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The Canadian geophysical long baseline interferometer

J. L. Yen,[1] P. Leone,[1] G. A. Watson,[1] J. K. Zao,[1] J. Popelar,[2]
W. T. Petrachenko,[2] G. Feil,[2] W. H. Cannon,[3] P. Mathieu,[3] P. Newby,
H. Tan,[3] R. D. Wietfeldt,[3] and J. A. Galt [4]

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The Canadian geophysical long baseline interferometer, a new very long baseline interferometer system, has been developed and put into operation. The system tracks source delay and fringe rotation during observation using a wave front clock. After the low-noise receiver the signals from radio sources are channelized and down converted to baseband, each baseband channel is one bit digitized at a rate of 12 mbar/s and then recorded on a single video cassette recorder for processing. The total bandwidth of the system can be easily increased by replication of baseband channels. During processing the tapes are played back in synchronism and the recovered astronomy data are processed in a simple correlator to obtain the source visibility. The use of wave front clock allows bursts of wideband astronomy data to be sampled at a high rate at each station and then recorded at a lower rate for processing. Because bursts recorded at different stations at the same wave front clock epoch are emitted by the source at the same time, they are correlated. The fringe visibility obtained from processing the bursts would provide high-delay resolution geodetic measurements commensurate with the wide bandwidth of the bursts.

INTRODUCTION

The technique of very long baseline interferometer (VLBI) has become a well-established tool in radio astronomy and in geodynamics. By this technique, radio signals from astronomical objects are received at widely separated observing stations and recorded on magnetic tapes for later processing and image reconstructions. This allows unconnected radio telescopes distributed over wide areas to be combined to form a single instrument of great angular resolving power. The use of precision independent clocks to down convert the radio frequency signals to video frequencies, and then to sample them for recording have completely removed the umbilical cord required to connect stations at different locations for coherent observations. Existing radio telescopes have been combined to form continental and global arrays operating as a single instrument to provide unprecedented angular resolution and high-precision mapping of distant compact radio sources *[Readhead, 1982].* A new major instrument using this technology, the very long baseline array (VLBA) is now under construction [Kellerman and Thompson, 1988]. To further enhance the resolution, two programs, the Radioastron of the USSR and the VLBI Space Orbiting Program (VSOP) of Japan, plan to deploy spaceborne interferometer elements to work with terrestrial telescopes in the near future [Schilizzi, 1986]. By observing a set of extragalactic compact radio sources, the Earth's rotational dynamics and deformation of crustal plates can be investigated with unprecedented precision [Whitney et al., 1976]. Thus VLBI has also become an important tool for geodynamic studies.

In two decades of VLBI history, five recording systems have been developed and have seen extended service. Most of these systems employ digital recording, except for the early Canadian LB1 system [Broten et al., 1967], which made use of analog recording on various forms of video tape recorders. The early Mk I digital recording system with its 720 kbar/s data rate [Bare et al., 1967] was soon replaced by the Mk II system with a 4 mbar/s data recording rate, developed by the National Radio Astronomy Observatory [Clark, 1973]. This system has seen worldwide use for many years and

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[1] Department of Electrical Engineering, University of Toronto, Toronto, Canada.

[2] Geophysics Division, Geological Survey of Canada, Ottawa, Canada.

[3] Institute of Space and Terrestrial Science, York University, Toronto, Canada.

[4] Dominion Radio Astrophysical Observatory, Penticton, British Columbia, Canada.

