Frequency standards in TAI and realization of TT(BIPM)

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TT(BIPMxx)

- To overcome some limitations of TAI, the BIPM computes a post-processed time scale TT(BIPM).
- Each yearly version TT(BIPMxx) updates and replaces the previous one.

- TT(BIPMxx) calculation
  - Post-processed using all available PFS data, after end of year 20xx.
  - Re-processing over last 5 years. In case of need, complete re-processing since 1993.
  - f(EAL) is estimated each month using available PFS. Monthly estimates are smoothed and integrated to obtain TT(BIPMxx).

- Last realization: TT(BIPM16), released in January 2017.

All results in ftp://ftp2.bipm.org/pub/tai/ttbipm/

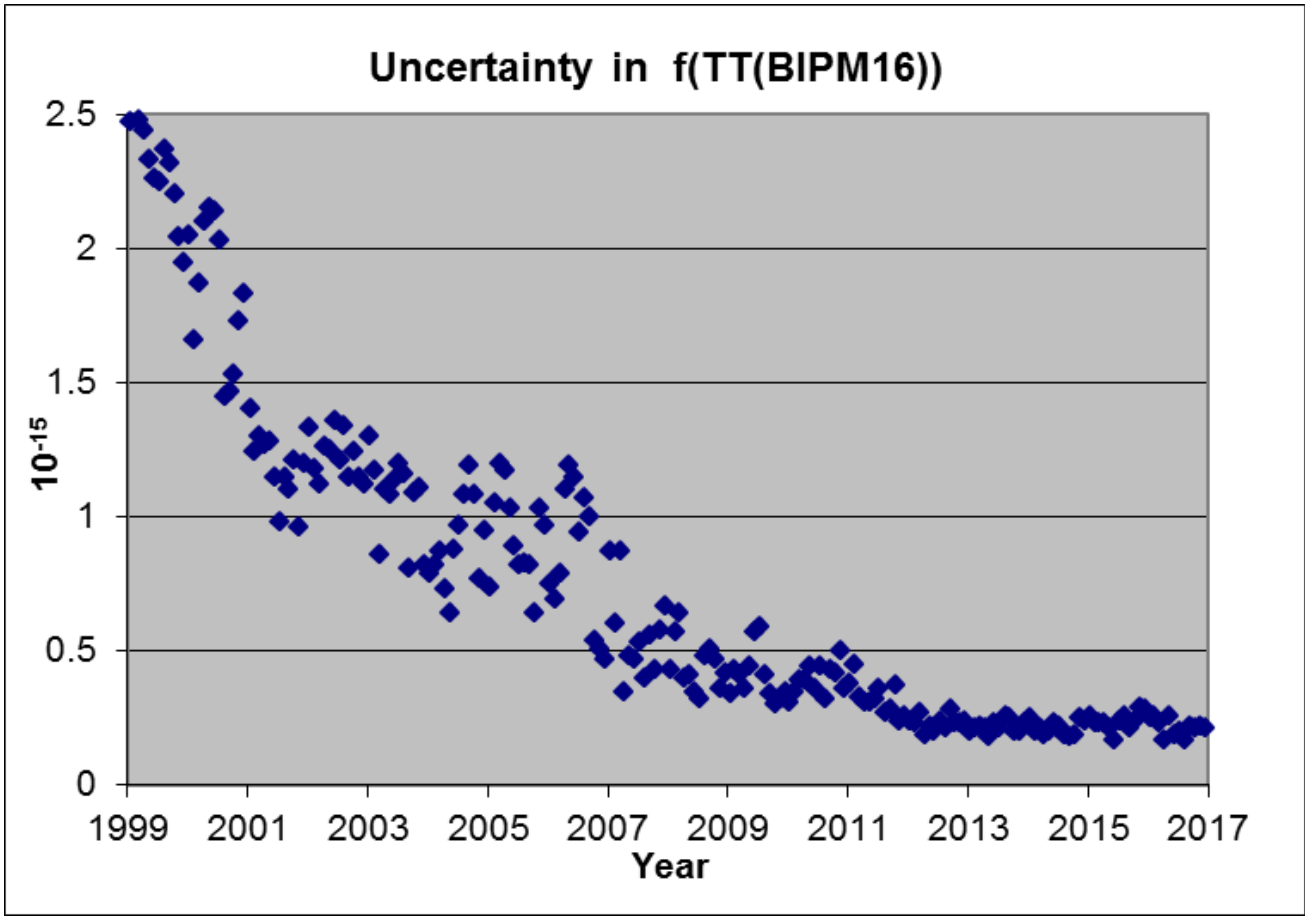
TT(BIPMxx)

