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Correlation and Fringe Finding

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Abstract

The current generation VLBI correlators have given us tremendous amounts of data products from regular IVS sessions. However, at the same time, it is also true that the capacity of the correlation processing is one of the limiting factors which are restricting the number of stations and frequency of sessions to be performed. At present, at least three large scale correlators are under discussions for developments. These projects are, LOFAR, ALMA, SKA, and EVLA. All of these projects are seeking possibilities to enlarge current limitations in numbers of baselines and maximum speed of data rates and we have to learn a lot from these projects. On the other hand, the processing speed of the software correlators with distributed processing are getting faster and it seems it will become feasible to use the software correlators for large scale VLBI processing by the year 2010. Real-time or near-real-time correlation using high speed network connectivity is also becoming feasible for global scale VLBI sessions. We would like to discuss various possibilities of correlators to be used for IVS sessions in 2010 and beyond.

1. Introduction

The major task of the "Correlation and Fringe Finding" subgroup for the VLBI2010 is to consider next generation correlation processing for global scale VLBI sessions. For this purpose, we would like to start by reviewing currently operating correlator systems and near future correlator systems currently under planning or consideration. Then we would like to discuss about the future strategies and scenarios of the correlator developments. Software correlation is in the primitive stage at present, but it will become feasible not far in the future and we would like to include the software correlator as one of the candidates of the future correlators. Real-time or near-real-time correlation using high speed network connectivity is also becoming feasible for global scale VLBI sessions. There are a category of applications which require short latency of the VLBI data processing for example UT1-UTC measurements for spacecraft navigation. Real-time correlation also has a potential to break the current limitation of the sensitivity by allowing higher data rate observations. It is also considered as our task to consider the adequate method for fringe checking after observations and post correlation processing including determination of delay and delay rate from correlation results and appropriate method for data archiving.

2. Currently Operational Correlators

Currently, various correlator systems are operationally used in geodetic, astrometric, and astronomical VLBI data processing. Table 1 lists the part of the major existing correlator systems currently in operation. It has to be noted that the number of stations are the maximum number of the actual configuration and some of the correlators are capable to process more stations if the additional play back units are connected to the correlators. Among the various correlator systems listed in the table, Mark 4, S2, and K4 correlators are regularly used to process the IVS regular sessions at present. All of the correlators listed in Table 1 have hardware correlator architectures. K4 correlator is using FPGA (Field Programmable Gate Array) chips while the other correlators are using specially designed custom correlation chips.

Table 1. Currently operational correlator systems.

Correlator	Location	Number of Stations	Maximum Data Rate (Mbps)	Maximum number of spectral points per IF channel	Reference
Mark 4	Haystack, USNO, JIVE, Bonn	16	1024	8192	[26]
S2	Penticton	6	128	8192	[3]
K4	Kashima, Tsukuba	4	256	256	[9]
VLBA	Socorro	24	512	1024	[2]
VSOP	Mitaka	10	1024	8192	[5]
GICO2	Kashima	4	2048	1024	[15]

Availability of the correlators including the operational staffs and capability of the correlators sometimes become one of the limiting factor which restrict the frequency of the observing sessions, number of stations in the session, and the observation mode, such as maximum data rate for each baseline. Many efforts have been made by various groups to expand the capability of the correlators and to improve the efficiency of the processing. Recent transition from Mark 4 recording system to Mark 5 system [25] at the Mark 4 correlators is in fact drastically improving the processing efficiency by the better reliability and easy operation of the hard-disk recording and playback system. There is a plan to expand the number of stations for the Mark 4 correlators by using Mark 5B system [27]. The Mark 5B system is under development and it will be capable to synchronize the reproduced data with the external control signal as specified in the VSI-H (VLBI Standard Interface, Hardware) specifications [24]. Because of its capability, Mark 5B system can be connected to the Mark 4 correlator without using station units and then the number of stations supported by the Mark 4 correlator will become 20.

