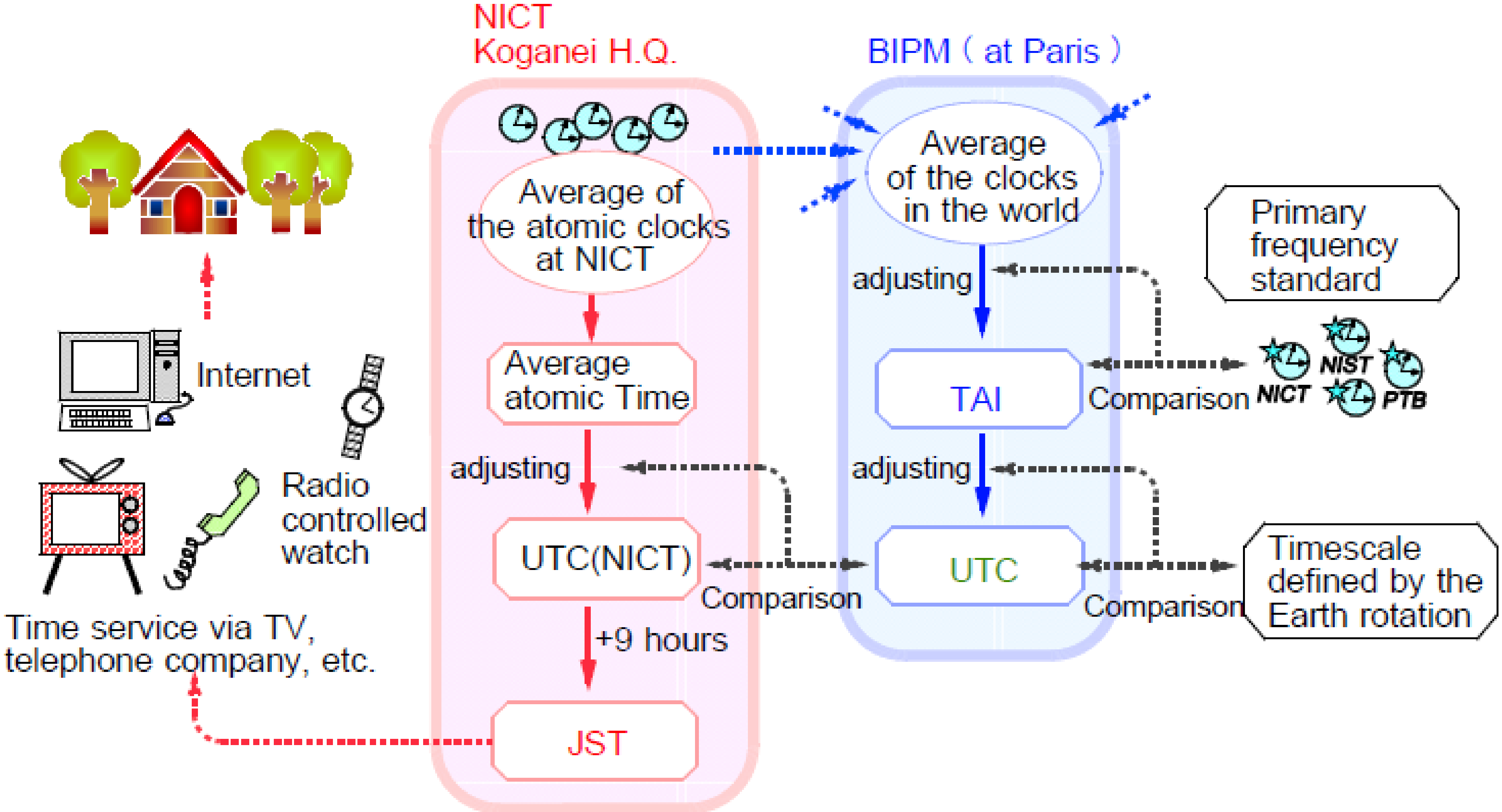
Welcome to the Home of

Japan Standard Time

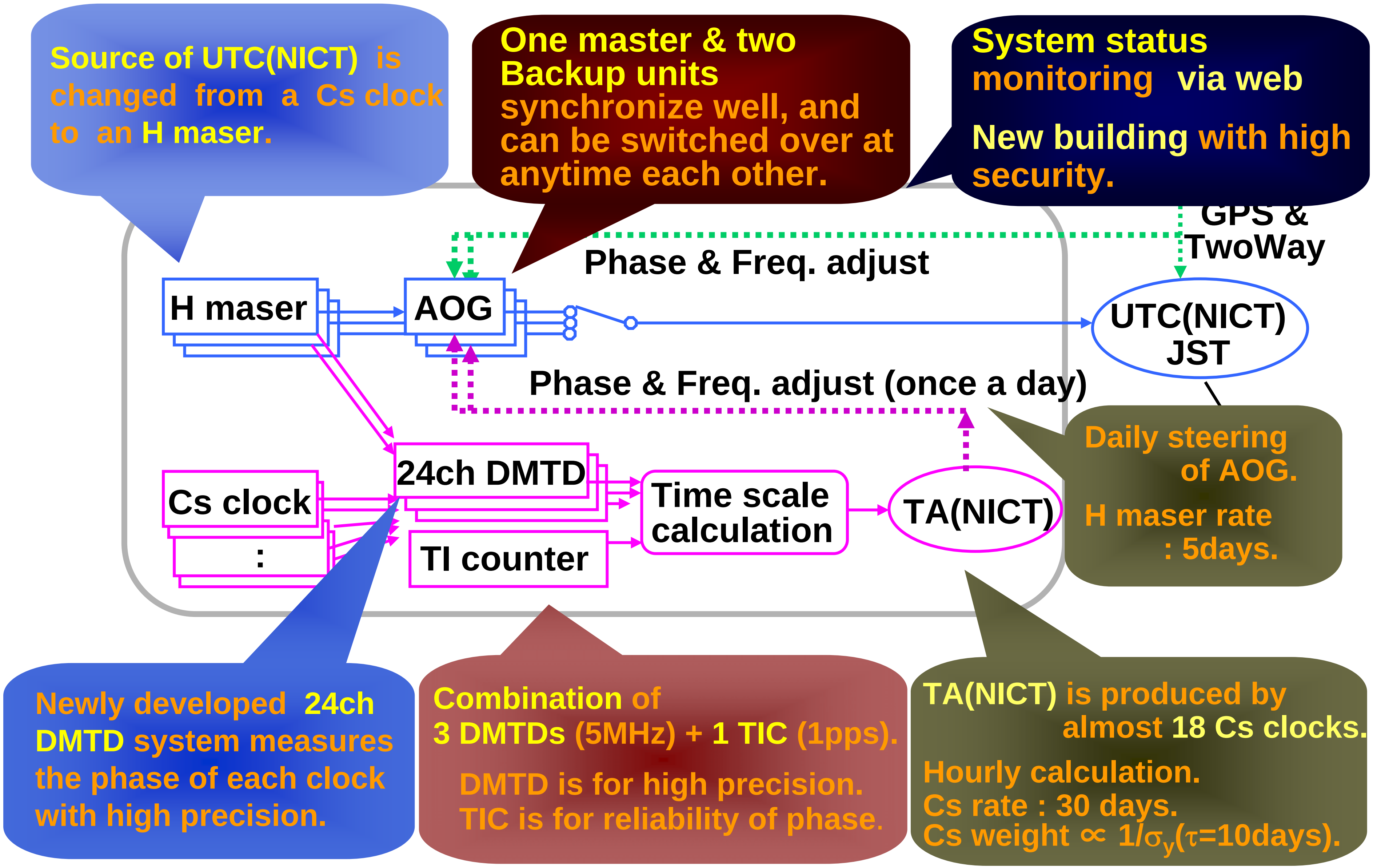
Kuniyasu IMAMURA, Fumimaru NAKAGAWA, Hiroyuki ITO

