5-2 Experimental Results of Time Comparison Using the Time Comparison Equipment on Board ETS-Ⅷ

TAKAHASHI Yasuhiro, NAKAGAWA Fumimaru, TABUCHI Ryo, NAKAMURA Maho, KUNIMORI Hiroo, AMAGAI Jun, TSUCHIYA Shigeru, HAMA Shin'ichi, and NODA Hiroyuki

The Engineering Test Satellite type Ⅷ (ETS-Ⅷ) was a geo-synchronous satellite launched on December, 2006. Using ETS-Ⅷ, mobile telecommunications experiment using the large deployable antennas is executed. ETS-Ⅷ is first satellite in Japan bearing atomic clocks, and basic experiments of satellite positioning are carried out.

In National Institute of Information and Communications Technology (NICT), highly precise time and frequency comparison experiment between the satellite and the ground is executed for the first time in the world. Highly precise time comparison experiment between ground stations using an on-board bent-pipe function and ranging experiment are also executed.

Keywords
Engineering test satellite, Satellite positioning, Time comparison, Ranging

1 Introduction

NICT has performed highly accurate time comparison experiments between satellite and ground in the aim of acquiring the satellite positioning element technology and ascertaining orbit characteristics of the on-board atomic clock using the ETS-Ⅷ. In addition, NICT has performed time comparison experiments between ground and ground and ranging experiments as applied experiments. The results of these experiments are being used in the recently commenced Quasi Zenith Satellite (QZS) Project. This paper describes the composition, outline and experimental results of the Time Comparison Equipment (TCE) on board the ETS-Ⅷ.

2 Satellite positioning technology development in Japan

Today in Japan, GPS (Global Positioning System) is being used to a large extent on all fronts such as car navigation, mobile phone positioning, ship and aircraft navigation, earthquake and tsunami observation and easily obtaining highly accurate time.

However, although GPS is an American system that, according to government policy, currently does not require users to pay subscription fees, it is unstable at times of emergency and has an uncertain future. Consequently, this apprehension about GPS and the risk of solely relying on GPS is here. Russia has operated of GLONASS. GALILEO program has started and launched of two test satellites. China and India have promoted and developed an independent positioning system.

In Japan, although research and development of a satellite positioning system has been delayed, discussions had been held since around 1996 in regard to the nature of satellite positioning system development. In March 1997, the Space Activities Commission released a subcommittee report[1] that enabled the development of the following satellite positioning system element technology.

- On-board atomic clocks
- Satellite time management technology
- Highly accurate satellite orbit determination technology

When the development of satellite positioning technology in Japan commenced, NICT are performing research and development of on-board atomic clocks of hydrogen masers[2] with a more stable frequency than, for instance, cesium and rubidium atomic clocks equipped with GPS, and the Japan Aerospace Exploration Agency (JAXA) and NICT are performing research and development of satellite time management technology and highly accurate satellite orbit determination technology.

JAXA decided to install a cesium atomic clock on the ETS-Ⅷ and conduct basic research on satellite positioning technology starting with acquiring satellite positioning elementary technology. NICT has proposed and obtained approval for the two way time transfer method regarding the highly accurate time and frequency method for atomic clocks and on the ground atomic clocks for the purpose of evaluating the performance of atomic clocks on board the ETS-Ⅷ in satellite orbit and installed Time Comparison Equipment (TCE) on the ETS-Ⅷ in order to perform practical experiments using this method.

Following this, in a joint project of government and private sector, the QZS plan commenced[3] from fiscal 2003, research and development on a communications and broadcasting service form the sky over Japan and a satellite positioning system of complement and augmentation of GPS enhancement and supplementary service began. Then, the non-installation of private communications and broadcasting mission was decided and the plan was changed to perform practical satellite positioning experiments using the QZS[4]. NICT is responsible for the time management system[6] that performs comparisons between all clocks used in the this accurate positioning experiment system[5] using the QZS, and the results of the TCE developed for the ETS-Ⅷ at NICT are being used.