The K4 correlator was designed to minimize the human operations by automating and pipelining all the procedures from the correlation setup through data analysis [13]. The Key Stone Project successfully demonstrated high efficiency and reliability of the automated observing and data processing system by daily or sub-daily VLBI sessions for more than five years. GICO2 correlator is an experimental development for high speed data rate correlation at the maximum data rate of 2 Gbps for each station. It is designed to be compliant with the VSI-H specifications. Because of its feature, it can be used for conventional tape-based correlation using GBR2000D recording system or for real-time correlation by using ADS1000 sampler unit and serial-parallel conversion interface for the ATM network. This system is a good example that the real-time correlation can achieve higher sensitivity by correlating high data rate streams without recording observed data to magnetic media since there is no single recording system which achieves the recording data rate of 2 Gbps.

3. Near Future Correlators Under Planning

There are several projects to develop next generation VLBI correlators. Korean VLBI Network [18] and Chinese VLBI Network projects [29] are currently planning to develop new correlator systems for their networks. Large scale correlator developments are considered in the LOFAR (Low Frequency Array), SKA (Square Kilometer Array), EVLA (Extended Very Large Array), and ALMA (Atacama Large Millimeter Array) projects. For the EVLA project, WIDAR (Wideband Interferometric Digital Architecture) design is proposed and developments will be proceeded in two stage phases [4]. During the first stage developments, 32 stations will be supported whereas the capacity of the correlator system will be expanded to accept 48 stations in the second stage developments. Sampling mode of 4096 Msps (sample per second), 3 bits per sample, eight 2 GHz bandwidth channels will be supported. For the ALMA project, maximum sampling rate will be 4000 MHz and number of stations which can be processed at once will be 80 stations. Experimental single baseline correlator which can process 4000 MHz frequency band was developed to technically demonstrate the feasibility of the correlator [19].

4. Software Correlators

In 1960's, the Mark I VLBI system was developed with digital recording systems and the recorded data were correlated by using a computing program [1]. It took about 90 minutes by using a main frame computer IBM360/50 to process 144 Mbits of data. It was equivalent to the data processing rate of 26.7 kbps. In 1980's, another software correlator named CCC (Cross Correlation in a Computer) was developed by a group at Kashima [11]. It took about 150 minutes to process 16 Mbits of data by using a minicomputer HP1000/A900 which is equivalent to the processing speed was thus 1.8 kbps. The CCC was used in the actual fringe tests of domestic VLBI sessions conducted in 1985. Therefore, the software correlation has a relatively long history, but it had not been practical until recently because data processing and data transmission were very slow. However, the recent improvements in the processing speed and data transmission speed are remarkable, and the software correlation is rapidly becoming realistic. At Jet Propulsion Laboratory, the developments of a software correlator program, SOFTC, began in middle of 1990's and was used for precise navigation of various space missions since 2001 [17]. At Swinburne University of Technology, a project to construct a large scale software correlator with a cluster of 180 2 GHz PC machines under the SKA project [23]. At Kashima, developments of the K5 software correlator are under way based on the CCC program developed in 1980's [12]. Figure 4 show the current performance of the XF type K5 software correlator program. In the figure, time required to correlate 1 second of data taken with 4 channels of input and 8 MHz 1 bit sampling mode (corresponding to 32 Mbits) are shown. The clock frequency of the CPU used for the processing is taken as a parameter expressing CPU power. The processed data contain 4 channels of data, so that processing time of 4 seconds (denoted by a dotted line) represents the border for real-time processing for 1 channel of data. As shown in the figure, fast CPU can process the data at the data rate of 10 Mbps. A series of geodetic VLBI experiments have been performed to evaluate the results obtained by the software correlator and it was confirmed that the software correlator can produce indistinguishable results with the hardware correlators [16].

At Kashima, another FX type K5 software correlator is also under development specializing in processing speed to process gigabit VLBI system data mostly for an astronomical use [8]. In

