3-10 Time Comparison Equipment

3-10-1 RF Part

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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 system 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 ETS-VIII (Engineering Test Satellite VIII) [1] will be launched in 2004 as part of a project to develop advanced basic technologies for future space activities. Various experiments are planned using this satellite, including a mobile communication experiment [2] involving a large deployable antenna.

Under the auspices of the Japan Aerospace Exploration Agency (JAXA), the ETS-VIII will be the first Japanese satellite to be equipped with an atomic clock. The atomic clock will also be used for basic research in satellite positioning technology [1].

The CRL has proposed a method of time comparison involving precise time transfer between an onboard atomic clock and an atomic clock on the ground, with the principal aim of evaluating the performance of the atomic clock in orbit. The proposal was approved for application to the ETS-VIII mission, and the CRL subsequently developed and manufactured the requisite onboard equipment. Overall satellite testing is now underway.

The same method of time comparison will also be employed in a satellite positioning system using a quasi-zenith satellite [3] to be launched in 2008 [4], based on the anticipated success of experimentation using the current equipment.

This paper outlines and describes the principles behind the highly accurate time comparison equipment (TCE) aboard the ETS-VIII (including a discussion of the configuration of the RF component, for example), and reports on the results of development of the TCE.

2 Development History

2.1 Satellite Positioning Technology Development in Japan

Presently, in Japan, GPS applications [5] have extended to a wide range of areas, such as vehicle navigation systems, ship positioning systems, time supply, reference time applications (e.g., international standard time) [6], and seismic observation networks. Although research and development in satellite positioning systems in Japan initially lagged behind similar R&D efforts elsewhere, attention began to focus on the technical development of satellite positioning systems in 1996. A subcommittee report of the Space Activities Commission was issued in March 1997, describing the elements of the basic satellite positioning technologies slated for development in the short term [7].

- Onboard atomic clock
- Satellite cluster time management
- Highly accurate satellite orbital determination

Within this framework, the CRL was placed in charge of research and development of a hydrogen maser atomic clock to be installed in the satellite [8]; this type of atomic clock offers greater frequency stability than cesium or rubidium atomic clocks currently carried aboard GPS satellites. JAXA was in turn placed in charge of research and development of technology for satellite cluster time management and highly accurate orbital determination.

2.2 ETS-VIII Development Project

The JAXA mission installation of an atomic clock aboard the ETS-VIII represents a first for Japan. The aim of the mission is not to develop the hydrogen atomic clock, but rather to determine the best method of using existing cesium atomic clocks currently employed in various GPS applications. The atomic clock under study will thus be examined in orbit primarily to establish the following basic satellite positioning methods and technologies.

- Evaluation of orbital performance of the onboard atomic clock and development of orbital management technology
- Precise management of satellite cluster time and ground time
- Evaluation of highly accurate orbital determination

The CRL has proposed a method of two-way time comparison for precise time transfer between the onboard atomic clock and a ground-based atomic clock. The purpose of this comparison is to evaluate the orbital performance of the atomic clock aboard the ETS-VIII. The CRL has thus been assigned the task of installing the requisite experimental equipment aboard the satellite.

3 Onboard satellite equipment

The onboard equipment includes an atomic clock referred to as the HAC (High Accuracy Clock), S-band and L-band communication devices developed by JAXA, and the CRL's TCE for precise time transfer between the satellite and the ground. The overall configuration of the TCE will be described below, including details relating to the RF component of this equipment.

A separate report provides details relating to the signal processing component of the TCE (TCE-PRO) [9].

3.1 Onboard atomic clock

For the atomic clock aboard the satellite (HAC-CFS), JAXA has selected an FTS (U.S. company) cesium atomic clock for GPS applications, as part of efforts to acquire the requisite basic satellite positioning technologies.

The atomic clock has the following parameters.

- Frequency: 10.23 MHz–5.5×10^{-3} Hz (A relativistic correction term is included.)
- Weight : 13.6 kg
- 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)

JAXA is also responsible for the installation of a range of additional devices, including an S-band transceiver, an L-band transmitter, a common S-band and L-band 1.0-mϕ antenna, and SLR (Satellite Laser Ranging) devices.

