4-4 Role of VLBI Technology in the Space-Time Standards

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In the VLBI observations, signals from Quasars which are realizing the current Celestial Reference Frame are directly used, and therefore all of the five Earth Orientation Parameters can be determined by the observations of VLBI. In addition, since the results of the VLBI observations are stable throughout the long time range, VLBI is playing an important role in establishing Terrestrial Reference Frame. The time and frequency difference between two places separated by a long distance can be precisely measured by using VLBI, and therefore VLBI is expected to have a potential to be used to compare and evaluate optical frequency standards. In the precise measurements, space and time have to be dealt together and the VLBI is expected to play an important role to establish the unified space-time standards.

Keywords
Very Long Baseline Interferometry, Spatial reference, Time and frequency standards, Reference frames

1 Introduction

In the realization of VLBI (Very Long Baseline Interferometry) technology which first appeared in the 1960s, the availability of technologies for high-speed and large-capacity data storage and the invention of the hydrogen maser frequency standard played important roles[1]. Until then, it was known that if signals received by multiple radio telescopes were superimposed and the amplitude of the superimposed signals measured, the radio source position and size could be accurately measured and the precise structure of the radio sources could be investigated. However, in order to do that, it was necessary to share the local frequency signal to convert the frequency of the single received, and to provide a common local frequency signal to each radio telescope using the coaxial cable. In addition, because it was not possible to record the received signal in such a way that it could be replayed, it was still necessary to transmit the received signal via the coaxial cable, and synthesize them as-is. For these reasons, there were limitations on having long distances between the radio telescopes. However, with the invention and development of the hydrogen maser, it became possible to generate local frequency signals based on independent frequency standards for each radio telescope, which in turn made it possible to convert the frequency while maintaining coherence. It also became possible to record accurate time information on signals, to carry out AD conversion at accurate timing, and then to increase the distance between radio telescopes. For these reasons, VLBI technology was first realized. In addition, the ability of VLBI technology to accurately measure the length and direction between two places separated by a long distance created new fields of its utilization. In geodesy, plate tectonics theory was established through plate motion theory verification experiments by using VLBI. And, the precision of the measurement of earth orientation changes was greatly improved by using

VLBI rather than optical telescope. As shown above, the introduction of the hydrogen maser frequency standard made possible measurements in astronomy and geodesy which were impossible up until then, and contributed to the cultivation of new research domains. It can be said that the VLBI technology was the bridge to these achievements.

At present, VLBI technology is the main observation technology in radio astronomy observations. The International VLBI Service for Geodesy and Astrometry (IVS), which has been formed by the International Association of Geodesy (IAG), carries out international VLBI observations for geodetic purposes systematically. The observation data is provided to the International Earth Rotation and Reference Systems Service (IERS), and used in the construction of celestial reference frame and terrestrial reference frame systems and the determination of earth orientation parameters. This paper describes the characteristics required of and roles played by frequency standards in the basic theory and realization of VLBI technology, introduces the roles played by VLBI in currently used reference frame construction, and in addition describes the roles expected for the realization of future space-time standard concepts which consider time and space in a unified way, all based on the above details.

2 VLBI measurement principles

2.1 VLBI measurement principles of time delay

In VLBI, radio waves from astronomical radio sources, such as quasars, are received simultaneously by multiple radio telescopes. At this time, the signal of a frequency band of f_0~f_0+B is frequency-converted to the so-called baseband of the 0~B band, and is converted to a digital signal through AD sampling at the Nyquist rate of 2B. In general, the signal outside the band B is cut off by using a band pass filter (BPF) first, and then the signal and a continuous wave (CW) signal generated by a phase locked oscillator (PLO) are input into a mixer. In the mixer, the PLO signal acts as the local frequency signal and the input signal is converted to an intermediate frequency (IF) signal. In the next stage, the IF signal is converted to multiple baseband signals by image rejection mixers (IRM). As above, frequency conversion is carried out in 2 or more stages. At this time, the signal received at the X station and converted to the baseband is expressed as $f_x(t)=G_x s(t)+n_x(t)$, and the signal received at the Y station and converted to the baseband is expressed as $f_y(t)=G_y s(t-\tau_g)+n_y(t)$. $n_x(t)$ and $n_y(t)$ are the independent noises added to the received signals at the X and Y stations, s(t) is the common signal received at both X and Y stations from an astronomical radio source, and the time lag between the reception of the signal at two stations, the time delay, is τ_g. The time variation of τ_g is not considered here for simplicity. G_x and G_y are the antenna gain of the X and Y stations respectively. By defining the cross-correlation function of $f_x(t)$ and $f_y(t)$, i.e. $c_{xy}(\tau)$, as $c_{xy}(\tau)=\int f_x(t)f_y(t-\tau)dt$, we can obtain the following equation.