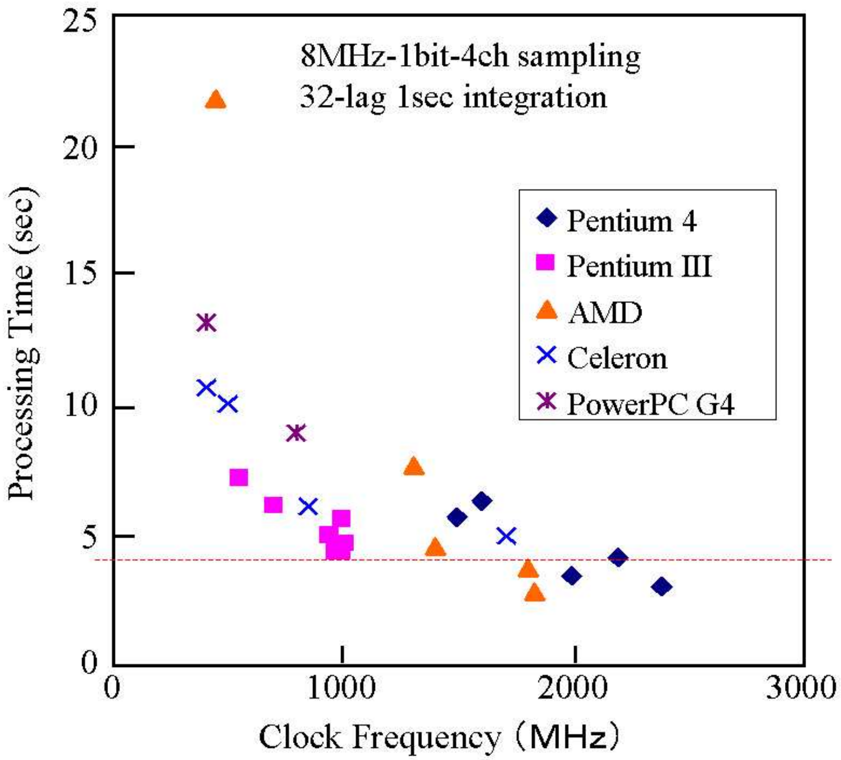

Figure 1. Current performance of the XF type K5 software correlator program.

order to maximize the performance of CPU, various kinds of optimizations, such as an effective use of multi-processors and utilization of SIMD (Single Instruction Multiple Data) technology for parallel processing, were taken into the development. An assembler language program was also used partially to improve the performance. Figure 4 shows results of performance test of the FX type K5 software correlator using a PC equipped with dual AMD Athlon 1.8 GHz processors. Throughput was measured for different lags, and reached about 90 Msps (it corresponds to the processing speed of 90 Mbps when 1 bit sampling are adopted) for lag numbers from 512 to 8192. The size of cash memory of CPU affected the performance at large number of lags, resulted in the performance loss. Multi-baseline correlations with multi-PCs are also planned to achieve further speed up of processing. By the use of the latest and fastest four PCs, it is possible to process 1 Gbps data in real time.

Combination of the software correlator and the disk-based recording system or the real-time data transfer is quite suitable for distributed correlation. Even if a single PC CPU can not process the entire data stream, processing load can be distributed to multiple CPUs. Figure 4 shows one of many examples how distributed processing system can be realized. In this case, observed raw data are divided into a number of short-segmented data for example one second. A PC (leftmost PC in the figure) correlates the first pair of segmented data (labeled 00 in the figure). After this processing, the PC processes next available pair of segmented data (labeled 06 in the figure). Second (from the leftmost in the figure) PC first correlates the second pair of segmented data (labeled 01), and then correlates next available pair of segmented data (labeled 07). In this way

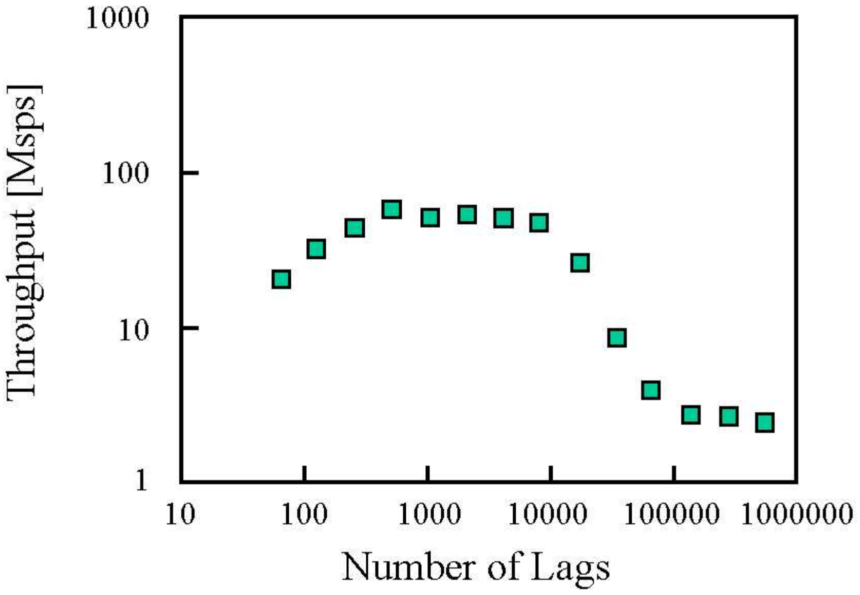

Figure 2. Performance evaluation results of FX type K5 gigabit software correlator program.

