A VLBI Correlator with Internet-based Distributed Computing

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ABSTRACT

An internet-based distributed computing system has been developed for the cross-correlation process of Very Long Baseline Interferometry (VLBI). Like SETI@home, client/server model is used in the system and screensaver-type correlator program runs only when the client PC is idle. No expensive dedicated hardware correlator is necessary, but standard low-cost personal computers in observatories provide CPU resources. Using software correlator, the type of correlator is selectable (e.g. XF or FX, geodetic purpose or astronomical purpose) and correlation processes can be easily repeated, changing correlation parameters (e.g. integration time, phase center of the map, number of lags, FFT size).Current processing speed for 32-lag XF correlator has reached to 20Mbps per single CPU. In this paper, we discuss the architecture of the developed system and look at the results of some test experiments using this system.

INTRODUCTION

As broadband networks become widely available, internet-based distributed computing technology is highlighted. One of the examples is SETI@home [1], developed at the University of California at Berkeley, to which worldwide PC users donate their unused processor resources in order to analyze radio signals from outer space for signs of extraterrestrial intelligence. Although there are some kinds of distributed computing applications recently, to divide and distribute data itself has no essential meanings in most cases but is merely a technique to increase the processing speed. On the other hand, signal processing for VLBI data is a special case because initial locations of the data to be processed are already distributed separately on worldwide VLBI stations. Thus, distributed computing has an intrinsic affinity to the processing of VLBI data. Conventionally, the large amount of data received at each VLBI station had to be recorded to magnetic media, and be physically transported to a correlator station to be cross-correlated. It had limited both data bandwidth (sensitivity) and realtimeness of VLBI experiments. The recent developments of international high-speed network infrastructure enable us to use the Internet for VLBI data transmission. Additionally, performance of commodity PCs has increased enough that we can use them for VLBI correlators. To utilize these technologies, we have developed a new PC-based VLBI data acquisition system and data processing system, named K5 VLBI system. Some software correlator programs were developed for the system. By using the high-speed network connectivity of the system, an internet-based distributed client/server-type correlator system, named VLBI@home, has been developed. Client/server-type distributed computing system is characterized by having following three features. First, a large amount of data is divided in small units and transferred to client PCs. Second, sent data are processed by the clients. And third, resulting data are sent back to the server. This type of system generally works well when the network speed is faster than processing speeds of each client PC. At present, XF-type 32-lag software correlator for geodesy have a capability to process 16-Mbps data in real-time when it runs on a PC equipped with a Pentium4 3GHz. Thus, distributed computing method has a potential to increase the speed of software correlator if 100Mbps, 1Gbps or more high speed network environments are equipped.

INTERNET-BASED DISTRIBUTED CORRELATOR SYSTEM

System Overview

In the system, received radio signals at each VLBI station are divided into appropriate short-time segments and each segmented data is assigned to one of the client PCs. In the case of multi-baseline observations, all the data received at the same time at different stations are gathered into one PC to minimize data transmission costs. As shown in the left side of Fig.1, system consists of following components: a control server which controls the whole system, a database server which stores processing conditions and statistics of each client PC, FTP servers at each VLBI station which transmit received VLBI raw data to clients, and many client PCs by which VLBI data are correlated. When client software activates, it ask the control server about filenames of the data to be processed and IP addresses of observed VLBI stations. The client

downloads the data from the FTP servers and correlates the data. Resulting data and related information such as download and correlation duration time are reported to the database server via the control server.