- No significant change in the computation of TT(BIPM) since CCTF'2015.
- Starting with TT(BIPM15), the residuals with respect to TT(BIPM) are provided in one file for each standard, with one plot.
- Since 2010, a prediction of TT(BIPM) is published .
  - Since TT(BIPM13), as a function of TAI valid for the whole year

    For 2017: $TT(BIPM16)_{ext}$ = TAI + 32.184 s + 27679.0 ns - 0.05x(MJD-57749) ns
- 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.

TT(BIPM16)

- Frequency accuracy of TT(BIPM) has regularly decreased since the introduction of Cs fountains from
  2.5×10^{-15} in 1999 to $< 1 \times 10^{-15}$ since 2004, $< 5 \times 10^{-16}$ since 2008
  $\sim 2 \times 10^{-16}$ since 2012.
- It directly depends on the uncertainty budget of the PFS, but is somewhat limited by frequency transfer noise.



Primary and secondary frequency standards in 2016

Primary Standard	Type /selection	Type B std. Uncertainty / 10^{-15}	Operation	Comparison with	Number/typical duration of comp.
IT-CsF2	Fountain	(0.17 to 0.48)	Nearly continuous	H maser	7 / 10 d to 35 d
NIM5	Fountain	1.4	Discontinuous	H maser	4 / 20 d to 20 d
NIST-F2	Fountain	0.31	Discontinuous	H maser	1 / 20 d
PTB-CS1	Beam /Mag.	8	Continuous	TAI	12 / 30 d to 35 d
PTB-CS2	Beam /Mag.	12	Continuous	TAI	12 / 30 d to 35 d
PTB-CSF1	Fountain	0.7 then (0.35-0.37)	Discontinuous	H maser	6 / 15 d to 35 d
PTB-CSF2	Fountain	(0.20 to 0.22)	Nearly continuous	H maser	10 / 10 d to 30 d
SU-CsFO2	Fountain	0.25	Discontinuous	H maser	4 / 15 d to 30 d
SYRTE-FO2	Fountain	(0.25 to 0.35)	Nearly continuous	H maser	12 / 10 d to 30 d
SYRTE-FORb	Fountain	(0.28 to 0.35)	Nearly continuous	H maser	13 / 10 d to 35 d

- Frequency standards reported and evaluated in 2016 (see annual report)
  - 44 from 7 PFS fountains (down from 68 in 2014, 52 in 2015)
  - 13 from 1 SFS
- Four of the fountains are nearly continuously operating

Contributions of frequency standards to TAI

No significant change in the content of Circular T for the publication of PFS evaluations between July 2015 (top) and March 2017 (bottom)

Secondary Standards contribute to the steering of TAI since July 2013, if deemed not detrimental.

=> new column introduced.

Standard	Period of Estimation	d	u_A	u_B	$u_{1/Lab}$	$u_{1/Tai}$	u	$u_s$rep	Ref(u_s)	Ref(u_B)	u_B(Ref)	Note
PTB-CS1	57199 57234	-9.80	6.00	8.00	0.00	0.06	10.00	PFS/NA		T148	8.	(1)
PTB-CS2	57199 57234	-1.60	3.00	12.00	0.00	0.06	12.37	PFS/NA		T148	12.	(1)
IT-CsF2	57199 57229	0.09	0.29	0.30	0.12	0.20	0.48	PFS/NA		T315	0.18	(2)
SYRTE-FO2	57199 57234	0.86	0.35	0.27	0.11	0.17	0.49	PFS/NA		T301	0.23	(3)
SYRTE-FORb	57204 57224	0.87	0.20	0.31	0.11	0.28	0.48	1.3	[1]	T301	0.32	(3)
SU-CsFO2	57199 57234	0.78	0.19	0.25	0.13	0.51	0.61	PFS/NA		T315	0.50	(4)

