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III. VLBI SYSTEM

III. 5 K-3 SOFTWARE SYSTEM FOR VLBI AND NEW CORRELATION PROCESSING SOFTWARE FOR K-4 RECORDING SYSTEM

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ABSTRACT

Communications Research Laboratory (CRL) has been conducting joint Japan-USA VLBI experiments with NASA in a crustal dynamics project (CDP) since 1984. CRL developed its own software system for the VLBI experiments to process and analyze the data. We have named this the "K-3" software system. The software system consists of 8 software programs for scheduling, data base handling, data base setting, correlation processing, bandwidth synthesizing, tape format converting, a priori calculating and parameter estimating. We were successful in the VLBI experiments due to the use of this software system.

Due to the many VLBI experiments being conducted around the world, a new high density recording system was requisite. CRL developed the new "K-4" recording system. Correlation processing software for the new recording system was developed with personal computer using BASIC language. The K-3 software system and the new correlation software are both described in this paper.

1. Introduction

VLBI started in the USA and Canada in 1967. The "Mark-III" VLBI system has been used worldwide since 1975. Using Mark-III software as a basis, we developed our own software system (K-3 software system) to correlate and analyze the data. Considerations in developing the software system were as follows:

1) that all software should be systematized to use the same data base and the same physical model;
2) its data base should be developed independently by CRL;
3) it should be compatible with the Mark-III system;
4) it should introduce its own conceptual and physical model.

The software system was developed from 1981 to 1984. As the basic algorithm for each software program is almost the same as for Mark-III software, compatibility is possible.

The software system consists of 8 software programs namely; scheduling software (KASER), data base setting software (KASET), correlation processing software (KROSS), bandwidth synthesis software (KOMB), tape format conversion software (KONV), a priori calculation software (KAPRI), parameter estimation software (KLEAR) and data base handling software (KASTL). Figure 1 shows the software system. Our "K-3 data base" combined all software program from scheduling to analysis.

Due to the many VLBI experiments being conducted around the world, the operation and correlation of data has became increasing labors. Furthermore, the transportation of tapes was expensive. Therefore new higher density recording systems were developed. CRL developed a new system of recording, the "K-4" system(1). It is very difficult to try to modify old correlation processing software (KROSS) for use in the "K-4" recording system. Therefore, new correlation processing software had to be developed for the new "K-4" recording system using a personal computer and BASIC language. We show that a minicomputer is not necessary for correlation processing on several baselines, and that a personal computer is available for correlation processing. The new software was used for VLBI experiments and the results are also described.

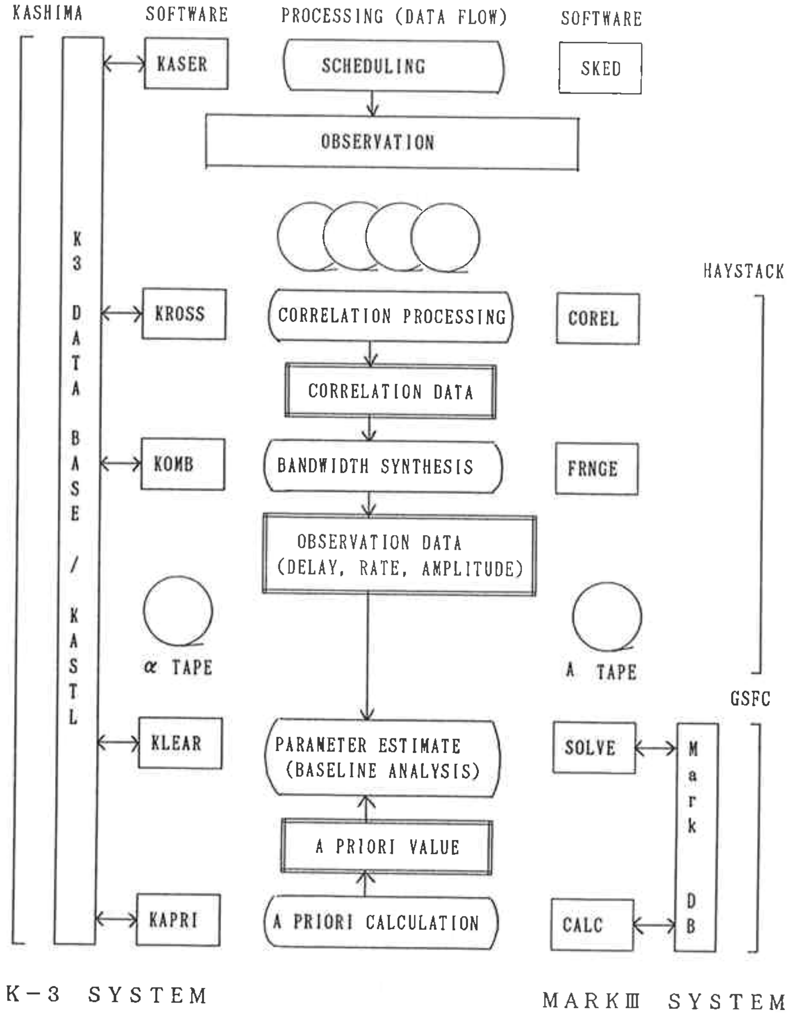

Fig. 1 Correlation and analysis software for K-3 system.

2. K-3 Software System

The development of the K-3 software system began in 1981 at the Kashima Space Research Center. We created 8 software programs to process and analyze the data for the joint Japan-USA VLBI experiments. All software programs use the same data base ("K3 data base"). The transfer of data between each software program is through the K3 data base. The data base is the basis of our system.

2.1 K3 Data Base

There are 3 types of data necessary for the geodetic VLBI as described below.

(1) First, essential data are the observation data as follows:

1) Bandwidth synthesis data (observation delays and rates, correlated amplitude, phase calibration data, observation time);

2) Calibration data (weather data and delay calibration).

(2) Second, basic data is as follows:

3) Source and station information;

4) Ephemeris data and earth rotation parameters;

5) Correlation data;

6) Propagation delay (atmospheric and ionospheric delay).

(3) Third is data for a priori calculation and analysis:

7) A priori delays, rates and calculation models;

8) The differential coefficient and contribution of each physical model;

9) Physical and mathematical constants;

10) Ocean tide and earth tide;

11) Nutation and precession constants.

VLBI data base manages all these items and many real data of each item. There are primarily 3 types of data base for VLBI such as the Mark-III, NGS format data file and K-3 data base. The NGS format data file including only the essential and basic data of items 1)-6), is a very compact data base, but requires the calculation of a priori values each time when baseline analysis is made. The NGS format data file is not suitable for the VLBI analysis of many experiments (global analysis). The Mark III data base includes all data, and data can be transferred easily to the data base using convenient software (data base handler). Mark-III is most familiar in the CDP VLBI group and this data base is used to transfer VLBI data. As the data for each experiment are in one file, data access is sequential not allowing random access. However, the Mark-III data base poses no problems in analysis since all data are read sequentially at the beginning of an analysis. At the first record of a file, the correspondence between each item and the position of each record is defined. Data are handled under the definition for each observation. It is unsuitable for the minor modification of values or random access for reading and updating. Our "K-3 data base" has both random and sequential access.