3 ETS-Ⅷ and the positioning mission equipment

3.1 ETS-Ⅷ

The ETS-Ⅷ[7] whose appearance is shown in Fig. 1 is a geostationary satellite launched from the Tanegashima Space Center on December 18, 2006, and performs mobile communications experiments using large deployable antennas for the purpose of developing the latest common base technology required for future space activities. Furthermore, in order to conduct basic experiments for satellite positioning, atomic clocks were installed on a Japanese satellite for the first time and all types of experiments are being performed at JAXA and NICT in the aim of acquiring satellite positioning element technology.

3.2 Highly Accurate Clock (HAC)[8]

HAC is a mission device installed on the ETS-Ⅷ by JAXA used to perform satellite positing experiments and consists of a Cesium Frequency Standard (CFS) atomic clock, S band transceiver, L band transmitter, 1.0m diameter antenna in common use for S band and L band and Satellite Laser Ranging (SLR) equipment. The US made cesium atomic clock that is also used for GPS was introduced to the CFS and the specifications are shown in Table 1. JAXA has performed experiments to acquire the fol-

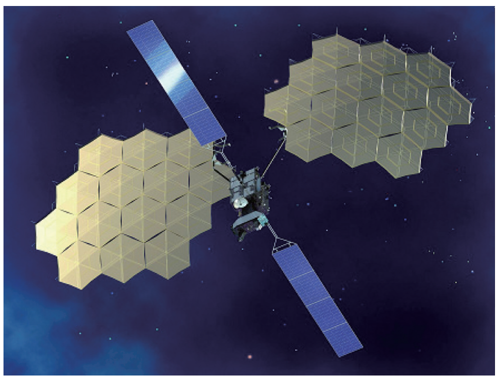

Fig.1 External view of ETS-Ⅷ

Table 1 *Specification of spaceborne atomic clock*

Frequency	10.23MHz
Weight	13.6kg
Precision	$\pm 1 \times 10^{-11}$
Stability	1×10^{-11} ($\tau = 1 \sim 3.6$s) $1.89 \times 10^{-11} \times \tau^{-0.5}$ ($\tau = 3.6 \sim 10^5$s) 6×10^{-14} ($\tau = 10^5 \sim 10^6$s) (τ : Averaging time)

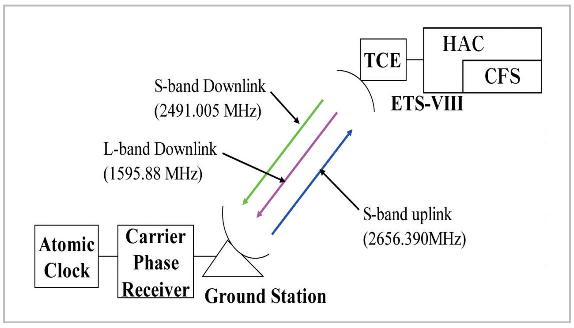

Fig.2 *Block diagram of time comparison*

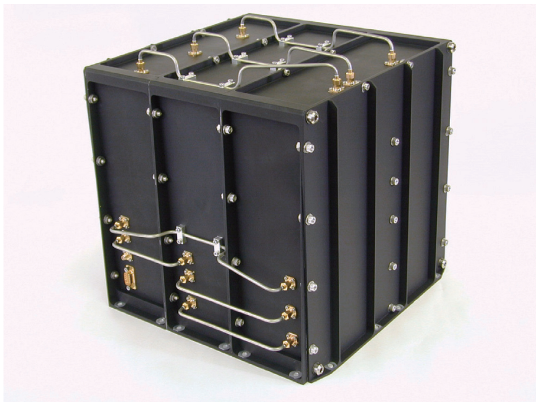

Fig.3 *External view of PFM of TCE*

lowing element techniques in regard to the technology using these.

