Observation of millisecond pulsar in 1997~2005 by Kashima 34m telescope and Brief introduction of atomic time scales

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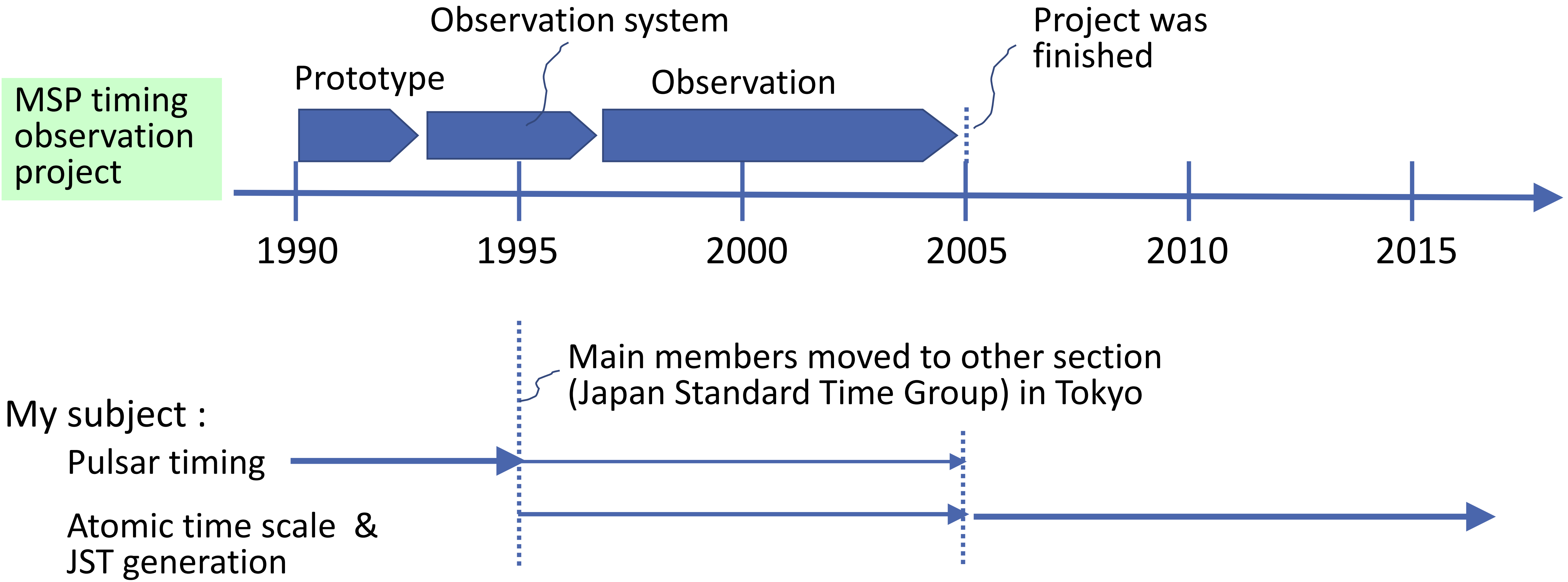
History of pulsar timing observation at Kashima



- Now I draw apart from pulsar research…

Contents

★1. Observation of millisecond pulsar (MSP) timing at Kashima

- ●Points of system design
- ●Observation results of “PSR 1937+21”* in 1997~2005 (*Currently “PSR J1939+2134)

★2. Atomic time scale as references of pulsar timing

- ● Relation between PSR timing observation and atomic standard time
- ● Introduction of atomic standard time

★3. How to make an averaging atomic time scale

- ● Principle
- ● Important points

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★3. How to make an averaging atomic time scale

- ● Principle of the algorithm
- ● Important points

★1: Our object of MSP timing observation

- Application of pulse timing of MSP to a new standard time scale.
- Trial of precise timing measurement by middle-size (34mϕ) telescope.

284 *Astronomical times*

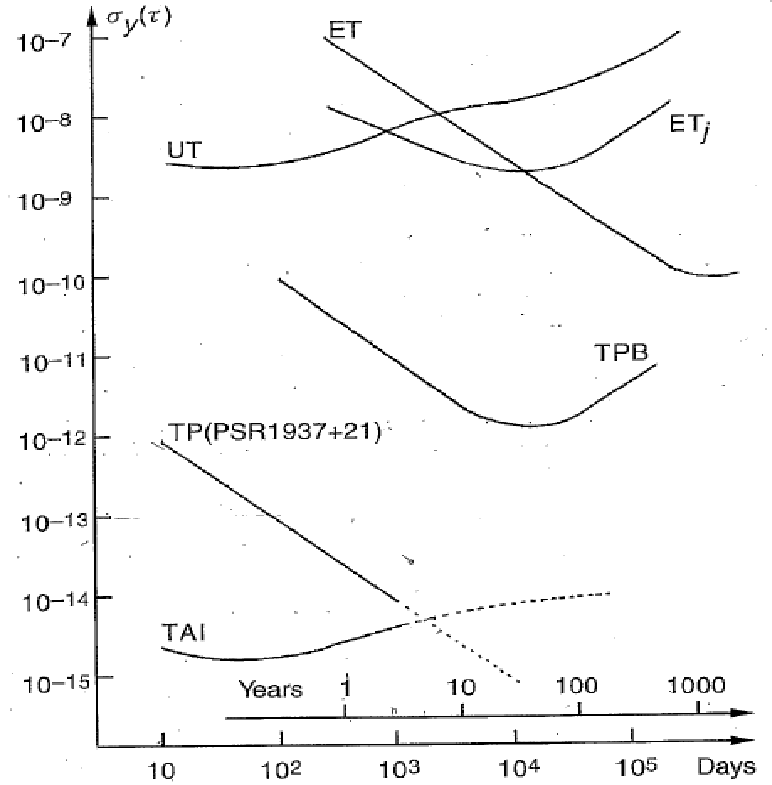


Fig. 8.7. Instability of astronomical time scales and TAI: ET and ET*j* are ephemeris time scales set up by observing the Sun and Moon, respectively; UT is Universal Time; TP (PSR1937+21) is time based on the rotation of the named pulsar; TBP is time based on the orbital motion of a binary pulsar (optimal case). Concerning TAI, properties for 1998 are projected into the future. This figure is based upon elements from [8.18] and [8.21].

Audoin & Guinot, "The Measurement of Time" ,p284 (Cambridge University Press, 2001)

★1: Requirement for observation system

- **Observation precision of pulse time of arrival (ToA):**

$$\sigma_t = \frac{W^{3/2} \cdot Tsys}{(B \cdot T \cdot P)^{1/2} \cdot G \cdot \langle S \rangle} \quad \text{(sec)}$$

W	:	half-width of pulse (sec)	P	:	pulse period (sec)
$\langle S \rangle$	:	flux density (Jy)			
$Tsys$	:	system temperature (K)	G	:	antenna gain (K/Jy)
B	:	bandwidth (Hz)	T	:	integration time (sec)

➡ **σ_t can be improved by expanding B and T.**

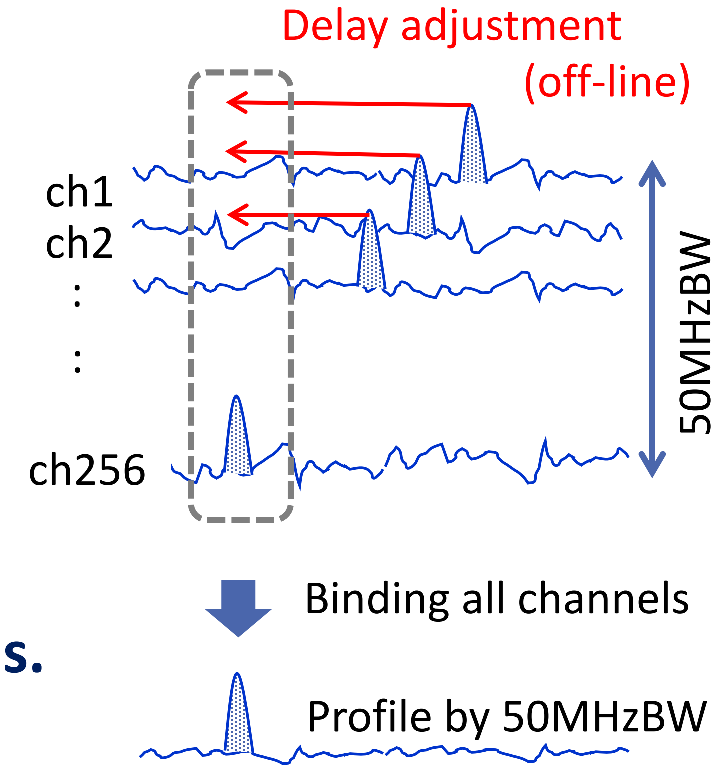
➡ **Wideband observation & Long integration are required.**

★1: Point in Wideband observation

- **Pulse broadening by Dispersion delay**
  - **Pulse arrival time is delayed by interstellar medium.**

$$dt_{DM} = 4.15 \times 10^{3} \times DM \times f^{-2} \quad \text{(sec)}$$

DM : Dispersion Measure (pc cm^{-3})
f : observation frequency (MHz)