$$\begin{aligned} c_{xy}(\tau) =& G_x G_y \int s(t)s(t-\tau_g-\tau)dt+ G_x \int s(t)n_y(t-\tau)dt \\ &+G_y \int n_x(t)s(t-\tau_g-\tau)dt+ \int n_x(t)n_y(t-\tau)dt \end{aligned} \tag{1}$$

Here, in general, signal component s is not correlated with noise components n_x and n_y, the 2nd and 3rd terms on the right side of Equation (1) can be included in the 4th term. The 4th term of the right side can be expressed as $T_x T_y/\sqrt{2BT}\sigma(\tau)$ with the noise temperature of receivers at X and Y stations as T_x and T_y, and the integral time as T. Here, $\sigma(\tau)$ is a noise with its standard deviation being 1 and its spectrum being flat. Meanwhile, the equation $G_x G_y T_s^2 \cos\pi B(\tau+\tau_g)[\sin\pi B(\tau+\tau_g)/\pi B(\tau+\tau_g)]$ can be deduced from the 1st term of the right side of Equation (1). T_s is the received signal power expressed in temperature. A graph of this function is shown in Fig. 1.

When $G_x G_y T_s^2$ is significantly larger than $T_x T_y/\sqrt{2BT}\sigma(\tau)$, τ_g is estimated from τ which gives the relative maximum of $c_{xy}(\tau)$. The estimated uncertainty of τ_g, i.e. $\sigma\tau_g$, is obtained as $\sqrt{3}/\pi$ B SNR, where SNR is the signal to noise ratio. If the SNR value is small, the effect of the

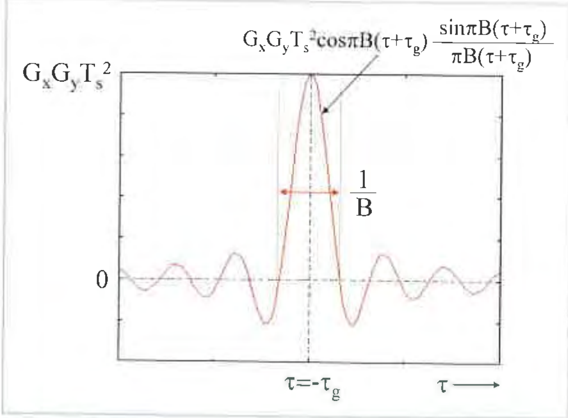

Fig.1 A graph of cross correlation function from signal components

4th term of the right side of Equation (1) which is added to Fig. 1 will be large, and the calculated maximum of Equation (1) may become different from the maximum derived only from the 1st term of the Equation (1) , and it can be seen that this contributes to the estimated uncertainty of τ_g. However, if observed frequency band B is larger, the peak width shown in Fig. 1 will become narrower by 1/B, and τ_g estimated uncertainty can be made smaller in inverse proportion to B. As such, in order to estimate τ_g with high precision, making observed band B larger is effective, however when carrying out AD sampling, the sampling rate must also be increased by the increment in B, requiring a larger amount of data to be recorded, so B is mainly limited by the speed of the recording equipment. Bandwidth synthesis was invented as a method for dealing with this. While keeping band B small for each channel, record data for multiple frequency channels, and calculate cross correlation function $c_{xyi}(\tau)$, and calculate sum $\sum_i c_{xyi}(\tau)$. The fine delay resolution function obtained from this result will have a main peak with width of approximately the inverse of the effective observed bandwidth σ_f defined from the standard deviation of the observed channel local frequencies, and the estimated uncertainty of τ_g will be $1/(2\pi\sigma_f \mathrm{SNR})$. If integral time is secured such that the SNR will be approximately 30, and σ_f is set to approximately 370 MHz, the estimated uncertainty can be calculated roughly as 14 ps. If a long integral time is set to make the SNR even larger, in theory the estimated uncertainty of time delay can be reduced. However, even if it is reduced to less than 10 ps, there are limitations to the accurate estimation of atmospheric delay. Since it is rather more effective to increase the number of observations per unit time for the estimation of the earth orientation parameters and station coordinates, it is required to minimize the integral time for each radio source, and it is common for the SNR to be set to approximately 30.

