High-Precision Time Comparison via Satellite and Observed Discrepancy of Synchronization

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Abstract—**A time comparison experiment via a geostationary satellite was conducted between the stations in the USA and in Japan by a two-way method in SHF band using the Spread Spectrum Random Access communication system. With this system, a high resolution of about 1 ns was obtained in the measurements. The light synchronization discrepancy in the rotating coordinate system of the earth was clearly observed. Making the correction for the error due to the discrepancy, the value measured via satellite coincided well with that obtained through the ground link within an uncertainty of a flying-clock measurement. The accuracy of this experiment was estimated to be about 10 ns.**

I. INTRODUCTION

THE SATELLITE technique is particularly appropriate for precision clock synchronization on an intercontinental scale. Many methods have been developed according to a combination of techniques and satellites used in time comparison [1]. It is thought that the two-way mode utilizing a microwave carrier frequency via a geostationary satellite gives the highest precision among various methods. There are two main problems in getting higher precision and accuracy, one of which is the precision of detecting the received-time pulse and the other is the uncertainty of the measurements and estimates of the difference between the total delays from one station to the other in two directions.

A time comparison experiment between the USA and Japan via the geostationary satellite ATS-1 was conducted in August, 1975 by the Radio Research Laboratories (RRL) with close cooperations of the GSFC, NASA, and the US Naval Observatory (USNO). In this experiment, the Spread Spectrum Random Access (SSRA) communication system was used to transfer the time signal, by which the transmission and the reception can be made simultaneously and also better signal-to-noise ratio (S/N) in detecting the received time pulse can be obtained. The expected precision and accuracy were as high as a few nanoseconds and about 10 ns, respectively.

II. SYSTEM DESCRIPTION

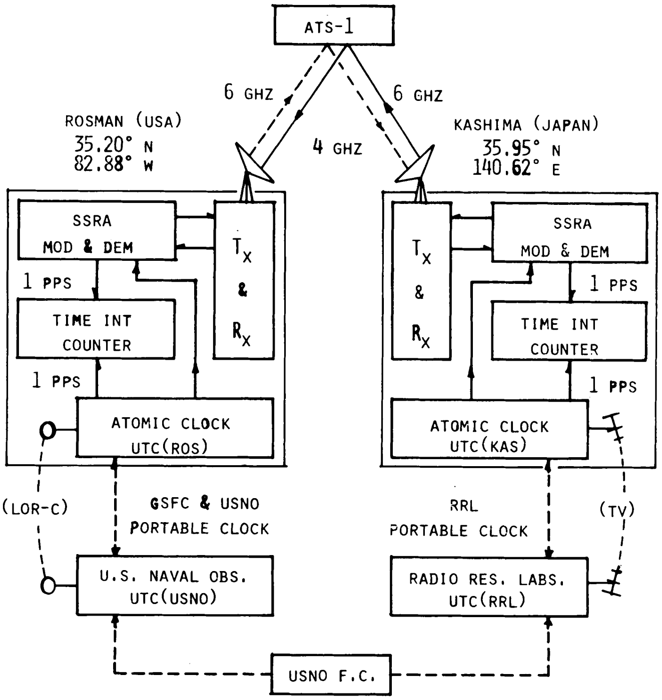

Fig. 1. Block diagram of time comparison experiment.

The overall system of the experiment is shown in Fig. 1. The reference time scale at each station was kept by a cesium-beam clock equipped with a commercial high-performance tube, whose stability for an averaging time of several hours is about 6×10^{-14} or better. The reference clock was monitored through the ground link, by methods such as TV or Loran-C signals and a portable clock measurement, with respect to a more stable time scale being kept by the USNO or by the RRL with an uncertainty of 10 ns or less. During the experiment, a flying-clock measurement was made by the USNO between the master clocks at the USNO and the RRL, and the result was compared with that obtained via the synchronous satellite ATS-1.

The SSRA system has been used at Kashima station of the RRL originally for the code division multiple-access communications and the range measurement satellite experiments [2], [3]. Fig. 2 shows the simplified functional block diagram of SSRA system for the time comparison. In the transmitting system, a 70-MHz carrier wave is biphase modulated to spread its spectrum to a wide bandwidth of about 30 MHz by the spreading pseudo-noise (PN) code. The specified pattern of the PN code is assigned to each station. The PN code is generated by a 11-stage feedback shift register (FSR) at the rate of 16.376 Mbit/s. Its frame length is 125 μs being composed of 2047 bits, and the instant that all stages of FSR are in "1" state occurs once in one period. In order to resolve an ambiguity of the measured time interval, another slow rate PN code, that is range PN code, of 8 kbits per second is generated