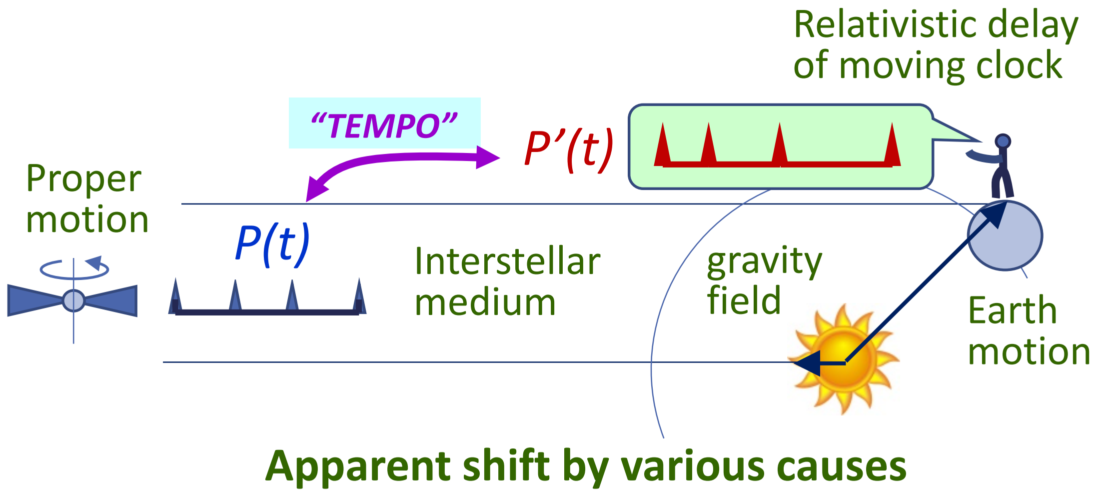


1. **Wideband signal should be received by narrow channels.**
   → Acousto-Optic spectrometer (256ch /50MHzBW)
2. ***dt_{DM}* should be adjusted in each channel before binding.**

★1: Point in long integration

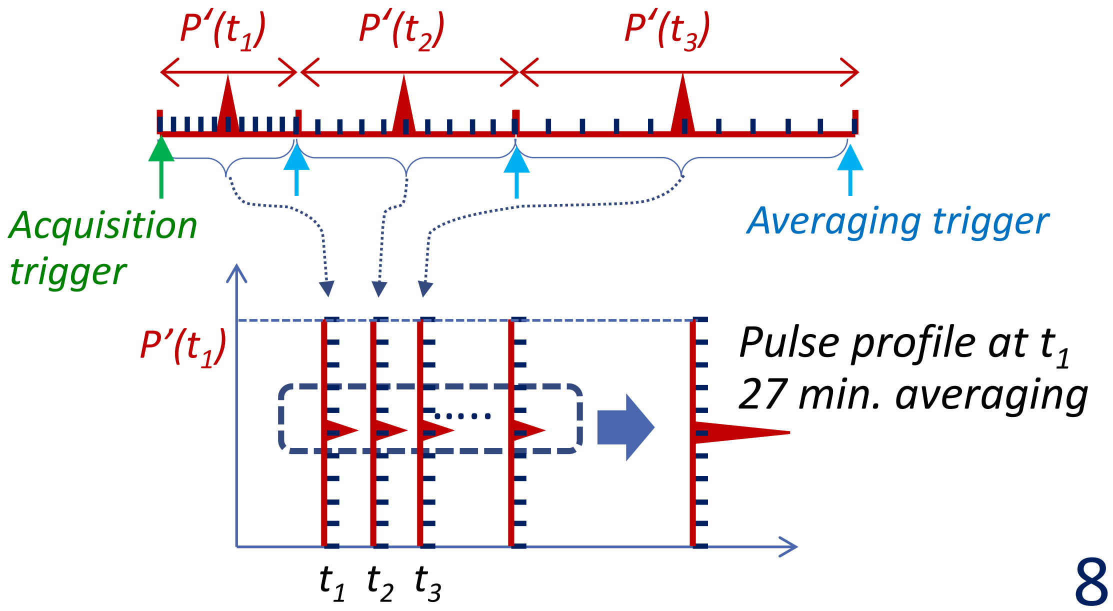
- **Apparent shift of observed pulsar period**

We need ~30 min. averaging for MSP. But,
Pulse periods apparently shift during 30 min.

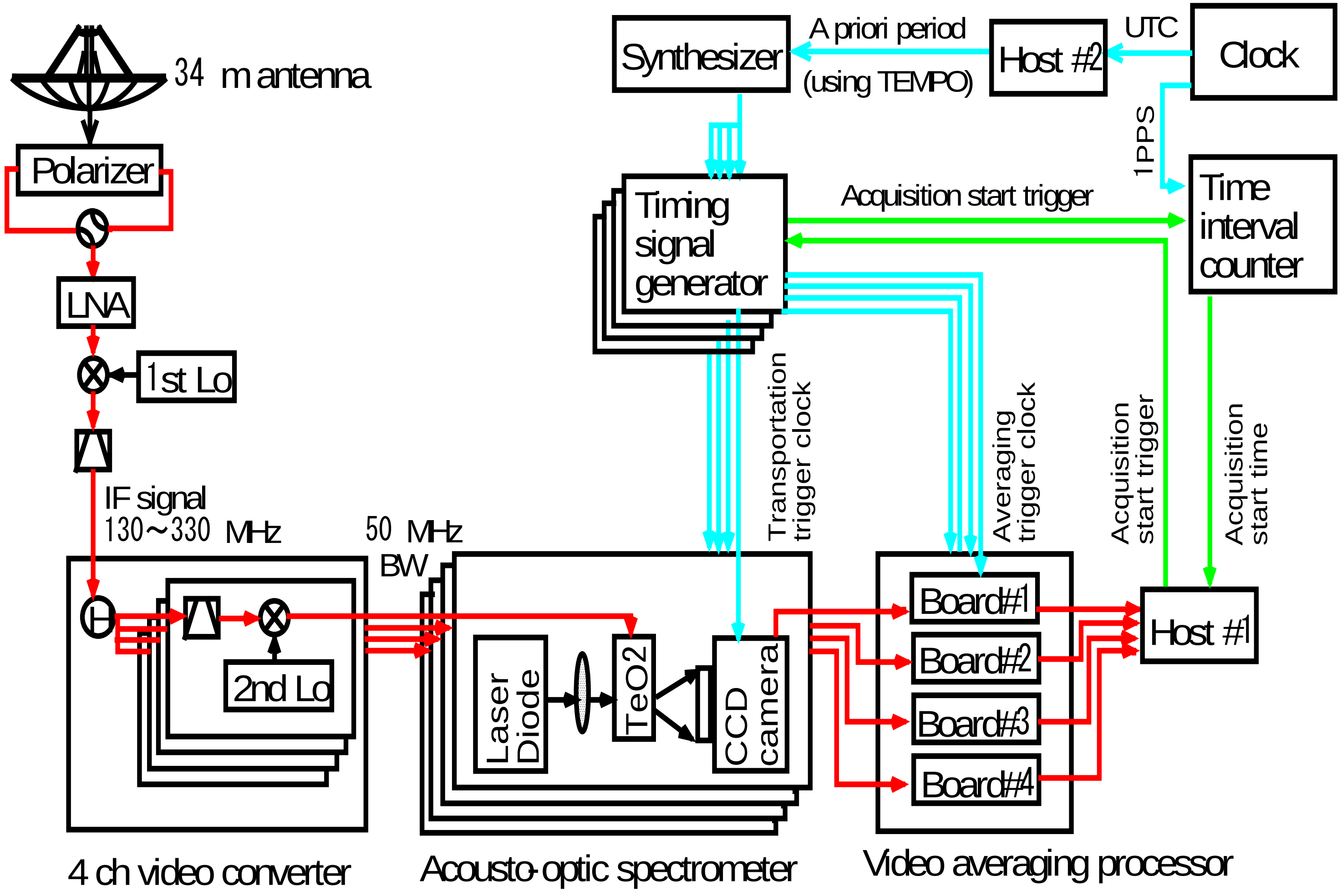


- **Averaging period was synchronized to *P'(t)*.**

1. *P'(t)* at averaging start time was estimated by "*TEMPO*" program.
2. Averaging triggers ↑ were synchronized with these *P'(t)*.
3. Sampling resolution was 1/100 of *P'(t)*.



