Frequency standards in TAI and realization of TT(BIPM)

Gérard Petit and Gianna Panfilo
Bureau International des Poids et Mesures
92312 Sèvres Cedex, France
gpetit@bipm.org

BIPM

TT(BIPMxx)

- As TAI is computed in real time and never corrected in retrospect, it is not optimal. Therefore the BIPM computes a post-processed time scale TT(BIPM).
- Each new version TT(BIPMxx) updates and replaces the previous one.

- TT(BIPMxx) calculation
  - Post-processed using all available PFS data, as of year 20xx.
  - Complete re-processing starting 1993 (possibly with change of algorithm).
  - f(EAL) is estimated each month using available PFS. Monthly estimates are smoothed and integrated to obtain TT(BIPMxx).

- Last realization: TT(BIPM11), released in January 2012.

ftp://tai.bipm.org/TFG/TT(BIPM)/TTBIPM.11

TT(BIPMxx)

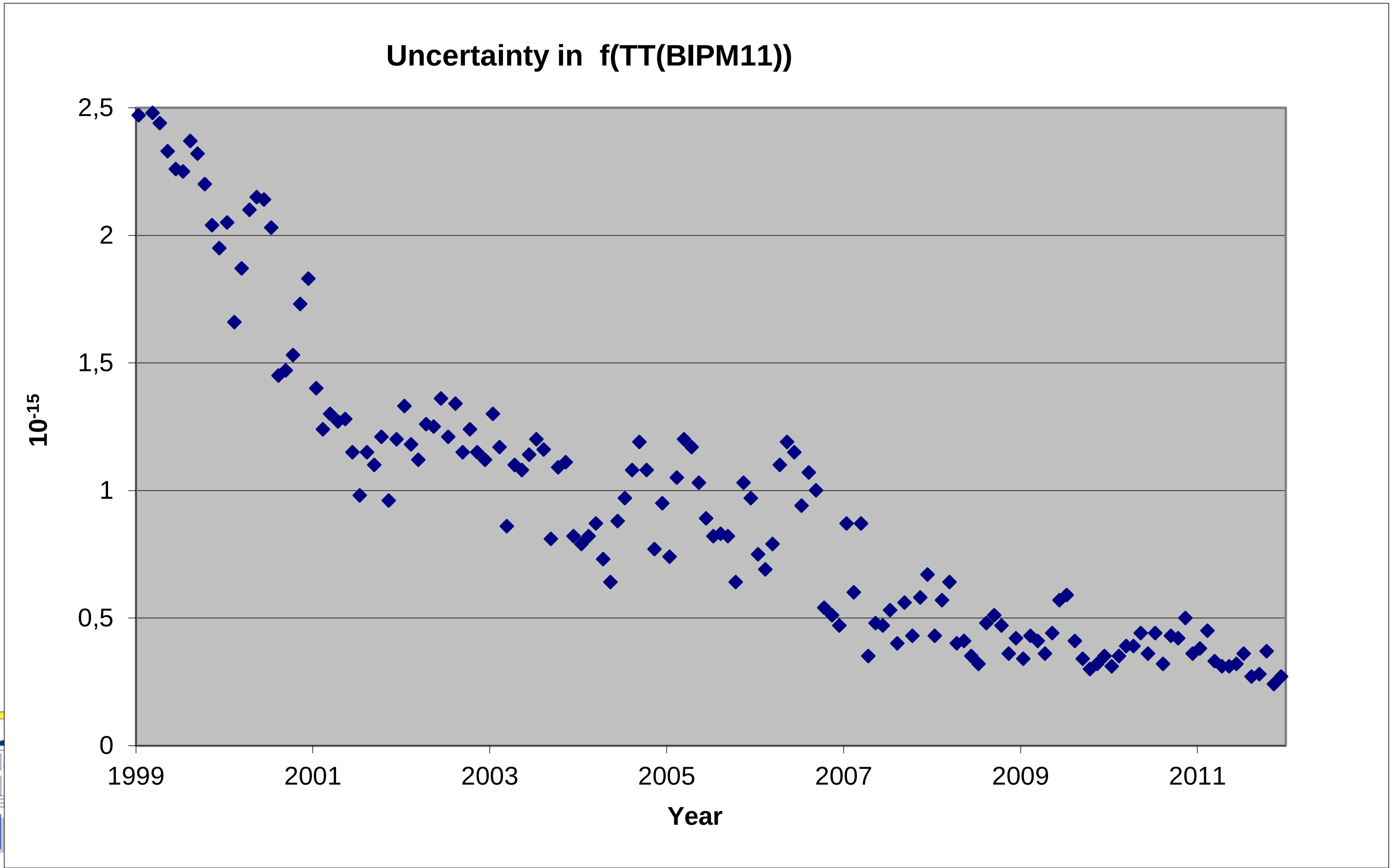
- No significant change in the computation of TT(BIPM) since CCTF'2009.
- Since 2010, a prediction of TT(BIPM) has been published each month
  - See the current one in ftp://tai.bipm.org/TFG/TT(BIPM)/TTBIPM.11.ext
- Since August 2011, a monthly computation of TT(BIPM) is performed to compute the clock drift to be used for TAI, but is not published.