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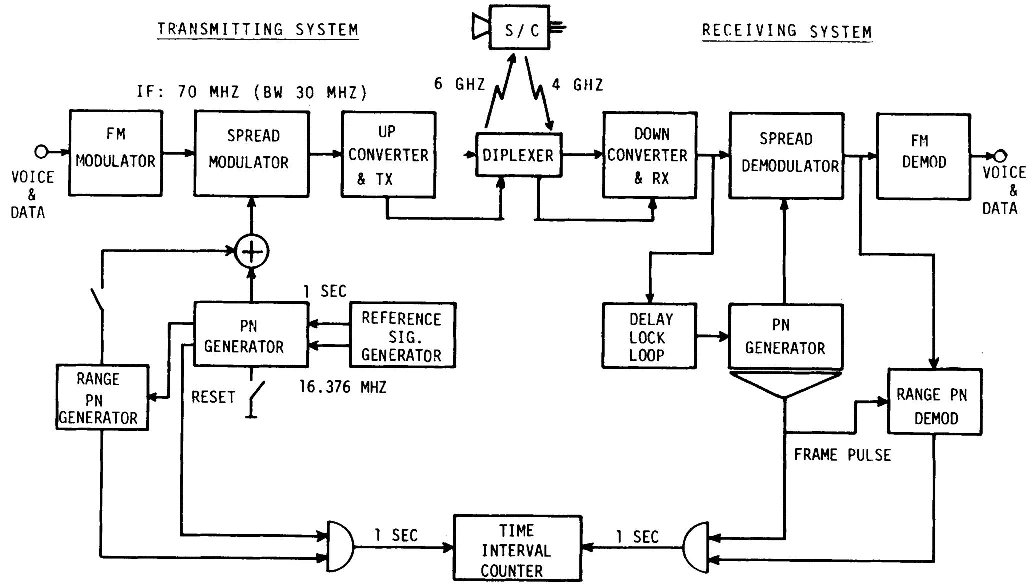

Fig. 2. Simplified SSRA and time comparison system.

by a 13-stage FSR. Its frame length is provided by 8000 bits so as to make one period exactly 1 s.

The driving signal of the 11-stage FSR for the spreading PN code maintains phase coherency with the 1-MHz signal of a reference atomic clock at each station. The 13-stage FSR for range PN code is derived by the pulse generated at an instant of all "1" state of the 11-stage FSR. At the beginning of the time comparison operation, the all "1" states of both FSR's should be synchronized with a second-pulse of the reference clock, and the pulse generated at the all "1" states is fed to the time interval counter as a start pulse.

The range PN code is combined with the spreading PN code by the exclusive OR logic circuit and transmitted by the time the SSRA receiver at the other station established the synchronization of the local range PN code.

In the receiving system, the received spread spectrum signal is inversely modulated by a locally generated PN code, whose timing and phase are kept synchronism by the delay-lock loop (DLL) with those of the received signal.

The DLL is composed of two correlation detector, a loop filter, a phase detector, a VCXO of 16.376 MHz, and a 11-stage FSR. From the spread demodulated signal, the received range PN code or the information signal is recovered by a range PN code demodulator or a FM demodulator, respectively. The recovered range PN code is fed to a 13-stage shift register, whose contents are compared bit by bit with that of a 13-stage FSR. After the coincidence of the contents is obtained, the pulse generated at the instant of all "1" state of the 11-stage FSR in the DLL starts to drive the 13-stage FSR, and then, the range PN code is locally generated. A pulse is generated at the all "1" state of both FSR and fed to the time interval counter as a stop pulse, which enables one to make the time interval measurements every second between the transmitted 1 pps pulse and the received one. After the stop of the transmissions of the range PN code at both stations, the measured values at Rosman station were sent back automatically and instantly to Kashima station by the same carrier wave simultaneously with the time comparison operation. A similar system has been used in time transfer experiments by the GSFC of NASA [4].

III. ESTIMATION OF ERRORS

With error due to the difference of total delays, the error due to the difference of the delays in space for two directions can be minimized, because the transmissions at both stations are made simultaneously through the same communication channel on the satellite with the SSRA system. In this experiment, the delay times in the systems at two earth stations were precisely measured. As a result, it was expected to get high accuracy of about 10 ns (1σ).

With instrumental error, the error due to the input noise at the SSRA receiver is less than 0.3 ns because the S/N of the received spreading PN code can be improved by the DLL. The steady-state phase error due to the drift of the satellite is also very small, less than 0.1 ns. Thus it is thought that the main errors are caused by the quantization error of the time interval counter and the stability of the SSRA system. The standard deviation of the measured time interval was expected to be a few nanoseconds, and it was confirmed that the stability of the SSRA system was about 1 ns by a satellite loop test.

