4-2 GPS Common View

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GPS common-view method was developed in the 1980s and it had been a world leading time transfer technology in the recent two decades. According to this method, daily averaged time comparison precisions obtained from the C/A code single channel receivers could reach 10^{-14} approximately. However, to meet the advancement of atomic clocks, we attempt to develop new methods for highly precise time comparison technology. This paper describes a fundamental theory of the GPS common-view method, data analysis and error sources as well as to express the improvements of the time transfer precision using multi-channel receivers, the improvements of satellite orbit, of the ionosphere model, and carrier phase observations. Especially, we show the evaluation results of multi-channel receivers and the ionosphere model improvements of recently observed data.

Keywords
GPS, International atomic time, Time transfer

1 Introduction

International Atomic Time (TAI), determined by the BIPM (Bureau International des Poids et Mesures), is calculated based on data from more than 200 atomic clocks maintained by over 50 organizations worldwide[1]. The International Time Link was established to collect data from these international atomic clocks. Prior to the introduction of the GPS, LORAN-C was used in the International Time Link[2]. The precision of time transfer with LORAN-C was in the order of a few hundred ns, and regions in which comparison could be performed were limited. The use of GPS has improved time transfer precision markedly and has made it possible to establish a global time transfer network, a feat that would have been impossible using the LORAN-C network.

The time transfer precision of the GPS is 2 ns/day on average, with frequency stability of approximately 3×10^{-14}. Additionally, the accuracy of TAI is currently maintained by lengthening averaging times for calculation. The stability of TAI is improved by a factor of ten roughly every seven years, in accordance with progress in atomic clock technology. If we continue to apply existing methods, it is probable that the stability of TAI will be limited over the course of the next several years not by the stability of atomic clocks but rather by limitations in link precision.

To improve the precision of time transfer, various systems are currently under development and study throughout the world. For example, a two-way satellite time and frequency transfer system using communication satellites makes it possible to perform highly precise time transfer easily, with some major countries in the Asian area already adopting this two-way system[3]. GPS is also leading to improvements in time transfer precision, through a number of applied techniques: development of multi-channel receivers, development of a time transfer receivers capable of receiving signals from two kinds of satellites (GPS and GLONASS), practical use of geodetic receivers for time transfer applications, and more.

2 GPS time transfer

2.1 GPS

GPS is the worldwide positioning satellite system originally developed by the U.S. Department of Defense as the NAVSTAR/GPS (Navigation System with Time and Ranging/Global Positioning System)[4]. GPS has been developed to enable real-time positioning anywhere on earth (except for the polar regions) through simultaneous reception of signals from four or more satellites.

Each GPS satellite carries an onboard cesium or rubidium atomic clock[5], which serves as the source of all frequencies and time for the given satellite. Specifically, the GPS satellite uses this atomic clock to create a reference frequency of 10.23 MHz and also generates two carrier frequencies by multiplying this value by 154 (1,575.42 MHz) and by 120 (1,227.60 MHz), respectively. These carrier frequencies are referred to as L_1 and L_2, respectively. The satellite transmits radio-wave signals with pseudo random noise (PRN) code serving as a ranging signal; the satellite also issues navigation signals containing orbital information and the like superposed on these two carrier frequencies. The two waves are used as carrier frequencies in order to correct for ionospheric delay, which will be described in detail in Section ***3.2.3***.

The ranging signal superposed on the carrier frequencies includes a C/A (clear and acquisition) code with a chip rate of 1.023 Mbps and a P (precise) code of 10.23 Mbps; the C/A code is superposed only on L_1, and the P code is superposed on both L_1 and L_2. Since the P code is superposed on both of the two waves, this code is referred to alternately as P_1 and P_2, according to the carrier frequency. The sequence for the C/A code is open to the public, allowing access to ordinary users. The P code was originally designed for military purposes, but recently nearly all geodetic receivers can decode the P code.

The observational precision of each signal depends on the performance of the receivers. Generally, the C/A code provides a precision of about 3 m (10 ns), the P code is accurate within approximately 30 cm (1 ns), and the L_1 carrier phase features accuracy of 2 mm (7 ps), assuming that a given index of precision is equivalent to one-hundredth of the wavelength corresponding to the code or carrier frequency.

2.2 GPS common-view

The GPS common-view method[6] is a system proposed by D. W. Allan of the former NBS (National Bureau of Standards; presently the National Institute of Standards and Technology, or NIST) in the early 1980s. The principle of the GPS common-view method is shown in Fig.1.