the use of a number of PCs allows to correlate raw data in real-time even though each PC has no capability of real-time processing. In order to realize this idea, it is necessary to develop a distributed processing system consisting of a server PC and client PCs [22]). It is also possible to concentrate the data taken during a specific time segment from all stations. It is especially effective if the data transfer speed over the network is slow. If the network speed is not a limiting factor, it is also possible to design the distributed correlation system to allocate a specific pair of data to a single PC. In any cases, the correlation core program is identical to all the client systems and the number of available client systems can be effectively used to minimize the processing time.

There is an empirical tendency in the past that the performance of PC capability has been improving by a factor of two every 18 months and the speed of the network transfer improvements is even faster. If this improvements continue in the future, we can expect the improvement of processing speed of a software correlator without any special improvement of software itself. Actually a software correlator run on a recent PC begins to have a practical processing speed to carry out routine correlation processing. A network-distributed processing system is also being developed to achieve further speedup. We think that a part of routine correlation processing carried out by a hardware correlator will be taken over by a software correlator in the future.

5. Real-time Correlation

The real-time VLBI and near-real-time VLBI are not very new form of concept. In 1977, the first real-time VLBI observations were performed between 46-m antenna station of the Algonquin Radio Observatory (ARO) in Ontario, Canada, and 43-m antenna station of National Radio Astronomical Observatory (NRAO) at Green Bank, West Virginia, USA [28]. During the observations, 20 Mbps of data obtained at the Green Bank station were transferred by using a joint communica-

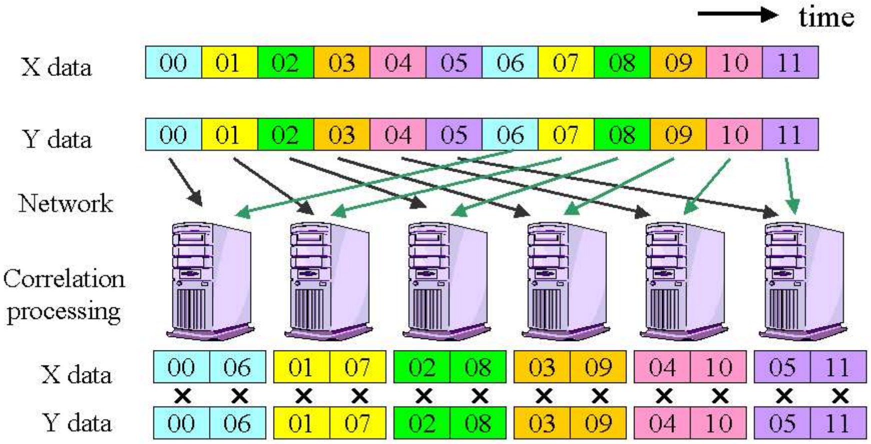

Figure 3. One example of distributed correlation processing.

tion satellite between Canada and USA called Hermes to the real-time correlation system at ARO. In early 1980's, Jet Propulsion Laboratory established the near-real-time VLBI system connecting three Deep Space Network sites at Goldstone (California, USA), Madrid (Spain), and Canberra (Australia) [6]. By switching the observation frequency, three frequencies were observed both in S-band and X-band at the data rate of 500 kHz. The observed data were transferred by using a satellite communication link and the correlated results were processed for bandwidth synthesis to obtain precise group delay observables. At Kashima, real-time VLBI observation and correlation system was developed and observations were made by using two VLBI stations at Kashima and Hiraiso by using a microwave link [10]. The baseline length was 47 km and 5 frequency channels with 2 MHz of bandwidth were observed sequentially, and the correlated data were processed for bandwidth synthesis. After these remarkable pioneering works, next progress of the real-time and near-real-time VLBI technique did not happen until high speed communication networks became available by using fiber optical cables.