In geodetic VLBI, the high precision time delay obtained in this way is used to estimate the relative positions of observing stations, earth orientation parameters, etc. The time delay τ_g obtained from one radio source includes all kinds of delays: geometric delay determined from the positional relationship of the observing stations and radio source direction, the cable delay that occurs at each observing station, propagation delay resulting from atmosphere and ionosphere, and the delay amounts resulting from the uncertainty of the synchronization of the time systems at each observing station. Propagation delay caused by the ionosphere can be compensated for by using the fact that ionospheric delay has a dispersing characteristic dependent on frequency to calculate the compensation values from the difference in the observed results of two different frequencies. Although atmospheric delay does not have a dispersion characteristic depending on frequency, it is common to estimate delay amount by using the variance of the distance which radio waves travel through atmosphere and the change of delay amount depending on the angle of elevation. For simplicity, suppose a 2D model like that shown in Fig. 2. Here, ionospheric and atmospheric delays and the earth rotation are not considered, and the cable delay is set as a fixed value.

The parabolic antennas used in VLBI have a sharp directional characteristic, so when observation of one radio source is completed, the antenna direction is changed a large amount towards the direction of the next radio source to be observed. During this if the length of the baseline which connects the centers of the an-

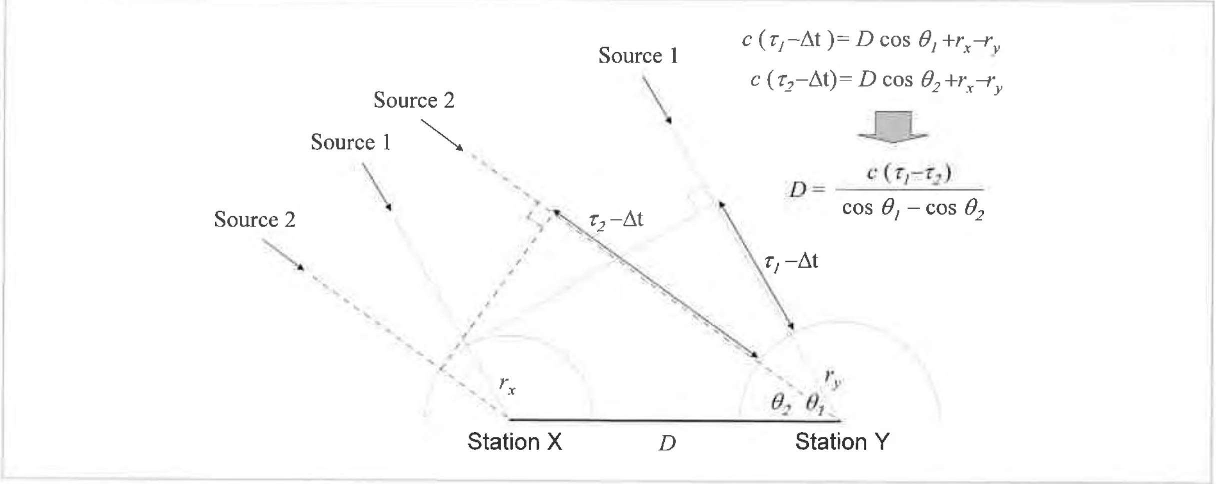

Fig.2 Model showing the relationships between datum points and time delay in geodetic VLBI

