5-2 Experimental Plans using Time Comparison Equipment

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The Engineering Test Satellite VIII (ETS-VIII) missions will include application experiments using Cesium atomic clocks in space. Using this satellite, the CRL (Communications Research Laboratory) and the JAXA (Japan Aerospace Exploration 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 experimental plan for precise time transfer between the ground reference clock and on-board clock.

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

1 Introduction

The mission of the Engineering Test Satellite VIII (ETS-VIII) [1], scheduled for launch in 2004, is to develop advanced common base technologies for future space activities. A variety of experiments are planned for the ETS-VIII, such as a mobile satellite communication experiment using large deployable antennas [2].

The ETS-VIII will also be the first Japanese satellite to be equipped with an atomic clock, part of a mission of the Japan Aerospace Exploration Agency (JAXA). The satellite will be used for experimental applications of the clock as part of basic research into satellite positioning technologies [1].

The Communications Research Laboratory (CRL) proposed a method of precision time comparison between the onboard atomic clock and the ground reference clock, and this proposal was subsequently accepted as one of the missions of the ETS-VIII. The CRL has since been developing the onboard instruments for the experiment; presently, all of the necessary instruments have been assembled and submitted for testing within the overall satellite system.

The method of time comparison used in the present system is similar to the method of time management in the planned quasi-zenithal satellite positioning system scheduled for launch in 2008 [3] [4]. Expectations are thus high for the success of the present system.

This paper will describe the details of experiments involving the precision Time Comparison Equipment (TCE) installed aboard the ETS-VIII.

2 ETS-VIII Development Project

Under the auspices of the JAXA mission, the ETS-VIII will be the first Japanese satellite to be equipped with an onboard atomic clock. The goal of this project is not to develop the atomic clock itself, but rather to confirm the in-orbit performance of a cesium atomic clock used in GPS and other applications, as well as to establish basic satellite positioning technologies.

To evaluate the in-orbit performance of the

ETS-VIII onboard atomic clock, the CRL has proposed a method of precision two-way time comparison between the onboard atomic clock and the ground reference clock. The CRL will thus be responsible for the installation of the experimental instruments required for this project aboard the ETS-VIII.

3 General Principles of Time Comparison

Fig.1 illustrates the basic principle behind precision time comparison between the atomic clock aboard the ETS-VIII and the ground reference clock. With this method of two-way time comparison, simultaneous time-comparison signals are transmitted from the satellite to the ground and from the ground to the satellite. The difference between the clock readings for the arrival times of the received signals at both ends is then calculated and divided by two to arrive at a determined clock difference.

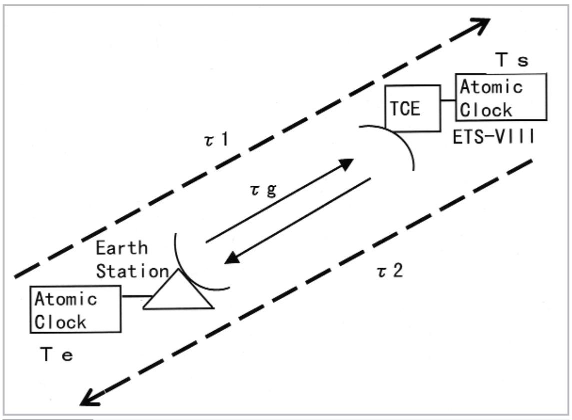

Fig. 1 *Principle behind the method of two-way time comparison*

Generally, precision time comparison can be realized through the two-way time-comparison method, since propagation delay and variation in the ionosphere and the troposphere is, in principle, canceled out, as are the effects of satellite motion. However, in the current TCE experiment, ionospheric delay cannot be canceled out, since the system uses different S-band frequencies for uplink and for downlink. Therefore, both S-band and L-band signals will be issued by the satellite for ground reception, to allow for correction due to ionospheric delay. Furthermore, with this method, the effect of thermal variations cannot be canceled out due to physical differences in the components of the transmission and reception systems. Thus, the delay time for both the onboard TCE and the TCE ground station will be measured for correction.

