OVERVIEW OF RESEARCH ACTIVITIES ON TIME AND FREQUENCY AT THE NATIONAL INSTITUTE OF INFORMATION AND COMMUNICATIONS TECHNOLOGY

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Abstract

A new organization, the National Institute of Information and Communications Technology (NICT), was founded in Japan in April 2004. The responsibility of the Communications Research Laboratory (CRL) for the national frequency standard and time dissemination has been succeeded by NICT. There are five time and frequency research and service groups. In this paper, we show the recent activities of these five groups.

INTRODUCTION

In April 2004, the Communications Research Laboratory (CRL), an incorporated administrative agency, and the Telecommunications Advancement Organization of Japan (TAO), a chartered corporation, were merged and reorganized into a new organization, the National Institute of Information and Communications Technology (NICT), an incorporated administrative agency. The responsibility of CRL for the national frequency standard and time dissemination has been succeeded by NICT.

Now we have following five Time and Frequency (T&F) related research groups in NICT. Their names and main research items are the following:

(1) Atomic Frequency Standards Group
  Research and development on cesium (Cs) primary frequency standards
    - Operation of the optically pumped Cs-beam frequency standard NICT-O1
    - Research and development on a fountain-type Cs frequency standard
  Research and development on a Ca^+ ion optical frequency standard
(2) Time and Frequency Measurements Group
  Precise time transfer
  Basic research on construction of a stable and accurate time scale
    - Time-scale algorithm

- Precise measurement techniques

Basic studies on GNSS, especially precise time-transfer techniques between the satellite and ground station

(3) Japan Standard Time Group

Daily job of timekeeping and time transfer

Dissemination of time and frequency

- LF broadcasting stations
- NTP and dial-up time service
- Trusted time for "time business"

Calibration service for time and frequency

(4) Quasi-Zenith Satellite System Group

Spaceborne atomic clock for QZSS

Time management system for QZSS

(5) Time Applications Group

Research and development on time applications

- Trusted time stamping
- Precise and trusted time distributions using Internet Protocol

Details of these research items are shown in the following sections.

ATOMIC FREQUENCY STANDARDS

OPTICALLY PUMPED CESIUM STANDARD, NICT-O1

NICT-O1, an optically pumped cesium primary frequency standard, formerly called CRL-O1, has been in use since April, 2000 **[1]**. The accuracy evaluation data were sent to BIPM once in 2003 and twice in the first half of 2004. The best accuracy among these data is 7×10^{-15}. Since the signal-to-noise ratio (S/N) become worse during operation, we baked the whole system in June and July 2004. After some improvements, operation will soon be started again.

FOUNTAIN-TYPE CESIUM STANDARD

Research and development on the atomic fountain Cs standard has been ongoing **[2]**. By using the first standard-size fountain system, a stability of 9×10^{-15} has achieved (Figure 1).

The stability of an atomic frequency standard is estimated by the following equation.

$$\sigma_y(\tau) \propto \frac{\Delta\nu}{\nu_0 \cdot (S/N)} \cdot \frac{1}{\sqrt{\tau}} \tag{1}$$

We have already obtained the linewidth $\Delta\nu$ less than 1 Hz. The signal-to-noise ratio, however, is not as good as was planned.

Now the second fountain system is being developed. In the system some improvements on the signal-to-noise ratio and the total stability of the mechanical and optical systems are planned.

OPTICAL FREQUENCY STANDARDS

Aiming at measuring the spectrum of the forbidden transition of a single Ca+ ion, we are now developing a new ion trap **[3-4]** (Figure 2). To observe the 4s2S1/2 - 3d2D5/2 forbidden transition (729 nm), a narrow linewidth laser is being developed. So far, a few tens Hz linewidth and the stability of 10^{-13} for the laser has been achieved **[5]** (Figure 3). To measure the optical frequency, we have used a femtosecond optical comb system Menlo FC 8003 and we have evaluated its performance **[6]**.

PRECISE TIME SCALE GENERATION AND TIME TRANSFER

TWO-WAY SATELLITE TIME AND FREQUENCY TRANSFER (TWSTFT)

TWSTFT network in the Asia-Pacific region has developed by the collaboration of NICT and major T&F institutes in the region **[7]**.