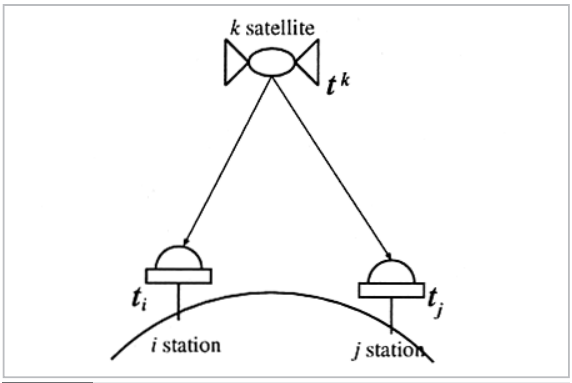

Fig. 1 GPS common-view

Stations *i* and *j*, which are to perform time transfer, receive a time signal (t^k) from a GPS satellite *k* simultaneously. Let the reception times of the stations be t_i and t_j; the time differences between the station *i* and the satellite *k* and between the station *j* and the satellite *k* (after correction for propagation delay) are thus expressed as follows, respectively.

$$\delta t_i^k = t_i - t^k \qquad (1)$$

$$\delta t_j^k = t_j - t^k \qquad (2)$$

By calculating the difference between formulas (1) and (2), time transfer can be performed using the GPS signal as an intermediary.

$$\delta t_{ij} = (t_i - t^k) - (t_j - t^k) = t_i - t_j \qquad (3)$$

As described above, the GPS common-view method cancels out satellite clock error and performs highly precise time transfer by ensuring that the stations that are to perform time transfer receive the signal from a single satellite simultaneously.

One advantage the time transfer purpose has over the navigation purpose is that only one GPS satellite is needed in order to obtain the offset of two clocks, because we are in fixed locations and know their position. The NBS initially proposed the common-view method and designed a receiver for time transfer using this method. Such a receiver is referred to today as an NBS-type receiver; a number of companies offer such receivers commercially. This NBS receiver is the most commonly used receiver in the International Time Link, enabling simultaneous receipt of a signal from a single satellite.

Formula (1) is a simplified expression of the principle of the common-view method. If effects of the propagation delay and the like are taken into consideration, an observed quantity δt_i^k at a certain time t can be expressed by formula (4).

$$\begin{aligned}\delta t_i^k(t) \quad = \quad & \frac{\rho_i^k(t, t-\delta t_i^k)}{c} + I_i^k + T_i^k + dm_i^k \\ & +[dt_i(t) - dt^k(t-\delta t_i^k)] \\ & +[d_i(t) + d^k(t-\delta t_i^k)] + e_i^k \qquad (3)\end{aligned}$$

Here, ρ_i^k represents the geometrical distance between the satellite and the receiver; I_i^k represents ionospheric delay; T_i^k represents tropospheric delay; dm_i^k represents multi-pass error; dt_i, dt^k represents clock errors of the receiver and the satellite; d_i, d^k represents internal delays of the receiver and the satellite equipment; e_i^k represents errors in the model and in observation; and c represents the velocity of light.

The precision of the GPS common-view method depends on errors in the correction model, in addition to the observational precision of the receiver. The effects of these model errors will be described in Section **3.2**.

2.3 International Time Link

Ordinary GPS time transfer receivers work for a single channel and are capable of receiving only the C/A code. For this reason, in order to construct the International Time Link based on the GPS common-view method, each station is required to receive the signal from the satellite following a predetermined schedule. Accordingly, for the International Time Link the BIPM establishes a GPS common-view schedule for single-channel receivers, and distributes this to participating network organizations via email. With this schedule, signal receipt is allocated to 89 satellites throughout a sidereal day (23 hours and 56 minutes), which is partitioned in 16-minute increments based on an original period determined by the BIPM. Due to the structure of this allocation, observation is not performed in the last 12 minutes of the sidereal day. In addition, the schedule is updated once every six months.

In order to allow efficient processing of data from the various organizations, a unique data format must be determined. The GPS common-view data format is the CGGTTS (Common GPS/GLONASS Time Transfer Standard) data format, and is defined in separate references[7][8]. In CGGTTS for data exchange, data is made by averaging process in 13 minutes in order to reduce file volumes. With this averaging method, data is divided into 15-second interval and a quadratic curve is applied to each. The 52 estimated values of this curve (corresponding to an observation time of 13 minutes) are then subjected to the following correction.