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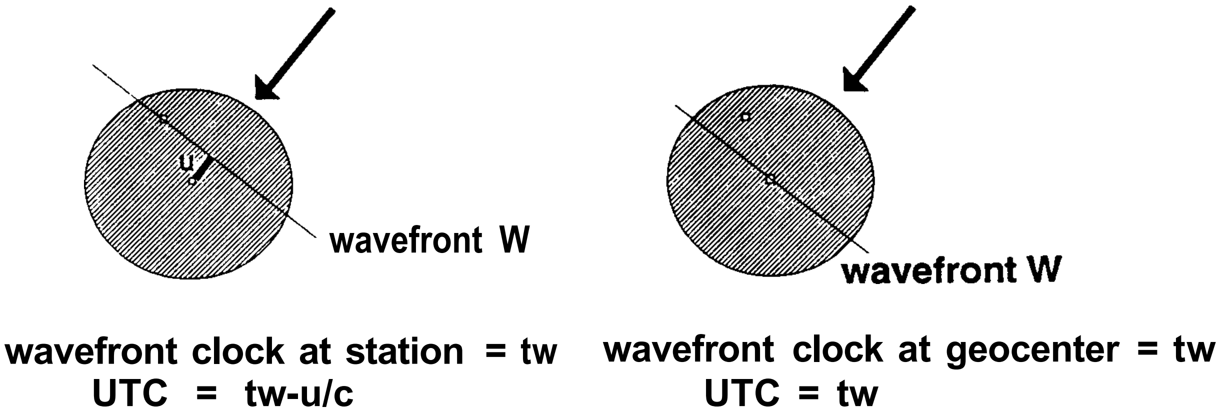


Fig. 1. Two snap shots of a single wave front.

has been implemented in three generations of helical scan video recorders. The system is still in extensive operation today. The high-density Mk III system using multitrack magnetic recording was subsequently developed at the Haystack Observatory of the Massachusetts Institute of Technology [Clark, 19791, providing 28 tracks of 4 mbar/s data. This greatly increased bandwidth results in a five times increase in sensitivity of VLBI and corresponding increase in accuracy of astrometric and geodynamic observations. The track density was further enhanced in the MK IIIA upgrade which permitted up to 12 passes to be recorded on the same tape, greatly increasing the tape storage capacity. A descendent of the MK IIIA, the new VLBA recording system, capable of 24-hour recording of 128 mbar/s data on a single reel of tape has been recently developed. The VLBA system, capable of further enhancement with advances in magnetic tape media, is likely to be the principal VLBI system in the next decade.

Compared with the simple MK II recording system, the MK III and its descendants are high-cost massive systems, requiring complex electronics to convert data to the large number of channels. These systems are designed for flexible large-scale operations in dedicated observatories. Although VLBI is a worldwide technology most suited for a single standard, the high cost of MK III and its descendants precludes small-scale implementation of VLBI for special and exploratory investigations. We have developed a small, adaptable VLBI system using a bank of current technology video cassette recorders. The main objectives of the development were simplicity, low cost, and growth potential. For simplicity the highest data rate commensurate with current technology is used to reduce the number of channels. To reduce cost, consumer type video cassette recorders (VCRs) have been selected and replication of electronics and VCRs provides a simple growth path. The system was developed for geodynamic and astrometric measurements and has been named the Canadian geophysical long baseline interferometer system (CGLBI).

The first distinctive component of the CGLBI is the recording system. Advanced signal processing means have been incorporated to achieve high data rate recording on the VCRs. The version in current operation uses a data rate of 12 mbar/s. The second feature is the use of delay tracking and fringe rotation before recording by means of a wave front clock at each station. A consequence of this feature is that only a simple correlator is required for signal processing. Finally, the presence of a wave front clock allows for "burst mode" recording, namely, the ability to record short bursts of high sampling rate data, resulting in large effective bandwidths for high-precision astrometric and geodynamic measurements. The system was under development for the past several years by a group comprising the University of Toronto, the Geophysics Division of the Geological Survey of Canada, and York University; funded by the Natural Science Research Council of Canada and the Department of Energy Mines and Resources. The system has been put into operation recently. In the following the major components of the system are described.