55919.	-805.5522	27.6474	
55924.	-805.8331	27.6486	
55929.	-806.1135	27.6501	! Extended TT1201 with f= 649.1 & d= 3.5
55934.	-806.3940	27.6516	
55939.	-806.6744	27.6531	
55944.	-806.9548	27.6546	
55949.	-807.2352	27.6561	
55954.	-807.5156	27.6576	
55959.	-807.7960	27.6589	! Extended TT1202 with f= 649.0 & d= 3.1
55964.	-808.0764	27.6603	
55969.	-808.3567	27.6616	
55974.	-808.6371	27.6630	
55979.	-808.9174	27.6643	
55984.	-809.1978	27.6657	
55989.	-809.4776	27.6674	! Extended TT1203 with f= 647.7 & d= 3.9
55994.	-809.7574	27.6691	
55999.	-810.0372	27.6708	
56004.	-810.3170	27.6725	
56009.	-810.5968	27.6742	
56014.	-810.8766	27.6758	
56019.	-811.1567	27.6769	! Extended TT1204 with f= 648.5 & d= 2.6
56024.	-811.4369	27.6781	
56029.	-811.7170	27.6792	
56034.	-811.9971	27.6804	
56039.	-812.2773	27.6815	
56044.	-812.5574	27.6826	
56049.	-812.8373	27.6837	! Extended TT1205 with f= 648.1 & d= 2.5
56054.	-813.1174	27.6847	
56059.	-813.3973	27.6858	
56064.	-813.6773	27.6869	
56069.	-813.9573	27.6879	
56074.	-814.2373	27.6890	
56079.	-814.5170	27.6901	! Extended TT1206 with f= 647.6 & d= 2.5
56084.	-814.7968	27.6912	
56089.	-815.0765	27.6923	
56094.	-815.3563	27.6934	
56099.	-815.6360	27.6945	
56104.	-815.9158	27.6956	
56109.	-816.1957	27.6963	! Extended TT1207 with f= 648.0 & d= 1.6
56114.	-816.4756	27.6970	
56119.	-816.7556	27.6977	
56124.	-817.0355	27.6984	
56129.	-817.3154	27.6991	
56134.	-817.5954	27.6997	
56139.	-817.8753	27.7004	

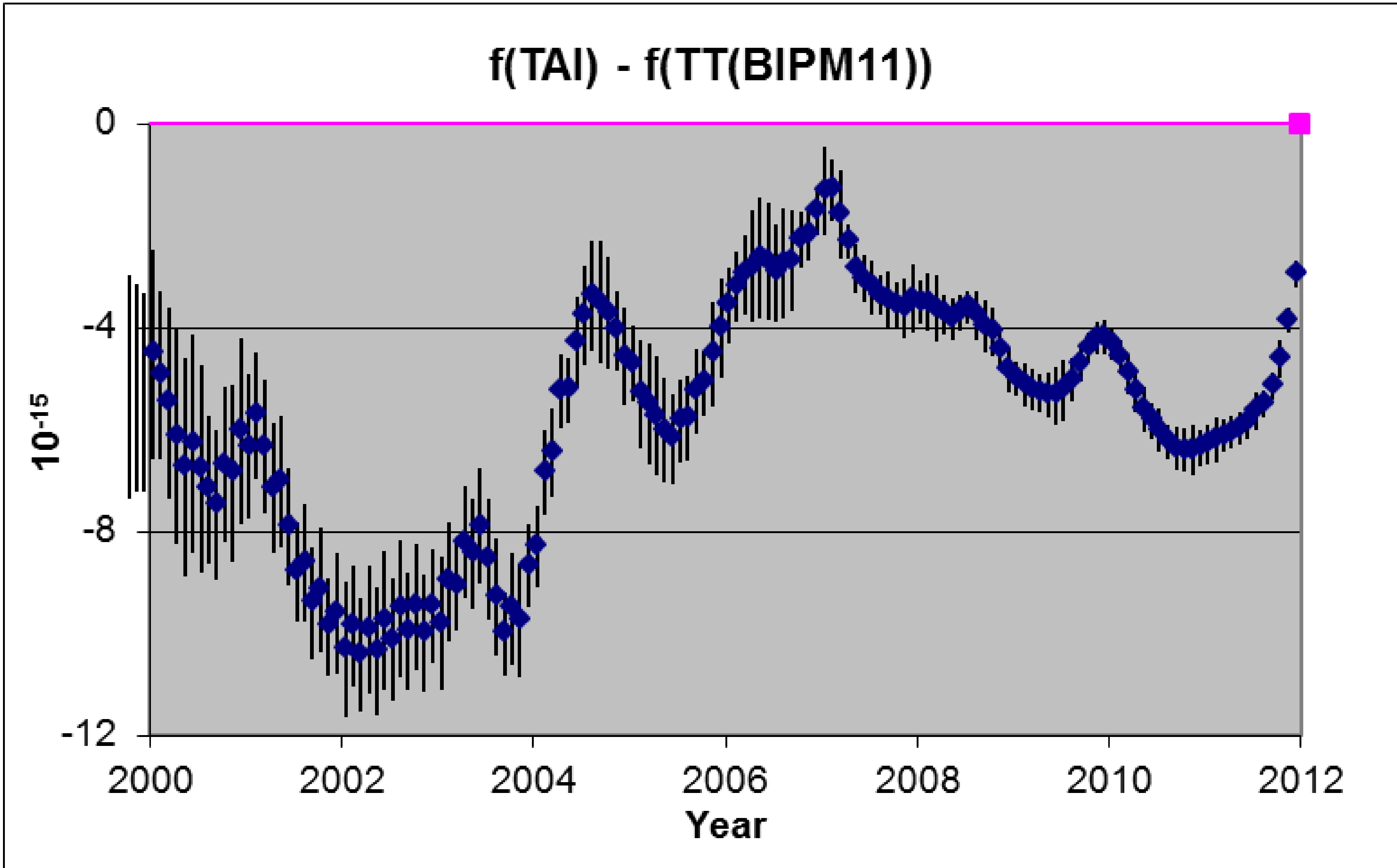
BIPM

TT(BIPM11)

