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EARTH ROTATION MONITORING WITH K-3 TYPE VERY LONG BASELINE INTERFEROMETRY SYSTEM

—Study of Possible Systematic Errors Appearing in the Earth Rotation Monitoring with Single and Multi Baseline VLBI—

By
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ABSTRACT

A Very Long Baseline Interferometry (VLBI) software system, which utilizes a data base accessible from an entire software system, was developed at the Communications Research Laboratory (CRL) for global geodesy and the Earth rotation monitoring. Using this system, we carried out the Earth rotation VLBI experiment with S and X frequency bands. The experiments comprised a single-baseline VLBI experiment (German-Japanese Earth Rotation Observations; GJRO campaign) and a multi-baseline VLBI experiment (International Radio Interferometric Surveying; IRIS-Pacific VLBI network). Through the experiments, we found systematic offsets between the Earth Rotation Parameter (ERP) determined by our measurements and ERP from other VLBI networks with both single-baseline and multi-baseline configurations. In the single-baseline experiment (GJRO campaign), UT1 is determined with 0.1 msec precision, and systematic offsets with other UT1 results are removed by adopting the published IRIS pole positions as *a priori* values. Thereby the accuracy of the UT1 determination with the single-baseline VLBI was within 0.2 msec. In the multi-baseline experiment (IRIS-P), obtained ERP becomes as accurate as other regular VLBI results by unifying all IRIS-P station positions with the IRIS coordinate system. The determined ERP by IRIS-P coincides with ones by other networks within 1 milli arc second on average. According to UT1 data analysis in the GJRO campaign, it is concluded that the theoretical amplitude of the 13.66 day tidal term increases by 5 to 10%. It is shown that an accurate ERP determination with an independent VLBI network becomes possible only by a consistent set of reference frames. Precise time comparison data between Kashima (CRL/Japan) and Richmond (USNO/USA) with 1 nsec accuracy is also obtained through an IRIS-P experiment as another observable. The influence of atmospheric excess path delay and the foundation of the VLBI antenna for global geodesy and the Earth rotation monitoring, are also discussed.

1. Introduction

Until a decade ago astrometry was based mainly on optical observations, in which the accuracy was limited by the angular uncertainty determined by atmospheric scintillation. Recently Very Long Baseline Interferometry (VLBI) using radio telescopes with baseline length of thousands of kilometers has overcome the problem. The available angular precision by VLBI is

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now better than 1 milli arc seconds, which is one hundred times better than that of optical telescopes. VLBI is one of the modern space techniques to determine UT1, pole position, precision and nutation (the Earth Rotation Parameters: ERP) more precisely than the conventional optical method. VLBI is now one of the best tools to make more precise astrometry and Earth rotation monitoring and making revolution in astrometry. It provides us not only with a lot of new knowledge with respect to radio astrometry and Earth physics, but is also a tool for the navigation of space vehicles in deep space.

This thesis mainly addresses the following two topics: 1) VLBI software system development for global geodesy and the Earth rotation monitoring and 2) precise Earth rotation monitoring in a consistent reference frame.

A VLBI system in each station consists of a large aperture radio telescope, low noise receiver, data acquisition terminal including data recorder for mass data storage, stable atomic clock and automatic controlling system. At least one data processor is required for data reduction. In addition, large software system for scheduling, data processing, data analysis and data management is required. To start global VLBI observations for geodesy and earth rotation monitoring, all of these hardware and software systems were developed at Kashima by measuring compatibility with the Mark III system developed by NASA in the United States. The developed system was named K-3. The structure of the K-3 software system is designed using the IMAGE-1000 commercial data base system, which is accessible from all K-3 software systems except for the automatic operation system. Since the structure of data base affects utilization of whole K-3 software system, the design was made carefully. Thereby each VLBI data is available efficiently from the K-3 data base. This ensures consistent data even in a large software system.

The IRIS (International Radio Interferometric Surveying) program for monitoring the Earth rotation by VLBI succeeds as one of the International Earth Rotation Service (IERS) programs started in January, 1988. The VLBI networks called IRIS-P (Pacific) and IRIS-S (Southern hemisphere)[1] began observations independently of the US-Europe IRIS-Atlantic (IRIS-A) network in the IERS program. The IRIS-P network is made to study independent and precise ERP monitoring with four stations for future IERS activity. Independent VLBI networks are required not only for the support of other networks, but also for increasing the reliability of ERP results. In particular, independent VLBI experiments require a unique reference frame which is necessary to have international service. A VLBI experiment is carried out every month by the IRIS-P network, every winter by the IRIS-S network, and in particular, every five days by the Atlantic network for regular ERP publication. Moreover, VLBI is useful for global geodesy. Hence, the CDP (Crustal Dynamics Project) program has also been carried out by NASA, in association with other international research teams, including Kashima, to study plate motion and crustal deformation[2]. Other regional campaigns for geodesy, are also carried out[3].

To exploit the VLBI in UT1 monitoring, a campaign called GJRO (German-Japanese Earth Rotation Observations) was carried out in 1985 with a single baseline between Japan and Germany. Observing frequencies were S and X bands. In GJRO a systematic offset in UT1 was found when it was compared with the published UT1 series by IRIS-A. Also in IRIS-P, a systematic offset was found on each ERP compared with the published ERP by IRIS-A. By monitoring the Earth rotation indenpendently, with other VLBI networks, it is possible to get reliable ERP results. Although ERP offsets among networks are often removed to study the variation of them only by practical reasons without deep understanding, they must be often a good indication of an inconsistent analysis of reference frame. In this paper, we studied how the systematic offsets appears in both single- and multi-baseline VLBI networks. The major source for an offset is often the inconsistency of adopted reference frames in tn analysis. After removing the UT1 offsets from GJRO data, fortnightly period UT1 variation due to a tide is also examined in a consistent data set and reference frame.

The purpose of the IERS is not only to monitor the Earth rotation, but also to establish and maintain the celestial and terrestrial reference frames. The construction of CIS (Conventional Inertial System) as a reliable celestial coordinate system shows a reference for CTS (Conventional Terrestrial reference System) through ERP monitoring by VLBI in IERS programs, where the two coordinate systems are connected to other. And the UT1 time scale is connected to the time system maintained by atomic clocks. Through upgrading the reference frame and extending the network on a global scale, it is expected to bring new knowledge in radio astrometry as well as geodesy.

In section 2, I describe fundamentals of Earth rotation observation by VLBI. In section 3, K-3 VLBI software system developed for global geodesy and the Earth rotation monitoring is described focusing on the data base system. I studied the Earth rotation determination and the reference frame in section 4 using a series of single baseline observation and multi baselines observations by VLBI. Time synchronization error is described there as a by-product of VLBI in a consistent reference frame. And geophysical condition of VLBI station is also described for a reliable monitoring in geodesy and Earth rotation. In appendices, fundamentals of tidal potential, expressions of rotational matrices and details of K-3 data base are described.

2. Fundamentals of Earth Rotation Observation by VLBI

In addition to precession and nutation, the movement of the geographic poles over the surface of the Earth called polar motion, and Universal Time (UT1) are fundamental in astrometry because they change the apparent direction of the sources from the observer on the Earth. The pole positions are expressed with respect to CIO (Conventional International Origin) as in Fig. 1[(4)]. Spin of the Earth is expressed either with the time difference between UT1 and the Coordinated Universal Time as (UT1-UTC) or with length of day. Since polar motion is influenced by the change of atmospheric angular momentum and the physical characteristics of the Earth's inner structure, in particular by the liquid core of which little is known, precise prediction of the pole position is still difficult. Conversely, the inner structure of the Earth may be understood through polar motion.

Earth rotation monitoring is also useful to connect the celestial reference frame with the terrestrial reference frame. Moreover, connection of UT1 and UTC is also required. Hence ERP are fundamental to pinpoint celestial objects precisely. Thus, ERP are used for precise tracking of satellites for gravitational field studies, laser ranging for studying lunar motion and precise maneuvering in deep space[(5)] (Fig. 2). Reliable ERP is available not only with the development of observing system, but also with stations which has a stable foundation in land and whose positions are regularly monitored relatively with other stations.

2.1 Fluctuations of the Spin of the Earth and Pole Wandering

The Earth seemingly rotates smoothly. However, the spin rate is always changing irregularly due to the deformation of the Earth, winds, ocean currents, and the inner structure of the Earth (Fig. 3), as well as the external tidal forces of the Sun and Moon. The relationship between the main forces affecting the Earth rotation is shown in Fig. 4[(6)]. Additionally the instantaneous pole

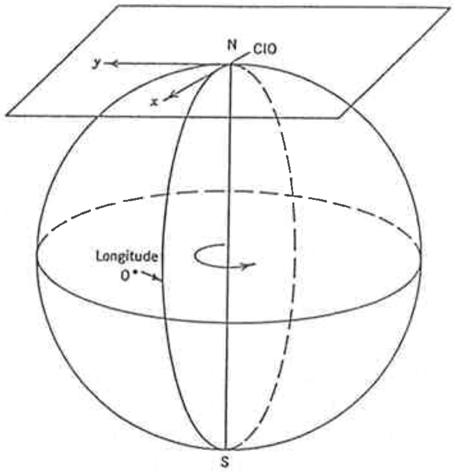


Fig. 1 Coordinate system for the measurement of polar motion. The x axis is in the Greenwich meridian and the y axis is 90 degrees to the west. CIO is the Conventional International Origin[4].

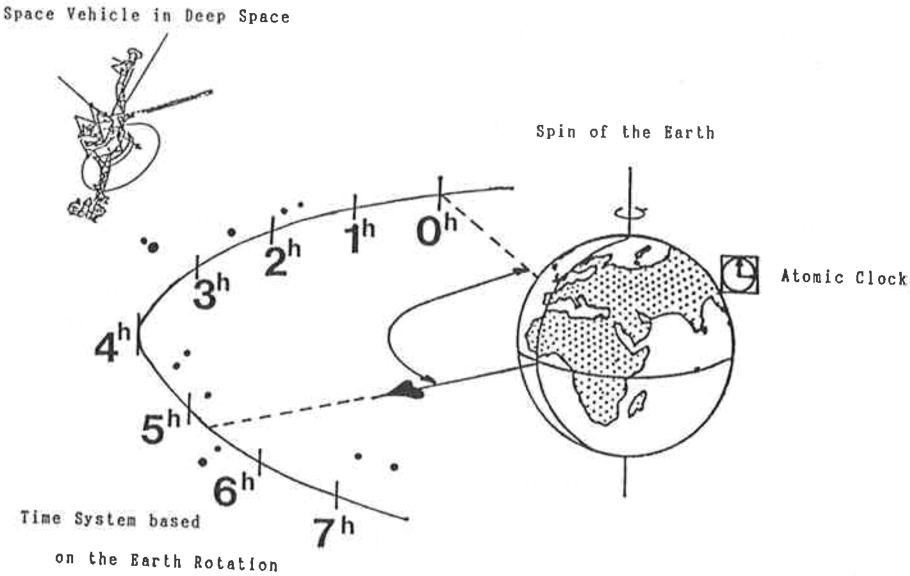


Fig. 2 Earth rotation and maneuvering of space vehicles in Deep Space.

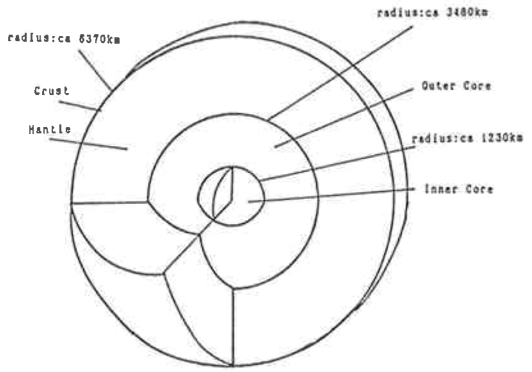


Fig. 3 Inner structure of the Earth.

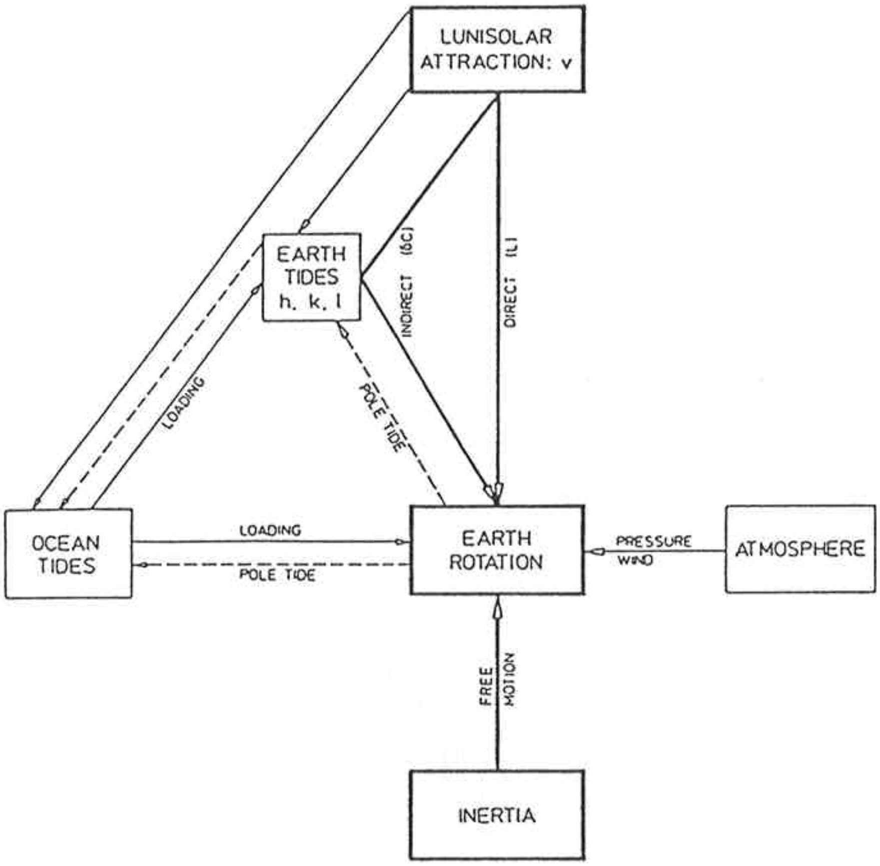


Fig. 4 Main forces affecting Earth rotation[8].

of rotation is also moving irregularly with respect to the solid Earth. This is called polar motion. An example of polar motion and UT1 are shown in Fig. 5(a) and (b).

A dominant effect in the Earth rotation fluctuation is a secular change in Length of Day (l.o.d.). It is mainly caused by tidal friction in the oceans. L.o.d. is often used to show fluctuation of the spin of the Earth as well as UT1. A change in UT1 and a change in l.o.d. are related by

$$\mathrm{d(UT1)} = \int \frac{\delta\omega}{\Omega}\,\mathrm{dt}$$

$$= -\int \frac{\delta\Lambda}{\Lambda_0}\,\mathrm{dt}, \quad \cdots\cdots \quad (1)$$

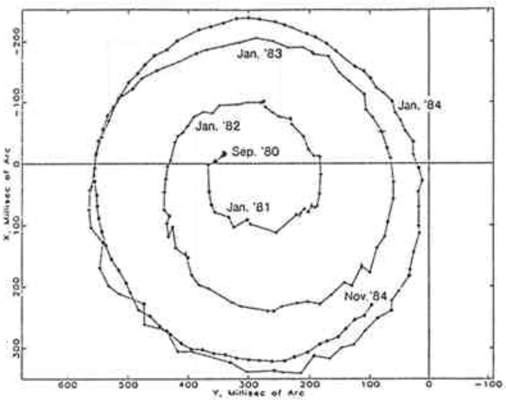


Fig. 5 (a) Locus of polar motion[58].

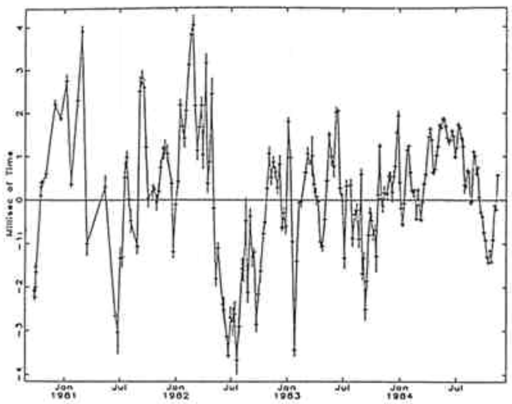


Fig. 5 (b) Determined UT1 shown as differences from the corresponding BIH CD values[58].

where ω is instantaneous angular velocity of the Earth, and Ω is a mean value of angular velocity of the Earth ($2\pi/86400$). And l.o.d. (Λ and Λ_0) are expressed as

$$\Lambda = \frac{2\pi}{\omega} \quad \cdots\cdots (2)$$

and

$$\Lambda_0 = \frac{2\pi}{\Omega} \quad \cdots\cdots (3)$$

The variation of the observed Earth rotation is seen in a frequency domain in Fig. 6 (a) and (b). Angular momentum L is a product of moment of inertia C about the spin axis and angular velocity ω: Eq. (4). According to the law of angular momentum conservation, L is constant if we do not take account of the slow and small change of L due to the tidal force. Thus the relation between small variation in ω and C is expressed in Eq. (5).

$$C\omega = L \quad \cdots\cdots (4)$$

$$\frac{\Delta\omega}{\omega} = -\frac{\Delta C}{C} \quad \cdots\cdots (5)$$

Earth tides are also major factors inducing periodic Earth rotation fluctuations, because they change the moment of inertia about the Earth spin axis. Since Earth tides are induced by the luni-solar attraction, there are many frequency components corresponding to the motion of the Sun and Moon. The period and amplitude of each tide are complied by the calculation based on theoretical Earth model and the observation by modern techniques. They were listed by Yoder(7). And in particular, short term tides are studied by Schuh(8) using VLBI data.

If the mass M is located at a distance r from the mass center of the Earth (Fig.7), tidal gravitational potential U is expressed as(9) (See Appendix 1),

$$U = \frac{3}{4} GM \frac{a^2}{r^3} \{\cos^2\phi\cos^2\delta\cos 2H + \sin 2\phi \sin 2\delta \cos H$$
$$+ 3(\sin^2\phi - 1/3)(\sin^2\delta - 1/3)\}, \quad \cdots\cdots (6)$$

where G is the gravitational constant, a is the Earth radius, ϕ is the latitude in a geocentric coordinate, δ is the declination of a perturbing body M and H is the local hour angle. The three terms in Eq.(6) represent functions of spherical harmonics. The first term is sectorial function (Fig.8(a)). The second term is tesseral function (Fig.8(b)). The third term is zonal function (Fig.8(c)). Since only zonal tide about the spin axis has symmetrical influence as a function of the latitude, it changes the moment of inertia of the Earth. Hence zonal Earth tide causes UT1 variation. The fundamental period of zonal tide is fourteen days in the case of the Moon and six months in the case of the Sun because of the squared sinusoidal function of the declination.

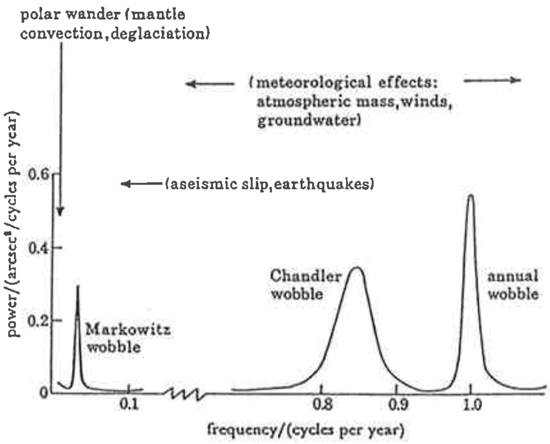


Fig. 6 (a) Schematic spectrum of the Earth's polar motion and possible excitation mechanisms[59].