3.2 Outline of highly accurate time comparison equipment (TCE)

Fig.1 shows a PFM (Proto Flight Model) of the TCE. The TCE was first developed in EM (Engineering Model) format, followed by construction of the PFM. The EM served to verify electrical and mechanical design factors, while the PFM was used in initial testing to evaluate portability aboard the satellite and similar characteristics. The PFM was then mounted on the satellite.

Fig.2 illustrates the principle of highly accurate time (frequency) comparison between the atomic clock aboard the ETS-VIII and the reference clock on the ground. This method of time comparison employs a two-way transmission system to determine the difference between the onboard atomic clock and the ground reference clock. Signals are transmitted from the satellite to the ground and from the ground to the satellite; at each station the received signal is evaluated and the time difference is calculated. This method of two-way time comparison can cancel out delay and account for variations in the ionosphere and in the air along the propagation path, and also allows for the effects of satellite motion, thus enabling highly accurate time comparison.

Moreover, due to the use of highly stable atomic clocks both on the satellite and on the ground, and with GPS-type coherent generation of the relevant signals (carrier signal, modulation signal, etc.), it is possible to make use not only of the modulation signal itself but also of the phase information of the carrier signal. Our aim in this context is to establish time-comparison accuracy on the order of millimeters and picoseconds.

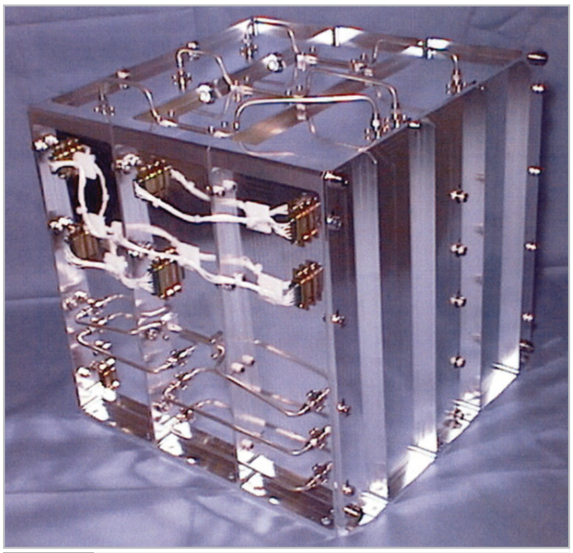

Fig.1 *The TCE-PFM*

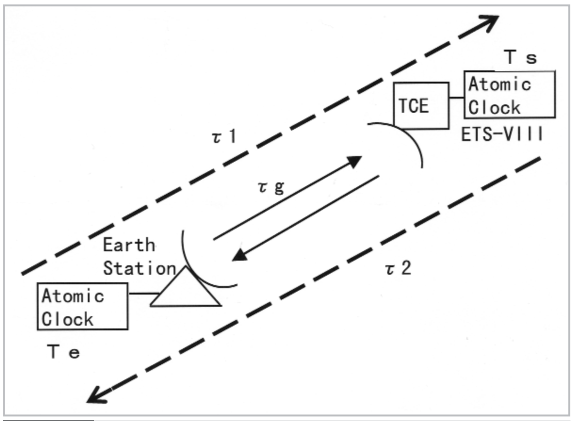

Fig.2 *Principle of two-way time comparison*

3.3 Principle of TCE

In experimentation using this equipment, signals for time comparison are transmitted from the satellite to the ground and from the ground to the satellite, as shown in Fig.2. In this case, each station measures the received signal and calculates the time difference. The measurement values are represented by the expressions below,

where

$\tau 1$: measured time difference between the signal from the ground and satellite time Ts;

$\tau 2$: measured time difference between the signal from the satellite and ground time Te; and

τg: propagation time between the satellite and the ground.

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

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

Adding and subtracting these expressions yields the following:

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

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

Subtraction yields the time difference, and addition yields the propagation time.

The distance between the satellite and the ground can be calculated from the propagation time, and can be used as ranging data.

