Vol. 39 No. 1 *Journal of the Communications Research Laboratory* Printed in Tokyo, Japan *March 1992* *pp. 91 – 100*

III. FREQUENCY AND TIME COMPARISON

III.3 TWO-WAY TIME TRANSFER VIA A GEOSTATIONARY SATELLITE

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(Received on May 20, 1991)

ABSTRACT

Both intermediary and direct time transfer methods are described here. In the direct methods, the time signal of each station is transferred directly to the other station. In the intermediary methods, one time signal is used as the reference signal for the other station's time transfers.

Global time transfer currently depends mainly on intermediary methods using the Global Positioning System (GPS). The error of GPS time transfer is usually no less than about 10 ns.

Two-way time transfer using a geostationary satellite, which is a typical direct method, showed a synchronization error of less than 1 ns. The two-way method is expected to be a time transfer method independent of the GPS, and an experiment using the INTELSAT satellite has been started. This section describes the principle and practice of two-way time transfer.

1. The Principle of Two-Way Time TRANSFER via a Geostationary Satellite

In the two-way time transfer, both ground stations transmit time signals to each other via a communications satellite. This transfer method differs from one-way time transfer methods such as those using the GPS, GMS (Geostationary Meteological Satellite) or LORAN-C (Long Range Navigation system). Whereas the accuracy of one-way time comparison depends on the measurement of the propagation delay, two-way transfer does not need this measurement because of the propagation delay is canceled. To make the cancellation complete, each path and frequency should be the same, but in actual transfer these two conditions are not completely satisfied. As shown in the following discussions, we therefore need to make some corrections to recover the differences.

In the system shown in Fig. 1, the time interval counters at each station measure the delay time difference between the local one-pulse-per-second (1PPS) signal and the arriving 1PPS signal. From the time difference measured at each station, Δt_1 and Δt_2 the difference Δt between the clocks can be determined as follows[1].

$$\Delta t = \frac{1}{2}(\Delta t_1 - \Delta t_2) + \frac{1}{2}(t_{12} - t_{21}) + \frac{1}{2}\left[(\tau_1 TX - \tau_1 RX) - (\tau_2 TX - \tau_2 RX)\right] + \Delta\tau_R, \quad \ldots (1)$$

where

$$t_{12} = \tau_1 U + \tau_{12} + \tau_2 D \qquad \text{.................. (2)}$$

$$t_{21} = \tau_2 U + \tau_{21} + \tau_1 D \qquad \text{.................. (3)}$$

and

Δt_1, Δt_2	: corresponding counter readings
$\tau_1 TX$, $\tau_2 TX$	: delay time in transmitters
$\tau_1 RX$, $\tau_2 RX$	: delay time in receivers
t_{12}, t_{21}	: propagation delay
$\tau_1 U$, $\tau_2 U$	: uplink delay from each station to satellite
$\tau_1 D$, $\tau_2 D$	: downlink delay from satellite to each station
t_{12}, t_{21}	: delay time in transponder
Δt_R	: Sagnac effect

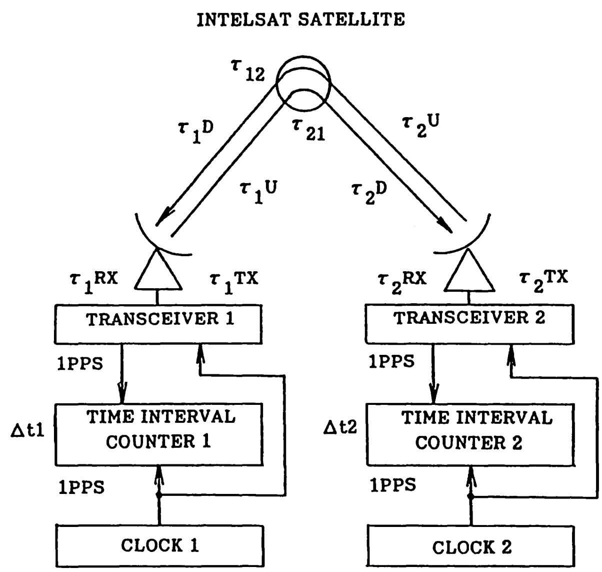

Fig. 1 System for tow-way time comparison.