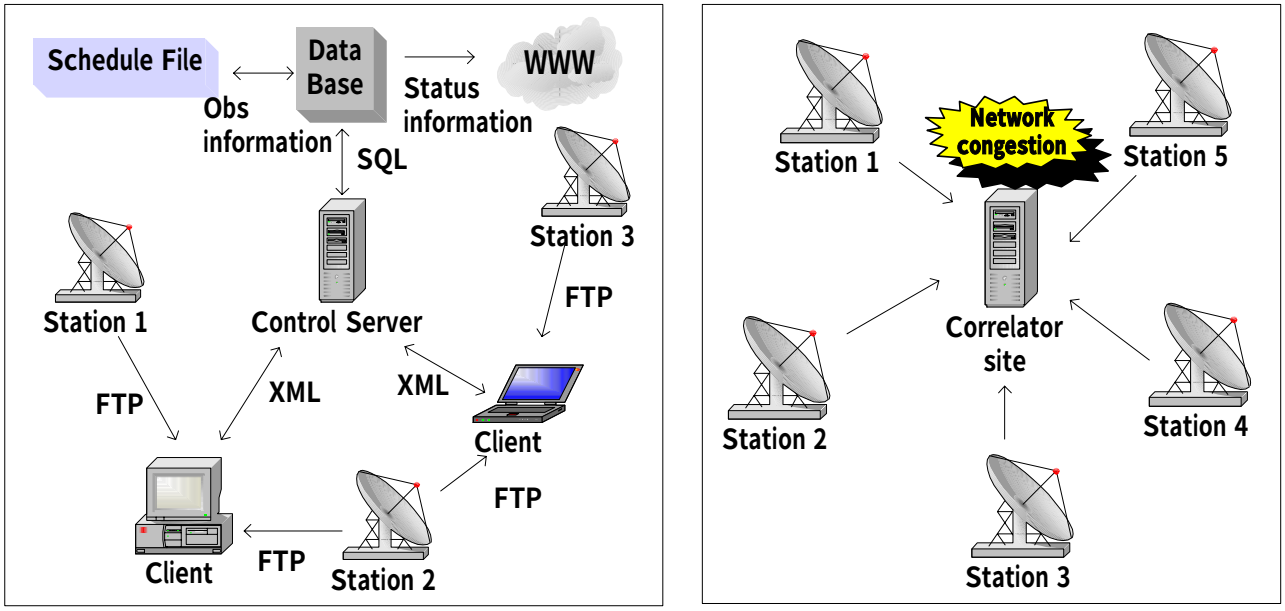

Fig. 1. Left: A schematic diagram of the whole system. It consists of a control server, a database server, FTP servers at each VLBI stations, and a number of client PCs distributed in the whole system. Right: A schematic of conventional correlator station model. Sampled data streams are concentrated to a correlator station. Network traffic at the correlator station becomes a limiting factor when the number of stations increases.

By the multi-thread FTP-client function of the client software, multiple data files from different VLBI stations are simultaneously downloaded. With the resume function, interrupted data transmission is automatically restarted. The correlator core program is selectable from the XF-type software, cor.exe, or the FX-type fx_cor.exe [2]. In a socket connection between a control server and a client PC, all the information is represented in XML format. Following three types of observation modes are provided:

- Non-real-time mode: Recorded VLBI data are gathered to a correlator station from each VLBI station with on-line or off-line data transmission after a session. After the data transfer, distributed correlation process is performed within the LAN at the correlator station.
- Quasi-real-time mode: Sampled data are recorded to HDDs on each VLBI station. At the same time, Internet-based distributed correlation process is performed over the Internet. If the processing rate or network rate is less than the data sampling rate, correlation process continues after the end of a session. Care must be taken to prevent performance decreases due to the simultaneous read-write access to HDDs.
- Real-time mode: Sampled data are buffered to RAM-disks at each VLBI station but not to HDDs. Processed data are removed from RAM-disks by clients. If the data processing rate or network rate is less than the data sampling rate, overflowed data are discarded.

System Performance Management

There are three factors which can become a bottleneck of the system: total data processing rate, network performance, and access speed of each FTP server. These three factors can be monitored using statistical data stored in the database server. Data processing rate of each client can be calculated from recorded duration times for each correlation process. A typical value of the rate using a single-CPU PC is 4 to 20 Mbps for 32-lag, single-baseline XF software (See Fig.2). If this factor

becomes a system bottleneck, it is necessary to increase the number of clients or to improve the algorithm of correlation programs. The download-time statistics of each client is used to evaluate a network performance. A typical network speed is 10Mbps to several Gbps. The network speeds around FTP servers determine the total performance of the system. If it is not enough compared to a total data processing rate, it becomes a bottleneck of the system. To monitor further detailed network statistics, use of the Real-time Transport Protocol (RTP) is effective. An RTP-based VLBI-data-transport protocol, VSI-E, is proposed [3]. Data transfer rate of an FTP server is limited by the access speed to RAID arrays. A typical value is 200Mbps for random accesses and 1Gbps for sequential accesses. If this factor becomes a bottleneck of the system, FTP mirroring is effective and RAM-disk can be used for real-time observations. Eliminating these factors, overall system performance can be increased up to 10Gbps, the highest network rate we can use at this time.