In actual measurement, PN code clock information (corresponding to the C/A code in the GPS) transmitted as a ranging signal and driven at a frequency of 1.023 MHz is used, along with the relevant carrier phase information; the former is used in navigation and the latter is used to maximize accuracy.

Further details of the TCE, including specifics related to error correction and the like, are available in a separate paper [10].

3.4 Overall configurations of TCE and HAC

The principal parameters of the TCE and the HAC are as shown in Table 1.

Table 1 *Principal parameters of TCE and HAC*

Transmitting power	5.7 W
S-band transmission frequency	2491.005 MHz
Received frequency	2656.390 MHz
L-band transmission frequency	1595.880 MHZ
PN code	Corresponds to GPS C/A code
Dimensions (TCE)	320×320×325 mm
Weight (TCE)	12.4 kg or less

Fig.3 shows block diagrams of the TCE (inside the blue frame) and the HAC (outside the blue frame), illustrating the following functions:

- Transmission of a signal for time comparison from the satellite to the ground (transmitted signal)
- Reception of a signal for time comparison from the ground (received signal)
- Real-time onboard satellite measurement of transmission and reception delay, using calibration signals

The time difference is measured using the transmitted signal and received signal within the established two-way transmission system. Further, using the transmission calibration signal and the reception calibration signal, correction is made for variation in delay between the transmission and reception paths due to factors such as temperature change, aging, etc. Accordingly, the signal processing component of the TCE (within the green frame) has been designed to perform simultaneous processing of three channels, for the received signal, the reception calibration signal, and the transmission calibration signal.

Below is a description of the respective signal paths.

- Transmitted signal: the transmitted carrier is generated by a synthesizer and the PN (Pseudo-random Noise) code is generated by the baseband signal synthesizer component. After PN modulation of the transmitting car-