(1) Correction of geometric delay between a satellite and an antenna using the navigation message

(2) Correction of ionospheric delay using the navigation message

(3) Modeled tropospheric delay

(4) Sagnac and periodic relativistic corrections

(5) Correction of $L_1 - L_2$ bias using the navigation message

(6) Correction of antenna delay and cable delay of the reference signal

After correction, least-square linear fit is performed, and the datum corresponding to the midpoint of observation time is adopted as an estimate for the overall observation. Details of each correction term will be described in Section **3.2**. A general explanation of the correction for the theory of relativity is given in reference [9] and details of the effect of the theory of relativity on GPS is given in reference [10].

The CGGTTS file is in ASCII file format, consisting of a header and a data record. The header contains the name of the receiver, position of the antenna, cable delay, the name of the reference signal, etc. Each single column of the data record corresponds to a single estimated datum. The contents of the data record are shown in Table 1.

Each participating station of the time transfer network collects and prepares five-day data for the latest period ending on a date with a final MJD digit of 4 or 9; this data is incorporated in the CGGTTS file and sent to the BIPM by email or via FTP. BIPM then establishes a link for TAI calculation using the data arriving from the various stations.

3 Research and development to improve time transfer precision

The GPS common-view method using the C/A code of a single channel has begun to reveal its limitations in terms of precision within today's International Time Link network. Standardizing organizations throughout the world are thus carrying out research and development to develop more precise methods of time transfer.

3.1 Use of multi-channel receiver

Common time transfer receivers are single

Table 1 *Contents of data record in CGGTTS format (20)*

Category	Explanation
PRN	the satellite vehicle PRN number
CL	the Common View class of the track
MJD	Modified Julian Date of the start of the track
STTIME	hour, minute, and second (in UTC) of the start of the track
TRKL	the track length in seconds
ELV	the elevation of the satellite at the midpoint of the track
AZTH	the azimuth of the satellite at the midpoint of the track
REFSV	the time difference(.1ns) between the laboratory reference clock and satellite time, referred to the midpoint of the pass via a linear fit
SRSV	the slope determined via the linear fit to produce REFSV(.1ps/s)
REFGPS	the time difference(.1ns) between the laboratory reference clock and GPS system time, referred to the midpoint of the pass via a linear fit
SRGPS	the slope determined via the linear fit to produce REFGPS(.1ps/s)
DSG	the root mean square of the residuals of the linear fit used to produce REFGPS
IOE	the index of ephemeris
MDTR	the modeled tropospheric delay(.1n) referred to the midpoint of the pass via a linear fit
SMDT	the slope determined via the linear fit to produce MDTR(.1ps/s)
MDIO	the modeled ionospheric delay(.1ns) referred to the midpoint of the pass via a linear fit
SMDI	the slope determined via the linear fit to produce MDIO(.1ps/s)
MSIO	the measured ionospheric delay(.1ns) referred to the midpoint of the pass via a linear fit
SMSI	the slope determined via the linear fit to produce MSIO(.1ps/s)
ISG	the root mean square of the residuals of the linear fit used to produce MSIO
CK	the data line check sum in hexadecimal format

channel receivers. By replacing these receivers with multi-channel receivers, the number of satellites that can receive data simultaneously can be increased. Theoretically, if the number of satellites capable of receiving is *n* times that of the single channel receiver, the time transfer precision will be improved by a factor of $n^{1/2}$.

Fig.2 shows the results of time transfer between CRL and Physikalisch-Technische Bundesanstalt (PTB) using single channel receivers and multi-channel receivers, respectively. The diagram at left shows the time transfer results over time, and the diagram at right shows Allan deviation. For the single channel receiver, data from a time transfer receiver used in the International Time Link was used; for the multi-channel receiver, data consisted of the output of a geodetic receiver (ASHTECH Z-XII3T) modified to CGGTTS format. The comparison period was three months, from October 1 to December 31, 2002. The CRL used UTC(CRL) as the reference signal for both the time transfer receiver and ASHTECH, whereas the PTB used UTC(PTB) for the time transfer receiver and uses a hydrogen maser signal for ASHTECH. As a result, the time-series data for the single channel and for the multi-channel exhibit different tendencies.