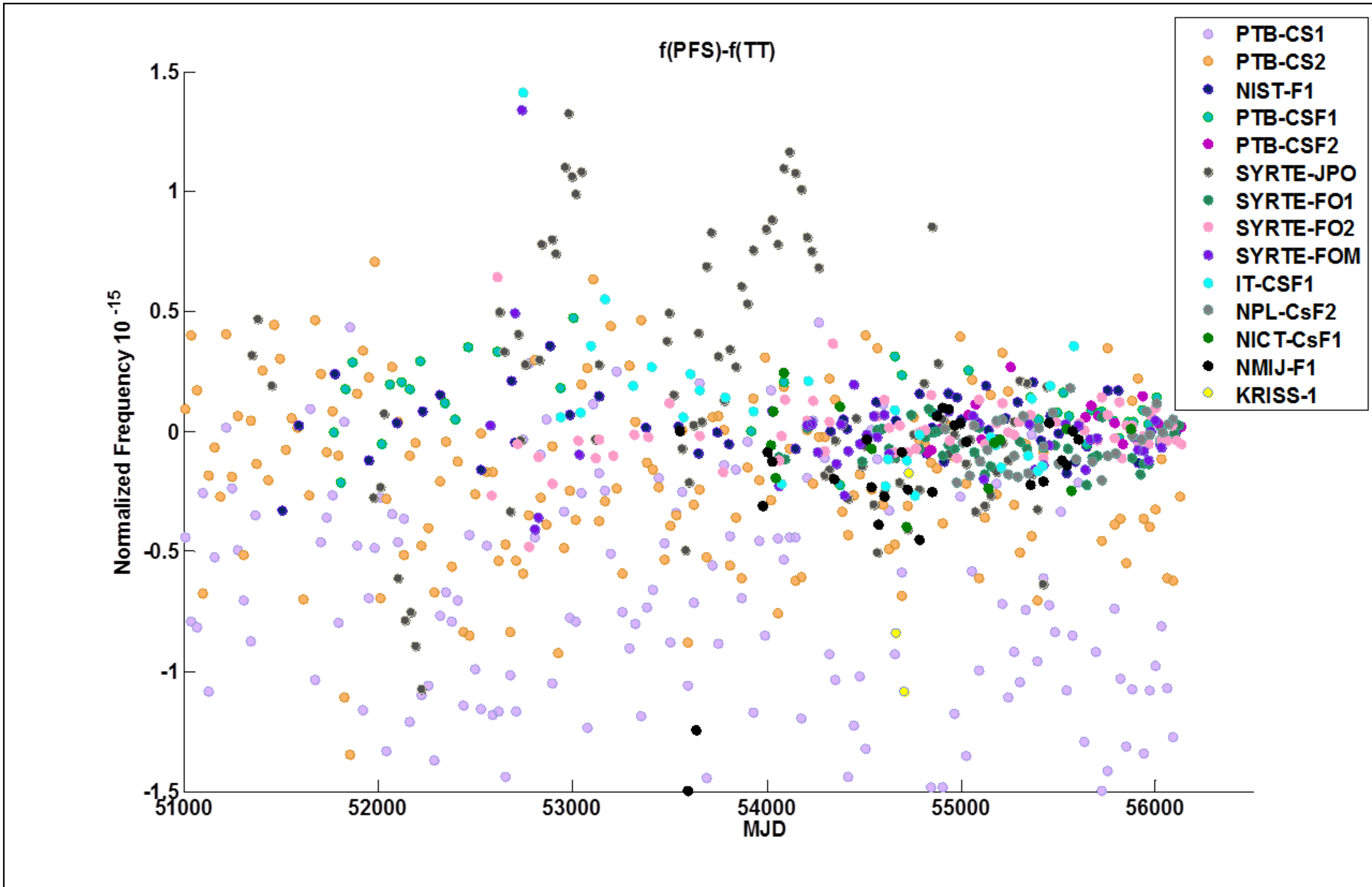
- Frequency accuracy of TT(BIPM) has regularly decreased since the introduction of Cs fountains from
  2.5×10^{-15} in 1999 to $<1\times10^{-15}$ since 2004, $<5\times10^{-16}$ since 2008
  ~$2\text{-}3\times10^{-16}$ in 2012.
- It directly depends on the uncertainty budget of the PFS