With two-way time comparison, the difference in the satellite and ground reference clocks can be measured by measuring the difference between the respective clock readings. Note that the round-trip distance between the satellite and ground can be calculated from the sum of the two clock readings.

4 Outline of the Experimental Instruments

4.1 Onboard Instruments

Fig.2 shows the configuration of the High Accuracy Clock (HAC) used in JAXA’s basic research in positioning technology, and also shows the TCE employed in CRL’s precision satellite/ground time comparison method. These two systems will be described in further detail in the following sections.

For details on the TCE signal processing unit (the TCE-PRO) and the radio-frequency unit, see the related papers in this issue [5] [6].

4.1.1 Outline of the HAC

The HAC is composed of an atomic clock, an S-band transmitter and receiver, an L-band transmitter and receiver, and a common 1.0-mf antenna, in addition to satellite laser ranging (SLR) equipment for the S- and L-bands. The atomic clock will be used to perform basic satellite positioning experiments using a cesium atomic clock (Frequency & Time Systems, Inc. (FTS); USA) previously employed as a GPS device. The specifications of this atomic clock (otherwise referred to as the Cesium Frequency Standard, or CFS) are as follows.

- Frequency: 10.23 MHz–5.5×10^{-3} Hz (contains the relativistic correction term)
- Weight: 13.6 kg

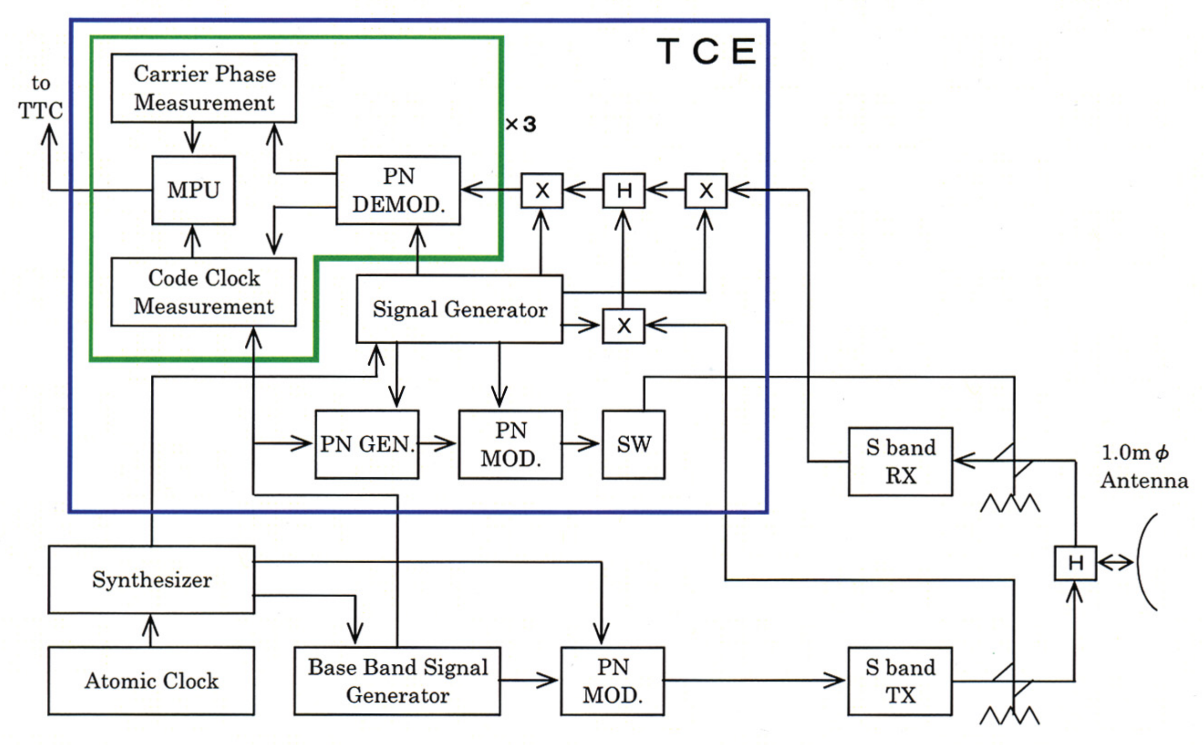

Fig.2 Configuration of HAC and TCE

- Accuracy: $\pm 1 \times 10^{-11}$
- Stability: 1.0×10^{-11} (1–3.6 s)
  $1.89 \times 10^{-11}/\sqrt{\tau}$ (3.6–10^5 s)
  6×10^{-14} (10^5–10^6 s)

Further, it is possible to use the clock in transponder mode, in which transmission is performed both in the S- and L-bands, through frequency conversion of the received S-band signals.