THE WAVE FRONT CLOCK

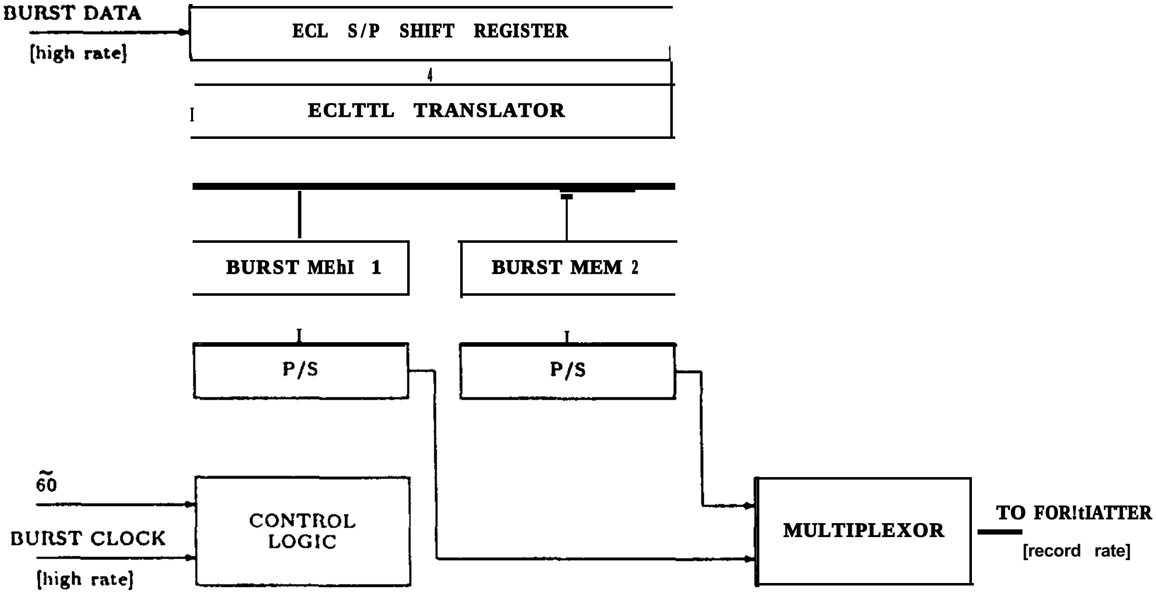
Because of the variations of the distance from the source to different observing stations, a single wave front emitted by a radio source will arrive at each station at different local times as shown in Figure 1. The frequency components of the signal will also suffer different Doppler shifts as a consequence of the different inertial velocities of each station. Unlike connected interferometers such as the very large array (VLA) [Napier et *al.,* 19831, where corrections must be applied before correlation of signals can be performed in real time, in current VLBI systems, both frequency conversion and data sampling make use of universal time. As a result, on playback processing, fringe rotation is required to correct the Doppler shift for each baseline and delay tracking is required to correct for the different arrival time of wave fronts. An alternative is to make these corrections at the observing station. In this latter scheme each station uses a clock whose timekeeping corresponds to the time of arrival at a reference point, such as the geocenter, of a wave front emitted from the reference position of the source [Yen, 19851. To derive the local oscillator for down conversion, the baseband sampling time, as well as the recorder drive, all from such a clock is equivalent to using a common clock attached to the source at the reference source position for operation at all the stations. Samples taken at different stations at the same wave front clock time are from the same wave front, hence they are correlated. Furthermore, using a local oscillator attached to the radio source for down conversion is equivalent to down converting the signal at the source, hence the main Doppler component is removed. In this manner, correlation of signals from different stations will have dc fringes, if no offset is introduced and no errors are present. Fringe rotation and delay tracking are therefore performed at the observing stations. With the advent of powerful microprocessors and complex very large-scale integration chips, wave front clock systems can be reliably implemented. In addition, as described in the next section, bursts of samples obtained at high speed can be stored and then recorded at a lower rate. In this manner a signal with a bandwidth larger than the inverse of the recording data rate can be handled, thereby increasing the delay measurement accuracy for astrometry and geodynamic observations. The wave front clock system is therefore adopted for the CGLBI.