★1: Pulsar timing observation system (* condition in 2003)



●34m telescope

- S-band RHCP
- Tsys : 71 K, Gain : 0.426 K/Jy

● Acousto-Optic Spectrometer

- Total Bandwidth : 200 MHz (50M x 4)
- Freq. resolution : 200 kHz (50MHz/256ch)
- Time resolution : P / 100

● Averaging processor

- A/D convertor : 8bit
- Pulse accumulation < 2^{24} times (~ 17 million pulses)

● Timing control

- Reference time : UTC
- UTC link precision : < 10ns
- Frequency reference : H-maser

★1:   Pulsar timing observation system (* condition in 2003)

★1: Process of timing determination (1)

(1) Detection of pulse profile

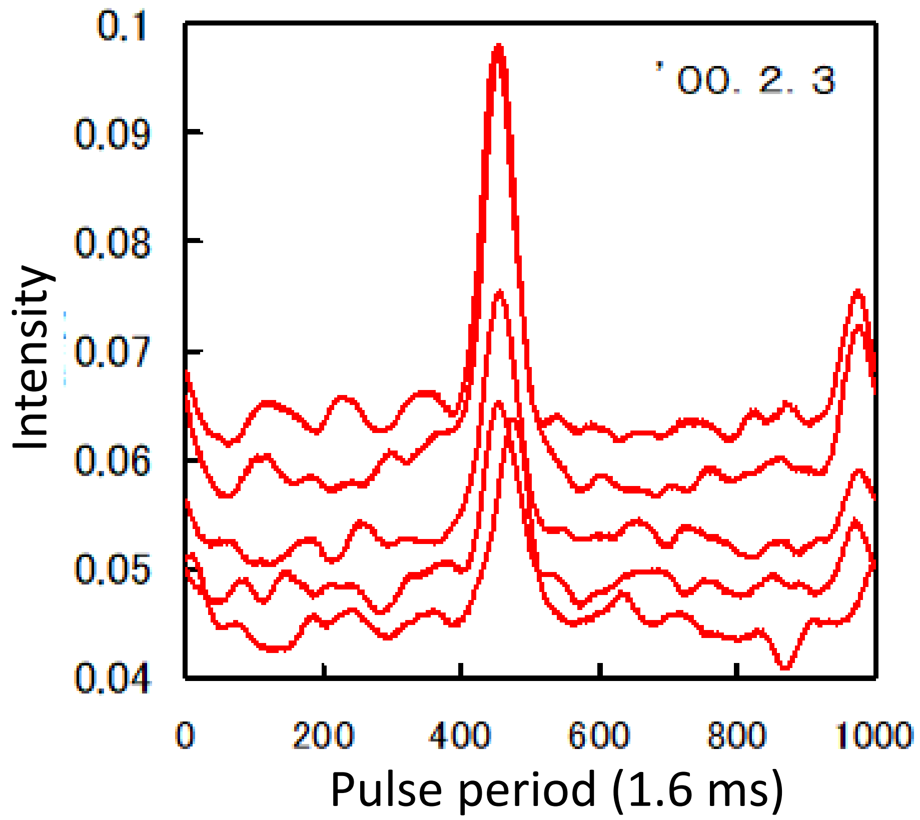
●PSR1937+21

- Pulse period : P ~ 1.6 ms
- Flux density : <S> ~ 3.3 mJy @ 2.2GHz

●Observation

- Frequency : S-band, RHCP
  Tsys ~ 71K, Gain~ 0.426K/Jy
- One profile : 50MHzBW, 27 min averaging
- Obs. Interval : 1 hour
- Usually, 6 ~ 8 hours observation in one day

5 Profiles (Feb.3, 2000)
in 50MHzBW
after 27min. averaging

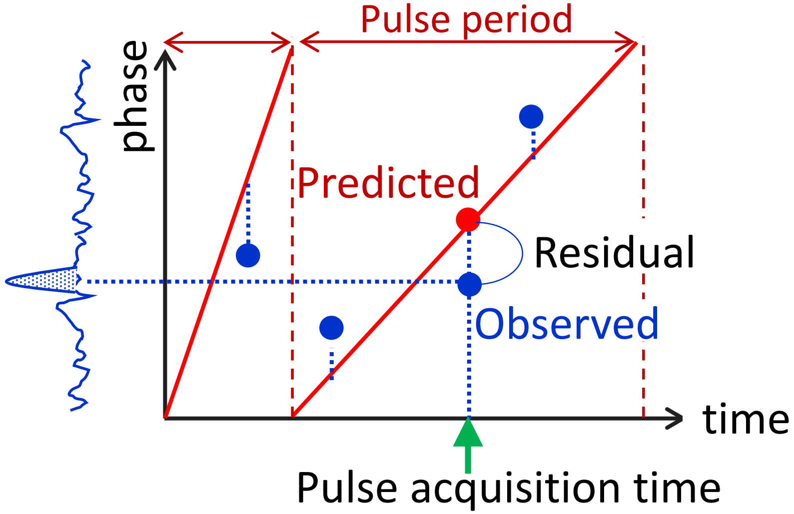


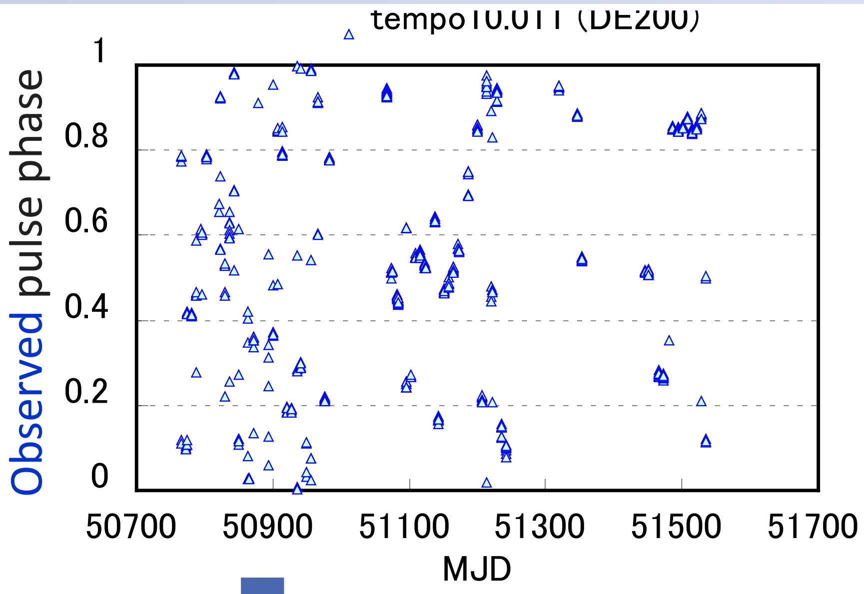
★1: Process of timing determination (2)

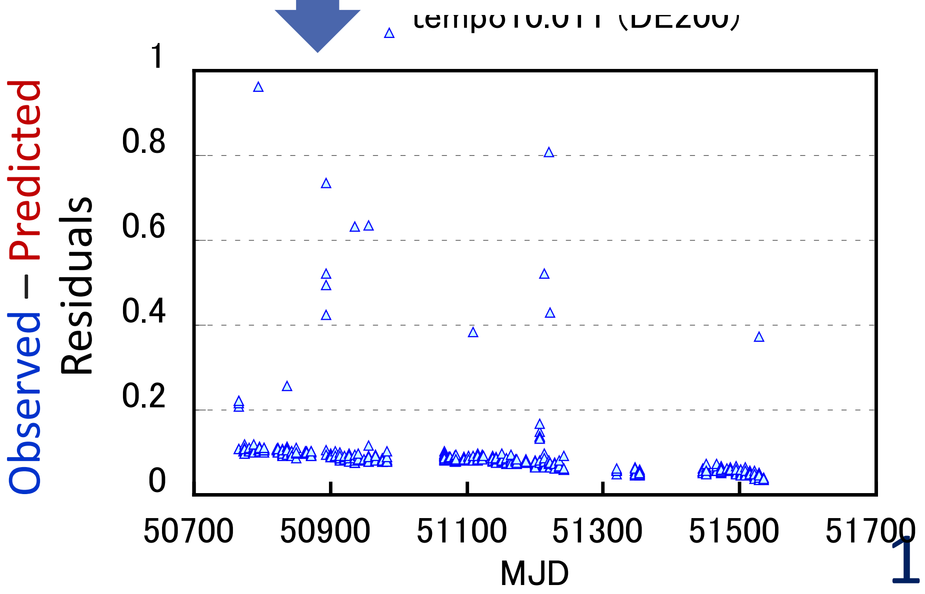
(2) Determination of pulse arrival timing

- **We need residuals from predicted pulse timing.**
- **Predicted timing was calculated from**
  - **Apparent shift :** $t_b = t - D/_{f^2} + (\vec{r}\cdot\vec{n})/_c + \Delta_{E\odot} + \Delta_{S\odot}$
  - **Rotation model :** $\emptyset(T) = \nu T + \frac{1}{2}\dot{\nu}T^2 + \cdots \quad \begin{cases} \nu = 1/_P \\ T = t_b - t_0 \end{cases}$