TT(BIPM) allows to estimate the accuracy of TAI

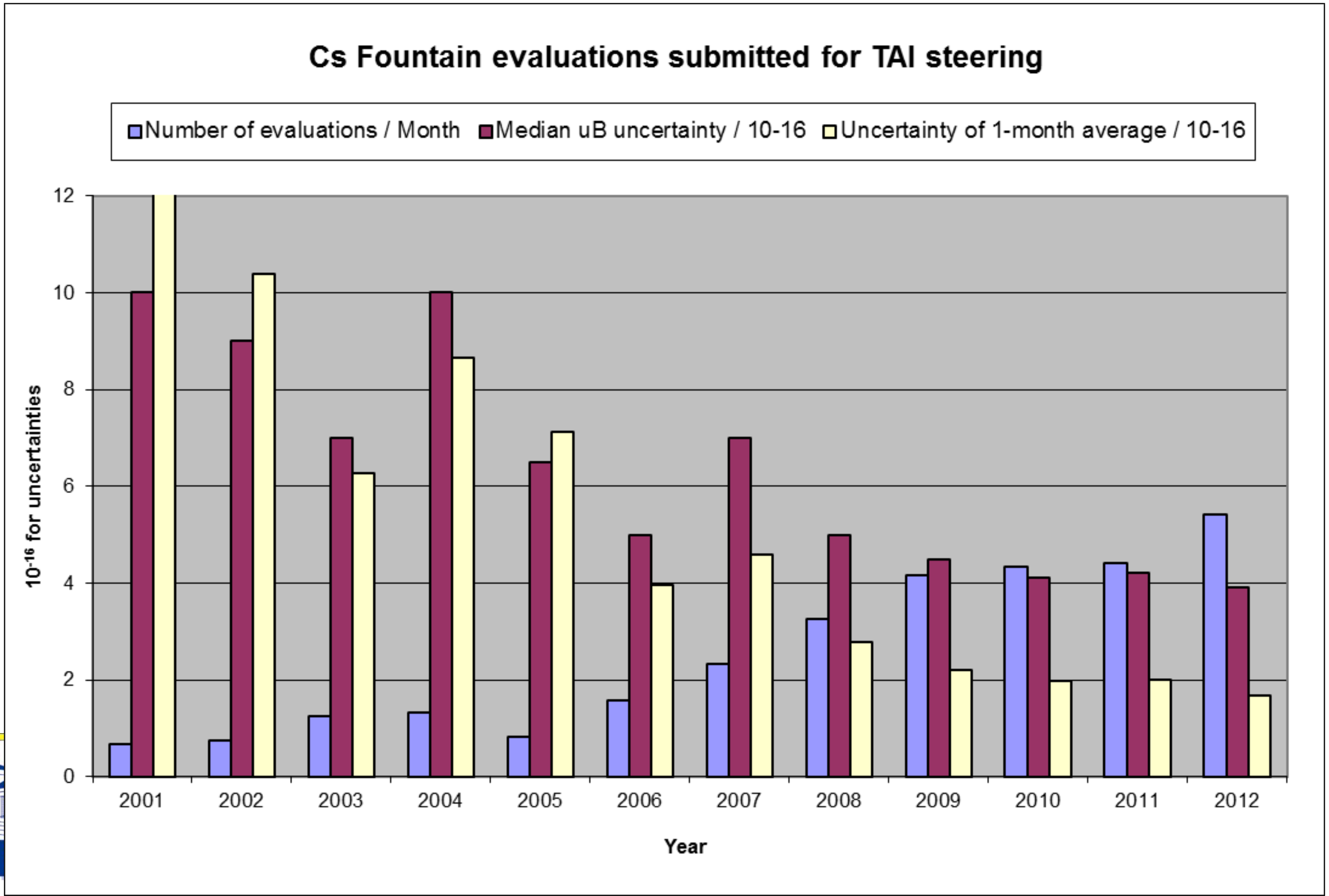


TT(BIPM) allows to estimate the performance of PFS



Contributions of frequency standards to TAI

- More than four Cs fountain evaluations each month since 2009.
- Median u_B uncertainty now < 4×10^{-16}
- Raw averaging put 1-month uncertainty of TAI frequency at ~2×10^{-16} (true evaluation is close to this value).



Contributions of frequency standards to TAI

- Little change in Circular T for the publication of PFS evaluations between April 2009 (top) and July 2012 (bottom)
  - 10^{-17} resolution
  - u_B(Ref)
- More later for Secondary frequency standards

April 2009

Standard	Period of Estimation		*d*	u_A	u_B	Ref(u_B)	$u_{l/Lab}$	$u_{l/Tai}$	*u*	Note
PTB-CS1	54919	54949	6.9	5.0	8.0	T148	0.0	0.1	9.4	(1)
PTB-CS2	54919	54949	5.5	3.0	12.0	T148	0.0	0.1	12.4	(1)
NIST-F1	54924	54939	6.8	0.3	0.3	T214	0.4	0.6	0.9	(2)
NMIJ-F1	54919	54949	6.2	0.7	3.9	T213	0.3	0.5	4.0	(3)
SYRTE-JPO	54919	54949	4.3	0.7	6.3	T160	0.3	0.3	6.4	(4)
SYRTE-FO1	54919	54949	4.7	0.3	0.4	T227	0.1	0.3	0.6	(4)
SYRTE-FO2	54934	54949	5.1	0.5	0.5	T227	0.1	0.6	0.9	(4)
SYRTE-FOM	54919	54944	6.1	0.2	0.7	T184	2.0	0.4	2.2	(5)

Notes:
(1) Continuously operating as a clock participating to TAI
(2) Report 23 APR. 2009 by NIST
(3) Report 28 APR. 2009 by NMIJ
(4) Report 04 MAY. 2009 by LNE-SYRTE
(5) Report 04 MAY. 2009 by LNE-SYRTE. FOM was in operation at CNES in Toulouse and the value u_l/lab also accounts for the GPS time transfer between Toulouse and Paris.

The second table gives the BIPM estimate of *d*, based on all available PFS measurements over the period MJD 54559-54949, taking into account their individual uncertainties and characterizing the instability of EAL as noted above. *u* is the computed standard uncertainty of *d*

Period of estimation	*d*	*u*	
54919-54949	5.1×10^{-15}	0.4×10^{-15}	(2009 MAR 29 - 2009 APR 28)

BIPM Circular T 256 - 4

July 2012

Standard	Period of Estimation		*d*	u_A	u_B	$u_{l/Lab}$	$u_{l/Tai}$	*u*	Ref(u_B)	u_B(Ref)	Note
PTB-CS1	56104	56139	-14.58	6.00	8.00	0.00	0.06	10.00	T148	8.	(1)
PTB-CS2	56104	56139	-0.93	3.00	12.00	0.00	0.06	12.37	T148	12.	(1)
NIST-F1	56089	56114	2.07	0.34	0.31	0.25	0.23	0.57	T214	0.35	(2)
SYRTE-FO1	56104	56129	2.05	0.30	0.55	0.12	0.23	0.68	T227	0.72	(3)
SYRTE-FO2	56099	56119	1.52	0.25	0.24	0.23	0.28	0.50	T227	0.65	(3)
SYRTE-FO2	56119	56139	1.25	0.20	0.24	0.14	0.28	0.44	T227	0.65	(3)
PTB-CSF2	56124	56139	1.99	0.21	0.39	0.02	0.12	0.46	T287	0.41	(4)