BURST MODE OPERATION

In position measurements the information is derived from delay of the correlation function and from the fringe phase. The accuracy of delay measurement can be a small fraction of the sampling interval, depending on the signal-to-noise ratio. High-precision delay measurements therefore require independent samples at small sampling intervals obtained from large bandwidth signals. With a limited recording data rate, multiple channels centered at judiciously chosen frequencies can be used to synthesize a larger effective bandwidth [Rogers, 19701. This method of making high-precision delay measurements is known as “bandwidth synthesis” and has been in use for many years. Alternatively, bursts of high-speed samples of a wideband signal can be buffered and subsequently recorded at a lower rate for later processing, as shown in Figure 2. As long as the bursts recorded at each station belong to the same sets of wave fronts they will be correlated. The use of the wave front clock at each station for recording guarantees that this is the case. This means the addition of a high-speed sampler and a data buffer, implemented using a fast-shift register and high-speed static random access memory, would allow the CGLBI system to operate in the burst mode, thereby easily achieving recorded bandwidth expansion of an order of magnitude. Since the number of samples recorded on each recording channel is left unaltered by the implementation of the burst mode, the burst mode does not result in an increase in signal-to-noise ratio, in spite of the larger signal bandwidth. In other words, the precision of delay measurement is the same fraction of the sampling interval as in the case of continuous recording. However, because sampling is now at the high-speed burst rate, the precision of delay measurements and the derived position and time data are correspondingly enhanced [Wietfeldt,19871 Image reconstruction can also benefit from large bandwidth because the (u,v) tracks in the baseline plane are smeared into bands. If the spectral index of the source is relatively constant within the band, enhancement of dynamic range may be achieved. The implementation of burst mode operation in the CGLBI system is therefore a simple means by which to increase the accuracy of geodynamic measurements and to facilitate broad-band image reconstruction.

THE RECORDING SYSTEM

The recording system makes use of low-cost video cassette recorders. The details of the high-



BURST MEMORY SCHEMATIC

Fig. *2a*

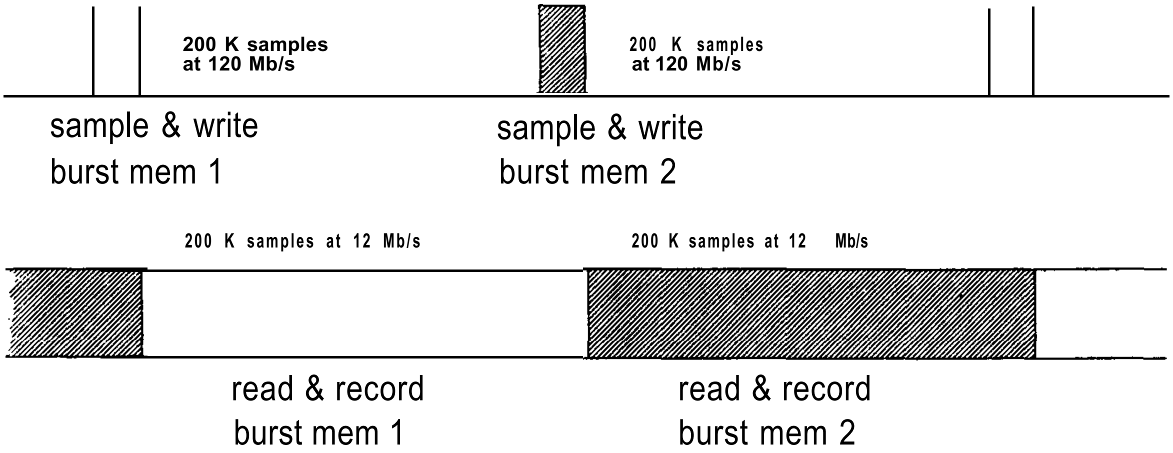


Fig. *2b*

Fig. 2. (a) Burst memory and *(b)* burst mode operation.