TEMPO program





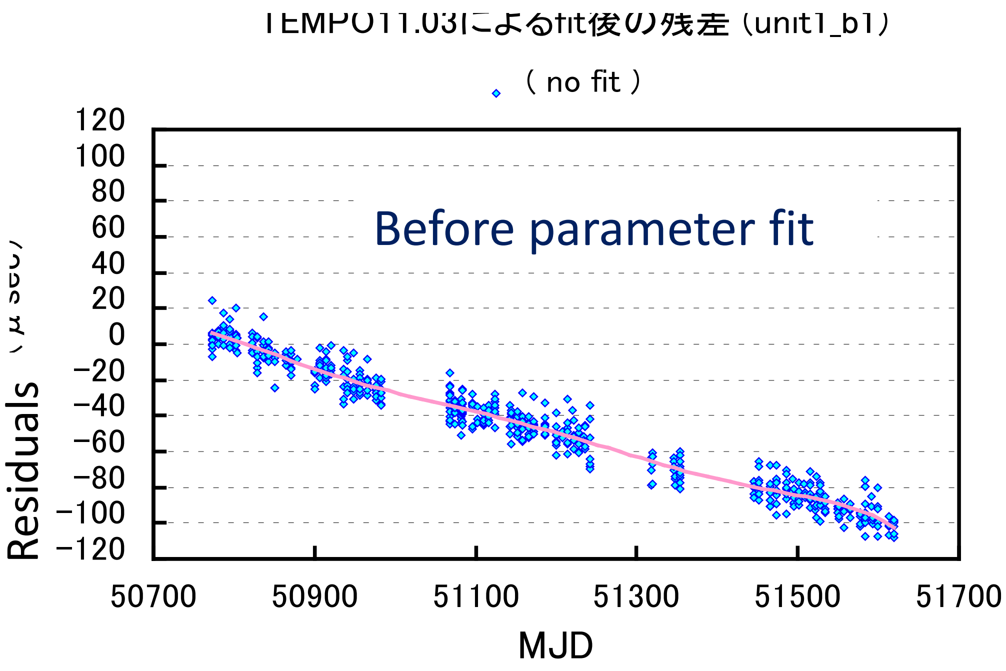


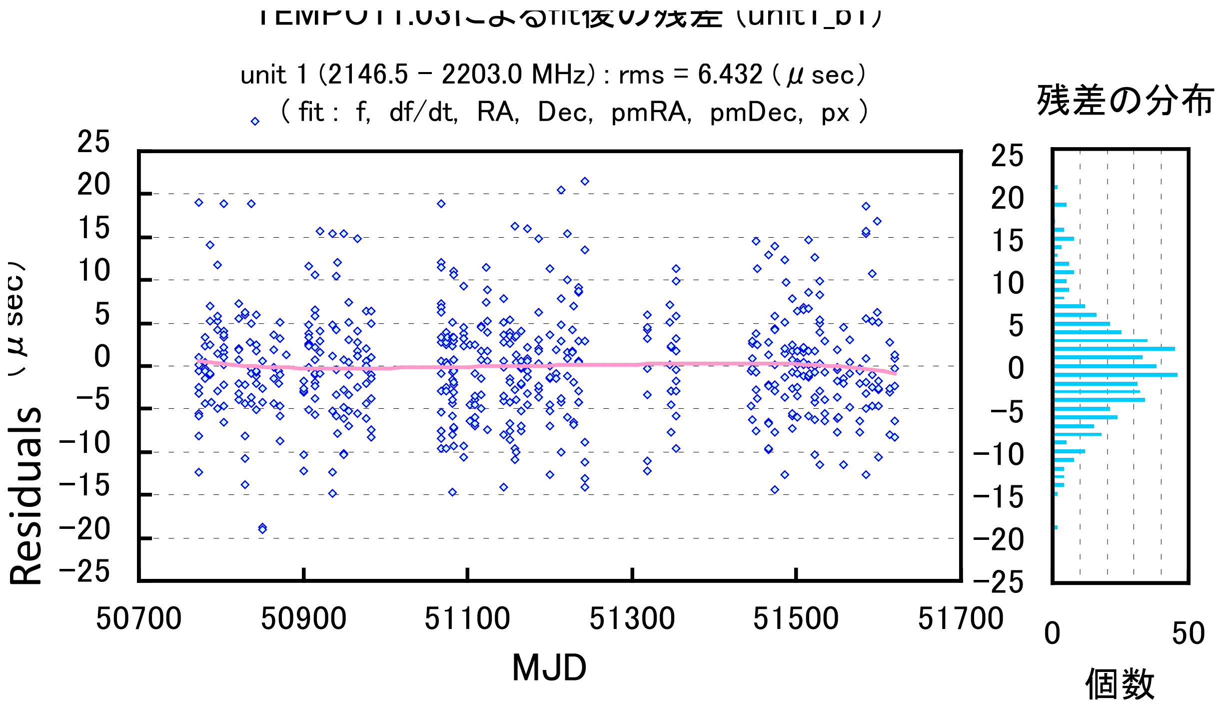
★1: Process of timing determination (3)

(3) Parameter fitting

- **Residuals showed some trend.**
- **Pulsar parameters were re-determined to minimize the residuals.**

TEMPO program





★1. Results of PSR1937+21 at Kashima (1997~2005)

● Observation

- Nov. ‘97 ~ Apr. ‘05 (~7.5yr)
- Weekly observation (6~8h /day)
- One data by 6~8 x 30min per day

● Reference

- UTC (by using GPS), Ephemeris: DE200

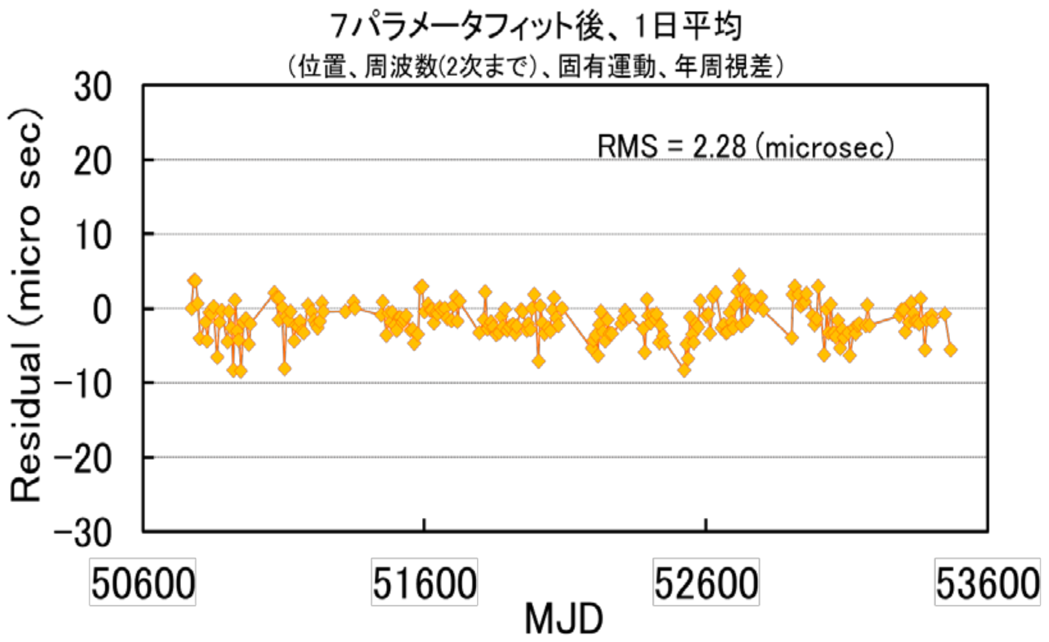
● Software

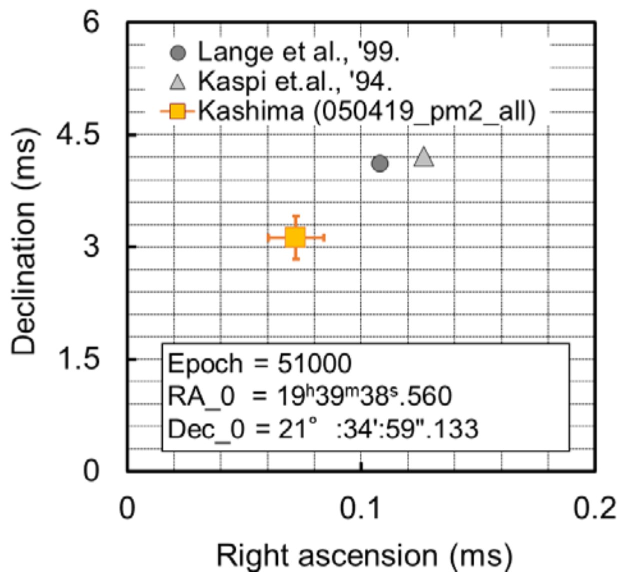
- “TEMPO ver. 11.005” : parameter fitting

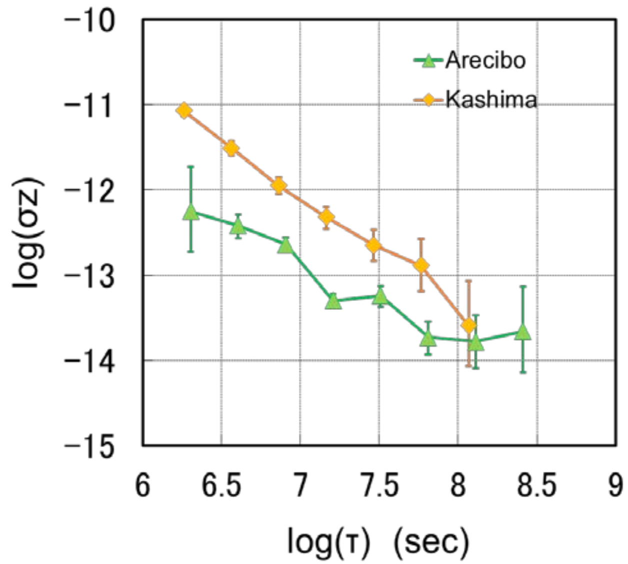
  In order to calculate the predicted TOA and parameter fitting, We use TEMPO program that is the pulsar timing analysis package developed by the Princeton pulsar group. (J.H.Taylor et al.,ApJ.,345,'89)

- “sigmaz” : frequency stability calculation

  (http://tycho.usno.navy.mil/pulsar/sigmaz/sigmaz.html)