Because the paths between the satellite and stations are almost the same in both directions, uplink and downlink delays are considered to cancel each other. This means that satellite positions and ionospheric and tropospheric effects are not major error sources in two-way transfers. The internal delays in ground stations and satellite transponder, however, must be known in order to know the time difference without an offset. And Sagnac effects should also be taken into account because of the relativistic difference between the uplink and downlink directions(2).

2. Examples of the Experiments and International Requirements

The CRL has played an important role in pioneering two-way time transfer experiments. In 1975, the first two-way time transfer experiment was performed between CRL and NASA stations by using Spread Spectrum Random Access (SSRA) via ATS-1[(3)]. In 1982, the same kind of SSRA two-way experiments, performed domestically via the first Japanese domestic communications satellite CS[(4)], yielded a precision of 1 ns. The CRL also developed a transportable two-way time transfer system combined with the CS-2 mobile earth station, and this system is precise to within 2 ns.

With the recent increase in the importance of international information exchange, needs for high-speed and large-capacity digital communications have increased dramatically. And meeting these needs requires high-precision international time transfer. The necessity of using space technology for time transfer was therefore included in the 1982 report of the CCIR (International Radio Consultative Committee). And in 1987, the CGPM (Conference Generale des Poids et Mesures) also decided that each national laboratory that keeps standard time should support and promote two-way time transfer using commercial communications satellites, such as INTELSAT.

The CRL had already prepared a Ku-band transceiver and the MITREX (Microwave Time and Ranging Experiments) modem, an internationally compatible time transfer modem. In cooperation with KDD and the INTELSAT Head Office in the US, the CRL also performed successful self-ranging experiments using the Pacific INTELSAT satellite. The results of this experiment (3) are described in Section 4.

3. Outline of MITREX Modem

The MITREX modem (Fig. 2), for the measurement of time transfer and for satellite ranging, was developed in Germany at Stuttgart University[(5)]. This modem is considered to be the international standard for two-way time transfer experiments. Like the CRL time transfer modem, MITREX uses a spread spectrum signal with pseudo-random noise (PN-sequence) and has following characteristics:

1) Ambiguity rejection of PN periodic signals is easy.

2) Joint use of a frequency-band is available for both time transfer signals.

3) The transponder can be used simultaneously for time transfer and other communications, though a relatively large bandwidth is necessary. PN generation, 1-sec pulse modulation, and spread modulation are necessary for signal transmission. For signal receiving, time signals are detected and reproduced by a correlation processor using the same PN code.

3.1 Transmitting Process

(1) Generation of PN signal

The PN signal is generated from M-sequence recursive shift registers with 14 stages. Though the maximum length of PN code N is $2^{14} - 1 = 16\,383$ chips, the MITREX modem uses only 10000 chips. The clock rate to the shift-register is 2.5 MHz and the main period of the code is 4 ms. This means that the modem repeats the codes 250 times per second. Eight kinds of PN codes can be selected

(2) Transmission of 1PPS signal

The signal transmitted via a geostationary satellite has a delay of several hundred milliseconds. Because this delay is greater than the code length, the 4-ms ambiguities occur at the receiving site. To identify the accurate code for selection, the modulation of one of the 250 codes is synchronized with the in-house 1PPS signal. The method of the modulation is 1-chip delay of the M-sequence.