With error due to the refraction in the ionosphere, the path difference between down-link (4 GHz) and up-link (6 GHz) does not occur in the troposphere as the refraction index is independent on frequency. However, an error will be caused due to the refraction in the ionosphere, which is a function of frequency. The error is proportional to the difference of the total electron content along the path from the satellite to the Kashima station or to the Rosman station. The amount of total electron content will be subjected to considerable variations, such as diurnal, day-to-day, seasonal, sun-spot cycle, and the elevation angle of the path. It was estimated that this error would be less than 5 ns, and would change diurnally, if observed.

The detail of the error considerations, especially on the measurement of system delay and the instrumental error, were described in [5].

IV. RESULT OF MEASUREMENTS

The measurements over several hours per day were made for 4 days. Each value in the data shown in Fig. 3 is usually an average of 240 measurements, namely for about 4 min, and its standard deviation was around 1 ns. Thus the high resolution of the measurement by the SSRA system was experimentally confirmed.

In Fig. 3, the straight line is the regression line for the whole period of the experiment. The standard deviation and the maximum deviation around this line were 1.7 and about 3.5 ns, respectively. It seems, however, that there exists a small and slow variation, especially for the data on August 26–27. One possible cause is the refraction effect in the ionosphere, but it was difficult to explain the data for other days.

On the other hand, a flying-clock measurement was made on 27th August by the USNO between their master clock and that of the RRL. The result obtained through the overall ground link including this flying-clock measurement showed that the clock at Kashima station was 9.42 ± 0.2 μs fast with respect to the clock at Rosman station at 02h 34m UTC on August 27. The corresponding value extrapolated on the satellite measurement was 9.106 μs. The difference between these values, that is 0.31 ± 0.2 μs is much larger than we expected in view of the estimated high accuracy, even if we take into consideration the uncertainty of 0.2 μs in a flying-clock measurement.

Thus two problems, the existence of small and periodic variations and an insufficient agreement in results, remain to be settled.

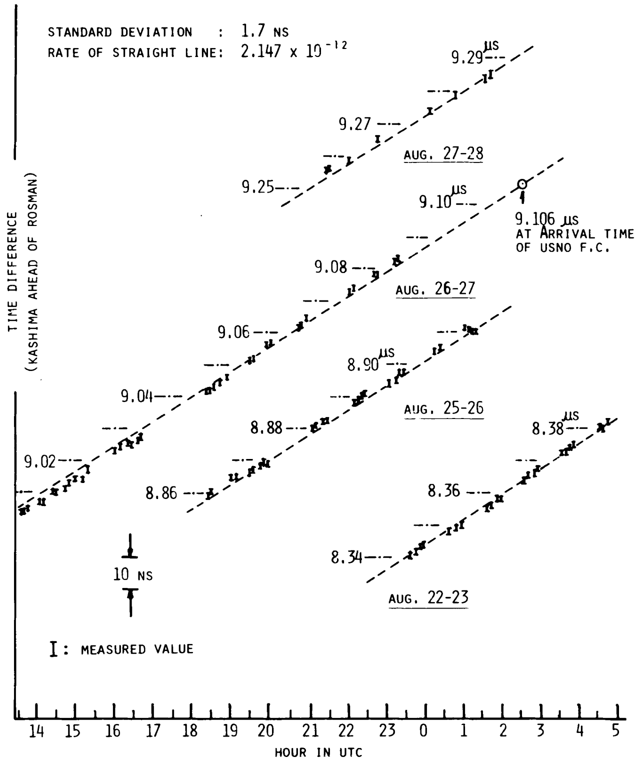

Fig. 3. Measured time difference via satellite.

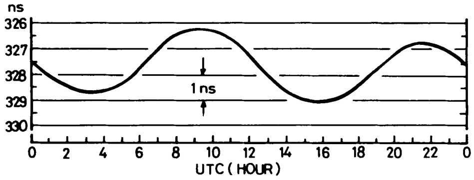

Fig. 4. Calculated synchronization error.

V. ERROR OF SYNCHRONIZATION IN A ROTATING COORDINATE SYSTEM

As one of the possible causes for the two problems in the results of the measurements, the effect of the earth's rotation on a time comparison was examined [6]. It has been known that the experimental evidence for the directional dependency of light propagation was made first by Sagnac in 1913 using a rotating plate, and a similar one by Michelson and Gale in 1925 for detecting the effect of the earth's rotation. These were reviewed in the first part of [7], entitled "Sagnac effect." From this point of view, it is easily understood that the time comparison experiment via a geostationary satellite is very similar to those old experiments except for the instruments and techniques used.