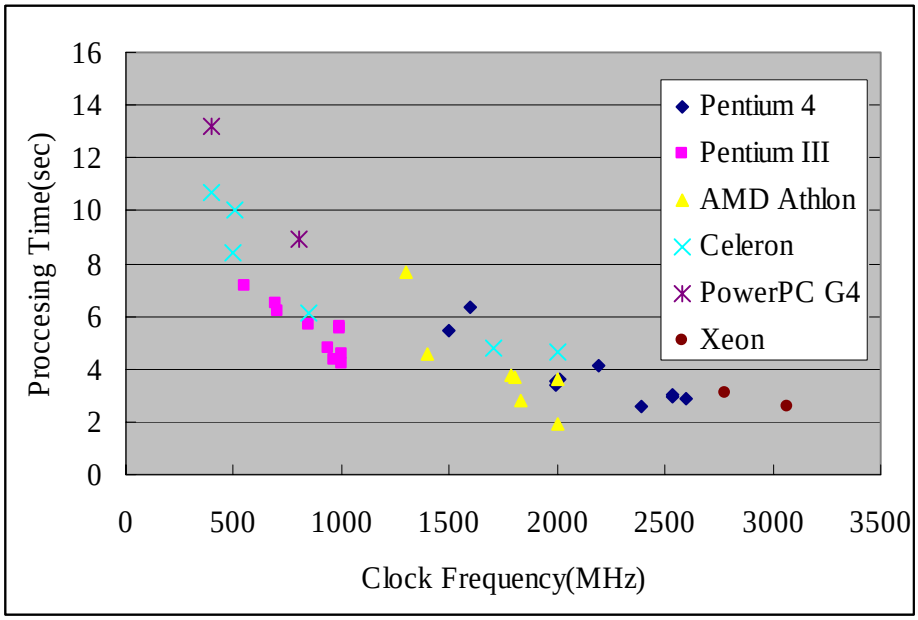

Fig. 2.Benchmark results of single-baseline XF-type software correlator
(Processing time for 8-MHz, 1-bit, 4-channel, 32-lag, 1-second data segment)

Future Possibilities as a Distributed Computing System

In the case of existing Internet-based GRID system like SETI@home, unanalyzed raw data are provided from one location. On the other hand, VLBI raw data are stored in multiple locations, and each client must access to multiple data storages. Additionally, in the case of multi-baseline observations, analyzed raw data are reusable on the other PC for the analysis of different baselines. Because of these unique features, there are some new possibilities as a distributed computing system as follows:

- Allocate different set of FTP servers to each client in order to optimize total network transmission cost.
- Multicast data transmissions from a VLBI station to multiple client PCs.
- Reuse of the analyzed VLBI raw data by P2P (peer-to-peer) data transmissions between clients.

Basically, all the data taken at the same moment at different VLBI stations should be gathered into one PC to minimize data transmission costs. However, if the number of observation stations (N) is increased, data processing time in one PC is increased on the order of N^2 and it may become impossible to analyze all baselines by a single PC. The above methods are effective to distribute a segmented data to multiple PCs in such a case.

EXPERIMENTS

A real-time monitoring of Earth Orientation Parameters (EOP) is one of the targets of global real-time geodetic VLBI. For this target, some experiments have been carried out with VLBI@home.

Japan-Fiji Distributed Correlation Experiment via Satellite TCP/IP Link

Full-time observations at globally distributed VLBI stations are desirable for the real-time monitoring of EOP. However, pacific and southern hemisphere coverage is not sufficient for this purpose. If we are able to use a high speed TCP/IP data link using an optical fiber network or wideband satellite communication at the South Pacific Islands, it will be able to fill a gap in the VLBI observation network. We started to develop the VLBI and GPS data transfer system using a satellite TCP/IP link between NICT, Koganei, Japan and the University of South Pacific (USP), SUVA, Fiji. To test the feasibility of use of the satellite link for VLBI@home, we performed non-real-time distributed correlation experiments via the geostationary communication satellite (Superbird C) during the period of January 16-21, 2005. Pre-prepared data sets were uploaded to FTP servers on each side and several client PCs were used at both stations. The link speed of the satellite network was 1.53Mbps full-duplex. Though the current bandwidth is not enough to transmit the huge data sets such as Gigabit VLBI data, we could evaluate the system performance on the actual network environment which has long TCP Round Trip Time (RTT) to the geostationary orbit. The total system performance decreases due to the large RTT is simply resolved as the number of client PCs increase because multiple TCP connections from multiple clients hides the delay in each connection. We could confirm that the system performance is improved as the number of TCP connections increased and approaches to the network link speed.

Kashima-Westford Rapid UT1 Estimation Experiment

VLBI@home was used for the session which intended to estimate UT1-UTC as soon as possible between Kashima and Westford on June 29, 2004 [4]. After the session, Mark-5 data received at Westford was transmitted to Kashima station. Mark-5 data files were converted to K5 format, and correlated with VLBI@home. Average processing speed of VLBI@home was 58.6Mbps using 8 consumer PCs in our laboratory. UT1-UTC estimation was completed 4hours and 30 minutes after the last observation in the session.

CONCLUSION

The average performance of the system for a 32-lag XF-type correlation is 70Mbps using sixteen low-cost PCs in our observatory. A rule of thumb, Gilder's law, indicates the network bandwidth grows at least three times faster than computer power. We expect that distributed computing will become more effective year by year, and will become a key technology for VLBI analysis in the next decade.

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