tennas during driving is expressed as D, the distance between the drive centers and receivers of each antenna as r_x and r_y, the angles which form the baseline and direction of the i-th radio source as θ_i, the estimated value of time delay found from observed results as τ_i, and the synchronization uncertainty of the X station and Y station as Δt, it can be seen that, as with the equation in the figure, D is derived solely from τ_i and is not dependent on r_x, r_y, or Δt. In actual data analysis, θ_i is uncertain and is not a known value, so a larger amount of observation data than the number of the estimated parameters is used, and the estimated value of the estimated parameter is found through least squares estimation. During this time as well, the datum point positions will be the intersection of the drive axes which is the fixed point during the driving of the antennas. Additionally, in reality, the radio waves from the radio source do not directly arrive at the receivers, but the system is actually structured such that the radio waves are reflected multiple times by a parabolic primary mirror, then a hyperboloid secondary mirror, etc. guiding them to the receiver. However, in any event, it can be reduced to a model where the area around rotational center point is transferred to the receiver on a spherical surface. At this time, it is also theoretically possible to measure r_x and r_y from the antenna drawings and specifications, however even if these are accurately measured, they are not related to the obtained positioning measurement results, so these remaining unknown is not problematic.

Meanwhile, we explained that in general the dependence on angle of elevation is used to estimate atmospheric delay. However, if there are anisotropic aspects which exist in the azimuth of the atmospheric delay or local structures, it will not be possible to carry out accurate compensation. In order to resolve this issue and carry out higher precision measurements, recent research is being carried out on using a detailed meteorological value model to accurately compensate for the time delay in the line of sight direction during measurements by the ray tracing method.

2.2 VLBI and frequency standard relationships

In VLBI observations, hydrogen masers are generally used as frequency standards. This is because, in order to maintain signal component coherence during the several seconds to several minutes required to maintain a sufficient SN ratio in the cross-correlation function given by Equation (1), short term frequency stability is required. The most important point is that the local frequency signal frequency f_0 used when converting the received f_0~f_0+B band signal to the 0~B baseband is stable. If the f_0 phase remains stable within the range $2\pi/8$ from beginning to end of the integration, the SN ratio can be improved by increasing the integral time which is to say, the coherence can be maintained. In order to fulfill these conditions for, for example, a 100 second integral time for the frequency of 8 GHz for X band used in the current general geodetic VLBI observations, a stability of 1.5×10^{-13} is required. For instance, with standard cesium atomic clocks it is difficult to achieve this degree of stability for a time scale of this level, however if hydrogen masers are used, it can be achieved. Meanwhile, for long terms, it is important to maintain Δt from Fig. 2 within the range of the uncertainty for estimating time delay. If, for example, 10 ps was set for these conditions, ideally it would be required to control time fluctuation so that it remained within 10 ps throughout the entire duration of an observation session which is typically 24 hours for usual geodetic VLBI experiments. The relative frequency stability at this time will be calculated as 1.1×10^{-16}. It is difficult to maintain stability throughout an entire day with hydrogen masers, so a method is used where the clock offset of other observing stations are normally estimated against that of the reference station every 1–3 hours, and then, data analysis is carried out on the assumption that it is converted to a linear form during that time. When estimating the clock offset every hour, the required frequency stability will be eased to 2.8×10^{-15}.

The above discussion is for geodetic VLBI experiments in the X band. However for astronomical VLBI observation, the major intention is to investigate structures of radio sources, and observations are carried out in a variety of frequencies. For example, at 210 GHz, which is the highest frequency at which observation has been carried out for VLBI, in order to maintain a phase fluctuation of $2\pi/8$ for an integral time of even just 1 second, a frequency stability of 6×10^{-13} is required, which is near the limit possible with hydrogen masers. At high frequencies such as this, the effect of delay variation due to atmospheric fluctuation is larger, and VLBI observation becomes fundamentally more difficult.