density recording system are given by Newby and Yen [1983]. Data is directly recorded on tape without using channel coding. In order to match the loss characteristics of the recording channel the signal on playback is equalized to a response characterized by $1 - D^2$, where D represents delay by one sample. As shown in Figure *3a* the response of a single-recorded flux reversal extends over three adjacent samples, while at all other sample points it is zero. This equalization introduces spectral nulls at dc and at the Nyquist frequency, as shown in Figure *3b,* where the signal to noise ratio of the playback channel is low, and results in a three-level detection waveform from which the data can be retrieved. This deliberate use of intersymbol interference is known as partial response signaling [Kable and Pasupathy, 1975]. In the CGLBI system, precoding of data in the form of $1/(1- D^2)$ is used prior to recording so that on playback the astronomical data is recovered directly. At play back a microprocessor in the analog data recovery module performs such functions as automatic gain control and clock recovery. A special feature of the system is the use of a tapped delay line adaptive equalizer to reduce intersymbol interference [Qureshi, 1985]. With the successful implementa-

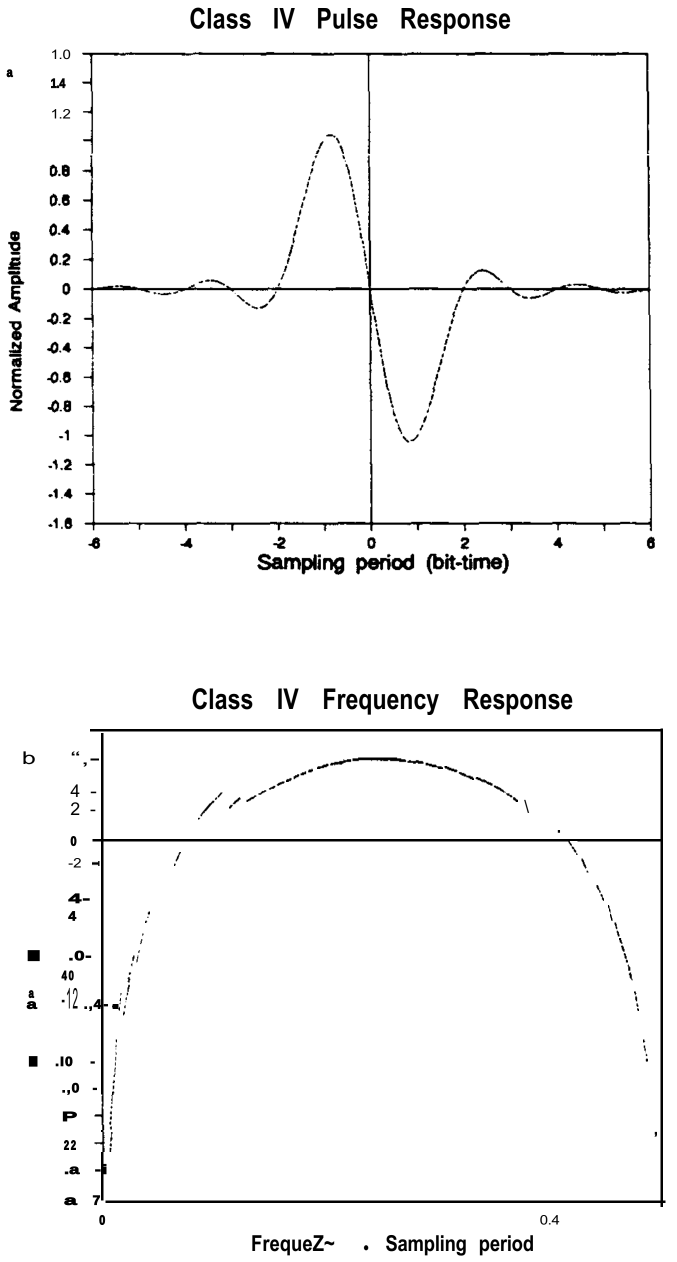
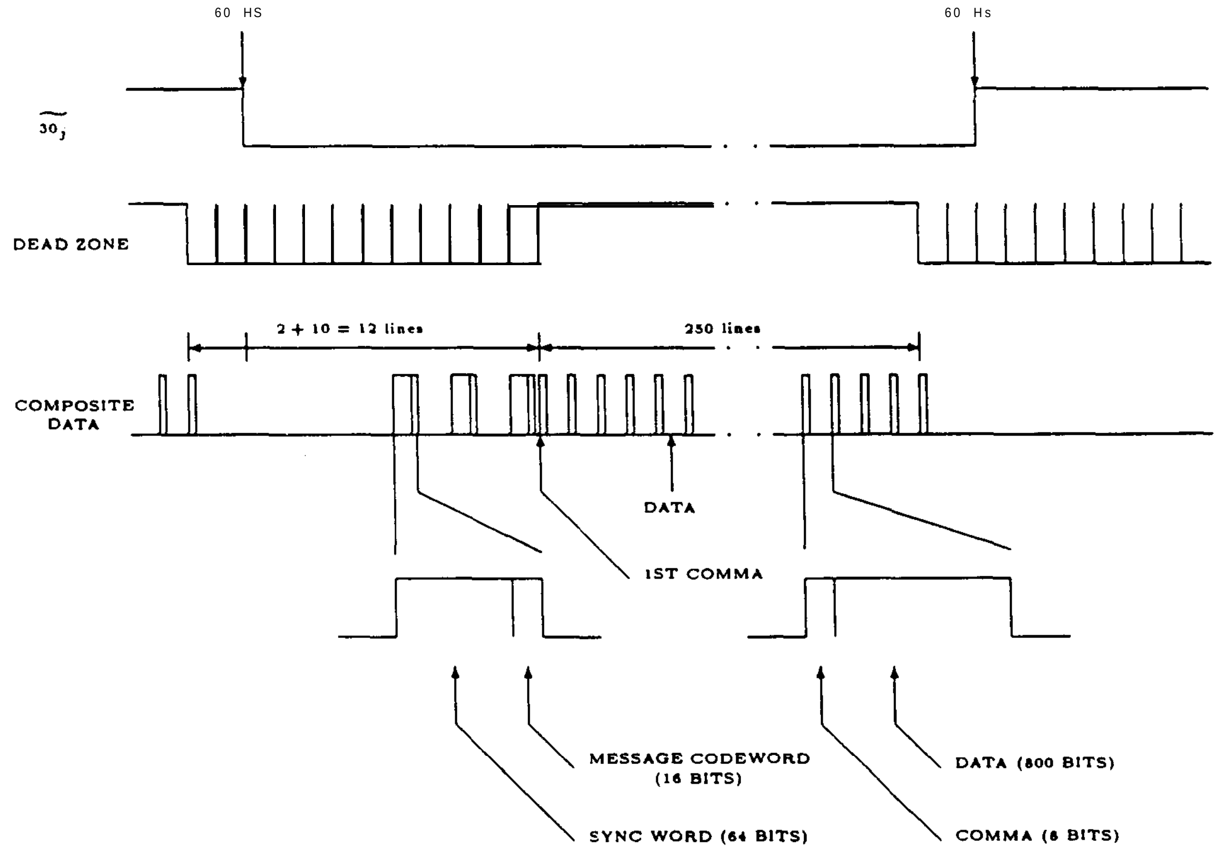


