t_{i-1}, t_i]

Effect of the new prediction algorithm

The difference (prediction-reality) of the EAL- H maser using two different prediction techniques



Linear Prediction



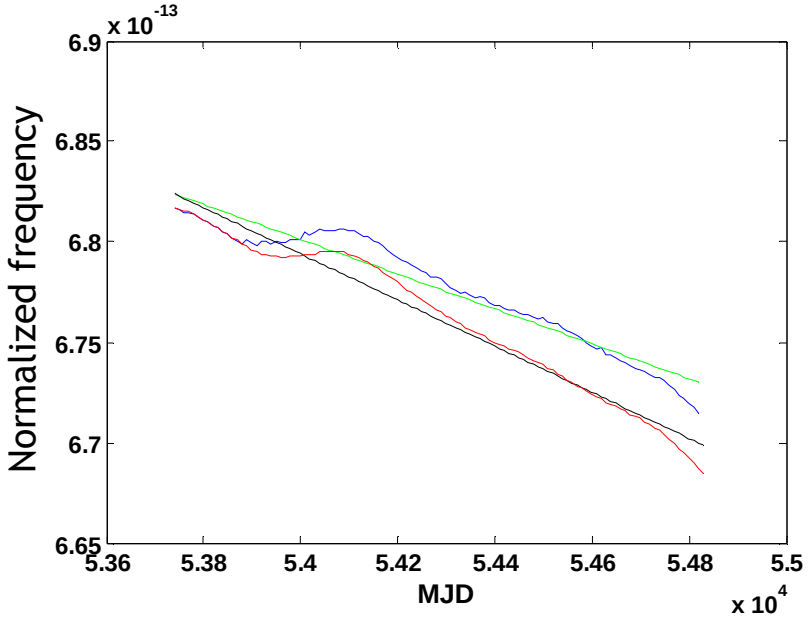
Quadratic prediction

Considering 20 (EAL-H-masers)

The mean value of the difference (prediction-reality) after 30 days is about **2** ns and the standard deviation at 30 days is about **45** ns

Effect of the new prediction algorithm

To show the influence of new prediction algorithm on EAL drift we use TT as independent frequency reference:



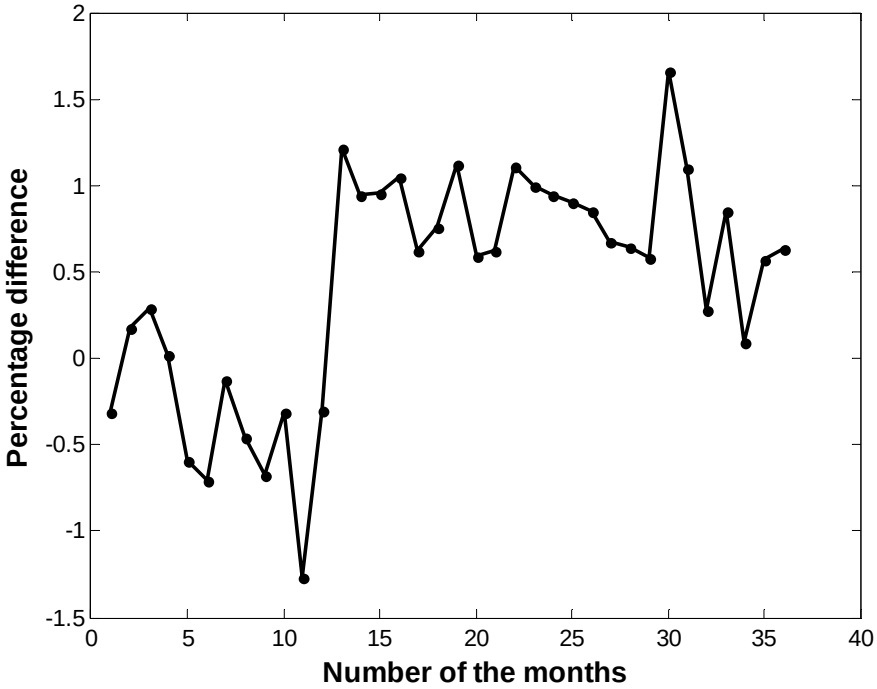
— $f(EAL_{\text{new predition algorithm}})-f(TT)$