Japan Standard Time Project

How to generate Japan Standard Time

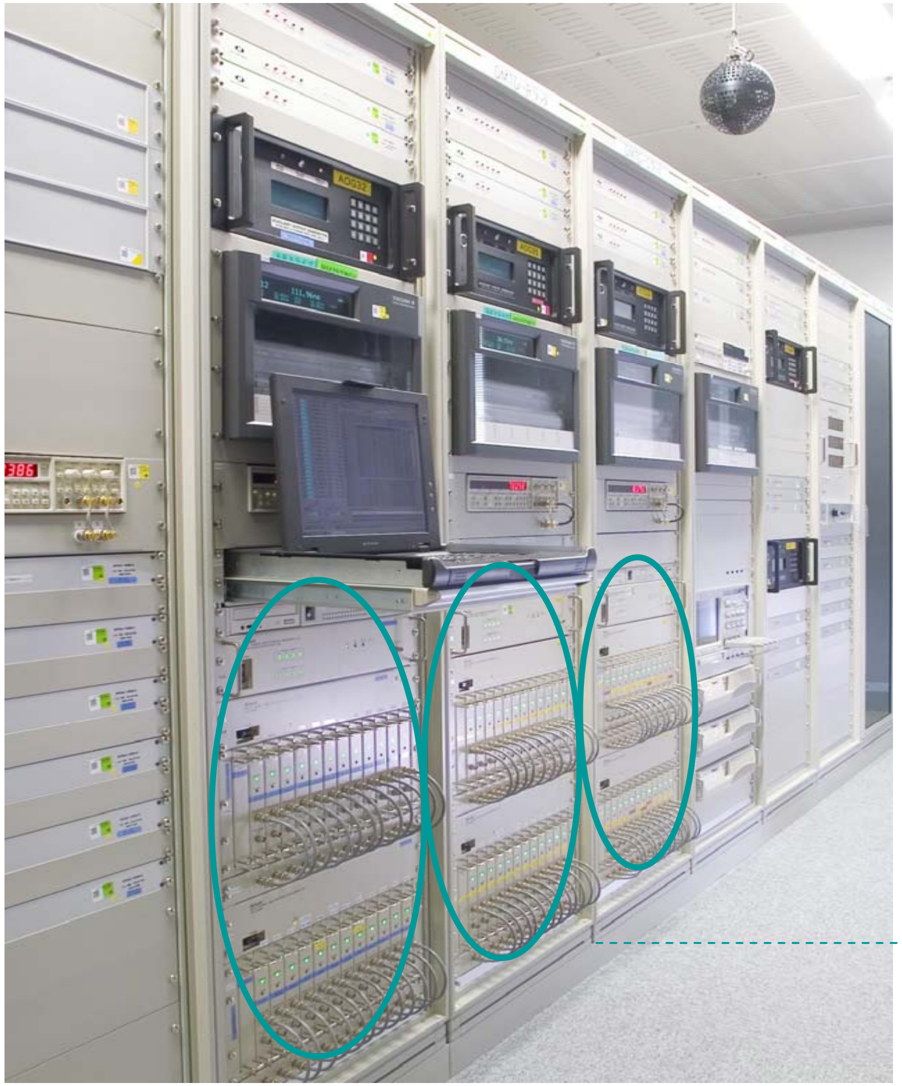


JST generation system



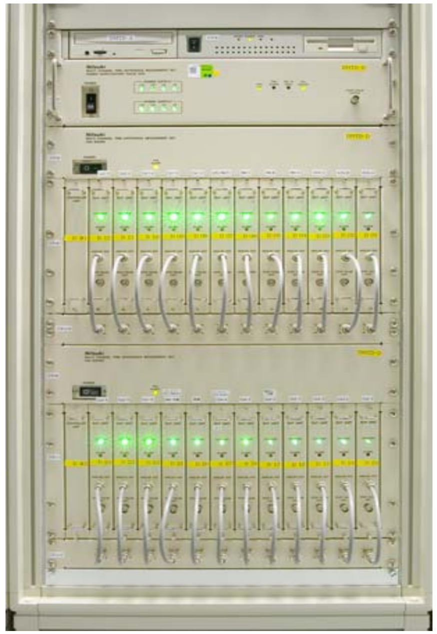
Outlook of the main units

24ch-DMTD system

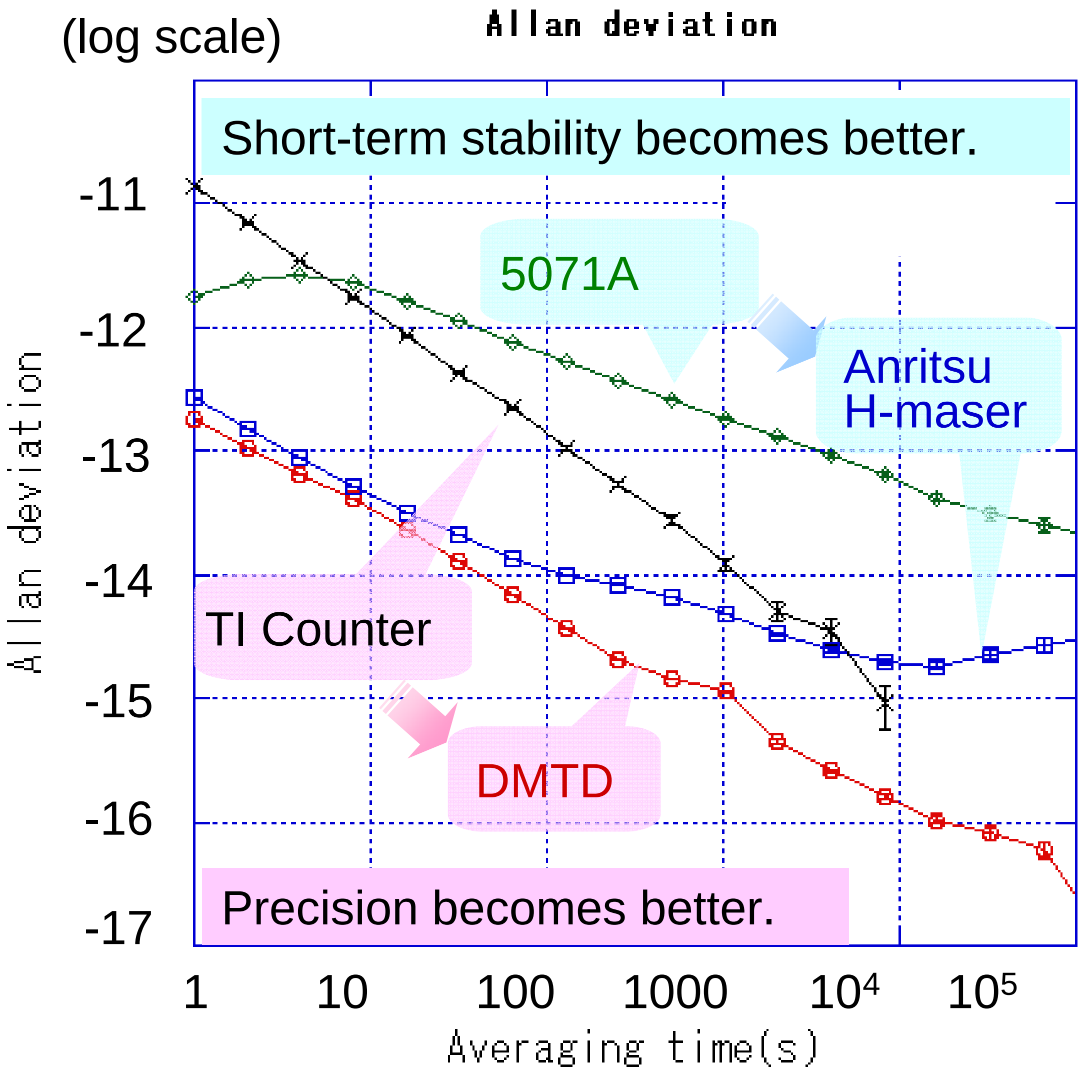


DMTD5
(Japan Communication Equipment Co., Ltd.)

- Beat down: 5MHz →1kHz.
- Output : average of 100 sampling data in every second.
- Precision: 0.2ps.
- Auto counting of cycle-slip.

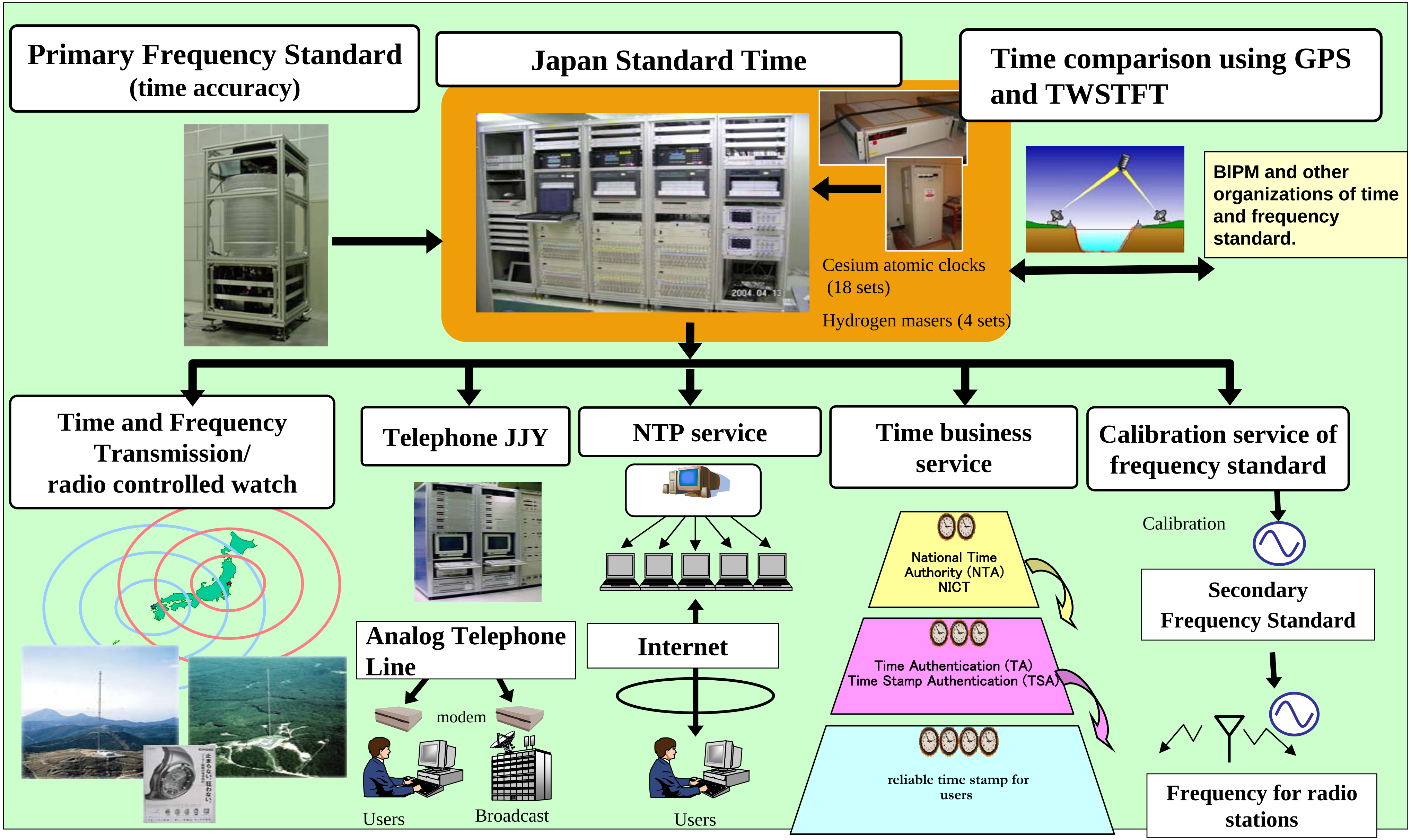


Hydrogen maser (RH401A / Anritsu Corp.)

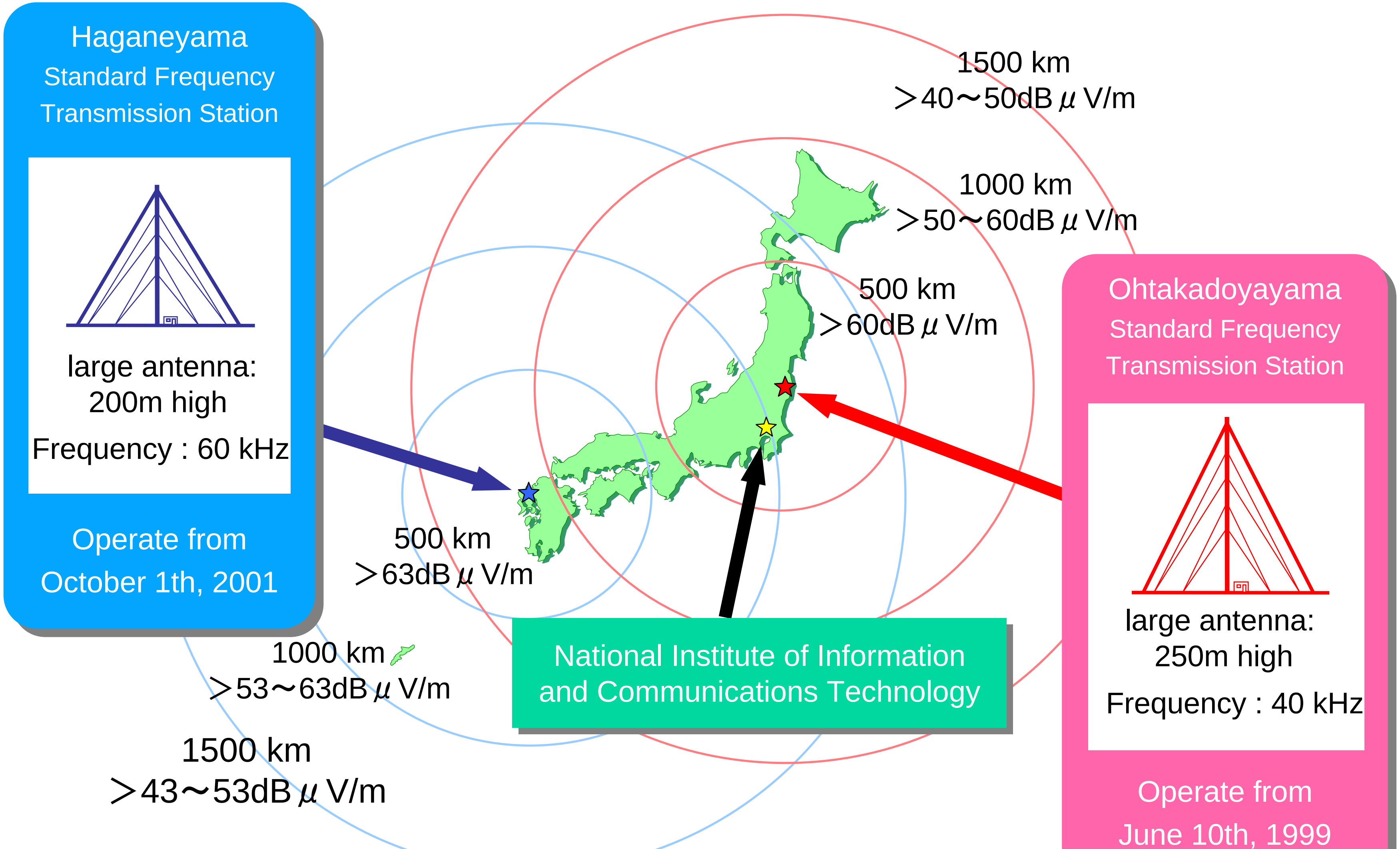


- Outputs: 5,10,100MHz,1pps
- Stability: $\sigma_y \leqq 4\text{x}10^{-13}$ (τ =1s)
  $\sigma_y \leqq 2\text{x}10^{-15}$($\tau$ =1000s)
- Auto-tuning mode and monitoring software are equipped.