Fig. 3. (a) 1 *D2* partial response signal and (b) the spectrum,

tion of these techniques a recording channel using a standard Video Home System (VHS) type video cassette recorder with a channel capacity of 12 mbar/s and an average bit error rate of a few parts in 10’ has been achieved. The error rate is currently being improved by the implementation of a maximum likelihood detector [Wood and Petersen, 1987], which makes use of the partial response characteristics of the read back signal. A bank of 8-10 video cassette recorders is capable of recording the same data rate as the Mk IIIA or the VLBA recording system. Such an arrangement would of course require more cassette handling; however, the low system cost per channel provides a simple path to future growth on demand.

DATA FORMAT

The CGLBI system uses a data format which has been selected to reflect the fact that each frame of a television picture is recorded on a single helical track on a VCR. In between frames the recording head is switched so that there is no continuity between two adjacent frames. This means such auxiliary but necessary tasks as timing acquisition and detection of beginning of frame must be performed for every frame. In addition, the data format must be robust enough to handle burst errors extending over many bits caused by occasional tape defects. As dictated by the helical scan VCR tracks, the 12 mbar/s astronomy data, i.e., data obtained from astronomical sources, is divided into frames at 60 frames per second, each containing 200 kbar of data. Since no offset of data from each station is required on playback and correlation other than to correct for errors in the a priori values of the station position, source position, and station clock, the frames are grouped in l-s groups. In each group a message giving UTC time, station name, source name, channel identification, and other relevant information pertinent to the recorded astronomy data are imbedded, one character to a frame, to yield a message of 60 characters once every second. The information is sufficient to reconstruct the wave front clock model used at recording. In each frame the data is augmented by a preamble “header” containing synchronizing words and a message character. A unique synchronizing word is used to designate the first frame of each l-s-long frame group. To ensure detection of frames in the presence of readback errors, the synchronizing word is repeated three times in the header of each frame. The message character is coded in a 1/2 rate Bose, Chaudhuri, Hocquenghem (BCH) code [Clark *and* Cain, 1981] to ensure its integrity. To detect bit slips within a frame, the astronomy data is further divided into 250 lines each of 800 bits in length, and an 8 bit code designated as “comma” is inserted between lines. However, no cyclic redundancy check (CRC) bit is included to detect presence of errors. In between frames a 1.5MHz square wave “locking sequence” with a length equivalent to 12



CGLBI DATA FORMAT

Fig. 4. The Canadian geophysical long baseline interferometer data format.

lines is inserted for timing acquisition on playback. The header, message character, commas, and the locking sequence are combined with the 12-mbar/s astronomy data to form a composite data stream of 12.7 mbar/s for recording. Figure 4 shows the composite data format. The overhead data are removed on playback, and a continuous stream of astronomy data at 12 mbar/s synchronized to the playback system clock is retrieved.

THE OBSERVING SYSTEM

The CGLBI observing system is more complex than the traditional VLBI recording terminal because of the wave front clock. In addition to a low-noise receiver each station has a wave front clock, a bank of baseband down converters, a bank of samplers, a multichannel formatter, and a bank of VCRs; all driven by the wavefront clock and controlled by a station computer as shown in Figure 5. The analog astronomy signal from the receiver i first channelized and down converted to baseband by local oscillators derived from the wavefront clock. They are then 1 bit sampled and the data streams are formatted into frames of composite data as described above by a multichannel formatted [Tan, 1984]. Each formatted data channel is the recorded on a VCR, also driven by the wave fron clock. One could implement the wave front clocl simply by replacing the station frequency standan by a wave front clock frequency standard from which all timing and local oscillator frequencie needed for operations are derived. Such a clock could be implemented by employing a numerically controlled oscillator chip in an appropriately designed phase lock loop. However, since local oscilator frequencies are usually much higher than that of the frequency standards, such an approach would require very high spectral purity. To avoid this, separate local oscillator and sampling clock