- The performance evaluation of the atomic clock on orbit and the acquisition of management techniques on orbit
- The acquisition of precision management techniques for satellites time and ground time
- The evaluation of highly accurate orbit determination techniques

3.3 Time Comparison Equipment (TCE)[9]

3.3.1 Outline

TCE is a mission device installed on the ETS-Ⅷ by NICT, performs highly accurate time comparison experiments between satellite and ground for performance evaluations of CFS in satellite orbit for the first time in the world.

The structure of the highly accurate time and frequency comparisons between CFS and the ground reference clock is shown in Fig. 2. These world first comparisons using the two way time transfer method between the satellite and ground that determines the time difference between two clocks by transmitting signals for time comparisons from the satellite to the ground and from the ground to the satellite, and measures each received signal and the time difference. In principle, the two way time transfer method is a method that can the delay and variation of the ionosphere and troposphere on the propagation route and the impact of satellite movements and enables accurate time comparisons.

In addition, since highly stable atomic clocks have been installed on the satellite and on the ground and all signals such as carrier signals and modulation signals are coherently generated as well as GPS positioning signals, this enables positioning information of both modulation signals and carrier signals to be utilized and time to be compared with ps (10^{-12} seconds) order accuracy.

In terms of the development of TCE, prior to the creation of the on board PFM (Proto Flight Model) the EM (Engineering Model) was created to verify performance and conduct electric experiments for the entire satellite system. Following tests, the PFM was installed on the satellite and launched when a test with the whole satellite was conducted. The appearance of TCE-PFM is shown in Fig. 3. It is designed to be efficiently utilized in a small area.

3.3.2 Composition

The main characteristics of the TCE and HAC are shown in Table 2 and a block chart of TCE (thick lines in the box) and HAC is shown in Fig. 4. This has the function of measuring the time difference of two way transfer by transmitting time comparison signals (transmission signals) from the satellite to the ground and receiving time comparison signals (receiving signals) from the ground. In addition, through the function of measuring in real time the time delay of the transmission and receiving systems within the satellite, it is possible to correct fluctuations of time delays caused by temperature or secular variation on different routes of the transmission and receiving systems. Consequently, in order to measure the 3 superimposed signals of receiving signals, receiving system calibration signals and transmission system calibration signals, the TCE signal processing component with 3 channels (thin line) can perform PN demodulation in each channel and measure carrier phases and code phases simultaneously.

Table 2 *Main specification of HAC and TCE*

Tramsmitting Power	S-band	5.7W
	L-band	18W
S-band	TX Frequency	2491.005MHz
	RX Frequency	2656.390MHz
L-band	TX Frequency	1595.880MHz
PN Code		Same as GPS C/A Code
Size (TCE)		320mm×320mm×325mm
Weight (TCE)		12.3kg

Next, an explanation according to each route is as follows:

(1) Transmission signals

Transmission carrier waves and pseudo random noise (PN) codes based on reference signals (10.23MHz, 1kPPS (1000 pulses per second)) are generated by the base band signal synthesis component and, following modulation, transmitted from the 1.0m diameter antenna via the diplexer (DIP) after amplified in the S band transmission system.

(2) Receiving Signal

The electric waves received from the 1.0m diameter antenna are amplified, the frequency is converted in the TCE, and PN demodulation and measurements are conducted by the signal processing component.

(3) Receiving system calibration signals

Following modulation, carrier waves generated by the signal synthesis component and PN codes that are generated by the PN code generator are inserted from the directional coupler on S band receiving system input side, superimposed with receiving signals using a mixer (X), and PN demodulation and measurements are conducted by the signal processing component. It is also possible not to use these signals.