The K3 data base uses the data base utility of the IMAGE-1000 for the Hewlett Packard minicomputer (HP1000). The data base consists of management files (Master Data Set) which have key items and their addresses, and data files (Detail Data Set) which contain chain information and real values. The data are classified according to individual attributes such as the data for 1)–11). Also, data are combined for common attributes, and the key word (key item) of the attribute is added. The data base is made up of the network of key items which are linked to detail values. The data for each item can be easily accepted at random by selecting the key item. The K-3 data base is useful for random access, that is, the reading and modification of individual items. All software can use the same values and data is transferred between software through the common data base. No inconsistencies exist for common values, such as physical constants, positions of sources and stations for all software. However, the sequential access for the K-3 data base is slower than that for the Mark-III data base. The K-3 data base requires a large region of the disk and any change in the structure would be laborious. The Mark-III data base is better in a minicomputer since access speed is a serious problem, but a K-3 data base is better in a high performance computer.

As the format for the K-3 data base is different from the Mark-III, transformation software between these two data bases was created. We made transformation software for the Mark-III format to send the results of our experiments to other VLBI groups.

2.2 Data Base Handler for K-3 Data Base (KASTL)

We can enter, read, update or delete data in the data base by using the IMAGE-1000 for the HP-1000 computer. However, the programing to make full use of its utility is complicated. We derived a data base handler to reduce programing efforts. An access number is used for this data base handler. The data used in the K-3 software system is classified in some data groups, and the access number is in addition to each data group. When we want to read the data group, we select the access number. We can easily obtain the data in the returned buffer. When we want to place the data, the access number and the update values are entered. This access method is used for all software.

2.3 Scheduling Software (KASER)

The "KASER" software was developed to schedule VLBI observations. This software has almost the same function as the scheduling software (SKED) of MARK-III. Both KASER and SKED make the 3 files which needed to conduct VLBI experiments. One is an original schedule file, the second is a SNAP schedule file and the third is a procedure file.

KASER initially makes the original schedule file. It has all the information required for VLBI experiments, such as observation sources and their positions, observation stations and their positions, antenna control parameters, frequency information, and the information for each observation. The information for sources, stations, frequencies and antennas is taken from the data base. The information for each observation includes the source, start time, duration, observing stations and tape counters for individual stations.

The SNAP file and the procedure file are made next with KASER from the original schedule file for each station. These contain the sequence of commands for observation, such as source tracking, the start and stop times of recorder, obtaining the calibration data and setting the frequency of video convertors and formatter mode. The format for commands is compatible with all the VLBI stations of MARK-III. The procedure files include common commands for one experiment and the SNAP files include the commands for each observation. The antenna and VLBI terminal are operated by 2 files at usual VLBI stations. Nevertheless, the new 34 m antenna is operated not by SNAP and procedure files but only the original schedule file, since the original schedule file includes all observation information and transformation to SNAP is not required.

2.4 Data Base Setup Software (KASET)

Data base setup software (KASET) sets various data for VLBI into data base. The main data are as follows:

1) Observation information such as source name, observing stations, observation time and

frequency code from the original schedule file for each experiment;

2) Calibration data such as weather data (temperature, pressure, humidity), cable delay data, water vapor radiometer data from log files for each station;

3) Ephemeris data such as the velocity of the earth barycenter at the solar barycentric coordinate and the distances between earth, moon and sun from a tape of JPL ephemeris (DE200/LE200);

4) Earth rotation parameters such as UT1 and wobbles.

The calibration data is interpolated for each observation. The data for the JPL ephemeris are the Chebyshev's coefficients which are fitted into the positions of the 9 planets, moon and sun every 32 days. KASET calculates their positions, velocities and acceleration for each observation, and sets them into the data base. Earth rotation parameters are interpolated for each observation from the 5 day VLBI data of IRIS (International Rotation Interferometric Surveying). The raw data for UT1 has large variations for durations less than 30 days. The interpolation of raw data every 5 days is unsuitable since it is difficult to interpolate variations over such a short time. Therefore UT1 modified data, from which short term UT1 variations, such as these caused by earth tides, has been removed, is used for interpolation. Short term tidal UT1 variations are corrected for every observation in a priori calculation software. Variations in wobbles during the short term are very small, so these do not require correction.

All data can easily be entered into the data base for each item. KASET can also delete and display entry experiments.

2.5 Correlation Processing Software (KROSS)

Correlation processing is an essential part of VLBI. The correlation software (KROSS) controls the K-3 recorders and the correlation processor by GPIB (IEEE-488 bus). Two computers using FORTRAN language are used in the software. One HP1000-45F computer transfers correlation parameters to the correlation processor and retrieves correlation data from it at very high speed (0.6 Mbyte/s) by using DMA (Direct Memory Access). The other HP1000-10L computer controls the recorders and correlation processor at normal speed. KROSS has the main 4 functions.

1) A priori calculation

The data is retrieved from the data base and a priori values (delay, rate, acceleration, 3 order derivation of time) are calculated at the middle of each observation (PRT). A priori values are used to stop fringe rotation in the correlation processor. Fringe rotation is caused by Doppler shift due to the earth's rotation. The correlation window for each unit of the correlation processor is within ±1 micro sec (±4 bit) for delays. The required precision of a priori delay needs to be less than 500 ns (2 bit) as a quarter of the window. The precision of delay rate needs to be less than 7 ps/s to maintain coherence at more than 90% for the 4 sec of the period of setting parameters at the X band as shown by Eq. (1).

$$\text{Coherence} = \sqrt{2(1-\cos\theta)}\,/\,\theta$$
$$\theta = 2\pi(\text{frequency}) \times (\text{error of rate}) \times (\text{parameter period}) \qquad \ldots\ldots\ldots\ldots\ldots\ (1)$$

A priori values are calculated according to the algorithm of the a priori calculation software (KAPRI). The essential part is almost identical to the "COREL" of Mark-III software. The nutation of Wahr's model is truncated to less than 10 mas. The aberration caused by the earth's orbital motion has been corrected to modify the source position as shown in the Appendix.

typical zenith path delay (7 ns). The precision of a priori value in KROSS is 20 ns for delay, and 2 ps/s for rate. These values are less than the required precision.

2) Synchronization of recorders

KROSS controls the recorders to synchronize all tapes. The time delays are corrected in the synchronization. After synchronization, correlation processing starts.

3) Setting parameters to the correlation processor(2)

The parameters of the correlation processing are set to the correlation processor every period, called the Parameter Period (PP). The PP is selected from 1, 2, 3, or 4 sec. This affects the coherence, resolution and search window of rate. The parameters of correlations are calculated for each PP by using a priori values at PRT. The format for setting parameters and the method of calculation are almost compatible with the Mark-III system.

4) Retrieving correlation data from the correlation processor(2)

Correlation data are transferred from the correlation processor into the file in the HP-1000 computer every PP. The correlation data include the counter number of the correlation, slip and parity errors and Phase Calibration (PCAL) data for each PP. The output data is almost compatible with Mark-III.