In a time comparison experiment via a satellite, it is considered that the effect of the gravitational potential on the light path is small and cancelled out by the two-way method, and that other relativistic effects are negligibly small. Thus the rotational effect can be analyzed by transforming the metric in Minkowsky coordinate (ct, x, y, z) into that for a rotating frame (ct, x', y', z) with an angular rate of ω. As a result, on the assumption of $\omega^2[(x')^2 + (y')^2] \ll c^2$, the error due to the earth's rotation in a two-way time comparison E is expressed as follows.

$$E = \frac{\omega}{c^2} \int_{\text{path}} (x'dy' - y'dx') = \frac{2\omega A}{c^2}$$

where A is a loop area projected on the $x' - y'$ plane or the equatorial plane in our experiment. The same conclusion in a different manner of the analysis was shown in the time of old optical experiments mentioned above, and also in the references recently published [8], [9].

The error for this experiment can be calculated using the orbital data of the ATS-1 satellite. As shown in Fig. 4, the error varies periodically with small amplitude of about 2 or 3 ns around the mean value of about 328 ns, because the projected loop area A changes slowly according to the diurnal drift of location of the satellite.

In comparison of the measured values with those calculated, the reduction of the data was made day by day and it was assumed that the frequency difference between the

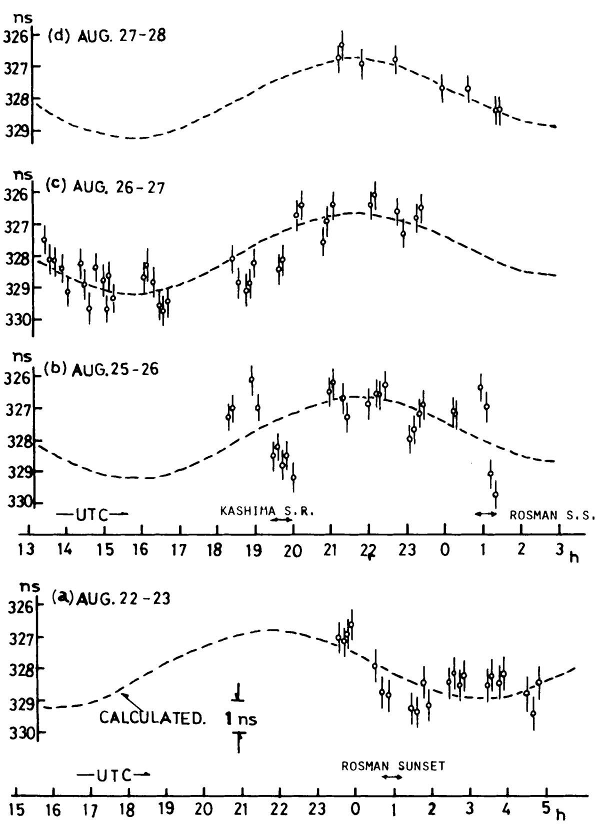

Fig. 5. Observed variation of synchronization error.

two clocks was kept constant during the observation time on each day. Thus the most probable rate of change of the time difference was decided for the data on each day, the deviation from which is shown in Fig. 5. Fig. 5 shows how well the measured small variation is coincident in amplitude and in phase with the calculated one shown by the dotted curves.

From numerical analysis, it was shown that the correlation coefficient is 0.83 for all data (67 points) except for August 25–26, when the large effect of the ionosphere was clearly observed about sunrise in Japan and sunset in the USA. The day-to-day changes of the frequency difference or the rate of change of the time difference between the two clocks were in a range of -0.8 to $+1.7 \times 10^{-13}$, which is conceivably possible in view of the stability of the atomic clocks used. However, it surely includes a daily change due to the effect of ionosphere to some extent, but it is difficult to determine it quantitatively because of the lack of data on the electron content during the period of the experiment. While the local time differs by about 10 hours at the two locations of the stations, the error due to the ionosphere must change diurnally, but it was not noticeable in the results of our measurements.

Applying a correction for this rotational error to the measured value via satellite, the time difference between the clocks at the two stations was calculated to be 9.439 μs at 02h 34m on August 27. Since the corresponding value through the ground link was 9.42 ± 0.2 μs, the difference between two values obtained by these different methods is reduced to -0.02 ± 0.2 μs.

