

A history of R&D on the optical frequency standards in NICT

A story from the author's point of view

Maybe different stories

from other persons' point of view

Mizuhiko Hosokawa

National Institute of Information
and Communications Technology (NICT)

Special thanks to all the researchers and
support staffs concerning this project



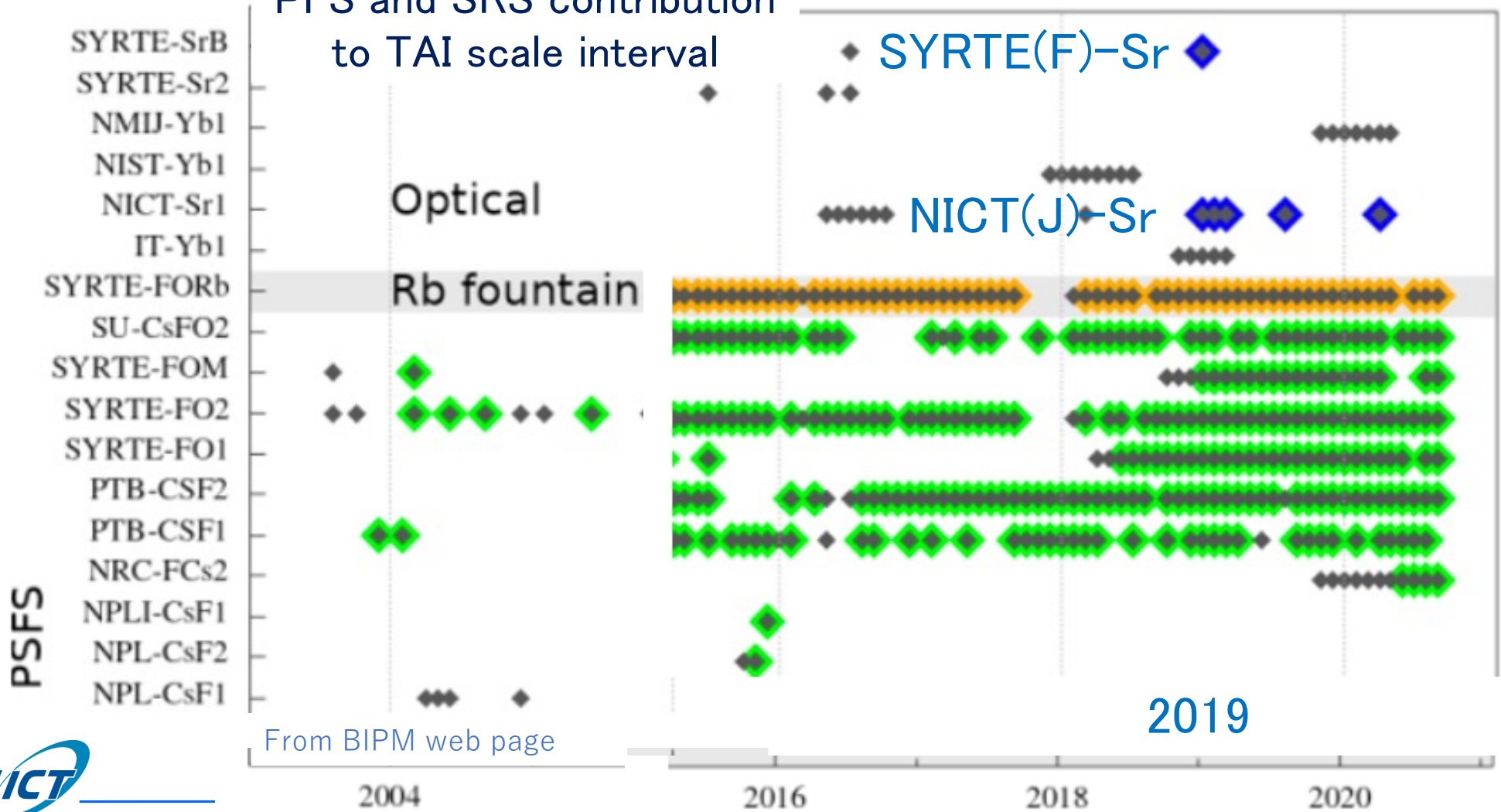
NICT Optical Freq. Standards - Current Status