A Service Request (SRQ) signal is used for the timing of access to data. The correlation processor instantly sends the SRQ signal to the host computer when the signals at the beginning of the PP are sent from all units of the correlation processor. After this, the host computer reads the correlation data from the correlation processor. Next, the host computer sends the correlation parameters to the correlation processor. Correlation data are obtained again to repeat the process.

2.6 Bandwidth Synthesis Software (KOMB)

Bandwidth synthesis is essential for the geodetic VLBI to obtain observation delays to a high precision of less than 0.1 ns. Group delays and rates are obtained in the geodetic VLBI. The group delays depend on effective bandwidth since delays are obtained by the slope of the phase change against frequencies. The effective bandwidth should be wider than 100 MHz to obtain delays to a precision of less than 0.1 ns. The analog signal of the radio source, converted to the video band, transfers to a digital signal. The sampling rate from an analog signal to a digital signal is more than 200 MHz, if the entire signal of a band wider than 100 MHz is converted. Since the sampling rate is not very high, it is difficult to immediately convert analog signals to digital signals for whole bands wider than 100 MHz. Therefore, several channels assign to bands wider than 100 MHz in the manner of a comb. The bandwidth for each channel is 2 MHz (or 4 MHz), and the total sampling rate is 56 MHz for 14 channels. The correlation data for each channel are combinted to accurately calculate the delay and rate. This is termed "Bandwidth Synthesis". Figure 2 shows the outline of a bandwidth synthesis. The ordinate is the correlation phase of each channel, and the abscissa represents observation frequencies. The raw phase is irregular for each channel as shown in Fig. 2(a) since the instrumental delay of hardware is different in each channel. The phase of each channel is corrected by phase calibration data as shown in Fig. 2(b). Group delay is the slope of the corrected phase against the frequencies. As the slope error depends on effective bandwidth, the precision of delay after bandwidth synthesis increases more than with a single band. Since only the data of several comb-like channels are obtained, the pattern of correlation is regularly repeated over a certain period. We term this "ambiguity", and it depends on the assignment of frequency.

The "KOMB" software synthesizes the bandwidth of correlated data for each channel. The algorithm for bandwidth synthesis is the same as the software "FRNGE" of the Mark-III system. The

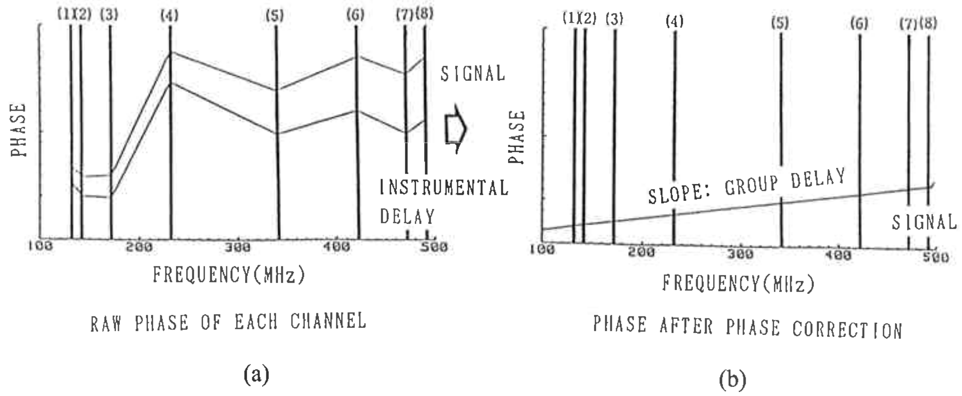

Fig. 2 Outline of Bandwidth synthesis. (a) raw phase data, (b) corrected phase data by PCAL.

observation delay and rate are searched to provide the largest correlation through the use of all correlated data. Initially, coarse delays are searched by using the correlated amplitude of each channel only without the phase information for each channel. These delays are similar to the delay of a single band. The error in an coarse delay is very large, more than 10 ns, but is free of ambiguity. More precise delays are finely searched around the coarse delay. The search for delay and rate uses an FFT module.

Essential data, such as observation delay and rate, errors, correlated amplitude and phase calibration are entered into the K-3 data base. All results of bandwidth synthesis and correlation processing are stored onto tapes. The format of each file is compatible with the Mark-III, but the tape format is different. The tape format is described in Subsection 2.9.

2.7 A Priori Calculation Software (KAPRI)

The observation data and essential parameters are set into the data base after running KOMB. After this, a priori vales are required for analysis. A priori values are required to be accurate to less than 0.1 ns since the standard precision of the geodetic VLBI is 0.1 ns. Many physical models and many calculations are needed to establish a priori values. The partial differential of each parameter is also used to estimate parameters. The calculation of values for each estimation is not a good technique. Therefore, the a priori values and differentials are set into the data base prior to the estimation. The "KAPRI" software accurately calculates a priori values and differentials, and sets the values into the K-3 data base.

Geometrical delay is calculated using baseline vector, the unit vector of source direction, and rotation matrix including precession, nutation and the rotation of the earth. The geometrical delay is the delay within the solar system, and it should be transferred to the delay on the earth. This transformation represents the relativistic effects corresponding to the aberration and the movement of stations during the delay. After these corrections, the a priori value is obtained to be added the atmospheric delay. The algorithm is almost the same as for the software "CALC" of Mark-III. The ocean tide and earth tide models and the access to the data base are different between KAPRI and CALC. The physical models adopted for KAPRI will be presented in another paper in detail(3)(4).

2.8 Data Analysis Software (KLEAR)[3]

The "KLEAR" software makes an analysis by using observation data (O) and a priori values (C). The algorithm is the same as the software (SOLVE) of Mark-III, and the least square method is used for estimation. The estimated parameters are obtained so that $\Sigma(O\text{-}C\text{-}\Delta C)^2/\sigma^2$ becomes the lowest value, where ΔC represents correction based on the estimated parameters. This equals the solution to the following Eq. (2)

$$WAx = Wb \qquad (2)$$

where x is the vector of the estimated parameters, A is the partial differential matrix, b is the vector of O-C and W is the weighted matrix according to the error. The estimated parameters can easily be selected on the display of the computer. The available estimated parameters are mainly clock offset and rate, atmospheric zenith path delay, station positions (X, Y, Z), earth rotation parameters, source positions and notations. The clock parameters and atmospheric delay are estimated between epochs that are selected at the discretion of an analyst.

Initially, the ambiguity caused by bandwidth synthesis should be eliminated from observation delay. Data of poor or dubious quality is suppressed. Next, parameters and its errors are estimated according to Eq. (2). The residual of O-C-ΔC is plotted, and an assessment is made whether systematic error exists. When the residual equals the random distribution, analysis is complete. Finally, re-weighting is conducted. The observation error is calculated from the SNR. The data of strong sources and the baseline between large antennas are more heavily weighted in the analysis since their observation errors are minute. However, the residuals of O-C for all sources are almost the same in standard analysis. Analysis errors and errors caused by atmospheric scintillation should be added to observation errors. However, it is difficult to estimate an analysis error. In reweighting, the formal error is added to the observation error for each baseline as an analysis error. Formal error is obtained by making the chi square equal 1 for each baseline.

