4-3 Two Way Satellite Time and Frequency Transfer

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Two Way Satellite Time and Frequency Transfer (TWSTFT) is one of the most precise time transfer methods. Its developments and technical attempts for practical uses are under progress. This paper presents the research and development activities performed in CRL, such as development of multi-channel modems for TWSTFT and construction of the TWSTFT network in the Pacific Rim region.

Keywords
Time transfer, Two way satellite time and frequency transfer, International atomic time

1 Introduction

Time and frequency standards are the most accurate of measurement standards available today, both in terms of accuracy and stability, with the world's top-level primary frequency standards offering accuracy better than 1 to 2×10^{-15}[1]. As described in a separate paper in this special issue, currently in Japan, two Incorporated Administrative Agencies—the Communications Research Laboratory (CRL) and the National Institute of Advanced Industrial Science and Technology—are in the process of developing cesium atomic fountain-type primary frequency standards, which are expected to achieve the highest accuracy of any such devices throughout the world[2].

The generation and keeping of time is performed by mutual comparison of cesium atomic clocks, hydrogen-maser type frequency standards, and the like, some 230 or so of which are currently in operation at approximately 50 organizations worldwide. The frequencies of these atomic clocks, frequency standards, and the like are subject to fine adjustments based on the accuracy data pro-

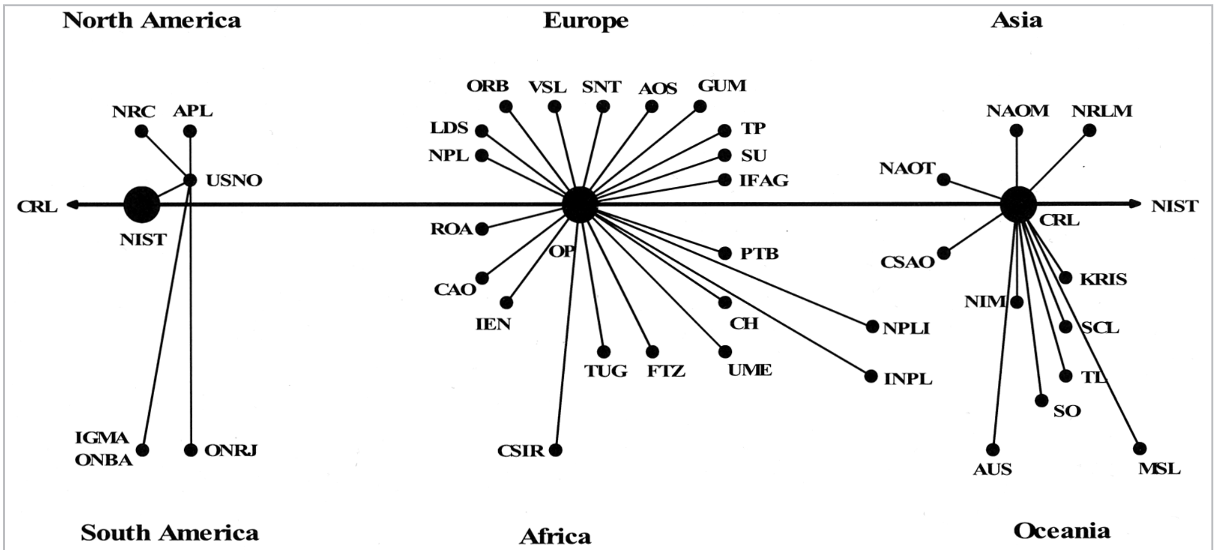


Fig.1 *International time transfer network contributing to TAI as of the beginning of the 1990s (Only the single-frequency, single-channel GPS common-view method is used in comparison.)*

vided by the above-mentioned primary frequency standards maintained by several organizations; final adjusted results are fed back to the Bureau International des Poids et Mesures (the BIPM, based in the suburbs of Paris), which then determines International Atomic Time (TAI)[3].

The GPS common-view method has been used as the leading means of time transfer and comparison among these primary frequency standards since the early 1980s, contributing directly to the establishment of TAI[4]-[6]. Fig.1 shows the international time transfer network established as of the early 1990s. As indicated in the figure, the Common-view method using GPS single-frequency C/A code single channel receiver was used for time transfer in every case.