Time and Frequency standard and its service

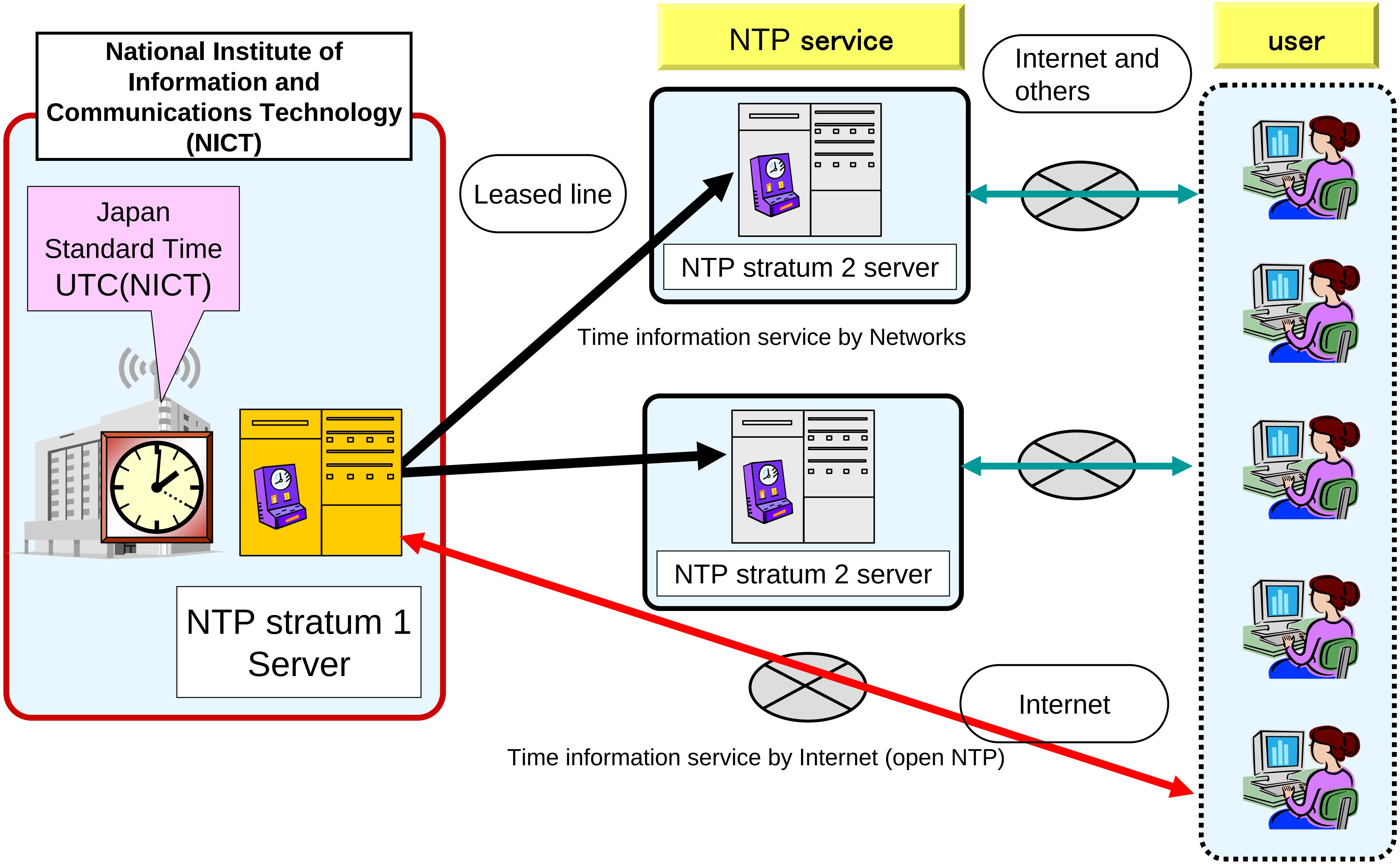


LF Transmission Stations



A numerical value below each distance (km) shows the value by calculating theoretically assumed field strength.

Concept of NTP



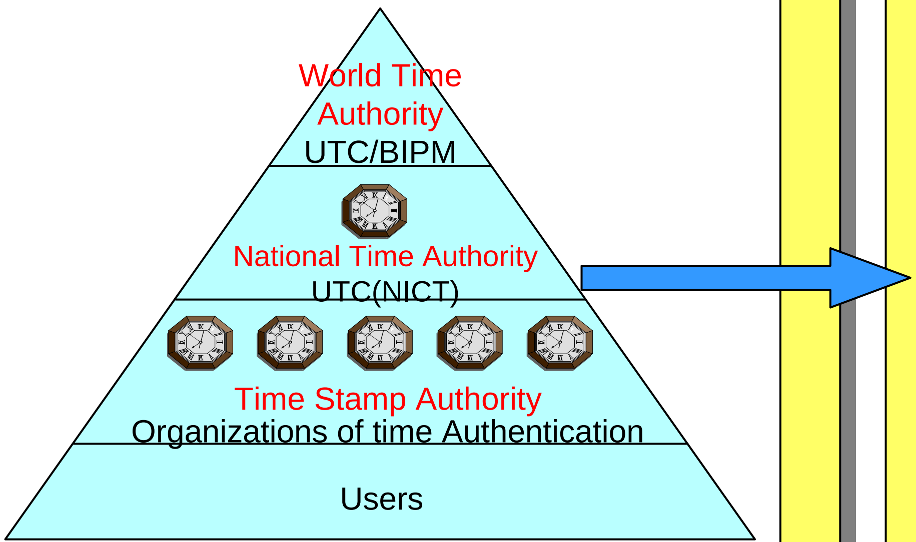
Stratified system of Japan Standard Time and Electronic Time Authentication

Japan Standard Time Project
National Institute of Information and Communications Technology

Dissemination system of Japan Standard Time for E-commerce (EC) and Japanese e-governance (e-Gov)

Hierarchical Structure of Standard Time

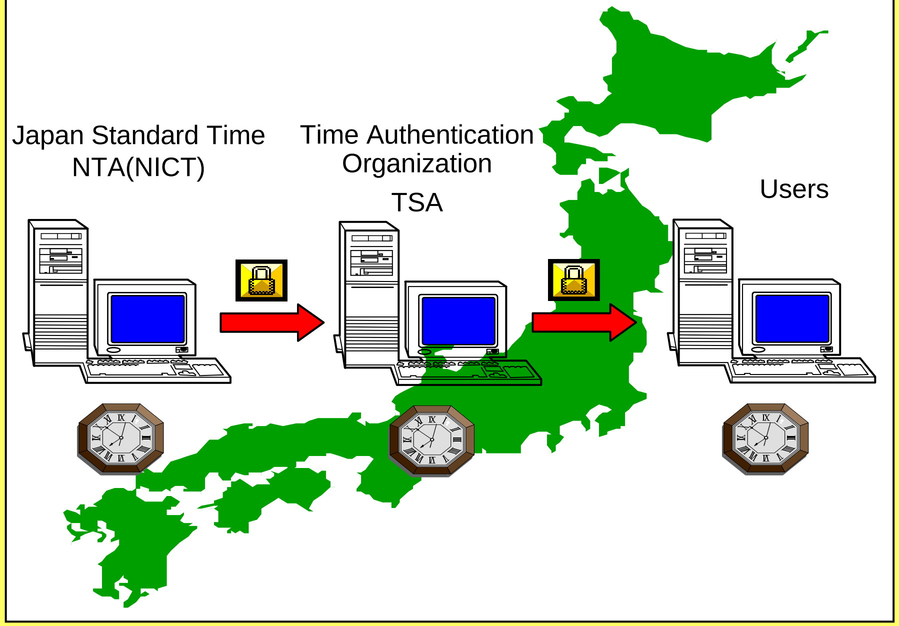
Japan Standard Time with traceability of international time standard organization
(UTC (NICT) synchronous with UTC(UTC))



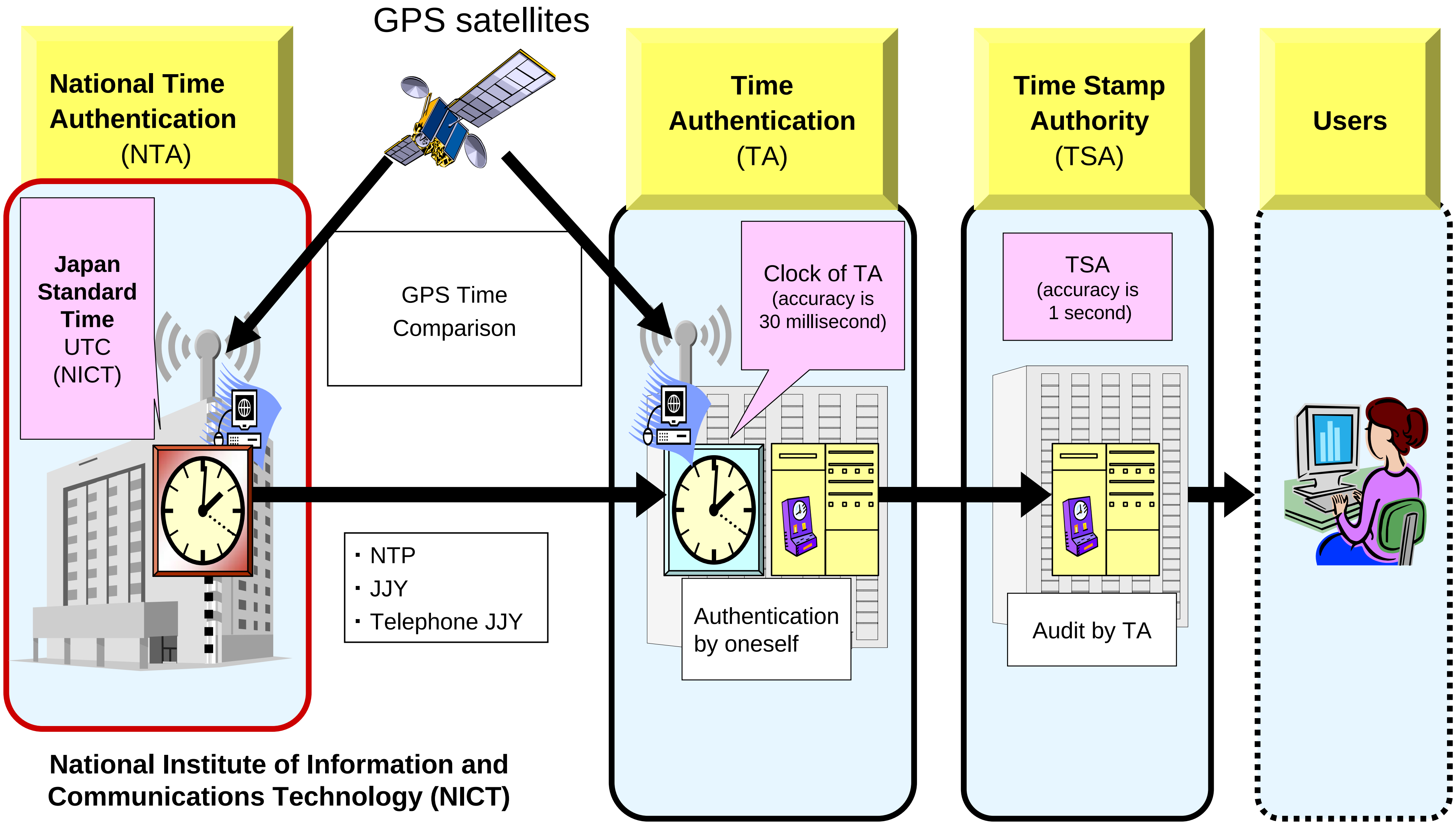
Japan Standard Time in the internet society

Developing technology of reliability and stability

Developing actual operation system through demonstration and experiment



Flow of Time Business Service



Frequency calibration

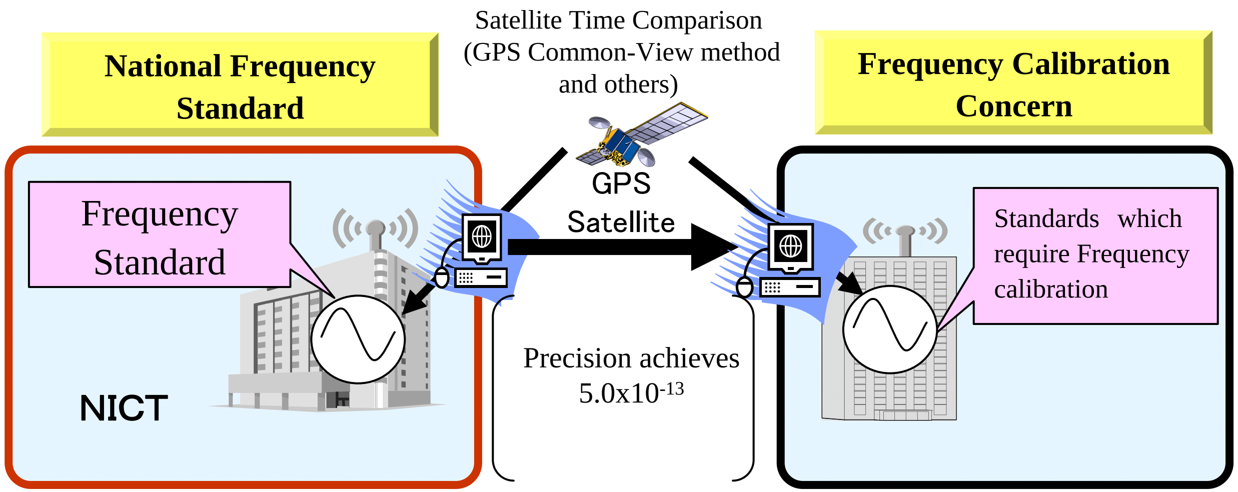
Commissioned Frequency Calibration service accordance with the ISO/IEC 17025 has been carried out
（ ”ASNITE-NMI certification” Certified by National Metrology Institute,
designated calibration organization by Measurement Law）