2.9 Data Format Conversion Software (KONV)

There are 3 types of format for the output data of correlation processing and bandwidth synthesis. One format is the α tape for the K-3 system. The second format is the A or B tape for the Mark-III system. They are used to make the Mark-III data base. This tape format differs from ours. The α tape provides the sequence of observation on each baseline. The A or B tape provides the sequence of correlation processing. The third format is the NGS format which includes the essential data listed in Subsection 2.1.

The "KONV" software is able to convert these 3 formats.

3. New Correlation Software

The K-3 system has been used since 1984. A high density recorder was required, as VLBI experiments were conducted with frequency. CRL developed a new recording system and called it the "K-4 system"[1]. New correlation processing software was also developed for the K-4 recording system. The disadvantages of the correlation processing software (KROSS) in the K-3 system are as follows:

1) It has to use 2 computers, and the software structure is complex making modification for the new system difficult;

2) It is difficult to maintain the computer system since the computer is obsolete and maintenance is no longer done. Computing speed is also very slow;

3) The preparation for correlation processing is not efficient since the creation of whole a data base is required;

4) Recovery after trouble is complex since it uses 2 computers;

5) Synchronization of recorders requires much time, about 30 sec;

6) The computer is used both for correlation processing and analysis. The two software packages interrupt each other since the facility of the minicomputer is limited. It is better to separate the computers for correlation and analysis.

To solve these problems, new correlation software was developed in the personal computer only for correlation processing. Two new computers were introduced in 1987. The first was the HP9000-330 personal computer. The other was the HP1000-A900 minicomputer. Controls for the recorders and correlation processor are necessary in the correlation processing software. Many modifications were made to the software in developing the software for the K-4 recording system. BASIC language controls the sequence of commands. Checking the controls and modifying the software are easy. Hardware control and a priori calculation for correlation processing on several baselines are unnecessary in a high performance computer system. The personal computer (HP9000-330) by itself is enough and BASIC language is used for the software.

Bandwidth synthesis and analysis require a computer with high speed. The HP1000-A900 minicomputer uses these software programs. Correlation data is transferred easily from the HP9000-330, for correlation processing, to the HP1000-A900 for bandwidth synthesis.

3.1 New Correlation Software Features

The usual correlation processing of VLBI is made at the correlation center. In routine correlation processing at the center, it is best to use a high performance computer and a large software program. However, correlation processing in any new research experiment requires trial and error, minor modifications and quick response for it. Recently, a compact portable correlation processor was developed at National Astronomy Observatory (NAO). Software in portable correlation system should be able to be run in any compact computer such as a personal computer. It is advantageous that the software can be developed in a personal computer and that it uses BASIC language. BASIC language is suitable for control using GPIB. The computer is able to be exclusively used for correlation because it is a personal computer. The time required to synchronize algorithms has been reduced to approximately 10 sec. Some files in the software are used to process correlations. As the files are automatically created using only original schedule file for individual experiments prior to correlation, the operator does not need to be familiar with the files. Since we use a personal computer and BASIC language, system recovery after trouble is easy. Figure 3 shows an outline of the new correlation software.

The parts within each physical model are separated into subroutines such as KAPRI. The software structure is arranged to use the rotation matrices of precession, nutation, diurnal rotation and wobbles. Delay is calculated by the algorithm shown in the appendix. Atmospheric delay is calculated by using the fixed zenith path delay and the elevation mapping function. Some stations are located in elevated regions over 1000 m above sea level. The zenith path delay varies by about 100 mb (10%). Because of this, we corrected for height in the zenith path delay as follows;

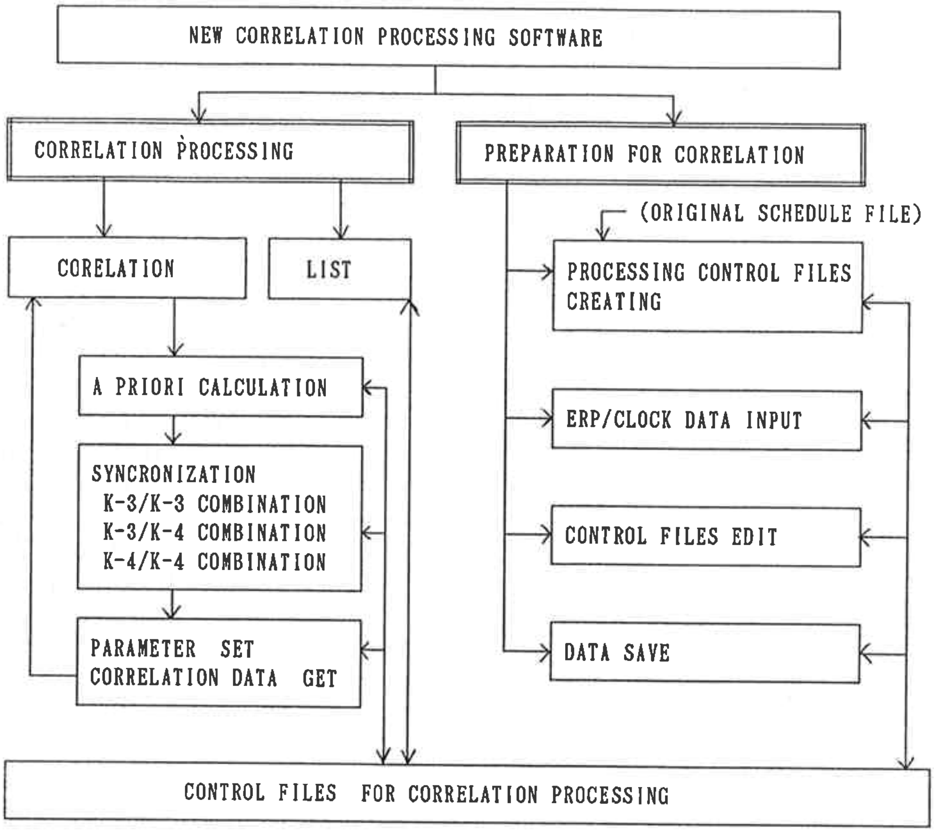

Fig. 3 Outline of new correlation software.

$$\text{Zenith path delay} = \left(7.98 - 8.74 \times 10^{-4} \times \text{height(m)}\right). \qquad (3)$$

The algorithm to calculate delay (τ), rate ($\dot{\tau}$), acceleration ($\ddot{\tau}$), and the 3 order derivation of time ($\dddot{\tau}$) was also improved. In the old software "KROSS", a priori values of them were calculated at the middle of each observation. Errors in delay and rate are larger at the beginning and end of each observation. In the new software, a priori values are calculated to accommodate the entire duration of each observation. This duration is divided into 4 parts ($-2T$ to $-T$, $-T$ to 0, 0 to T, T to $2T$ while $4T$ is complete duration). Furthermore the delays are calculated for the 5 points ($-2T$, $-T$, 0, T, $2T$). A priori values for each observation are calculated for the least square fittings as follows;

$$\tau = \tau_0 + \left(12\left(\tau_2 + \tau_3 - 2\tau_0\right) - 3\left(\tau_1 + \tau_4 - 2\tau_0\right)\right)/35$$
$$\dot{\tau} = \left(\tau_1 - \tau_4 - 8\left(\tau_2 - \tau_3\right)\right)/(12T)$$
$$\ddot{\tau} = \left(2\left(\tau_1 - \tau_0\right) - \left(\tau_2 - \tau_4\right) - \left(\tau_3 - \tau_4\right)\right)/\left(7T^2\right)$$
$$\dddot{\tau} = \left(2\left(\tau_2 - \tau_3\right) + \left(\tau_4 - \tau_1\right)\right)/\left(2T^3\right), \qquad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where τ_1, τ_2, τ_0, τ_3, τ_4 are the delays at PRT$-2T$, PRT$-T$, PRT, PRT$+T$, PRT$+2T$ for every observation.

