4-4 Time Comparison Equipment for ETS-Ⅷ Satellite —Part 1 Development of Flight Model—

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The Engineering Test Satellite Ⅷ (ETS-Ⅷ) is a Japanese geostationary satellite which will be launched in 2004. Its missions will include mobile communication experiments and application experiments using Cesium atomic clocks in space. Using this satellite, the CRL (Communications Research Laboratory) and the NASDA (National Space Development Agency) is planning to conduct a precise time and frequency transfer between an atomic clock on-board the satellite and a ground-reference clock. This paper describes the system for precise time transfer between the ground reference clock and on-board clock. The system is designed to make the time transfer at a precision of around 10 ps.

Keywords
ETS-Ⅷ, Satellite positioning system, On-board atomic clock, Time comparison

1 Introduction

The ETS-Ⅷ (Engineering Test Satellite Ⅷ) [1], scheduled to be launched in 2004, is designed to contribute to the development of cutting-edge, universal, basic technologies that will be useful in future space activities. A variety of experiments will be carried out using this satellite, including a mobile communications experiment[2] in which a large expandable antenna will be deployed.

Designed in line with the mission goals of National Space Development Agency of Japan (NASDA), the ETS-Ⅷ will be the first Japanese satellite equipped with an atomic frequency standard (atomic clock). Application experiments will include basic research on satellite positioning technology[1].

To evaluate the performance of the atomic clock aboard the satellite, the CRL has proposed a high-precision method of comparing time between the space-borne atomic clock and a ground-based atomic clock. This method was subsequently approved, and the corresponding system has been slated for installation aboard the ETS-Ⅷ. Development and manufacture of this onboard system is now complete, and the equipment is undergoing evaluation as part of overall pre-deployment satellite testing.

This paper describes the outline, operating principle, and structure of the high-precision time comparison equipment (TCE) to be installed aboard the ETS-Ⅷ, as well the work leading to its development. We will also demonstrate how time comparison in the order of 10 picoseconds becomes possible through the minimization of errors relating to propagation delay, ionosphere delay, and delays in the transmitter and receiver.

2 Japanese satellite-based positioning technology

GPS[4]-based systems such as car navigation systems, ship positioning systems, and time-data dissemination systems are currently in wide use throughout Japan. GPS technology is also used in a number of earthquake-observation networks and in international standard time comparison[3].

GPS is, however, a system developed by the United States military. To date, the US government has not charged users, for political reasons, but its use in the future or in the event of a defense emergency is not guaranteed. A similar satellite-based positioning system—Russia's GLONASS[5]—presents concerns in terms of future stability due to potential political instability. In Europe, a satellite-based positioning system has long been under discussion. To reduce the risk of relying too much on GPS, the Europeans have begun development of the GALILEO project[6], now in the system-design phase. Commercial operation is planned to begin roughly by 2008.

Japan had lagged behind other nations in research and development of satellite-based positioning systems, but in around 1996 discussions began on a future Japanese satellite-based positioning system. In particular, a working group of the National Space Development Agency of Japan presented a report in March 1997, in which they agreed as an initial step to develop the following basic technologies[7] in satellite-based positioning.

- Space-borne atomic clock
- Time-management technology for satellite networks
- High-precision satellite orbit-determination technology

It was agreed that the CRL would develop the hydrogen maser space-borne atomic clock[8], which offers frequency stability higher than that of the Cs atomic clock and Rb atomic clock aboard the GPS satellite, and that NASDA would push forward with research and development of time-management technology required for satellite networks, in addition to technology to enable high-precision satellite orbit determination.

As part of these efforts NASDA will install a Cs atomic clock in the ETS-Ⅷ. While deployment of a Cs clock is not part of the mission, the introduction of this device—with its known track record within the GPS—will provide basic information on the underlying techniques of satellite-based positioning.

The CRL has proposed a bi-directional method of time comparison used in the TCE for high-precision time comparison between the on-board atomic clock (pre-launch) and a ground-based clock. This method will eventually be used to evaluate the performance of the atomic clock aboard the orbiting ETS-Ⅷ. The goal of the CRL in this context is to provide the equipment required for this experimental system aboard the ETS-Ⅷ.