A multi-channel TWSTFT modem has been developed by NICT. The performance evaluation shows that it is capable of sub-nanosecond time transfer for a 1-second averaging time or a frequency transfer precision of 5×10^{-14} for an averaging time of 10,000 seconds. The result of an intercomparison of NICT modem TWSTFT, ATLANTIS modem TWSTFT, and GPS common view (CV) in the case of the NICT-TL link is shown in Figure 4, and the stability obtained by the link is shown in Figure 5.

A transportable TWSTFT station is under development for calibration in the Pacific Rim region. The performance evaluation is expected at the end of this year, followed by a calibration trip next year. We also plan to extend a TWSTFT link between NICT-PTB using the PAS-4 satellite.

GPS, P3, AND CARRIER PHASE

NICT is developing precise orbit analysis software called “CONCERTO” and applying it to GPS carrier-phase time transfer by solving the ambiguity problem. Analysis shows that it can be well applied for time transfer on a baseline of less than a few hundred km by using a Niell mapping function with IGS products for tropospherical delay correction **[8]**. For the time transfer on a longer baseline, real-time estimation of tropospherical delay is conducted **[9]**.

By using a dual frequency receiver ASHTEC Z-XII3T, GPS P3 time transfer **[10]** has been carried out. The result between NICT and PTB is shown in Figure 6. As for the filtering process used here, see Ref. **[11]**.

TIME-SCALE ALGORITHM

Some improvements have been achieved as a result of research on the algorithm of the present UTC (CRL) system. The frequency change of UTC (NICT) resulting from the insertion or deletion of a clock to/from the Cs ensemble has been greatly reduced. The short-term stability of UTC (NICT) has been also improved by optimizing the control gain of daily frequency adjustment **[12]**. We have developed a system which predicts UTC-UTC (NICT) by using the data from BIPM’s Circular-T and the Cs ensemble paper clock at NICT. We have been developing an algorithm for a new system in cooperation with the Japan Standard Time Group.

TIMEKEEPING AND DISSEMINATION

DAILY TIMEKEEPING AND TIME TRANSFER

At the headquarters of NICT, 15 cesium atomic clocks with high-performance beam tubes are operated to generate UTC (NICT) at present. UTC (NICT) is used for Japan Standard Time (JST) and for the national frequency standard. UTC (NICT) has been kept within 50 ns compared with UTC since January 2003. UTC (NICT) has been used as the reference value for the NICT's frequency calibration service.

A new UTC (NICT) system is under development. The biggest change in the new system is to use a hydrogen maser as the source of UTC (NICT) instead of a Cs clock. The short-term stability of UTC (NICT) will be very much improved by this change. In order to improve the measurement precision, a new multi-channel DMTD system has been developed. The new algorithm is going to be introduced for using a hydrogen maser. The main parts of the system are triply redundant for reliability. By using this system, we aim to achieve the UTC (NICT) synchronized to UTC within 10 ns. Now we are building up the whole system, and confirming the system performance. An evaluation of the system noise of the multi-channel DMTD system is shown in Figure 7. A block diagram of the system is shown in Figure 8.

The main tool for the daily time transfer has been the GPS L1 single-channel common-view (CV) method. However, because its performance is lower than the clock's, it became insufficient for the daily time transfer for the contribution to TAI. Therefore, we are now conducting the regular time comparison using multi-channel GPS CV and TWSTTF. The TWSTFT results between NICT-NMIJ, NICT-NTSC, NICT-TL, and NICT-AUS have been used as the primary time transfer link for the TAI calculation since 2002. TWSTFT has been also performed between NICT-USNO (Vandenberg) twice a week. Figure 9 shows the TWSTFT network in the Asian and Pacific Rim.

LF BROADCASTING

NICT transmits the standard time and frequency wave signal on the LF band, and two stations cover the entirety of Japan 24 hours a day. The locations of the stations are shown in Figure 10. Ootakadoya-yama Station has been operating since 10 June 1999 and Hagane-yama Station since 1 October 2001. The basic specifications of these stations are listed in Table 1. The radio-controlled clocks are popular in Japan and more than 10 million are already used. A nationwide survey for measuring field strengths of LF standard frequency waves has been made, and the observed diurnal variations of received strengths show fairly good agreement with the theory. Figure 10 shows the LF stations of NICT in Japan.