The software is available for both the K-3 (Mark-III) system and the new K-4 recording system, that is, correlation processing can be achieved between K-3 and K-3 systems, the K-3 and K-4 systems, and K-4 and K-4 systems. The calculation of a priori values and access to the correlation processor are exactly the same for all K-3 and K-4 system combinations. Only the tape synchronization is different. At present, the K-4 recorder system does not have a fine speed adjustment like the K-3 recorder does. In correlations between the K-3 and K-4 systems, the K-4 recorder serves as the master for synchronization and is not controlled for. The controls are the same as those for K-3 to K-3 systems. One command "COR" in the recording system is used to automatically synchronize between K-4 systems. Before fine automatic adjustment, rough tape synchronization to within 1 sec is achieved by using position search command "PRL". Figures 4 and 5 show the correlation processing for each system combination.

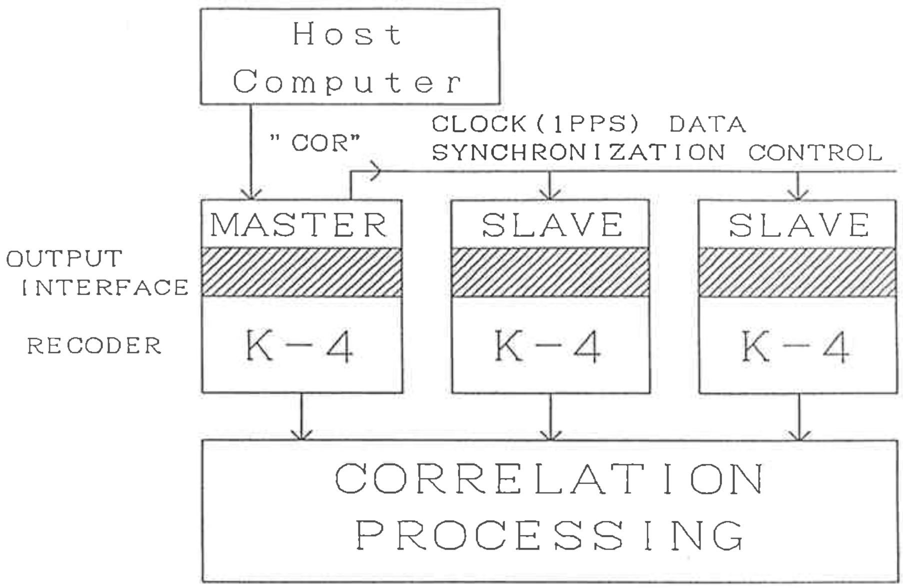

Fig. 4 K-4 correlation.

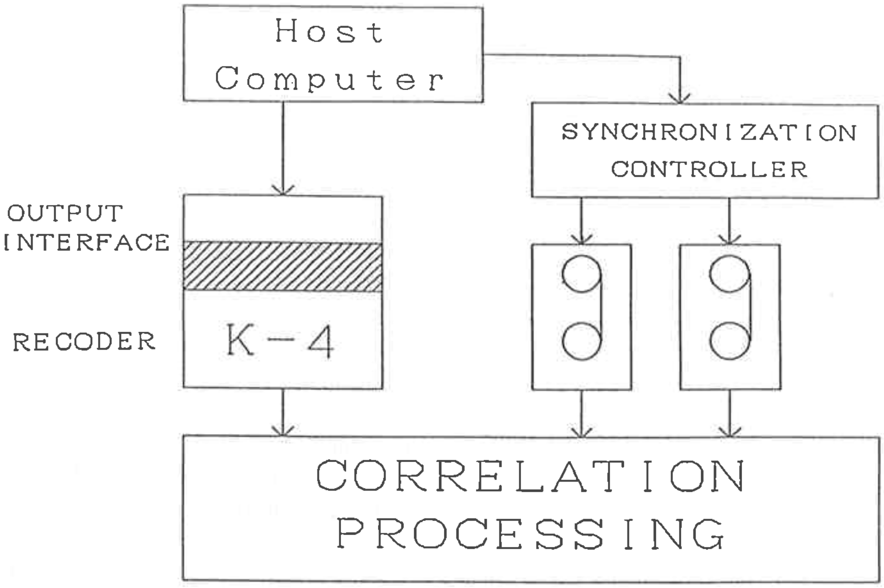

Fig. 5 K-4, K-3 mixing correlation.

3.2 Comparison of Two Software Programs

The software was checked by using experiments conducted on the Kashima and Tsukuba 55 km baseline in June 1989. The experiments were conducted simultaneously using the K-4 and K-3 systems. Correlation processing was conducted on 62 observations and 14 normal K-3 tapes using both old and new software.

Figure 6 shows the ratio of correlated amplitude of the new software against the old software. In most cases, the amplitudes of the new software were larger than those of the old. The mean ratio was 1.08.

Figure 7 shows the differences in integration time for the correlation. The integration time for the new software was long since the synchronization time was short.

Figure 8 shows the differences in observation delays. Some observations, either those catching the side lobe or those with incorrect delays, were removed. The differences were scattering within 0.2 ns less than the delay residuals of usual VLBI. The r.m.s. of the difference in delay rate is 0.035 ps/s less than the r.m.s.. of the residual delay rates (0.1 ps/s).

We confirmed that the new software could be used for correlation, that is, a priori values and control of the K-3 hardware created no problems.

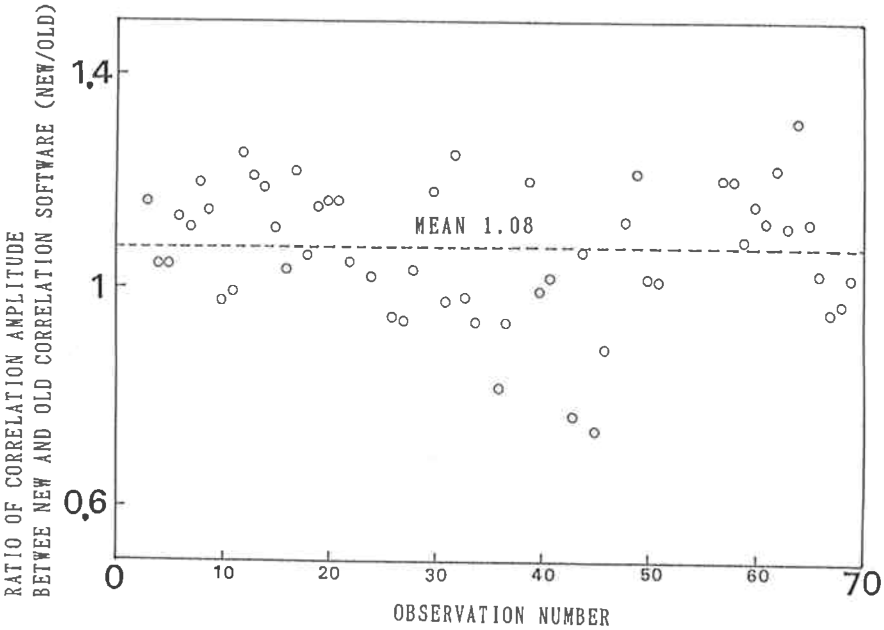

Fig. 6 **Ratios of correlation amplitude between new and old correlation software (new/old).**