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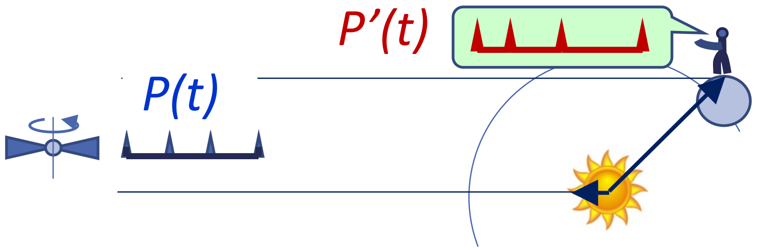
★2: Role of atomic time scale

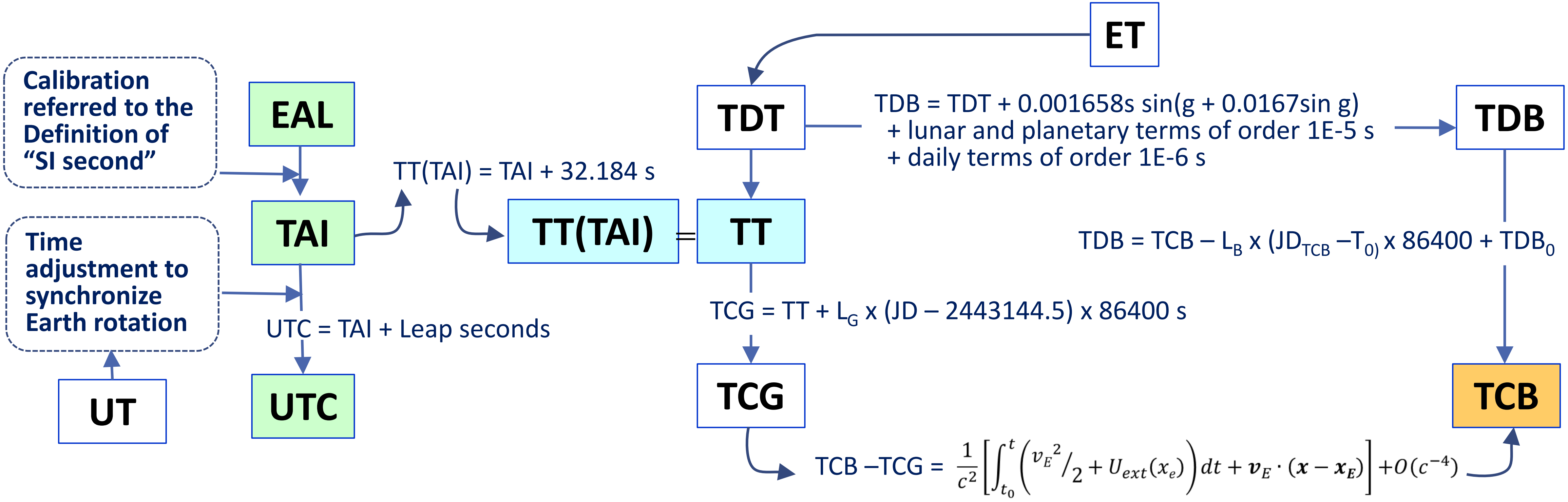
- Observed timing data are always relative value with reference to some reference time.
- What reference time should we use?
- Currently, world standard time for practical use is established from atomic time scale. Atomic time scale is also regarded as most stable.
- Pulsar timing is evaluated by comparing with atomic time scale.

★2: Comparison with atomic time scale

- **Observed *P'(t)* at a telescope should be converted to *P(t)* in Barycentric Coordinate Time (*TCB*) by *"TEMPO"*.**



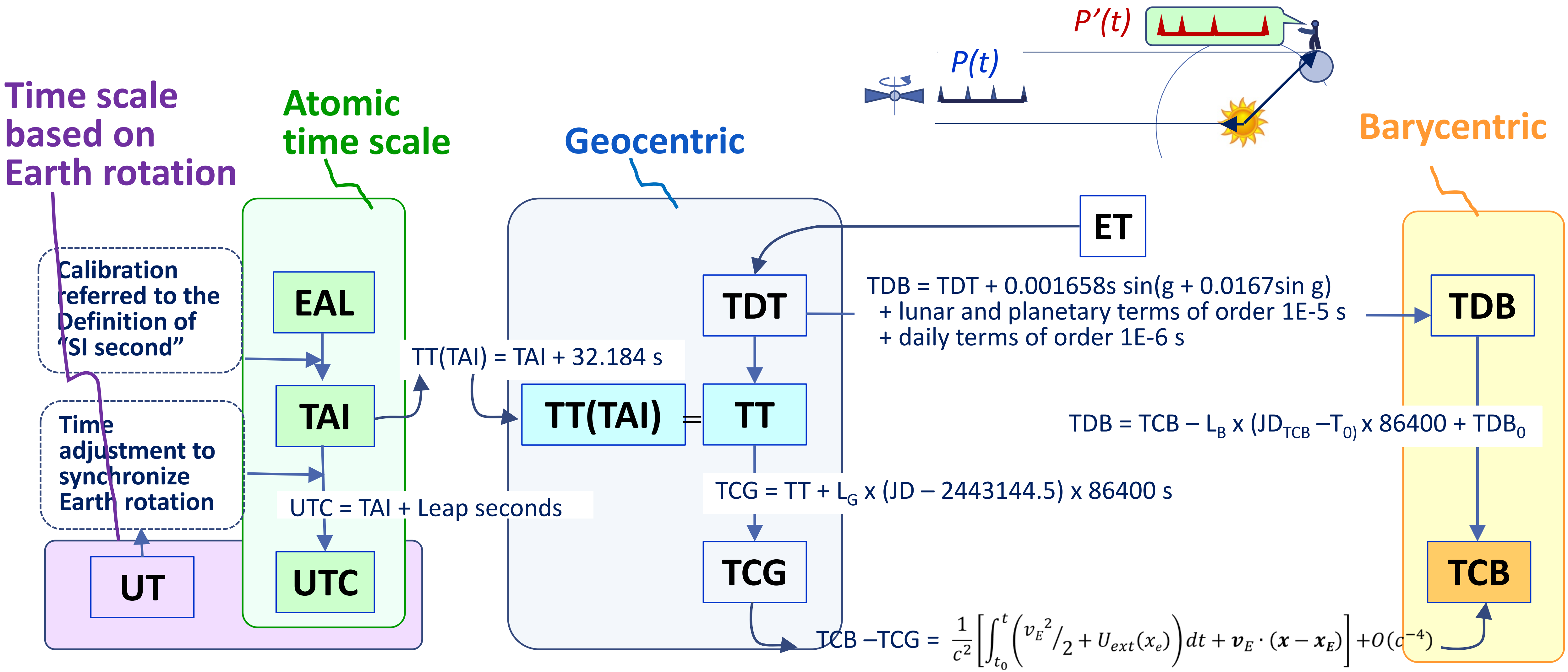
- **Observed residuals after "*TEMPO*" conversion w.r.t *UTC* show the pulse timing fluctuation at Barycenter w.r.t *TT*.**



*References : D.D.McCarthy, Metrologia, **48** (2011), S132-S144*

C. Audoin & B. Guinot, "The Measurement of Time", Cambridge Universal Press, 2001

★2: Comparison with atomic time scale



*References : D.D.McCarthy, Metrologia, **48** (2011), S132-S144*

C. Audoin & B. Guinot, "The Measurement of Time", Cambridge Universal Press, 2001

★2: Atomic Standard Time (1)

●EAL (free atomic time scale) :