Notes:
(1) Continuously operating as a clock participating to TAI
(2) Report 29 JUL. 2015 by INRIM
(3) Report 03 AUG. 2015 by LNE-SYRTE
(4) Report 03 JUL. 2015 by SU
[1] CIPM Recommendation 1 (CI-2013) : Updates to the list of standard frequencies in Proces-Verbaux des Seances du Comite International des Poids et Mesures, 102nd meeting (2013), 2014, 188 p.

July 2015

The second table gives the BIPM estimate of *d*, based on all available PFS and SFS measurements over the period MJD 56839-57234, 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	
57199-57234	0.55×10^{-15}	0.27×10^{-15}	(2015 JUN 26 - 2015 JUL 31)

Standard	Period of Estimation	d	uA	uB	ul/Lab	ul/Tai	u	uSrep	Ref(uS)	Ref(uB)	uB(Ref)	Steer	Note
PTB-CS1	57784 57809	-18.71	6.00	8.00	0.00	0.15	10.00	PFS/NA		T148	8.	Y	(1)
PTB-CS2	57784 57809	-0.28	3.00	12.00	0.00	0.15	12.37	PFS/NA		T148	12.	Y	(1)
SYRTE-FO2	57784 57809	-1.30	0.40	0.32	0.11	0.32	0.61	PFS/NA		T301	0.23	Y	(2)
SYRTE-FORb	57784 57809	-0.91	0.20	0.29	0.11	0.32	0.49	0.7	[1]	T328	0.34	Y	(2)
SYRTE-SR2	56954 56964	0.81	0.20	0.04	0.10	0.53	0.57	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SR2	57179 57199	0.46	0.20	0.04	0.10	0.28	0.36	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SR2	57469 57479	-1.39	0.25	0.20	0.11	0.53	0.63	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SR2	57539 57554	-1.24	0.30	0.04	0.11	0.37	0.49	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SRB	57539 57554	-1.22	0.25	0.05	0.10	0.37	0.46	0.5	[1]	[2]	0.05	N	(3)
PTB-CSF2	57779 57809	-1.36	0.09	0.20	0.03	0.13	0.26	PFS/NA		T287	0.41	Y	(4)