Certification by National Metrology Institute

Notification of designated calibration organization by measurement Law

Working equipment for calibration in a room with temperature and humidity controlled and with electromagnetic shielded

Remote Frequency Calibration (from May in 2005）



Algorithm of JST system (Redundancy and robustness)

H.Ito, F.Nakagawa, K.Imamura, M.Hosokawa and Y.Hanado

National Institute of Information and Communications Technology (NICT)
Japan

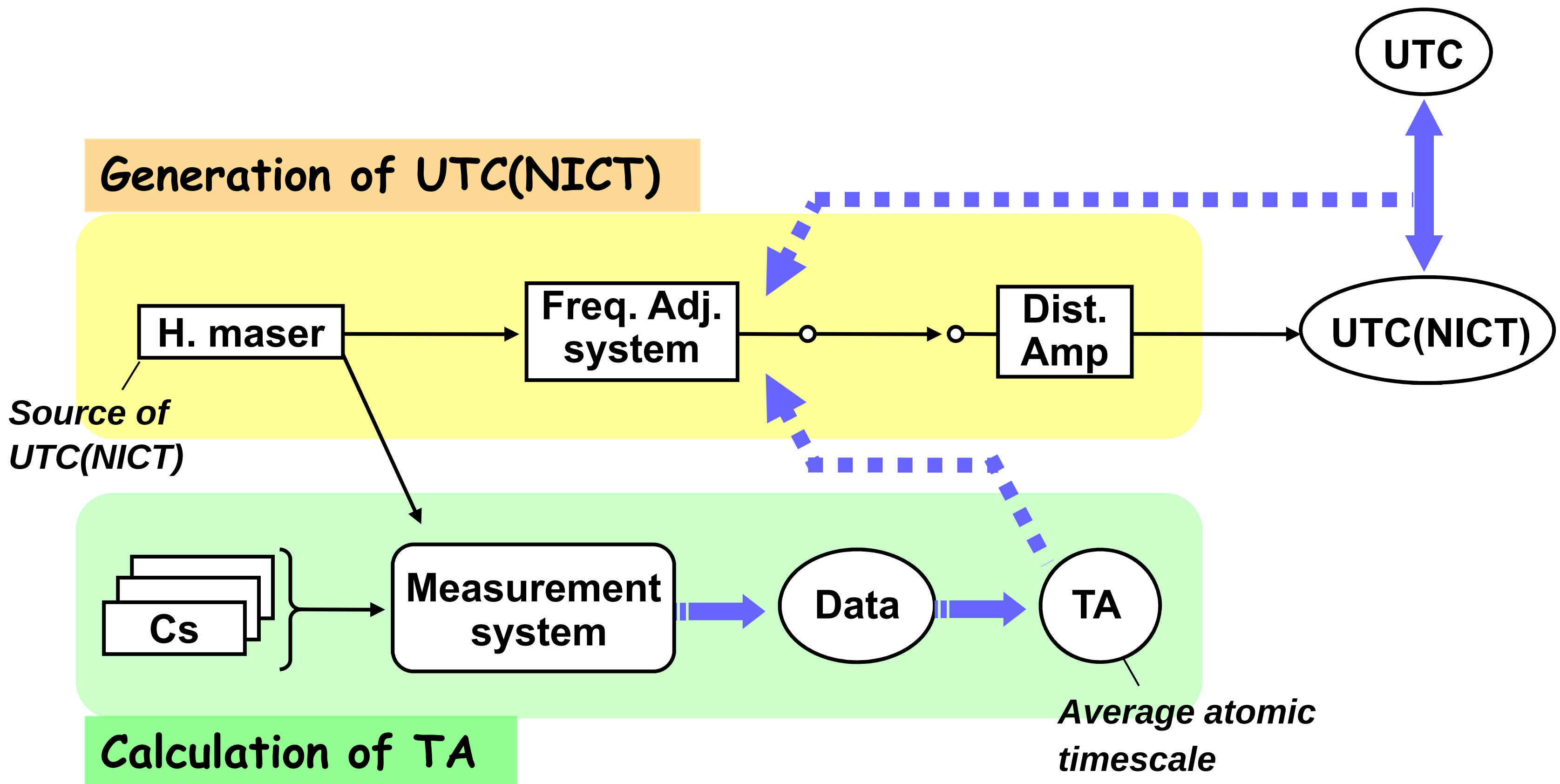
What should we do to keep robustness?

- **Basic standpoint**
  - Time scale should be continuous.
  - Troubles inevitably happen. Perfect protection is impossible.
  - We should, however, try to minimize the damage.

- **To realize a robust system,**
  - We should forecast troubles in advance and remove their causes as much as we can.
  - If unexpected troubles happen nevertheless, urgent recovery of system performance is required.
    - For rapid anomaly detection: system monitoring
    - For rapid recovery: **redundant system**

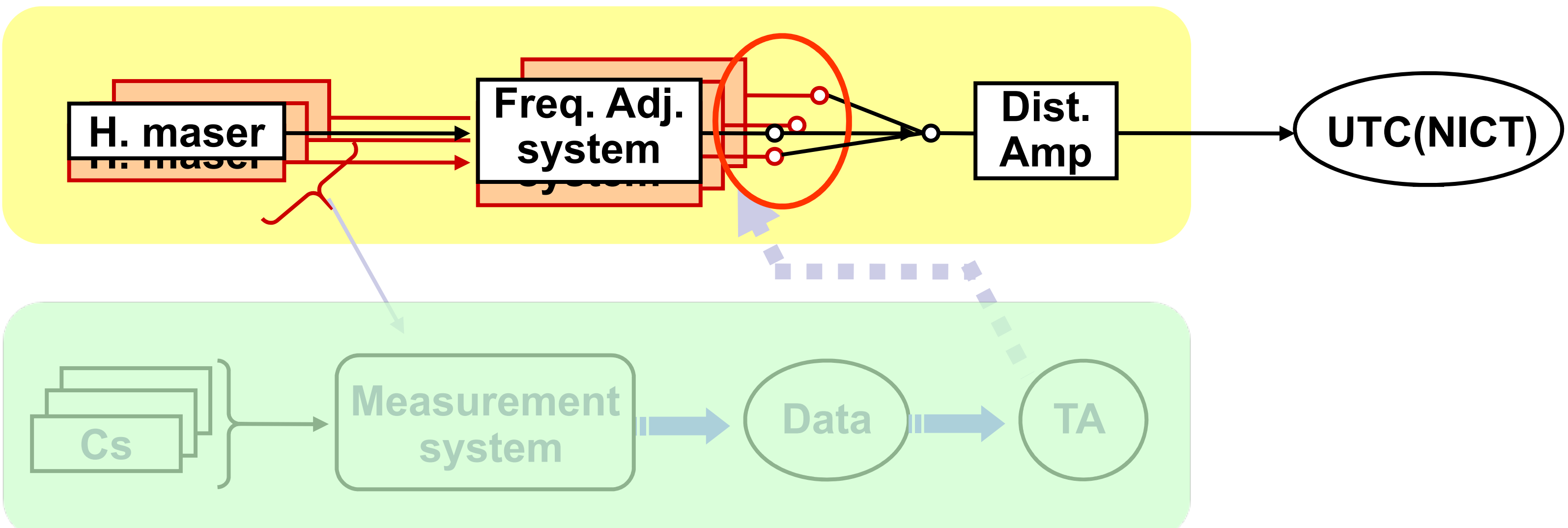
NICT system is introduced as one example.

Basic structure of UTC(NICT) generation system



Redundancy of UTC(NICT) generation part

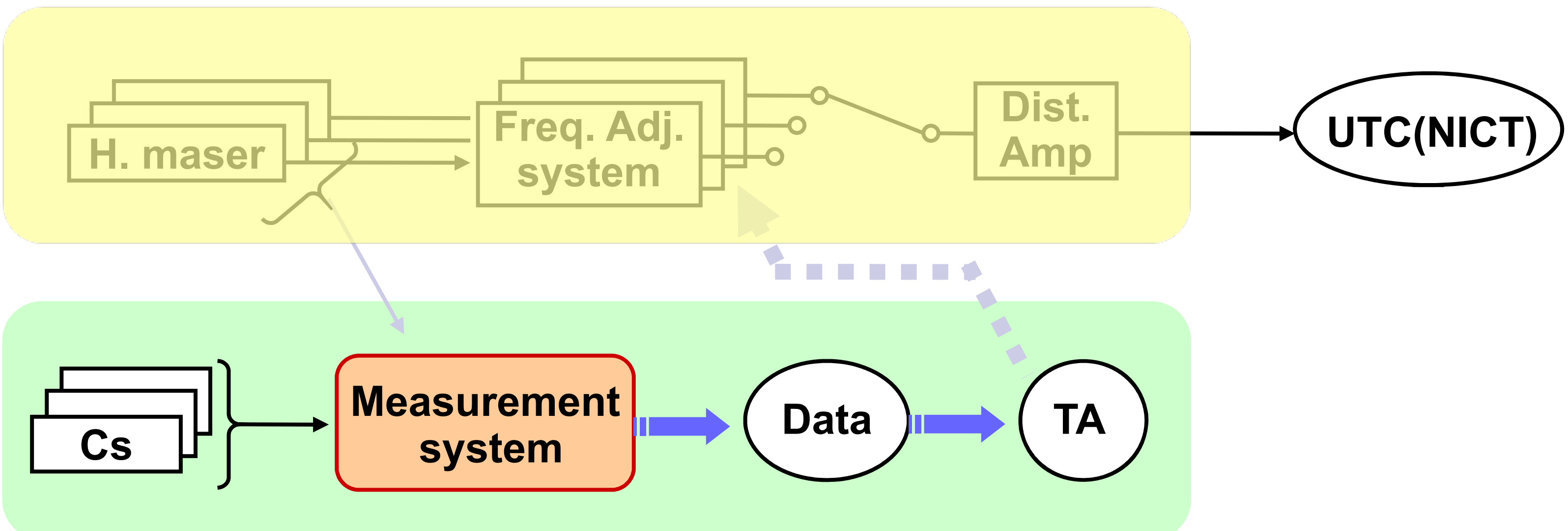
- Stopping time of UTC(NICT) should minimize.
- Urgent switching to back-up signal is necessary in an emergency, so generation part should be multiplicate.



- Three output signals are always synchronized with each other.

Redundancy of measurement part

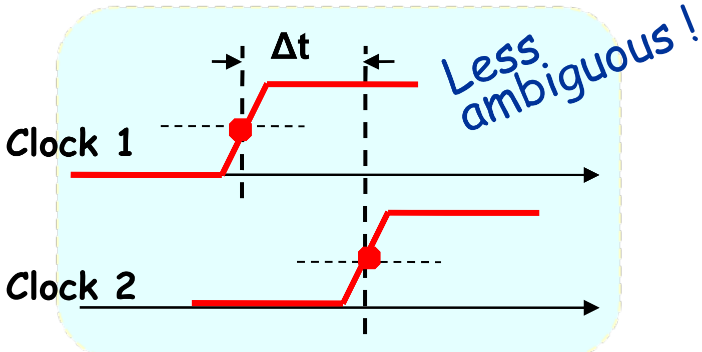
- *As clock measurements are periodic and discrete, switching to the back-up system is not so emergent in general.*