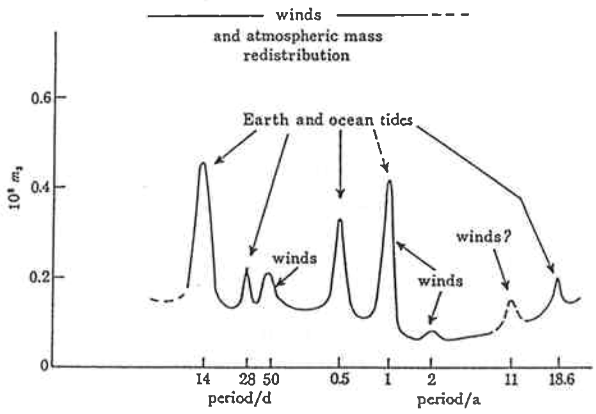


Fig. 6 (b) Schematic spectrum of the Earth's changes in length of day and possible excitation mechanisms[59].

The periods of dominant tides longer than five days are six months, 27 days and 14 days. These tides are named SSa, Mm and Mf. Each of them is the abbreviation of Sun Semi-annual, Moon monthly, and Moon fortnightly. The UT1 variations due to the latter two tides are important factors to determine the Love number precisely. The two short-period variations (Mm and Mf) are caused by zonal tides on the rotation of the Earth. Through the precise VLBI observation of Mm and Mf tidal term, the frequency dependence of Q (Quality factor) is also obtainable. The SSa tide is related to semi-annual atmospheric excitation, and other theoretically-known small oscillations are below the observational errors.

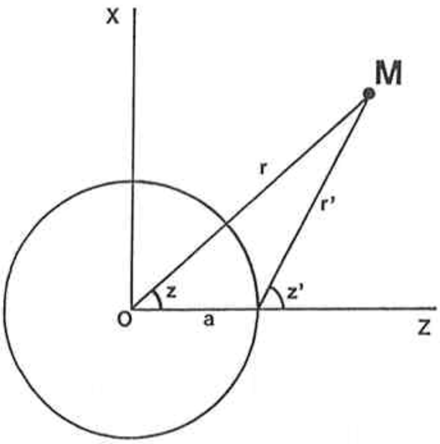


Fig. 7 Geometry of tidal analysis.

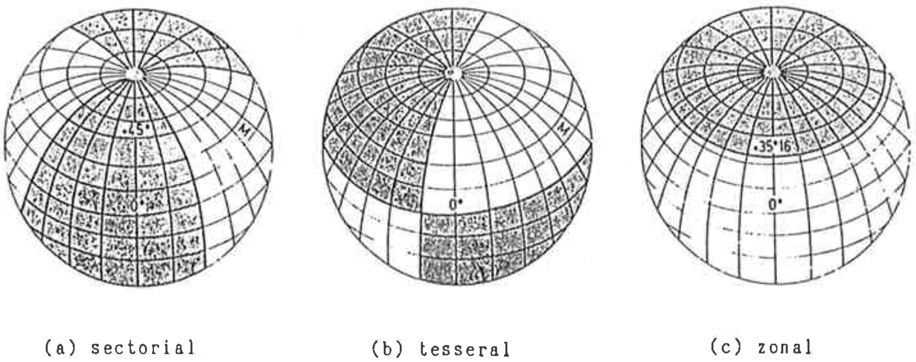


Fig. 8 The three kinds of tides[9].

Atmospheric angular momentum changes also induce fluctuations of the Earth rotation velocity, because the atmospheric angular momentum is coupled to the angular momentum of the Earth[10].

Pole position wandering has two major frequency components, which are of 12 and 14 month periods. The former period is induced by the annual redistribution of the angular momentum of water and atmosphere on the Earth. The latter, which is called the Chandler wobble, is a free oscillation. Their behaviors are determined not only by the density and elasticity of the Earth but also through the characteristics of the ocean and atmosphere. However, the driving force of the Chandler wobble is still a question.

2.2 Earth Rotation Measurements by VLBI

The principles of VLBI and its application to the Earth rotation measurement are outlined here. In the beginning, the geometry of VLBI is shown in Fig.9. A radio signal transmitted from an extragalactic source, such as a quasar, is received with the same time schedule at more than two

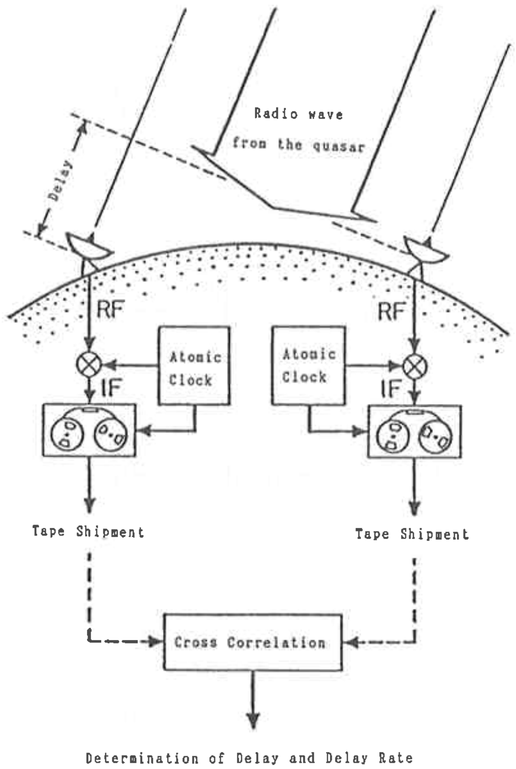


Fig. 9 Concept of VLBI.

stations, normally using large aperture antennas. Radio frequency (RF) signals are converted to video band signals. Then the signal is one-bit sampled with the Nyquist frequency, and recorded onto magnetic tapes at a high recording speed. The recorded tapes are transported to a data processing station for cross correlation. Then a data base is produced with the processed data, logged data, and calculated delay / delay rate and its partial derivative from physical models. Finally, ERP are obtained by analyzing these data.

The entire K-3 VLBI hardware system is described by Kawaguchi et al.[11] The remarkable progress in the VLBI technique, compared to that of a conventional radio interferometer, is primarily due to the development of an extremely stable local oscillator (Hydrogen maser) and tape recording system of massive data. The concept of the K-3 system is the same as that of the Mark III system, so that the functions may be compatible with each other. A specific feature of the K-3 system is a unified hardware control using an IEEE-488 bus. Since no other device control software is adopted in the K-3 system, the automatic control software for the VLBI system is relatively easier than that of the Mark III.

An interferometric delay time τ provides information about a baseline vector (B), a source vector (s) and Earth rotation as[12]

$$\tau = [P][N][S][W]\mathbf{B} \cdot \mathbf{s}/c, \quad (7)$$

where P is the precession, N is the nutation, S is the spin of the Earth and W is the wobble (polar motion). P, N, S and W are expressed in rotational matrix forms (Appendix 2) as:

$$[P] = R_z(z)R_y(-\theta_0)R_z(\zeta_0), \quad \cdots\cdots (8)$$

$$[N] = \begin{bmatrix} 1 & -\delta\psi\cos\varepsilon & -\delta\psi\sin\varepsilon \\ \delta\psi\cos\varepsilon & 1 & -\delta\varepsilon \\ \delta\psi\sin\varepsilon & \delta\varepsilon & 1 \end{bmatrix}, \quad \cdots\cdots (9)$$

$$[S] = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad \cdots\cdots (10)$$

and

$$[W] = \begin{bmatrix} 1 & 0 & -W_x \\ 0 & 1 & W_y \\ W_x & -W_y & 1 \end{bmatrix}, \quad \cdots\cdots (11)$$

where $\delta\varepsilon$ is a nutation in obliquity, $\delta\psi$ is a nutation in longitude, θ is GAST (Greenwich Apparent Sidereal Time), W_x is x-pole position and W_y is y-pole position. Here the notations of z, ζ_0 and θ_0 follow Lieske(13). Using the physical models of precession, nutation, spin of the Earth and wobble, partial derivatives and *a priori* values to the delay and delay rate are calculated. Then ERP are finally determined from the difference between observed and calculated values using the least squares method.

According to Eq.(7), a baseline vector change has an influence on ERP estimation. Actually, plate motion and crustal deformation cause the baseline vector change. Hence, the change of the baseline vector should also be monitored by multi-baseline VLBI to identify the deformations. Using an iterative method or a global solution for a series of experiments, it is possible to estimate both ERP and station coordinates.

2.3 VLBI Reference Coordinate System

A reliable reference system is fundamental for astrometry and geodesy. The reference frame should be defined in an inertial system. According to Mach's principle, an inertial frame is fixed with respect to the rest of the material in the universe, and the origin of the coordinate is not accelerated with respect to the rest of the universe(14). Since a radio reference coordinate system using extragalactic sources is regarded as a good approximation of an inertial reference frame, each position of extragalactic radio sources in the celestial sphere can be used as the reference points in an extremely stable coordinate system for astrometric observations. Thus extragalactic radio sources are used in VLBI observations for astrometry and geodesy instead of galactic objects. Thereby influences of solar motion and galactic rotation are avoidable.

Geodetic measurements by VLBI should be made in an inertial reference frame observing celestial radio sources, while observations are made from the surface of deformable Earth. Hence, it is necessary to establish an Earth fixed reference frame using VLBI stations as reference points which is an averaged position in the terrestrial frame with deformation due to periodic tidal changes and other effects. For precise calculation of VLBI observables, a barycentric origin is used as the original point of the terrestrial coordinate, rather than a heliocentric origin.

In a geodetic VLBI, delay and delay rates are determined by the geometrical configurations of the baseline vector between stations on the Earth and the source vector to extragalactic radio sources. Since any errors in the celestial radio reference frame lead to errors in the terrestrial reference frame and vice versa, it is important to be careful about the adopted reference frames when VLBI networks extend to the other stations whose positions are determined by independent programs.

To define right ascension and declination in a celestial sphere, a real reference source or a source position catalog is needed. A strong quasar such as 3C273B has been regarded in the past as a reference source in a celestial sphere[15]. Since it is not a point source, but has a structure, the radio source, 0229⅞131, is proposed as a new reference point instead of 3C273B[16]. As another approach, Ma defined the right ascension zero point in his catalog by minimizing the difference of the right ascensions of the 28 extragalactic sources between radio and FK5 optical source positions[17]. To define the terrestrial coordinate, the geodetic position of Haystack Observatory (US) was determined using VLBI and other space techniques so that the original point of the VLBI station coordinate may coincide with the geocentric origin. Now, the geodetic reference point was moved to Westford (US). In spite of these definitions, there is still a difference between the VLBI coordinate systems such as in CDP and in IRIS.

The original point of the VLBI terrestrial frame is, in principle, arbitrary according to Eq.(7), because a baseline vector is a relative position between two stations . Hence the two terrestrial coordinates in Fig.10, (U_0, V_0, W_0) and (U,V,W) are equivalent to each other for VLBI. Thereby

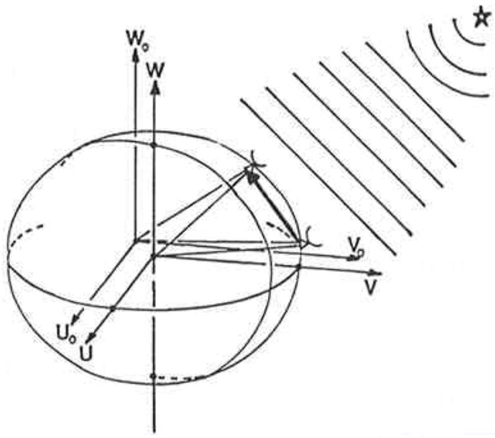


Fig. 10 Two equivalent terrestrial coordinate system in VLBI.

large systematic offsets in station coordinates may be induced between the station catalogs of different programs. Furthermore, the source positions could be systematically different if the adopted models of precession and nutation are different in each analysis system. In fact, source and station catalogs have been developed independently by some VLBI groups. Though they are selfconsistent in each system, it is very important to take both source and station coordinates from only one catalog for consistent data analysis.

3. K-3 VLBI Software System Development for Global Geodesy and the Earth Rotation Monitoring

A large K-3 VLBI system for global geodesy and ERP determination, was developed to carry out international VLBI experiments. The implemented system consists of K-3 hardware and software[(18)]. The details of the K-3 hardware system were described in the special issue of 'Review of the Radio Research Laboratories (1984)'. K-3 VLBI software was developed on a newly designed K-3 data base management system[(19)], having consistency with the entire K-3 hardware system in addition to having compatibility with the Mark III system[(20)]. The outline and functions of the K-3 software system are described here.

There are four specific features in the K-3 software system. First, fundamental data in a data base can be accessed from all the subsystems, which ensures data integrity. Thus, no inconsistent data set is made. Secondly, the software is interactive, while the interactive command sequence can be also executed with automatic batch operation in every K-3 software system. Thirdly, all the physical models and fundamental catalogs are based on the J2000.0 system. Furthermore, the compatibility of data format with Mark III is taken into account regarding the schedule file and the data base tapes as well as raw-data tapes.

Many kinds of data items are produced by VLBI experiments. Even after data reduction the number of data items is still large. Stored data in the disk increases rapidly with the frequency of the experiments and the number of baselines. Furthermore, physical and mathematical constants to be used in the VLBI software are also stored in the data base. Hence a data management capability is required for the total VLBI software system. By making use of the IMAGE/1000 data base (Appendix 3) in the HP-1000 computer, K-3 software was developed to have data integrity and quick data access using a hashing algorithm (Appendix 4).

A data base system introduced to the Mark III software in the United States is the first attempt for VLBI use. It is, however, used only in the data analysis, while VLBI data is commonly used from scheduling to data analysis. Therefore, a data base management system was introduced to the entire K-3 VLBI system for consistent data use. The K-3 software system was developed following the data base system design[(19)] by a special development group. The data base management system is as important to the K-3 software subsystems as the IEEE-488 bus control is to the K-3 hardware devices.

3.1 Software-system Structure

Since the VLBI technique is applied to global geodesy and astronomy, the data value lasts a long time, and it should be accessible to any researcher. Hence the data base management system is one of the best ways to handle a considerable number of VLBI data. The K-3 VLBI software system is designed as illustrated in Fig.11. This system was developed by a special team in Kashima led by Yoshino. First the data base handler system (KASTL) is described. Then, an

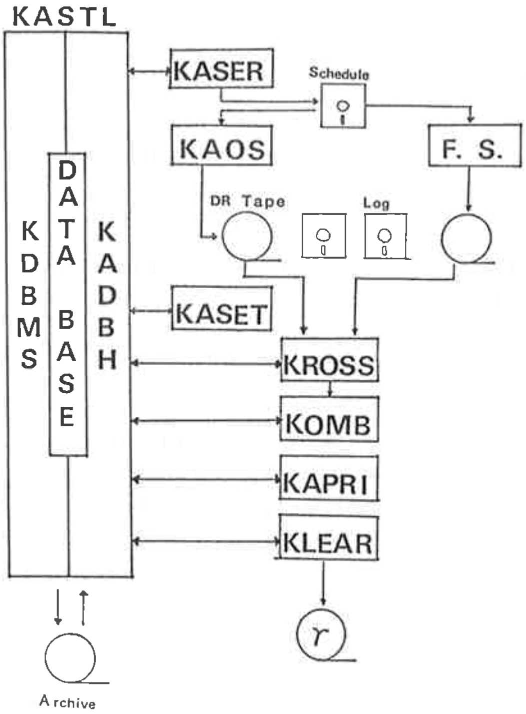


Fig. 11 K-3 VLBI software system.

outline of the scheduling software (KASER), the automatic operation software (KAOS) and the data reduction software (KROSS, KOMB) are described. Then *a priori* value calculation software (KAPRI), and parameter estimation software (KLEAR), are also described.

Before starting a VLBI experiment, a schedule is created interactively using KASER, which has K-3 data base access utility, and also an automatic-scheduling utility. Then a VLBI experiment is carried out automatically by KAOS following the schedule file. Only KAOS software does not have data base access capability because the data and parameters for hardware control are taken from the schedule file. After the experiment, the data area, in which the experiment data is to be written, is created in the data base according to the schedule file and logs of each station through KASET software. KASET also sets the Earth rotation parameters around the experiment date as *a priori* value. Then KROSS produces the correlation data file by controlling the data recorder and correlator. KROSS accesses the data base to make a control file and to set the correlation results into the data base. A precise fringe search with two dimensional FFT computations is made by KOMB to have the final delay and delay rate. Final results are stored in a data base. The delay and delay rate for observations are fixed here. KAPRI calculates the delay and delay rate contributions of the physical effects and their partial derivatives according to the models as *a priori* values for data analysis. They are to be put into the data base. Finally, KLEAR gets the KOMB output (O:observed data) and KAPRI output (C: *a priori* data). Then the parameters are adjusted using a delay and delay rate difference (O-C). Since the Mark III data base format is most popular as the VLBI data format, a data base conversion utility between K-3 and Mark III is developed. Thereby it is also possible to use Mark III analysis software.

3.2 Data Base Management System

An easy data access tool was developed at NASA as one of the Mark III VLBI systems[12] because VLBI data is large and frequently accessed. Thus the update of VLBI software became independent of the data base.

The design of the data base structure and the data handler is most important to introduce the data base management system. There is no fixed way to design the best data base schema, however.

The data base is one of the projections of the real world. A logical data structure can be seen by grouping the several hundred VLBI terms. Thus, the data item is classified into some groups, where the physical meaning and the occurrence are marked. A group of data ensembles is combined along the flow of data reduction and analysis. There are two types of data in a VLBI data base. One is the data such as observables and constants which do not change. The other is the data which are used only as an index. Both are important for reduction and analysis of the VLBI. Then, each data group is linked from the physical meaning as shown in Fig. 12[19]. When designing the data structure, not only the physical meaning but the data producing factor has to be taken into account, because it determines the required size of the data set size and its disk area. The data producing factor of each data set is listed in Table 1. The difference of the K-3 and Mark III data

Table 1 Main factors of data producing

(Producing Factor)	(Example)
Experiment	Experiment code, Number of Observation
Observation	Delay, Observation Start Time
Station	Name of Station, Station Position
Baseline	Delay, Ionospheric Delay Correction
Constants	Astronomical and Mathematical Constants
Estimation	Date of Estimation, Baseline Length
Frequency	Receiving Band, Receiving Band Width
Day	UT1, Pole Position
Raw Tape	Tape Number, Name of Station
KROSS Run	Number of Processing, Output file name
KOMB Run	Delay, Fringe Amplitude

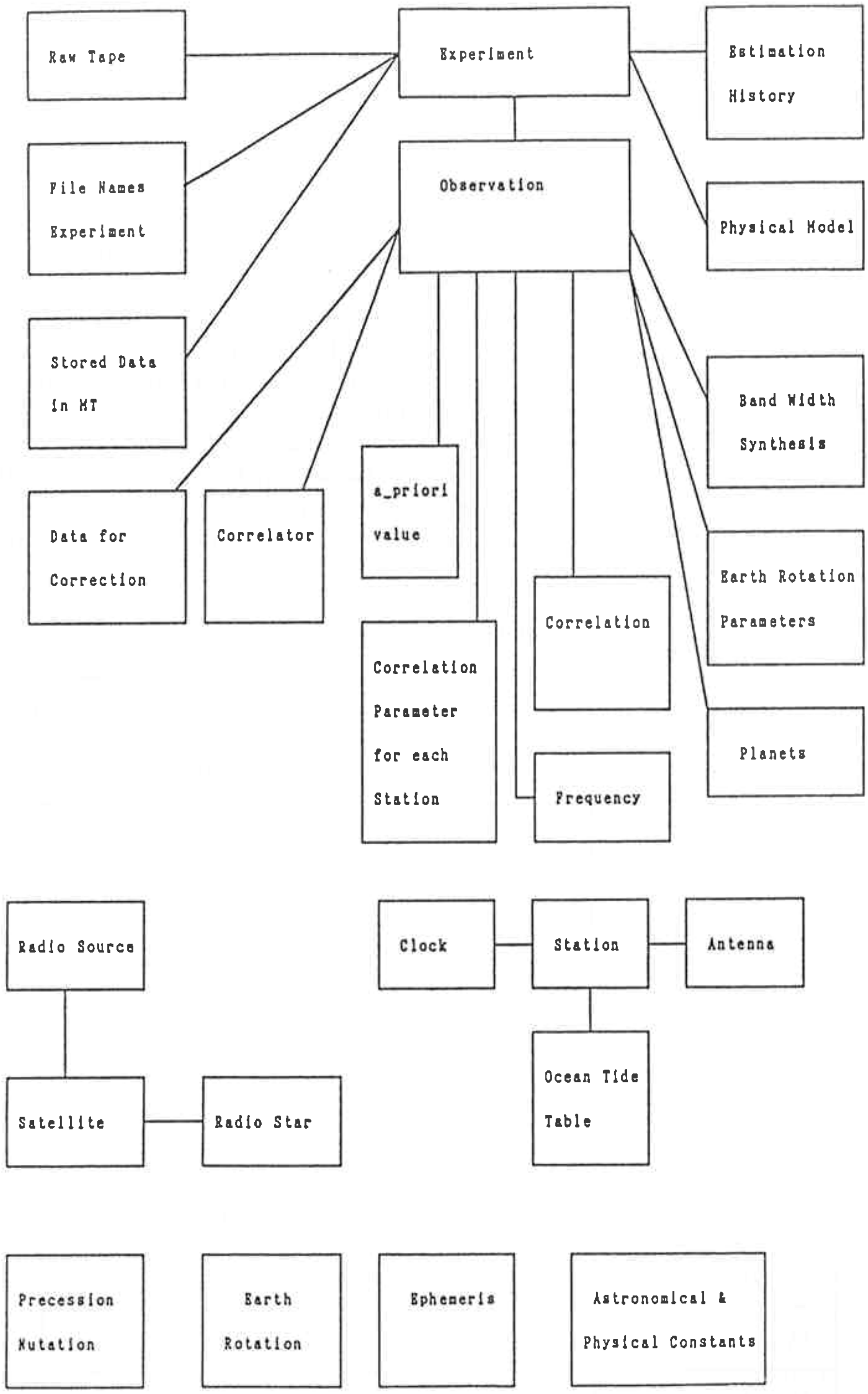


Fig. 12 Linkage of data group in K-3 data base.

base is as follows: constants and observed data are unique in the K-3 data base, while even the constants can be changed at a different version of the same data base in the case of Mark III.