However, with recent improvements in the accuracy of primary frequency standards and improvements in the performance of atomic clocks used for TAI, the conventional GPS Common-view method has come to be seen as insufficient in terms of comparison precision.

In the latter half of the 1990s, the need for research and development of a more precise methods of time transfer method began to be addressed in a number of international forums, such as the CCTF (Consultative Committee for Time and Frequency, affiliated with the International Committee of Weights and Measures), the ITU-R (Radio Communication Sector of the International Telecommunications Union), and more. In response, time and frequency standards institutes in many countries have begun to investigate methods of achieving higher precision in time transfer. Two overarching methods have emerged:

(1) Two-way transmission time transfer method using communication satellites for

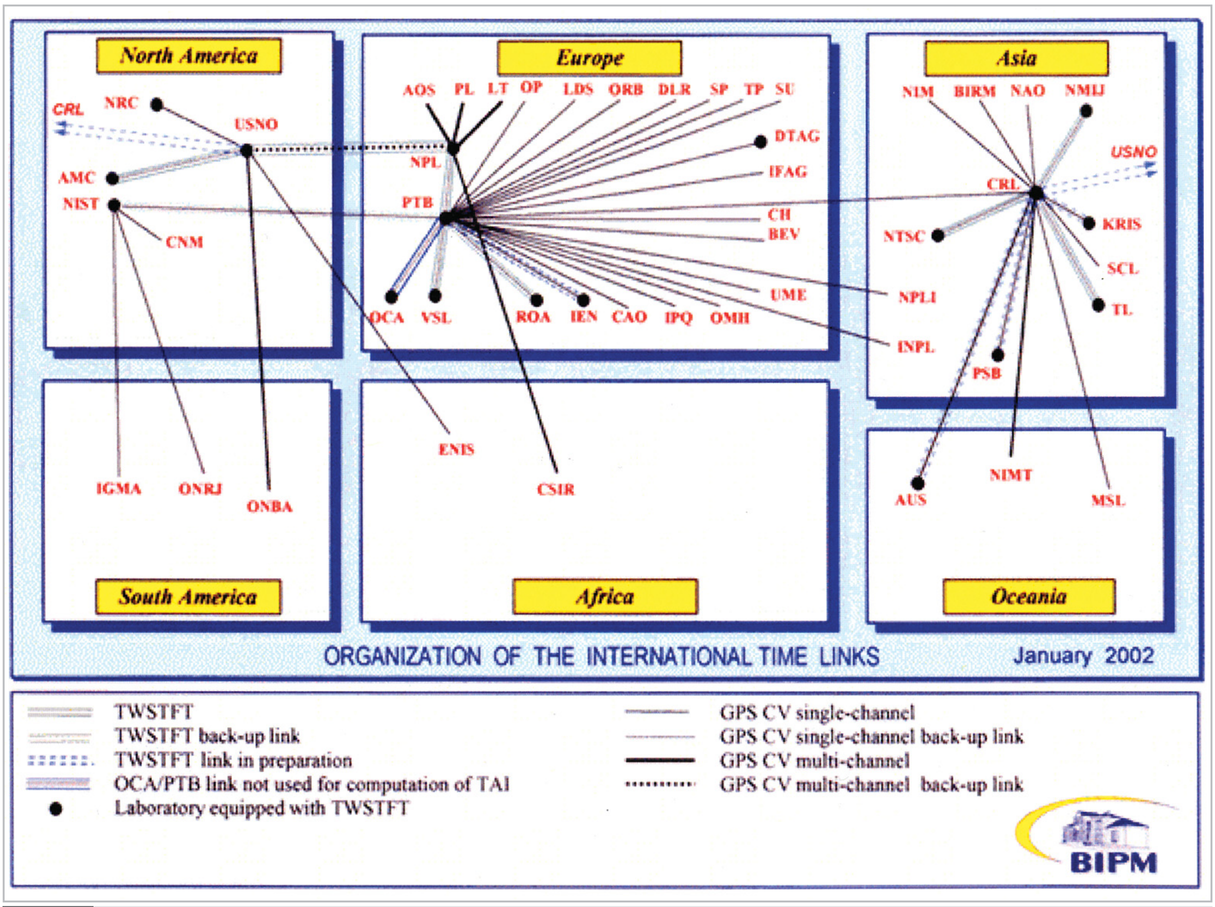


Fig.2 International time links for the calculation of TAI, as of January 2002 (From the BIPM website. The single-frequency single-channel GPS Common-view method, the multi-channel version of this method, and two-way satellite time and frequency transfer are combined to form a unified system of time comparison.)