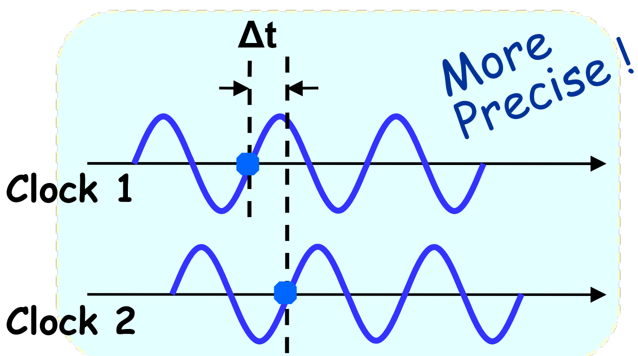
Some ideas for measurement system

Measurement signals

(A) Using 1PPS signals

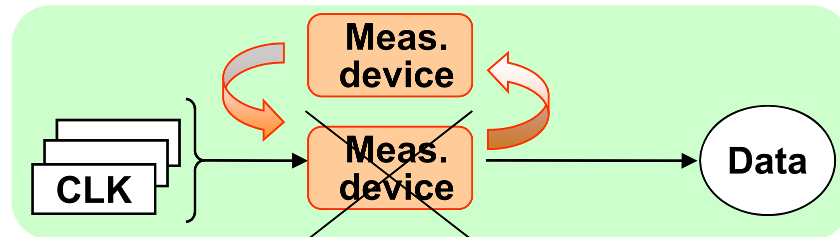


(B) Using carrier signals

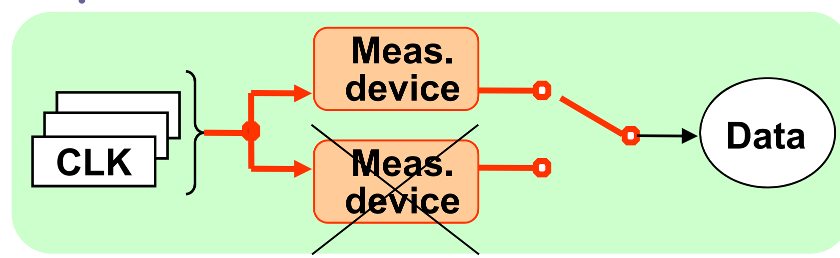


Back-up methods

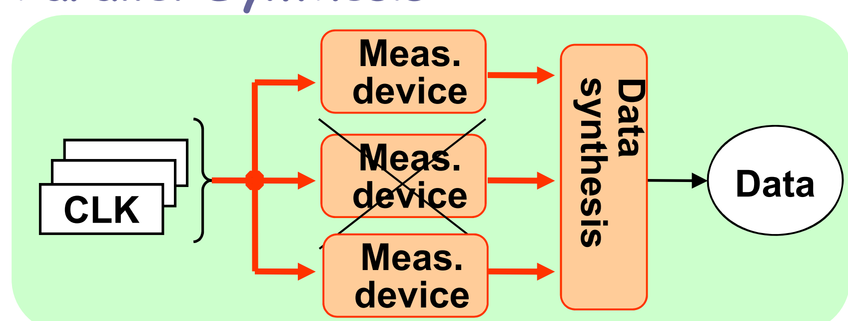
(1) Device Exchange



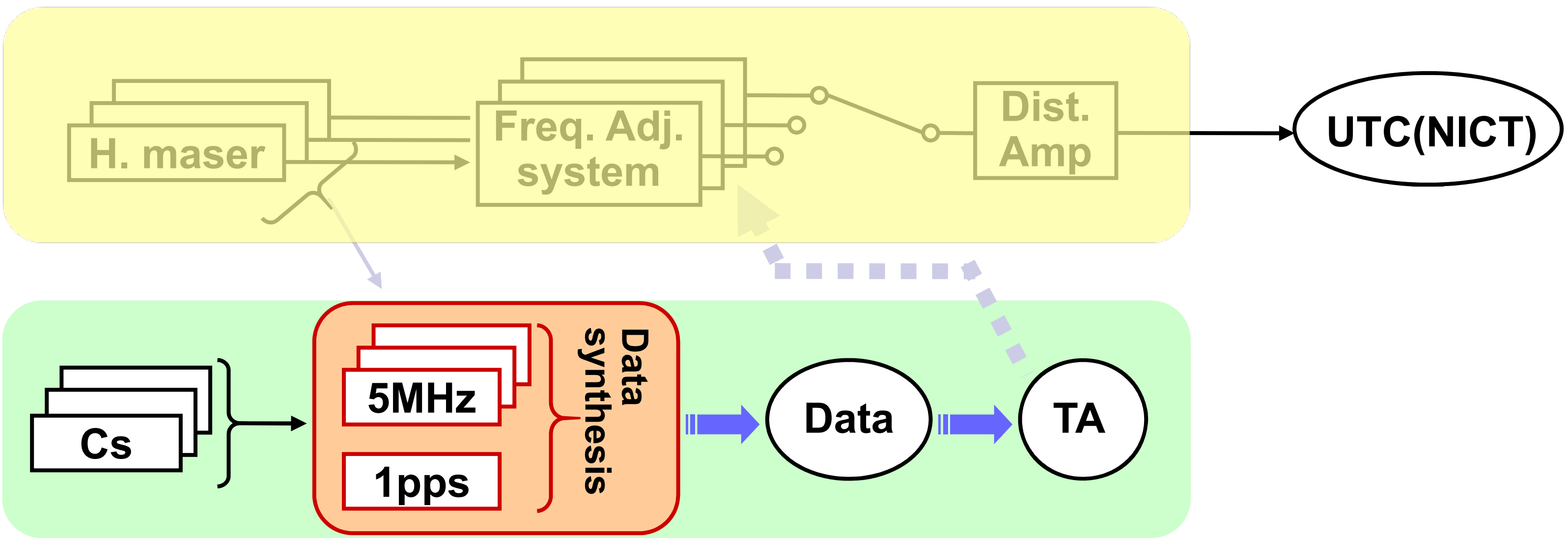
(1) Duplicate & Switch



(1) Parallel Synthesis



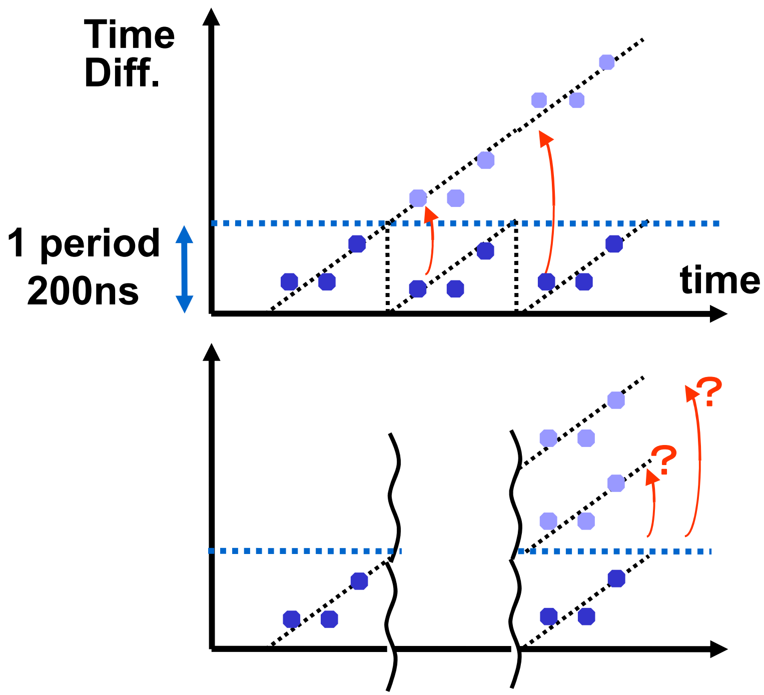
Setup of UTC(NICT) measurement part



- Our choice = 5MHz data (3) & 1pps data (1)
  (precise) (reliable)

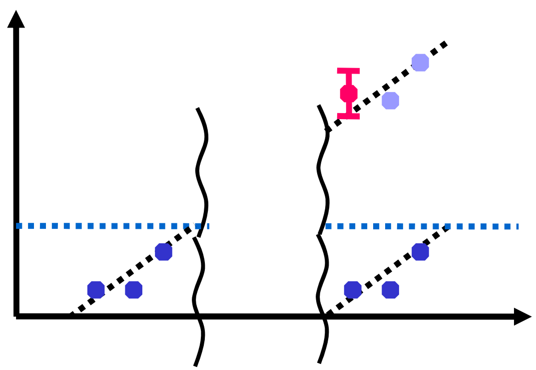
Why is 1pps measurement necessary?

Data measured by 5MHz



5MHz measurement is precise,
but cycle slip may occur
after a long-term lack of data.

Synthesis of 5MHz & 1pps data



1pps measurement is less precise,
but more reliable
in phase determination.

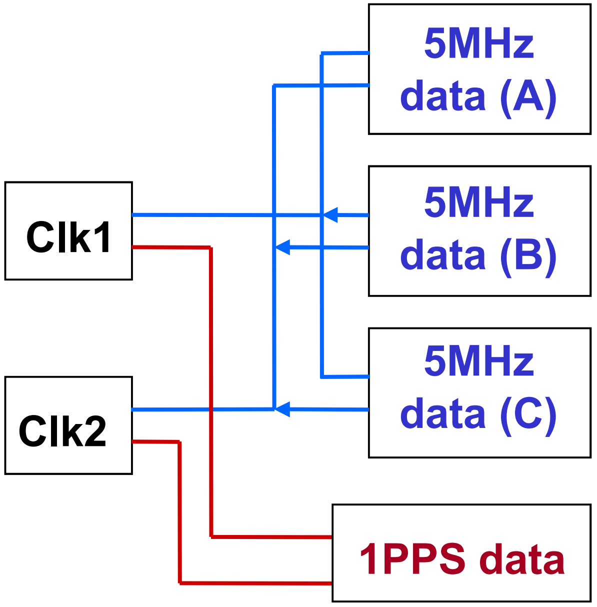
1pps data is effective for initial phase determination without ambiguity after a long-term lack of data.

Merit of multiple simultaneous measurements

"Decision by majority" method
by multiple simultaneous measurements.

(ex.)
If only data (B) is largely different,
it is due to the anomaly of device (B).

If all three data are strange,
it is due to the anomaly of clock itself.



Measured data processing program

- Simultaneous data comparison
- Anomaly detection /data selection

If at least one device works well, time difference data will be automatically obtained.

Summary

- Generation part,

  keeping multiplicate synchronized outputs

  is used for quick recovery of UTC(NICT) signal.

- Measurement part,

  some choices among measurement methods and back-ups.

  - We choose a combination of " 5MHz (3) & 1pps (1) ".
    - 5MHz measurement is for precision.
    - 1pps measurement is for initial phase determination.
    - Multiplex system is for decision by majority method.

Comments

- We should think about the balance of redundancy and simplicity.
  - Redundant system tends to be complicated.
  - Complicated system may cause human errors.
  - Simple system is easier to handle with.

- Basic preparation is important to keep robustness.
  - Possible pre-check should be thoroughly done.
  - Trouble simulation is very effective for quick recovery.

A quick review of time scale algorithms

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Outline

- **What is a time scale?**
- **How to make a time scale**
  - Simple examples
  - Needs of weighting and detrending
  - Basic expressions
  - Actual calculations
- **Examples**
  - BIPM timescale
  - NIST timescale
  - USNO timescale
  - Result of a test calculation

What is a time scale?

- **Time scale : A useful average of clocks**
  - Time scale is needed to create a reference more stable than a single standard, and better reliability than a single clock.
  - Usually, a time scale is a weighted average of observed minus predicted data.
  - However, a time scale should be optimized for goals of interest, and is not unique.

***** Let's start with a simple example. ******

Reference: D. Matsakis, Tutorial of timekeeping, personal communication.
T. E. Parker, Tutorial at 34th PTTI, 2002.

Simple example

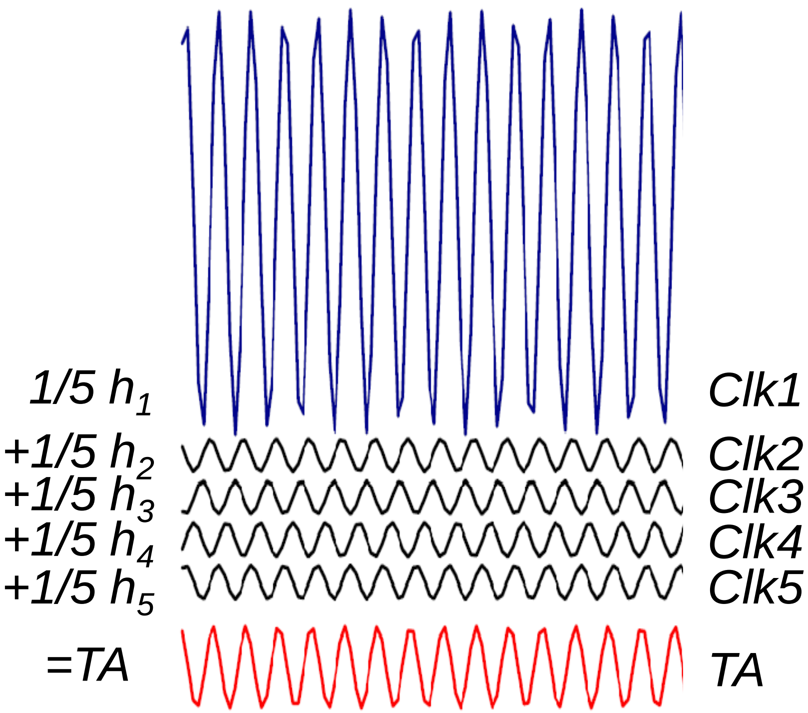
- **Simple average**

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

TA(t) : average atomic time

$h_i(t)$: time(phase) of Clk *i*

The bad clock
has a large effect.