The design of the data base is expressed with the so called schema language of IMAGE/1000. Two ways to realize the data base handler were used. One was a standard IMAGE/1000 utility subroutine-call and the other was a KASTL-call (Appendix 5). A KASTL-call consists of several IMAGE/1000 calls so that the programmer may avoid repeating similar subroutine calls. The KASTL program is independent of the application program. Another advantage of the KASTL-call is easy maintenance of application programs. Without KASTL, if the application programs have bugs on the accessing data base, the programs have to be fixed one by one. On the other hand, using KASTL, bugs in the data accessing program can be localized to a small number of programs. Hence, it is much easier to fix them than to fix each program. KASTL calls are, however, slower than direct IMAGE/1000 use, because KASTL schedules other programs for each call.

3.3 Observation Scheduling System

Since VLBI experiments are simultaneous radio observations done on usually one day or more with several stations in the world, an observation schedule should be prepared and delivered to each station manager for the automatic operation. The K-3 scheduling software KASER was developed[21], which is connected to the data base to get the site, source and frequency information. The basic concept of KASER is similar to SKED, a Mark III scheduling software[22]. KASER is named after the typical VLBI source Quasar. KASER adopts the J2000.0 system.

The VLBI schedule file consists of sites, sources, the RF frequency data set and observation time sequence. A scheduler makes a schedule as optimal as possible taking into account many constraints, such as minimum detectable flux density, mutual visibility, antenna slew rate, antenna cable wrap etc. Therefore it is hard to compile a VLBI schedule without computer assistance. The KASER software aids VLBI scheduling by showing the situation of visible sources and judging the input as valid or not. Furthermore, KASER provides an automatic scheduling utility. Though each observation is usually made one by one using the interactive method, if a certain idea of the observation sequence is there, it is only necessary to give a command file to KASER. Thereby a schedule can be obtained automatically. Subsequent schedules can be compiled by modifying the previous trial. This utility is helpful because we often improve schedule with cut and try. KASER makes an original schedule file and converts the file into the so called SNAP command which is accepted as an input file of the KAOS software. The schedule file format is independent of the purpose of the experiments.

Usually observing one source at one time is called one observation. An ensemble of observations is called one experiment. A schedule for geodesy should be made so that a change of the baseline vector on the projected plane perpendicular to the source vector, (u,v) plane, is large enough to be sensible between observations. In the case of Earth rotation monitoring, a change of the hour angle and declination is important for UT1 and pole position.

3.4 Automatic Operation System

The Automatic Operation System is necessary to perform a number of operations in VLBI experiments on time with computer assistance. An HP-1000 computer is used to control the VLBI hardware system during the experiment following the SNAP command sequences. KAOS also monitors the status of each hardware device and logs the experiment. If the status is not normal, KAOS notifies the operator with a beep and messages. KAOS software is made being compatible with the Mark III system software, called the Field System, in essential points because it should accept the same SNAP command file delivered from NASA or other VLBI groups. There are, however, some differences between KAOS and the Field System. KAOS consists of only IEEE-488 bus hardware control routines[23] while the Field System consists of both RS232C and IEEE-488 bus routines. KAOS does not make use of the VLBI data base because a VLBI station does not always have a data base system.

3.5 Data Reduction System

Recorded data on magnetic tapes is cross correlated at a data processing center. The main functions of data processing are data recorder control for data synchronization, *a priori* delay / delay rate calculation and correlator control. These are performed by KROSS software[24] in the K-3 system. To start KROSS software, KASET software has to be run in advance for the data base set up (Appendix 6). *A priori* values are calculated using a data base, and the correlation results are stored in a data base. A data base is set up by the KASET routines. Then, stored data in the data base is passed to KOMB software[25], where final delay and delay rates are calculated using a band width synthesis technique[26]. Final results are stored in the data base for data analysis. These processes are identical in both geodetic VLBI and Earth rotation monitoring VLBI.

3.6 Data Analysis System

Data analysis software consists of an *a priori* physical value calculation section (KAPRI) and a parameter estimation section by the linear least squares method (KLEAR)[27]. The former is used to linearize data by making (O-C), and to calculate partial derivatives for each physical parameter[28]. In general, MERIT (International program to Monitor Earth Rotation and Intercomparison of Techniques) standards[29] are adopted as the physical constants and physical models in KAPRI. Hence celestial coordinates are calculated at epoch J2000. Precession and nutation models are also taken from the MERIT standard.

When KLEAR software is running, a residual of the delay / delay rate observable, and a statistic number are shown on computer display. If ERP parameter is estimated at one epoch in a single experiment, the result represents the averaged value during the experiment. The epoch and number of epochs are changeable in an estimation. Geodetic parameter estimation is comprehensive with ERP estimation because site displacement is strongly coupled with an ERP change. Thus, in principle, it is impossible to estimate both station coordinate and ERP simultaneously. An adjustment from an *a priori* value is made in analysis software. This software gets observed values from the data reduction software through a data base. After a primary analysis, the data base is exchanged with other VLBI groups for further analysis.

Another data analysis software is available in the Communications Research Laboratory (CRL) in a main frame computer, ACOS-850. ACOS computer gets data base in Mark III format as an input. The data format is converted so that the ACOS machine can handle it, because one word is 36 bits in ACOS while it is 16 bits in HP-1000 in which Mark III data base is produced. It has several analysis tools. Not only parameter estimation software for one baseline experiment such as KLEAR, but also quasi global solution software and Kalman filtering software[30] are available. To run global solution with numbers of VLBI experiment data bases, very large memory area is required. Moreover, the number of data bases is increasing. In quasi global solution software, it does not adjust the parameters simultaneously. Local parameters (short arc parameters) are adjusted by each experiment, then global parameters (long arc parameters) are adjusted. The data is fed back and this procedure is iterated until its convergence. Running time for a quasi global solution is one tenth for actual global solution.

4. Earth Rotation Monitoring

Precise Earth rotation monitoring is necessary for (i) orbit determination and control of space vehicles, especially in deep space, for (ii) detecting small responses of the Earth to the luni-solar tidal forces and other effects in the ocean and atmosphere for the Earth science, and for (iii) studying the structure and characteristics of the inner Earth.

Using global VLBI networks, Earth rotation monitoring projects are performed. Here, two types of VLBI campaigns for monitoring ERP are described. One is a daily single-baseline UT1 monitoring and the other is a monthly multi-baseline ERP monitoring. A rigid coordinate system is essential in both cases for precise ERP results. These efforts are aiming more precise and accurate ERP monitoring in the international service in future.

4.1 Fortnightly-Period UT1 Monitoring with VLBI between Japan and Germany

The first experiment between Japan and Germany was performed in 1985 with S and X frequency bands. The campaign was named GJRO (German-Japanese Earth Rotation Observations). Daily VLBI observations were conducted between Kashima (Japan) and Wettzell (FRG) for 14 days, from Nov. 23rd to Dec. 6th, 1985, to monitor short-time-scale UT1 variations[31]. The baseline vector from Kashima to Wettzell is capable of determining UT1 precisely due to its considerable length (8500km) and its large component in the equatorial plane.

One of the most important goals of this campaign is to provide independent UT1 results to compare with the daily IRIS intensive (INT) VLBI observations, which have been regularly performed on the Wettzell-Westford baseline (6000km) since April 1984. Through intercomparison of the results of the two campaigns, inconsistency of the reference frame or adopted physical model, if it exists, is expected to be clarified.

4.1.1 Single-Baseline VLBI Observation in GJRO Campaign

In principle, it is impossible to solve the three ERP parameters simultaneously with single-baseline VLBI experiment data, because direction of single-baseline vector is specified by only two parameters. However, it is possible to track one ERP parameter with single-baseline by a series of daily short-term experiments, getting the other one or two parameters from independent observations. Usually UT1 is of interest for the parameter to be solved because it has higher frequency components than polar motion. The GJRO and the INT baselines for monitoring UT1 variations are shown in Fig.13. The GJRO experiments were schemed as in Fig.14.

The GJRO-campaign consists of 12 short-term experiments (100 minutes), each with 16 observations, and of one long-term experiment (22 hours, 203 observations). Even for future experiments, it is necessary to do the experiment in a relatively short time in a day due to limited telescope time, manpower resources, tape budget and the resulting correlation time. Hence, the scheduled time in one day for GJRO is made to be 100 minutes, and the campaign duration is slightly longer than a 13-daysperiod (Mf) tide. The starting time of each short-term experiment was set close to the daily sessions between Wettzell and Westford in order to compare these two

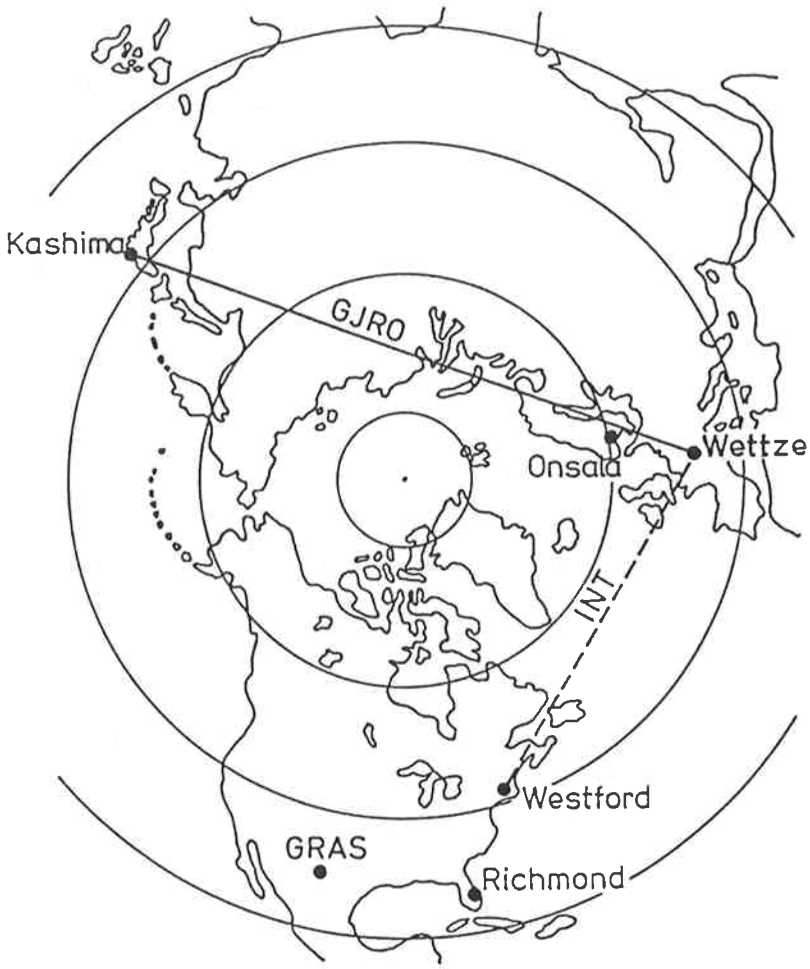


Fig. 13 GJRO and INT baselines for monitoring UT1.

independent UT1 determinations. For the short experiments two types of schedules were used. For each type the experiments were repeated at the same sidereal time during the campaign to have identical schedules. The observed sources are shown in Table 2. In most cases the type 1 schedule was used, but for the days occupied by the regular 24 hour IRIS-A experiments a different schedule (type 2) had to be used. The low elevation limit was set to 20 degrees in type 1 and 15 degrees in type 2 to minimize the influences of the propagation medium. There is, however, no fundamental differences between the two schedules except for the elevation cut off. For the long-term experiment on Dec. 5th/6th the elevation is limited to 10 degrees.

The experiments were conducted in S and X bands using 26m antenna in Kashima and 20m antenna in Wettzell. In Wettzell, the Mark III system was installed, whereas the K-3 system, compatible with the Mark III system, was used in Kashima. The data of the GJRO experiments were correlated at the Max-Planck-Institut fuer Radioastronomie in Bonn. The quality codes of many data points were low due to S-band radio interference in one channel at Kashima station.

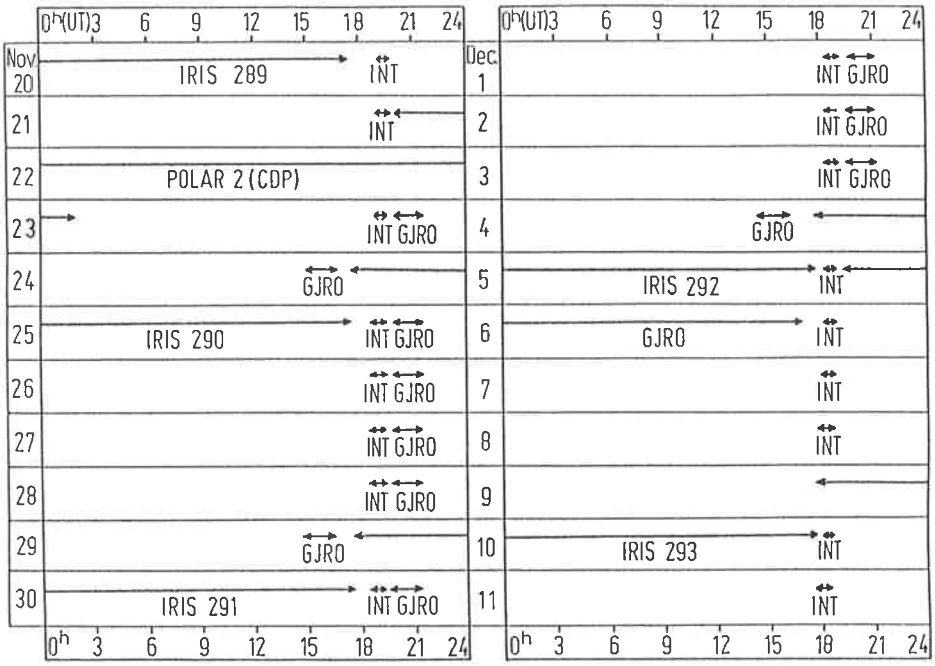


Fig. 14 Schedule of GJRO experiment.

Table 2 Observed sources in GJRO compaign

Type 1	Type 2
0212+735	0106+013
0528+134	0212+735
0552+398	0229+131
1803+784	0234+285
	1803+784

However, this channel could be removed without significant influence on accuracy.

The total number of successful observations during all sessions is 314, or 80 percent of the planned observations. UT1 was determined on each day without adjusting station positions and pole coordinates, but with solving for clock and atmospheric parameters. The adopted reference frame is the BLOKQ catalog, which is compiled by Ma[32] and is used as a CDP reference coordinate.

4.1.2 Systematic Error and the Network Geometry

A series of UT1 is determined as the analysis of the GJRO experiments at the Geodetic Institute of Bonn University. After creating preliminary data bases, the ionospheric, tropospheric and cable corrections were applied to each data base. ERP around the GJRO sessions were taken from BIH (Bureau International de l'Heure) Circular D final data and placed in the data bases. The UT1 results from each experiment of GJRO were compared with the published 5-day regular IRIS-A data (Fig.15). Referred to the BIH UT1 data, a similar trend was found in the GJRO and IRIS results, but with an offset of about −0.5msec (GJRO lags) between them. The INT data bases (8 observations per session) were also analyzed similarly using BIH pole coordinates. For the INT analysis only clock offset, rate and UT1 were adjusted, whereas the larger number of observations of the GJRO sessions allowed us to solve additionally the atmospheric parameters at each station. The UT1 trend of INT is also similar to that of IRIS but with an offset of about +0.7msec (INT advances; see also Fig.15). Since the time of GJRO observation is set to be as close as possible to the INT observation series (mostly 30 minutes difference), the UT1 results in both series are compared as the simultaneous data.

The main reason for offset between the two independent UT1 determinations by VLBI was presumed to be errors of the input BIH pole positions, because the adopted source and station reference coordinates are taken from one consistent catalog, the CDP catalog. Another available

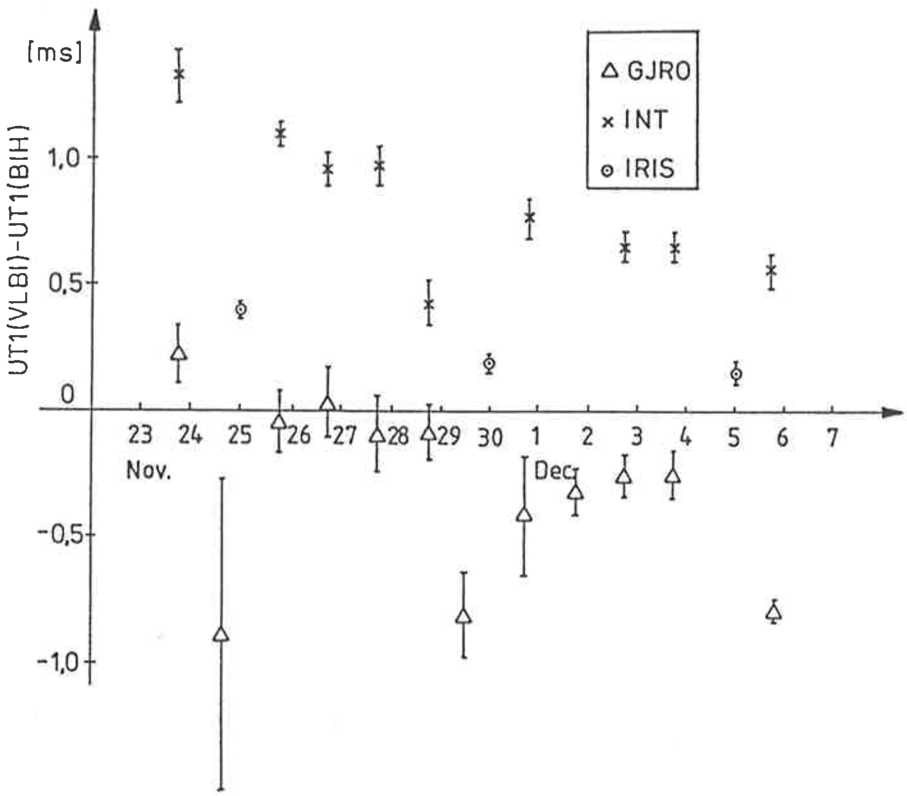


Fig. 15 Observed UT1—UT1(BHI) (based on BIH pole coordinates).