The decision was subsequently made to launch a quasi-zenith satellite in 2008, and the development of a satellite-based positioning system using this satellite is now underway. The CRL, which is responsible for the management of the time standard for this system, will develop a TCE-based method for time comparison between the satellite and a ground station.

3 ETS-Ⅷ (Engineering Test Satellite Ⅷ)[1]

An external view of the ETS-Ⅷ is shown in Fig.1. The satellite is scheduled to be launched in 2004. A variety of experiments, including a mobile communications experiment using a large expandable antenna, will be carried out using this satellite to develop sophisticated, universal, basic technologies that will prove useful in a range of future space activities.

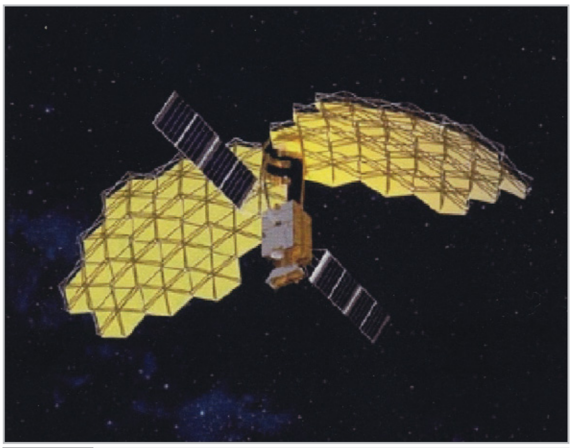

Fig.1 *External view of ETS-Ⅷ*

NASDA intends to equip the ETS-Ⅷ with an atomic clock-the first such deployment on a Japanese satellite-in order to examine its performance in orbit and to acquire the basic techniques of satellite-based positioning. In addition, basic applied experimental research will be conducted on satellite-based positioning.

3.1 On-board atomic clock

NASDA has selected the US FTS Cs atomic clock, often used in GPS applications, as the on-board atomic clock. The use of this device will enable us to acquire the basic techniques of satellite-based positioning.

The specifications of the Cs atomic clock are as follows:

- Frequency: 10.23 MHz - 5.5×10^{-3} Hz (including relativistic correction)
- Weight: 13.6 kg
- Certainty: $\pm 1 \times 10^{-11}$
- Stability: 1.0×10^{-11} (1 to 3.6 s)
  $1.89 \times 10^{-11}/\sqrt{\tau}$ (3.6 to 10^5 s)
  6×10^{-14} (10^5 to 10^6 s)

The equipment NASDA will use includes an S-band transceiver, an L-band transmitter, an S-band/L-band common 1.0 m ϕ antenna, and SLR (satellite laser ranging) equipment. These devices will be used to acquire basic satellite-based positioning techniques relating to the following:

- Performance evaluation of the on-board atomic clock in orbit and acquisition of in-orbit management techniques
- Precision management techniques of satellite network time and ground time
- Evaluation of a techniques of high-precision orbit determination

3.2 Outline of high-precision time comparison equipment (TCE)

Fig.2 illustrates the method for precise time (frequency) comparison between the ETS-Ⅷ-borne atomic clock and the reference ground clock. The satellite sends a signal for time comparison to the ground station and vice versa. Under this method, referred to as bi-directional transmission time comparison, the difference between the space-borne atomic clock and the reference ground clock is calculated using received signals and the difference in the reception times. This method allows for high-precision time comparison because delays caused by the ionosphere and atmosphere along the propagation path can be virtually canceled out in calculation, even when these delays fluctuate; satellite motion can similarly be accounted for.