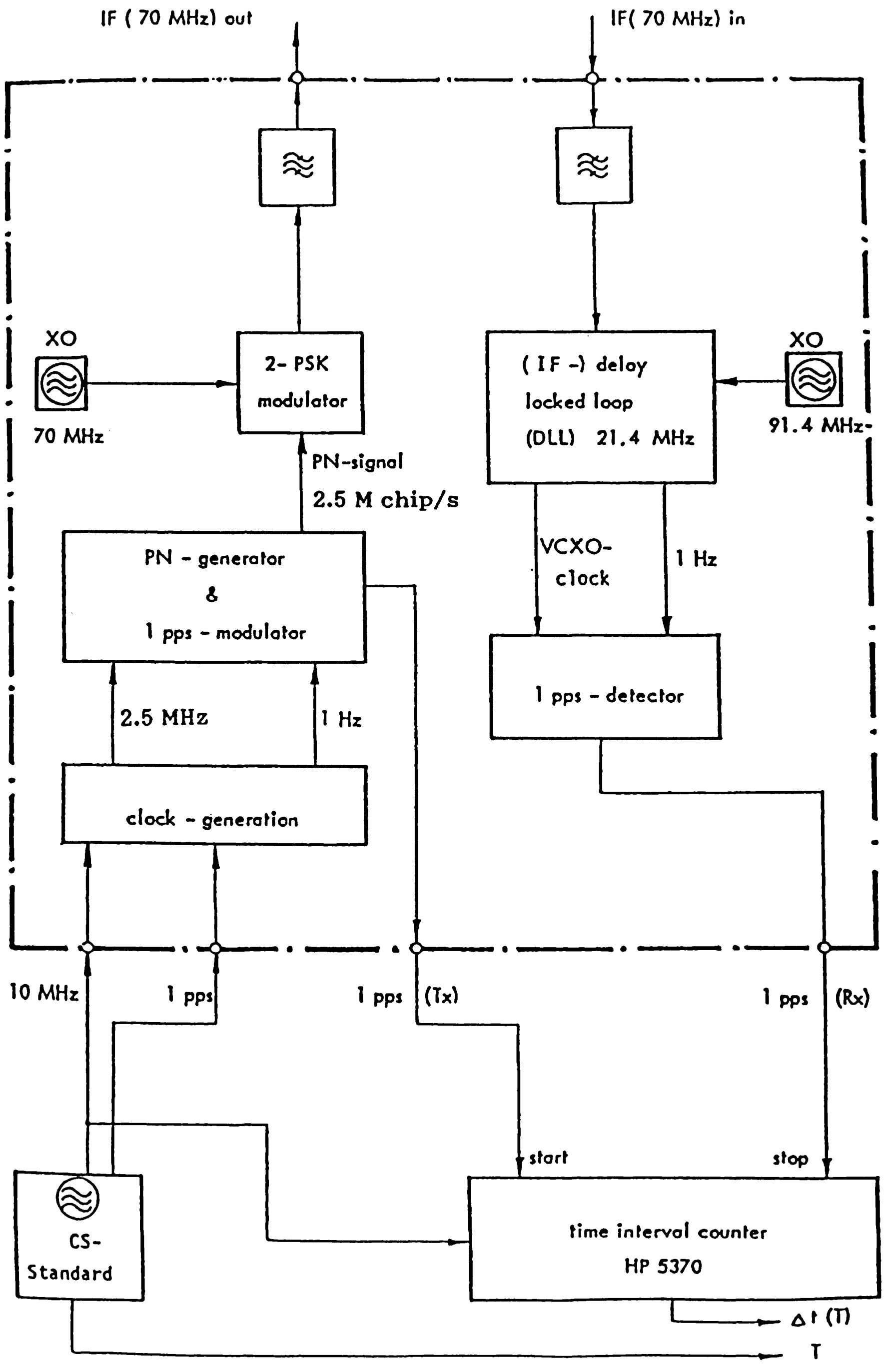

Fig. 2 Block diagram of the MITREX modem.

(3) Generation of the transmission signal

The intermediate frequency (IF) is 70 MHz and the IF 70-MHz carrier is bi-phase modulated by the PN signal. Figure 3 shows the power spectrum of the PN signal at the IF level. The power included in the 5 MHz bandwidth is 90% of the total power. After the sidelobes of the PN signal is filtered to decrease their effect on adjacent channels, the signals are transmitted to the satellite.

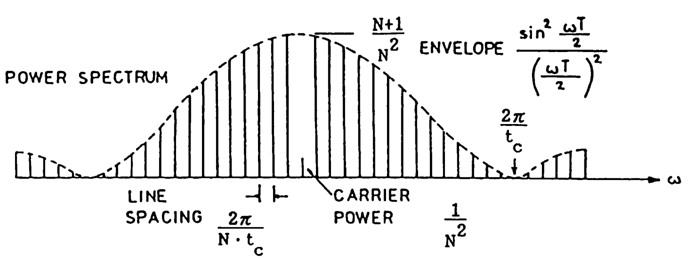

Fig. 3 Power spectrum of PN-sequences.