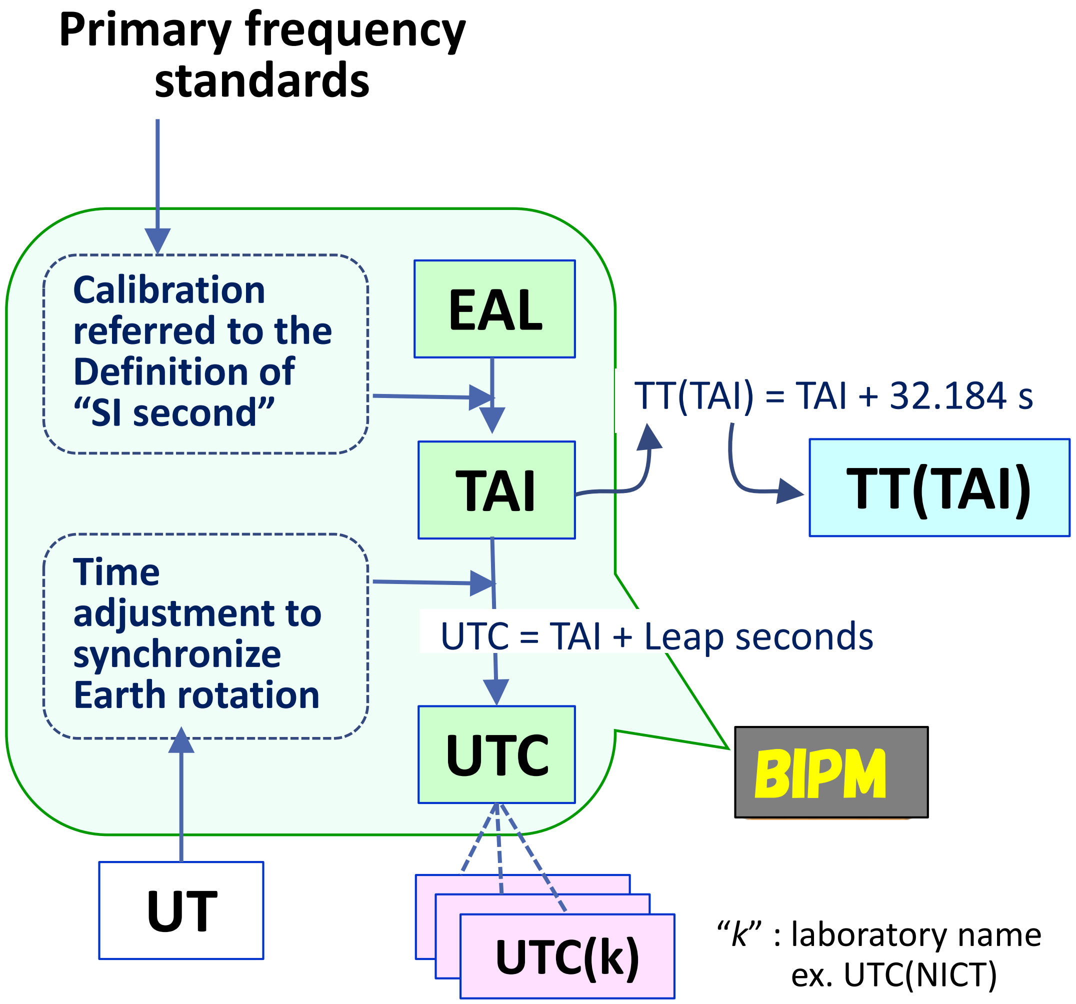
- Weighted average of about 500 atomic clocks.
- Calculation is once per month, using the batches of the last month data with 5 days interval.
- Target is long-term frequency stability.
  Stability : 2×10^{-16} @ 30d (BIPM report at CCTF2017)

●TAI (International Atomic Time) :

- TAI = EAL + calibration to ensure the accuracy.
- Target is Ultimate traceability to the SI second.
- Accuracy : 4×10^{-16} (BIPM report at CCTF2017)

●TT (Terrestrial Time) :

- TT was defined from TDT, but its “one second” is defined by proper time on the rotating geoid.
- TAI is a realization of TT (with time offset).
- “TT(TAI)” means “realization of TT based upon TAI”.



★2: Atomic Standard Time (2)

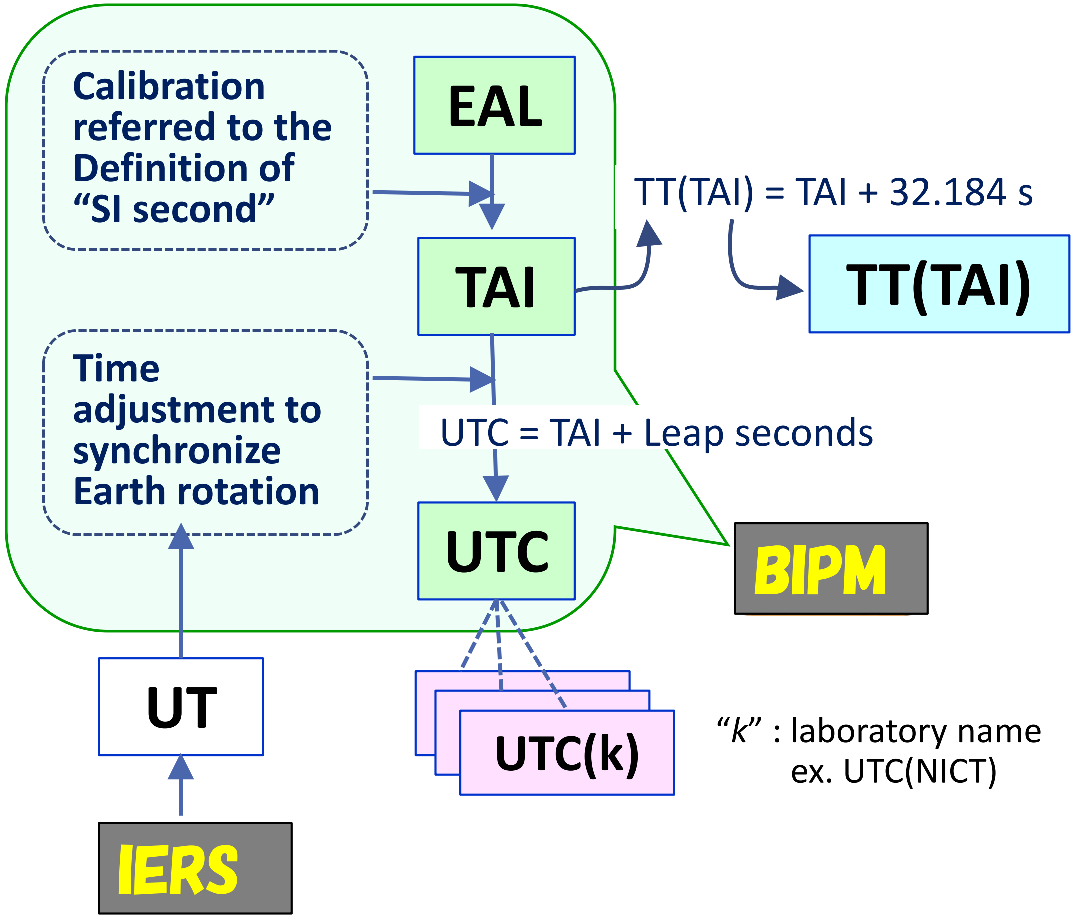
● **UTC (Coordinated Universal Time) :**

- UTC = TAI + leap second.
- UTC is used as world standard time.

UTC are not real-time (~ one month behind), discrete (every 5 days), and only numerical values.

● **UTC(*k*) :**

- UTC(*k*)s are local realization of UTC, and actually used as national standard times.
- UTC(k) is continuous and real-time timescale.
- BIPM monthly reports "*UTC – UTC(k)*", and national institutes adjust UTC(k) to trace UTC.



★2: TT(BIPM) : Reference for astronomy and deep space navigation

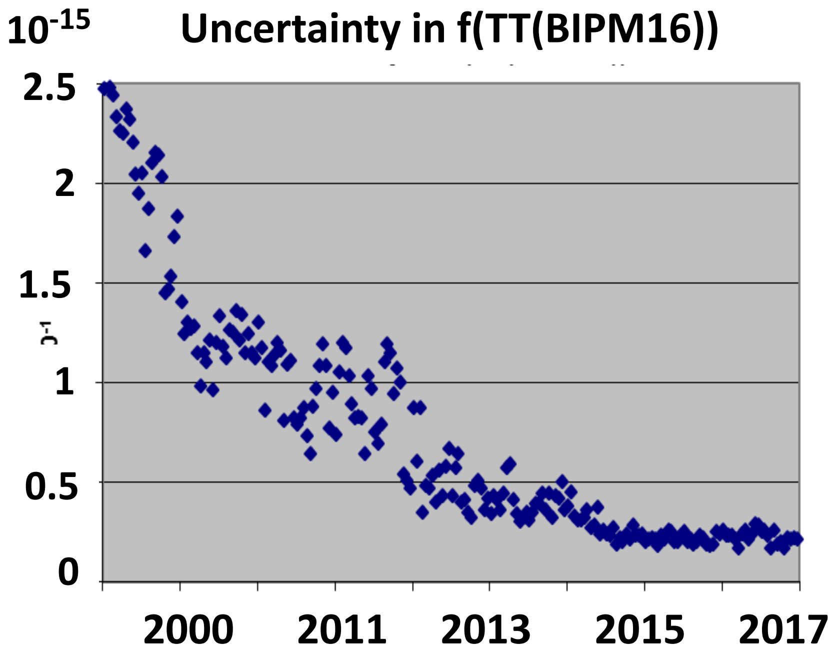
- As TAI is computed in real time and never corrected in retrospect, it is not optimal. Therefore the BIPM computes a post-processed time scale TT(BIPM).
- Each yearly version TT(BIPMxx) updates and replaces the previous one.

- 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(BIPM) − TAI"



Accuracy < 3 x 10^{-16}

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From BIPM report (CCTF2015,CCTF2017)

G.Petit and G. Panfilo, "Frequency standards in TAI and realization of TT(BIPM)", https://www.bipm.org/cc/CCTF/Allowed/20/CCTF_15-36-FS-TT.pdf, and https://www.bipm.org/cc/CCTF/Allowed/21/CCTF_17-36_FS-TT.pdf

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“EAL” is one of ensemble atomic time scales

★3. How to make an ensemble atomic time scale

- Basic theory
- Important points

It may be useful for making a pulsar ensemble atomic time scales.