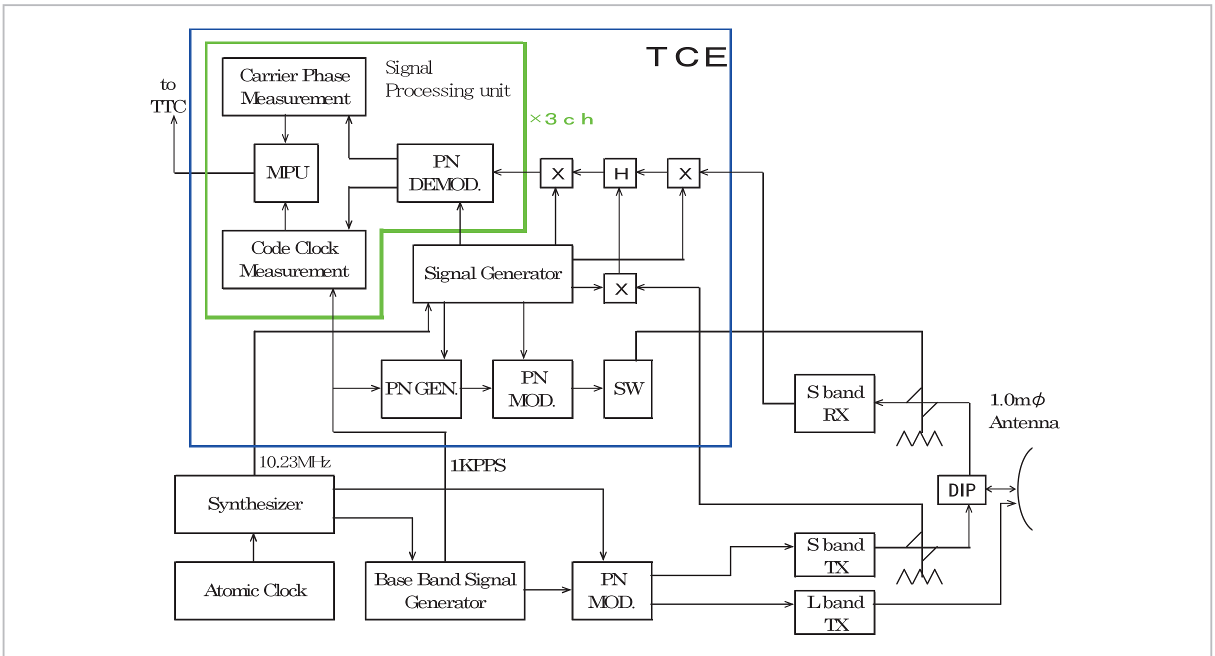

Fig.4 *Block diagram of HAC and TCE*

(4) Transmission system calibration signals

A portion of transmission signals are divided by the directional coupler in front of the antenna and, following frequency conversion in the TCE, these signals are superimposed with the receiving signals and receiving system correction signals using a separating and synthesis device (Hybrid), and PN demodulation and measurements are conducted by the signal processing component.

4 Ground system

As shown in Fig. 5, a fixed station and transportable station with a 2.4m diameter antenna have been created as earth stations to conduct TCE experiments (TCE earth stations). TCE earth stations contain an S band transmitter, and, in the same manner as the satellite, the time comparison component performs code and carrier phase measurements, time delay calibration for the transmission system and receiving system can also be performed, and both S band and L band frequencies can be measured.

In addition to performing highly accurate time comparisons between satellite and ground, these 2 TCE earth stations were also created for the purpose of performing ground to ground highly accurate time comparisons. By placing these 2 earth stations in different locations and measuring different reference signals, such ground to ground highly accurate time comparisons can be performed as application experiments.

As a result of using the two way time transfer method, it is necessary to transmit measurement values from the satellite to the ground using the TCE telemetry. This connects the JAXA Tsukuba Space Center which performs tracking management including the TCE monitoring function and command control function by a communications line and transmits and receives data.