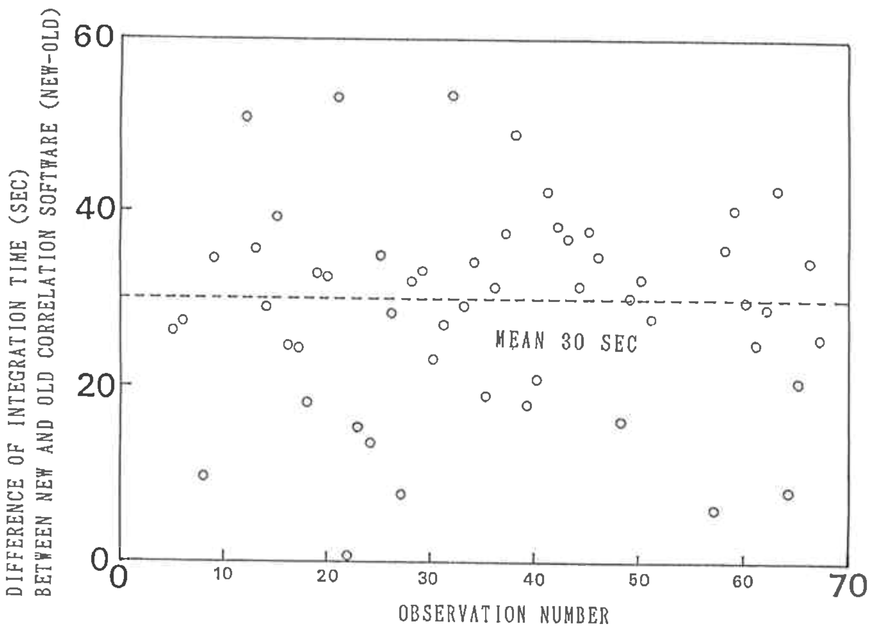

Fig. 7 **Differences in integration time (unit: sec) between new and old correlation software (new-old).**

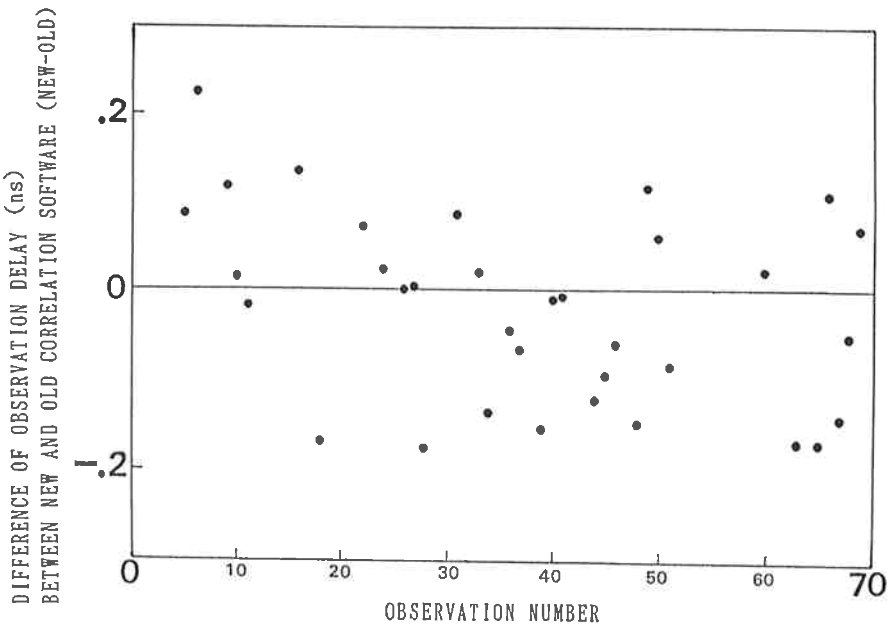

Fig. 8 Differences in observation delay (unit: ns) between new and old correlation software (new-old).

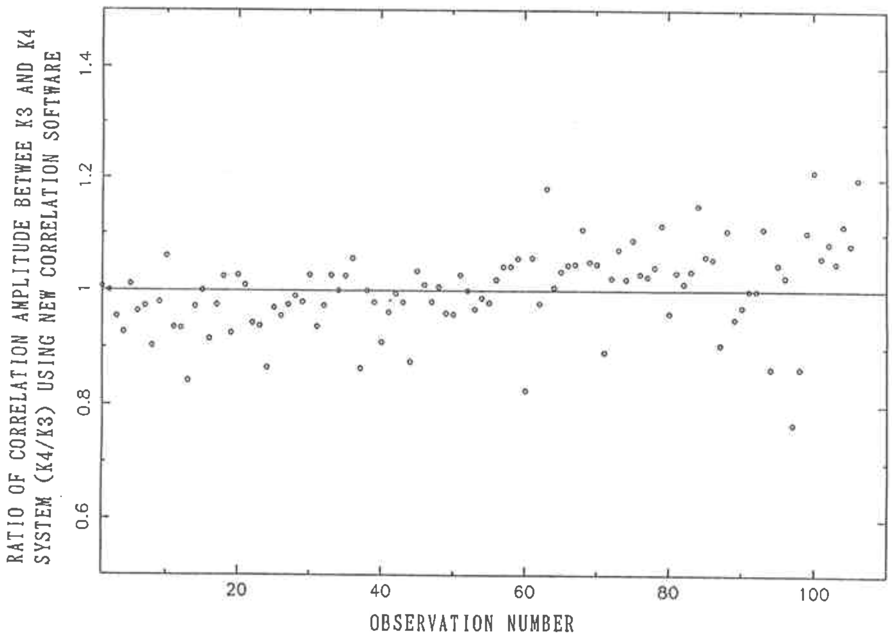

Fig. 9 Ratios of correlated amplitude between K4 and K3 systems using new correlation software (K4/K3).

3.3 Correlation for K-4 System

New correlation software is available to correlate the K-4 system. Correlations for the K-4 and K-3 test experiment were processed on the Kashima-Tsukuba baseline for both the K-4/K-4 combination and K-3/K-3 combination using new correlation software. Figure 9 shows the correlated amplitude ratios for the K-4 system to the K-3 system. The ratios were almost 1 and varied by less than 10%. Figure 10 shows the differences in delays between the K-4 and K-3 systems. The differences were smaller than 0.1 ns. Table 1 shows the results of K-4/K-4 correlation on the Kashima-Tsukuba baseline together with the results of another experiment using the old software and K-3/K-3 correlation. The baseline between Kashima and Tsukuba does not change during half the year since the two stations are so close. The differences were smaller than 1 cm. These results indicate that it would create no problems to correlate the K-4 system.