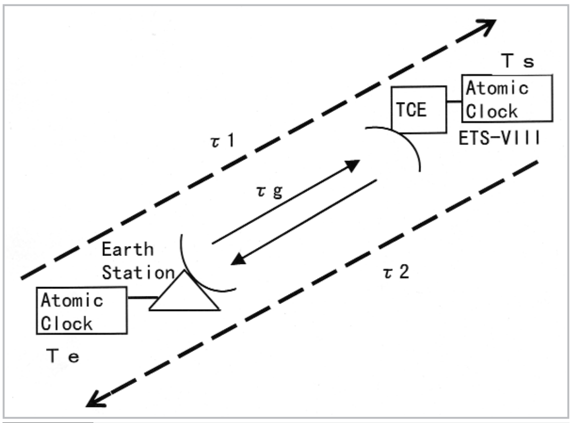

Fig.2 *Principle of bi-directional time comparison*

In this method, both the satellite and ground station are equipped with a high-stability atomic clock, allowing for the generation of coherent carrier signals and coherent modulation signals, as with GPS. Thus not only the modulation signal but also phase information in the carrier signal can be used in comparison. It then becomes possible to compare time on the order of picoseconds, or to compare length on the order or millimeters.

3.3 TCE principle

As shown in Fig.2, signals for time comparison are exchanged between the satellite station and the ground station. The satellite and the ground station measure the received signals and the time difference.

Subjects of measurement are as follows:

$\tau 1$: Difference in time between the satellite and the ground station, with reference to the satellite time, Ts;

$\tau 2$: Difference in time between the satellite and the ground station, with reference to the ground time, Te; and

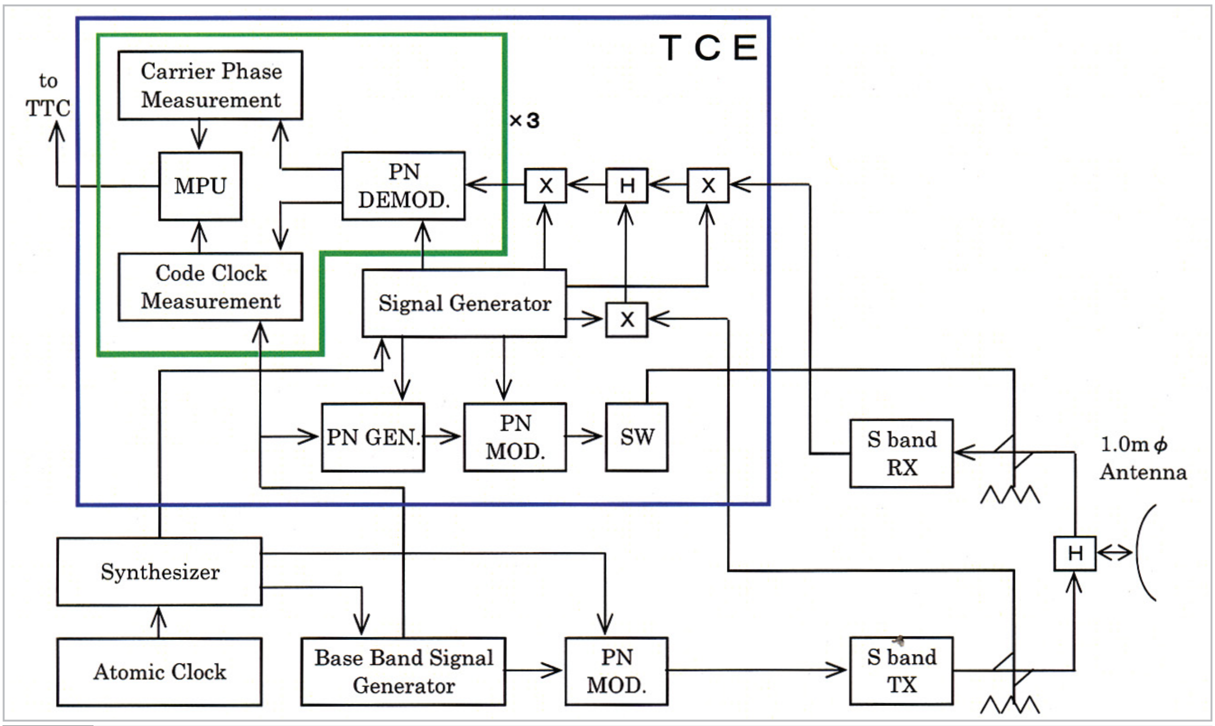

Fig.3 *Block diagram of high-precision time comparison equipment aboard ETS-Ⅷ*

τg: Satellite-ground propagation time.