3 Construction of reference frames and earth orientation parameters

In addition to the continuous changes of the shape of the earth resulting from the tidal effects caused by the astronomical gravity of the sun and the moon, etc., the surface of the earth is covered in over a dozen hard solid structures called plates, and these plates each have their own speeds and move. As such, it is fundamentally difficult to accurately define the standard reference frame for determining the position of the earth. The earliest method for doing so was to define latitude with the latitude of the north pole and south pole both at 90 degrees, and to set the longitude of a meridian line passing through a specified point at 0 degree, and thereby to allow for the determination of the latitude and longitude of arbitrary points. However, it was already known in the 19th century that the north pole position moved due to a phenomenon called “wobble”, and it would be inconvenient if the latitude of a given place changed due to this wobble, so from 1900 to 1905 the Conventional International Origin was calculated and used based on the average position of the north pole. In addition, for a longitude standard, an international agreement was made at the International Meridian Conference held in Washington D.C. in the United States in 1884, that the meridian line which passes through the Greenwich Observatory in Great Britain would be the prime meridian with a longitude of 0 degree. These definitions made it possible to express any location in the world using longitude and latitude. In Japan, an imperial edict proclaiming the adoption of this prime meridian was issued in 1886, and thereafter in 1892 it was determined that the meridian circle at what was then the Tokyo observatory would be used as the origin point for domestic longitude and latitude. The device referred to as a meridian circle is a telescope which is designed so that it can only be moved accurately in north-south directions in order to allow for the accurate measurement of the time and altitude (the angle at which it becomes longitudinal) of a fixed star when it culminates. If the culmination time of a given fixed star is measured, the longitude of the observation point can be found from the difference with the time when the same astronomical body culminates at the Greenwich Observatory. Conversely, if the longitude of the observation point is already known, the time at that point can be found. Additionally, if a star catalogue with accurate right ascension and declination is available, measurement can be carried out independently at any observation point in the world in the same manner by observing the culmination of the fixed stars noted in the catalogue. A set of star catalogues prepared for these purposes is called the Catalogue of Fundamental Stars. In reality, first clocks at two distant locations are synchronized using international telegraphic communication, then by observing the culmination time of a fixed star noted in the star catalogue, the difference in longitude of the two points can be measured, so this method is used to measure longitude, then afterwards time is measured based on the value of that longitude. Latitude can be calculated from the declination of the fixed stars noted in the star catalogue and the culmination altitude of the fixed star. Incidentally, the imperial edict of 1886 mentioned above stipulated one standard time for Japan, and thereafter the Tokyo observatory was given the responsibility of determining the standard time using the meridian circle.

Through later accurate measurements, it became clear that a large degree of uncertainty accompanied the longitude and latitude determined in this manner. For example, the latitude and longitude of the Japan Geodetic Datum, which was revised in 2002, were found to have about 12 arcsecond difference between the revised values and the values up until that point for both longitude and latitude. This difference is equivalent to an approximately 450 m difference based on the same reference system. A number of factors can be thought to have brought about this degree of position uncertainty, however, for example, if the longitude uncertainty was instead a time synchronization uncertainty, this would have caused an uncertainty of approximately 0.8 seconds. An inconsistency of this small degree in a geodetic system would have once been difficult simply to detect, however, with the introduction of space geodetic techniques including VLBI, it has become possible to carry out highly precise position measurement globally which has in turn given birth to the need for a high precision reference frame. The first systematically constructed international terrestrial reference frame was the ITRF88 constructed in 1988[3]. When ITRF88 was announced, the ITRF, which was a terrestrial reference frame being announced by IERS, was regarded as an abbreviation for the IERS Terrestrial Reference Frame. The IERS is an international organization which is responsible for releasing earth orientation parameters using data of space geodetic techniques such as VLBI, and constructs and releases terrestrial and celestial reference frames as required for these purposes. At the general meeting of the International Astronomical Union (IAU) and International Union of Geodesy and Geophysics (IUGG) held in 1991, the terrestrial reference frame and celestial reference frame announced by the IERS were recommended and adopted as the official reference frames, and thereafter the ITRF abbreviation stood for International Terrestrial Reference Frame. Further, a celestial reference frame that stipulated the right ascension and declination of radio astronomical bodies was adopted in place of the star catalog based on fixed stars which was used as the Catalogue of Fundamental Stars up until then, and this can be said to be an acknowledgement that radio astronomical body measurement techniques using VLBI were much more highly precise than the methods using optical measurements such as meridian circles.