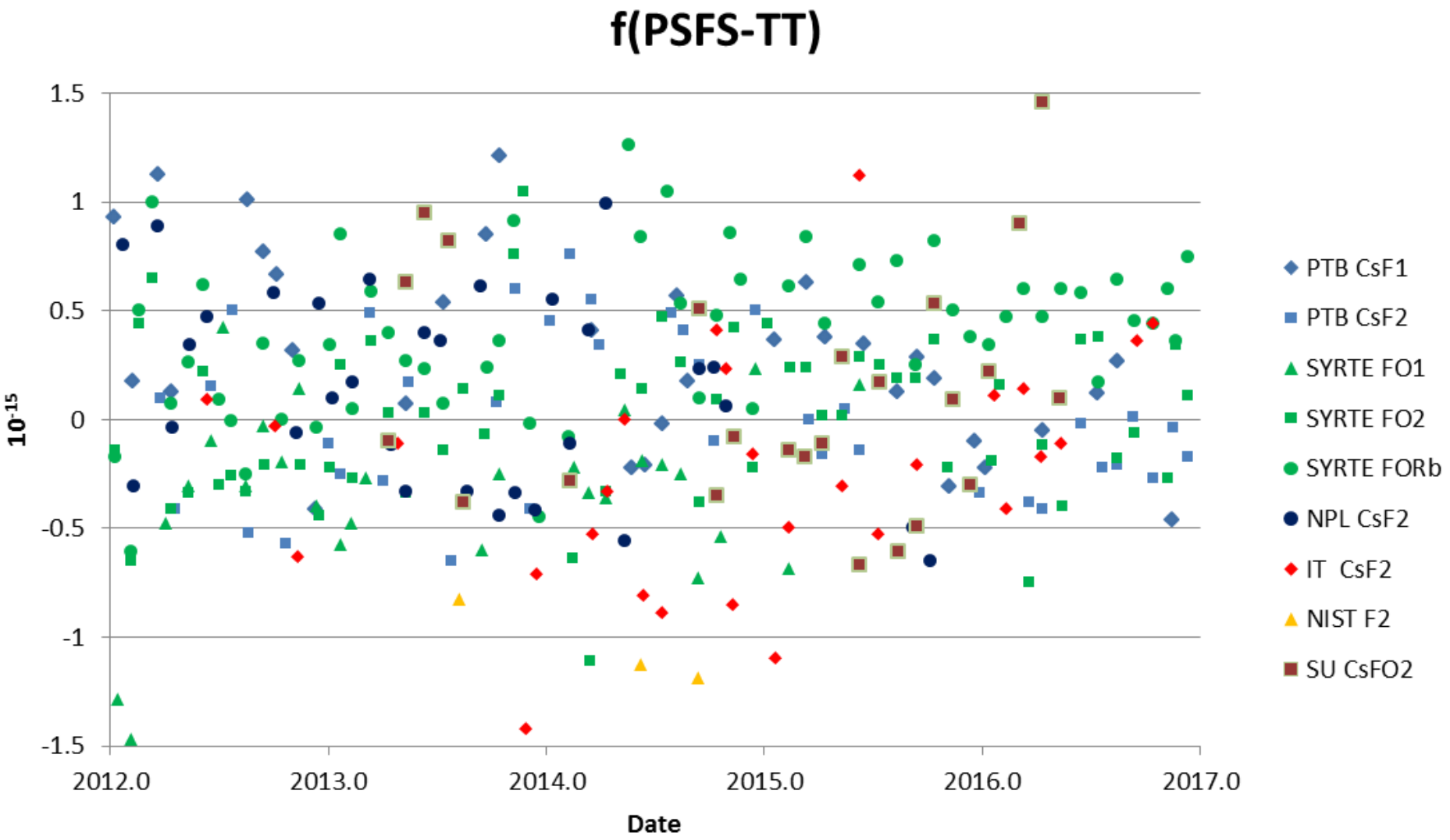
Notes:
(1) Continuously operating as a clock participating to TAI
(2) Report 03 MAR. 2017 by LNE-SYRTE
(3) Report 16 AUG. 2016 by LNE-SYRTE
(4) Report 02 MAR. 2017 by PTB
[1] CIPM Recommendation 2 (CI-2015) : Updates to the list of standard frequencies in Proces-Verbaux des Seances du Comite International des Poids et Mesures, 104th meeting (2015), 2016, 47 p.
[2] Optical to microwave clock frequency ratios with a nearly continuous strontium optical lattice clock. Lodewyck J., Bilicki S., Bookjans E., Robyr J.L., Shi C., Vallet G., Le Targat R., Nicolodi D., Le Coq Y., Guena J., Abgrall M., Rosenbusch P. and Bize S.. Metrologia 53(4), 1123, 2016.

March 2017

Table 2: Estimate of d by the BIPM based on all PSFS measurements identified to be used for TAI steering over the period MJD57424-57809, and corresponding uncertainties.