UPLINK : $\tau 1 = \tau g + Ts - Te$ ·····(1)

DOWNLINK : $\tau 2 = \tau g + Te - Ts$ ·····(2)

Then,

$UP - DOWN = \tau 1 - \tau 2 = 2(Ts - Te)$ ···(3)

$UP + DOWN = \tau 1 + \tau 2 = 2 \tau g$ ·········(4)

In this way, the subtraction of one measurement value from another provides the time difference, while adding measurement values provides the propagation time. The propagation time in turn provides a value for satellite-ground distance.

In actual measurement, the code clock signal of the 1.023MHz PN code (equivalent to the GPS C/A code) (sent as a ranging signal) and its carrier wave-phase data. The former signal is used to measure the approximate distance, while the latter completes high-precision measurement.

3.4 TCE configuration

Table 1 summarizes the major specifications of TCE and the on-board atomic clock system.

Fig.3 is a block diagram of the TCE (inside the blue frame) and of the on-board atomic clock (outside the blue frame). These have the following functions:

- Transmission of a time comparison signal from the satellite to the ground (transmitting function)
- Receipt of the time comparison signal from the ground (receiving function)
- Measurement of delay in the satellite transmitter and receiver systems in real time (transmitter correction signal and receiver correction signal)

These transmitter and receiver signals enable calculation of time difference under the

Table 1 *Major specifications of TCE and the atomic clock*

Transmitter Power	5.7W
S-band Transmitter Frequency	2491.005MHz
S-band Received Frequency	2656.390MHz
L-band Transmitter Frequency	1595.880MHz
PN Code	Same GPS C/A Code
Size (TCE)	< 32cm×32cm×32cm
Weight (TCE)	< 12.4kg

bi-directional transmission method. The transmitter correction signal and receiver correction signal are used in parallel to correct propagation delay fluctuations, due for example to temperature changes and other changes over time that are not common to the transmitter and receiver. For this purpose, the signal processing unit of the TCE (inside the green frame) is designed to handle three channels of signals concurrently—the received signal, the receiver correction signal, and the transmitter correction signal.

The signals are handled as follows in each of the signal routes.

- Transmitter signal: The base-band signal processor generates transmission carrier waves and a PN code, which are PN-modulated and amplified by the S-band transmission unit and then sent out from a 1.0 mϕ antenna.
- Receiver signal: The signals received by a 1.0 mϕ antenna are branched by the S-band receiver unit. They are frequency-converted, PN-demodulated, and used for carrier-wave phase analysis and code clock measurement.
- Receiver correction signal: The carrier waves generated by the signal synthesizer and PN code generated by the PN code generator are PN-modulated, inserted in the directional coupler in front of the S-band receiver unit, and then processed along with the received signals.
- Transmitter correction signal: The transmitted signals are branched by the directional coupler in front of the antenna, frequency-converted, and processed along with the received signal and receiver correction signal.

3.5 Ground station

We are in the process of constructing two ground stations, each having an antenna with a diameter of 2 m, for experimental use: one will be installed at the CRL Headquarters facility and the other will be used as a mobile station. The time comparison unit of the ground station is a modified EM of TCE. We will conduct the same measurement, transmitter correction, and receiver correction as will be performed in the satellite.

3.6 Correction of errors

(1) Propagation delay

Because the signals from the satellite and ground station take the same propagation path, the delay caused by the ionosphere and atmosphere, including fluctuations in this delay will be canceled out. Additionally, errors due to satellite movements can be corrected by calculation.

The above will be true if τg in uplink is exactly the same as τg in downlink. In fact, however, the satellite moves in orbit during the time from signal transmission to reception, and the ground station on Earth also moves during this period, due to the Earth's rotation. These movements are not the same, and thus τg in uplink is different from that in downlink. These movements do, however, represent errors that can be calculated from the positions of the satellite and ground station and can be corrected by calculation. Additionally, the satellite orbit is not an ideal orbit, and if this difference is large τg in uplink will differ further from τg in downlink. This error can also be corrected through calculation of the satellite's orbit.