4.1.2 Outline of Precision Time Comparison Equipment (TCE)

Fig.3 shows an exterior view of the Proto Flight Model (PFM) of the TCE, following on the development of an earlier Engineering Model (EM) that had been constructed for the main purpose of verifying electrical and mechanical design. The PFM has now been submitted for qualification testing applicable to onboard instruments; after approval, the PFM will be placed aboard the ETS-VIII.

In this system, an HAC will be installed both on the satellite and in the ground station, resulting in coherent carrier and modulated signals, as seen in GPS applications. It will thus become possible to use the phase information not only of the modulated signal but also of the carrier signal. This will enable comparison of distances on the order of millimeters and time comparison featuring picosecond-level precision.

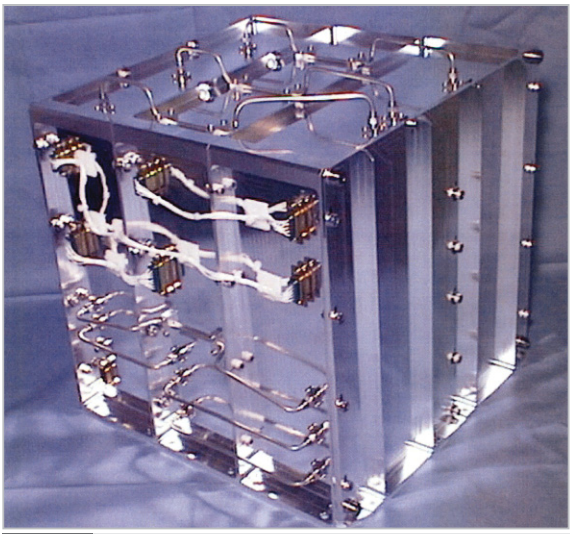

Fig.3 Exterior view of the TCE-PFM

4.2 Outline of the TCE Ground Station

Fig.4 shows the configuration of the TCE ground stations, one of which is fixed and one of which is mobile. The fixed station, featuring antennas 2.4 meters in diameter, will be installed at the CRL Koganei Headquarters in Tokyo, with experiments using these instru-

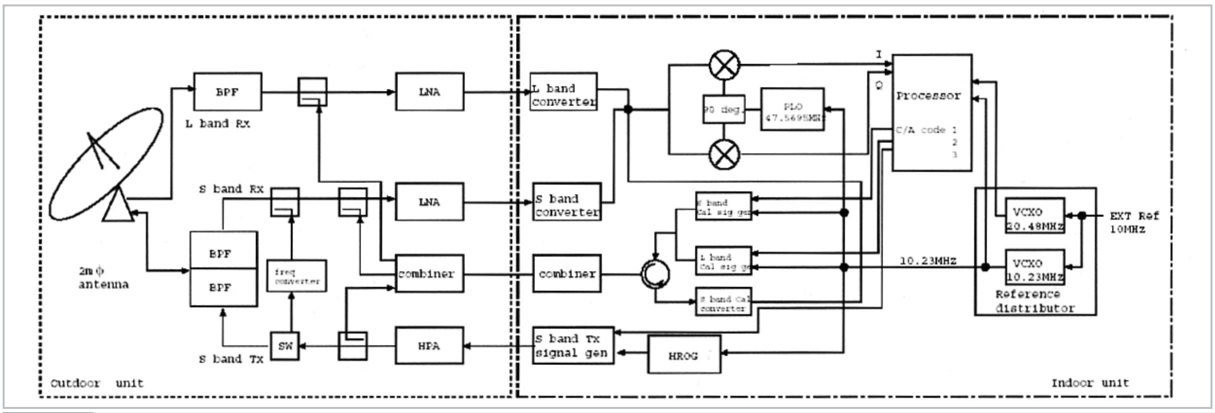

Fig.4 Block diagram of the TCE ground station

ments to be conducted at this fixed location. The mobile station will feature a 1.8-m modular antenna based at the CRL Koganei Headquarters and transported to various atomic-clock facilities in Japan and abroad for a range of experiments.