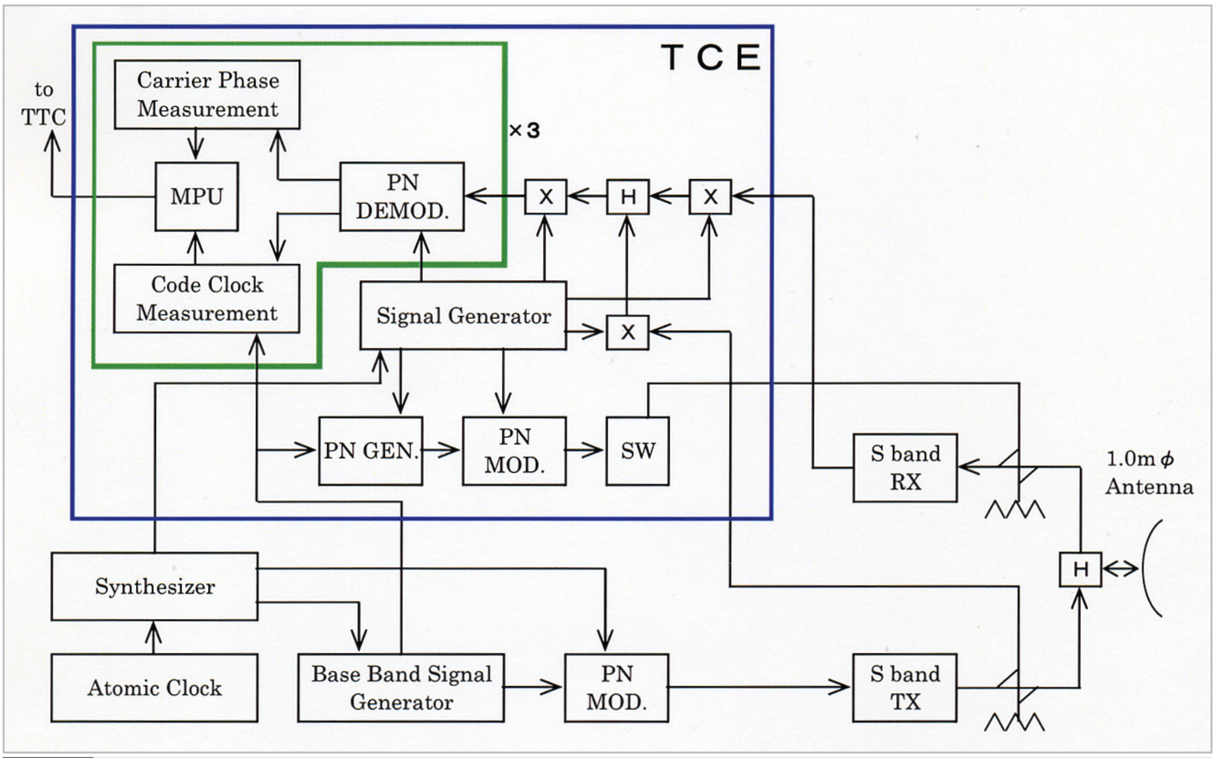

Fig.3 *Block diagram of the highly accurate time comparison system aboard the satellite*

rier, the transmitted signal is amplified within the S-band transmission system and transmitted from the 1.0-m ϕ antenna.

- Received signal: The radio wave received with the 1.0-m ϕ antenna is split within the S-band reception system, then subjected to frequency conversion and subsequent PN demodulation, followed by carrier phase measurement and code clock measurement.
- Reception system calibration signal: The carrier generated in the signal synthesizing component and the PN code generated in the PN code generator are subjected to PN modulation, and then processed together with the received signal in the S-band reception system after passing through a directional coupler.
- Transmission system calibration signal: The transmitted signal is split by a directional coupler just before the antenna, subjected to frequency conversion, and subsequently processed together with the received signal and the reception calibration signal.

3.5 Detailed configuration of RF component of TCE

The RF component of the TCE is composed of a local element, a converter element, and a power supply element. This configuration is described in more detail below.

3.5.1 Local element

The local element generates frequencies required by several components of the TCE in a coherent manner from a reference signal of 10.23 MHz input from the HAC.

(a) 20.46-MHz local signal

Since the 20.46-MHz local signal is used also as a clock in the TCE-PRO, it must be generated with excellent stability. Accordingly, this signal is generated stably from a reference signal of 10.23 MHz, as shown in Fig.4, using a diode doubler. An HAC/TCE test of the EM (Engineering Model) revealed that operation of the TCE-PRO may become unstable due to the high levels of harmonics in the reference signal. To resolve this problem, the PFM is equipped with a notch filter, thus ensuring stable operation of the TCE-PRO.

(b) Local signals at other frequencies

For local signals at other frequencies, a 47.5695-MHz signal is generated by an LO (Local Oscillator). Signals at three frequencies in the S-band can then be derived through the initial generation of half frequencies using a PLO (Phase Lock Oscillator), a Sub LO, and a PLA (Phase Lock Oscillator Amplifier), followed by subsequent doubling.

(c) Other signals

In addition, a 1-kpps (1023 pulse/sec) signal supplied from the HAC is combined with the RS-422 in the local element, and signals from two systems are combined using an OR circuit and supplied to the TCE-PRO.

3.5.2 Converter Element

As shown in Fig.7, the converter element converts the 2656.390-MHz signal (in which the received signal and the calibration signal are superposed) into an IF frequency of 50.127 MHz; similarly, the transmitted 2491.005-MHz signal is converted to an IF frequency. Moreover, these two signals are superposed within a hybrid circuit, generating a signal in which the three signals are superposed. Subsequently, the 47.5695-MHz local signal is split into two signals whose phases differ by 90 degrees, which are used to convert the IF frequency (in which the three signals have been superposed) into two signals (I and Q), each at 2.5575 MHz with phases differing by 90 degrees. These signals are then processed by the TCE-PRO.