The software was used to process the correlations of all domestic experiment(5)-(7) some international experiments and the test VLBI experiments with the Syowa station in Antarctic(8). Figure 11 shows domestic experiments using the K-4 system. Correlations were processed using the new software and reasonable results were obtained for all experiments. We could also confirm that the cross correlation processing of K-3 and K-4 mixed combination had no problems in these experiments.

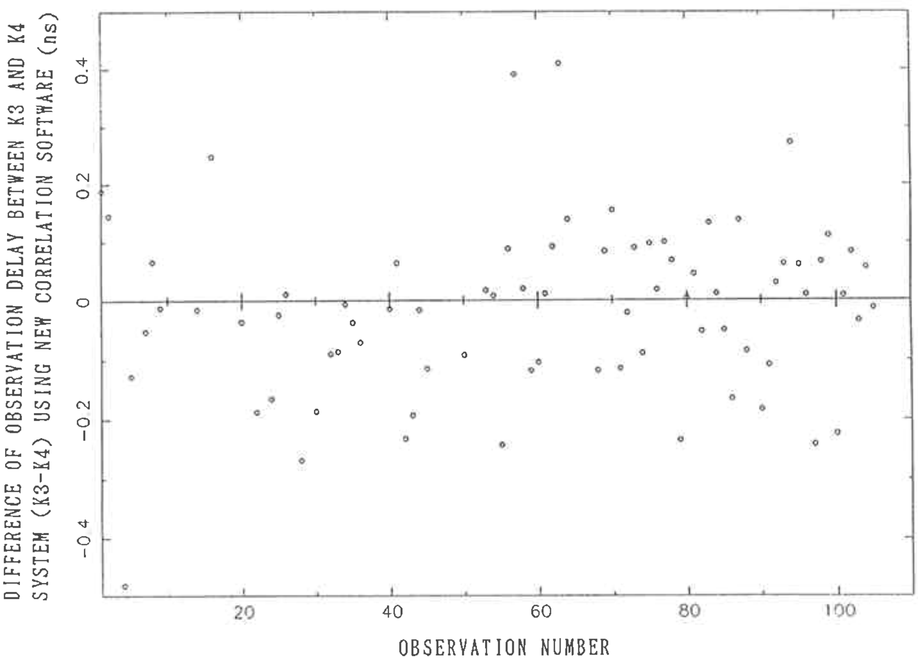

Fig. 10 Differences in the observation delay (unit: ns) between K3 and K4 system using new correlation software (K3-K4).

Table 1 Experiments comparing K3 and K4 recorders

Baseline components		
ΔX (cm)		−0.1 ± 1.7 cm
ΔY (cm)		0.6 ± 1.5 cm
ΔZ (cm)		1.8 ± 2.1 cm
ΔL (cm)		0.8 ± 1.0 cm
Difference in delay		r.m.s. 0.145 ns
Ratio of correlated amplitudes		1.001 ± 0.075
	K4	K3
r.m.s. of residual delays	0.084 ns	0.113 ns
number of analysis data	103 observations	73 observations

(Kashima-Tsukuba 55 km baseline on June 15, 1989)

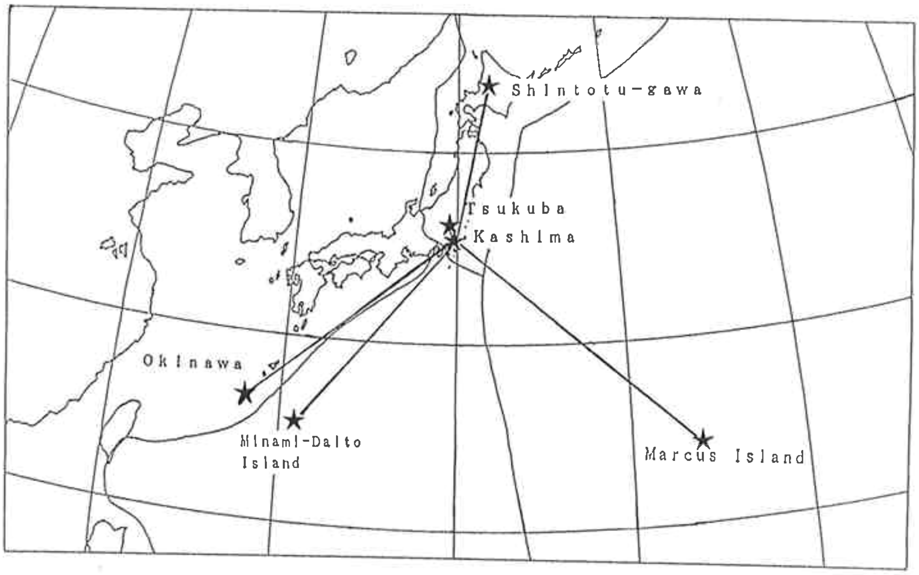

Fig. 11 Domestic VLBI experiments conducted with K-4 recording system.

4. Conclusions

CRL developed data correlation and analysis software termed the "K-3 software system" for the joint VLBI experiments in CDP. The software system has been used for CDP experiments, domestic VLBI experiments such as experiments with GSI(5) and mobile CRL experiments(6)(7), along with experiments in China(9) and experiments with the Commonwealth Scientific & Industrial Research Organization (C.S.I.R.O.) in Australia. We succeeded in the VLBI experiments through using this improved software, and obtained significant results such as changes in the Kashima-Hawaii base-line.

Due to the many VLBI experiments being conducted around the world, and the operation and processing of data had become increasing labors. Furthermore, the transportation of tapes was expensive. CRL developed a new high density recording system and called it the "K-4 recording system"(1). The correlation software for the new recording system was developed with a personal computer using BASIC language. Good correlations were obtained for all combinations of K-3 and K-4 systems.

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Appendix

The algorithm for a priori delay (τ) is described as a reference in making the correlation software.

$$\tau = \tau_g + \left(\tau_a^2 - \tau_a^1\right) + \left(Co^2 - Co^1\right) + \left(Cr^2 - Cr^1\right)t \quad \text{.................... (A-1)}$$

where τ_g is geometric delay, τ_a is atmospheric delay, Co is clock offset, Cr is clock rate and t is the interval from the clock epoch. The superscript 1, 2 indicates the reference station and remote station, respectively.

The atmospheric delay (τ_a) is calculated using the zenith delay path Z shown in Eq. (3) and Chao's mapping function $f(El)$ as follows;

$$\begin{aligned} &\tau_a = Z \cdot f(El) \\ &f(El) = 1/\left(\sin(El) + 0.00143/\left(\tan(El) + 0.0445\right)\right) \end{aligned} \quad \text{.................. (A-2)}$$

The geometric delay is calculated as follows;

$$\begin{aligned} &\tau_g = \left(\vec{S} \cdot R\vec{B}\right)/c \\ &R = RpRnRdRw \end{aligned} \quad \text{.................................. (A-3)}$$

where $\vec{S}$ is the unit vector of source direction, $\vec{B}$ is the baseline vector, ($\vec{B} = \vec{X}_1 - \vec{X}_2$; $\vec{X}_{1,2}$ is the position vector for reference and remote stations), R is the matrix for earth rotation, and c is the velocity of light. Rp is the precession matrix, Rn is the nutation matrix, Rd is the diurnal rotation matrix and Rw is the wobble matrix.