NTP

Concerning the Network Time Protocol (NTP) service, NICT does not provide the service directly to general users, but does provide it indirectly through Internet Service Providers (ISPs). NICT has stratum-1 NTP servers installed at NICT headquarters, and they serve only the stratum-2 NTP servers operated by the ISPs through a common-carrier leased line or ISDN line. We continue the test experiment of NTP service.

TRUSTED TIME

As the national time authority (NTA) of Japan, NICT has researched a trusted time-serving system for time authorities (TA). The Japanese government has established the "Time Business Forum" (*http://www.scat.or.jp/time/*) to promote and study the trusted time service system in Japan. For this activity, NICT is contributing a technical field to provide a secure UTC (NICT) to TAs.

RESEARCH AND DEVELOPMENT OF A SATELLITE POSITIONING SYSTEM

PRECISE TIME COMPARISON USING ETS-VIII

NICT has developed a precise time and frequency comparison system for ETS-VIII, a Japanese Engineering Test Satellite, which will be launched in FY 2005. Using a two-way time-transfer method and carrier-phase information, this precise time-comparison system will attain a precision of around 10 ps when measuring the time differences between an onboard atomic clock and ground reference clocks **[13]**.

QUASI-ZENITH SATELLITE SYSTEM

A plan to develop a regional satellite navigation system called the Quasi-Zenith Satellite System (QZSS) was recently announced. It makes use of three satellites on inclined orbits separated 120 degrees from one other, as shown in Figure 11, to improve the visibility of satellites, particularly in urban canyons. NICT is to develop time and frequency technology for this system, such as a spaceborne hydrogen maser atomic clock and time management system **[14-15]**.

SPACE BORNE HYDROGEN MASER

Development of a spaceborne hydrogen maser (SHM) is one of the basic research and development themes for QZSS. So far, we have succeeded in developing a Bread Board Model (Figure 12) whose stability is better than 10^{-14} at 10,000 second, with the weight and power consumption of less than 60 kg and 100 W, respectively **[16]**. The approach to obtain 10-year lifetime in space was also confirmed. We are currently designing an engineering model (EM) to meet space-use requirements.

TIME MANAGEMENT SYSTEM

Precise time comparison between onboard clocks (SHM, Rb, and/or Cs) and between an onboard clock and ground stations is required to provide precise positioning timing service and keeping interoperability and equal performance with GPS (modernized). QZSS satellite will have a precise time comparison unit and bent-pipe function to meet those requirements. We have carried out the basic design for the onboard equipment, and have started making an EM and designing the ground system for it, as shown in Figure 13.

TIME APPLICATIONS

Accurate and trusted time is indispensable for safe use of electronic commerce or other important information exchange. NICT has started research on standard time applications and related technologies, including trusted time stamping and Internet time distributions.

INTERNET TIME-TRANSFER TECHNIQUES

NICT has developed a high-precision hardware time stamper that can put time stamps with accuracy of 4 ns on UDP packets in a "wire-speed" of gigabit Ethernet or 10 Gbit Ethernet. We have measured the packet delay of about 40 km gigabit link using these stampers and cesium clocks, and the results show that the high-speed IP network can be used for clock synchronization with the accuracy of microseconds.

TRUSTED TIME-TRANSFER TECHNIQUE

NICT is conducting research on a trusted time-transfer method for safe use of time stamping based on Japan Standard Time. As one method for realizing this safety, we are developing a hardware-accelerated trusted time stamper that can process long electronic signatures at sufficient speed **[17]**. Improvement in the speed by hardware-izing is planned.

DEMONSTRATION EXPERIMENTS ON TRUSTED TIME STAMPING

NICT is constructing the demonstration system of trusted time stamping for finding out possible problems through real operations. We had already prepared some important subsystems, including the trusted time stamper and the TSA software, by the end of 2003. The demonstration experiments are planned to be conducted in collaboration with TA / TSA service providers in 2004 and 2005.