(2) Influence of the ionosphere[9]

The S-band frequency used in our system is 2,656.390 MHz for uplink and 2,491.005 MHz for downlink; there is a difference of about 170 MHz between the two. With the employed frequency, f, and the total number of electrons per unit area in the ionosphere, Ne, then the delay distance, ΔL, which changes with the group delay in the ionosphere, can be calculated as:

$$\Delta L = \frac{40.3}{f^2} Ne \quad (5)$$

When the above frequencies are used in uplink and downlink, ΔL is calculated as shown in Table 2. The difference becomes 0.024 m in the nighttime during a solar minimum, and 0.78 m in the daytime during a solar maximum. It is thus difficult to account for delays caused by the ionosphere. On the other hand, since the difference in delay between the ranging signals of the two frequencies (S-band and L-band) transmitted from the ETS-Ⅷ can be monitored in real time, the difference in measured delay between the two frequencies, ⊿⊿L, can be calculated by the following equation.

$$\Delta\Delta L = 40.3\left(\frac{1}{f_S{}^2} - \frac{1}{f_L{}^2}\right) Ne \cdots (6)$$

The total number of electrons in the ionosphere per unit area, Ne, can then be determined (f_S is the S-band frequency, f_L is the L-band frequency). In this way, delays can be corrected even when different frequencies are used in uplink and downlink.

(3) Delay caused by the communications hardware[10]

Table 2 *Difference in the delay distance due to use of different frequencies*

	Furequency (MHz)	Delay Range in Ionosphere	
tec		3×10^{16} (m^{-2})*1	1×10^{18} (m^{-2})*2
uplink	2656.390	0.171m	5.71m
downlink	2491.005	0.195m	6.49m
difference		0.024m	0.78m

tec : total electoron contents in the ionosphere per unit area

*1 : in the period of minimum solar activity, night time, toward zenith

*2 : in the period of maximum solar activity, day time, toward zenith

Even in bi-directional time comparison, delay (and the change in delay over time) not

Table 3 *Example of channel design and accuracy in time comparison*

		S−Band		L−Band
		Earth→ Satellite	Satellite →Earth	Earth→ Satellite
Transmitter Power (W)		18.00	18.00	18.00
Antenna Gain(dBi)		31.90	21.30	16.90
Feed Loss (dB)		3.00	5.90	2.90
E. I. R. P (dBW)		41.45	27.95	26.55
Propagation Loss (dB)		192.52	191.96	188.10
Rain Loss (dB)		0.10	0.10	0.10
Atmospheric Loss (dB)		0.40	0.40	0.40
Antenna Gain (dBi)		22.30	31.34	27.47
Feed Loss (dB)		3.30	3.00	3.00
Pointing Loss (dB)		0.20	0.20	0.20
System Noise Temperature (T : K)		300.00	100.00	100.00
Noise Power Density (No= k T:dBW/Hz)		-203.83	-208.60	-208.60
Received Signal Power (C : dBW)		-132.57	-134.42	-134.12
Loss due to Calibration Signal (dB)		5.00	5.00	5.00
C/No (dB·Hz)		66.26	67.43	65.83
Measurement accuracy (BW=1Hz)	Code Phase(m)(1sec)	0.43	0.37	0.45
	〃 (nsec)	1.43	1.25	1.50
	Career Phase (mm) (1sec)	0.16	0.15	0.29
	〃 (psec)	0.55	0.51	0.96
	Code Phase (m) (100sec)	0.043	0.037	0.045
	〃 (nsec)	0.143	0.125	0.150
	Career Phase(mm) (100sec)	0.016	0.015	0.029
	〃 (psec)	0.055	0.051	0.096

common to both transmitter and receiver cannot be accounted for; these delays translate into error in the measurement of time difference. Our system, however, can monitor and correct these delays in real time.