signal transfer (two-way satellite time and frequency transfer method)
(2) Improvements of the precision of GPS time transfer method

Thus today's international time transfer link consists of multiple means of time transfer, as shown in Fig.2[7].

This paper will introduce the two-way satellite time and frequency transfer method currently under study at the CRL.

2 History of two-way satellite time/frequency transfer method

Although the two-way satellite time and frequency transfer method was first employed in the mid-1970s, today it has evolved into a revolutionary method of time comparison, featuring experimental accuracy on the order of 1 ns.

The basic principles and details of this system are discussed in elsewhere in this special issue[8]. Among other achievements, the high accuracy of this method of comparison led to verification of the Sagnac effect, a phenomenon predicted under the theory of relativity[9].

Although the two-way satellite time/frequency transfer method was recognized as considerably superior to other methods in terms of precision, it was not put into practice until the 1990s, when it began to be applied to the international time links used in the establishment of TAI.

3 Problems facing the two-way satellite time/frequency transfer method

With the GPS common-view method reaching limit accuracy in atomic clock applications, the two-way satellite time/frequency transfer method has come to be reconsidered as a means of attaining higher precision in transfer operations. Since the mid-1990s, Europe and America have played the dominant role in research, development, and practical application in this area. In around 1998, a number of organizations in Europe and America began conducting two-way satellite time and frequency transfer three times a week (at two minutes per station-to-station transfer) [10]. The accuracy of transfer in these sessions is on the sub-nanosecond level, significantly more precise than results obtained using the multi-channel GPS common-view method, which involves nearly 100 observations per day.

However, the conventional two-way satellite time and frequency transfer method is not versatile, and faces the following problems.
(1) High operational costs
(2) Incapable of simultaneous time transfer to multiple stations using conventional modem
(3) Variations resulting from difference between transmission and reception signal paths cannot be canceled out

Among these problems, (2) is attributed to the fact that conventional two-way satellite time/frequency transfer modem supports only a single channel in one transmission/reception unit. In order to perform time transfer among many stations, measurement times must be shifted. Consequently, not only is simultaneous time transfer impossible, but the satellite transponder is monopolized for a significant length of time, further exacerbating problem (1). Moreover, problem (3) not only necessitates calibration of the fixed internal delay of the Earth station but also leads to the problem of variation of delay during the time transfer operation.

The multi-channel two-way satellite time/frequency transfer modem described in the next section has been developed by the CRL specifically to resolve a number of the above-mentioned problems.

4 Development of multi-channel time transfer modem capable of multi-point simultaneous time transfer[11]

This modem allows multiple Earth stations to transmit time transfer signals simultaneously, as illustrated in the diagram in Fig.3. The same frequency band can be used to transmit these signals because the respective station signals are modulated by different pseudo