In terms of time-series data, no significant difference is seen between the single channel receiver and the multi-channel receiver, but in terms of stability, the multi-channel receiver clearly performs better with an averaging time of 10,000 second or less. Since there were an average of 13 common-view satellites per day with the time transfer receiver and an average of 97 such satellites per day for ASHTECH, it was expected that the precision of the latter would be 2.7 times better than that of the former. Actual data shows that, with an averaging time of 16 minutes, the time transfer receiver attained a stability of 4.5×10^{-12} and ASHTECH attained a stability of 1.8×10^{-12}, 2.5 times that of the time transfer receiver, a value consistent with the theoretical prediction.

Further, with reference to the stability diagram, this improved stability should continue until the stability of the clock comes out, but the diagram for this experiment shows that the longer the averaging time, the smaller the difference in stability becomes. This is considered to result from the lack of improvement in the stability of the multi-channel receiver—improvement that would otherwise correspond to $1/\tau$—due to the effect of frequency adjustment, as shown in the vicinity of MJD52565.

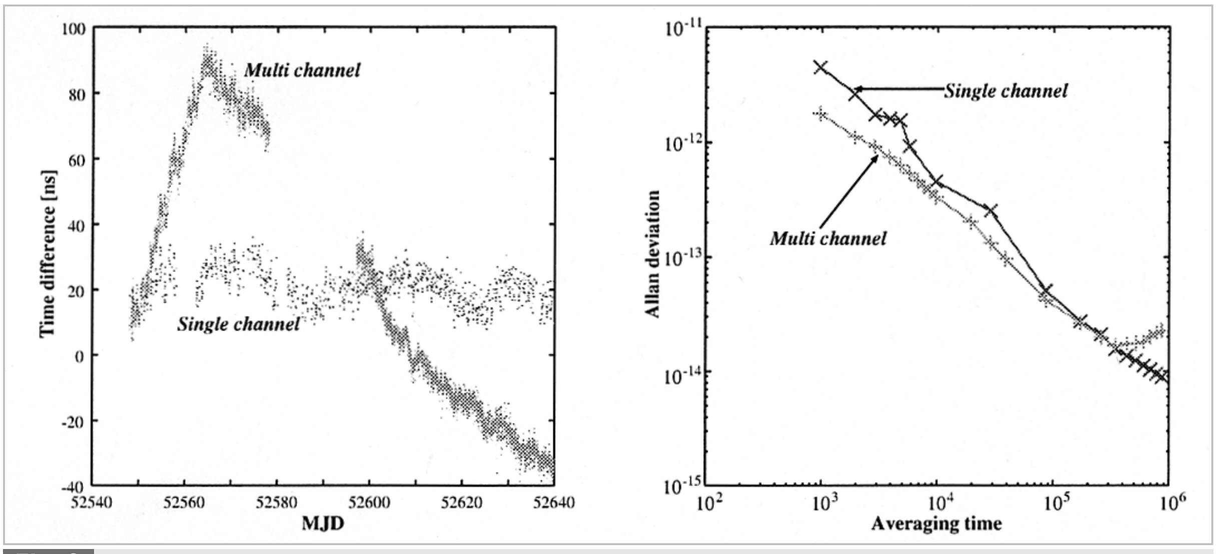

Fig.2 Comparison of time difference and stability between a single-channel receiver and a multi-channel receiver

Left: time difference over time; right: Allan deviation

3.2 Improvement to the model of propagation delay

The GPS receiver corrects propagation delay in real time for the observed quantity expressed by formula (4), as described in Section **2.3**, and outputs the results in CGGTTS format. Therefore, the model used for calculation of the propagation delay carries out calculation using the navigation message acquired in real time. The delays to be corrected in formula (4) using the navigation message include satellite orbital error, ionospheric delay, and satellite clock error. However, since satellite clock error will be cancelled out when the common-view method is executed, only two error values will actually affect time transfer precision: orbital error and ionospheric delay.

3.2.1 Orbital correction using precise orbit

An orbital element acquired from the navigation message is called a broadcast orbit[11], and is distributed in modified Keplerian format on the WGS-84 coordinate system. Accuracy is about 2 to 5m. Meanwhile, the international GPS service (IGS)[12] presents precise satellite orbits on the Internet. The orbits are obtained by combining orbital data determined by seven analysis centers participating in the IGS, based on information obtained from some 400 observation sites throughout the world. Each such precise orbit includes a predicted orbit, a rapid orbit, and a final orbit. The final orbit features an accuracy of 5cm or less. However, it takes about two weeks for this final orbit to be publicized.

