Correlators in 2010 and Beyond

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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 today 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, ALMA, SKA, and Extended VLA. 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. 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. 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. Current and Next Generation 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. In these lists, Mark-4, K4, and S2 correlators are regularly used to process the IVS regular sessions at present. 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. 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.

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	[12]
K4	Kashima, Tsukuba	4	256	256	[7]
S2	Penticton	6	128	8192	[2]
VLBA	Socorro	24	512	1024	[1]
VSOP	Mitaka	10	1024	8192	[4]
GICO2	Kashima	4	2048	1024	[8]

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 are using specially designed custom correlation chips.

There are also several projects to develop next generation VLBI correlators. Korean VLBI Network and Chinese VLBI Network projects 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 [3]. 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 [9].

3. 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 [11]. 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

[6]. 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.

4. 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 [5]. 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.

5. 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 [10] 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.

6. 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.

References

[1] Benson, J. M. (1995), The VLBA Correlator, in Very Long Baseline Interferometry and VLBA, ASP Conference Series, by J. A. Zensus, P. J. Diamond, and P. J. Napier (eds.), **82**, pp.117-131.

[2] Carlson, B. R., P. E. Dewdney, T. A. Burgess, R. V. Casorso, W. T. Petrachenko, and W. H. Cannon (1999), The S2 VLBI Correlator: A Correlator for Space VLBI and Geodetic Signal Processing, Pub. Astro. Soc. Pacific, **111**, pp.1025-1047.

[3] Carlson, B. R. and P. E. Dewdney (2003), VLBI Capabilities of the EVLA Correlator, in New Technologies in VLBI, by Y. C. Minh (ed.), ASP Conference Series, **306**, pp.271-286.

[4] Chikada, Y., N. Kawaguchi, M. Inoue, M. Morimoto, H. Kobayashi, S. Mattori, T. Nishimura, H. Hirabayashi, S. Okumura, S. Kuji, K. Sato, K. Asari, T. Sasao, and H. Kiuchi (1991), The VSOP

Correlator, in Frontiers of VLBI, by H. Hirabayashi, N. Inoue, and H. Kobayashi (eds.) (University Academy Press, Tokyo), pp.79-84.

[5] Gontier A. and M. Feissel (2002), PIVEX: a Proposal for a Platform Independent VLBI Exchange Format, IVS 2002 General Meeting Proceedings, NASA/CP-2002-210002, pp.248-254.

[6] Kimura, M and J. Nakajima (2002), The Implementation of the PC-based Giga bit VLBI System, IVS CRL-TDC News, No.21, pp.31-33.

[7] Kiuchi, H., M. Imae, T. Kondo, M. Sekido, S. Hama, T. Hoshino, H. Uose, and T. Yamamoto (2000), Real-time VLBI System Using ATM Network, IEEE Trans. Geosci. Remote Sensing, **38**, pp.1290-1297.

[8] Koyama, Y., T. Kondo, J. Nakajima, M. Sekido, and M. Kimura (2003), VLBI Observation Systems Based on the VLBI Standard Interface Hardware (VSI-H) Specifications, in New Technologies in VLBI, by Y. C. Minh (ed.), ASP Conference Series, **306**, pp.135-144.

[9] Okumura, S. K., S. Iguchi, Y. Chikada, and M. Momose (2003), Recent Development of Digital Spectro-Correlators for Radio Interferometers - ALMA Second-Generation Correlator, in New Technologies in VLBI, by Y. C. Minh (ed.), ASP Conference Series, **306**, pp.259-270.

[10] Schwab, F. R. and W. D. Cotton (1983), Global Fringe Search Techniques for VLBI, Astron. J., **88**, pp.688-694.

[11] Whitney, A. R. (2001), VLBI Standard Interface Specification, IVS 2000 Annual Report, NASA/TP-2001-209979, pp.18-49.

[12] Whitney, A. R., R. Cappallo, and W. Aldrich, B. Anderson, A. Bos, J. Casse, J. Goodman, S. Parsley, S. Pogrebenko, R. Schilizzi, and D. Smythe (2004), Mark 4 VLBI Correlator: Architecture and Algorithms, Radio Sci., **39**, RS1007, doi:10.1029/2002RS002820.