Effect of weight

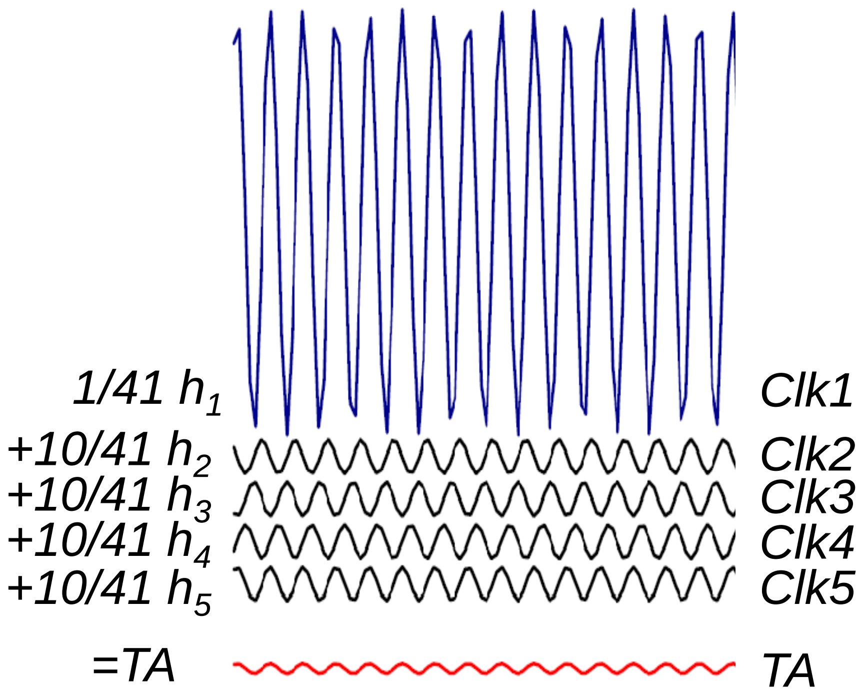
- **Weighted average**

$$TA(t) \equiv \sum_{i=1}^{N} w_i \cdot h_i(t)$$

w_i : weight of Clk i

Bad clock's effect becomes smaller.

TA becomes more stable than any of the clocks.



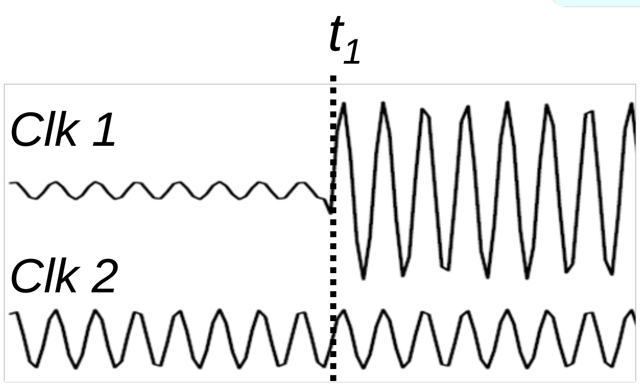
Weighting is an effective tool to make a stable time scale.

Effect of weight

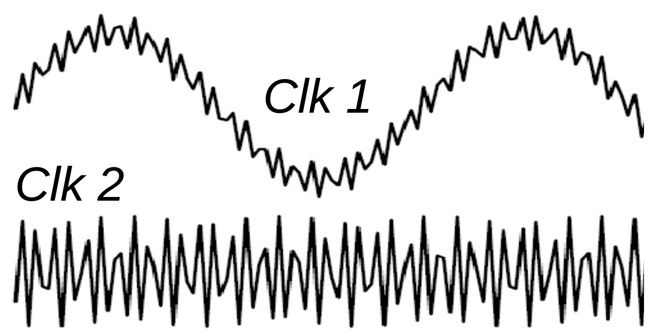
- **Weight optimization**

Weight should change to reflect the clock's behavior.

$$w_i \Rightarrow w_i(t)$$



$w_1(t) > w_2(t)$ $w_1(t) < w_2(t)$



Initially: $w_1(t) > w_2(t)$

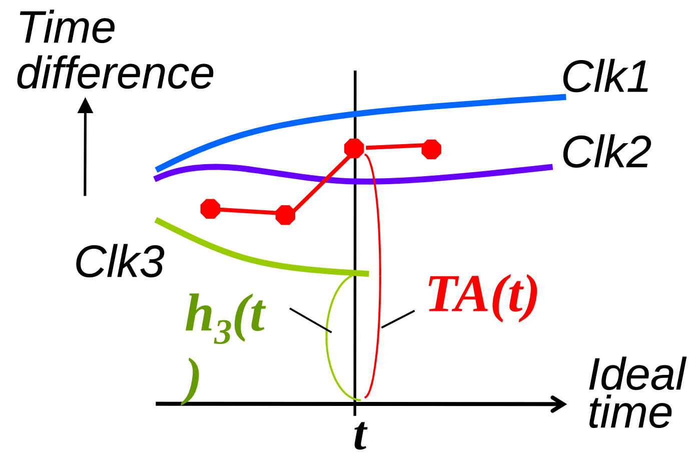
Later: $w_1(t) < w_2(t)$

Effect of detrending

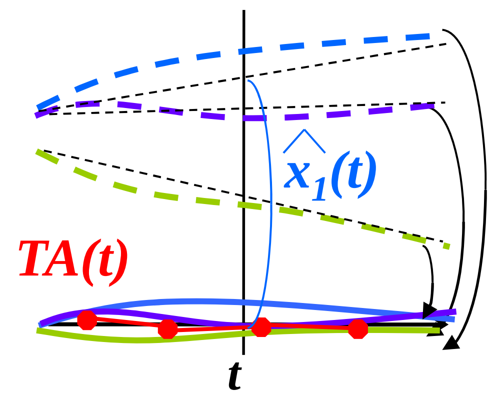
- **Weighted average**

$$TA(t) \equiv \sum_i w_i(t) \cdot h_i(t)$$

TA jumps when a clock is removed.



- **Weighted and Detrended**
  - *We remove a deterministic trend from each clock preliminarily,*
  - *and sum up the remainder.*



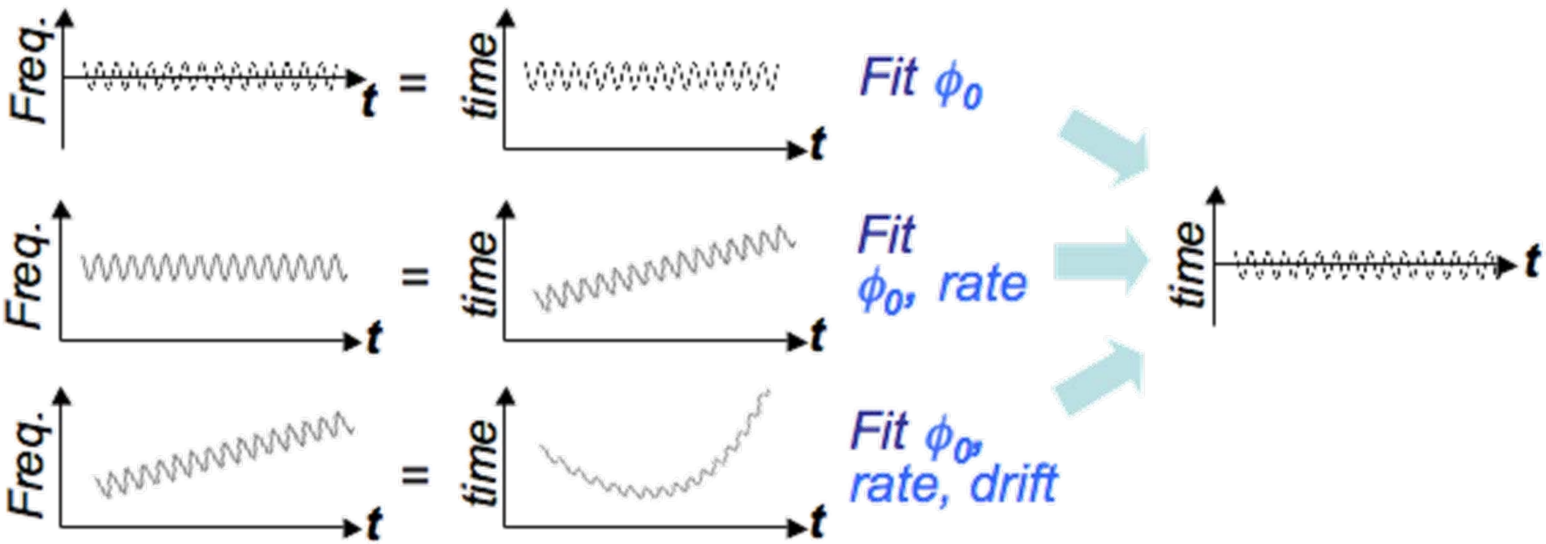
$$TA(t) \equiv \sum_i w_i(t) \cdot \{h_i(t) - \hat{x}_i(t)\} \quad \dots(1)$$

This value is predicted from a deterministic trend.

Effect of detrending

- **Variation of detrending**

The optimal way to detrend depends on the clock's behavior.



Basic expression of *TA*

- **Basic expression of *TA***

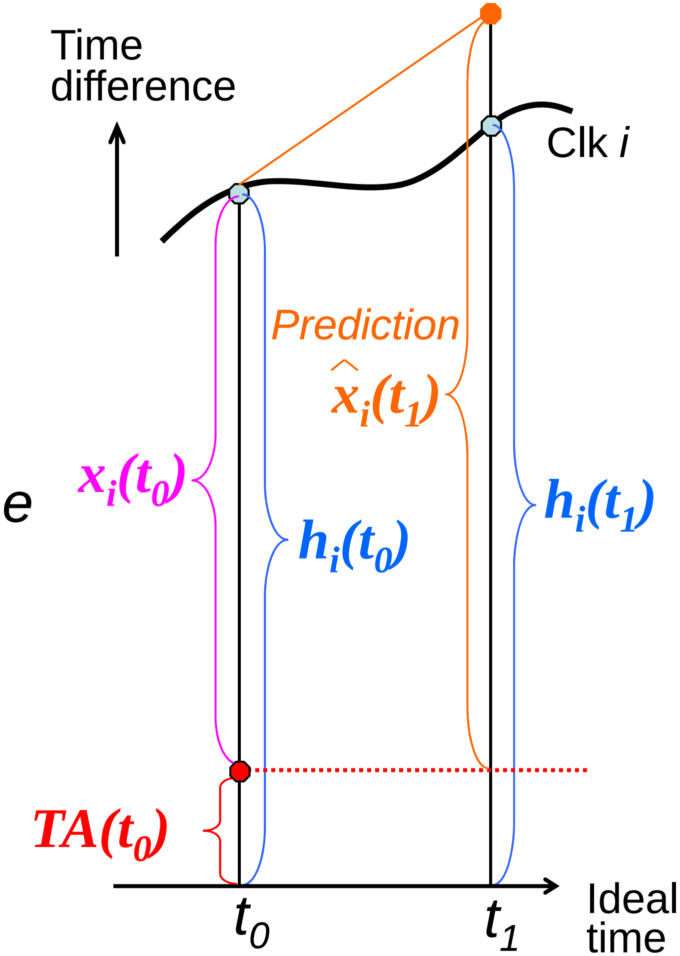
$$TA(t) \equiv \sum_i w_i(t) \cdot \{h_i(t) - \hat{x}_i(t)\} \quad \ldots(1)$$

w_i : *Weight of Clk* i

h_i : *Time difference of Clk* i *and ideal time*

$\hat{x}_i$: *Prediction of* x_i *(for detrending)*

x_i : *Time difference of Clk* i *and* TA



Basic expression of *TA*

TA(t) is the accumulation of ε (t).