The relationship between orbital error and time transfer accuracy depends on the length of the baseline between stations to be compared. In the case of a short baseline, when viewed from the stations to be compared, the line of sight to the satellite is virtually the same for both stations, and accordingly orbital error exerts little influence. However, with a longer baseline, the line of sight to the satellite is different for the two stations, and consequently the influence of orbital error becomes non-negligible. According to separate reports [6], the influence of orbital error on time transfer precision is $\sqrt{2}$ times larger than the orbital error at maximum.

3.2.2 Correction by Global Ionosphere Map

When a radio wave passes through the ionosphere, it is subject to the ionosphere's refractive index; this affects the wave's propagation velocity, resulting in delay. It is known that ionospheric delay is proportional to total electron content (TEC) in the propagation path and is inversely proportional to the square of frequency. If the value of TEC at a certain altitude is known, a zenith delay can be calculated from the position of the satellite and the position of the receiver. An ionospheric delay can be calculated by the product of the zenith delay and elevation-dependent mapping function.

The ionospheric correction parameter that is sent from the satellite in the navigation message is not a TEC value; rather, it is a value obtained through slight modification of the results of the ionospheric delay correction model[13] devised by J. A. Klobuchar. This is referred to as a GPS ionospheric model, and is used to determine the delay in the vertical direction relative to a certain position from four amplitude components and four periodic components; this method is said to be capable of correcting about 50% of ionospheric delay.

On the other hand, the Center for Orbital Determination in Europe (CODE), one of the IGS analysis centers, uses IGS observation data to generate an estimated map of the global ionosphere (GIM). The data after estimation is published on the Internet in IONEX[14] file format. The IONEX file contains TEC values at an altitude of 400 km, with a mesh of 2.5 degrees in latitude and 5 degrees in longitude and a time resolution of 2 hours. In terms of GIM accuracy, it has been reported that TEC quantities obtained by highly precise VLBI measurement (at 2GHz and 8GHz) agree with each other with an accuracy of approximately 0.7 TECU (10^{16} electrons/m^2, corresponding to RMS of the error) and the

TEC quantity in observation can be estimated with an error of 10% or less[15].

In GPS time transfer using the C/A code, it is assumed that ionospheric delay has a greater effect than orbital error. BIPM thus conducts correction using GIM for all observation stations, whereas correction using the precise orbit is applied only in the comparison of stations having a long baseline, spanning more than one continent[16].

3.2.3 Ionospheric delay correction by observed values

When a dual-frequency receiver is used, ionospheric delay can be cancelled out through the use of the frequency dispersion characteristic of ionospheric delay. Based on formula (4), the difference in the observed quantities for stations *i* and *j* when satellite *k* is used as an intermediary can be expressed by formulas (5) and (6).

$$P^k_{1,ij} = \frac{\rho^k_{ij}}{c} + \frac{f_2^2}{f_1^2 - f_2^2} I^k_{ij} + T^k_{ij} + dt_{ij} + e^k_{1,ij} \quad (5)$$

$$P^k_{2,ij} = \frac{\rho^k_{ij}}{c} + \frac{f_1^2}{f_1^2 - f_2^2} I^k_{ij} + T^k_{ij} + dt_{ij} + e^k_{2,ij} \quad (6)$$

Here, P_1 denotes a pseudo range on L_1, and P_2 denotes a pseudo range on L_2. An observed quantity in which the ionospheric delay quantities are cancelled out can be created by deriving formula (7) from the linear combination of formulas (5) and (6)[17].

$$P^k_{3,ij} = \frac{f_1^2}{f_1^2 - f_2^2} P^k_{1,ij} - \frac{f_2^2}{f_1^2 - f_2^2} P^k_{2,ij} \quad (7)$$

If $f_1 = 150$ and $f_2 = 120$ are inserted into the coefficients of formula (7), P_1 and P_2 become multiplied by factors of approximately 2.8 and 1.8, respectively, and e_1 and e_2 are enlarged by corresponding amounts; therefore, P_3 features an error value roughly 3 times larger than those of P_1 and P_2, assuming $e_1 \simeq e_2$. The BIPM is considering the application of P_3 to the International Time Link, initiating tentative use in April 2002.