The terrestrial reference frame and celestial reference frame are both 3D Cartesian coordinate systems. As such, the conversion of coordinates between the two is defined in a 3 row by 3 column rotation matrix. The scale of the celestial reference frame is discretionary, so if it is considered that freedom of expansion and reduction is unnecessary, the number of independent parameters is 5. The selection of the 5 parameters allows for a degree of discretion, however a parameter of UT1-UTC, two parameters for wobbles and two parameters for precession and nutation are defined as the earth orientation parameters. UT1-UTC here indicates the difference between Coordinated Universal Time (UTC) and Universal Time (UT0) after compensation for wobble, and expresses the amount Coordinated Universal Time deviates from the earth's rotational phase. UTC is a time system which is determined based on the length of a second defined from the frequency of quantum transition of cesium atoms, and leap seconds are adjusted at the one-second time scale in order to always maintain the difference with UT1 at 0.9 seconds or less. Wobble expresses the movement of the point at which the earth's axis of rotation passes through the surface of the planet with the angle at which the north pole position deviates from the CIO point in the longitude 0 degree direction is expressed as ω_x, and the angle at which it deviates in the west longitude 90 degree direction as ω_y. Precession and nutation both indicate changes in the orientation of the globe on the rotational axis, the largest of these changes, which occurs in an approximately 25,800 year cycle, is called precession, and other smaller changes are called nutation. The amount of nutation is expressed as two amounts: one is the component of deviation in the vernal equinox ecliptic longitude direction from the model computation amount of the main component, and the other is the component of deviation in the obliquity of the ecliptic. For 3 out of the 5 parameters discussed here, UT1-UTC and the 2 parameters of nutation and precession, there are no other methods of direct measurement except for VLBI which are able to directly observe quasars which make up the celestial reference frame and measure the relationship of the terrestrial reference frame to the celestial reference frame. In both satellite laser ranging (SLR) where a laser shined onto a corner cube reflector mounted on an artificial satellite, and the round trip time is accurately measured, and global navigation satellite systems (GNSS), so long as observation is carried out by artificial satellite for both, length of day fluctuation (LOD) measurement is possible, however UT1-UTC cannot be directly measured. If the LOD fluctuation amount is integrated, the UT1-UTC fluctuation amount can be found, however because the satellite orbit rotates against the inertial frame space and cannot be distinguished from UT1-UTC fluctuations, a long term stable solution cannot be found. For precession/nutation, because measurement of the diurnal motion of the astronomical bodies is essentially necessary for observation of astronomical bodies, at present measurement is only carried out using VLBI observation data. Table 1 shows the suitability of the 3 main space geodetic techniques for the measurement of the 5 earth orientation parameters.

The major factors behind precession/nutation are the gravitational pull of the sun, the moon and the planets of the solar system, whereas wobble and UT1-UTC is thought to be caused by factors such as the interaction between the solid earth, atmosphere and the oceans, as well as the interaction between the fluid core and mantle. These processes cannot be completely modeled, so actual measurement is necessary to be carried out to clarify the relationship between the original celestial reference frame and terrestrial reference frame. Accurate earth orientation parameters are used for control of deep space probes and determination of precise orbits of artificial satellites in satellite positioning, and in addition, research into the internal physical structures and characteristics of the earth through analysis of earth orientation parameter fluctuations is developing, so the IERS comprehensively uses space geodetic techniques like those in Table 1 to determine

Table 1 Space geodetic techniques and earth orientation parameters relationships

	VLBI	SLR	GNSS
UT1-UTC	○	×	×
LOD	○	○	○
Wobble	○	○	○
Precession/Nutation	○	×	×

estimate amounts and releases them in the form of periodically issued bulletins and technical reports[4].