RELATED RESEARCH ON TIME AND FREQUENCY STANDARDS

ATOMIC PHYSICS

As a basis of the research and development of atomic frequency standards, research on atomic physics has been conducted. Examples of recent subjects are the laser stabilization with a thin Cs-vapor cell **[18]** and the molecule trap **[19]**.

MILLI-SECOND PULSAR TIMING

Millisecond pulsars are expected to supply a source of new time and frequency standard. We have been carrying out weekly timing observations in S-band by using the 34 m antenna at Kashima Space Research Center since 1997. We estimated the intrinsic parameters of PSR1937+21 from our own data, and a long-term change of dispersion measure of this pulsar was detected from the cooperation with Russian pulsar group **[20]**. Another millisecond pulsar PSR1713+07 has been observed since 2003. In addition, a new digital system is now under development for the next observation system.

RELATIVISTIC EFFECTS IN T&F STANDARDS

Research on relativistic effects in the space-time references and standards has been conducted: (1) measurement of the gravitational redshift of atomic clocks transported from NICT headquarters to LF stations **[21]**; (2) theoretical investigation on applying gravitational lensing for the measurements of galactic structure and stellar mass **[22]**.

SUMMARY

The Communications Research Laboratory (CRL) was reorganized into the National Institute of Information and Communications Technology (NICT). At NICT, the same research, development and service activities on time and frequency has been conducted as were done at CRL, or even more actively than ever.

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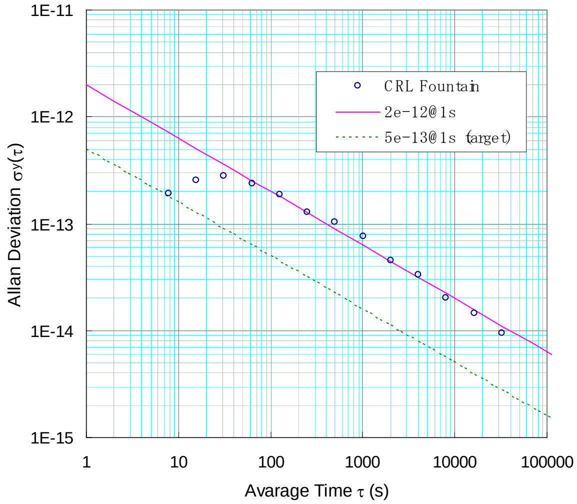

Figure 1. Frequency stability of the first NICT atomic fountain.

Figure 2. Miniature trap for a single Ca+ ion.

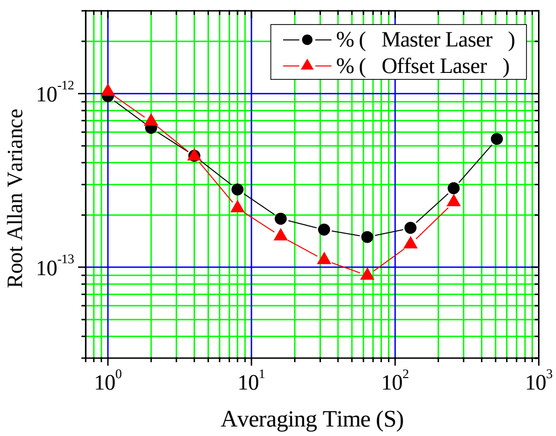

Figure 3. Allan variances of master laser and offset laser.

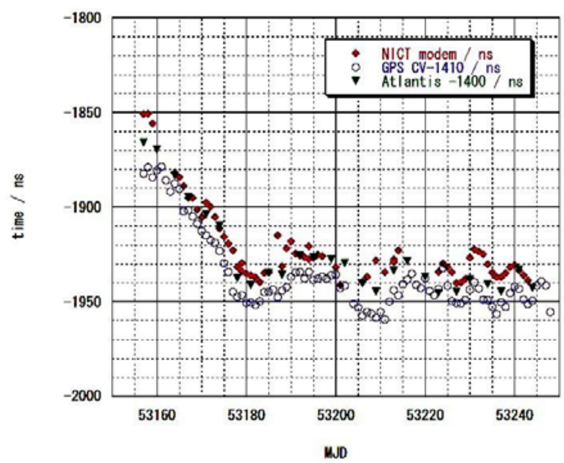

Figure 4. Comparison between UTC (NICT) and UTC (TL) by multiple methods.