ε_i : *Error remained after detrending*

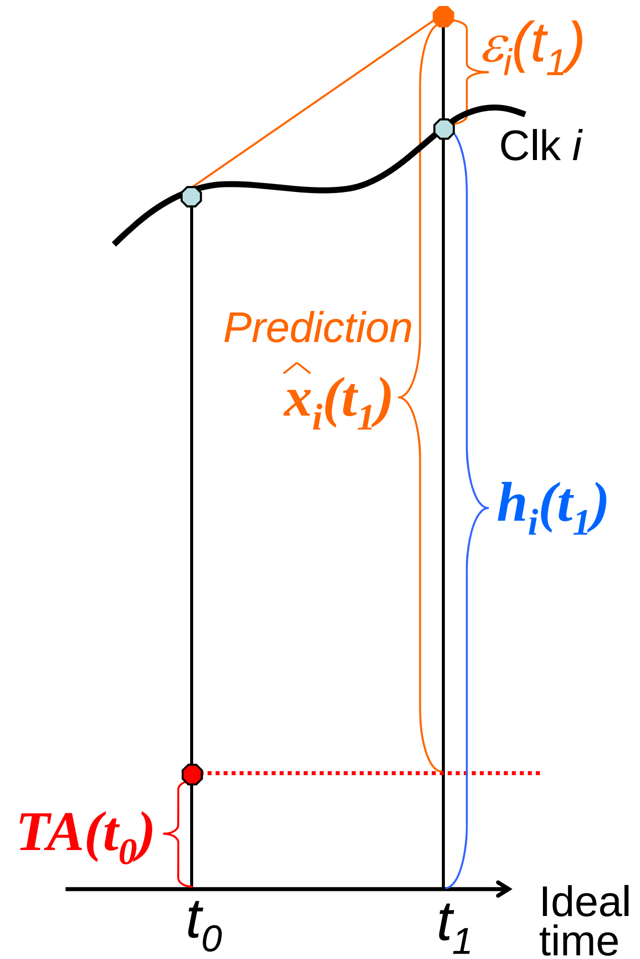
$$TA(t) \equiv \sum_i w_i(t) \cdot \{h_i(t) - \hat{x}_i(t)\} \quad \ldots(1)$$

$$h_i(t_k) = TA(t_{k-1}) + \hat{x}_i(t_k) + \varepsilon_i(t_k) \ldots(2)$$

(2) => (1)

$$TA(t_k) = TA(t_{k-1}) + \sum_i w_i(t_k)\varepsilon_i(t_k)$$

$$= TA(t_0) + \sum_k \sum_i w_i(t_k)\varepsilon_i(t_k)$$



Actual calculation

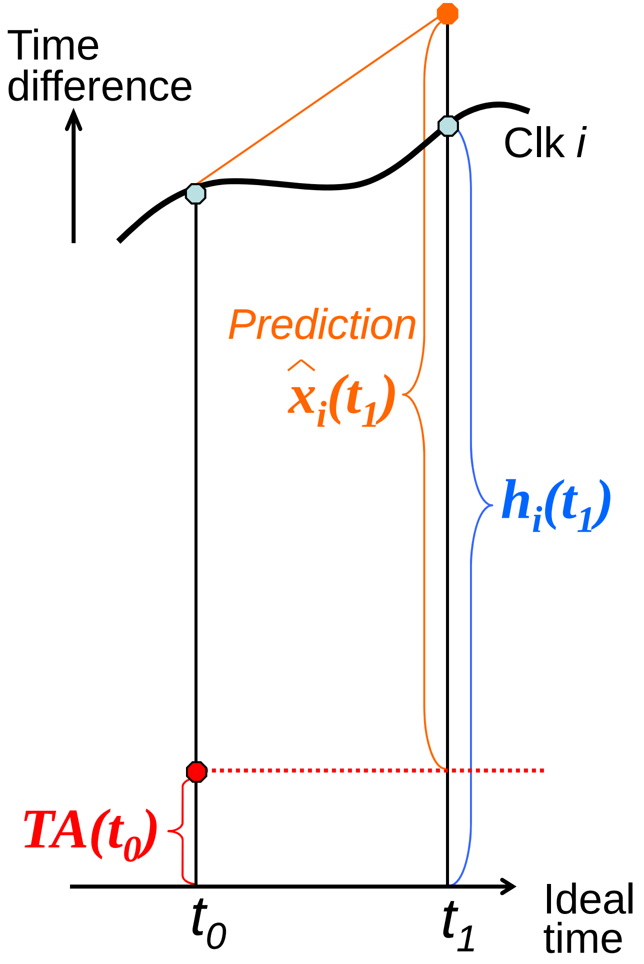
- **How can we get *TA* ?**

$$TA(t) \equiv \sum_i w_i(t) \cdot \{h_i(t) - \hat{x}_i(t)\} \quad \ldots(1)$$

In this expression,
we cannot calculate
the value of $TA(t)$, because
the value of $h_i(t)$ is unknown.

⇩

What should we do ?



Actual calculation

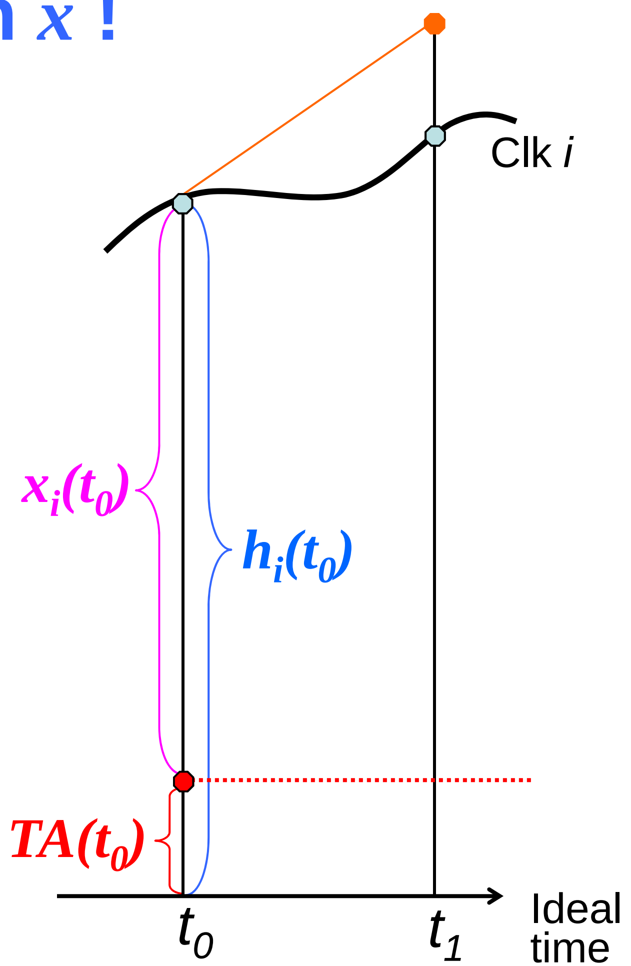
- **How can we get *TA*? => from *x* !**

We define TA from x.

$$x_i(t) \equiv h_i(t) - TA(t) \ldots (3)$$

"*TA* is the time shifted
from the time of Clk ***i*** by x_i."

Timescale algorithm is the procedure of calculating the time series of x(t).



Actual calculation

- **How to calculate** x

$$TA(t) \equiv \sum_i w_i(t)\cdot\{h_i(t) - \hat{x}(t)\} \quad \ldots(1)$$

$$x_s(t) \equiv h_s(t) - TA(t) \quad \ldots(3)$$

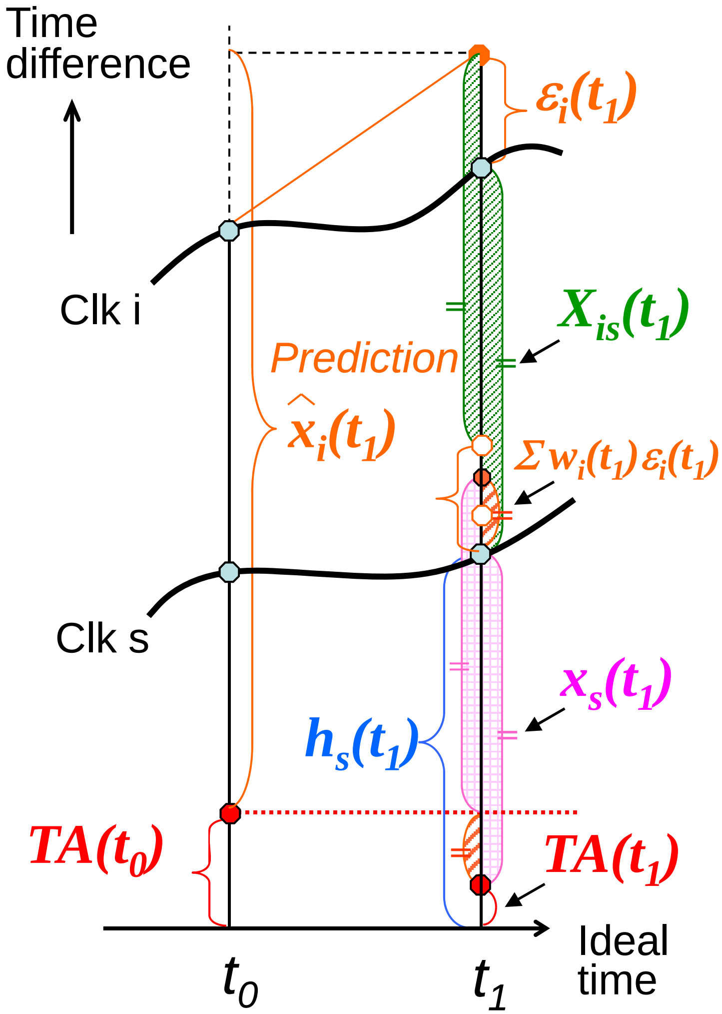
(1) => (3)

$$x_s(t) = \sum_i w_i(t)\cdot\{\hat{x}_i(t) - X_{is}(t)\} \quad \ldots(4)$$

X_{is}: *Measured Clk* **i** *– Clk* **s**
(Clk **s** *is a reference clock)*

$$X_{is}(t) \equiv h_i(t) - h_s(t) = x_i(t) - x_s(t)$$

$x_s(t_k)$ is obtained by the measured $X_{is}(t_k)$.



How to run a time scale

$$\hat{x}_i(t_k) = x_i(t_{k-1}) + y_i(t_k)\cdot(t_k - t_{k-1}) \quad \ldots(5)$$

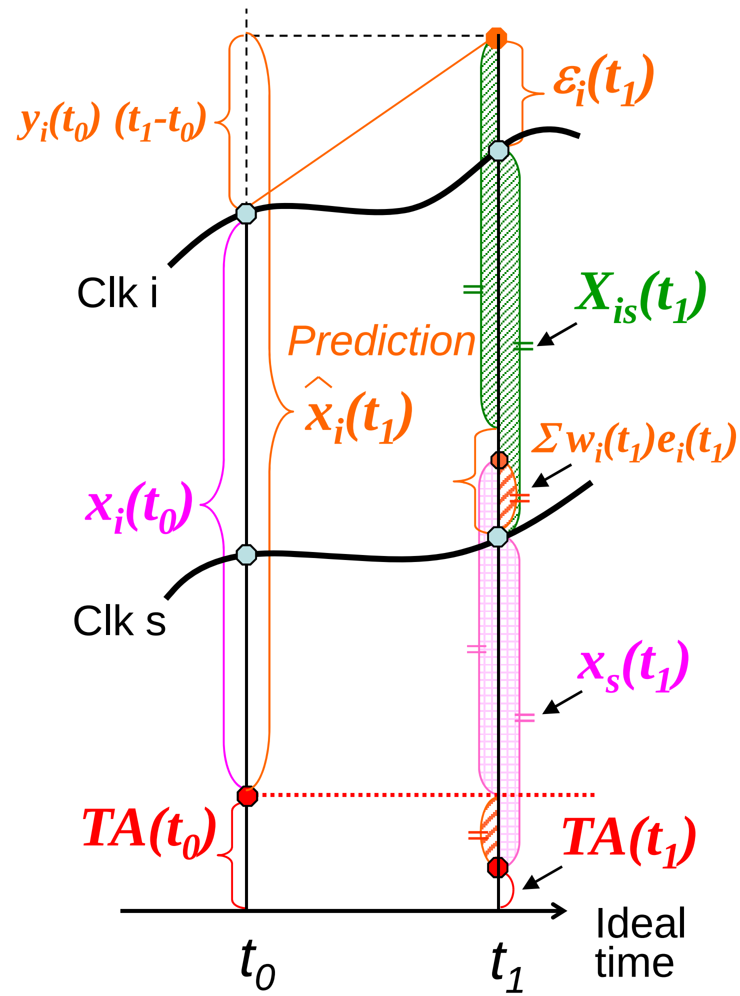
$$x_s(t_k) = \sum_i w_i(t_k)\{\hat{x}_i(t_k) - X_{is}(t_k)\} \quad \ldots(4)$$

$$x_i(t_k) = x_s(t_k) + X_{is}(t_k) \quad \ldots(6)$$

:Measured :Predicted :Output

:Calculated from x_i

Recursive calculation gives a time series of $x_i(t_k)$.