The precession matrix is described as follows;

$$
\begin{aligned}
&Rp = Rz(\xi)Ry(-\theta)Rz(\zeta)\\
&\xi = \left(2306.2181T + 0.30188T^2 + 0.017998T^3\right)\ \text{(arcsec)}\\
&\theta = \left(2004.3109T - 0.42665T^2 - 0.041833T^3\right)\\
&\zeta = \left(2306.2181T + 1.09468T^2 + 0.018203T^3\right) \qquad \cdots\cdots\cdots\cdots \text{(A-4)}
\end{aligned}
$$

where Rx, y, z are the rotation matrices around the x, y, z axes respectively, and T is the UTC time from J2000 epoch (2451545.0 Julian Day) in century unit (T = (UTC(Julian day) – 2451545.0)/36525).

The nutation matrix is described as follows;

$$
\begin{aligned}
&Rn = Rx(-\varepsilon_0)Rz(\Delta\psi)Rx(\varepsilon)\\
&\varepsilon_0 = \left(8.4381448\times10^4 - 46.815T - 5.9\times10^{-4}T^2 + 1.813\times10^{-3}T^3\right)\\
&\varepsilon = \varepsilon_0 + \Delta\varepsilon\\
&\Delta\psi = \sum_i A_i\, sin(\omega_i(T))\\
&\Delta\varepsilon = \sum_i B_i\, cos(\omega_i(T))\\
&\omega_i(T) = L_i^1 L + L_i^2 Ld + L_i^3 F + L_i^4 D + L_i^5 O, \qquad \cdots\cdots\cdots\cdots \text{(A-5)}
\end{aligned}
$$

where ε_0 is the mean obliquity of the ecliptic and $\Delta\psi$, $\Delta\varepsilon$ are the nutations of longitude and obliquity. The Wahr's nutation model is used for A_i, B_i, L_i. L, Ld, F, D, O are the astronomical arguments in arcsec units as follows;

$$
\begin{aligned}
&L = 485866.733 + \text{MOD}(1325T)\times1296000 + 715922.633T + 31.31T^2 + 0.064T^3\\
&Ld = 1287099.804 + \text{MOD}(99T)\times1296000 + 1292581.224T - 0.577T^2 - 0.012T^3\\
&F = 335778.877 + \text{MOD}(1342T)\times1296000 + 295263.137T - 13.257T^2 + 0.011T^3\\
&D = 1072261.307 + \text{MOD}(1236T)\times1296000 + 1105601.328T - 6.891T^2 + 0.019T^3\\
&O = 450160.280 - \text{MOD}(5T)\times1296000 - 482890.539T + 7.455T^2 + 0.008T^3. \qquad \text{(A-6)}
\end{aligned}
$$

Since the requisite precision in delay is 10 ns in the correlation software, 13 terms with amplitudes larger than 10 mas are selected from Wahr's nutation table in Table 2.

The diurnal rotation matrix is described in second units as follows;

Table 2 Nutation Table indicating deviance of more than 10 mas in Wahr's model

i	A_i (mas)	B_i (mas)	L_i^1	L_i^2	L_i^3	L_i^4	L_i^5	Period
1	–17199.6	9202.5	0	0	0	0	1	18.6 years
2	–1318.7	573.6	0	0	2	–2	2	182.6 days
3	–227.4	97.7	0	0	2	0	2	13.7 days
4	206.2	–89.5	0	0	0	0	2	9.3 years
5	142.6	5.4	0	1	0	0	0	365.3 days
6	71.2	–0.7	1	0	0	0	0	27.6 days
7	–51.7	22.4	0	1	2	–2	2	121.7 days
8	–38.6	20.0	0	0	2	0	1	13.6 days
9	–30.1	12.9	1	0	2	0	2	9.1 days
10	21.7	–9.5	0	–1	2	–2	2	365.2 days
11	–15.8	–0.1	1	0	0	–2	0	31.8 days
12	12.9	–7.0	0	0	2	–2	1	177.8 days
13	12.3	–5.3	–1	0	2	0	2	27.1 days

$$
\begin{aligned}
&Rd = Rz(-GAST)\\
&GAST = GMST + \Delta\psi\cos(\varepsilon)\\
&GAST = GMST_0 + \omega \times t\\
&GMST_0 = 24110.54841 + 8640184.812866 T_0 + 0.093104 T_0^2 - 6.2\times10^{-6} T_0^3\\
&\omega = 1.002737909350795 + 5.9006\times10^{-11} T_0 - 5.9\times10^{-15} T_0^2, \qquad \text{(A-7)}
\end{aligned}
$$

where t is a fraction of UTC time from 0 hour UTC in second unit, T_0 is the Julian day of 0 hour UTC in century unit.

The wobble matrix is described as follows;

$$Rw = Rx(-WOBY)Ry(WOBX), \qquad \text{(A-8)}$$

where $WOBX$, $WOBY$ are the x, y components of the wobble, that is, the position of the earth's axis during rotation in a right hand system.

Finally, the unit vector of source direction $\vec{S}_0$ is described by declination δ and right ascension α in a solar barycentric coordinate system as follows;

$$\vec{S}_0 = \left(\cos(\alpha)\cos(\delta),\ \sin(\alpha)\cos(\delta),\ \sin(\delta)\right). \qquad \text{(A-9)}$$

Since the earth moves around the sun, the aberration effect $\vec{S}$ is corrected in this vector as follows;

$$\vec{S} = \left(\vec{S}_0 + \Delta\vec{S}\right) / \left|\vec{S}_0 + \Delta\vec{S}\right|$$
$$\Delta\vec{S} = \vec{V} / c$$
$$= \begin{pmatrix} k(\sin(s) - e\sin(w)) \\ k(-\cos(s) + e\cos(w))\cos(\varepsilon) \\ k(-\cos(s) + e\cos(w))\sin(\varepsilon) \end{pmatrix}$$
$$e = 0.01670862 - 0.00004204T - 0.000000124T^2$$
$$w = 282.937348 + 0.000047078 \times (36525T) + 0.0004597T^2 - 180 \ \text{(degree)}$$
$$s = F - D + O + \Delta\psi, \qquad \text{(A-10)}$$

where k is the aberration constant ($k = 20.49525$ arcsec $= 9.93637 \times 10^{-5}$ radian), e is the eccentricity of revolution, w is the longitude of the earth's perihelion (the longitude of the sun's perigee $-180°$), s is the longitude of the sun. $\vec{V}$ is the velocity of the earth within solar barycentric coordinate, and c is the velocity of light. The effects of aberration and normalization correspond to the relativistic effects of transformation from the delay in the solar barycentric coordinate to the delay on the earth, and the movement of remote station during delay time.

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