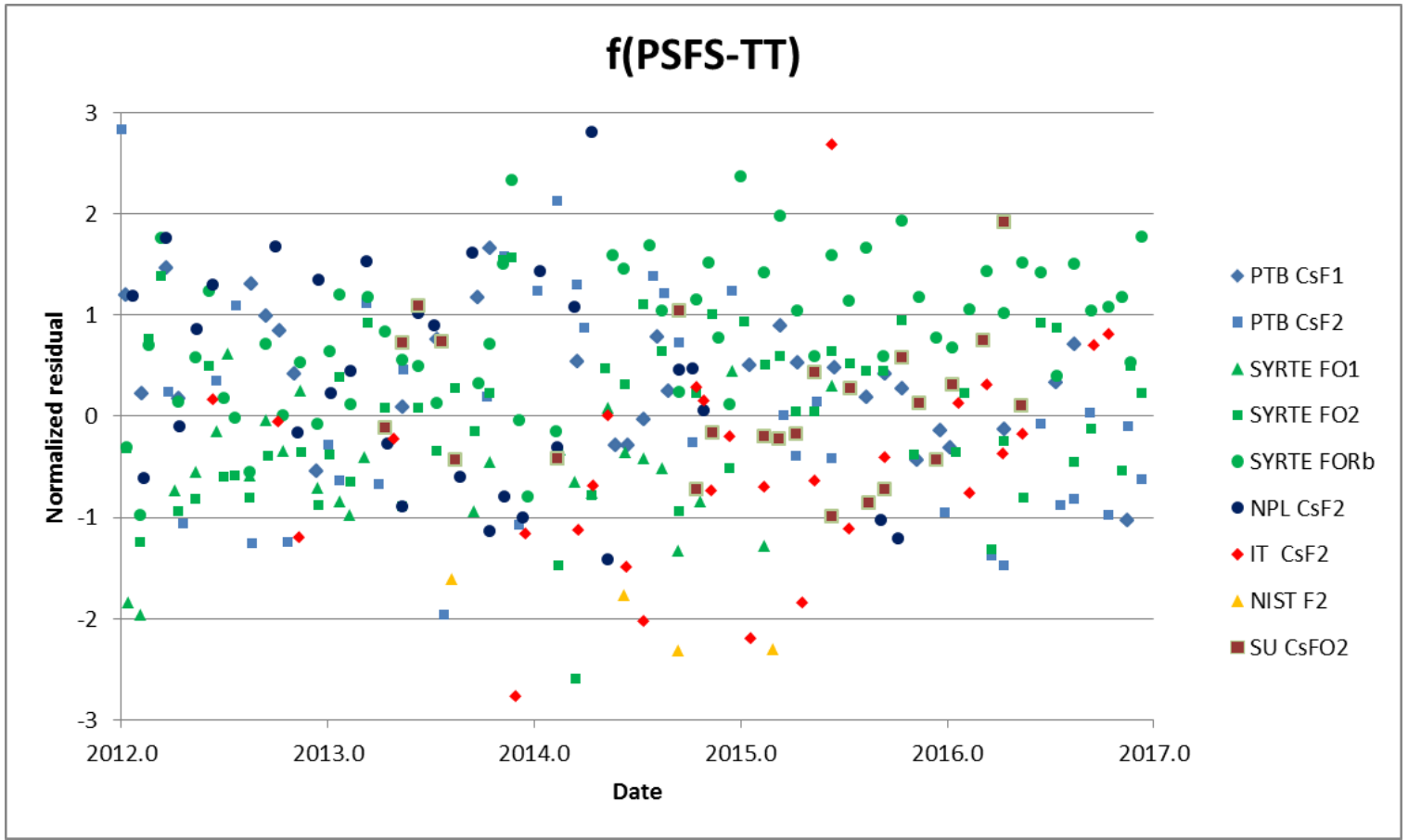
Period of estimation	d	u	
57784-57809	-1.24x10**-15	0.25x10**-15	(2017 JAN 31 - 2017 FEB 25)