Notes:

(1) Continuously operating as a clock participating to TAI
(2) Report 31 JUL. 2012 by NIST
(3) Report 02 AUG. 2012 by LNE-SYRTE
(4) Report 01 AUG. 2012 by PTB

The second table gives the BIPM estimate of *d*, based on all available PFS measurements over the period MJD 55744-56139, taking into account their individual uncertainties and characterizing the instability of EAL as noted above. *u* is the computed standard uncertainty of *d*

Period of estimation	*d*	*u*	
56104-56139	1.6×10^{-15}	0.3×10^{-15}	(2012 JUN 26 - 2012 JUL 31)

BIPM Circular T 295 - 4

BIPM

Primary frequency standards in 2010

Primary Standard	Type /selection	Type B std. Uncertainty / 10^{-15}	Operation	Comparison with	Number/typical duration of comp.
IT-CSF1	Fountain	(0.5 to 0.9)	Discontinuous	H maser	6 / 15-35 d
NICT-CSF1	Fountain	(0.9 to 1.0)	Discontinuous	UTC(NICT)	2 / 15-25 d
NIST-F1	Fountain	0.31	Discontinuous	H maser	7 / 15-25 d
NMIJ-F1	Fountain	3.9	Discontinuous	H maser	5 / 15-35 d
NPL-CSF2	Fountain	(0.40 to 0.59)	Discontinuous	H maser	18 (8 in 2009)/10-40 d
PTB-CS1	Beam /Mag.	8	Continuous	TAI	12 / 30 d
PTB-CS2	Beam /Mag.	12	Continuous	TAI	8 / 30 d
PTB-CSF1	Fountain	(0.76 to 0.81)	Discontinuous	H maser	4 / 15-30 d
PTB-CSF2	Fountain	0.60	Discontinuous	H maser	1 / 15 d
SYRTE-FO1	Fountain	(0.40 to 0.48)	Discontinuous	H maser	6 / 15 to 30 d
SYRTE-FO2	Fountain	(0.38 to 0.41)	Becoming nearly continuous	H maser	9 / 15 to 30 d
SYRTE-FOM	Fountain	(0.82 to 0.86)	Discontinuous	H maser	5 / 15 to 35 d
SYRTE-JPO	Beam /Opt.	6.3	Nearly continuous	H maser	9 / 5 to 35 d

- 10 fountains and 3 beams (one stopping operation)
- 9 fountains with u_B uncertainty < $1x10^{-15}$
- 52 evaluations of fountains

Primary frequency standards in 2011

Primary Standard	Type /selection	Type B std. Uncertainty / 10^{-15}	Operation	Comparison with	Number/typical duration of comp.
IT-CSF1	Fountain	0.7	Discontinuous	H maser	1 / 25 d
NICT-CSF1	Fountain	(1.0 to 1.2)	Discontinuous	UTC(NICT)	2 / 10-20 d
NIST-F1	Fountain	0.31	Discontinuous	H maser	5 / 15-30 d
NMIJ-F1	Fountain	3.9	Discontinuous	H maser	2 / 30 d
NPL-CSF2	Fountain	0.40 then 0.23	Discontinuous	H maser	7 / 15-25 d
PTB-CS1	Beam /Mag.	8	Continuous	TAI	12 / 30 d
PTB-CS2	Beam /Mag.	12	Continuous	TAI	7 / 30 d
PTB-CSF1	Fountain	(0.74 to 0.79)	Nearly continuous	H maser	10 / 15-25 d
PTB-CSF2	Fountain	(0.36 to 0.56)	Discontinuous	H maser	6 / 15-25 d
SYRTE-FO1	Fountain	(0.42 to 0.49)	Discontinuous	H maser	6 / 10 to 25 d
SYRTE-FO2	Fountain	(026 to 0.39)	Nearly continuous	H maser	12 / 15 to 35 d
SYRTE-FOM	Fountain	(0.82 to 0.92)	Discontinuous	H maser	6 / 20 to 30 d

- 10 fountains and 2 beams
- Some improvement in u_B uncertainty in three fountains
- 53 evaluations of fountains
- Two fountains maintain nearly continuous evaluations

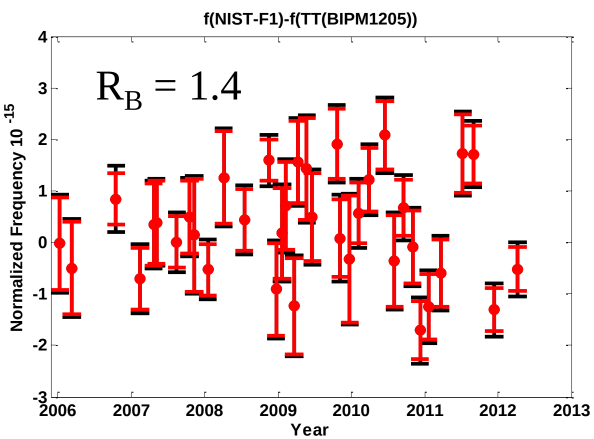
Evaluation of PFS performance

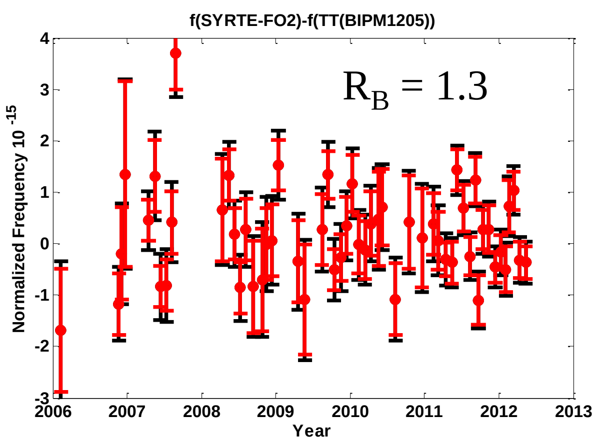
- Study for CPEM'2012 (to be published)