ERP service is only IRIS bulletin. The ERP in IRIS bulletin is based on radio observation, while ERP determination at BIH was mainly dependent on the optical observation. Thus the IRIS pole coordinates were put into the data bases. And the data analysis was repeated in order to determine consistent UT1 values. Through the test to adopt the IRIS reference coordinate system in GJRO analysis, significant error was not detected in UT1 as a result. The mean difference between the IRIS and the BIH pole coordinates was +10 mas in Wx and −4 mas in Wy (Table 3). The pole positions determined by BIH and IRIS are depicted in Fig.16 around the GJRO campaign. The UT1 results of both campaigns coincided within about 0.2 msec (Fig.17), but there is still a small remaining offset of about 0.1 msec. The residual discrepancies between the two UT1-series from GJRO and INT may be caused by the introduced pole positions. Errors in these daily pole coordinates probably result from the interpolation of the 5 day IRIS-A values. Small residual systematic errors of the IRIS pole coordinates cannot be excluded.

In a further analysis, all regular IRIS data bases between Nov. 20th and Dec. 10th were used to investigate the dependence of the UT1 parameters from input pole positions and also from the VLBI network geometry. For each experiment UT1 was determined in three versions:

ver.1 multi-baseline solution (four or five stations) using the BIH pole coordinates as fixed values (Table 3, column 1),

ver.2 multi-baseline solution but with both pole positions (W_x, W_y) solved, which means that the UT1 result is not affected by errors of the *a priori* pole coordinates (Table 3, column 2),

ver.3 single-baseline solution (Westford-Wettzell) using the BIH pole coordinates as fixed values (Table 3, column 3).

It can be seen from Table 3 that the results from the multibaseline solutions using the BIH pole coordinates as fixed values, and from the single baseline solutions, agree very well (offset : 0.04msec). However, both solutions have almost identical offsets (0.3 and 0.32msec) to the multi-baseline solutions where the pole coordinates are solved. From this investigation it is obvious, that even from single baseline VLBI observations with a long east-west component, accurate UT1 determinations can be expected, if precise and consistent pole coordinates are available as input parameters.

The opposite sense of UT1 offset to the published IRIS result that appeared in GJRO and INT is discussed here. Suppose UT1 error is coupled with the x pole position error.
Then

Table 3 UT1(IRIS)-UT1(BIH) from multi- and single- (Wettzell-Westford) baseline solution (oh UTC) and differences of pole coordinates between IRIS and BIH

date	1 (multi baseline) BIH xp,yp	2 (multi baseline) solving xp,yp	3 (single) BIH xp,yp	differences 1-2	differences 3-2	differences 1-3	IRIS-BIH xp mas	IRIS-BIH yp mas
Nov.20	1.28 msec	1.08 msec	1.25 msec	0.20	0.17	0.03	7.5	-4.4
25	0.92	0.39	0.91	0.43	0.42	0.01	12.2	-5.5
30	0.73	0.23	0.67	0.50	0.44	0.06	12.6	-4.4
Dec. 5	0.58	0.16	0.54	0.42	0.38	0.04	9.2	-3.9
10	-0.25	-0.49	-0.30	0.24	0.19	0.05	10.4	-3.1
			mean	0.36	0.32	0.04	10.4	-4.3

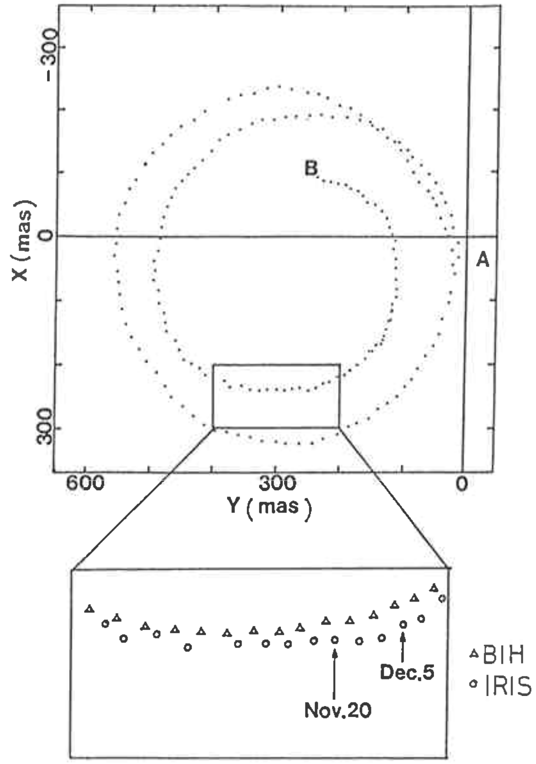


Fig. 16 Pole Positions around GJRO campaign (A: Nov. 17 in 1983, B: May 24 in 1986).

$$\Delta\tau_g = \frac{d\tau_g}{dW_x}\Delta W_x$$

$$= \frac{d\tau_g}{dUT1}\Delta UT1 \quad \cdots\cdots (12)$$

Therefore,

$$\Delta UT1 = \frac{\dfrac{d\tau_g}{dW_y}}{\dfrac{d\tau_g}{dUT1}}\Delta W_x \quad \cdots\cdots (13)$$

In the same way, UT1 error is supposed to be coupled with the y pole position error. Then we get

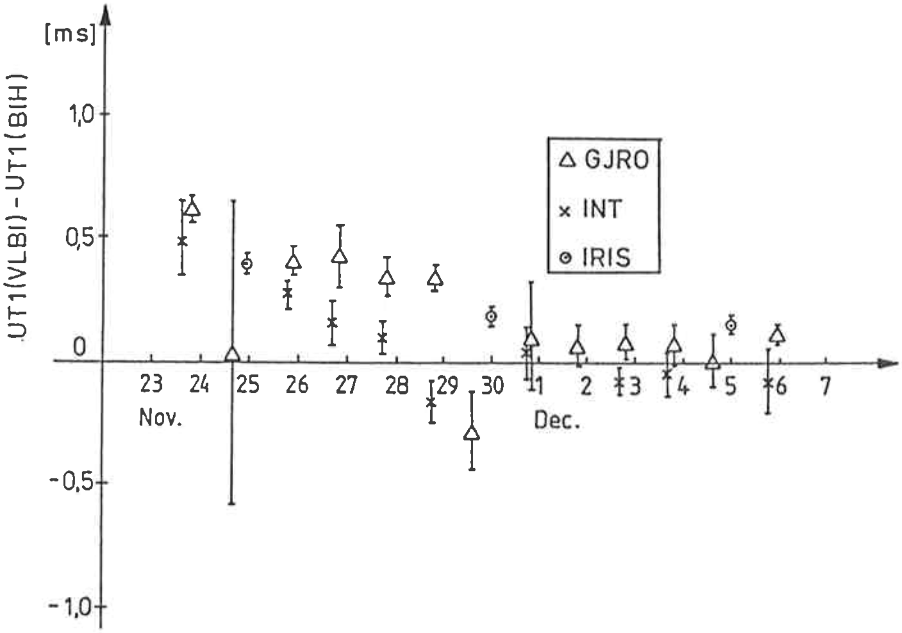


Fig. 17 Observed UT1—UT1(BIH) (based on IRIS pole coordinates).

$$\Delta UT1 = \frac{\frac{d\tau_g}{dW_x}}{\frac{d\tau_g}{dUT1}} \Delta W_y \quad \cdots\cdots (14)$$

Here it was assumed that the baseline vectors in GJRO and INT are parallel to the equator plane. Source vector ($\mathbf{s}_i$: i=0,1) is orthogonal to the baseline vector and declination of the source is larger than zero. The assumed configuration is shown in Fig.18. The baseline vector error $\Delta\mathbf{B}_i$ (i=0,1), equivalent to the UT1 error, is expressed in Fig.19(a). According to the basic VLBI equation, we obtain

$$\Delta\tau_{gi} = -\frac{1}{c}\Delta\mathbf{B}_i \cdot \mathbf{s}_i \quad (i=0,1). \quad \cdots\cdots (15)$$

In Eqs.(13) and (14), the relation of sense between each pole position error and UT1 error is estimated using Fig.19 ((a),(b) and (c)) and Eq.(15). According to the fact that ΔW_x is +10mas and ΔW_y is −4mas during the GJRO campaign, the sense of Δ UT1 is the opposite between the GJRO and INT cases in Eq.(13) and the same in Eq.(14) (Table 4). As a fact, the influence of the x-pole position error to the UT1 error was larger than the y-pole position error. Hence, it is understood that the reason of the opposite sense UT1 offset in the GJRO and INT campaign was mainly by the influence of the x-pole position error.

4.1.3 Analysis of Fortnightly Period UT1 Variation

Changes of the Earth's moment of inertia by the Earth tides causes periodic UT1 variations,

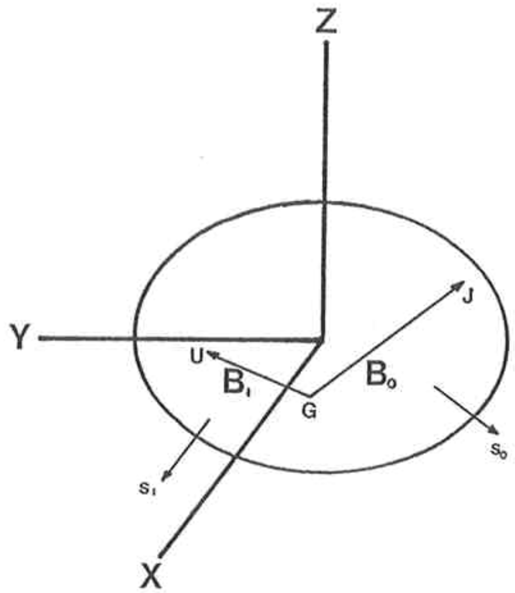
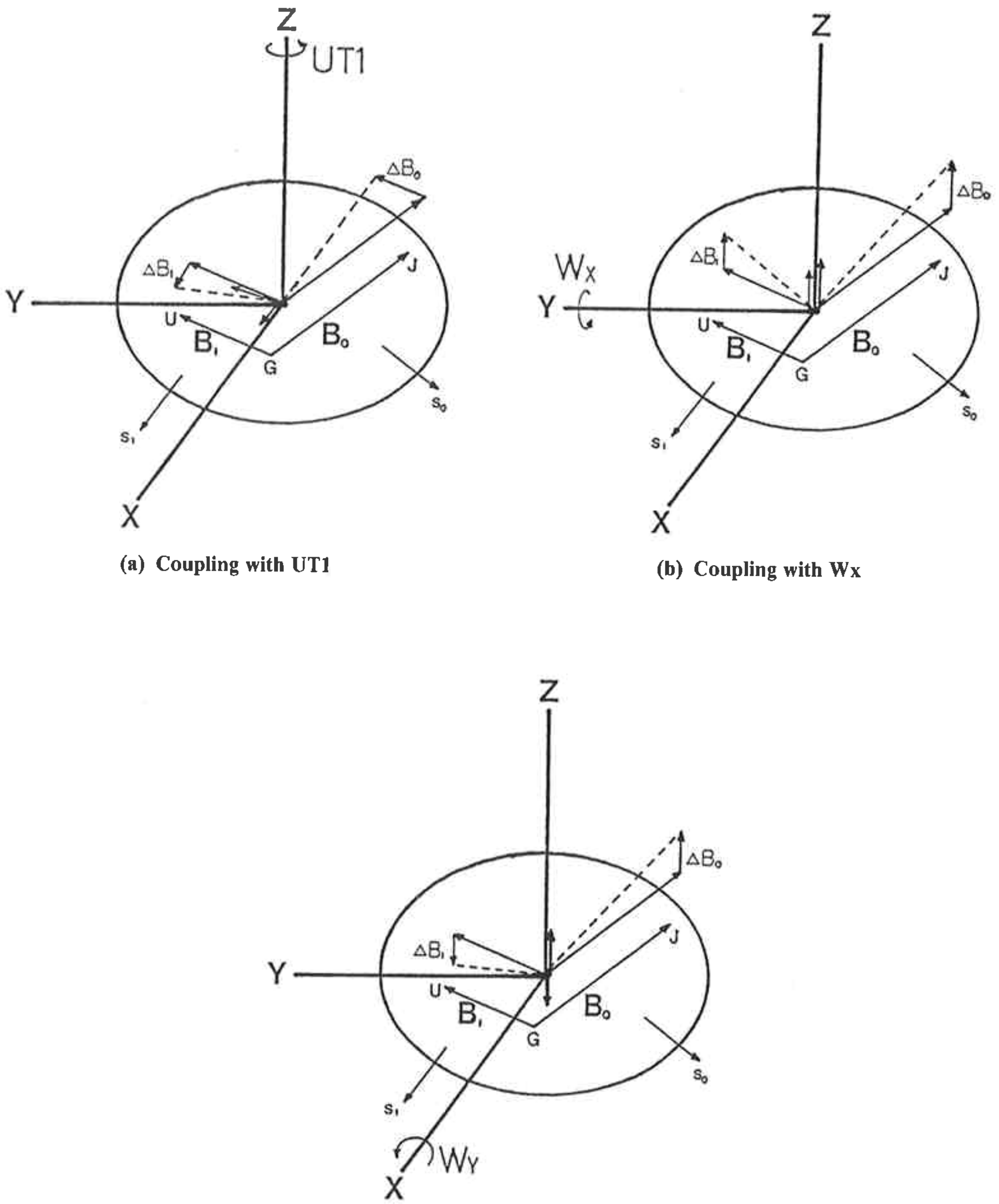


Fig. 18 Configuration of simplified GJRO and INT baselines. U, G and J denote stations in USA, Germany and Japan, respectively).

as was described in Sec. 2.1. For variations shorter than 35 days, the monthly period (27.56d) and the fortnightly period (13.6d) are dominant. The UT1 observations by GJRO contain the "true" variations due to the effects of zonal tides, whereas the BIH-values include the theoretical variations [UT1(BIH)=UT1R(BIH)+ effects of zonal tides] published by Yoder which is shown in Table 5[7]. Since the GJRO experiment lasted 14 days, a small fortnightly period can be seen in the differences [UT1 (GJRO) - UT1 (BIH)], if the observed UT1 variations due to the tidal deformations is different from theoretical estimation.

Both UT1-series agree within 0.2msec if the regular IRIS pole positions are used, but there is still a remaining offset of 0.1msec. After removing an offset and a drift, two sinusoids with fixed periods of 13.66d and 27.56d were fitted to the data (Fig.20). Since the model of tidal variation in UT1 by Yoder is adopted in the MERIT standard, the residual UT1 shows a discrepancy from the theoretical one. Depending on the method of choosing input data weights, amplitudes between +0.07 and +0.10 ±0.04 msec were obtained for the 13.66d-period. The phase, referred to Nov. 23rd, Oh UT, was between 211 degrees and 249 degrees while the theoretical phase is 189 degrees. Fixing also phases in the least squares fit, the amplitude of the 13.66d-term was determined to ⅞0.04 msec. These results would correspond to an increase of the theoretical amplitude of the 13.66d-term[33] (+0.78msec) by the magnitude of 5-10%. This seems to confirm former determinations of the 13.66d-amplitude using UT1 data from other VLBI experiments[34]. The monthly period could not be resolved significantly, due to the time span of the data.

Even with rather brief VLBI observations it is possible to explore further the spectrum of UT1 fluctuations on short time scales. Thus, in the present example a small difference between the theoretical and the observed fortnightly UT1 variation could be detected.



(a) Coupling with UT1

(b) Coupling with Wx

(c) Coupling with W_y

Fig. 19 Baseline vector error coupled to UT1 and pole position error.

Table 4 The sense of UT1 error induced by x and y pole position error in INT and GJRO campain

	INT	GJRO
△UT1 induced by △Wx	(+)	(-)
△UT1 induced by △Wy	(+)	(+)

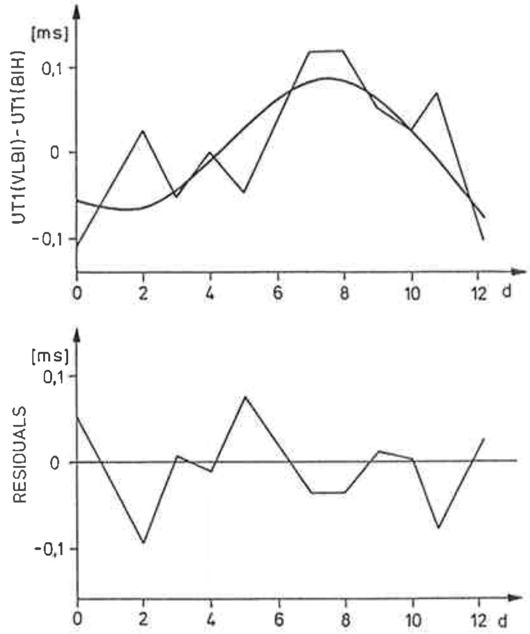


Fig. 20 Sinusoidal curve fitting for GJRO UT1 results. Starting date is Nov. 23 in 1985.

4.2 Earth Rotation Measurements with the IRIS Pacific Network

ERP are monitored independently with multi-baseline VLBI networks in the IERS program. ERP results obtained since April 1987 by the Pacific and Atlantic networks are compared(35). Available ERP from different VLBI networks should be consistent and comparable with each other. However, systematic offsets in ERP appeared in two different IERS networks as was seen in GJRO and INT UT1 monitoring by single-baseline VLBI (Section 4.1.2). Thus, a question arises whether the adopted reference frames in two IERS networks are really consistent.

4.2.1 VLBI Observation with Four Stations

The schedule for the IRIS-P experiment was made at Kashima with KASER scheduling software (Section 3.3) and distributed to each observatory from Mizusawa (Japan) where the IERS analysis center is located. Observing frequency bands are S and X which are the same as in

Table 5 Periodic UT1 variations[7]

No.	l	l'	F	D	Ω	Period days	Amplitude x 0.1us
1	1		2	2	2	5.64	25
2	2		2		1	6.85	43
3	2		2		2	6.86	105
4			2	2	1	7.09	54
5			2	2	2	7.10	131
6	1		2			9.11	41
7	1		2		1	9.12	437
8	1		2		2	9.13	1,056
9	3					9.18	19
10	-1		2	2	1	9.54	87
11	-1		2	2	2	9.56	210
12	1			2		9.61	81
13	2		2	-2	2	12.81	-23
14		1	2		2	13.17	-27
15			2			13.61	318
16			2		1	13.63	3,413
17			2		2	13.66	8,252
18	2				-1	13.75	-23
19	2					13.78	360
20	2				1	13.81	-19
21		-1	2		2	14.19	26
22				2	-1	14.73	50
23				2		14.77	781
24				2	1	14.80	56
25		-1		2		15.39	54
26	1		2	-2	1	23.86	-53
27	1		2	-2	2	23.94	-107
28	1	1				25.62	-42
29	-1		2			26.88	-50
30	-1		2		1	26.98	-188
31	-1		2		2	27.09	-463
32	1				-1	27.44	-568
33	1					27.56	8,788
34	1				1	27.67	-579
35				1		29.53	-50
36	1	-1				29.80	59
37	-1			2	-1	31.66	-125
38	-1			2		31.81	1,940
39	-1			2	1	31.96	-140
40	1		-2	2	1	32.61	-19
41	-1	-1		2		34.85	91
42		2	2	-2	2	91.31	61
43		1	2	-2	1	119.61	-35
44		1	2	-2	2	121.75	2,005
45			2	-2		173.31	-267
46			2	-2	1	177.84	-1,245
47			2	-2	2	182.62	51,327
48		2				182.63	206
49	2			-2	-1	199.84	-52
50	2			-2		205.89	582
51	2			-2	1	212.32	-39
52		-1	2	-2	1	346.60	48
53		1			-1	346.64	-98
54		-1	2	-2	2	365.22	-881
55		1				365.26	16,339
56		1			1	386.00	147
57	1			-1		411.78	-37
58	2		-2			1095.17	146
59	-2		2		1	1305.47	-449
60	-1	1		1		3232.85	-43
61					2	-3399.18	-8,404
62					1	-6790.36	1720,498

IRIS-A. In the IRIS-P network, two stations (Kashima and Gilcreek) are regular CDP stations mainly developed to study tectonic plate motion and crustal deformation, while other two (GRAS and Richmond) are regular IRIS-A stations. IRISP and IRIS-A networks are shown in Fig.21. Hence, strictly speaking, IRIS-P and -A networks are not independent because of two common stations. IRIS-P is rather an extensive network from both CDP and IRIS programs. Despite two common stations in the IRIS-A and -P networks, the number of common baselines is only one between them, while the other five baselines are completely independent.