TT(BIPM) allows to estimate the performance of PSFS



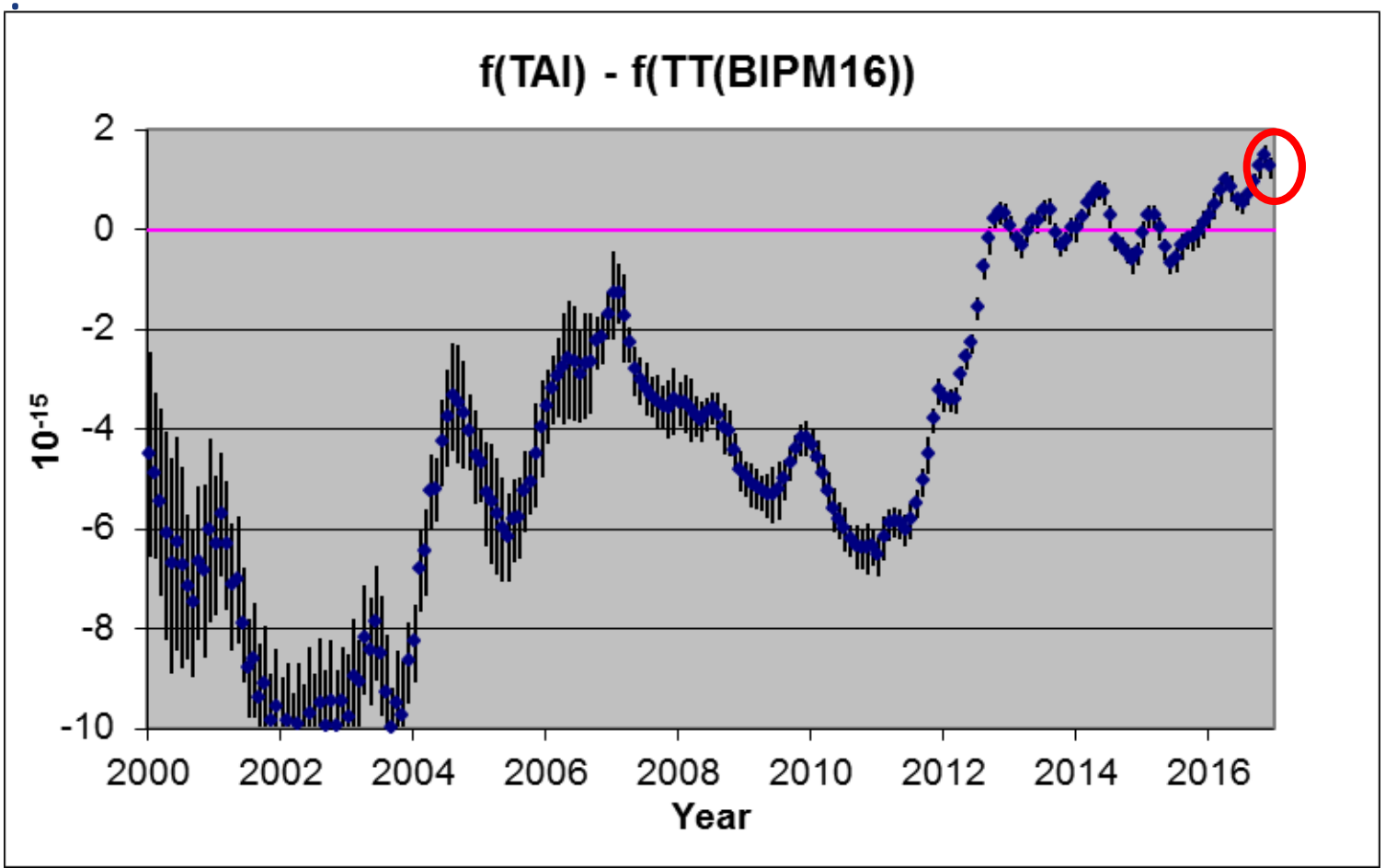
- Overall (1396 evaluations over 24 years) normalized residuals have a standard deviation of 1.0
- Still OK in recent years
  - Since 2010 (630 evaluations) Stdev = 1.01, since 2014 (270 evaluations) Stdev = 0.93
- Cs fountains regularly operating since 2010 have no significant systematic bias

  SYRTE-FO1 and IT-CsF2 marginally below TT; PTB CsF1 marginally above TT; NIST F2 has 4 values only