3.7 Accuracy of time comparison

Table 3 shows an example of channel calculation and accuracy of time comparison. In terms of channel quality, 65 dB•Hz or higher is expected, while the accuracy of time comparison is 1 ns or so in an ideal, completely error-free case using the PN code clock for diffusion in an integral of one second. Use of the carrier-wave phase data will further improve the accuracy to the order of picoseconds. In reality, some errors cannot be accounted for or eliminated, so the accuracy of time comparison will be around 10 ps. Nevertheless, this level of accuracy is much higher than previously available under conventional systems.

3.8 Proto-flight model (PFM)

Fig.4 shows an external view of the TCE-PFM. The PFM will be examined to obtain approval for deployment aboard the satellite. After approval is obtained, the PFM will be installed on the satellite. We have performed the following PFM check procedures:

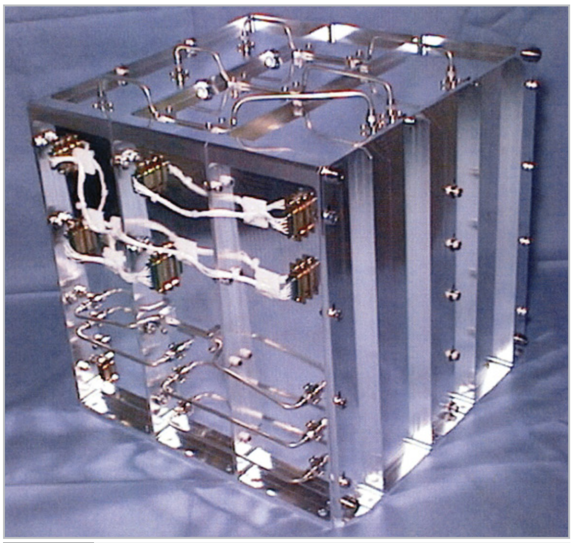

Fig.4 *External view of TCE-PFM*

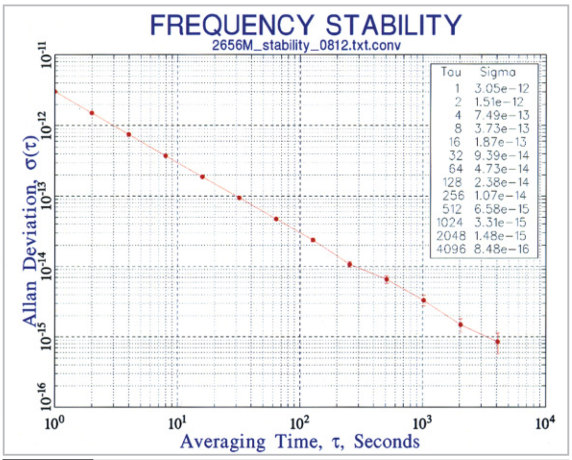

Fig.5 *2,656.390 GHz signal frequency stability*

- Oscillation frequency, level, and stability of each local signal
- PN code and carrier-wave phase measurement capability, which will prove important when the transmitter correction signal and receiver correction signal are overlaid on the received signal
- Thermal-vacuum test, vibration test, shock test, and EMC test

Fig.5 demonstrates the frequency stability of the 2,656.390 MHz signal. The test results show that PFM is sufficiently reliable for use in time comparison.

4 Conclusions

We have described the TCE principle, structure, and specifications, and have shown that a time comparison in the order of 10 ps can be conducted by minimizing errors due, for example, to propagation delay, ionosphere delay, and delays in the transmitter and receiver. A manufacturing and performance check of the PFM has been completed to prepare for the 2004 launch. In the future, we will perform an overall satellite test and a connection test on the ground, when the ground stations are built.

We would like to thank those who assisted in enabling our system to be installed aboard the ETS-Ⅷ.

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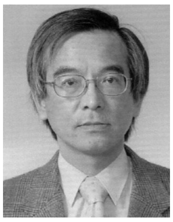

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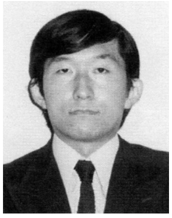

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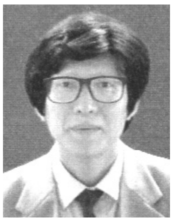
Development of the Satellite Positioning Experiment System



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