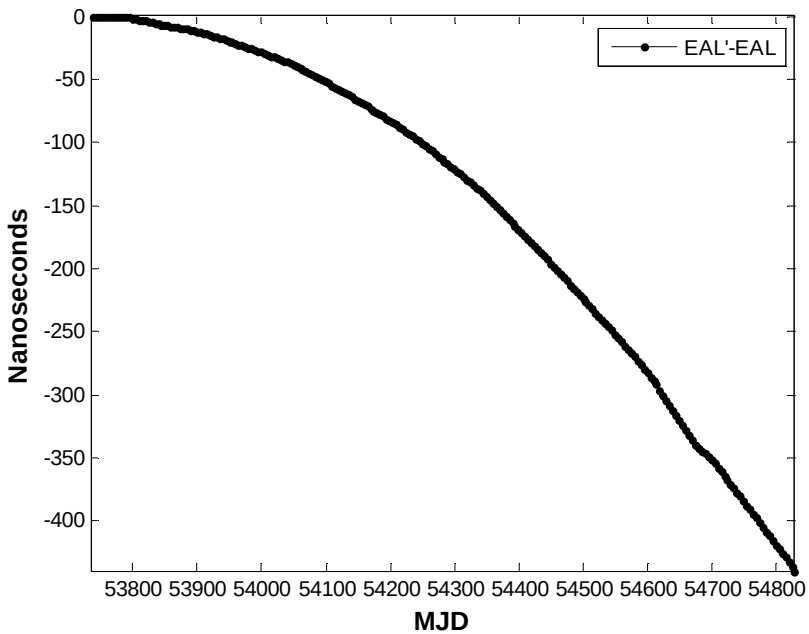
— $f(EAL)-f(TT)$

About 20% of EAL frequency drift is due to the linear prediction used in ALGOS

Frequency drift on f(EAL)-f(TT) is: **4×10^{-16}/ month**

Frequency drift on $f(EAL_{\text{new prediction algorithm}})-f(TT)$ is: **3.2×10^{-16}/ month**





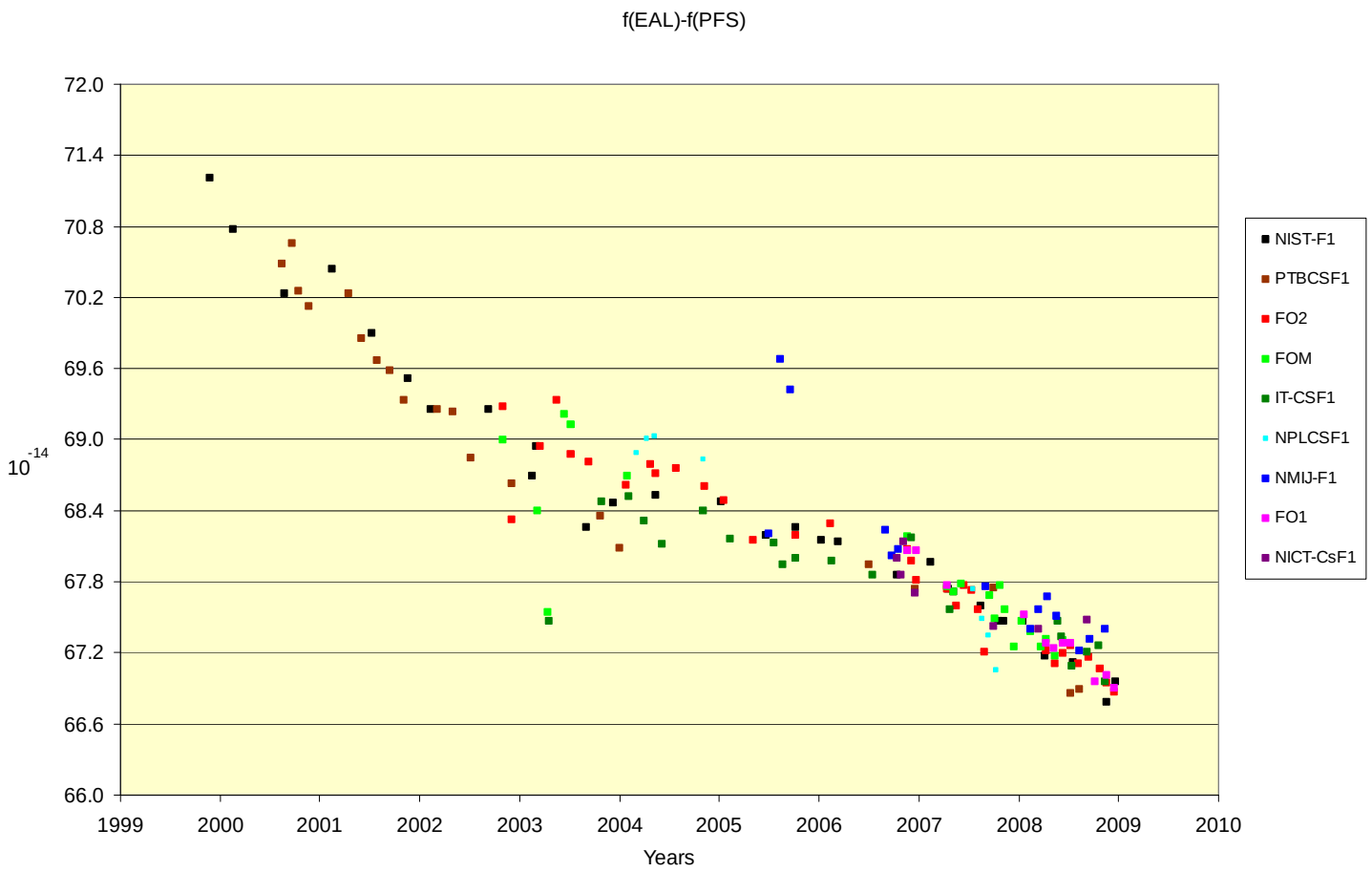
Difference of total weight of H-masers when a linear and a quadratic prediction is used. Weights increase. The drift of EAL increases when the prediction model is quadratic. Four months used for estimating the drift.