The IRIS-P experiment schedule is repeated every month before or after IRIS-A on the same sidereal time. The duration of the experiment is 24 hours. The number of observations in IRIS-P is smaller than that in IRIS-A because of the limited mutual visibility. Thus, the subnet schedule is used to increase the number of effective observations. Nevertheless, the precision of the ERP by IRIS-P is better than IRIS-A due to the longer baseline vectors. The experiments are carried out in S and X receiving bands at the four stations using the Mark III (USA) or K-3 (Kashima) type VLBI acquisition terminals. Recorded tapes are shipped from each station to the United States Naval Observatory (USNO) for data processing. Then a data base is created at the National Geodetic Survey (NGS). Finally, the data base is sent to Japan and analyzed at Kashima and Mizusawa. CALC/SOLVE type analysis software and similar software in a main frame computer (ACOS-850) are used to get final ERP for a single data base analysis and global analysis. Reweighting technique which make improvement in the parameter fitting was not adopted in the analysis because the chi square as an indication of parameter fit was close to unity in each solution.

4.2.2 Source and Site Coordinate System

The catalog differences in source and station positions are vital for precise ERP determination. Source and site catalogs of the CDP and IRIS are shown in Table 6. The difference in determined source position by the two groups is also plotted in Fig. 22. In particular, a declination difference shows a clear systematic error as large as 9mas p-p which is seen in Fig. 22(b), indicating the rotation of defined celestial sphere between the two catalogs. The reason for the systematic error would be differences in the definition of celestial reference frame including the precession and nutation models. Hereafter, in this article the coordinate system composed of the source and station catalog in each group are called CDP and IRIS systems.

To investigate the systematic offsets in ERP, updating the IRIS-P data bases in both consistent systems is attempted. First, the positions of GRAS (US) and Richmond (US) stations are taken from the CDP catalog. Kashima (Japan) and Gilcreek (US) station coordinates are also updated using recent results of CDP experiments. Secondly, a unified IRIS system was attempted.

4.2.3 ERP Comparison with IRIS Atlantic Network

Pole position, UT1 and nutation parameters are determined using the nine IRIS-P data bases from April, 1987 to January, 1988, both in the CDP and in the IRIS system. The discrepancy of each ERP and nutation parameter between the IRIS-P and -A is plotted in Fig. 23., where IRIS-A results are regarded as references. The published IRIS-A results are interpolated to have the same epoch with IRIS-P. Both ERP results of IRIS-P based on CDP and IRIS systems are plotted in the same figure. Here *a priori* plate velocity was not taken into account because it is not big enough between the stations. The systematic error is smaller in the case of the IRIS system than in the case of the CDP system in each ERP. The average offset of ERP and nutation parameters are,

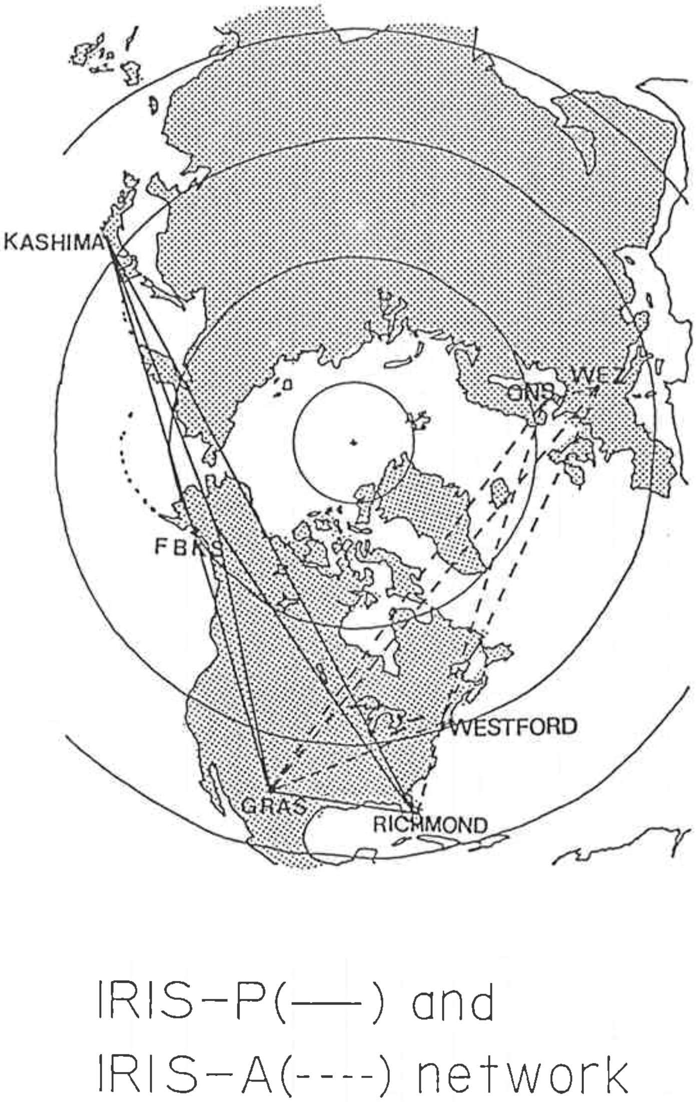


Fig. 21 IRIS-P and -A networks.

x-pole: 0.45 mas, y-pole: -1.14 mas, UT1: 0.035 ms, nutation in longitude: -0.82 mas and nutation in obliquity: 0.18 mas if the IRIS system is adopted. The random error of each point in Fig. 23 is composed of both IRIS-P and -A. Though formal errors in the pole positions and UT1 are not always constant, they are around 0.6 mas, indicated by error bars. The formal error is almost comparable to the offsets. Significant time dependencies of the offsets are not found in all parameters.

Table 6 Source and station catalog in the CDP and IRIS system

(a) Source catalog

CDP-IRIS	$\Delta\alpha$ (HMS)	$\Delta\delta$ (DMS)
SOURCE	ss.sssss	ss.ssss
0106+013	-0.00004	0.0056
0212+735	0.00033	0.0019
0229+131	-0.00013	0.0041
0528+134	-0.00009	-0.0014
0552+398	0.00011	-0.0002
0851+202	-0.00002	-0.0027
0923+392	-0.00006	-0.0027
1226+023	0.00001	-0.0036
1404+286	-0.00019	-0.0022
1637+574	-0.00044	0.0022
1641+399	-0.00030	0.0014
1803+784	-0.00049	0.0026
2134+004	-0.00016	0.0051
2200+420	-0.00013	0.0041
2251+158	-0.00006	0.0047

(b) Station catalog

CDP	X(M)	Y(M)	Z(M)
KASHIMA	-3997890.59	3276580.39	3724118.79
GILCREEK	-2281545.2	-1453645.83	5756993.71
GRAS	-1324209.1306	-5332024.023	3232118.958
RICHMOND	961259.8698	-5674090.9847	2740534.2543
WESTFORD	1492208.5576	-4458131.3422	4296015.8845
WETTZELL	4075541.8755	931734.2282	4801629.3785

(BLOKQ AND KASHIMA ANALYSIS)

IRIS86	X(M)	Y(M)	Z(M)
KASHIMA	-	-	-
GILCREEK	-	-	-
GRAS	-1324210.756	-5332023.002	3232118.577
RICHMOND	961258.232	-5674089.913	2740533.823
WESTFORD	1492206.923	-4458130.340	4296015.490
WETTZELL	4075540.267	931735.238	4801629.038

(BIH ANNUAL REPORT 1986)

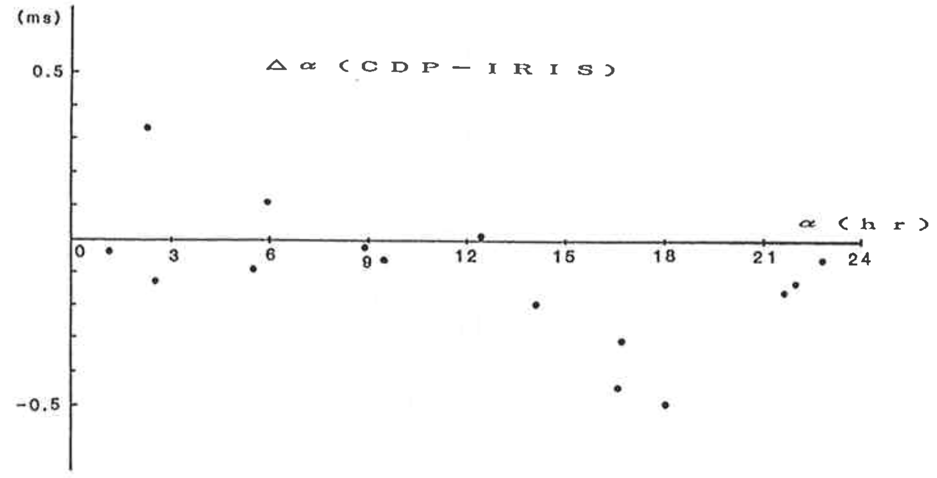


Fig. 22 (a) Differences in the right ascension between the CDP and IRIS catalog in each radio source.

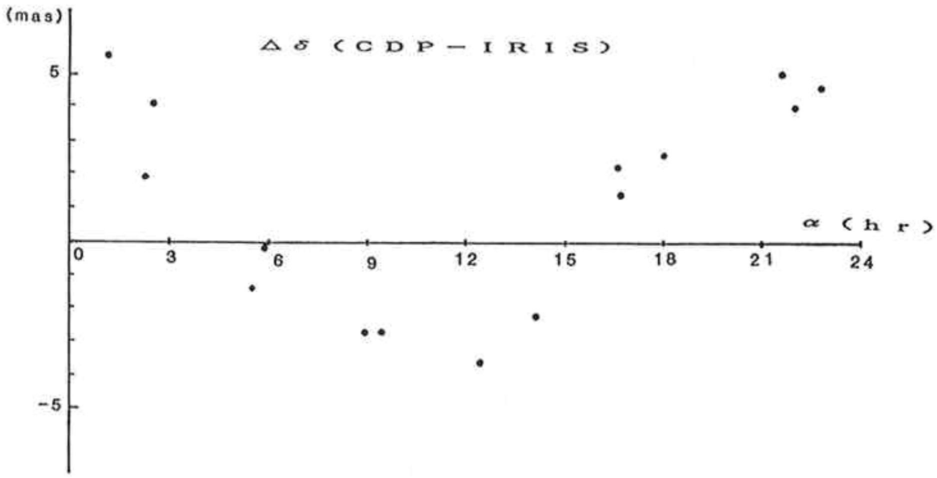
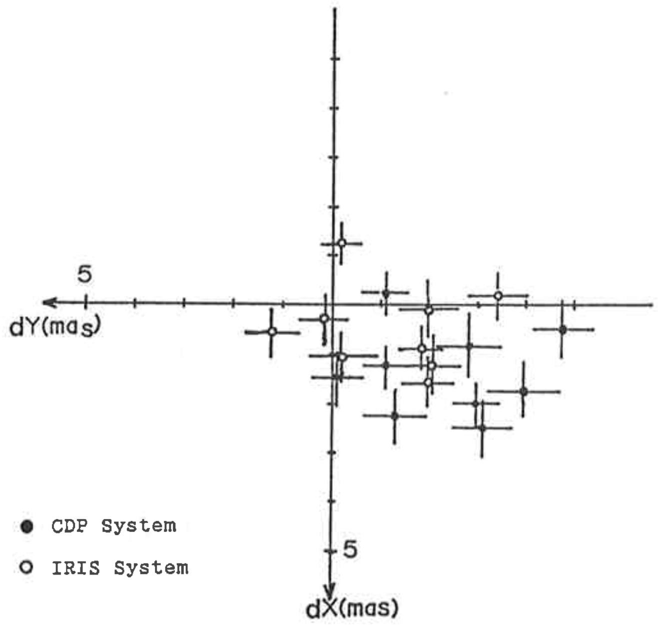


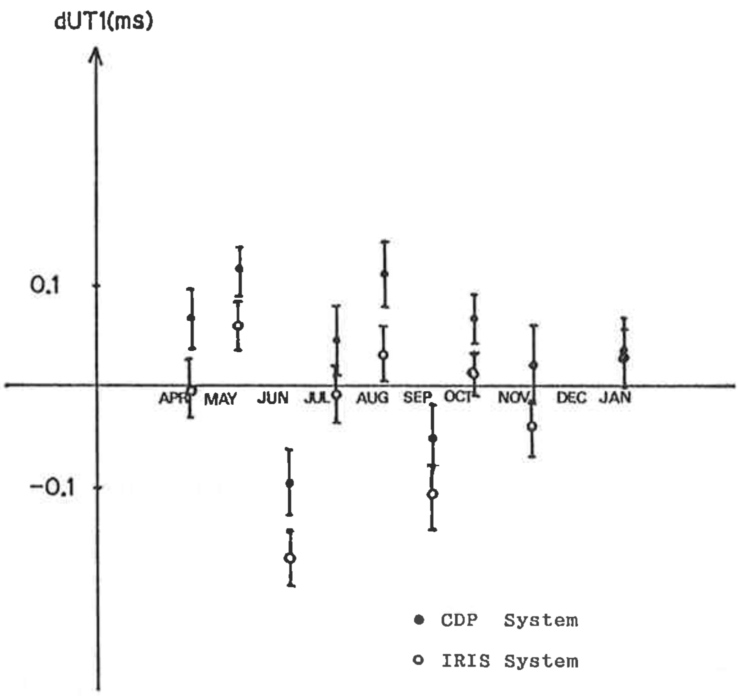
Fig. 22 (b) Differences in the declination between the CDP and IRIS catalog in each radio source.

4.2.4 Systematic Error in ERP and the Reference System

Systematic errors in pole position, UT1 and nutation are clearly seen between the IRIS-P and published IRIS-A results, as seen in Fig.23, when the CDP system is adopted. Since the adopted CDP coordinate system including IRIS regular stations (Table 6 [(36)(32)]) is suspected to be inconsistent, attempts were made to determine the ERP using the IRIS system. Kashima and Gilcreek station coordinates, however, should be obtained in the IRIS system so that the data base

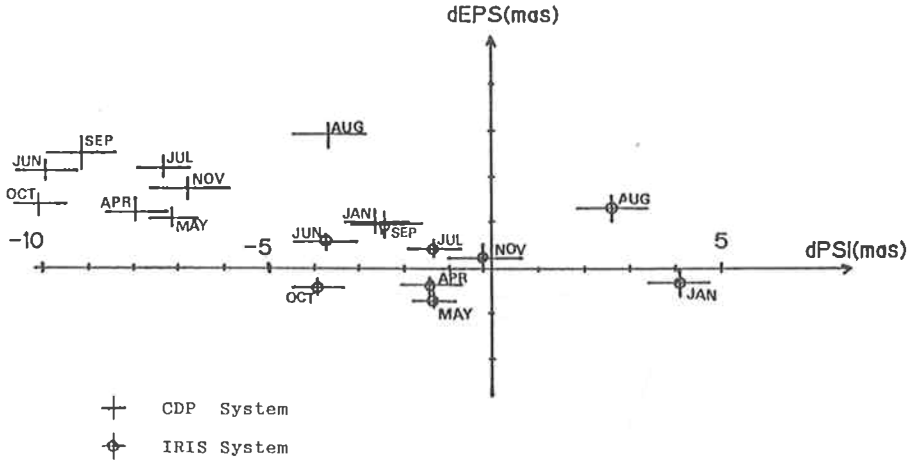


(a) Pole position



(b) UT1

Fig. 23 Copmparison of the Earth rotation parameters between April 1987 and Jan. 1988.



(c) Nutation

Fig. 23

may be consistent. But the station coordinates of Kashima and Gilcreek have not been described by the IRIS system. Thus, three cases are considered to solve the problem.

First, Kashima and Gilcreek station coordinates are solved only within the IRIS-P data base, holding the other two regular IRIS station coordinates and taking the published IRIS-A ERP. However, the obtained coordinates of the two stations were unstable in each data base. This is probably due to the small number of simultaneous observations with all stations due to the limited mutual visibility in the IRIS-P network.

Secondly, the station coordinates can be obtained by global solution using a combination of the IRIS-P data base and the published IRIS-A ERP.

The third case is one of the CDP experiment series called "POLAR" which has been performed twice a year with regular CDP stations (Kashima, Gilcreek), and also regular IRIS stations since 1984 (Fig.24). The positions of Kashima and Gilcreek can be solved in the IRIS system using the POLAR data base by holding the other three station coordinates, which are Onsala (Sweden), Westford (US) and Wettzell (FRG). The positions of the three stations in the IRIS system are certain because they are regular IRIS stations.

The third way was chosen to solve the problem because mutual visibility is better in POLAR than in IRIS-P, and POLAR has more observations than IRIS-P. The stations taking part in the POLAR, IRIS-A and IRIS-P experiments are shown in Table 7. The number of tied stations for the frame connection is three in the third case (POLAR and IRIS-A), instead of two in the first and second cases. Source coordinates are also taken from the IRIS catalog in the solution. The published ERP results of IRIS-A are used in every solution as fixed parameters. The epochs of ERP and nutation parameters are set to 0 hour on each date. Finally, the determined station coordinates from each POLAR data base are averaged (Table 8). Since the GRAS and Richmond positions are already correctly determined in the IRIS system, they are adopted in the IRIS-P data base[32]. The baseline vector change, which may cause an error in ERP analysis, was not taken into account in the analysis of the POLAR experiment series because the plate motion rate between

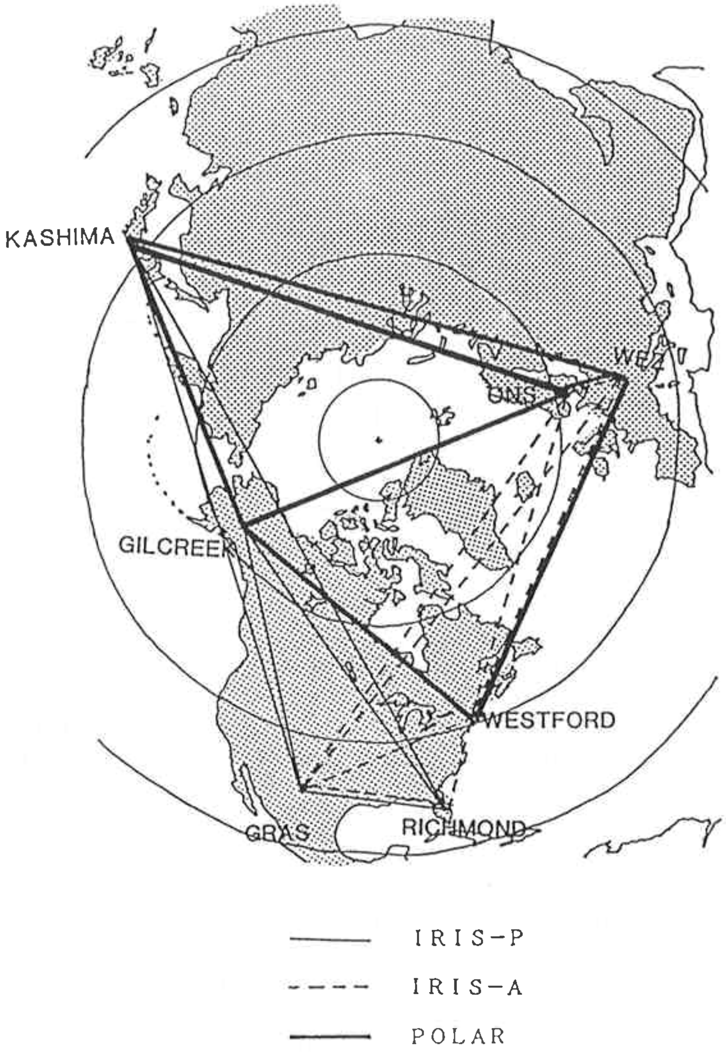


Fig. 24 VLBI networks of IRIS-A, IRIS-P and POLAR.

these stations is negligible. Though a global solution to get the Kashima and Gilcreek positions from all the POLAR experiment data bases was also attempted as a second way, there were larger formal errors in the solution.