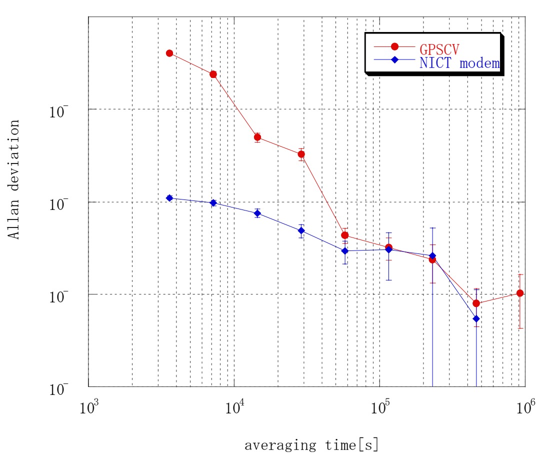

Figure 5. Allan deviation of intercomparison of UTC (NICT) - UTC (TL) between GPS CV and NICT modem TWSTFT.

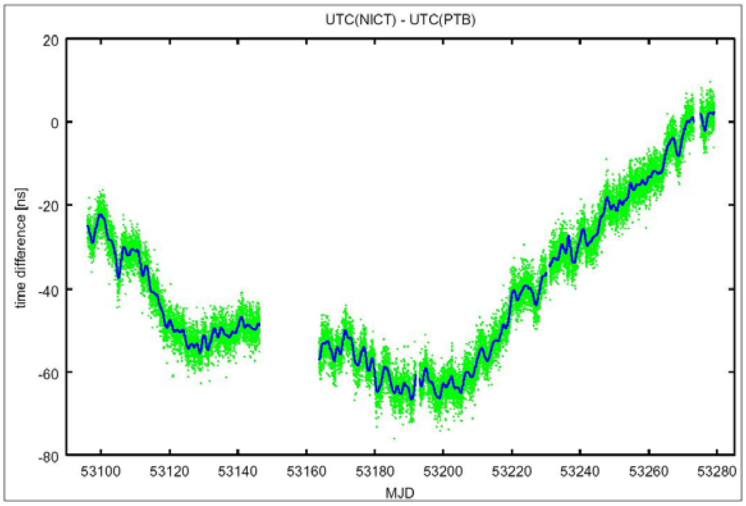

Figure 6. A time comparison result between UTC (NICT) and UTC (PTB) by GPS P3 in the period 2004/04/01-2004/09/30. Green dots show the measured values and the blue line is obtained by a filtering **[11]**.

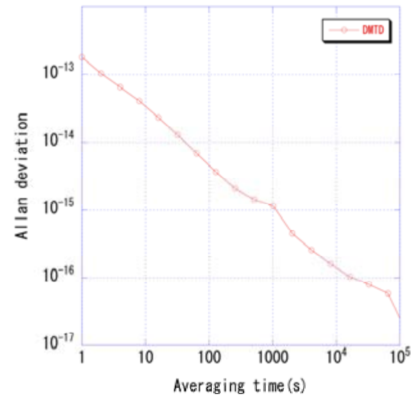

Figure 7. System noise of the multi-channel DMTD.