Fig.3 shows the results of time transfer residual over time and Allan deviation for three kinds of corrections: correction using the navigation message, correction using the precise orbit and GIM, and correction using the precise orbit and P_3. The receivers employed are the ASHTECH Z-XII3T models used at both the CRL and the PTB. The comparison period is approximately four months, from November 19, 2002 to March 21, 2003. The figure shows residuals after least-square liner fit was applied to the time transfer results of the CRL and the PTB. Note that, to make the figure more legible, an offset of +50 ns is applied to the navigation-message correction,

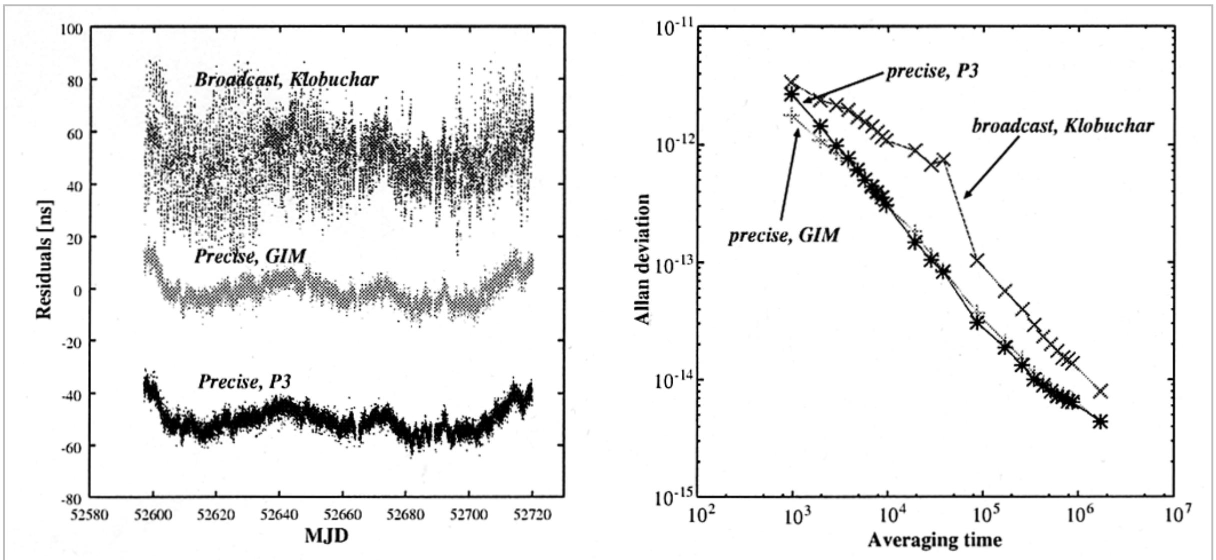

Fig.3 *Comparison of residual and stability among correction methods*

Left: residual over time; right: Allan deviation and an offset of −50 ns is applied to the precise-orbit and P_3 corrections.

P_3, which uses observed values, is expected to yield better results than GIM, which uses estimates drawn from the model. However, no clear difference between GIM and P_3 results was observed in the data from the CRL and the PTB. In terms of stability with an averaging time of 1,000 seconds, P_3 is worse than GIM. This is considered to result from the amplification of error by the linear combination of formula (7). It is assumed that the lack of a distinct difference between P_3 and GIM results (even over the long term) is attributable both to better GIM accuracy and to less variation in ionospheric delay resulting from the placement of the two stations in the middle latitudes. Since there are no participating TAI P_3 link stations in zones where the ionosphere is relatively active, such as near the equator, it would be impossible to clarify the effectiveness of P_3. We assume that the number of participating TAI P_3 link stations will increase in the future, at which point differences between the use of P_3 and GIM will be able to be demonstrated.

3.3 Time transfer using carrier phase observations

As mentioned previously, when time transfer is performed using a carrier phase instead of a pseudo-range transmitted from the GPS, observational accuracy of 10 ps or less may be obtained. Rewriting formula (4) as a formula in which the carrier phase is set as the observed quantity, formula (8) is derived.

$$\begin{aligned}\Delta t_i^k(t) \quad = \quad & \frac{\rho_i^k(t, t-\Delta t_i^k)}{c} - I_i^k + T_i^k + \delta m_i^k \\ & +[dt_i(t) - dt^k(t-\Delta t_i^k)] \\ & +[\delta_i(t) + \delta^k(t-\Delta t_i^k)] \\ & +\frac{\phi_i(t_0) - \phi^k(t_0)}{f} + \frac{N_i^k}{f} + \varepsilon_i^k \qquad (8)\end{aligned}$$