By adjusting the Kashima and Gilcreek station coordinates in the IRIS system using another independent VLBI program (POLAR), the ERP determined by IRIS-P coincided with the results by IRISA. However, this does not indicate that IRIS coordinates are superior to CDP coordinates. Unified coordinates were obtained only in the IRIS system. The problem of systematic error in ERP from the IRIS-P data is similar to ones found in a single baseline UT1 monitoring experiment[31]. Thus it should be emphasized that the data base to analyze ERP should

Table 7 VLBI stations participation in the POLAR, IRIS-A and IRIS-P experiments

STATION

	GIL	KAS	ONS	WES	WEZ	GRAS	RICH
POLAR	x	x	x	x	x		
IRIS-A			x	x	x	x	x
IRIS-P	x	x				x	x

Table 8 Station positions in the IRIS system adjusted by the POLAR experiment data base

	X(M)	Y(M)	Z(M)
KASHIMA	-3997892.113	3276581.412	3724118.486
GILCREEK	-2281546.807	-1453644.838	5756993.338
# GRAS	-1324210.756	-5332023.002	3232118.577
# RICHMOND	961258.232	-5674089.913	2740533.823
# WESTFORD	1492206.923	-4458130.340	4296015.490
# WETTZELL	4075540.267	931735.238	4801629.038

(# : FIXED TO IRIS86)

consist of one consistent data set.

As a result, it is understood that the precision of ERP by IRIS-P is as good as by IRIS-A. Hence it could work as an independent network. If both the networks work in parallel, it is possible for them to be mutually supportive, so ERP can be published regularly. The performance of ERP observations by the VLBI network in the northern hemisphere is, however, almost identical. Hence, we also need the stations in the southern hemisphere for the next step. Then the terrestrial coordinates need to be extended to be consistent with the current system as well as the southern celestial sphere.

The process to acquire a consistent system in GJRO and IRIS-P would be good examples of extending a VLBI network in the future. When these VLBI coordinates are connected with the SLR and GPS coordinate systems[37], VLBI will play an important role in making the reference system because VLBI is based on a very rigid celestial coordinate system. A consistent VLBI reference frame should be established before a collocation experiment with a different space technique.

4.3 Discussion on Systematic Error

As was discussed in Section 4.1.2, the UT1 observation with a single-baseline suffered systematic error caused by the different adopted pole positions. The different pole positions may be caused by different definitions of radio and optical reference frames, because BIH has determined the pole positions mainly according to optical source observations. Though radio data was available to BIH, the definition of a pole coordinate is not easy to change. Thereby the difference appeared in the GJRO UT1 result. Moreover, even ERP observations with a multi-baseline VLBI experiment suffered a similar offset induced by the difference of adopted VLBI reference frames. Though both of them are determined by the VLBI technique itself, they still had a slight difference. If a similar trend is seen in ERP between independent VLBI observations, systematic errors should be studied carefully because such offsets are often accompanied with an inconsistent data set, which might cause an error in another geodetic or astrometric parameter determination. Hence, it is often a good indication of an inconsistent data set. Geodesy by the VLBI technique to determine each cartesian component of the station is dependent on ERP, and vice versa. CIS and CTS of each VLBI program are connected only by using identical ERP with observations in independent networks.

4.4 VLBI Time Synchronization

The time difference of atomic clocks between two stations is available as another VLBI observable. Indeed another purpose of the IRIS-P experiment is the test of VLBI time synchronization between Japan and the USA. Kashima station belongs to the Communications Research Laboratory, and Richmond station belongs to the United States Naval Observatory. Both institutes are responsible for keeping a national standard of time and frequency.

If all the influences of physical effects on delay are removed from the delay observables with well-determined source and station coordinates, the time difference and its time variation are exactly known, but with offsets. The observation equation for VLBI time synchronization is as follows:

$$\Delta\tau = \tau^{o} - \tau_{g}^{c} = \begin{matrix} 1 & t_0 & t_0^2 \\ 1 & t_1 & t_1^2 \\ 1 & t_2 & t_2^2 \\ \\ 1 & t_n & t_n^2 \end{matrix} \begin{bmatrix} c_0 \\ c_1 \\ c_2 \end{bmatrix}, \quad \cdots\cdots (15)$$

where t_n is an epoch for n-th observation, c_0 is the time offset, c_1, is drift and c_2 is the drift rate between two station clocks. These coefficients of clock polynomials are determined by the least squares analysis. To obtain the UTC difference of stations, the biggest problem is the instrumental delay in each station because it is coupled with each station clock. Instrumental delay of a VLBI station was directly measured within 5 ns precision[38]. However, it is still hard to measure the absolute delay of each station with the comparable precision of VLBI. In contrast to the insufficient absolute instrumental delay measurement, it is easier to get the difference of each station delay precisely using a Zero Baseline Interferometer (ZBI) unit[39]. Since the instrumental delay difference between Kashima and Richmond was measured by ZBI, IRIS-P data is used also to monitor the difference of time standards in Japan and the USA. The expected time synchronization error is less than lnsec.

A systematic error in time synchronization may also be induced by the adopted coordinate sy,stem error. Let the error of baseline and source vector, be **ΔB** and **Δs.** θ_1, θ_2 and θ_3 are the angles between (**B** and **Δs**), (**ΔB** and **s**) and (**ΔB** and **Δs**) respectively. Then the basic VLBI equation with errors are expressed in Eq.(16)[40].

$$c\tau_g' = (\mathbf{B} + \Delta\mathbf{B}) \cdot (\mathbf{s} + \Delta\mathbf{s})$$

$$= \tau_g + |\mathbf{B}| \cdot |\Delta\mathbf{s}| \cos(\theta_1) + |\Delta\mathbf{B}| \cdot |\mathbf{s}| \cos(\theta_2) + |\Delta\mathbf{B}| \cdot |\Delta\mathbf{s}| \cos(\theta_3) \quad \ldots\ldots\ldots\ldots (16)$$

If we assume

$|\mathbf{B}| = 10{,}000$ km

$|\Delta\mathbf{B}| = 5$ cm

$|\Delta\mathbf{s}| = 5$ mas

$|\mathbf{s}| = 1$ (definition),

then we obtain

$1/c\,|\mathbf{B}| \cdot |\Delta\mathbf{s}| = 0.8$ ns

$1/c\,|\Delta\mathbf{B}| \cdot |\mathbf{s}| = 0.2$ ns,

where the last term of Eq.(16) is negligible. Though an assumed error in the baseline and source vector is pessimistic, it is understood that the VLBI time synchronization error also depends upon uncertain coordinates, and the expected error is less than 1 nsec. If VLBI experiments are carried out on a regular basis, a simultaneous time synchronization experiment is also possible using a well-determined coordinate system. It is, however, necessary to conduct the ZBI experiment in advance, as a calibration to get an absolute time difference between two stations.

4.5 Geophysical Condition of VLBI Station for ERP Monitoring

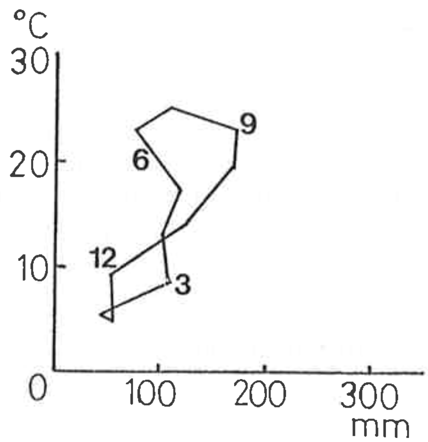
Ambient conditions of VLBI stations such as weather, antenna foundation etc., may affect the delay observable. VLBI observed delays consist of geometrical delay, propagation delay, instrumental delay and clock differences of each station. Instrumental delay and clock error are relatively easy to remove from the observed delay as they are independent of each source observation. However, propagation delay depends on the source direction. The propagation delay consists of an ionospheric part and an atmospheric part. The delay due to the ionosphere can be eliminated by the dual frequency (S and X) band observation. The problem remains in the atmospheric part, where the delay is partly due to dry air and water vapor.

One of the problems in current VLBI geodesy is the relatively high uncertainty of the site position in a vertical component. The vertical component is determined only by observing the sources in both high elevation angles, and in low elevation angles physically limited to more than zero degrees. Furthermore, observations of sources in low elevation angles induce much larger atmospheric excess path errors than in high elevation angles. Since a site position error has a strong influence on the earth orientation determination, the atmospheric excess path should be determined as precisely as possible.

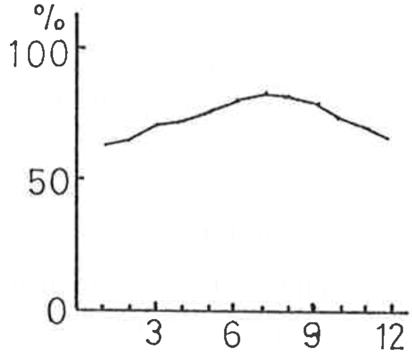
The delay due to water vapor is, in particular, hard to estimate because of the inhomogenious density of water vapor in the sky. Hence, after the atmospheric part is corrected by an atmospheric mapping function, the residual is adjusted. The atmospheric delay contribution is not a bias of the observed delay during the experiment, but a function of source direction in the two stations. Since the atmospheric delay adjustment is equivalent to the estimation of atmospheric height, adjustment of the atmospheric part couples with the vertical position of each station. Obviously the uncertainty of the site position reflects on the precision of the determined ERP. Available precision in VLBI geodesy is currently approximately 2 cm horizontally and 6 cm vertically in position determination.

To measure propagation delay due to water vapor, several types of Water Vapor Radiometers have been developed[41], while the atmospheric mapping function has also been improved. It is particularly important to know the water vapor delay contribution in stations, such as Kashima, where the humidity is high (Fig.25).

Another approach to the problem of vertical components of a station is the use of an absolute gravimeter. The gravimeter can detect the site gravity and gravity change due to tides or crustal deformation. Its precision is better than 1 micro-gal. Since the precision of the absolute gravimeter is equivalent to only a 3mm in height change, it is useful for geodesy. Collocative measurements



(a) Climograph



(b) Relative Humidity

Fig. 25 Weather condition of Kashima station.

were carried out at Kashima VLBI station[42]. Though the uncertainty of gravity measurements is ten times higher than that obtained at Esashi tide station, it is understood that the problem is not induced by the vibration of antenna mechanical drive, but by traffic noise from the road. Thus the collocative measurements with VLBI and absolute gravimeter will be effective to study the vertical component of the station if it is located under the condition of less traffic noise.

It is preferable to have radio telescopes which satisfy the requirements for geodesy. There are, however, still only a few stations in the world which are dedicated to geodetic VLBI at the moment. In other VLBI stations, telescopes which were constructed previously, for other purposes, are used. Hence it is important to know the specific features of a station. For the planning station, it is also important to survey the geophysical condition of the planning site.

According to plate tectonics, the lithosphere is split, and it shows relative motion with other plates. The antenna position should correctly reflect the plate motion and/or crustal motion of that area. Usually the antenna position is assumed as the fiducial point. If the antenna foundation is unstable, the delay observable might be changed very slowly due to deformation of the land. Hence, it is vital to know about the coupling between the foundation of the antenna and the lithosphere. The lithosphere is about 100 km thick in land, and it is composed almost entirely of rock. The juncture of antenna foundation and the rock or hard stratum, is investigated in the case of a 26m antenna in Kashima[43]. That antenna structure is shown in Fig.26. The bottom part of the foundation is set about 5 m into the ground. Thirty PC piles are driven into the ground. The height of the antenna in this figure is as high as the depth of the piles. The weight of the antenna above ground is about 1,221 tons, while the underground portion weighs about 1,278 tons. The soil profile is shown in Fig.27. The N-values, representing the hardness of the layers, increases abruptly at about the 30 m depth. It is recognized from these facts that the piles reach this hard stratum, and the weight is dispersed to the stratum. Moreover, the VLBI experiment with a 54 km baseline vector between Kashima and Tsukuba has, since 1984, shown the millimeter level repeatability of the reference point of the 26m antenna in Kashima[44]. Thereby no serious ERP error is expected due to the local motion, but not plate motion, of Kashima station.

Another larger radio telescope was newly developed in Kashima, whose diameter is 34m. Although it has capabilities for wide band astronomical observation from 300 MHz to millimeter wave band (49 GHZ)[45], main purpose is the geodetic VLBI in S/X band to study the plate motion around Japan. And it will participate in IERS also to study Earth rotation. Hence we paid attention also to the 34m antenna foundation when it was constructed because stability of reference point is very important. But it is expected other factors which might cause fluctuation of reference point. Generally speaking, VLBI reference point is more unstable if it has larger aperture than other stations. First, it has larger mechanical structure which affects more thermal expansion due to weather change. Secondly, mechanism of antenna drive is not "king post" type (Kashima 26m), but "track on wheel" type (Kashima 34m and most of larger telescopes). More stability is expected in king post type than track on wheel type drive. To study the problem, "geodimeter" stations were installed in the vicinity of the 34m antenna for the distance measurement by laser between ground points and the VLBI reference point. The precise measurement is in course of preparation.

5. Discussion

It is well known that precise Earth rotation monitoring is one of the excellent capabilities of VLBI technology. However, VLBI networks are still limited in special area on the Earth. To start

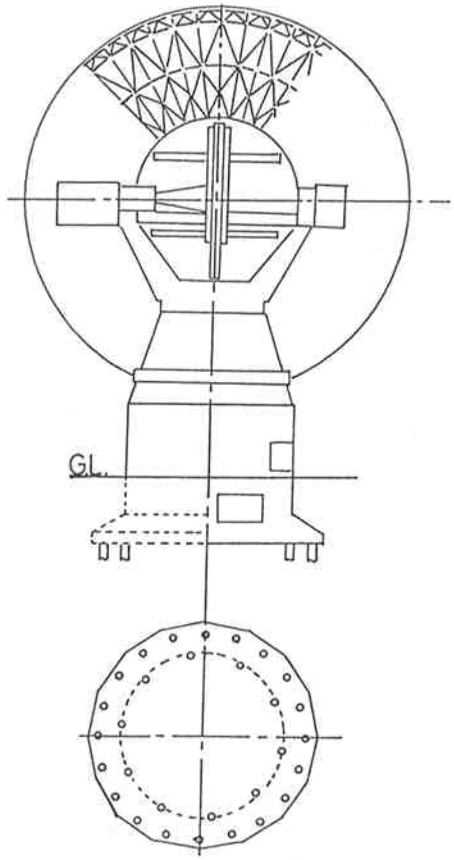


Fig. 26 Structure of the Kashima 26 m antenna.

the international service, there are many problems to overcome, such as establishment of source and station catalog whose data are well distributed on the Earth and celestial sphere, connection between optical and radio source catalog, and connection of terrestrial reference coordinates between different space techniques. One of the ideal ERP monitoring by VLBI in future, is a combination of single and multi baseline monitoring. The GJRO campaign and IRIS-P series are not only for the precise ERP monitoring but also for carrying out pioneering works besides regular IRIS-A series to study the possible problems for the future of IERS particularly in terms of reference frame.

Precession, nutation and ERP (Earth Rotation Parameters) serve as a set of parameters which provide a tie between the CIS (Conventional Inertial System) and the CTS (Conventional Terrestrial reference System). In order to determine these parameters as accurately as possible, it is essential to have a reliable observing system and a consistent reference frame. Since Japan islands locate far from Western countries where most VLBI stations locate, the baseline vector between Kashima station and other stations are considerably long, which mostly determines the precision of ERP results. It can be said Kashima is one of the key stations to have very long baseline.

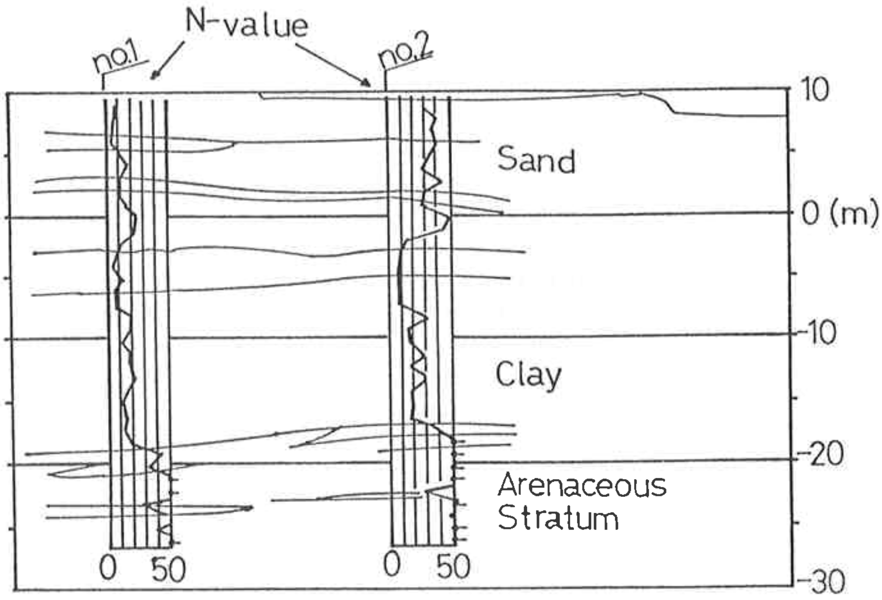


Fig. 27 Soil profile at the 26 m antenna at Kashima.

The K-3 data base system was developed for efficient and reliable data handling in the entire VLBI system for geodesy and Earth rotation monitoring, because the VLBI software system consists of large software sub-system and because the software handles a considerable number of data. The concept of "one data base system for entire VLBI software system" was accomplished in the large K-3 software system. This concept makes clear contrast to the Mark III data base which produces many version of data base. Though Mark III data base has advantage to have evolution following the various attempts of analysis, version number is confusing at the K-3 system because the number of operator and analysist is not one. Moreover, the size of one data base in K-3 is too large to make many versions. Although the data access speed of the K-3 data base is slower than that of Mark III, "data integrity" is ensured in the entire K-3 software system. A data base exchange has been carried out with the Mark III data base format because it is the most common format. The K-3 data base is the first one to cover the entire VLBI software system for geodesy and Earth rotation monitoring. In future, VLBI data base should be accessible by astronomers and geodesists using international computer network. Then data base management system will be more important than the current system. There are a lot of approaches for a VLBI data base design. Better specification of main computer will provide chances to make better data base. K-3 data base is a first step for this goal.

Inconsistencies of the adopted reference frame and the pole coordinates were revealed in the GJRO and IRIS-P experiments through the intercomparison of ERP values from independent networks. The offset in determined ERP set normally indicates an inconsistent solution of VLBI data. Unknown phenomena could also be discovered with independent observations if an offset is unremovable. Thus, it is important to see whether the ERP difference between the independent observations is random. If it is not random, the adopted frame or model should be re-checked. Actually there still remains a few mas difference in UT1 (Fig.17), though major factor of the systematic difference in UT1 results was made clear in Section 4.1.2. The difference is minimal around the date of IRIS-A because the available pole position error is the smallest. And largest error is seen at the date in the almost middle of regular IRIS-A experiments. Moreover the GJRO results are always larger than the INT results except the date when extraordinarily large UT1 error is found in GJRO data. This must be caused by the interpolation error in pole position and the error of determined pole position by IRIS-A.

We used the CDP system to analyze GJRO, as stated in Section 4.1.1. The final obtained UT1 result was reasonable when published IRIS pole positions were introduced. Therefore, the reason for systematic error in the IRIS-P analysis in the CDP system can be concluded that the station position of GRAS and Richmond had not been correctly determined in the CDP system. Though the remaining error is 1 mas on average, it has a few mas fluctuation. One of the reasons for this error is the change of presumed station position caused by crustal deformation and plate motion. The ERP error fluctuates in random. And it is too big to explain the remaining only by this reason, however.