3.2 Receiving Process

(1) PN synchronization

The time signal received from a site is reproduced by correlation with the PN signal of the receiving site. The cross correlation function of PN codes is given by following equations:

$$\phi(\tau)=\begin{cases}1-\left(1-\dfrac{1}{N}\right)\cdot\dfrac{|\tau-kNt|}{t}: & (kN-1)t\le\tau\le(kN+1)t\\ -\dfrac{1}{N}: \text{ another } \tau. & \end{cases} \qquad \cdots\cdots\cdot (4)$$

The synchronization is compensated by using the sliding correlation method. After the sync-detection, the receiver tracks the code-phase by delay-lock loop and keeps the clock-phase synchronized with the internal clock of the receiver.

(2) 1PPS synchronization

Figure 4 shows the time sequence for transmitting and receiving 1PPS pulses. As mentioned above, the 250th bit is modulated on transmission. After the correlated reproduction, we can detect the 1PPS pulse. If this pulse is synchronized with the bit clock, we can remove the jitter and make a precise received 1PPS. A time-interval counter measures the delay between the in-house 1PPS and the received 1PPS.

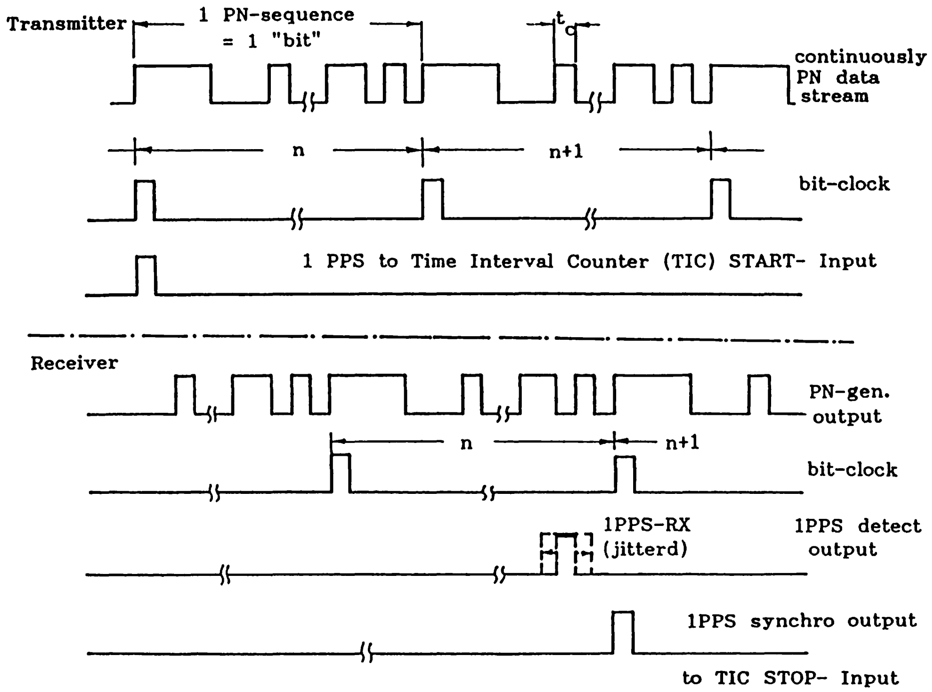

Fig. 4 Time sequence of the MITREX modem.

Table 1 Performance of the CRL system

antenna	size	1.8 mø, efficency 63 %
	gain	TX: 46 dB, RX: 44 dB
TX part	frequency range	14.0 – 14.5 GHz
	output power	4 W
	E.I.R.P.	52 dBW
	IF range	70 ± 20 MHz
	input level	– 30 dBm
RX part	frequency range	10.95 – 11.45 GHz
	input level	– 80 – – 127 dBm
	noise figure	2.7 dB (270 K)
	IF output	70 ± 20 MHz
modem part	standard freq. input	10 MHz
	IF input level	– 42 – – 22 dBm
	minimum C/No	50 dB/Hz

4. Outline of the CRL System

Figure 5 shows the outline of the CRL system for two-way time transfer, and Table 1 lists its specifications. The RF frequencies used are in the Ku-band.