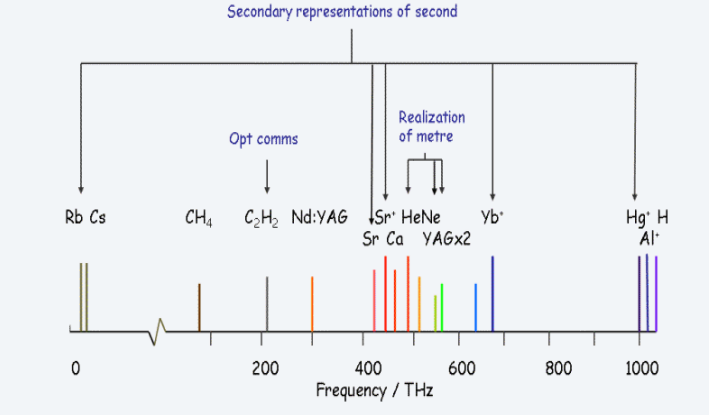
TT(BIPM) allows to estimate the accuracy of TAI

- Since end 2012, the drift of clocks is determined vs. TT
- f(TAI –EAL) remained constant (no steering) until end 2016.
- Too much « drift » over 2016 => steering reintroduced 12/2016 to 04/2017.



Secondary representations of the second (1/2)

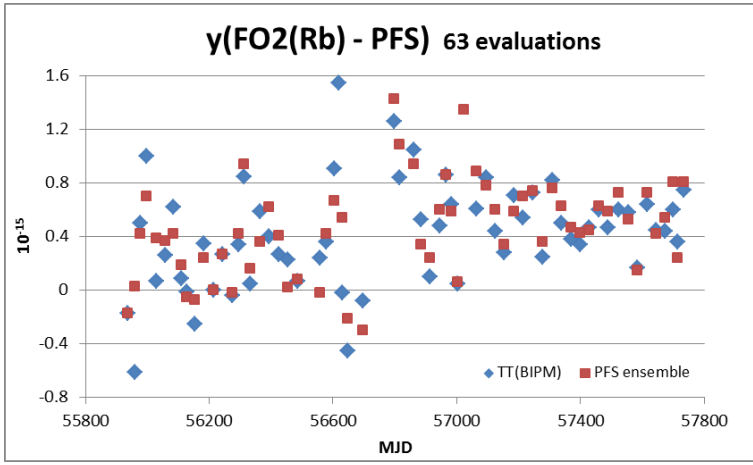
- CCL-CCTF working group on Frequency Standards: producing and maintaining a single list of *Recommended frequency standard values for applications including the practical realization of the metre and* ***secondary representations of the second***.



- Since 2012 SYRTE has reported > 65 evaluations of the Rb fountain FO2(Rb).
- Early 2017, the CCTF WG on PSFS endorsed the submission by the SYRTE of evaluations of two Sr lattice standards.
  - Results published (starting CirT 350), not to be used for steering.

Secondary representations of the second (2/2)

- 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.
- The evaluation of transition frequencies (by the WG FS) serves two purposes
  - Obtain the most consistent and accurate set of values;
  - Obtain values to be used in reporting evaluations for TAI;
- Case of the Rb
  - The 2015 value is an average of two determinations differing by ~7.4×10^{-16} ;
  - One of them has provided > 65 reports to the BIPM, the other one 0; => New 2017 value
  - A 5×10^{-16} shift in the Rb frequency may bias TT(BIPM) and the estimation of the TAI frequency by fractions of 10^{-16}, up to 1×10^{-16} .



- Case of the Sr
  - New 2017 value of the transition frequency OK.
  - We have two (+?) reported standards => correlations to take into account

Conclusions

- Primary frequency standards still continue to gain in accuracy. We are at / slightly below 2×10^{-16}.
- The full accuracy of PFS is not completely passed to TAI and TT(BIPM) because of
  - (mostly) the noise of frequency transfer;
  - (also possibly) TAI instability, slightly inconsistent PSFS evaluations;

- The PFS reported uncertainties are globally consistent with the data.
  - this implies that TT(BIPM) accuracy is $\sim 2 \times 10^{-16}$ since 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 / check their reference frequency
  - to prepare for future changes
- Recommend that SFS evaluations, used in the WG FS, should as much as possible be traceable to TAI.