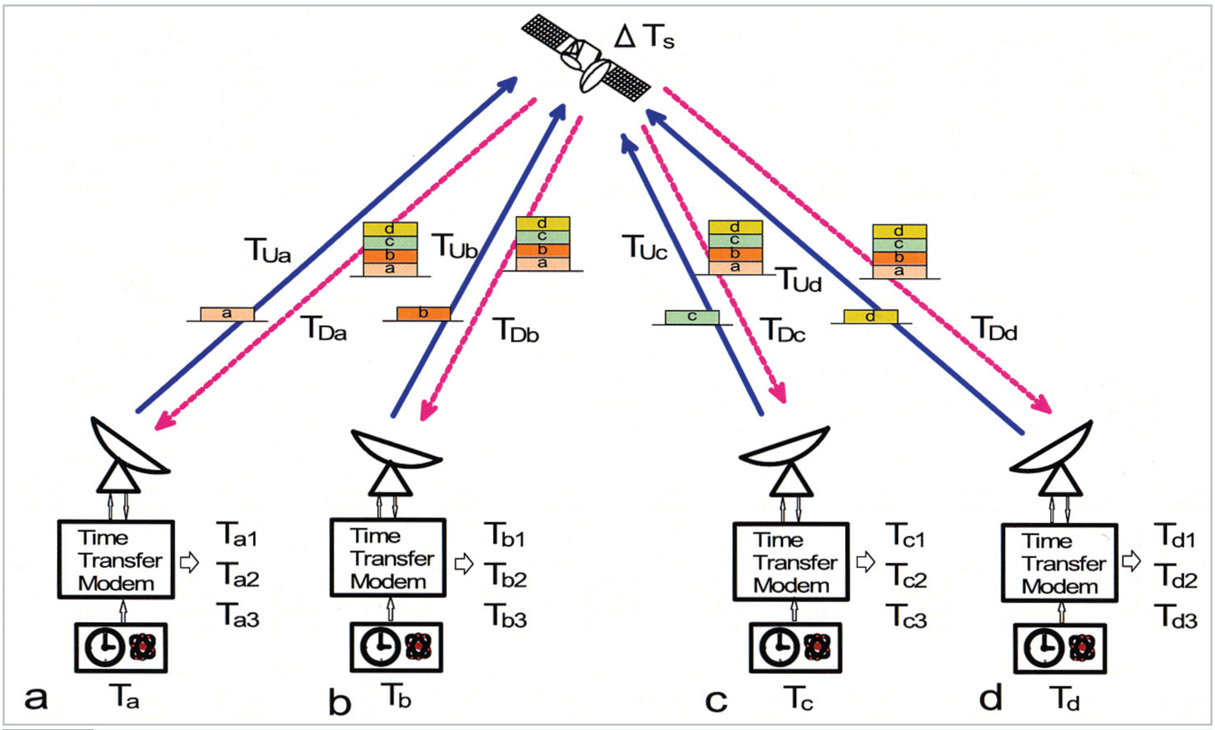


Fig.3 *Conceptual diagram of multi-site simultaneous time transfer using multi-channel two-way satellite time/frequency transfer modem*

noise codes (PN codes). The station signals are superimposed in the satellite transponder and transmitted to the ground. Each of the Earth stations uses multiple receiving channels, which separate the signals transmitted from other local stations from the satellite signal (in which the various station signals are superimposed), and processes the signals thus separated to determine arrival times.

Time transfer can be performed simultaneously among multi-site by transmitting the signals modulated by PN code.

Through this method, time transfer can be performed simultaneously between any two participating stations. That is, in the example shown in Fig.3, transfer for all combinations of the stations (A-B, A-C, A-D, B-C, B-D, and C-D), can be performed simultaneously. Therefore, problems (1) and (2) described in the previous section can be minimized. In this context the realization of simultaneous time transfer is of particular significance.

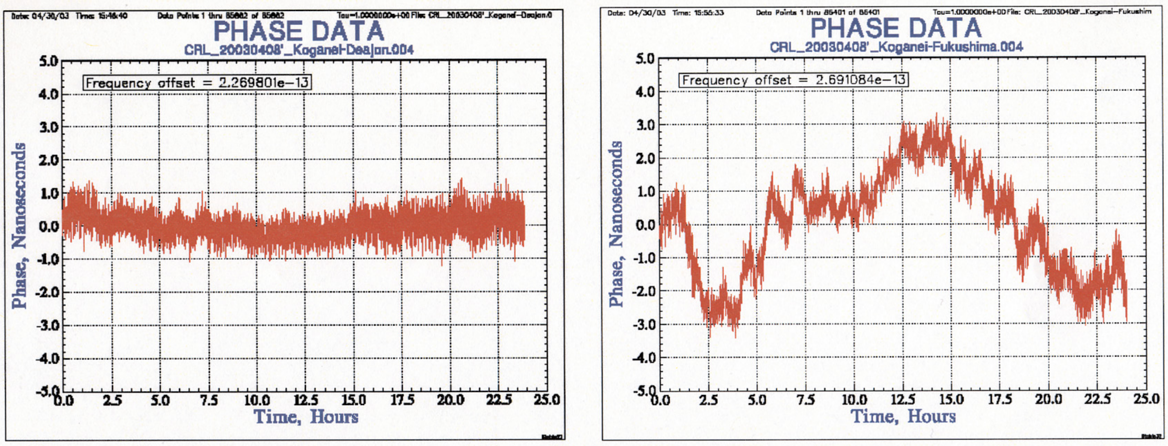
The equipment shown in Fig.4 makes this possible. As the specifications shown in Table 1 indicate, the equipment features two transmitting channels and eight receiving channels, and is theoretically capable of performing the time transfer for nine stations simultaneously using a single satellite transponder. However, it is assumed that two receiving channels will be used for measuring variation in internal delay time of the Earth stations; as a result a maximum of seven stations are available for simultaneous time transfer.