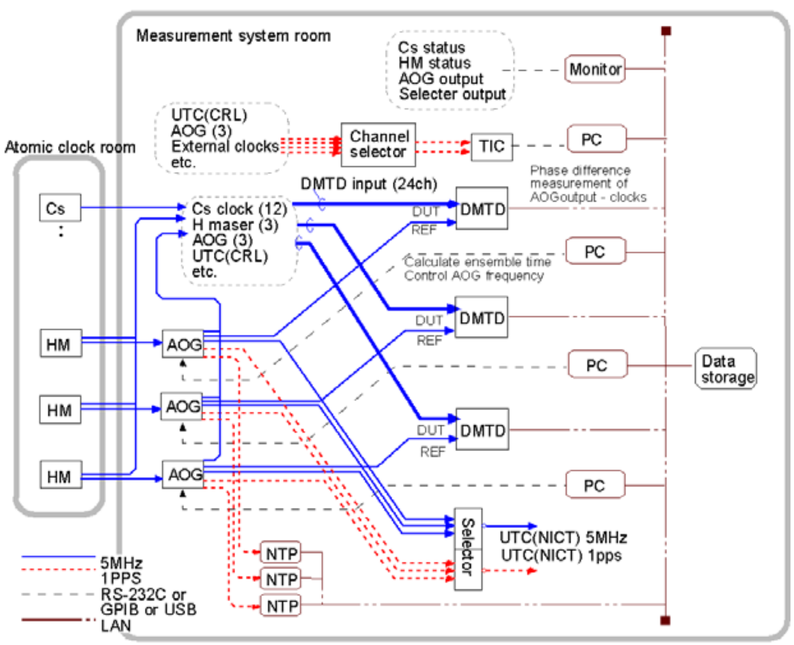

Figure 8. Block diagram of the new UTC (NICT)

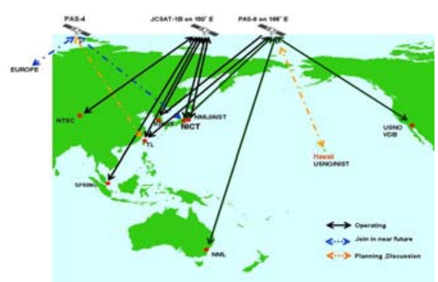

Figure 9. The TWSTFT network in the Asian and Pacific Rim.

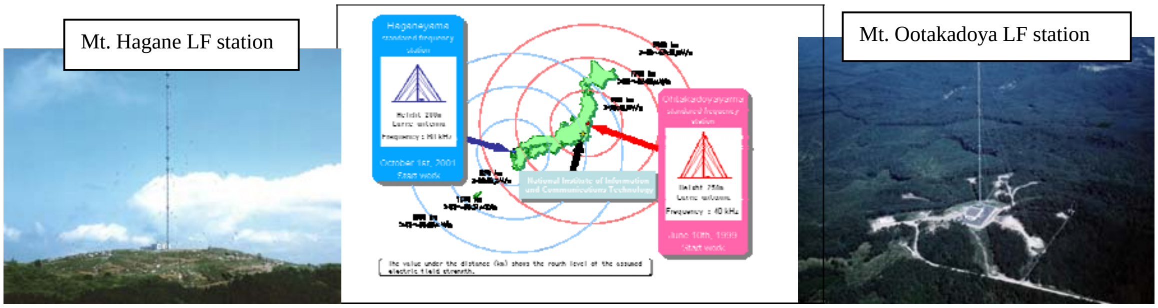

Figure 10. LF stations of NICT in Japan.

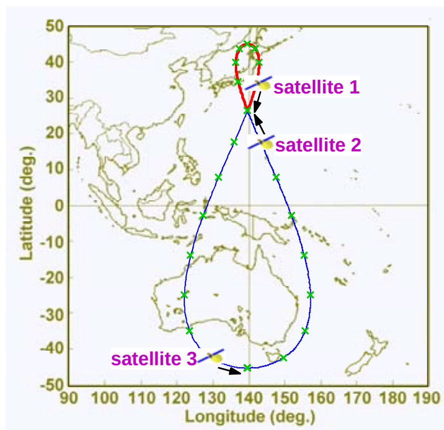

Figure 11. QZS orbit projected onto the earth and the configuration of three satellites.