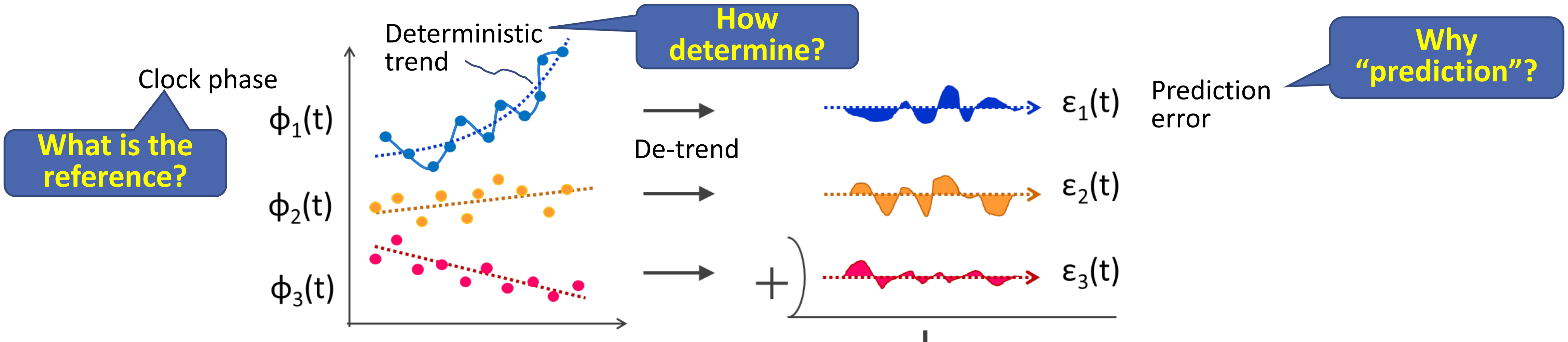
★3. Basic theory of ensemble atomic time scale

●Object:

- To obtain a stable frequency by averaging a fluctuation of each atomic clock.

●What we have to do:

- To average the fluctuation of each clock after removing the deterministic trend in advance.



■ **Ensemble atomic time scale *TA*:**

Weighted average of prediction error of each atomic clock phase

$$TA(t_k) = TA(t_{k-1}) + \sum_{i=1}^{N} w_i(t_k)\varepsilon_i(t_k)$$

★3. Important point ： Prediction process

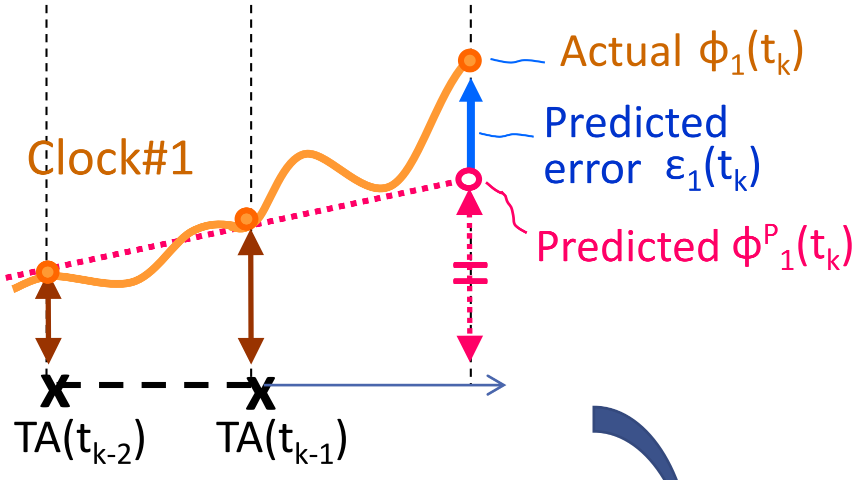
●**What is the reference?　Why prediction?**

- The reference of TA calculation is past TA, because the most stable time scale is TA itself.
- Therefore, in a procedure of TA(t_k) calculation, reference TA(t_k) has not determined yet.
- So, Prediction process is required.

*　If there is only Clock#1, TA(t_k) is pulled by the shift of Clock#1.　　However ….

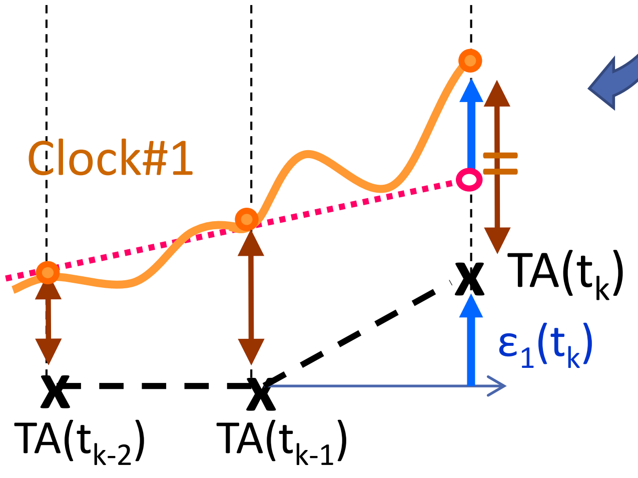
*　If quadratic prediction is done, $\varepsilon_1(t_k)$ may become small, so that the shift of TA(t_k) may be small.

*　If there are many clocks and average of $\varepsilon(t_k)$ becomes around zero, the shift of TA(t_k) may be small.



If there is only Clock#1,

$TA(t_k) = TA(t_{k-1}) + \varepsilon_1(t_k)$



★3. Important point : Concept of TA construction

- For establishing standard time, there is no reference in principle. So ensemble atomic time scale (= basement of the atomic standard time), should be independently constructed (= self-referenced).

- TA construction principle is based on an assumption that "clock trend is roughly predicted from its past behavior". If this assumption is collapsed, TA cannot be stable.

- It is very important to distinguish "what is deterministic behavior" and "what is not".

Investigation of clock behavior in advance is very important to find a proper algorithm.

★3. Important point : how to find a proper algorithm?

- Investigation of clock behavior;

1. Gathering sufficient clock data with reference to an available best reference.
   (UTC is usually used in long-term evaluation).
2. Grouping atomic clocks depending on their typical behaviors.
   (Cs clocks and Hydrogen Masers show different trends.)
3. Investigating the most suitable method for de-trending (i.e. prediction).
   (Linear fitting or quadratic ? Trend evaluation for 10 days or 3 months?)
4. Investigating the most suitable weighting.
   (Dynamical weighting is very effective for handling clock anomalies.)

- Proper parameters for TA algorithm are determined.

Summary

- We succeeded to develop a MSP timing observation system with 34m telescope at Kashima. According to the observation results of PSR1937+21 in '97-'05, frequency stability reached 10^{-14} order.

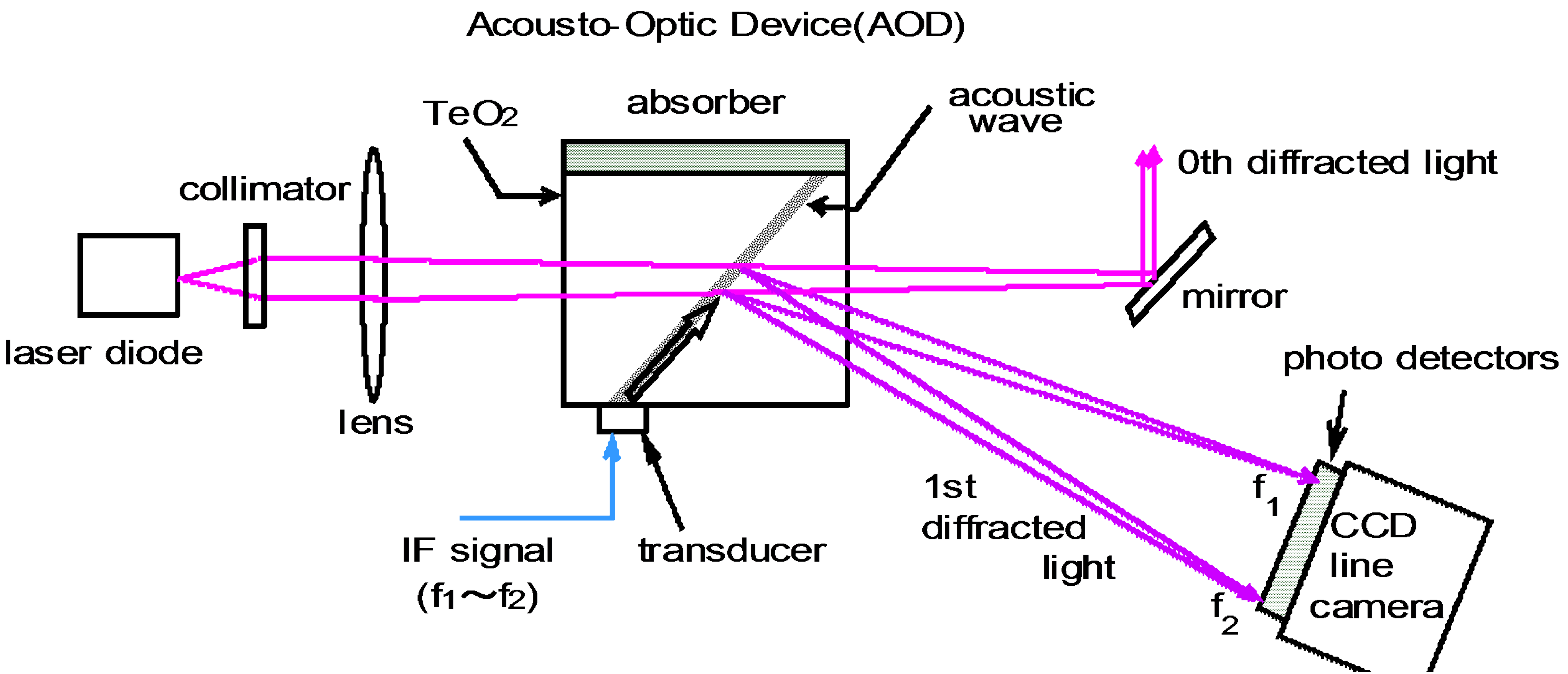
- Frequency stability of pulsar timing should be evaluated with reference to atomic standard time. BIPM supplies TAI and UTC as the world standard time. BIPM also supplies TT(BIPM) which is the best reference for pulsar timing.