3.5.3 Power Supply Element

The ETS-VIII employs a 100-VDC bus voltage; a first in Japanese experimental satel-

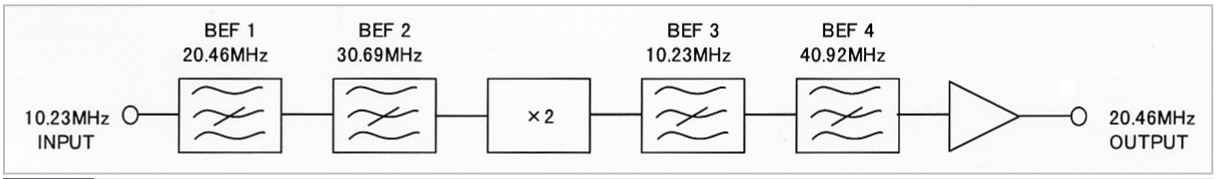

Fig.4 *20.46-MHz signal generation method*

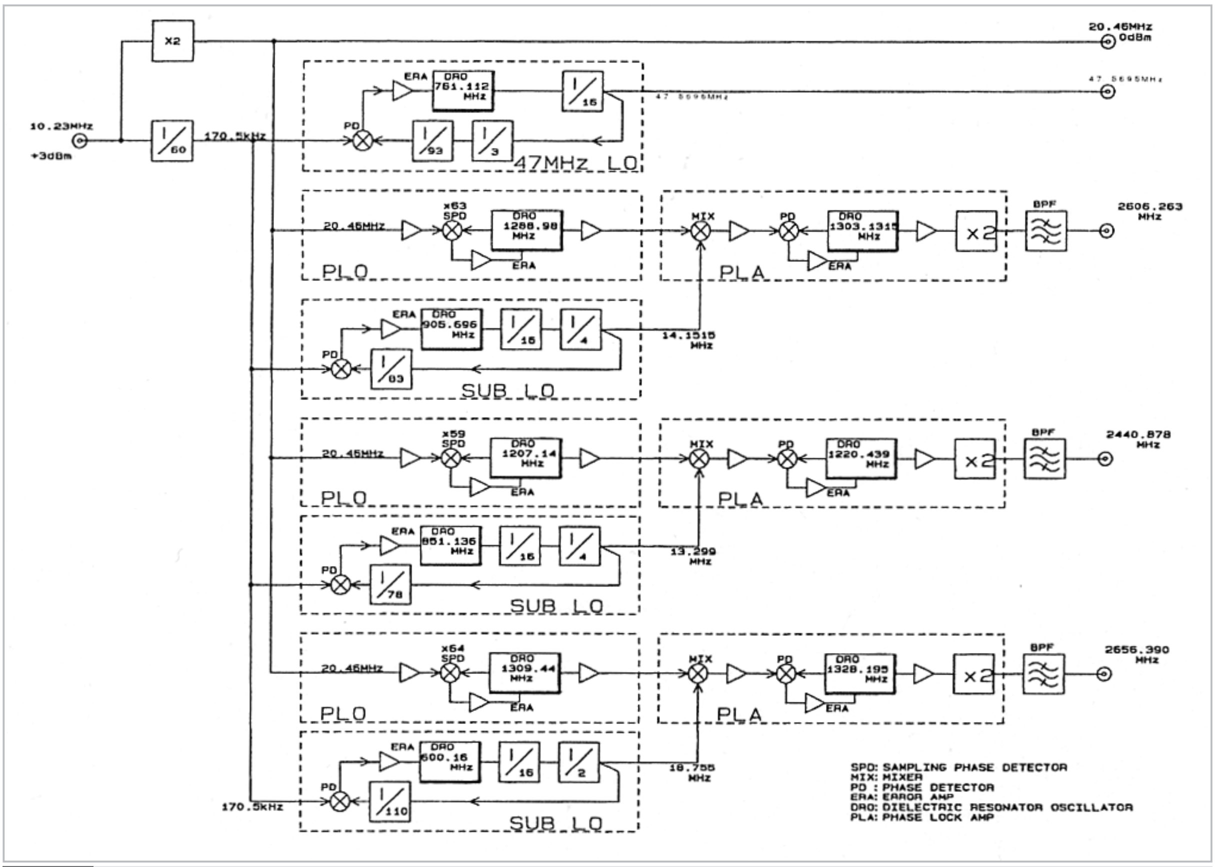

Fig.5 Block diagram of the local element

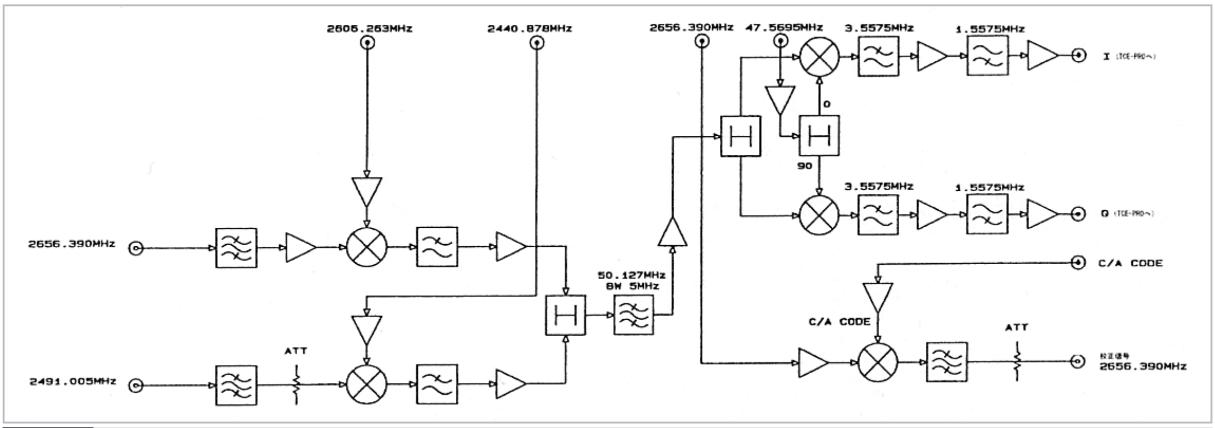

Fig.6 Converter element

lite applications. The power supply element produces and supplies the +5 V and ±15 V outputs required by several components of the TCE from this 100-VDC bus voltage using a DC-DC converter.

3.6 TCE-PFM Test results

The TCE-PFM has undergone the following tests.

- Oscillation frequency, level, and stability of each local signal
- Measured performance of each PN code and carrier phase when the received signal is superposed on transmitted and received calibration signals
- Heat vacuum test, vibration test, impact test, and EMC test
- Connection test with the TCE earth station

Fig.7 shows sample measurement results for frequency stability. Frequency stability

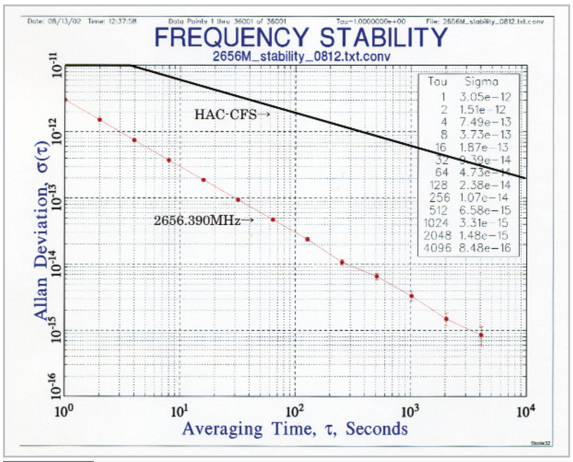

Fig.7 Measurement results for frequency stability at 2.65639 GHz

was determined to exceed that of the HAC-CFS, in accordance with anticipated performance. The TCE-PFM was also verified as capable of installation aboard the satellite and showed sufficient performance in precise time transfer.

4 Conclusions

We have made significant progress in the development of the TCE, working to establish a system of time comparison between the atomic clock aboard the satellite and an atomic clock on the ground with precision on the order of picoseconds. In the course of this development, the design was modified several times, until the desired performance was achieved.

In the future, we intend to develop the earth station and the ground components of the data processing element, among others, and to complete preparations for orbital experimentation using the TCE.

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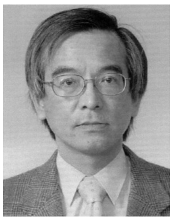

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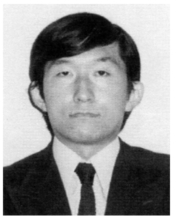
Frequency Standard, especially on Precise Time Transfer



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