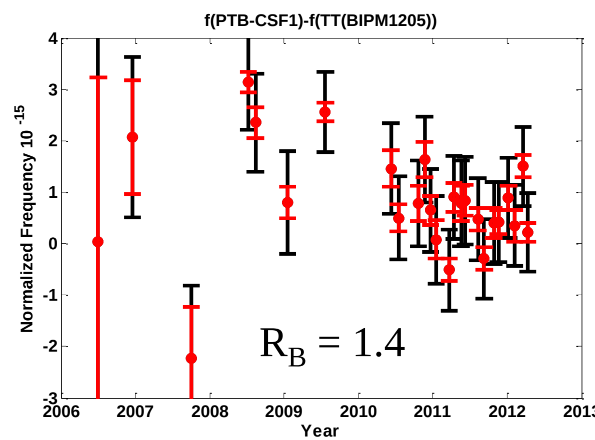
> Comparison of frequency standards used for TAI
> G. Petit* and G. Panfilo*

1. Comparisons using TT(BIPM)

- Study each PFS by comparison to TT(BIPM)
  - Estimate one frequency bias $Y_i = \langle y(PFS_i - TT(BIPM)) \rangle$ for each PFS_i
  - Estimate goodness of fit for each PFS_i (Reduced Chi square χ^2, Birge ratio R_B)
- Study the ensemble of PFS:
  - Estimate if the distribution of frequency biases Y_i is consistent with the uncertainties u_{Bi}