Although the TCE offers limited signal-processing capabilities due to the restrictions imposed on onboard instruments, the TCE ground stations will have the following additional functions to complement the onboard TCE.

- Adjustment of transmission power
- High-resolution power for code phase measurement
- Phase adjustment of the transmission code and carrier wave
- Removal of Doppler frequency; transmission frequency calibration

For details on the TCE ground station, see the relevant separate paper in this issue [7].

5 TCE Experimental Plans

At present, a number of experiments are planned, as described below. Some of these experiments will employ the onboard and ground-station TCE, while others will only make use of the HAC and the ground-station TCE.

For details on signal processing and data acquisition using the onboard TCE and the TCE ground station, see the relevant separate paper in this issue [8].

5.1 Initial Experiments

Initial experiments will be performed to confirm the operation of onboard equipment during the initial check shortly after launch, immediately followed by TCE experiments.

5.1.1 Operational Confirmation Tests

The following check items will be verified during operational confirmation.

(1) TCE Unit Test

The TCE unit test will be conducted to confirm proper operation of the TCE unit itself.

- A command will be issued to turn TCE power on; telemetry from the TCE must be properly received at the telemetry and command unit installed at the TCE ground station.
- The TCE must respond appropriately to the main commands sent from the telemetry and command unit.
- The temperature telemetry of the TCE must correctly reflect temperature changes.

(2) TCE and HAC Combination Testing

In tests of the TCE and HAC, TCE-PRO operation will be confirmed with the following signals (satellite alone).

- Calibration signal: Signal returned to the TCE via the HAC reception system in response to the calibration signal sent from the TCE
- Transmission signal: Signal entering the TCE from the HAC in response to transmission signal sent from HAC
- The above two signals (the calibration signal and the transmission signal) are simultane-

ously input to the TCE

(3) TCE Ground Station Unit Test

For the TCE ground station unit test, the tests described in (1) and (2) above will be performed prior to (4) below.

(4) TCE and TCE Ground Station Counter Testing

In these tests, the proper operation of the signal-processing unit of the TCE and of the TCE ground station will be confirmed using the signals below.

- Reception signal: Signal input to the TCE in response to the received radio wave transmitted from the TCE ground station via HAC
- A double-convolution signal of the reception signal combined with a calibration signal
- A triple-convolution signal of the double-convolution signal combined with a transmit signal
- Ground-station S-band reception signal: Signal received at the TCE ground station to be used in S-band transmission from the HAC
- A double-convolution signal of the ground-station S-band reception signal combined with a signal for calibration of ground-station S-band reception system
- A triple-convolution signal of the double-convolution signal combined with a signal for calibration of the ground station transmission system
- Ground-station L-band reception signal: Signal received at the TCE ground station in response to L-band transmission from HAC
- A double-convolution signal of the ground-station L-band reception signal combined with a signal for calibration of the ground-station L-band reception system

5.1.2 Functional Confirmation Tests

These tests will be performed following the Operational Confirmation Tests described in ***5.1.1***, to confirm appropriate operation of the TCE and TCE ground-station functions.

(1) Time Comparison Function of the TCE and TCE Ground Station

The results of time comparisons between the satellite and ground station will be evaluated.

(2) Calibration Function of the TCE and TCE Ground Station

The calibration results both for the TCE and TCE ground station will be checked to determine whether the calibration signals have been processed correctly and to assess the response of the system to temperature changes.

(3) Removal of Doppler Frequency and Calibration of Transmission Frequency

Tests will be performed to confirm whether the Doppler-frequency removal and transmission-frequency calibration functions of the TCE ground station are properly performed, as well as to confirm proper calibration of data acquired by the TCE.