Here, Δt_i^k is the carrier phase observed quantity; a large Δ is used to distinguish this from the code observed quantity δt_i^k. Other symbols designate the following: δ_i, δ^k represents equipment delays of the receiver and the satellite; $\phi_i(t_0)$, $\phi^k(t_0)$ represents the initial phases of the receiver and the satellite; N_i^k is the carrier phase ambiguity; and ε_i^k represents errors of the model and of observation. When the carrier phase is used, ionospheric delay becomes phase delay, and thus the sign of I is reversed. Moreover, observational error is improved by a factor of about 1,000 relative to that of the C/A code. Since time transfer using the carrier phase can be handled in the same way as the code (except for the term of carrier phase ambiguity), time transfer under this method can be treated as a highly precise observed code quantity.

Since N_i^k expresses an integer in units of wavelength, if terms other than the carrier phase ambiguity in formula (8) can be determined within the accuracy of the carrier wavelength, the carrier phase ambiguity can be determined definitively. However, because it is impossible to determine the equipment delays, clock errors, and initial phases of the satellite and the receiver, the carrier phase ambiguity cannot be determined as long as the variation between the respective time differences is expressed by formula (8). On the other hand, the common-view method can eliminate equipment delay, clock error, and the initial phase of the satellite, but cannot eliminate these terms for the receiver; therefore, the carrier phase ambiguity similarly cannot be determined in this case.

The geodetic analysis determines the carrier phase ambiguity using an observed quantity referred to as a "double difference," calculated by linear combination (Δt_{ij}^{kl}) of the two receivers and two satellites. Performing the time transfer also requires that the carrier phase ambiguity be determined using the double difference, followed by determination of the carrier phase ambiguity for a single difference (common-view method)[18]. Thus, in terms of carrier phase analysis, while frequency transfer using the carrier phase is currently widespread, only a few reports are available on time transfer using the carrier phase. This may be because time transfer requires more geodetic analysis than required for time transfer.

The CRL has formulated a plan to perform GPS carrier phase time transfer using the CONCERTO orbit-analyzing software[19]. The present version of CONCERTO can handle only satellite laser ranging data. However, Otsubo et al. are developing a new version of CONCERTO that can enable analysis of GPS data. More specifically, the new version is intended to determine orbits of low-orbit satellites using GPS. In addition, we intend to increase the capabilities of the program further, ultimately to enable the performance of common view analysis.

4 Concluding remarks

We have examined the fundamental theory of the GPS common-view method and ways to improve the precision of this method, using data from the CRL and from the PTB. It has been shown that in terms of hardware, precision could be improved by switching from a single-channel receiver to multi-channel receiver. As seen in the results of time transfer between the CRL and the PTB, in the case of the common-view method between continents, the number of satellites that the single channel receiver can "see" simultaneously is only about 10 satellites per day, whereas the number of visible satellites for a multi-channel receiver is nearly 100 per day. Consequently, precision may be improved by a factor of approximately 3. The results obtained using the IGS's orbital elements and CODE's GIM also pointed to an improvement in precision by a factor of approximately 3, as an average of all times at which time transfer was performed. On the other hand, results did not indicate the effectiveness of correction based on dual-frequency ionospheric observation. However, for stations near the equator, it is highly possible that correction by GIM conducted every two hours will fail to eliminate the effects of short-term fluctuations of the ionosphere; we thus conclude that correction based on observation is effective in correction of stations near the equator separated by long baselines.

The adoption of the multi-channel receiver, ionospheric correction using the dual-frequency receiver, the adoption of the IGS precise orbit, and similar measures enable the GPS common-view method to achieve narrow compliance with the required TAI accuracy. However, in time transfer using the C/A code, it is difficult to improve precision further, and it is therefore desirable to establish, as soon as possible, a time transfer method that employs the carrier phase. On the other hand, since time transfer using the C/A code can still secure sufficient precision in the case of time transfer over short or medium-sized baselines between stations (such as within Japan), and since the system may be constructed using only a GPS receiver and an antenna, the GPS common-view method will remain an effective method for remote time transfer within such ranges.

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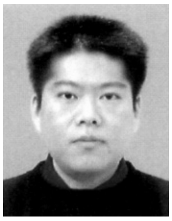

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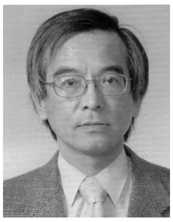

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Frequency Standards