Incidentally, in Japanese reference frames and reference system are generally referred to with the same phrase, however in English system and frame are used separately. A system is something that stipulates definitions required for the construction of a reference frame, and the notation for celestial reference frames is International Celestial Reference System (ICRS) and for terrestrial reference frames International Terrestrial Reference System (ITRS). In contrast, in order to be in accordance with these definitions and be used in detail, the term frame is used for lists of coordinates for ground observation stations (XYZ components) and their variation (speed). Once a system is defined, continuity is prioritized, and only the minimum required revision is carried out, however a frame is updated more frequently as observation data accumulates and the frame becomes more precise. For example, ITRF was revised each year after 1988 with versions from ITRF89 to ITRF94, and thereafter revised as needed with ITRF96, ITRF97, ITRF2000, ITRF2005 and ITRF2008, and still continues to be revised today[5]. For ICRF, after it was announced by IERS in 1997, ICRF2 was announced in 2009[6].

In ITRF2008, the observation data of 4 types of space geodetic techniques, VLBI, SLR, GNSS, DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite), obtained up until 2008 is all used. In order to integrate data measured using different methods, ground surveying results are used from collocation sites where multiple facilities are established close together. As expected, ground surveying results also include a degree of uncertainty, so the scales between each of the space geodetic techniques are adjusted using least square estimation while weighting each in accordance with the uncertainty of the corresponding ground surveying methods. In ITRF2005, VLBI is used as a standard because it has excellent long term stability to adjust the scale of the 3 other space geodetic techniques, however in ITRF2008, the average of the VLBI and SLR scales is used as a standard. The origin point position is set as the earth's center of gravity, however because VLBI cannot estimate the earth's center of gravity, the origin point position is determined from SLR, GNSS and DORIS data. Thereafter, rotation was added to minimize the square sum of the difference with the NNR-Nuvel-1A model (No-net-rotation Nuvel-1A model) which is a plate movement model where the momentum sum of horizontal velocities of the all of the points of the earth is adjusted to be 0, and ITRF2008 was constructed. Within Japan there are 68 observation points published in ITRF2008, however among these, there are 2 VLBI observation points, 2 SLR observation points and 29 GNSS observation points where the XYZ coordinate standard uncertainty is the minimum of 1mm. Among these are the 4 NICT observation points of Kashima Space Research Center, VLBI observation point, Koganei SLR observation point and Kashima and Koganei GNSS observation points. These observation point positions were without a doubt determined to be high precision because of NICT's accumulation of high precision observation data over a long period of many years. In particular, it deserves special mention that there are only 4 collocation points in Japan which have been assigned high precision positions in 2 or more space geodetic techniques, of which 2 are NICT facilities. In fact, it can be said that because the Kashima Space Research Center VLBI observation point was determined to be high precision in the international terrestrial reference frame, the Kashima Space Research Center location was used as a reference point for recalculating geodetic datum in the revised survey act enforced in 2002[7], and has built an important position information foundation in Japan.

4 Future roles expected of VLBI in construction of space-time standards

At present, international atomic time (TAI) and the coordinated universal time (UTC) based on it are built on the cesium atomic clocks and hydrogen masers at time and frequency measurement standards institutes throughout the world. National Metrology Institutes in various countries are linked to the PTB in Germany by one of two methods, either with the two-way satellite time and frequency transfer method using communications satellites or a GPS observation method, and the comparison results carried out over these links are reported to the Bureau International des Poids et Mesures located in France to determine international atomic time. For example, the uncertainty of the time transfer between NICT and PTB, Germany's measurement standards organization, is evaluated as 300 ps for type A uncertainty and 5 ns for type B uncertainty. In order to improve the precision of international atomic time even more hereafter, it is necessary to reduce these 2 types of uncertainties. For example, if using GPS for time transfer with an uncertainty of 100 ps, it is necessary to determine the GPS antenna position with a precision of approximately 3 cm. If attempts are to be made to reduce the uncertainty of these time transfers in the future, the importance of the location of facilities for carrying out time transfer will become even more important. In addition, in recent years optical frequency standard research and development is being actively pursued. NICT is also carrying out research and development of 2 optical frequency standards: the calcium single ion trap method and the strontium atom optical lattice clock method. In these frequency standards frequency accuracy and frequency stability of 10^{-16} to 10^{-17} is aimed for, and actually the accuracy and stability of the order of 10^{-15} and 10^{-16} has been achieved respectively. If minute frequency differences such as 10^{-17} are to be discussed, it will be necessary to accurately assess an approximately 10 cm height difference from the general theory of relativity. The height mentioned here is the height which occurs in gravitational potential, and the height from the geoid surface is important. The height above the reference ellipsoid can be found through a simple calculation from the three components of XYZ in ITRF, and that precision will be exactly the precision reflected in ITRF. The uncertainty of the geoid height, or the height from the reference ellipsoid of the geoid which is the equipotential surface of the earth, is estimated to be a standard deviation of approximately 15 cm across the entire globe in even the latest data[8]. The long term earth gravitational field has been able to be determined with high precision through satellite missions which observe gravity from orbit, however it is necessary to measure the local geoid height components through leveling, and the fact that the uncertainty accumulation grows the further the deviation from the coastline is a factor in this large uncertainty. If optical frequency standards become able to measure a frequency difference of 10^{-18}, the geoid height measurement precision will increase from the measurement of the general relativistic theory, and space and time standards will play important mutual roles.