5.2 Performance Testing

Performance tests will be conducted following initial testing and periodically thereafter.

(1) Time Comparison Precision

Time comparison will be performed between the satellite and ground station to verify precision.

(2) Removal of Ambiguity

Approximately 1 μsec of ambiguity (corresponding to a distance of approximately 300 m) is present in coded time comparison, calculated based on a chip rate of 1.023 MHz and a PN code length of 1,023 bits. Testing will be performed to determine whether this ambiguity can be removed using orbital information transmitted from JAXA.

In time comparison by carrier phase, approximately 0.4 nsec of ambiguity results from the carrier frequencies used (2656.390 MHz and 2491.005 MHz for uplink and downlink, respectively). A test will be performed to confirm whether this ambiguity can be removed by code-phase time comparison.

(3) Accuracy of Ionospheric Calibration

The amount of ionospheric calibration is calculated via TCE ground-station reception of S-band and L-band ranging signals transmitted from the satellite. The accuracy of these values will be determined initially based on the results of time comparison and later through comparison with TCE data from other institutions.

(4) Temperature Corrections for Calibration Systems and Temperature Compensation for Measured Temperature

The delays measured by the TCE, HAC, and TCE ground station are all susceptible to variation in the communication instruments caused by thermal variations and deterioration over time. Thus, delay must be measured and corrected in each calibration system. These tests will evaluate these corrections.

Data on the temperatures of the TCE (at 2 points), HAC components, and the satellite body (all obtained by satellite telemetry) will be used for evaluation of the above corrections, in addition to temperature measurement data for the various components of the TCE ground station.

(5) Precision and Carrier-to-Noise Ratio

Although measurement precision is high both in the TCE-PRO and ground-station PRO with high carrier-to-noise (C/No) ratios, measurement linearity tends to be poor; for low C/No ratios, the opposite holds true. The following measurements are to be taken for various C/No ratios to evaluate these tendencies.

- Adjustment of TCE ground-station transmission power
- Adjustment of the HAC transmission attenuator
- Adjustment of TCE ground-station reception signal
- Addition of noise to TCE ground-station reception signal
- Measurement during solar interference (Solar interference occurs at a point on the ground directly beneath the satellite near noon before and after the summer solstice, when the sun passes behind the satellite. In these cases increased noise is observed in the receive signal at the ground station, leading to lower C/No ratios.)

5.3 Parameter Settings

(1) Temperature Compensation

The results of Section ***5.1.2*** (2) will be used to calculate the correction coefficient for temperature.

Furthermore, a coefficient will be set to perform the correction procedure using temperature telemetry when the calibration system cannot be used, such as when two TCE ground stations are busy transmitting signals, in the event of instrument failure, when contrasting signal levels prevent simultaneous calibration, or when the calibration signal cannot be convoluted due to high noise.

(2) C/No Ratios

The results of the measurements of characteristics described in Section **5.2** (6) will be used to determine the C/No ratio normally employed, and the transmission power of the ground station and the HAC transmission attenuator will be set based on this ratio.

5.4 Basic Experiments

5.4.1 Measurement of Frequency Stability of HAC-CFS

Frequency stability measurements will be taken to confirm the behavior of the HAC-CFS in orbit. Ideally, frequency measurement will be performed routinely throughout the duration of the experiment (planned for three years) to confirm stability. However, since a tight ETS-VIII experimental schedule will render this difficult, short-term and long-term frequency stability will be evaluated separately, in principle as follows.

- Long-term: 2-hour to 4-hour measurements repeated routinely from once every two weeks to twice a week for 3 years
- Short-term: 24-hour measurements lasting 4–7 days approximately 4 times a year

However, taking other scheduled experiments into consideration, it is anticipated that the above experiments will in practice be conducted as follows.

- Long-term: 3-hour measurements taken once a week for 3 years
- Short-term: 24-hour measurements lasting 7 days taken every 3 months for the first year after launch, then twice again in the third year

With this plan, short-term measurement will cover a range from 1 second to 1.5×10^5 seconds (approximately 24 hours × 7 days ×

1/4), and long-term measurement will range from 6×10^5 seconds (approximately 24 hours × 7 days) to 2.3×10^7 seconds (approximately 24 hours × 365.25 days × 3 years × 1/4).