(1) transceiver

The antenna is a 1.8-m dish and has a low-noise amplifier with a 2.7-dB noise figure at 11 GHz. After the signal is downconverted to the 70-MHz IF, it is given to the MITREX modem. And, vice versa, output signals from the modem are upconverted to the 14-GHz band and transmitted from the 4-W transmitter. The effective radiation power is 52 dBW.

In the present test phase of this experiment, a frequency setup function is needed to select a free channel for our cost-free use of INTELSAT. Our system has independent 1-MHz synthesizers that select uplink and downlink channels separately.

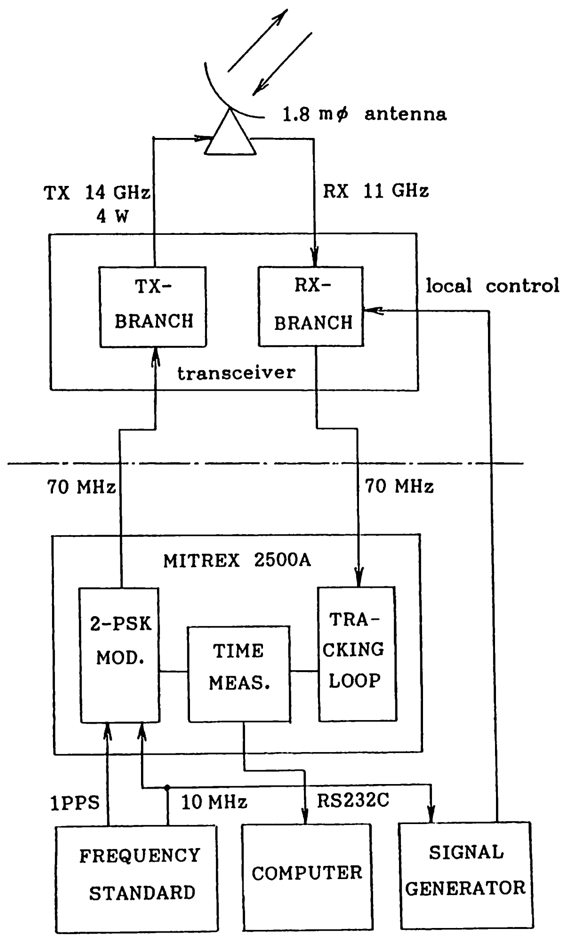

Fig. 5 Schematic diagram of the CRL system.

(2) Link budget

Because two-way time transfer is almost unaffected by the propagation paths and site-internal delays and because other source of error are almost constant, the major error is caused by noise. Thus C/N_0 is the most important factor to evaluate when analyzing the error.

From Table 2, which shows the link budget of the INTELSAT-V experiment between the US and Japan, we get on estimated total C/N_0 of 59 dB. The beam-edge C/N_0 is 53 dB which is 3 dB less than the C/N_0 at the beam center (6 dB less from uplink and downlink). This is because the Ku-band beam is a spot beam. The minimum C/N_0 to get the delay lock in MITREX modem is 50 dB and a C/N_0 greater than 53 dB gives us a precision of less than 1 ns. The measurement accuracy with the MITREX modem is improved in proportion to the square root of C/N_0[5].

Table 2 Link budget

INTELSAT-V: 174° E Transponder in high-gain mode		
Earth station transmit E.I.R.P.	52	dBW
Uplink pass loss	207	dB
Uplink tracking loss	1	dB
Satellite G/T at beam edge	0	dB/K
Uplink C/T	– 156	dBW/K
Gain of 1 m^2 antenna	45	dBi/m^2
Power flux density arriving at satellite	– 111	dBW/m^2
Transponder saturation flux density toward the earth station	– 79	dBW/m^2
Input back-off	32	dB
Output back-off	26	dB
Total transponder saturation E.I.R.P.	43	dB
Downlink E.I.R.P.	17	dBW
Downlink pass loss	205	dB
Downlink tracking loss	1	dB
Earth station G/T	19	dB/K
Downlink C/T	170	dB/K
Total C/No	59	dB·Hz