The real-time VLBI or near-real-time VLBI has a lot of advantages. Firstly, the tape changes at the observation sites and at the correlator site can be eliminated to realize fully automated operations. Recorded tapes at the observing sites do not have to be packed and then shipped to the correlator site. These operations require considerable human resources and are obstacles for frequent observations. Secondly, the time to obtain results from VLBI observations can be minimized. It is especially true when many radio telescopes in many countries are used in an observing session. At present, it can take more than two weeks to process all the data obtained from an international geodetic VLBI observing session. Shortening the time gap required to process global VLBI data is one of the current short-term technical targets wished by IVS [20]. Also, because of its nature, a problem at an observing site can be noticed immediately by actually processing the observed data at the correlator site. Lastly, limitations of the sensitivity and the number of baselines caused by the capability of the correlator system can be eliminated by using distributed processing and the direct real-time correlation by not using recording media. The minimum detectable limit of the VLBI observation is inversely proportional to the square root of the bandwidth of the observing signal and hence the data rate of the data recorders. The data rate of the data recorders with magnetic tapes have been gradually improved since the beginning of the VLBI observations but it is still limited to the current maximum of 1024 Mbps with a single recording system. The processing capacity of the correlator systems also have been expanded, but it is still limiting the number of radio telescopes to be included in a VLBI observing session. The transferred data can be correlated by hardware correlator systems or by software correlation programs either in real-time or near-real-time. In the case of software correlators, the correlation processing can be performed by multiple computer systems by using distributed computing and the processing capacity of the correlation processing can be freely expanded. In the e-VLBI system, the observed data can be correlated simultaneously with the observations, or the data can be correlated after the observations. In both cases, the data can be correlated much faster than in the case of tape-based VLBI, and all the procedures from the preparations of the VLBI observations to the end of data analysis can be automated.

Real-time VLBI operations by using hardware correlator system and the high speed ATM (Asynchronous Transfer Mode) network were demonstrated in the Key Stone Project [14]. During the Key Stone Projects, four VLBI stations were connected with the OC-48 (2.4 Gbps) ATM link. Real-time correlator system was placed at the Koganei station and the observed data at the data rate of 256 Mbps were transfered to the real-time correlator from four stations. By automating all the process from observations to the data analysis, daily or sub-daily geodetic VLBI sessions were performed and the results were published immediately after each session. The Key Stone Project network was later extended to Usuda and Nobeyama stations and the GALAXY network was established. In the GALAXY network, 1 Gbps (1024 Mbps) real-time correlation was demonstrated by using a GICO correlator at Kashima. Recent developments of the real-time VLBI is shifting to use IP (Internet Protocol). The IP network is widely used by high speed research networks in recent years, and IP is considered to be most suitable to establish global scale real-time VLBI. In March 2004, a successful demonstration was made between Westford and Onsala stations by using Mark 5 systems and the Mark 4 correlator at the Haystack Observatory. The observed data rate was 32 Mbps during the demonstration, but it is planned to examine much higher data rates as soon as the network connection between VLBI sites is improved.

6. Future Correlators

To define the detailed architecture of the future correlator systems, it is essential to define the observing mode and number of stations in the observing sessions. Cost of developments and the automation will also have to be considered. To consider actual design of the correlator, it is also very important to ensure compatibility among different data acquisition system. The lack of the compatibility used to be the major obstacle which sometimes prevented inter-operability of different observing systems. To solve the problem, VLBI Standard Interface specifications were either defined or under developments for hardware, software, and data transport format [24]. The use of these standard specifications will be quite important in the future correlator developments.

At present, efforts to develop software correlation programs are being pursued by various groups. The current capability seems still primitive to realize large scale operational correlator. However, the maximum processing data rate of about 70 Mbps was achieved by using ordinary available single chip CPU and it seems promising that the capability will be dramatically improved [8]. Since capacity of the software correlator can be easily expanded by using distributed processing, software correlation will become one of the candidates for future correlator systems in 2010 and beyond. Software correlator has various advantages since it can be modified according to the observational requirements such as frequency resolution and pulsar gating. In principle, if maximum possible data rate is most important for high sensitivity, custom chip LSI will be the most adequate choice whereas the software correlator and FPGA architectures will be more favorable if the cost becomes the major issue.