Notes

- Initial conditions (original epoch and rate) of a timescale are arbitrarily chosen or given by the external constrains.

- The spans for the weight calculation and trend calculation are important.

- The effects of clock's time jump, clock's frequency change, and adding or removing clocks should be suppressed.

!!! Caution !!!

- The calculations of weight and trend utilize the past *TA* itself.
  It means that a time scale algorithm includes the following risks:
  a weight concentration to a few clocks, and
  a miss-evaluation of clock trends.

Various algorithms are used in various institutes.

Example : BIPM time scale

- ***EAL*** (created with *ALGOS*)

Cycle: Every 5 days

Equation: Eq. (4) $$x_s(t_k) = \sum_i w_i(t_k)\{\hat{x}_i(t_k) - X_{is}(t_k)\}$$

Detrend: Rate of each clock

Rate: Slope of the Least Squares (LS)
(Span is 30 days to avoid dependence on previous month's data.)

Offset: Value of last point of previous month

Weight: Inverse freq. Variance @ τ =1 month (for past 12 months)
No distinction between masers and cesiums
Weights are limited to avoid dominance by a few clocks

Anomaly check: Rate change is monitored

Reference: P. Tavella and C. Thomas, metrologia, 28,57-63, 1991.
J. Azoubib, proc. of 32th PTTI, pp.195-210, 2000.
D. Matsakis, Tutorial of timekeeping, personal communication.

Example : NIST time scale

- ***AT1***

Cycle: Every 2 hours

Equation: Eq. (4) $x_s(t_k) = \sum_i w_i(t_k)\{\hat{x}_i(t_k) - X_{is}(t_k)\}$

Detrend: Rate and drift of each clock

Rate: With exponential filter

$$Y_i(t) = \{y_i(t) + m_i \cdot Y_i(t-\tau)\}/(1+m_i), \quad y_i(t) = \{x_i(t) - x_i(t-\tau)\}/\tau$$

Weight: With exponential filter

$$w_i(t) \propto 1/E_i^2(t)$$

$$E_i^2(t) = \{\varepsilon_i(t) + n_i \cdot E_i^2(t-\tau)\}/(1+n_i), \quad \varepsilon_i(t) = |\hat{x}_i(t) - x_i(t)|$$

Weights limited to 30%.

Anomaly check: Error change is monitored

Reference: T. E. Parker, Tutorial at 34th PTTI, 2002.

Example : USNO time scale

- ***A.1*** (based on the *Percival Algorithm*)

Cycle: Every 1 hour

Equation: Eq. (4) (but detrended in fit to frequency)

1. *Create Cs-only freq. Scale*
2. *Detrend HM and Cs against Cs-only freq. scale*
3. *Adjust detrending as needed*
4. *Create A.1 by averaging Cs + HM, using dynamic weights*

Detrend: Rate, and drift of each maser

Rate&drift: Slope of the LS from fit to data since clock change

Weight: All Cs are equally weighted, all HM are equally weighted

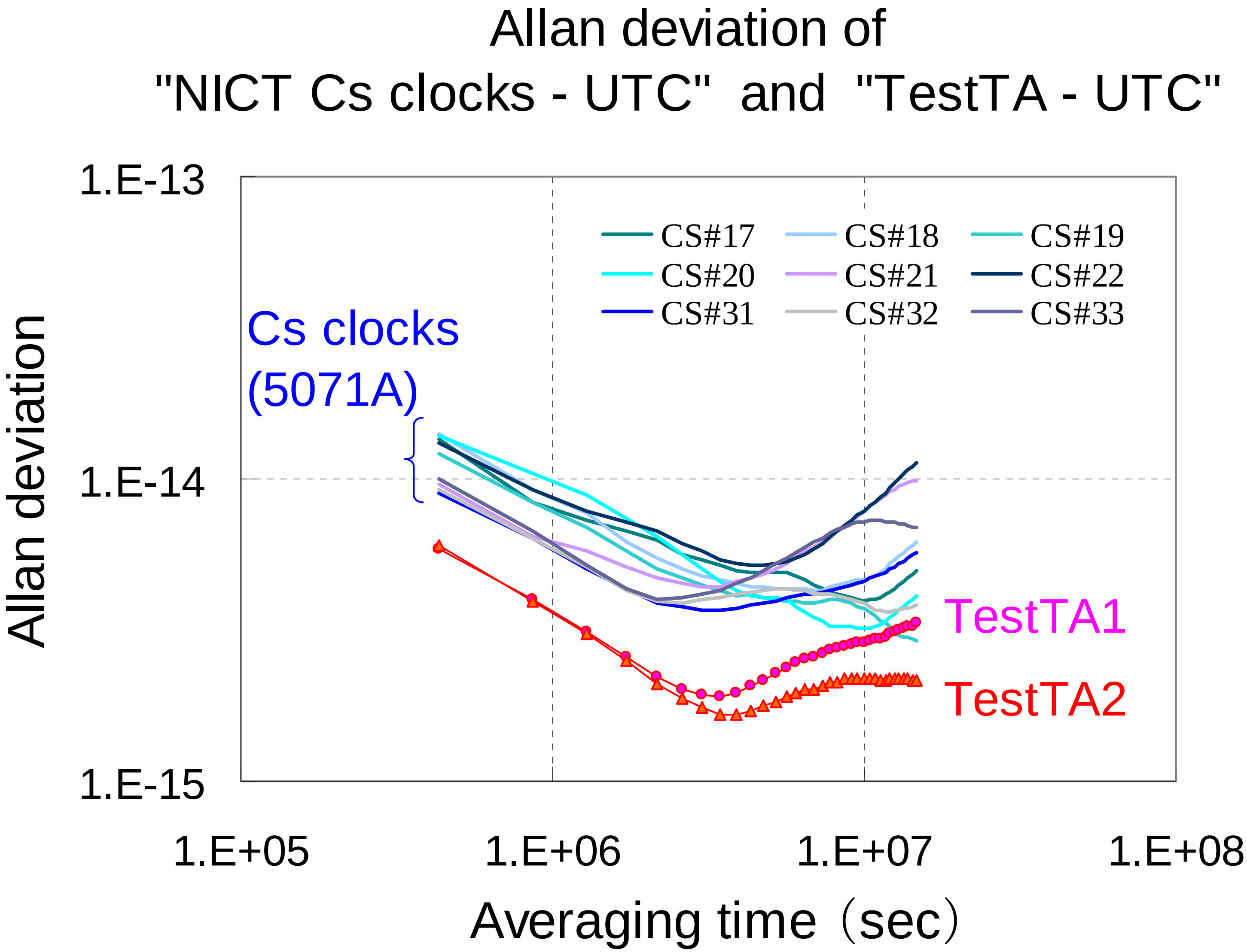
(Weight depends upon Allan variance over interval from present.)

HM weights fall to 0 in 60 days

Anomaly check : Rate and drift changes are monitored

Reference: D. Matsakis, Tutorial of timekeeping, personal communication.
D. Matsakis, Proc. 17th CCTF, 2006.
L. A. Breakiron and Matsakis, proc. of 32th PTTI, pp.269-288, 2000.
D. B. Percival, IEEE Trans. on Inst. and Meas.,IM27,pp.376-385,1978.

Example : Test TA (made by Y.H.)



Summary

- **Time scale is made from an average of atomic clocks.**

  Weighting **:** To make more stable paper clock than each clock

  Detrending : To eliminate the effect of clock anomalies

  - ***TA*** **is an accumulation of errors remaining after detrending.**
  - **Various methods of making a time scale.**

- ***TA*** **is defined by** $x(t)$**. (Absolute time of** ***TA*** **cannot be obtained.)**

  $x_i(t)$: **Time difference between the clock** i **and** ***TA*****.**

  Time scale algorithm :

  Procedure of computing a time series of $x(t)$**.**

  - $x_i(t)$ is calculated from the **measured time differences** between the clocks.
  - $x_i(t_k)$ is **calculated recursively** from the former $x_i(t_{k-1})$ and measured time differences $X_{is}(t_k)$.

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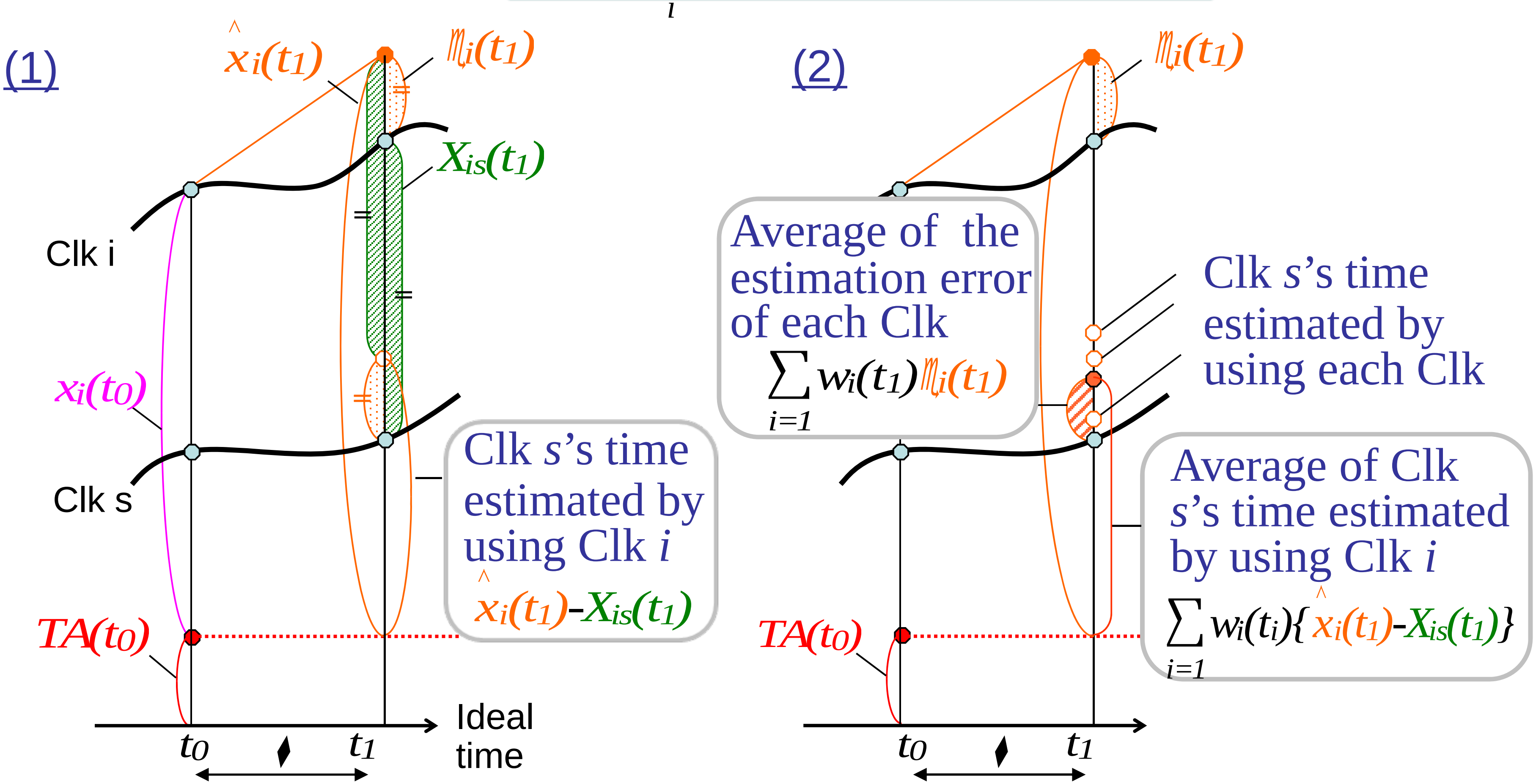
How to make a time scale

- **Meaning of the** $x_s(t) = \sum_i w_i(t) \cdot \{\hat{x}_i(t) - X_{is}(t)\}$ …(4)



How to make a time scale

- **Meaning of the** $x_s(t) = \sum_i w_i(t) \cdot \{\hat{x}_i(t) - X_{is}(t)\} \ldots(4)$ **and** $TA(t) \equiv h_s(t) - x_s(t) \ldots(5)$