Fig.4 *Multi-channel two-way satellite time/frequency transfer modem Equipment features two transmitting channels and eight receiving channels*

Table 1 Specifications of multi-channel time transfer modem

Number of channels for Tx part	2 channels
For time trasnfer	1 channel
For internal delay variation measurement	1 channel
Number of channels for Rx part	8 channels
For time trasnfer	6 channels
For internal delay variation measurement	2 channels
Modulation method	Bi Phase Modulation by Pseudo Random Noise code
Chip rate for PN code	2.0475 MHz
PN code length	4095 bits
Operationable quality of satellite link	> +45 dB Hz
Time transfer precision	< 0.5 ns(depends on C/No)
Time transfer	Once / second
Data transfer function	Measured Data are distributed to all participating stations using PRN code
Remote control function	Controllable from remote site using Internet

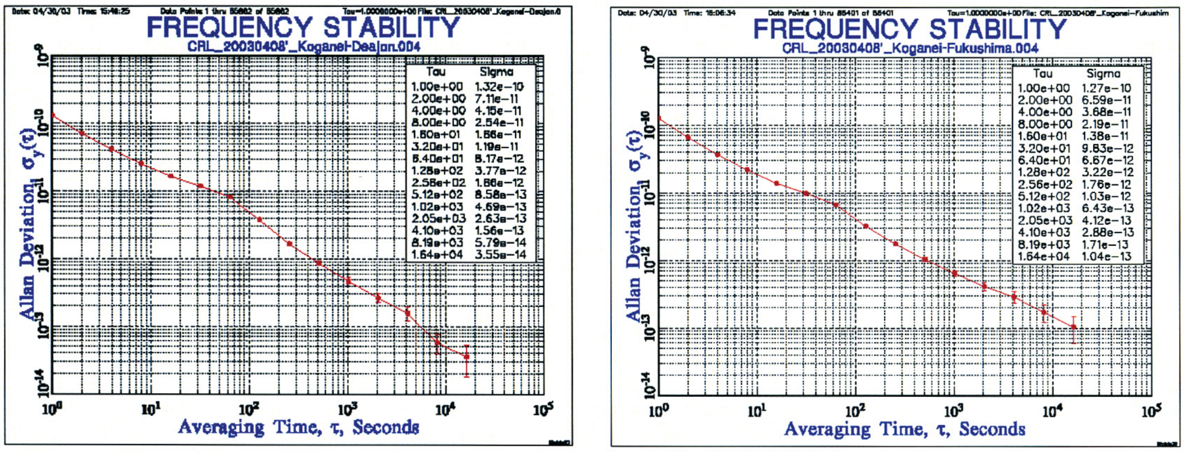
Fig.5 shows the results of the time transfer, performed using the same equipment, among three stations: the CRL Headquarters (Koganei-shi, Tokyo), the Korean Research Institute of Standards and Science (KRISS; Deajon, Korea), and the CRL Mt. Ohtakadoya (Ohtakadoya-yama) LF Station (Fukushima pref.). The CRL Headquarters and KRISS used hydrogen maser frequency standards as reference clocks, while the Mt. Ohtakadoya LF Station used a cesium atomic clock as its reference clock.