- Pulsar time scale should be constructed independently from atomic time scale. There may be common consideration points with the algorithm of autonomic ensemble atomic time scale.

Filter bank is popular, but it is not practical for numerous channels.

→ AOS (Acousto-Optic Spectrometer)

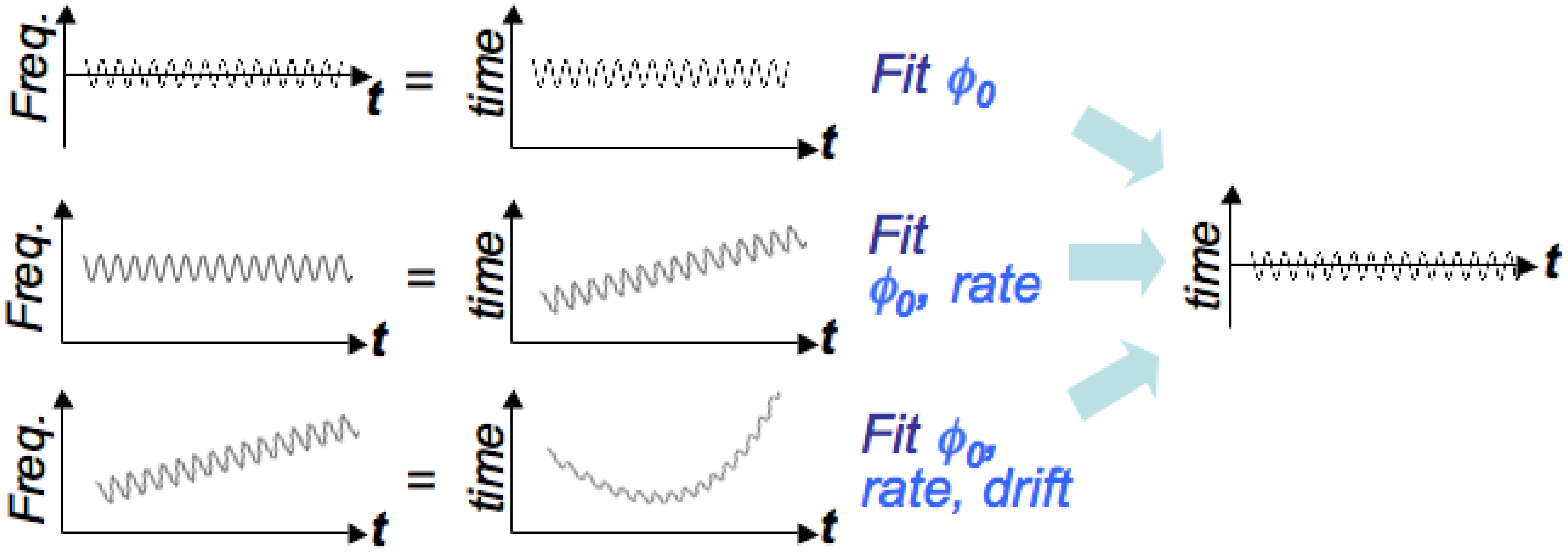
It is effective for dividing a wideband to many narrow channels.



★3. Important point ： Prediction (2)

●How determine the trend?

- Typical behavior should be checked from sufficient measurement data in advance.
- Evaluation span is also important.
  (Linear fitting in short term is safety, however, is sometimes insufficient.)



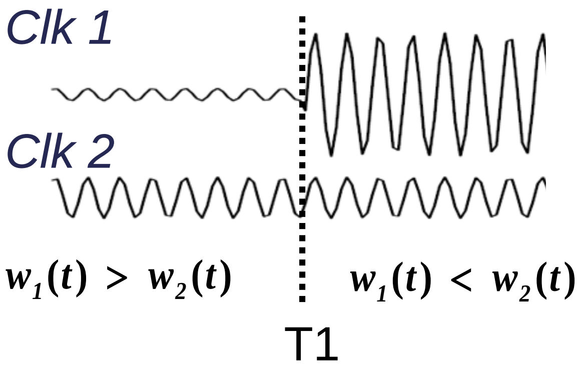
★3. Important point : Weighting

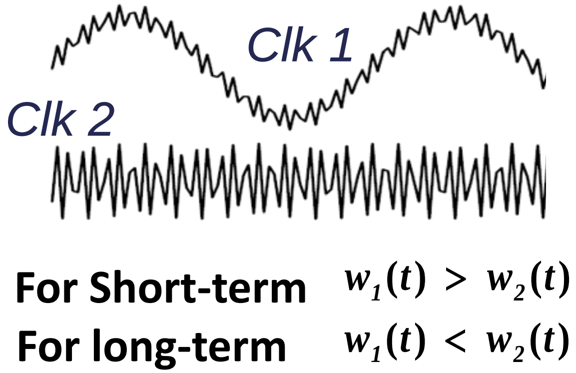
- **Basically, weighting depends on each clock's instability.**

$$w_i(t) \propto \frac{1}{\sigma(t)_i^2}$$

  - classical variance, predicted error^2, Allan variance
  - Even weighting is sometimes used when ensemble consists of similar and stable clocks.

- **Weighting should be change to reflect the clock's behavior.**
  - How to detect and reflect the clock anomalies are important problem.





★3. Important point : for reliable data acquisition

● System monitoring:

- To distinguish system anomaly from clock intrinsic anomaly is important.

● Time transfer technique:

- For combining remote clocks, it is as important as clock measurement.

Time transfer equipment calibrations

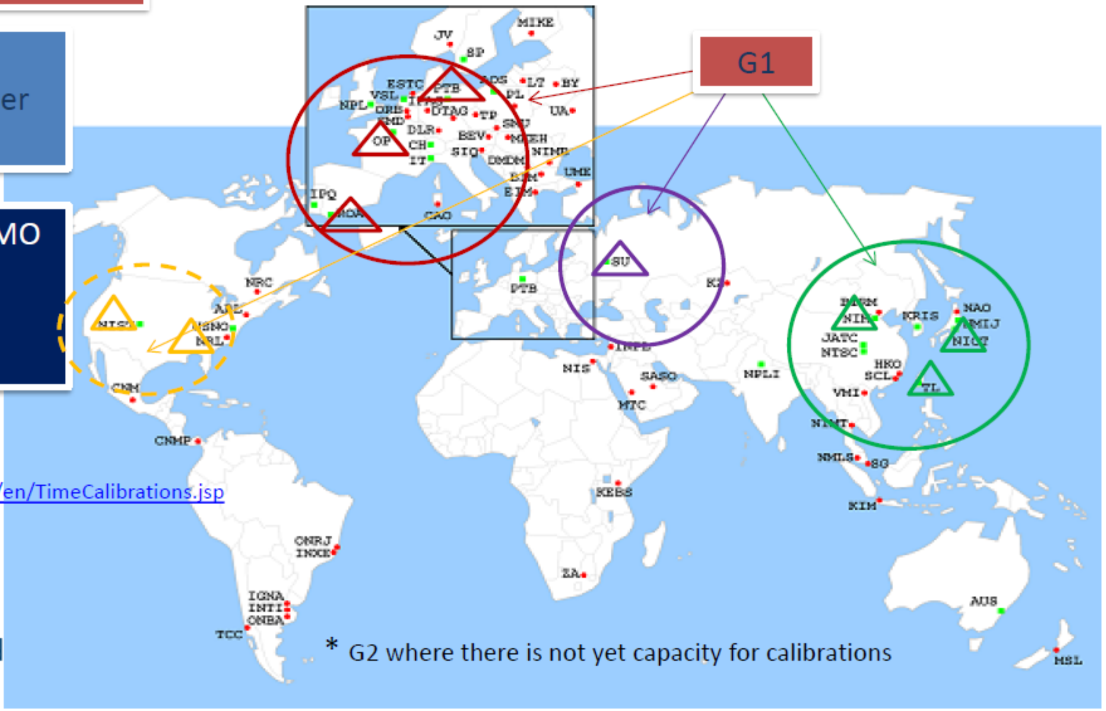
improving the accuracy of UTC-UTC(k) by implementing continuous calibration campaigns for reducing time link uB from 5 ns to < 2.5 ns

BIPM calibrates equipment in selected labs per region (G1) + G2*

- ✓ 1st campaingn to all G1 concluded/results implemented
- ✓ 2nd campaign ongoing in EURAMET and SIM G1
- ✓ ZA (NMISA) G2 equipment calibrated

RMOs calibrate equipment in other labs (G2)

BIPM validates RMO calibrations and computes final results



http://www.bipm.org/jsp/en/TimeCalibrations.jsp

* G2 where there is not yet capacity for calibrations

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E. F. Arias, "Report on the activities of the BIPM Time Department to the 21st Meeting of the CCTF", 21st Meeting of the CCTF
https://www.bipm.org/cc/CCTF/Allowed/21/CCTF_17-35_BIPM_TDept-report.pdf