In the Consultative Committee for Time and Frequency established under the Comité International des Poids et Measures, the redefinition of the second in the near future is being considered, however in order to achieve this, it is necessary for multiple independent research facilities to compare and evaluate optical frequency standards and verify the accuracy of frequencies. For this, it will be necessary to accurately determine the height above the geoid surface of each optical frequency standard, and in addition for accurate comparison, accurate position information for the antenna, etc. used for comparison will be necessary. If thought of in this way, the accurate defined points for positions in the terrestrial reference frames discussed in Chapter **3** have an extreme high value. High precision space geodetic techniques such as VLBI have the potential to be able to measure position with high precision as well as to carry out time and frequency comparison between distant locations with high precision, and the construction of space-time standards which handle time and space in a unified manner by increasing the precision and advancement of these measurement techniques can be assumed to become more and more important in the future. Discussion on future planning is continuing under the name of VLBI2010 as a plan for the next generation of international geodetic VLBI observation under the IVS[9]. In VLBI2010, the band of the received signal is greatly expanded over former geodetic VLBI observation, with use of wide frequency band signals from 2 GHz to 18 GHz being considered. Moreover, whereas the determination of time delay up until now has used information called group delay, the active use of the phase delay which can determine more precise time delay is being considered. As a result the time delay determination precision target is being set at 4 ps. Up until now at NICT an approximately 1.5 m diameter, ultra compact VLBI measurement antenna has been developed for the development of a distance standard measurement system, and preparation is continuing for distance standard measurement performance using this and evaluation of performance in time transfer[10]. This type of compact observation system is advantageous for moving and carrying out observations, and there are great expectations for its application in high precision time transfer in the future through collaboration with research facilities overseas which are working on development of optical frequency standards.

5 Conclusion

In this paper a simple explanation of the basic principles of VLBI technology was provided in addition to an introduction of the construction of reference frames based on this and used in space up until now as well as their large role in the determination of earth orientation parameters. VLBI technology is a technology where essentially a high stability frequency standard called a hydrogen maser is used to carry out precision time measurements, and to measure positions in space based on this. So it can be said that it serves as a bridge between both time standards and space standards. At one time, the accurate measurement of longitude was tied to the accurate determination of time at point. Now that measurement technologies have progressed and precision has greatly increased, the relationship between time and space measurement is becoming still more inseparable. And, it is becoming more vital to handle time and space in a unified way in order to realize the new definition of a second through optical frequency standards. Considering that the realization of highly stable frequency standards made VLBI technologies possible, and in turn, the increase in precision of space standards leads to an increase in the precision of international atomic time, it is obvious that a large role is imposed on VLBI technology in space and time standards. If optical frequency standard technologies are established and information can be recorded for signals while they maintain coherence in the optical frequency domain, VLBI technology using light may also become possible in the near future. If this happens, new breakthroughs can be expected in both astronomy and geophysics.

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