(3) Example of the self-ranging experiment

A self-ranging experiment using the INTELSAT-V satellite at 180 degrees East longitude over the Pacific Ocean was performed by the INTELSAT time transfer system of the CRL. In this experiment, a C/N_0 of 65 dB was obtained for the return signal, and we got a full day's worth of ranging data between the ground station and the satellite. Figure 6 shows the residuals after calculating quadratic regressions of the self-ranging measurements at the CRL. The RMS error here was about 0.4 ns. This system thus confirmed that the high resolution expected could be obtained in actual measurements.

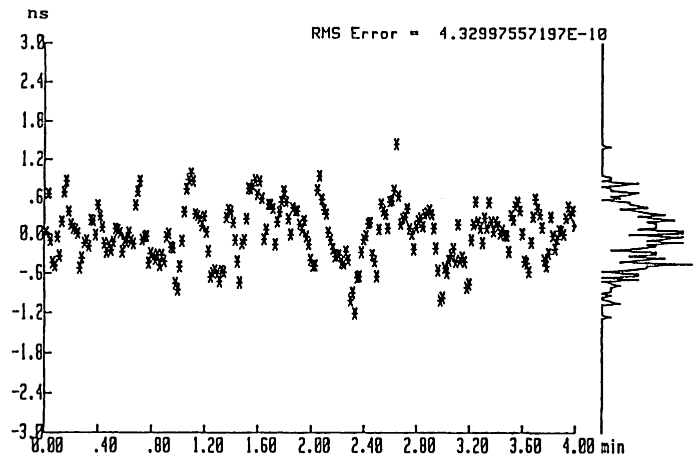

Fig. 6 Residuals from quadratic regression of the ranging measurements.

5. Calibration of INTERNAL Delay

The accuracy of time transfer is evaluated by measuring the absolute time delay between two clocks. Error are generally caused by the following factors:

1) Error in the position of the satellites and earth stations
2) Effect of ionospheric and tropospheric propagation
3) Influences from satellite missions and ground facilities (Offset and its time variation)

Position errors of are not important because they are canceled by the almost identical lengths of the paths from each station to the satellite. The ionospheric part of the propagation error depends on the total electron content (TEC) of the transmission paths and is given by following equation:

$$\Delta T = \frac{40.5Nt}{cf^2}(\mathrm{ns}), \qquad \qquad (5)$$

where

Nt : TEC (electrons/m^2)
f : signal frequency (Hz)
c : light velocity (m/s).

Ionospheric delay should in principle be canceled if the uplink and downlink paths are exactly the same, but differences between uplink and downlink frequency and local ionospheric changes over time may produce small difference between the two paths. If we use higher frequencies, the error should be smaller. When the satellite elevation is low, the local time of the two stations differ and with Ku-band INTELSAT communications, the ionospheric delay difference between uplink (14 GHz) and downlink (11 GHz) is several hundreds of picoseconds. Because the tropospheric effect has no frequency dependence, it has no affect on two-way time transfer. The effects of other missions and facilities are result from transponder differing between the two transmission directions.

Accurate calibration the internal delays in ground stations is also very important for improving the accuracy of time transfers: as shown in Section 1, it is necessary to measure ($\tau TX - \tau RX$). If we can transport one site receiver to another site, we can use a common clock to directry measure the difference between their internal delays. In general, accurate measurement of each component of the systems at each station is essential.

6. Discussion

For one day, we performed a preliminary, self-ranging test from the CRL (Tokyo) by using the INTELSAT satellite covering the Pacific region. With a C/N_0, of 65 dB, the rms range fluctuation was equivalent to 0.4 ns. Random error can be reduced by increasing the C/N_0, and systematic error can be reduced by more precisely knowing both the orbit of the satellite and the propagation delay. The results of two-way time transfer should be compared with independent methods such as VLBI time synchronization and laser time synchronization via a geodetic satellite.

Acknowledgement

We thank the staff of KDD who assisted in accessing the INTELSAT and in getting a station license.

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