Fig.5 *Antenna of TCE earth station (fixed station, transportable station)*

The fixed station is located in Building 2 of NICT head office (Koganei City, Tokyo) and utilized UTC (NICT) as the reference signal. The transportable station can be transported anywhere in Japan. It is placed at the HIKARI Center approximately 150m from NICT head office Building 2 when the experiments discussed in **5.5** and **5.6** are conducted and utilized a hydrogen maser as a standard.

5 Experiment results

The experimental items and results of the TCE experiments conducted by NICT are detailed below.

5.1 Performance verification experiments

(1) Time Comparison Performance

The time comparison performance of TCE and the TCE earth station is described in **5.2** Short-Term Stability Measurement. Expected satisfactory performance was verified by the initial check-out after the launch and the subsequent periodic measurements.

(2) Ionosphere Correction

Time comparisons using the TCE and the TCE earth station utilizes the two way time transfer method. In principle, this method enables ionosphere and troposphere delays on the propagation route and satellite movements to be offset. However, since there is a frequency variation with the S band uplink (2656.390MHz) and downlink (2491.005MHz), a ionosphere delay for that variation will remain. This can be corrected by calculating measured values of the S band downlink and L band downlink (1595.88MHz).

An example of the ionosphere delay correction volume calculated from the results of the fixed station calculations is shown in Fig. 6. During the experiment period, the solar activities were in a clam period. Consequently, since the ionosphere delay was small, the correction volume only had a maximum of 150ps which was not sufficient for corrections.

5.2 Short term stability measurements

Short term stability measurements were performed during the experiment period. These were conducted through the highly accurate time comparisons between satellite and ground and utilized the Japan standard time UTC (NICT) as ground standard time. UTC (NICT) comprised of 18 cesium atomic clocks (Cs) and 3 hydrogen masers. This has a two-digit higher stability than CFS.

An example of the results for highly accurate time comparison between satellite and ground is shown in Fig. 7. Of these results, (a) shows the difference between UTC (NICT) and CFS and most seem to refer to the movements of CFS. This shows that there was a 187 ns change over a 25 hour period, and since this as a uniform change, the 10.23MHz CFS frequency had around a 0.02mHz variation. (b) is a calculation of the frequency stability (Allan variance) after removing the first drift component in (a). The code phase calculations had a calculation accuracy of an average of 0.7ns per second and the carrier phase calculations had an average of 3ps (approx.) per second. The stability of carrier phase calculations is better than the CFS specification values and it seems that the CFS stability could be seen after one second of measurement.

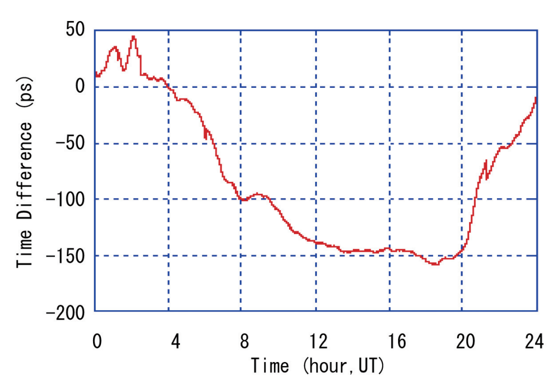

Fig.6 *An example of numerical result of ionospheric delay correction*

5.3 Long term stability calculations

Although it was scheduled that long term stability would be determined from the results of the periodical time comparisons between satellite and ground, absolute values have not yet been achieved. In terms of a long term CFS evaluation, as shown in Fig. 7 (b), it appears that there has been no significant change on CFS stability since no variation have been visible over a two year period. In terms of the frequency difference, shown by the inclination of the time comparison results in Fig. 7 (a), the change over approximately two years is plotted in Fig. 8. This shows the frequency change (approximately 2×10^{-12}Hz/s) as the difference from 10.23MHz reference signal, which is the difference between the CFS and UTC (NICT) frequencies, and it seems that most of it was the change of CFS. This change ratio of this inclination was -1.35μHz/year.