- NICT Sr lattice clock: one of the earliest Secondary Representation of the Second to contribute to the calibration of TAI scale interval.
- NICT has also developed Ca^+ ion and In^+ optical frequency standards
- UTC(NICT) : Sr optical lattice clock disciplined timescale

- So it can be said that currently, NICT is one of the leading institutes on the development and use of optical time and frequency standard...
- However, the timing NICT start the research on the optical frequency standards was rather late.



PFS and SRS contribution to TAI scale interval



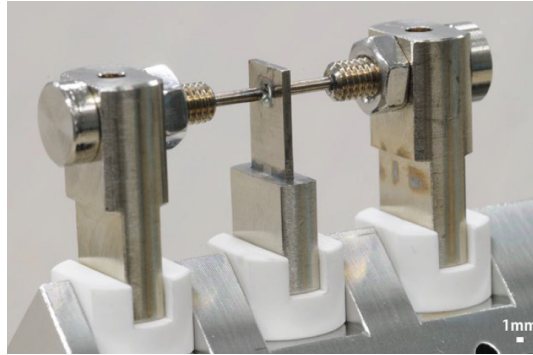
From BIPM web page

2019



Ca⁺ single ion
optical freq.
Standard

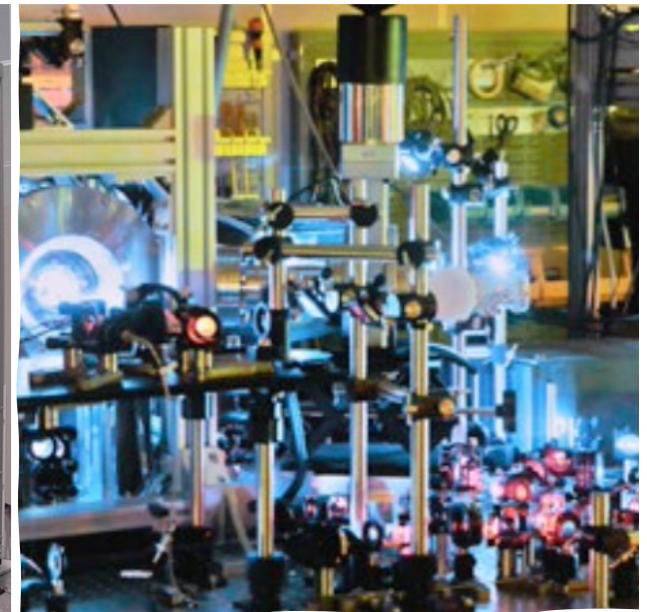
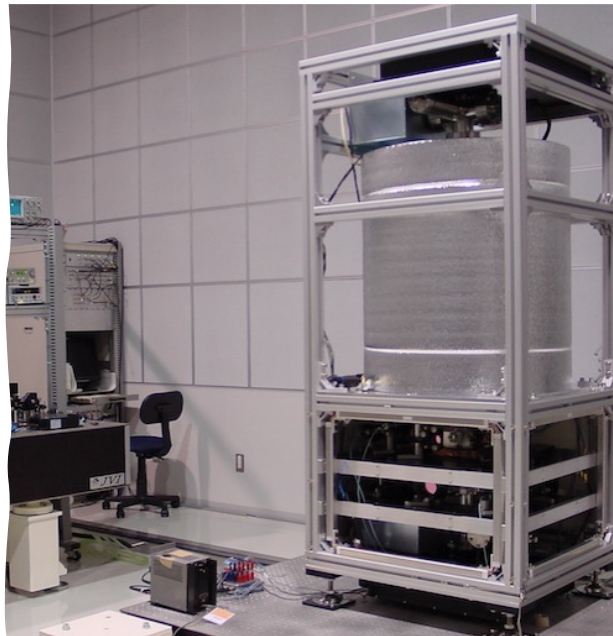
Optically
pumped Cs
CRL-01



Atomic clocks developed by NICT

Cs atomic
fountain PFS
NICT-Cs1

Sr optical
lattice clock
NICT-Sr1



The status of optical frequency standards around 2000

We found very rapid progress on the many aspects of optical frequency standards.