It is necessary, however, to estimate an amount of the relativistic effects on a flying clock, because the correction was not applied in the reduction of the USNO flying-clock measurement. Assuming that the flight was at an altitude of 10 km and had a ground speed of 900 km/h along the great circle path between Washington, DC, and Tokyo via Hawaii, a flying clock would gain 87 ns for the westward trip and would lose 4 ns for the eastward trip. In consideration of the round-trip schedule of 24 days in this measurement, it is roughly estimated that the correction to be applied would be 80 ns. Then, the time difference between the station clocks through the ground link was calculated to be 9.50 ± 0.2 μs, which should be compared with the value of 9.439 μs via satellite link with the correction for the rotational effect mentioned above. It is considered that the difference between these values of 0.06 ± 0.2 μs is reasonable in value, taking into consideration an uncertainty of 0.2 μs in the flying-clock measurement.

The complexity of precise clock synchronization in the rotating frame of the earth was thus experimentally confirmed by these two facts, that is, the observed small and periodic variation and better consistency between the values obtained via satellite and through the ground link. It is noted that the observation of the rotational effect on the light synchronization in this experiment corresponds to that of the same effect on an atomic clock flying around the world to eastward or to westward examined by Hafele and Keating [10].

VI. CONCLUSIONS

The experiment showed that the satellite time comparison can be performed by the SSRA system with a high precision of about one nanosecond. The light synchronization error due to the earth's rotation was clearly observed and testified to by two experimental results. The accuracy of the experiment of about 10 ns was also confirmed with reasonable certainty. In future experiments, the effect of refraction in the ionosphere on a time comparison should be studied in detail.

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A New Determination of the Rb85 Unperturbed Hyperfine Transition Frequency

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Abstract—**The unperturbed hyperfine transition frequency of the Rb85 atoms has been measured using a beam maser device operating under pulsed conditions. Population inversion is achieved through optical pumping in a storage cell. Using a double conversion receiver, frequency measurements were made to a few tenths of a hertz. Magnetic-field effect, cavity pulling, wall shift, and density dependent shift, are the main frequency shifts discussed and evaluated. The unperturbed frequency obtained is 3 035 732 440 ± 3 Hz, which is in agreement with previously published results. The absolute-wall frequency-shift coefficient for Paraflint is measured to be: −176 ± 25 Hz · cm at 72°C. The uncertainties reported are mostly attributed to the reproducibility of the maser storage cell coating.**

I. INTRODUCTION

THE PURPOSE of this experiment is to measure the hyperfine transition frequency of free Rb85 atoms. To do so, we used a beam device in which the beam is directed in a storage cell where it is optically pumped. We succeeded in measuring the resonance frequency with a high degree of precision by operating the maser under pulsed conditions. After all the necessary corrections were made, it was shown that the accuracy in the measurement of the unperturbed transition frequency is limited by the determination of the wall frequency shift. The value obtained is in agreement with previously published results by Penselin *et al.* [1] who used a beam interrogated by a Ramsey type of microwave cavity, and Vanier *et al.* [2], [3] using the pressure-dependent frequency shift of various buffer gases.

II. MASER DESCRIPTION

The apparatus used in this experiment is schematically represented by the Fig. 1. Its design is inspired by the hydrogen-maser technology [4]. A thermal source of natural rubidium supplies a beam of up to 10^{15} atoms/cm^2 · s well collimated by a multitubes ejector. The storage bulb is coated with Paraflint[1] and centered in a right cylindrical cavity tuned at 3035 MHz and operating on the TE_{011} mode. Fine tuning and variable coupling are provided. The cavity temperature is controlled to within a few tenths of a degree Celcius, and can be varied from room temperature to about 100°C. The whole system is under a vacuum in the order of 10^{-7} torr. A solenoid generates a static magnetic field parallel to the axis of the cavity and two magnetic shields improve the homogeneity of the field at the bulb site and reduce the stray fields. Population inversion is produced by the following optical pumping device [5]: light is generated by an electrodeless discharge lamp containing a few milligrams of Rb85 and 2 torrs of Argon excited by a 80-MHz oscillator delivering approximately 5 W. It is then filtered through an isotopic filter containing a few milligrams of Rb87 and about 60 torrs of helium. Operating temperatures of the lamp and the filter are 115 and 75°C, respectively.

III. FREQUENCY MEASUREMENT SETUP

The frequency of the signal generated by the atomic vapor is measured with the double-conversion receiver shown in Fig. 2. A first heterodyne mixing is made at the 3-GHz level giving a nominal 30-MHz intermediate frequency. This intermediate signal is added to a 30-MHz

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[1] Paraflint is a trade name of a hydrocarbon of the polyethylene type sold by Moore and Munger, Inc., Stamford, CT.