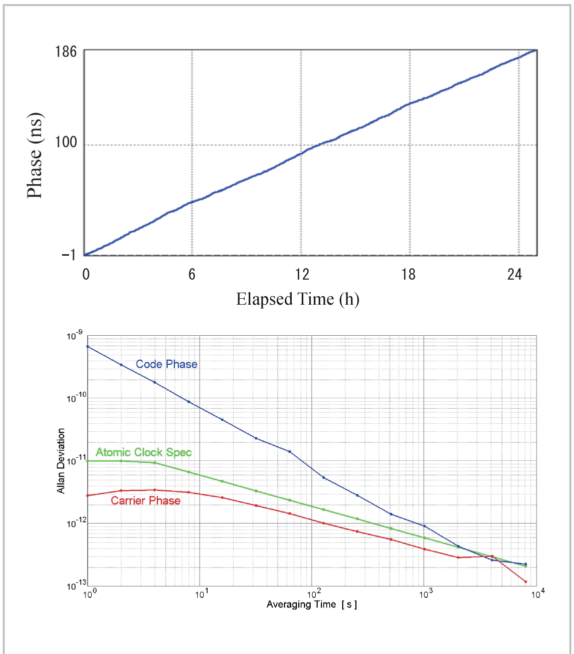

Fig.7 *An example of time comparison result*

Above: (a) time comparison result
Under: (b) Allan deviation

5.4 Measurements at the time of turbulence

Among temperature variation, attitude variation, orbit variation, electrical voltage variation and signal transmission and reception level variation that can be considered measurements at the time of turbulence, no one has been observed as an apparent major impact on time comparisons. Except for these, it has recently turned out that variation due to ionosphere disturbances is significant. The total electron content variation caused by ionosphere disturbances as seen from the results of calculations at the fixed station is shown in Fig. 9. This shows a maximum change of 10 TECU (TECU is the Total Electron Content Unit. 1 TECU is 10^{16} electrons per m^2). The impact on time comparisons at this time is approximately 100ps but this can be corrected. However, as this figure represents the period when solar activities are calm, it is predicated that it can increase by approximately 10 times when solar activities are in an extreme period.

5.5 Ground to ground time comparisons

Highly accurate ground to ground time comparisons are conducted between atomic clocks placed in two locations such as between national time standards, using GPS positioning signals or the two way time transfer method of code phase measurement relayed by geostationary communications satellite.

Ground to ground time comparisons conducted as an application experiment using TCE and HAC use the following two methods.

(1) Time comparisons via satellite clocks

Satellite to ground time comparisons are simultaneously conducted in two locations and ground to ground time differences are determined by calculations via CFS.

(2) Time comparisons via satellite repeater

HAC contains a relaying function for conducting relay experiments for positioning signal and conducts ground to ground time comparisons using this function. A highly stable relay becomes possible by using atomic clock signals as frequency-converted local signal on the satellite, which differs from regular repeaters by communications satellites.

An example of the frequency stability resulting from ground to ground time comparisons between a fixed station and a transportable station using these two methods is shown in Fig. 10. This shows the conventional time comparison using the code phase relayed by a geostationary communications satellite, time comparison via satellite clock (career phase measurement) and time comparison via satellite relay (career phase measurement). Consequently, satellite clocks showed a better result than the code phase relayed by a geostationary communications satellite by 1–2 digits and satellite relay showed an even better result by 1 digit. This shows the possibility of higher stable time comparison of atomic clocks on the ground.