(a) CRL(Japan,H-Maser) vs. KRISS(Korea,H-Maser)

(b) CRL(Tokyo,H-Maser) vs. LF Station (Fukushima,Cs clock)

Fig.5 Results of time/frequency transfer among three stations (CRL Koganei, Korea's KRISS, and the CRL Mt. Ohtakadoya LF Station) using multi-channel two-way satellite time/frequency transfer modem



(a) CRL (Japan,H-Maser) vs. KRISS (Korea,H-Maser)

(b) CRL (Tokyo,H-Maser) vs. LF Station (Fukushima,Cs clock)

Fig.6 *Frequency stability of time/frequency transfer results of Fig. 5*

In addition, Fig.6 shows the frequency stability of these transfer results. Looking at these results, in particular at the results of transfer between the CRL Headquarters and the Mt. Ohtakadoya LF Station, it is clear that the noise characteristics of the reference clocks of the two stations (especially that of the cesium atomic clock of the Transmitting Station) were successfully detected with averaging times exceeding several hundred seconds. On the other hand, the results of transfer between the CRL Headquarters and KRISS show accuracy of 4 to 5×10^{-14} in frequency comparison with an averaging time of 10,000 seconds, suggesting that separate sets of time and frequency transfer equipment could be compared with accuracy in the order of 10^{-16} within approximately one week.

5 Construction of two-way satellite time/frequency transfer network in the Pacific Rim region

The CRL, in cooperation with the National Institute of Advanced Industrial Science and Technology and major time frequency standards research organizations in the Pacific Rim region, is currently working to establish a two-way satellite time/frequency transfer network in this region.

Specifically, the CRL is carrying out the following experiments in time and frequency transfer periodically (twice each week):

- Satellite time-transfer experiments between the CRL in Japan and Australia's NML (initially using INTELSAT; replaced by the PAS-8 satellite as of fiscal 2003)
- Using the JCSAT-3 satellite (previously using the JCSAT-1B satellite)

(1) Experiments beginning late October 1998 between Japan (CRL) and China (Shaanxi Astronomical Observatory in China; now the NTSC)

(2) Experiments beginning late March 1999 between domestic facilities; specifically, between the CRL and the National Research Laboratory of Metrology in Tsukuba (presenty the NMIJ; the National Institute of Advanced Industrial Science and Technology)

(3) Experiments beginning in June 2000 between Japan and Taiwan (Telecommunication Laboratories (TL))

After the CRL offered these results to the BIPM in order to contribute to TAI, the BIPM began processing this data using these results. Transfer with data obtained under the conventional GPS common-view method led to the conclusion that two-way satellite time/frequency transfer yielded better performance than the GPS Common-view method, even with the above-mentioned frequency (twice each week). Consequently, as of January