Age of the
Revolution

- Single ion trap
 - Hg⁺, Sr⁺, Yb⁺...
- Proposal of optical lattice clock, ...
- ULE cavity stabilized clock laser
 - a few Hz line width
- Optical frequency comb development, 2000.
 - Nobel prize 2005 just after 5 years since development.

CRL (former NICT) Atomic Freq. Std. R&D in 2000

Main mission was R&D on Cs primary frequency standards and their operation.

- Operation of **CRL-O1**, an optically pumped Cs thermal beam standard
- Development of **atomic fountain** Cs standard

April 2000, M. Hosokawa was appointed as a new group leader,
who has done some works on the relativity and space-time measurements,
but knew very little about the atomic clock development.

In 2000, CRL staff had many chances to hear the R&D on new optical freq. standard

- Within Japan, NMIJ conducted the very advanced R&D on optical comb.
- ATF2000 (Dec.), the first Asia-Pacific T&F International Conference was held, hosted by CRL
 - CRL invited Dr. Drullinger (NIST): we expected him to talk about NIST Cs fountain and optically pumped frequency standards.
 - In reality, he chose to tell us about NIST optical standard: it was whole new world to us.
 - In his talk, he said that on the optical frequency measurement, “Game is over”. It was very impressive for us.



CRL, discussion to start opt. freq. std. R&D in 2001

- Some very advanced institutes in the world → we were already large behind
- If we start the new project on opt. freq. std., we need to hurry for catch up
- Some objection inside CRL standards division on the new project
 - Atomic fountain R&D should be first
 - A group who cannot develop the Cs fountain would not be able to develop the optical freq. standard.
- We made a negotiation with board members (President, Vice Presidents)
 - Board members showed some interest and understanding, but they requested a clear plan to proceed to the next step.
- Executive director gave us an advice: to make an external project evaluation committee
 - Members from Kyoto Univ., Tokyo Univ., Osaka Univ., Univ. of Electro Comm.
 - To prepare for the committee, all the investigation and discussion was done by all CRL atomic frequency standard group members
-  The investigation and discussion by all the group members to make the project plan to the committee was very useful for that members understand the project, target, and the role of each member.

Outline of the plan we made and submitted to the committee

Resources are limited. Important to select emphasis on and off.

On the issue which atom is the best, situation was very chaotic.

Our thought: *First target* should be to get the techniques and **to get the early results**, not to aim for the development of the best optical frequency standard.

Survival of the project with some appreciable result is the **first** target.

Development of the best optical clock should be the **next** target

In CRL, another group in Kobe had good experience and Ca^+ ion trap for basic science. They already succeeded to trap the single Ca^+ ion first in the world. Required lasers for cooling and transition detection were able to be prepared using LD.

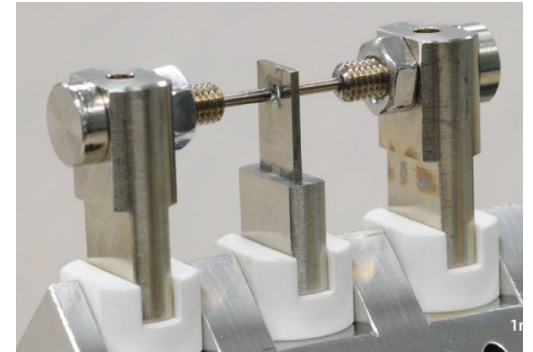
- So we chose to develop a Ca^+ ion optical frequency standard.
- Clock laser was to be developed by ourselves using LD and ULE cavity
- Optical comb : Already Menlo Systems supplied the commercial product.
 - buy the commercial one to save the human resource
 - concentrate on acquiring a proficiency in using comb



20 years ago, CRL had more abundant funds than now. Also Japanese Yen was more strong.