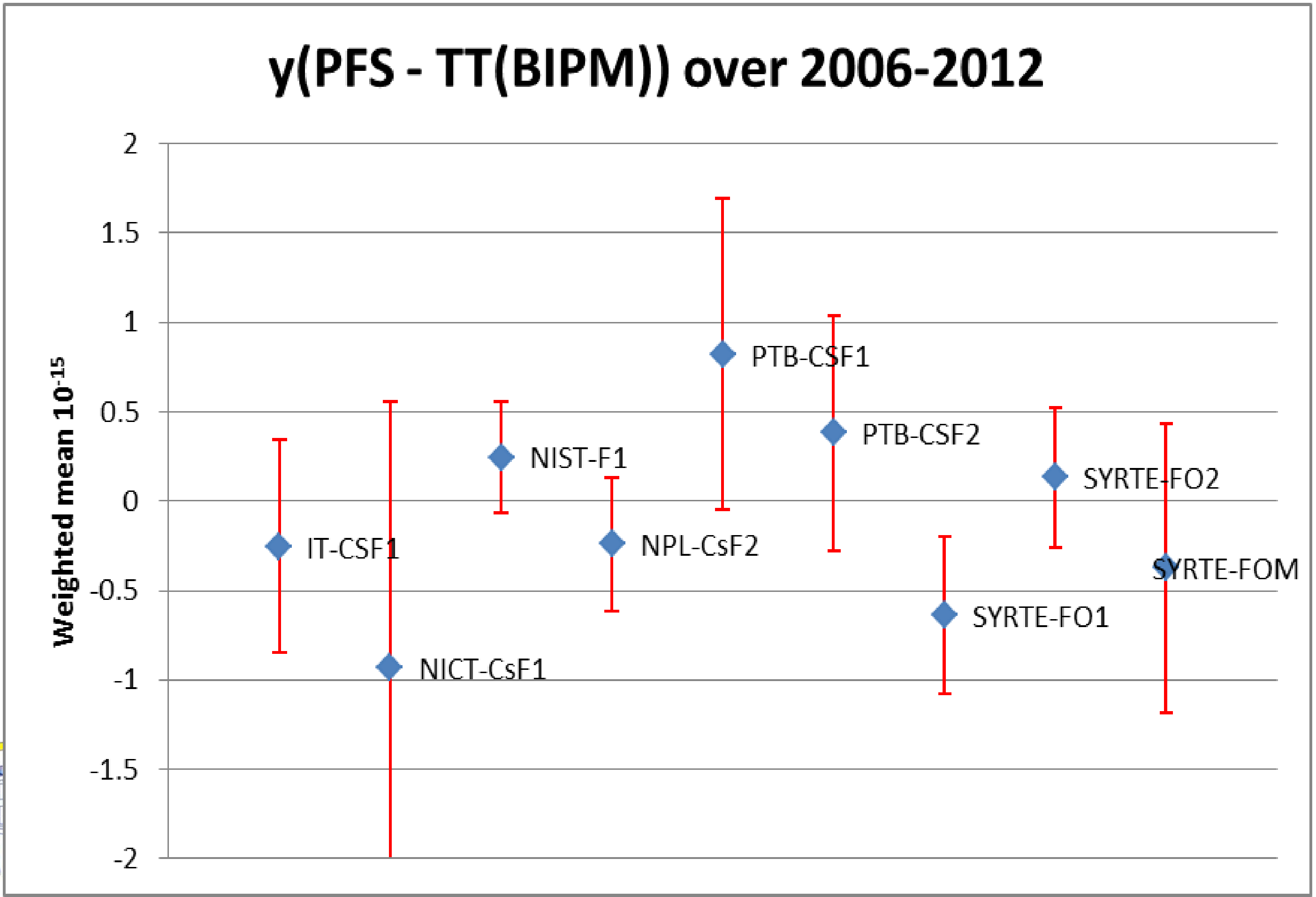




2. Direct comparison of PFS

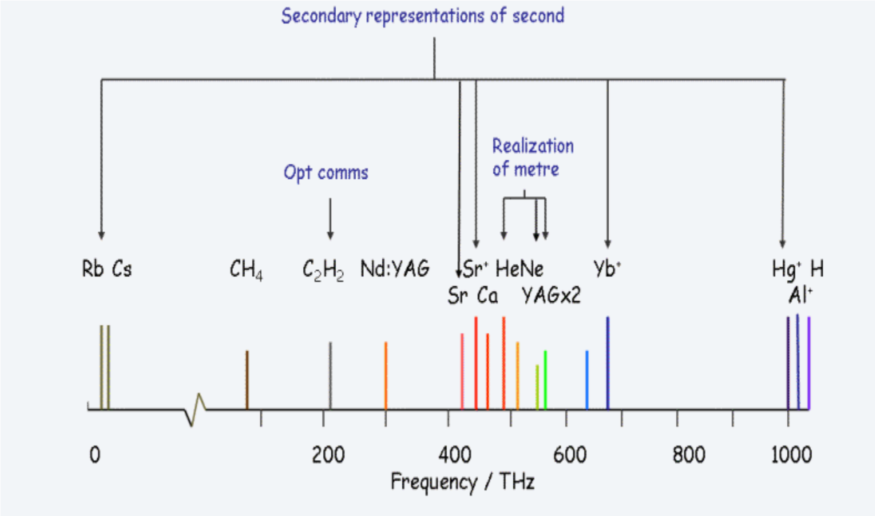
Comparison of PFS to TT(BIPM): The ensemble of PFSs

- The mean frequency bias computed for each fountain is plotted with mean uncertainty u_B
- The Birge ratio of this series is 0.86: No indication of underestimation of u_B or of any significant systematic shift.
  - Most significant shift: SYRTE-FO1 = -1.45 u_B
- This confirms the estimations given for the accuracy of TT(BIPM)



Secondary frequency standards

- CCL-CCTF working group merged in 2005: producing and maintaining a single list of *Recommended frequency standard values for applications including the practical realization of the metre and secondary representations of the second*.



CIPM-2006 / 2009:

Unperturbed optical transition $5s^2\ ^1S_0 - 5s\ 5p\ ^3P_0$ of ^{87}Sr: 1×10^{-15}

Unperturbed ground-state hyperfine transition of ^{87}Rb: 3×10^{-15}

Unperturbed optical $5d^{10}\ 6s\ ^2S_{1/2}\ (F = 0) - 5d^9\ 6s^2\ ^2D_{5/2}\ (F = 2)$ transition of $^{199}Hg^+$: 3×10^{-15}

Unperturbed optical $5s\ ^2S_{1/2} - 4d\ ^2D_{5/2}$ transition of $^{88}Sr^+$: 7×10^{-15}

Unperturbed optical $6s\ ^2S_{1/2}\ (F = 0) - 5d\ ^2D_{3/2}\ (F = 2)$ transition of $^{171}Yb^+$: 9×10^{-15}

BIPM

Contributions of secondary frequency standards to TAI

- For some secondary frequency standards (SFS), all systematic effects can be estimated with an uncertainty equivalent to or lower than for the best PFS, e.g.
  - ^{87}Sr: < $2x10^{-16}$ (several teams)
  - ^{87}Rb : $4x10^{-16}$ (Guéna et al, 2010; 2012)
  - Some other transitions may have better uncertainty of systematic effects, but not yet in the list of SFS
- First SFS report to the BIPM in January 2012: SYRTE FO2(Rb)
- The BIPM Time department expects to receive new SFS evaluations in order to provide visibility and to get experience with their possible use in TAI steering.

BIPM

SYRTE FO2(Rb) in TAI

- First SFS report to the BIPM in January 2012: SYRTE FO2(Rb)
  - Submitted for review to the WGPFS, like for a new PFS.
  - 13 evaluations published in Circular T193 June 2012 => New table
  - More each month.

In the third table, *d* is obtained on the given periods of estimation by comparison of the TAI frequency with that of the given individual Secondary Frequency Standards (SFS). This table is organized similarly to the first table, with the addition of u_{Srep} which represents the recommended uncertainty of the secondary representation of the second and of Ref(u_s) which provides the reference for the frequency of the transition and its uncertainty uSrep. All values are expressed in 10^{-15} and are valid only for the stated period of estimation. Note that SFS are not used for the estimation of *d* provided in the second table above, nor for determining the steering correction reported in section 3.

Standard	Period of Estimation	*d*	u_A	u_B	$u_{l/Lab}$	$u_{l/Tai}$	*u*	u_{Srep}	Ref(u_s)	Ref(u_B)	u_B(Ref)	Note
SYRTE-FORb	55194 55224	3.98	0.40	0.46	0.11	0.43	0.75	3.00	[1]	[2]	0.45	(1)
SYRTE-FORb	55224 55254	2.97	0.20	0.44	0.11	0.46	0.67	3.00	[1]	[2]	0.45	(1)
SYRTE-FORb	55254 55274	2.80	0.30	0.53	0.11	0.66	0.90	3.00	[1]	[2]	0.45	(1)
SYRTE-FORb	55354 55374	4.59	0.35	0.57	0.11	0.66	0.94	3.00	[1]	[2]	0.45	(1)
SYRTE-FORb	55409 55429	3.17	0.20	0.46	0.11	0.66	0.83	3.00	[1]	[2]	0.45	(1)
SYRTE-FORb	55854 55894	3.04	0.20	0.46	0.17	0.15	0.55	3.00	[1]	[2]	0.45	(1)
SYRTE-FORb	55894 55924	1.66	0.20	0.44	0.11	0.20	0.53	3.00	[1]	[2]	0.45	(1)
SYRTE-FORb	55924 55949	1.15	0.30	0.39	0.10	0.23	0.55	3.00	[1]	[2]	0.45	(2)
SYRTE-FORb	55954 55969	0.63	0.30	0.38	0.14	0.37	0.62	3.00	[1]	[2]	0.45	(2)
SYRTE-FORb	55969 55984	2.03	0.40	0.38	0.25	0.37	0.71	3.00	[1]	[2]	0.45	(2)
SYRTE-FORb	55984 56014	2.38	0.30	0.43	0.11	0.20	0.57	3.00	[1]	[2]	0.45	(2)
SYRTE-FORb	56014 56044	0.96	0.20	0.41	0.14	0.20	0.52	3.00	[1]	[2]	0.45	(2)
SYRTE-FORb	56044 56074	0.80	0.20	0.32	0.11	0.20	0.44	3.00	[1]	[2]	0.45	(3)