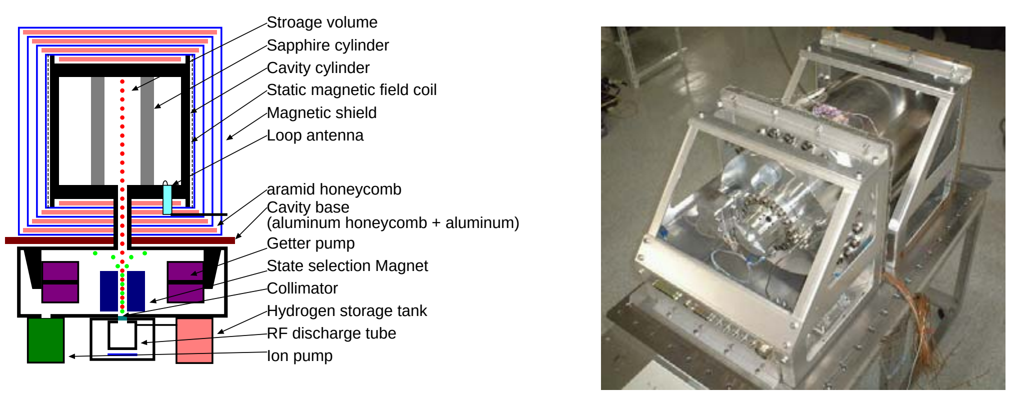

Figure 12. BBM of the Spaceborne Hydrogen Maser (SHM).

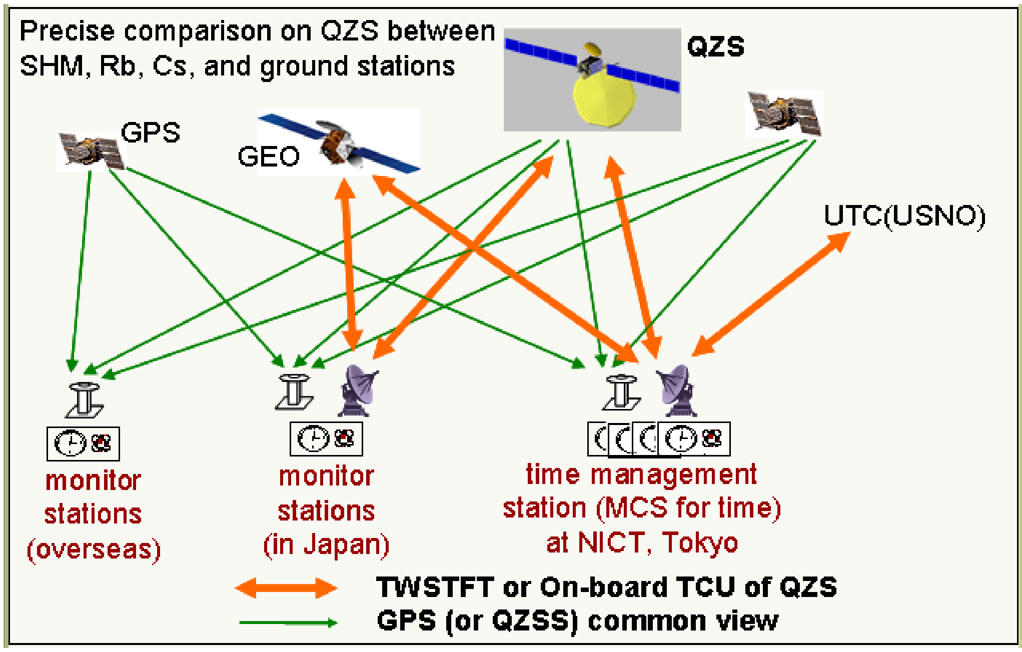

Figure 13. Basic design of QZS time management system.

	Ohtakadoya-yama LF station	Hagane-yama LF station
Running date	10th of June, 1999	1st of October, 2001
Approximate Location	Fukushima pref.	Saga/Fukuoka pref.
Latitude Longitude	N 37° 22′ E 140° 51′	N 33° 28′ E 130° 10′
Land height of the station	790m	900m
Type of antenna	Omni-directional	same as left
Antenna Height	250m	200m
Transmission power	50kW	50kW
Antenna efficiency	more than 25% or above	more than 45% or above
Carrier frequency	40kHz	60kHz
MODE	A1B	A1B
Frequency uncertainty	$\pm 1\times 10^{-12}$	$\pm 1\times 10^{-12}$

Table 1. Characteristics of the JJY-LF stations.