CRL started optical frequency standard R&D in 2002

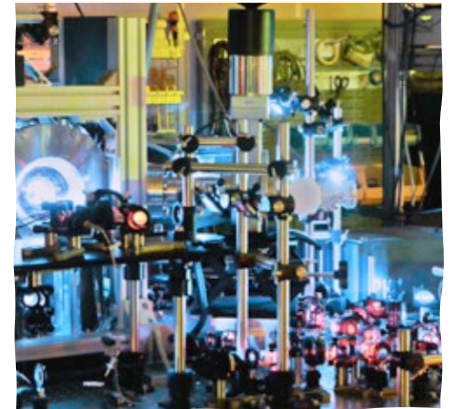
- Evaluation committee's evaluation to our proposal.
 - This optical frequency standards project is very important
 - The proposal, to develop a Ca⁺ ion optical clock might be not so ambitious.
 - However, for such important project, an early start should be better
- Hearing the evaluation comment, CRL board allowed us to start the project
- Within a few years, some of the good early results were achieved.
 - Cooling laser system for Ca⁺ ion trap (Matsubara, Hayasaka)
 - Clock laser with ULE cavity, 10⁻¹³ stability at 1 s (Li)
 - Ca⁺ single ion trap and signal detection (Matsubara, Hayasaka)
 - Evaluation of lasers by optical comb (Ito)
 - Theoretical investigation on cooling condition (Kajita)



2006, more aggressive restart

Based on the early results, we require the expansion of the project, and it was, on the large part, accepted.

Two new researchers joined: Dr. Ido and Dr. Nagano



We started some new developments and more good results were achieved.

- Ca⁺ ion optical clock, system and accuracy largely improved within reach (Matsubara, Hayasaka)
- Sr optical lattice clock development was started (Ido)
- Optical combs without photonic crystal fiber were developed. (Ito, Nagano)
- Cryogenic Sapphire oscillator was installed (Kumagai, with the help of U. West. Australia,)
- Optical fiber time and frequency transfer technique was developed. (Kumagai and Fujieda, with NICT photonic network testbed)
- More stable clock laser was developed. (Li)

➤ Sapphire oscillator → Comb → Clock laser, 10^{-15} at 1s, 2007

➤ Ca⁺ ion opt. clock, 10^{-14} uncertainty, CCL-CCTF JWG, 2008

2008, Hosokawa left, group more and more active

July 2008, Hosokawa moved to Planning Division. Then, the group become more and more active. This personnel change might be very lucky for the group.

Group leader successors are, Y. Koyama, Y. Hanado, and T. Ido. All they have acted as good leaders and been very active in URSI, APMP and CCTF.

➤ The group achieved many good results since 2008

- Ca⁺ ion uncertainty decrease, Sr Lattice clock operational
- 2011, Sr Lattice clock comparison with U. Tokyo Katori Group, via optical fiber. 10^{-15} agreement, after 50m (5×10^{-15}) gravitational red shift corrected.
- 2015, Sr Lattice clock 10^{-17} uncertainty. This standard contribute to the improvement of the CCTF and CCL SRS WG recommend frequency value.

➤ Most accurate clock vs timescale generation (around 2015)

- After the development of practically operational good Sr lattice clock, there are two choice for the next step. To develop the more accurate clock, or to use the clock as a practical standard.
- Human resources are limited to pursue both. Hosokawa gave an advice that to make the most of the present Sr clock to apply for time metrology would be metrology institute's important role.



➤ NICT Sr lattice clock has made a lot of contribution to TAI, UTC and PES-SRS WG.

Lessons learned

- The authority outside the institute is powerful.
 - After University professors helped us, we paid attention so that both they and we get merit through collaboration and/or recruiting students.
- Research fund is very important.
 - The plan should be made within the available fund.
 - If money can allow us to concentration of human resource, it is worth consideration.
- Discussing the plan by all members was very important
 - to share the vision, and to make each target clear.
 - let the researchers free and think for themselves.
- We should check the situation and consider the target frequently.
 - The **first target** should be **not too high**, since to get the **early results** is very important for project survival
 - It is important to consider what is the valuable target for the institution and community. Sometimes it might be different from researcher's hoping target.