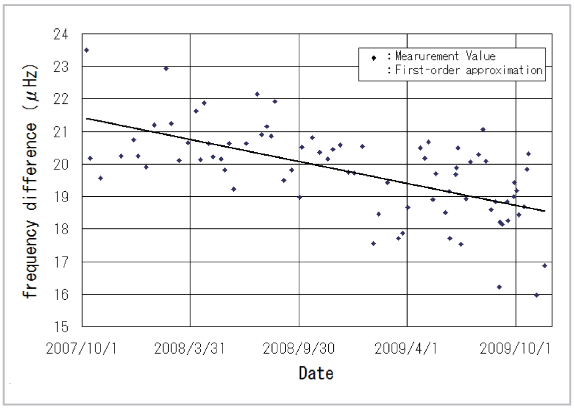

Fig.8 *Secular distortion of frequency difference*

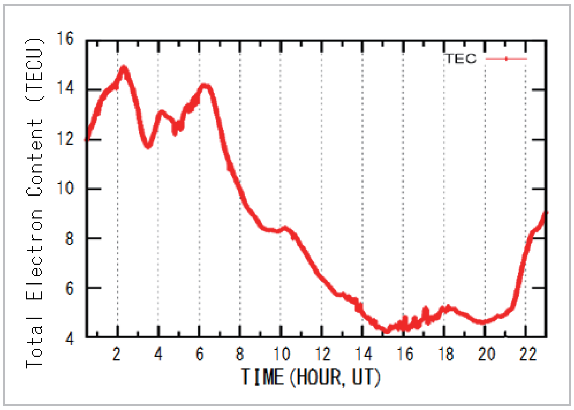

Fig.9 *An example of influence by ionospheric perturbation*

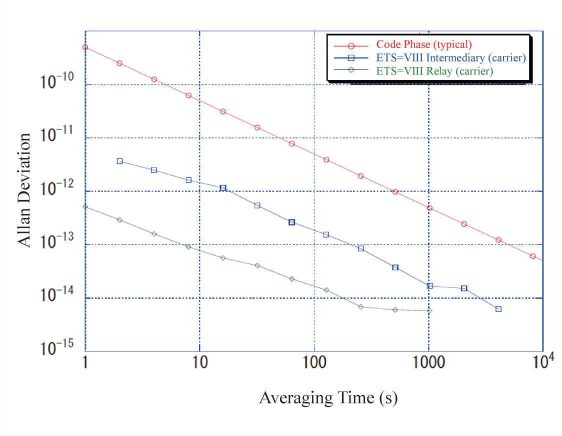

Fig.10 *An example of time comparison result between ground stations*

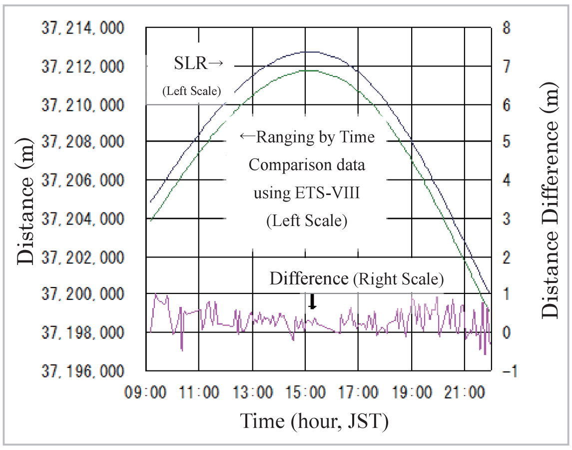

Fig.11 *An example of ranging result between ETS-Ⅷ and ground station*

5.6 Ranging experiments

In principle, the two way time transfer method enables the distance between satellite and ground to be determined by modifying the calculations, and in principle, this can offset the movements of the two atomic clocks and perform highly accurate ranging.

An example of the results of ranging calculated from time comparison data is shown in Fig. 11. This is the difference from SLR (Satellite Laser Ranging) results determined at NICT HIKARI Center.

The ranging using TCE can be considered useful for highly accurate orbit determination since the measurement falls within the difference of ±80cm from with SLR results. Still, its absolute values are unclear and therefore relative values.