[1] CIPM Recommendation 1 (CI-2006) "Concerning secondary representations of the second" in *Procès-Verbaux des Séances du Comité International des Poids et Mesures*, 96th meeting (2006), 2007, 258 p.
[2] J. Guéna et al., "Demonstration of a Dual Alkali Rb/Cs Fountain Clock", *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, 57 (3), pp. 647-653, 2010. J. Guéna et al., "Progress in atomic fountains at LNE-SYRTE", *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 59 (3), pp. 391-410, 2012.

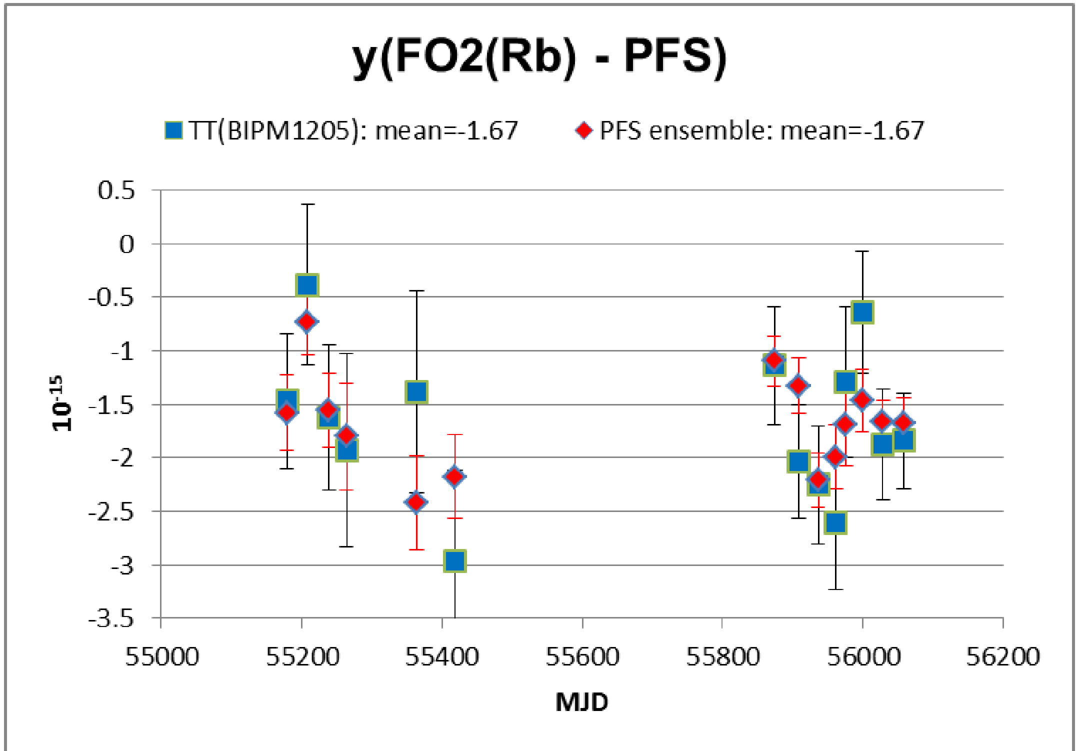
-Notes :

(1) Report 19 January 2012 by LNE-SYRTE. SYRTE-FORb is the fountain SYRTE-FO2 operated with Rb87 atoms. It has been approved by the CCTF Working Group on Primary Frequency Standards on 24 May 2012.
(2) Report 04 May 2012 by LNE-SYRTE.
(3) Report 31 May 2012 by LNE-SYRTE.

BIPM

Correction to the reference frequency of ^{87}Rb

- Comparisons to PFS indicate that the Rb transition recommended frequency is off by about -1.5×10^{-15}.
  - Local comparison by SYRTE to SYRTE PFS: -1.48×10^{-15}
    - Based on data over 1998-2012, communicated by SYRTE to the WG on PFS
  - Comparison to TT(BIPM11): -1.67×10^{-15}.
    - Based on data over 2010-2012, communicated by SYRTE to the BIPM
  - **Comparison to the best estimate of PFS over the SFS evaluation intervals: -1.67×10^{-15}**
    - Based on same data. Results (red diamonds) much less dispersed: $R_B = 0.64$



Conclusions

- Primary frequency standards still continue to gain in accuracy ("typical" rate is one order of magnitude every 10 years). We are at $2\text{-}3\times10^{-16}$.

- The full accuracy of PFS is not completely passed to TAI and TT(BIPM) because of
  - the noise of frequency transfer
  - (possibly) some slightly inconsistent PFS evaluations
- Nevertheless the PFS reported uncertainties are globally consistent with the data.
  - this implies that TT(BIPM) accuracy is $\sim3\times10^{-16}$ in 2012 and the TAI frequency is known with the same uncertainty.

- We need evaluations of secondary standards
  - to gain experience and promote their use
  - to determine their reference frequency
  - to prepare for future changes