- Revise the weighting strategy
- Re-considering the use of clocks in the scale formation (caesium-based scale for long-term stability + H-masers for improving short term stability)

Primary standards in TAI

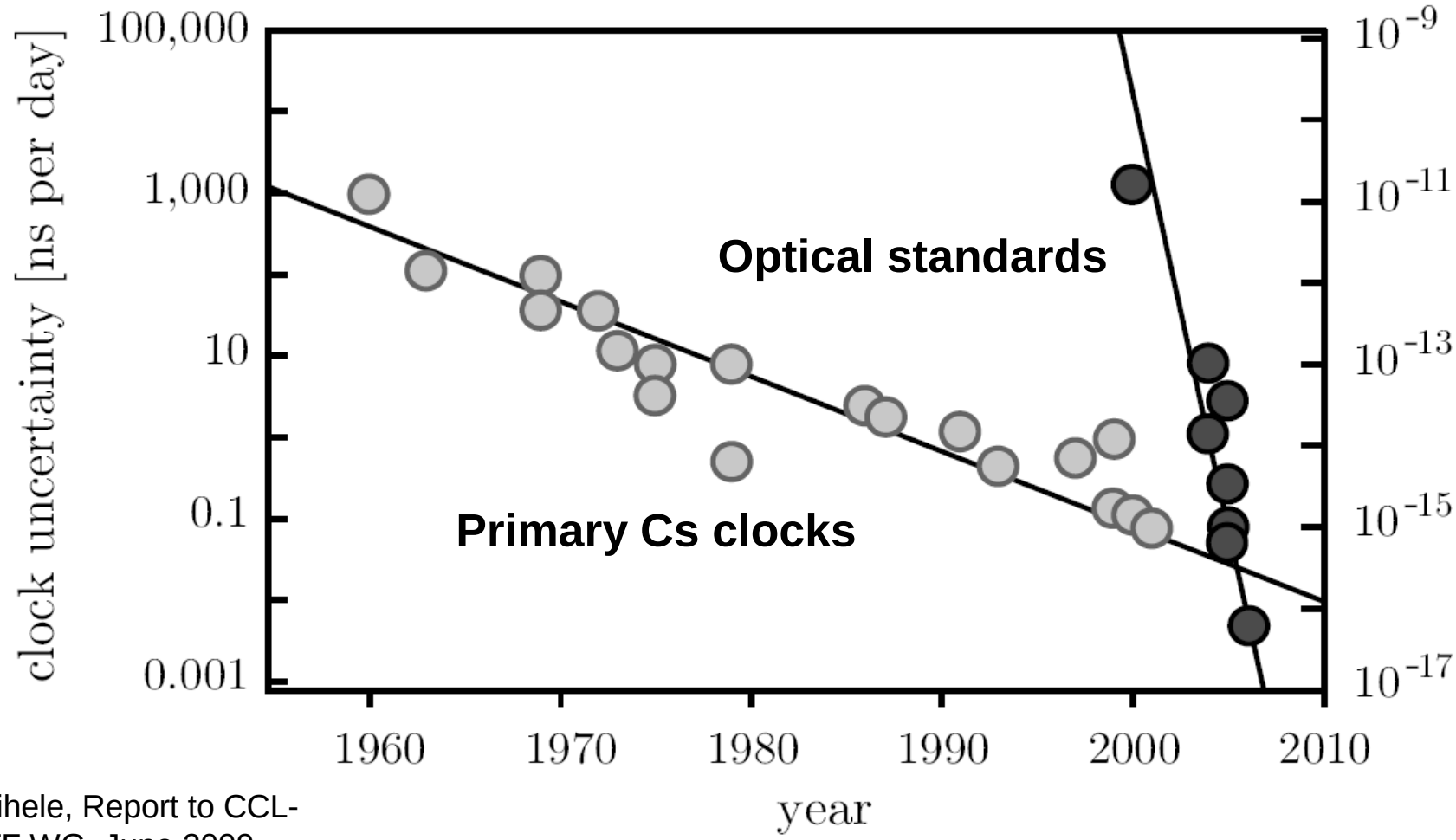
Primary Standard	Type /selection	Type B std. Uncertainty	Operation	Comparison with	Number/typical duration of comp.
IT-CSF1	Fountain	$(0.5 \text{ to } 0.7)\times10^{-15}$	Discontinuous	H maser	6 / 10 to 20 d
NICT-CSF1	Fountain	$(0.8 \text{ to } 1.5)\times10^{-15}$	Discontinuous	UTC(NICT)	2 / 10-15 d
NIST-F1	Fountain	0.3×10^{-15}	Discontinuous	H maser	5 / 15 to 25 d
NMIJ-F1	Fountain	3.9×10^{-15}	Discontinuous	H maser	7 / 15 to 25 d
PTB-CS1	Beam /Mag.	8×10^{-15}	Continuous	TAI	10 / 30 d
PTB-CS2	Beam /Mag.	12×10^{-15}	Continuous	TAI	12 / 30 d
PTB-CSF1	Fountain	0.9×10^{-15}	Discontinuous	H maser	2 / 25 d
SYRTE-FO1	Fountain	$(0.4 \text{ to } 0.6)\times10^{-15}$	Discontinuous	H maser	8 / 10 to 30 d
SYRTE-FO2	Fountain	$(0.4 \text{ to } 0.6)\times10^{-15}$	Discontinuous	H maser	9 / 10 to 30 d
SYRTE-FOM	Fountain	$(0.7 \text{ to } 0.9)\times10^{-15}$	Discontinuous	H maser	6 / 10 to 30 d
SYRTE-JPO	Beam /Opt.	6.3×10^{-15}	Discontinuous	H maser	12 / 10 to 30 d

f(EAL) respect to PFS



By using the PFS we evaluate the systematic variation of EAL

Uncertainty of Optical Clocks