The remained inconsistency in the solution process of GJRO is the introduction of IRIS published pole position into the CDP reference system. Nevertheless analyzed UT1 from GJRO and INT data converged. Moreover the change of adopted reference system does not show clear difference. Thus it is concluded that the difference of CIO position between CDP and IRIS is small.

Formal error of determined UT1 by GJRO baseline is not always smaller than that in INT baseline in spite of longer baseline vector in GJRO. The reason must be in the observation schedule, except the case when a few observation were lost due to troubles. Because the observation was made mostly over 20 degrees in elevation to avoid the atmospheric excess path uncertainty, formal error is larger than one in the case of lower elevation schedule.

The amplitude of the detected fortnightly UT1 variation in the GJRO campaign is slightly higher than expected, by about 5-10%, from the current model, if the fortnightly zonal tide is the main reason for the variation. However, it can not be denied that the obtained amplitude might be affected by an error in the common coefficient which scales the rotational series of tides.

A longer duration experiment which involves a fortnightly term and some dominant tides, such as monthly (Mm) term, could distinguish the two possibilities. The Mm term was not detected from GJRO data because of the short campaign. According to Yoder(7), the common coefficient is also sensitive to errors in the orientations of the Earth. On the other hand, atmospheric effect to the Earth's spin should be also taken into account through the AAM (Atmospheric Angular Momentum)(46) in longer time scale. The long period nutation model should also be improved to determine the UT1 series accurately.

It should be stated that because of the strong dependence of the UT1 determinations from (W_x,W_y), the short-term behavior of the pole should also be monitored by additional daily VLBI sessions whose baseline is relatively in the north-south direction. Since more frequent VLBI observation is necessary to have more resolution in time variation of ERP, the number of experiments will increase. Thus the network configuration should be most effective to have ERP efficiently with small number of stations but with switching the global network to reduce the load of observation. Ideally VLBI network for ERP monitoring should be consisted of orthogonal baselines such as GJRO and other baseline with north-south direction(47).

The GJRO and IRIS-P experiments were carried out only in the northern hemisphere. ERP observations from just the northern hemisphere might produce systematic errors. Moreover, determination of the source position in declination is worse than in right ascension because there are few long N-S baselines. For the next step, it is necessary to have VLBI stations in the southern hemisphere. A global reference frame tied with the southern frame will be done by the process as the IRIS-P station coordinate determination.

It should be stressed that accurate ERP monitoring provides us not only with academic results, such as spectral analysis of UT1 variations[48], but also with a tool to detect environmental problems, such as El Nino[49] and to control a space vehicle in deep space having information of precise direction from the Earth. NASA also stating the importance of ERP study in their SESP (Solid Earth Science Program). They are possible only by considerably long baselines on the Earth, but with international cooperation. Here, consistent reference frame which can be used commonly in the international society, is strongly requested again.

The VLBI station coordinate systems are to be integrated with the coordinates of other space techniques such as SLR[50] for mutual assistance, because VLBI and SLR refer completely independent objects (extragalactic radio sources and satellite orbits). This kind of work is unavoidable for future VLBI network extension and a unified reference frame.

Precise time comparison by VLBI is made between Kashima and Richmond within the IRIS-P experiment. VLBI is thought to be the most powerful method to link the national time standard. Hence, the results is to be affected to the national time and be linked domestically and Asia using space techniques such as GPS and other geostationary satellites with the accuracy better than 10 ns[51]. However, the time comparison between Kashima and Tokyo is required as precise as Kashima and Richmond to complete the international and domestic time synchronization system in 10 ns accuracy.

6. Conclusions

A large-scale K-3 VLBI software system was developed introducing a data base management system. A first attempt was made in K-3 VLBI system to design data base accessible to entire VLBI software system from scheduling to data analysis. It ensures the consistent data handling in VLBI to get precise results of geodesy and Earth rotation. Using K-3 and also Mark III software, VLBI data analysis for Earth rotation measurement, time synchronization and geodesy were done in cooperation with GSFC/NASA, NGS, USNO and a German VLBI group.

The GJRO campaign and IRIS-P experiments are carried out to demonstrate the possibility of this system for the Earth rotation monitoring. The UT1 observation series by GJRO proved the possibility of monitoring UT1 and its spectrum even in short time single-baseline sessions. The formal error of determined UT1 is 0.1 msec in the case of GJRO. And almost identical accuracy is obtained if the pole position is available as accurate as in IRIS-A. The formal error of determined ERP in IRIS-P is almost the same as one from IRIS-A.

It is found that the difference in pole coordinates in BIH and IRIS caused systematic offset in UT1 determination in independent baseline. The GJRO campaign indicated the difference of reference frame in optical and radio systems.

By monitoring the daily UT1 value for 14 days, UT1 results show the discrepancy in the amplitude of fortnightly tidal terms from the Yoder model. It indicates an increase in the term by 5 to 10 % in amplitude. However, an independent daily UT1 monitoring experiment with duration longer than 14 days should be done to confirm this.

The situation was explained how a UT1 offset was caused in an opposite sense by coupling the pole position error from the almost orthogonal geometry of GJRO and INT baseline vectors. it is understood that UT1 is critically dependent on accurate values of pole position.

ERP take an important role in the connection of CIS and CTS. An inconsistent station due to the independent catalog of CDP and IRIS programs caused the systematic ERP error in though each of them is self-consistent[52]. The station coordinate in the IRIS-P is unified using the data from experiments covering both CDP and IRIS stations. The systematic error was due to a difference of the adopted reference frames, or an inconsistency of the reference frame. As a intercomparisons of the ERP[53]-[54] between IRIS-P and -A coincide. In a future daily session of single baseline, a pair of stations should be chosen carefully so that those station coordinates are in a consistent reference frame and monitored frequently, because only small numbers of are adjusted from those data base.

These conclusions are summarized as follows:

(1) A large-scale VLBI software system was developed for global geodesy and Earth rotation in which newly designed data base system is utilized.

(2) Difference of radio and optical reference frame induced systematic error between two series of independent UT1 determination series. The problem was solved by introducing the IRIS pole position as *a priori* value so that data set may be consistent for analysis.

(3) CDP and IRIS station coordinate systems are tied in the IRIS-P data base using another (POLAR) data base.

(4) Through the comparison of determined ERP in both GJRO and IRIS-P experiments, of the adopted reference frame is understood.

(5) According to the determined UT1 series in 14 days by GJRO, it is concluded that the UT1 with fortnightly period indicates the increase of 5-10 % in amplitude.

These efforts demonstrate the future activity of the IERS (International Earth Rotation and future extension of its global network.

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Appendix 1 Tidal Gravitational Potential

If the mass M is located at a distance r from the mass center of the earth (Fig.7), gravitational is expressed as,

$$U = \frac{GM}{2}\frac{a^2}{r^3}(3\cos^2 z - 1), \qquad \text{(A1-1)}$$

where G is Newtonian gravitational constant, a is Earth radius and z is zenithal distance. Using the formula (A1-2), tidal potential U is expressed in (A1-3)[9].

$$\cos z = \sin\phi \sin\delta + \cos\phi\cos\delta\cos H, \qquad \text{(A1-2)}$$

where ϕ is latitude in a geocentric coordinate, δ is the declination of a perturbing body M and H is the local hour angle.

$$U = \frac{3}{4} GM \frac{a^2}{r^3}\{\cos^2\phi\cos^2\delta\cos 2H + \sin 2\phi \sin 2\delta \cos H$$
$$+ 3(\sin^2\phi - 1/3)(\sin^2\delta - 1/3)\} \qquad \text{(A1-3)}$$

Appendix 2 Rotation Matrices

Three principal rotations about the x, y and z axes are expressed in the following forms :

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix}, \qquad \text{(A2-1)}$$

$$R_y(\theta) = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}, \qquad \text{(A2-2)}$$

and

$$R_z(\theta) = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}. \qquad \text{(A2-3)}$$

Appendix 3 IMAGE/1000 Data Base Management System

IMAGE/1000 for the HP-1000 computer is one of the networktype data base management It is designed for efficient data storage and data access having reliability and data integrity of inconsistent data). It is naturally independent of application programs. All data linkages in a base are defined in a schema file with its own language. It has a two-level network hierarchy. One of the data items on each top level data set (master data set) is selected to be a key item for prompt access. A hashing algorithm (Appendix 4) is used for this purpose. There are three kinds of data in IMAGE/1000 such as

(1) Automatic Master Data Set
(2) Manual Master Data Set
(3) Detail Data Set.

(1) and (2) are high level and (3) is low level. Most data are stored in (3). (1) and (2) are often used indices to find data in (3). (1) is particularly useful to search the corresponding entry in (3) quickly because the "hashing algorithm" is adopted here. The addition and deletion of the entry in the Data Set is automatically made in (3) though the number of items in (1) is limited to only one, is the key item. Instead, (2) can have more data items. On the other hand, management of the key has to be done manually by the user.

The interactive data handling language "QUERY" is also available in the IMAGE/1000 system, which is a manual utility to access specific data. Data can be searched, added, deleted and reported by QUERY commands as well as by the FORTRAN program.

Since IMAGE/1000 has only a single precision function, the double precision numbers in the item are replaced by ASCII characters in the K-3 software.

A data base system depends on a magnetic disc as a random access media. A large disc area is necessary for VLBI use. The K3 data base requires a 10 MByte area per experiment of 100 with 5 stations experiment. IMAGE/1000 also provides some tools for monitoring and backing the data base. The disc area for the data base is regularly stored in a magnetic tape using the tools.

DBULD/DBLOD – Only the contained data is stored;
Necessary when a data set size is changed.
Corrupt data base is fixed by this tool.
It takes longer than DBSTR/DBRST
DBSTR/DBRST – Both data and data structure are stored.
WRITT/READT – Disc cartridge back up utility;
This is the quickest way to store the data base.
DBSPA – Data base system status monitoring

Appendix 4 Data Access with Hashing Algorithm

IMAGE/1000 uses a hashing technique to enable prompt data access. Master Data Sets and Data Sets in IMAGE/1000 are linked so that a Master Data Set works as an index file. In quick data access is possible from Automatic Data Set by the hashing technique because the key in a Master Data Set is exploited fully as an index to find the data entry. If one knows the address the key item, a quick data search is easy. However, it is not easy to keep a key-to-address table at If we can convert each key value to the number less than the capacity of the disc area at random, and easy data access is possible. One of the key-to-address transformation techniques is called hashing(55). There can be also a variety of hashing algorithm. A poor hashing algorithm often makes the same address to different key values. This is called a "synonym". If a synonym occurs we add another datum, a different address is assigned to the other datum. As a result, data access becomes slower on average. To avoid the synonym, the address of the key item should be as randomly as possible in a disk. Hashing is a technique which distributes the address of the key uniformly in the storage area(55). In IMAGE/1000 hashing, the capacity of the data set is set to a prime number because the address of the key item is determined as follows:

$$IRN = MOD(KV, IPN), \qquad \text{(A4-1)}$$

where IRN, KV and IPN denote an address of the key item, a key value and a prime number, respectively. Thus IRN is determined as a modulo of KV and IPN. The IRN can be expected to be random in an assigned disc area.

For quick search of an entry regarding a specific observation, an experiment code (ex. and observation number (ex. 0123) are coupled, such as $89JANOlSX0123 because frequent is the expected for this item. It is defined as a key item in the K-3 data base. Up to 16 key items are in one Detail Data Set (bottom level of data set). A reasonable number of keys should be selected so that data access will be efficient.

Appendix 5 KASTL Utilities

KASTL provides utilities of the K-3 data base for programmers. KASTL is designed to the load of the programmer who accesses the K-3 data base by its data handling routines. It the data handling procedure from the application program, which enables memory size of the program to be free from KASTL. The more convenient the data base utility is, the lower response is expected. The capabilities of the computer and the disc space limits the performance of the data There are three major functions in the KASTL utilities.

⟨1⟩ Display of data base status (Data Processing status, Active Data etc.)
⟨2⟩ Access Key number data base handling
⟨3⟩ Deletion of data base (Experiment, Processing)

⟨2⟩ has important functions. Common or frequent procedures which use the data base system are invoked by specifying an access key number. The access key number is classified for reading/writ- and corresponding data sets. One key number usually consists of some IMAGE/1000 calls. Addition and deletion of the access key is possible by the user. ⟨3⟩ is also important because the of one experiment located on many data sets should be consistently deleted automatically. the remaining data will fill up the limited disc area.

Table Ap-1 Data base item correspondence

(a) Table of contents for TOC type (1) of Mark III data base

(Mark III)						(K-3)				
LCODE	DIM			TYPE	UNITS	DSET	ITEM	TYPE	UNITS	PROD.
SITERECS	3	N	1	R	m	#STOBS	XYZ	3X24	m	T
SITEZENS	N	1	1	R	ns	#FDELY	ZPATH	2R2	s	MBOX
STAR2000	2	N	1	R	rad	#STAR	RA,DEC	4I15I1	rad	A
AXISOFFS	N	1	1	R	m	#ANTNA	OFSET	R2	m	T
COR DATA	2	1	1	R	- -	#MATH	NUMBER	X24	- -	C
ETD DATA	3	1	1	R	- -	#MATH	NUMBER	X24	- -	C
PRE DATA	1	1	1	R	- -	#MATH	NUMBER	X24	- -	C
REL DATA	1	1	1	R	- -	#MATH	NUMBER	X24	- -	C
PI	1	1	1	R	- -	#MATH	NUMBER	X24	- -	C
VLIGHT	1	1	1	R	m/s	#MATH	NUMBER	X24	m/s	C
ACCELGRV	1	1	1	R	m/s/s	#MATH	--	--	m/s/s	--
EARTHRAD	1	1	1	R	--	<None>	--	--	--	--
E-FLAT	1	1	1	R	--	<None>	--	--	--	--
DNP DATA	1	1	1	R	--	<None>	--	--	--	--
ROTEPOCH	2	2	1	R	--	#PMDL	RTEPOC	20X24	--	X
UT1EPOCH	2	2	1	R	--	#PMDL	UTEPOC	20X24	--	X
WOBEPOCH	2	2	1	R	--	#PMDL	WBEPOC	20X24	--	X
# SITES	1	1	1	I	--	#EXPER	SITE	I1	--	X
# STARS	1	1	1	I	--	#EXPER	VALUE	I1	--	X
AXISTYPS	N	1	1	I	--	#ANTNA	TYPE	X6	--	T
DELTFLAG	1	1	1	I	--	<None>	--	--	--	--
INTERVAL	5	2	1	I	--	#OBSAT	--	--	--	OX
NUMB OBS	1	1	1	I	--	#EXPER	NO	I1	--	X
SITNAMES	4	N	1	A	--	#EXPER	--	--	--	--
STRNAMES	4	N	1	A	--	#OBSAT	SATAR	X8	--	OX
ERROR K	2	1	1	R	--	#INFER	ERROR	2X24	--	--
CBL SIGN	10	1	1	A	--	<None>	--	--	--	--
CBL STAT	4	10	1	A	--	#EXPER	SITE	--	--	--
WVR STAT	4	20	1	A	--	#EXPER	SITE	--	--	--
MARISTAT	4	20	1	A	--	#EXPER	SITE	--	--	--
ERROR BL	4	2	1	A	--	#INFER	BASEID	X2	--	--

(c) Table of contents for TOC type (3) of MK-III Data base

(Mark III)						(K-3)				
LCODE	DIM			TYPE	UNITS	DSET	ITEM	TYPE	UNITS	PROD.
SEC TAG	1	1	1	R	s	#OBSAT	PRT	5I1	s	OX
REF FREQ	1	1	1	R	MHz	#BAND	FREQ	R2	Hz	MBOX
UTC TAG	5	1	1	I	--	#OBSAT	PRT	5I1	--	OX
STAR ID	4	1	1	A	--	#OBSAT	STAR	X8	--	OX
BASELINE	4	2	1	A	--	#FDELY	BASEID	X2	--	MBOX
RATOBSVM	1	1	1	R	s/s	#BAND	CPDELY	2X24	s/s	MBOX
INCOHAMP	1	1	1	R	--	#BAND	FAMP	R2	--	MBOX
SRCHPAR	6	1	1	R	s,s/s	#BAND	SAERCH	8R2	s,s/s	MBOX
FALSEDET	1	1	1	R	%	#BAND	FDETCT	R2	%	MBOX
INCOH2	1	1	1	R	--	#BAND	SEGAMP	R2	--	MBOX
GCRESPHS	1	1	1	R	deg	#BAND	PHRD	R2	deg	MBOX
DELTAEPO	1	1	1	R	s	#BAND	CEPOCH	5I1	s	--
EFF.DURA	1	1	1	R	s	#BAND	EVTIME	R2	s	MBOX
DISCARD	1	1	1	R	%	#BAND	DSTATA	R2	%	MBOX
TOTPCENT	1	1	1	R	deg	#BAND	TPHASE	3R3	deg	MBOX
DELOBSVM	2	1	1	R	us	#BAND	CPDELY	2X24	s,s/s	MBOX
DLYEPO+1	2	1	1	R	us	#BAND	PHASDY	3X24	s	MBOX
DLYEPO-1	2	1	1	R	us	#BAND	PHASDY	3X24	s	MBOX
VLB2 UTC	6	1	1	I	--	#BAND	DATE	4I1	--	MBOX
UTCM TAG	6	1	1	I	--	#BAND	CEPOCH	5I1	--	MBOX
PROC UTC	2	14	1	I	--	#CORRI	DATE	4I1	--	SBOX
ERRORATE	2	2	14	I	--	#BAND	TAPERR	56R2	--	MBOX
CORBGASCD	1	1	1	A	--	#FDELY	BASEID	X2	--	MBOX
FRQGROUP	1	1	1	A	--	#BAND	SUBID	X2	--	MBOX
TAPQCODE	3	1	1	A	--	#BAND	QUALTY	X6	--	MBOX