6 Summary

NICT has performed time comparison experiments using a time comparison equipment on-board the ETS-Ⅷ and the results have been incorporated in the highly accurate positioning experiment system that uses the QZS. The first quasi-zenith satellite “Michibiki” (QZS-1) was launched on September 11, 2010 and after completing the initial function verification tests, it commenced conducting technology validation experiments. In the future, we perform experiments for constructing an independent positioning system.

Acknowledgements

We wish to sincerely thank all JAXA personnel involved in the development and operation of the ETS-Ⅷ and the tracking and control facilities, all personnel from Toshiba Co. (currently, NEC Co. and NEC Toshiba Space Systems Co.), Japan Communication Equipment Co., Ltd., Cosmo Research Co. and Space Engineering Development Co., Ltd. that were involved in the development of HAC, TCE and the ground facilities. We would also like to thank all personnel who cooperated with the TCE experiments and all NICT personnel involved in TCE and the development of ground systems.

References

1 Space Activities Commission, Report on satellite positioning technology subcommittee, “Policy on the development of satellite positioning technology in Japan,” 1977.

2 H. Ito et al., “Development of a Spaceborne Hydrogen Maser for QZSS,” 49th Space Sciences and Technology Conference, No. 2D13, pp. 731–734, Nov. 2005.

3 S. Nagano and H. Fujiyama, “Concept of the Quasi-Zenith Satellite System Project,” 48th Space Sciences and Technology Conference, No. 2G01, pp. 1068–1074, Nov. 2004.

4 Positioning and geographic information system promotion conferences, ”Basic policy of promotion of Quasi-Zenith Satellite System plan,” March 31, 2006.

5 M. Kishimoto et al., ”Status of the Quasi-Zenith Satellite System and Experiment Plan,” 53rd Space Sciences and Technology Conference, No. 2E18, pp. 1292–1295, Sep. 2009.

6 S. Hama, Y. Takahashi, K. Kimura, H. Ito, and J. Amagai, “Quasi-Zenith Satellite System (QZSS) Project,” Special issue of this NICT Journal, 5-3, 2010.

7 M. Homma et al., “Engineering test satellite-8 for mobile communication and navigation experiment,” 51st IAF, No. IAF-00-M.3.019.

8 H. Noda et al., “Positioning experiment system and positioning experiment using engineering test satellite types eight (ETS-VIII),” Japan Institute of Navigation, Aerospace Navigation Research Committee, Oct. 2004.

9 Y. Takahashi et al., “Experimental Plan for Time Comparison Equipment for ETS-VIII Satellite,” Trans. of IEICE B, Vol. J84-B, No. 12, pp. 2101–2107.

(Accepted Oct. 28, 2010)

TAKAHASHI Yasuhiro

Senior Researcher, Space-Time Standards Group, New Generation Network Research Center

Satellite Communication, Satellite Navigation System

***NAKAGAWA Fumimaru,** Ph.D.*

Senior Researcher, Space-Time Standards Group, New Generation Network Research Center

Time and Frequency Standard

***TABUCHI Ryo,** M.S.*

Technical Expert, Space-Time Standards Group, New Generation Network Research Center

***NAKAMURA Maho,** Ph.D.*

Expert Researcher, Space-Time Standards Group, New Generation Network Research Center

Ionosphere, Information Engineering

KUNIMORI Hiroo

Senior Researcher, Space Communication Group, New Generation Wireless Communications Research Center

Satellite Laser Ranging

AMAGAI Jun

Research Manager, Space-Time Standards Group, New Generation Network Research Center

Time and Frequency, Radio Interferometer

TSUCHIYA Shigeru

Senior Researcher, Space-Time Standards Group, New Generation Network Research Center

Time and Frequency Standard, Radio Wave Propagation

HAMA Shin'ichi

Research Manager, Space-Time Standards Group, New Generation Network Research Center

Satellite Navigation System, Satellite Communication

NODA Hiroyuki

Mission Sub-manager, Quasi-Zenith Satellite Project Team, Space Applications Mission Directorate, Japan Aerospace Exploration Agency

Satellite Navigation System