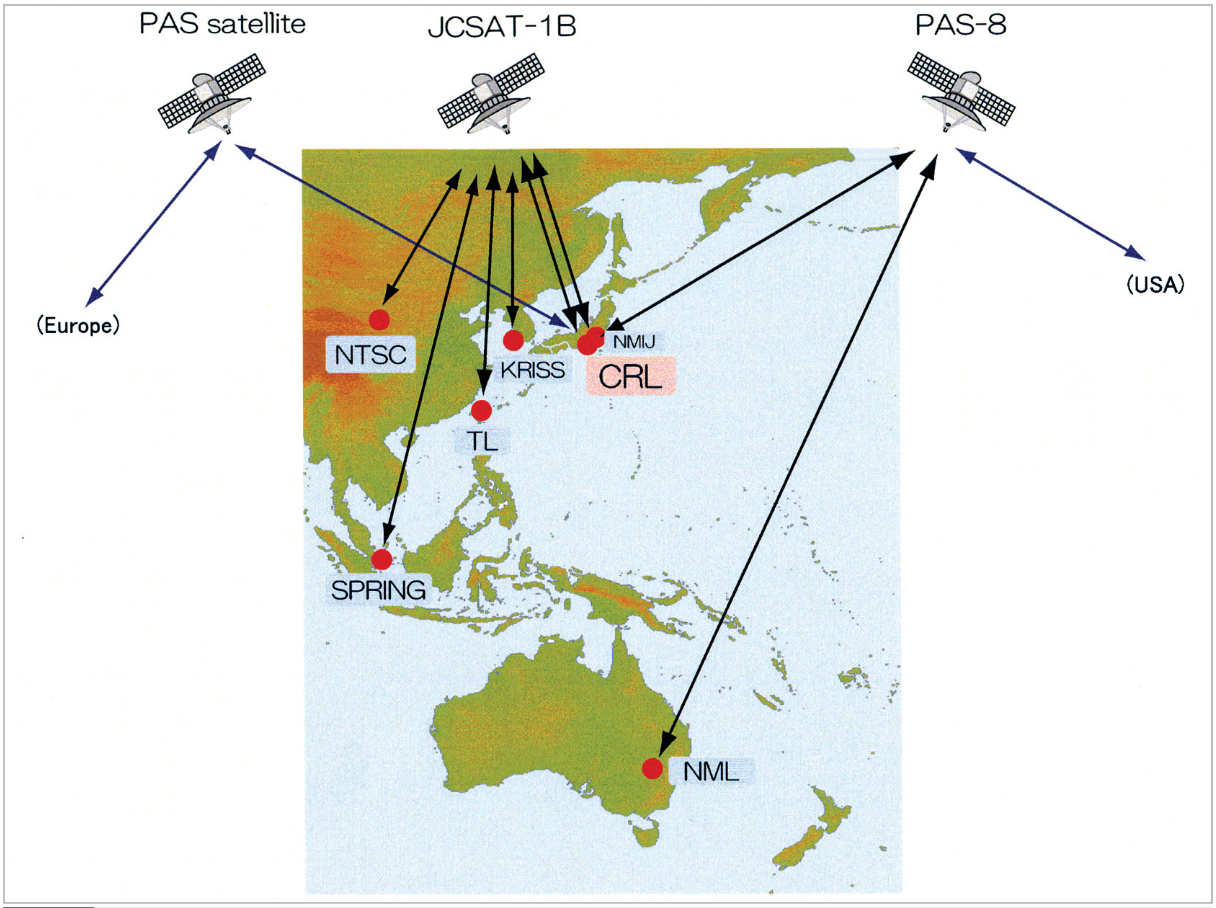


Fig.7 *Current status of two-way satellite time/frequency transfer network in the Pacific Rim region*

2002, the results of CRL-NTSC, CRL-TL, and CRL-NMIJ transfer are now formally incorporated into the computation of TAI.

To expand the two-way satellite time/frequency transfer network further, the CRL is conducting preliminary experiments to establish transfer operations with the relevant organizations in Korea (KRISS) and Singapore (SPRING). Fig.7 shows the current status of the two-way satellite time/frequency transfer network in the Pacific Rim region as of the end of March 2003. In particular, in the CRL/KRISS link, both stations are capable of employing hydrogen-maser standards, which excel as reference clocks in short-term stability. Accordingly, this link is being used to test a range of multi-channel time transfer equipment.

6 Concluding remarks

Although research and development of highly precise time/frequency transfer is not as publicized as that of atomic frequency standards, it is essential in the transfer of frequency standards among remote sites; further, it is crucial to the evaluation of the stability and accuracy of atomic frequency standards, and as a result forms an important element of international atomic time.

In this paper, we have introduced the CRL's latest research and development and discussed the performance of two-way satellite time and frequency transfer, with a particular focus on CRL's contribution to international atomic time. This technology is also finding wide application in the fields of telecommunications and satellite positioning, and is consequently of growing importance within today's information infrastructures.

We intend to pursue further research and development to increase the precision and enhance the technology of time/frequency transfer.

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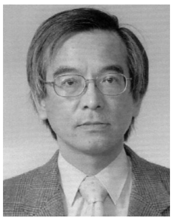

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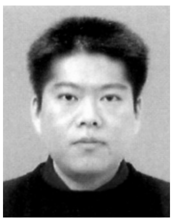

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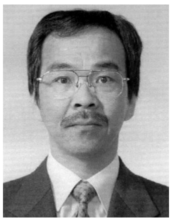

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