This means that the frequency stability measurements will cover a range from 1 to 2.3×10^7 seconds (excluding the 1.5×10^5 to 6×10^5-second range). When measuring HAC-CFS characteristics, a duration of 2.3×10^7 seconds is more than sufficient. However, since the effect of deterioration over time of the HAC-CFS also requires confirmation, measurements will continue throughout the entire 3-year period of the ETS-VIII experiment.

5.4.2 Measurements During Disturbances

Confirmation experiments will be performed whenever deemed necessary in response to changing conditions affecting the TCE and HAC.

(1) Temperature Variations

The effects on time comparison of daily and annual temperature variations will be investigated, as well as the effects of temperature variations during eclipses.

The validity of temperature correction using calibration signals and correction using temperature telemetry will also be confirmed.

(2) Attitude

Satellite attitude is subject to significant deviation during entry into and exit from eclipses, during wheel unloading and other maneuvers, as well as during antenna pattern measurements requiring attitude shift. Since the phase center of the HAC antenna does not correspond to the satellite's center of mass, a shift in attitude will have an effect on the distance between the satellite and the TCE ground station. An experiment will be conducted to determine whether the TCE will be able to measure this change, and if possible, the validity of measurement will also be confirmed.

(3) Power Supply

Tests will be conducted to check for any changes in measured TCE values corresponding to variations in the power supply voltage (daily variations, variation during eclipses, etc.).

(4) Orbit

During normal diurnal motion, the satellite path will change in a single direction during maneuvers. Experiments will check whether the TCE will be able to measure the change in distance between the TCE and the TCE ground station associated with this motion. When possible, the validity of measurement will also be examined.

5.4.3 Mobile Experiments

(1) Other Test Sites

In the CRL's system of two-way time comparison using the communication satellite, GPS common-view time comparison will be carried out routinely. At the same time, time comparison testing will be conducted using a mobile TCE ground station transported to a facility within the region of HAC antenna coverage.

In the experiment, comparison will be made between the ground clock and the onboard clock through time comparisons between the two sites (i.e., the fixed station at the CRL headquarters in Koganei City and the mobile station). Another experiment will address the return mode, in which the HAC will be used as a transponder to effect time comparison between the two sites. Differences among the results of time comparisons will be measured using these and other methods.

For cases in which the mobile station has been positioned overseas, an experiment will be performed to determine the ranging capabilities of the system; in this experiment the mobile station will be treated as a ranging station featuring higher precision than available at a standard ETS-VIII monitoring station.

(2) Combination with SLR Experiments

When SLR/HAC experiments are to be performed at the CRL Space Optical Communication Ground Station or at the SLR station, the mobile station will be moved to the vicinity of the testing facilities. This will enable comparison between the SLR ranging results and those of the onboard/ground-station TCE, permitting evaluation of the ranging performance of the two systems.

5.5 Application Experiments

The following application experiments are planned. For details of the experiments, please see the relevant separate article in this issue [9].

- Verification of the effects of general relativity
- Time comparison experimentation between two TCE ground stations using the HAC-CFS as the standard clock
- Time comparison experimentation between two TCE ground stations using the HAC as a transponder
- Comparison of ranging using light and radio waves

6 Conclusions

This paper presented an outline of current plans for various experiments using the TCE. In the future, experimental plans will be drawn up in more detail and compiled into a final plan. The number of experimental items may increase, as experiments will be required to test the quasi-zenithal satellite positioning system. Planned items will thus be re-examined whenever deemed necessary to ensure the most effective and productive use of the ETS-VIII.

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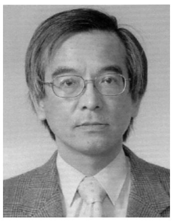
Satellite Communication, Satellite Positioning System



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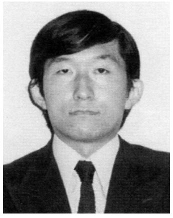

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