There are other discussions to perform station based fringe stopping processing at the observing site. It will separate the part of the correlation processing task to the data acquisition system at observing sites and hence will simplify the design of the correlator. On the other hand, it will fix the fringe rotation spatial reference point and therefore will limit the field of view for astronomical mapping purposes. Investigations will be necessary to figure out how it can contribute to develop the high speed simplified correlator system.

7. Operational Aspects of the Correlation Processing

For fringe checking after observing sessions, data transfer of the part of the observed data and correlation of these data are very effective to confirm the observations were successful. In the future beyond 2010, such e-VLBI fringe checking will become usual practice. However, even in the future, there will be some stations which will not have high speed network connection such as at Syowa station in Antarctica and e-VLBI operation with these stations will be very difficult. In such a case, satellite communication will become an alternate method to transfer observed data for fringe checking.

For geodetic and astrometric VLBI sessions coordinated by IVS, Mark 3 format database files are created from correlator output data for S-band and X-band, at present. The software package CALC and SOLVE are used to perform initial data analysis and NGS data card format files are generated for data analysis by other software packages such as OCCAM. The Mark 3 format database files can only be handled on HP-UX operating system at present, and it is desired to develop standard data file format for data archiving which can be handled on any operating systems. Platform Independent VLBI Exchange (PIVEX) file format has been proposed for data archive [7]. The PIVEX format has been designed to be transportable to any operating platforms and it is expected to help developing softwares for data analysis on any operating systems. However, if we consider the situation if only part of the observing stations are connected with high speed Internet, these data will be correlated first and then the remaining baselines will be correlated later. In such cases, the database files have to be updated every time the correlation processing are performed. Then the analysis centers will have to retrieve the updated database files and repeat data analysis from the initial processing. In this case, current practice of using database files may not be the most appropriate way of data archiving. If we follow the similar mechanism of "data clearing house" commonly used by other field such as Geographical Information System (GIS), we can archive the up-to-date in the centralized data servers. Then the analysis centers will request necessary data set from the data servers according to their purpose of data analysis. If rapid UT1-UTC estimation is the purpose, the data for for the specific time period will be used. If the structure of a specific source have to be investigated, all the data obtained with the source will be retrieved. Also, the initial data processing such as ambiguity removal and bad data screening will be performed once and the results will be reflected to the original data set at the data servers. Then the initial data processing does not have to be repeated. If such a clearing house like mechanism is adopted, it can be expanded to centralize the control of distributed correlation processing. The data servers will allocate data to the distributed processors so that the computing resource will be effectively used for correlation processing. The processed data will be stored at the data servers and the analysis center will be able to estimate UT1-UTC on the fly even during the observing session is continuing.

8. Post Correlation Processing

Currently, all geodetic VLBI data processing are using delay and delay rate determined for each baseline. In this case, if the adequate signal to noise ratio was not obtained for a specific baseline, such data are not used for data analysis. In addition, correlation factors between these values are usually ignored. This is, however, simplified approximation. If we consider the situation where we have raw observation data at each observing station $x_i(t)$) and we have to estimate delay τ_i and delay rate $\dot{\tau}_i$ at i-th station ($i \geq 2$) with respect to the reference station 1, the problem is to find maximum likelihood set of τ_i and τ_i ($i \geq 2$) by maximizing the following.

$$\max \sum_{i=2}^{n} \int_{t_0}^{t_1} x_1(t) x_i(t - \tau_i - \dot{\tau}_i(t - t_0)) dt$$

The idea of the global fringe fitting was discussed by [21] and the technique is now sometimes used in the astronomical VLBI data processing. It should also be possible to estimate correlation factors between τ_i and $\dot{\tau}_i$. To use these values, the database file structure have to be extended and the data analysis software also have to be modified. But it is will be a necessary direction of developments especially the number of observing stations in the session increases.

9. Summary

The future correlation processing and other related issues before data analysis were briefly reviewed and considered. Unless the observing mode and the size of the observing network is defined, it is impossible to specify detailed design of the future correlator systems. However, the important points would be to use standard such as VSI and PIVEX. The considerations of the use of global fringe fitting technique and correlation factors between delay and delay rate determinations may become a good opportunity to revisit long ignored aspects of the VLBI data processing.

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