F. Rihele, Report to CCL-CCTF WG, June 2009

In the future a new definition for the second will be required.

Secondary Representations (CIPM 2006)

CCL-CCTF FSWG

μ-wave clock	Studied at	Value / Hz	Relative uncertainty
^{87}Rb	LNE-SYRTE, USNO, NPL,..	6 834 682 610.904 324	3×10^{-15}

Optical clocks	Studied at	Value / Hz	Relative uncertainty
$^{199}Hg^{+}$	NIST	1 064 721 609 899 145	3×10^{-15}
$^{88}Sr^{+}$	NPL, NRC	444 779 044 095 484	7×10^{-15}
$^{171}Yb^{+}$	PTB	688 358 979 309 308	9×10^{-15}
^{87}Sr	NMIJ / U. Tokyo, JILA, LNE-SYRTE, PTB, …	429 228 004 229 877	1.5×10^{-14}

These clocks can be used alternatively to the Cs clock,
but can never have an uncertainty better than the Cs clock.

Conclusions

The effect of the linear prediction algorithm has been studied

- on the Cesium clock — it works well
- on the H-masers — it does not work well

The impact of the H-masers on EAL frequency drift has been analyzed.

A new mathematical expression for the prediction has been found. It includes the treatment of H-maser frequency drift.

More work is needed to adapt the algorithm to the proposed frequency prediction.

PFS number and accuracy has increased; the accuracy of TAI is approaching 10^{-16}.

The challenge is to be able to compare the optical frequency standards at the level of their performances.


Thank You!