Producing factor

X = Experiment
R = Raw tape
T = Station
A = Star
O = Observation
S = KROSS RUN

B = Baseline
F = Frequency code
M = KOMB RUN
L = KLEAR RUN
C = Constant
D = Day

list between Mark III and K-3

(b) Table of contents for TOC type (2) of MK-III Data base

	(Mark III)						(K-3)			
LCODE	DIM			TYPE	UNITS	DSET	ITEM	TYPE	UNITS	PROD.
DELTFLAG	1	1	1	I	--	<None>	--	--	--	--
DEL FRQS	1	1	1	R	MHz	#BAND	FREQ	R2	Hz	MBOX
RAT FRQS	1	1	1	R	MHz	#BAND	FREQ	R2	Hz	MBOX
SEC TAG	1	1	1	R	s	#OBSAT	PRT	5I1	s	OX
RFREQ	14	1	1	R	MHz	#BAND	FQTABL	28R2	Hz	MBOX
REF FREQ	1	1	1	R	MHz	#BAND	FREQ	R2	Hz	MBOX
RAT OBSV	1	1	1	R	s/s	#BAND	GPDELY	2X24	s/s	MBOX
SB DELAY	1	1	1	R	us	#BAND	NBGDLY	X24	s	MBOX
GPDLAMBG	1	1	1	R	deg	#BAND	GDLYAM	R2	s	MBOX
APCLOFST	1	1	1	R	us/s	#CORRI	ACLKER	X24	s	SBOX
AMPBYFRQ	2	14	1	R	deg	#BAND	AMP	28R2	deg	MBOX
PHASECAL	2	1	1	R	us/s	#BAND	PRATE	2R2	s/s	MBOX
DELRESID	1	1	1	R	s	#BAND	KROSER	R2	s	MBOX
DELSIGMA	1	1	1	R	s/s	#BAND	DLYERR	R2	s	MBOX
RATSIGMA	1	1	1	R	--	#BAND	DRERR	R2	s/s	MBOX
COHERCOR	1	1	1	R	--	#BAND	RVALUE	R2	--	MBOX
TOTHASE	1	1	1	R	deg	#BAND	TPHASE	3R3	deg	MBOX
UVF/ASEC	2	1	1	R	Fr/ds	#CORRI	U,V	X24	Fr/s	SBOX
STARELEV	2	1	1	R	rad	#CORRS	SOAZEL	2X24	s/s	SBOX
URVR	2	1	1	R	MHz/aS	#CORRI	UF,UV	X24	Hz/aS	SBOX
SBRESID	1	1	1	R	s	#BAND	RSDUAL	R2	s	MBOX
SNRATIO	1	1	1	R	--	#BAND	SNR	R2	--	MBOX
GC PHASE	1	1	1	R	deg	#BAND	TPHASE	3R2	deg	MBOX
STARTSEC	1	1	1	R	s	#BAND	TIME	8I1	--	MBOX
STOP SEC	1	1	1	R	s	#BAND	TIME	8I1	--	MBOX
SB SIGMA	1	1	1	R	us	#BAND	SDLYER	R2	s	MBOX
DEL OBSV	2	1	1	R	us	#BAND	GPDELY	2X24	s	MBOX
JUL DATE	1	1	1	R	--	<None>	--	--	--	--
ATM PART	2	2	1	R	--	#FERD	MODLID	4X24	--	MBOX
ATM CONT	2	2	1	R	--	#FERD	MODLID	4X24	--	MBOX
EL-THEO	2	2	1	R	deg	#FDELY	EL	4X24	deg	MBOX
AZ-THEO	2	2	1	R	deg	#FDELY	AZ	4X24	deg	MBOX
AXO PART	2	2	1	R	--	#FERD	MODLID	4X24	--	MBOX
COR PART	2	2	1	R	--	#FERD	MODLID	4X24	--	MBOX
DNP PART	2	1	1	R	--	#FERD	MODLID	4X24	--	MBOX
ETD PART	3	2	2	R	--	#FERD	MODLID	4X24	--	MBOX
NUT PART	2	2	1	R	--	#FERD	MODLID	4X24	--	MBOX
PRE PART	2	1	1	R	--	#FERD	MODLID	4X24	--	MBOX
REL PART	2	1	1	R	--	#FERD	MODLID	4X24	--	MBOX
SIT PART	3	2	2	R	--	#FERD	MODLID	4X24	--	MBOX
STR PART	2	2	2	R	--	#FERD	MODLID	4X24	--	MBOX
UT1 PART	2	2	1	R	--	#FERD	MODLID	4X24	--	MBOX
WOB PART	2	2	1	R	--	#FERD	MODLID	4X24	--	MBOX
CT SITE1	1	1	1	R	--	#FDELY	CT	X24	--	MBOX
THODELAY	2	1	1	R	us	#FDELY	TAU	X24	s	MBOX
THODRATE	1	1	1	R	s/s	#FDELY	TAU1	X24	s/s	MBOX
MARI.ATM	2	2	2	R	--	#PROFI	WVRPAS	R2	--	TOX
TEMP C	2	2	1	R	deg.C	#PROFI	TEMP	R2	deg.C	TOX
ATM PRES	2	2	1	R	mBar	#PROFI	PRES	R2	mBar	TOX
REL.HUM.	2	2	1	R	%	#PROFI	HUMID	R2	%	TOX
CABL DEL	2	2	1	R	s,s/s	#PROFI	INSTR	2R2	s,s/s	TOX
ION CORR	2	1	1	R	s, s/s	#PROFI	IONOS	2X24	s,s/s	TOX
IONSIGMA	2	1	1	R	s, s/s	#PROFI	SIGMA	2X24	s,s/s	TOX
UTC TAG	5	1	1	I	--	#OBSAT	PRT	5I1	--	OX
RECSETUP	3	1	1	I	--	#CORRI	RATE	X24	--	SBOX
#CHANELS	1	1	1	I	--	#BAND	--	--	--	--
NO.OF AP	2	14	1	I	--	#BAND	PP	28I1	--	MBOX
DELUFLAG	1	1	1	I	--	#BAND	D#	I1	--	MBOX
# DELAYS	1	1	1	I	--	<None>	--	--	--	--
# RATES	1	1	1	I	--	<None>	--	--	--	--
# AMBIG	1	1	1	I	--	#BAND	AMBIG#	I1	--	MBOX
CALBYFRQ	3	2	14	I	--	#BAND	PCTABL	56R2	--	MBOX
ION CODE	1	1	1	I	--	#PROFI	CIONOS	I1	--	TOX
STAR ID	4	1	1	A	--	#OBSAT	STAR	X8	--	OX
BASELINE	4	2	1	A	--	#FDELY	BASEID	X2	--	MBOX
VLB1FILE	3	1	1	A	--	#CORRI	FILECR	X6	--	SBOX
QUALCODE	1	1	1	A	--	#BAND	KOMCOD	X2	--	MBOX

Appendix 6 Data Base Set up Routine

Before starting the VLBI data reduction and data analysis, a new data base has to be created, and certain items in the data base have to be prepared. The preparation is made by a data base set up routine. Most data are available from both the original schedule file and logging data files of each station. The schedule file is used to create the structure of each experiment data base, while logging files are used to fill the subsidiary data such as temperature, relative humidity and pressure in the data base. In addition to these data, *a priori* Earth rotation parameters and an ephemeris set in the data base. The software called "KASET" is designed for the data base set up[56]. Since data entry is random accessible in the K-3 data base, it is not necessary to sort the logging data of each station in a time sequence for setting up one experiment data base. This ensures quick data input. KASET is also used for data base checking and monitoring. Major functions of KASET are as follows:

(1) From the original schedule file, experiment code, stations, sources, observations time) and recording tape management are set into the data base.
(2) From log files, weather data, WVR (Water Vapor Radiometer) data and system noise temperature are set into the data base. Each observation is identified by ST (tape start) and ET (tape stop) command pair in the logging file.
(3) *A priori* Earth Rotation Parameters are picked up from a publication such as the IERS bulletin, and set into the data base.
(4) From the JPL ephemeris tape, every 32 days' Chebyshev interpolation coefficients on ephemeris are set into the data base.
(5) Deletion of experiment code.
(6) Empty data item is checked and alarmed.
(7) Display of the data base.

It is currently common to send the data base in a Mark III format tape when VLBI data is between institutions. Hence a data base conversion utility has been made between K-3 and Mark III in an HP-1000 computer. The item to item correspondence is shown in Table Ap-1[57]. The data item does not always correspond one to one because the structure of the data base is different. the structure of the Mark III data base tape is open, efforts are also successfully made to convert data to our main frame computer (ACOS-850).

References

(1) Carter, W. E., Robertson, D. S. and Nothnagel, A., Nicolson, G.D., Schuh, H. and J.: "IRIS-S: Extending Geodetic Very Long Baseline Interferometry Observations to the Hemisphere", J. Geophys. Res., 93, B12, pp.14947-14953, 1988.
(2) Kondo, T., Heki, K. and Takahashi, Y.: "Pacific Plate Motion Detected by the VLBI Conducted in 1984-1985", J. Rad. Res. Labs., 34, 141, pp.1-14, 1987.
(3) Kawaguchi, N., Amagai, J., Kuroiwa, H., Takahashi, F., Yamamoto, K., Yun-Fei, Z., W. and Tong-Shan, W.: "The First Japan-China VLBI Experiment", J. Rad. Res. Labs., 141, pp.15-29, 1987.
(4) Thompson, A.R., Moran, J.M. and Swenson, G.W.: "Interferometry and Synthesis in Radio Astronomy", Wiley Interscience, 1986.
(5) Lambeck, K. : "The Earth's Variable Rotation : Some Geophysical Causes", Proc. IAU No.128, pp.1-20, ed. Babcock,A.K., 1986.

(6) Moritz, H. and Mueler, I.I.: "Earth Rotation", Ungar, 1987.
(7) Yoder, C.F., Williams, J.G. and Parke, M.E.: "Tidal Variations of Earth Rotation", J. Geophys. Res., 86, B2, pp.881-891, 1981.
(8) Schuh, H.: "Die Radiointerferometrie auf langen Basen zur Bestimmung von Punktverschiebungen und Erdrotationsparametern", Dissertation, Munich, 1987.
(9) Melchior, P.: "The Tides of the Planet Earth", PergamonPress, 1978.
(10) Hide, R., Birch, N. T., Morrison, L. V., Shea, D. J. and White, A. A. : "Atmospheric angular momentum fluctuations and changes of the day", Nature, 286, pp.114-117, July, 1980.
(11) Kawaguchi, N., Sugimoto, Y., Kuroiwa, H., Kondo, T., Hama, S., Amagai, J., Morikawa, T. and Imae, M.: "K-3 VLBI Hardware System Being Developed in Japan and its Capability", IAG Tokyo, 1982.
(12) Ma, C.,: "Very Long Baseline Interferometry Applied to Polar Motion, Relativity and NASA Technical Memorandum, 79582, 1978.
(13) Lieske, J.H.: "Expression for the precession quantities based upon the IAU (1976)system of astronomical constants", Astron. Astrophys., 58, pp.1-16, 1977.
(14) Green, R.M.: "Spherical Astronomy", Cambridge University Press, 1985.
(15) Robertson, D.S., Fallon, F.W. and Carter, W.E.: "Celestial reference coordinate systems: precision demonstrated with VLBI observations", Astron. J., 91, 6, 1986.
(16) Takahashi, Y., Kawaguchi, N., Heki, K., Kunimori, H. and Kondo,T. : "Celestial Reference Coordinate System of VLBI with US-Japan Joint VLBI Experiments", Proc. IAU Symp., pp.83-89, ed. Babcock, A.K., 1986.
(17) Ma, C., Shaffer, D.B., De Vegt, C., Johnston, K.J. and Russell, J.L.: "A radio optical reference frame. I. Precise radio source positions determined by Mark III VLBI: Observations from 1979 to 1988 and a tie to the FK5", Astron. J., 99, 1990.
(18) Takahashi, F., Yoshino, T., Murakami, H., Koike, K., Kunimori, H. and Kondo, T. : "K-3 VLBI Software Development for International Experiments", IAG Tokyo, 1982.
(19) Yoshino, T., and Koike, K.: "Part IV. K-3 VLBI Data Analysis Software, IV-2. The of data base system", Rev. Radio Res. Labs., 30, Special Issue on "K-3 System development" (in Japanese), Nov. 1984.
(20) Vandenberg, N.R., Corey, B.E., Mowles, K.N., Foster, L.N., Whitney, A.R. and Ma, C.: Mark III Field System documentation Ver.5.0, 1984.
(21) Yoshino, T., and Koike, K.: "Part IV. K-3 VLBI Data Analysis Software, IV-7. The software", Rev. Radio Res. Lab., 30, Special Issue on "K-3 System development" (in Japanese), Nov. 1984.
(22) Vandenberg, N.R.: "Scheduling Program", Mark III Software Documentation, 1982.
(23) Kaneko, A., Murakami, H., Kozono, S., Takahashi, F. and Yoshino, T.: "Development of VLBI Automatic Operation Software", J. Rad. Res. Labs., 32, 137, pp.155-166, 1985.
(24) Kunimori, H. and Hama, S.: "Part III. K-3 VLBI Data Processing System, III-4. Cross-correlation and data acquisition software"", Rev. Radio Res. Labs., 30, Special Issue on "K-3 System development" (in Japanese), Nov.1984.
(25) Kondo, T. and Kunimori, H.: "Part III. K-3 VLBI Data Processing System, III-5. Bandwidth Synthesizing Software (KOMB)", Rev. Radio Res. Labs., 30, Special Issue on "K-3 System development" (in Japanese), Nov.1984.
(26) Rogers, A.E.E.: "Very long baseline interferometry with large effective bandwidth for measurements", Radio Science, 5, 10, pp.1239-1247, 1970.

(27) Takahashi, F. and Yoshino, T.: "Part IV. K-3 VLBI Data Analysis Software, IV-6. Parameter estimation software", Rev. Radio Res. Labs. 30, Special Issue on "K-3 System (in Japanese), Nov.1984.

(28) Takahashi, Y. and Manabe, S.: "Part IV. K-3 VLBI Data Analysis Software, IV-5. "A priori physical model software", Rev. Radio Res. Labs., 30, Special Issue on "K-3 System (in Japanese), Nov.1984.

(29) Melbourne, W., Anderle, R., Feissel, M., King, R., McCarthy, D., Smith, D., Tapley, B., Vincente, R.: "MERIT Standard", United States Naval Observatory Circular, 167, 1983.

(30) Heki, K.: "Kalman Filtering Technique for Very Long Baseline Interferometry", Journal of Geodetic Society of Japan, Vol.33, No.4, pp.337-345, 1987.

(31) Yoshino, T., Hama, S., Shiomi, T., Campbell, J., Cloppenburg, H., Schuh, H. and Kilger, "First VLBI Experiments between Kashima and Wettzell for Monitoring UT1", Adv. Space Res. Vol.6, No.9, pp.13-16, 1986 (XXVI COSPAR).

(32) Bureau International de l'Heure: 1987: "ANNUAL REPORT FOR 1986".

(33) Ryan, J.W. and Ma, C.: "Crustal Dynamics Project Data Analysis (Fixed Station VLBI Results)", NASA Technical Memorandum 86229, Goddard Space Flight Center, NASA, 1985.

(34) Robertson, D.S., Carter, W.E., Campbell, J. and Schuh, H.: "Daily Earth Rotation from IRIS Very Long Baseline Interferometry", Nature, 316, pp.424-427, 1985.

(35) Yoshino, T., Takahashi, Y., Kawaguchi, N., Heki, K., Yokoyama, K. and Manabe, S.: "Intercomparison of the Earth rotation parameters determined by two independent VLBI networks", Astron. Astrophys., 224, pp.316-320, 1989.

(36) Bureau International de l'Heure: 1986: "ANNUAL REPORT FOR 1985".

(37) Ryan, J.W. and Himwich, W.E.: "Toward a unified terrestrial coordinate system", Proc. IAU Symp., No.128, p.121-129, ed. Babcock, A.K. 1986.

(38) Yoshino, T. and Ojima, T.: "Total Instrumental Delay Measurement", Rev. Radio Res. 24, No.130, Sept.1978 (in Japanese).

(39) Hama, S., Yoshino, T., Kiuchi, H., Morikawa, T., Sato, T., Shiomi,T., Takahashi, F. and Klepczynski, W.J.: "First International Time and Frequency Comparison Experiment by Very Long Baseline Interferometry", J. Rad. Res. Labs.,34,142, pp.85-93, 1987.

(40) Yoshino, T., Koike, K., Kiuchi, H., Morikawa, T. and Sato,T.: "Japan-USA VLBI Time Experiments", Proceedings of the Symposium on Relativistic Framework and New Techniques in Astrometry and Geodesy, Kashima(Japan), 1984.

(41) Kuroiwa, H. and Kawaguchi, N.: "Part II. K-3 VLBI Data Acquisition System, II-ll. Water Vapor Radiometer", Rev. Radio Res. Labs., 30, Special Issue on "K-3 System development" (in Japanese), Nov.1984.

(42) Hanada, H., Tsubokawa, T., Tsuruta, S. and Yoshino, T.: "Collocative Measurements by Absolute Gravimeter at the VLBI Station, Kashima", Journal of the Geodetic Society of Vol.34, Nos. 3-4, pp.177-184, 1988.

(43) Yoshino, T. and Takahashi, F.: "Investigation of Geophysical Conditions at Kashima VLBI Station", IAG, Tokyo, 1982.

(44) Kawaguchi, N., Kurihara, N., Amagai, J., Takahashi, F. and Yoshimura, Y.: "Millimeter Accuracy of Geodetic VLBI Measurements Achieved on a 54-km Baseline", IEEE-IM, 38, pp.668-671, April, 1989.

(45) Yoshino, T., Kuroiwa, H.: "Outline of Whole System", Rev. Commun. Res. Lab., 36, Special Issue on Development of Western Pacific VLBI Network (in Japanese), No.8, Jan. 1990.
(46) Rosen, R.D., Salstein, D.A., Eubanks, T.M., Dickey, J.O. and Steppe, J.A. : "An El Nino in Atmospheric Angular Momentum and Earth Rotation", Science, 225, pp.411-414, 1984.
(47) Yoshino, T., Takahashi, F. and Yokoyama, K.: "Earth Rotation Monitoring with VLBI Baselines", Western Pacific Geophysics Meeting (Kanazawa, Japan), 1990.
(48) Schuh, H.: "Analysis of UT1 Determinations by VLBI within Project IRIS", Proc. IAU Symp., No.128, p.171-180, ed. Babcock, A.K., 1986.
(49) Carter, W. E., Robertson, D. S., Petty, J.E., Tapley, B.D., Schutz, B.E., Eanes, R.J. and Lufeng, M.: "Variations in the Rotation of the Earth", Science, 224, pp.957-961, June, 1984.
(50) Dickey, J.O., Fanselow, J.L. and Melbourne, W.G.: "The Earth's Rotation and Reference Frames for Geodesy and Geodynamics", Proc . IAU Symp . No .128, pp . 41-47, ed. Babcock, A.K., 1986.
(51) Yoshimura, Y., Imae, M., Urazuka, M., Morikawa, T., Yoshino, T., Kobayashi, S. and T.: "Research Activities on Time and Frequency Transfer Using Space Links", Proc. IEEE, 74, No .1, pp .157-160, Jan. 1986.
(52) Mallama, A., Clark, T.A. and Ryan, J.W.: "The Earth's Rotation and Reference Frames Geodesy and Geodynamics", Proc. IAU Symp., No. 128, pp. 187-192, ed. Babcock, A.K., 1986.
(53) Eubanks, T.M., Steppe, J.A. and Spieth, M.A.: "The accuracy of Radio Interferometric of Earth Rotation", TDA Progress Report 42-80, pp . 229-235, 1984.
(54) Nothnagel, A., Nicolson, G. D., Schuh, H., Campbell, J., Cloppenburg, H. and Kilger, R.: Earth's Rotation and Reference Frames for Geodesy and Geodynamics", Proc. IAU Symp., No.128, pp.193-198, ed. Babcock,A.K., 1986.
(55) Wiederhold, G.: "Database Design", McGrawhill, 1983.
(56) Takahashi, Y. and Kondo,T.: "Part IV. K-3 VLBI Data Analysis Software, IV-3 . "Data Base Set-Up Software", Rev. Radio Res. Labs., 30, Special Issue on "K-3 System development" (in Japanese), Nov. 1984.
(57) Koike, K. and Yoshino, T.: "Part IV. K-3 VLBI Data Analysis Software, IV-4. "Data Base Utilities", Rev. Radio Res. Labs., 30, Special Issue on "K-3 System development" (in Nov .1984.
(58) Carter, W. E., Robertson, D. S. and MacKay, J. R.: "Geodetic Radio Interferometric Applications and Results", J. Geophys. Res., 90, B6, pp.4577-4587, 1985.
(59) Rochester, M. G.: "Causes of fluctuations in the rotation of the Earth", Philos. Trans. R. Lond. A313, pp.95-105, 1984.

Abbreviations

AAM	1a1Atmospheric Angular Momentum
BIH	Bureau International de l'Heure
CDP	Crustal Dynamics Project
CIS	Conventional Inertial System
CRL	Communications Research Laboratory
CTS	Conventional Terrestrial reference System
ERP	Earth Rotation Parameters

GAST	Greenwich Apparent Sidereal Time
GJRO	German-Japanese Earth Rotation Observations
GRAS	George R. Agassiz Station
GSFC	Goddard Space Flight Center
IERS	International Earth Rotation Service
IRIS	International Radio Interferometric Surveying
IRIS-A	IRIS Atlantic Network
IRIS-P	IRIS Pacific Network
IRIS-S	IRIS South Network
KSRC	Kashima Space Research Center
MERIT	International program to Monitor Earth Rotation and Intercomparison of Techniques
NASA	National Aeronautics and Space Agency
NGS	National Geodetic Survey
RF	Radio Frequency
SLR	Satellite Laser Ranging
UT	Universal Time
UTC	Coordinated Universal Time
VLBI	Very Long Baseline Interferometry
WVR	Water Vapor Radiometer
ZBI	Zero Baseline Interferometer