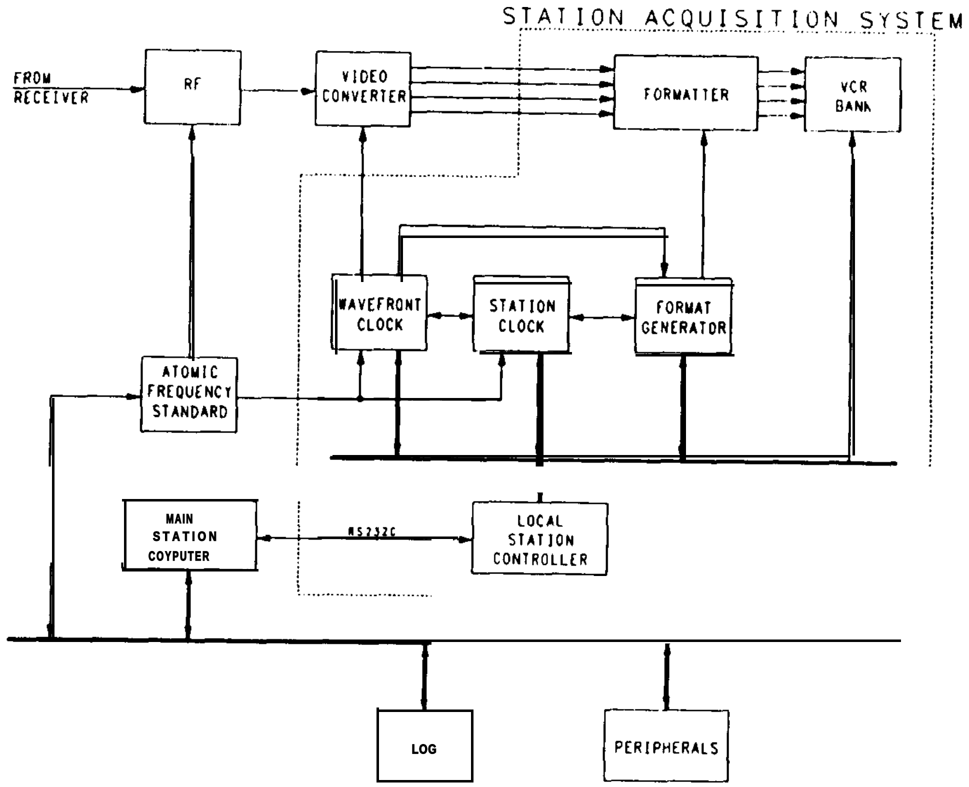


Fig. 5. The Canadian geophysical long baseline interferometer observing system.

are adopted for the present implementation. A wave front clock is generated for the baseband converter local oscillator frequency, while the first local oscillator is derived directly from the station frequency standard. Both the 12 mbar/s sampling clock and the baseband converter local oscillator are implemented using four phase clocks with the clock phases selected by two rate multipliers controlled by an 8086/8087 coprocessor pair [Zao, 1987] as shown in Figure 6. The timing resolution of the

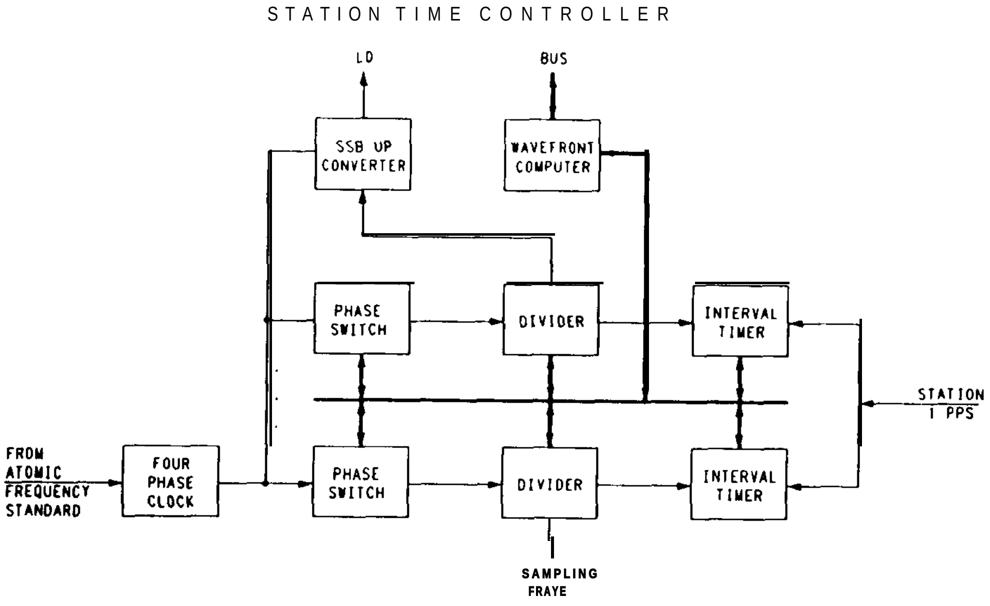
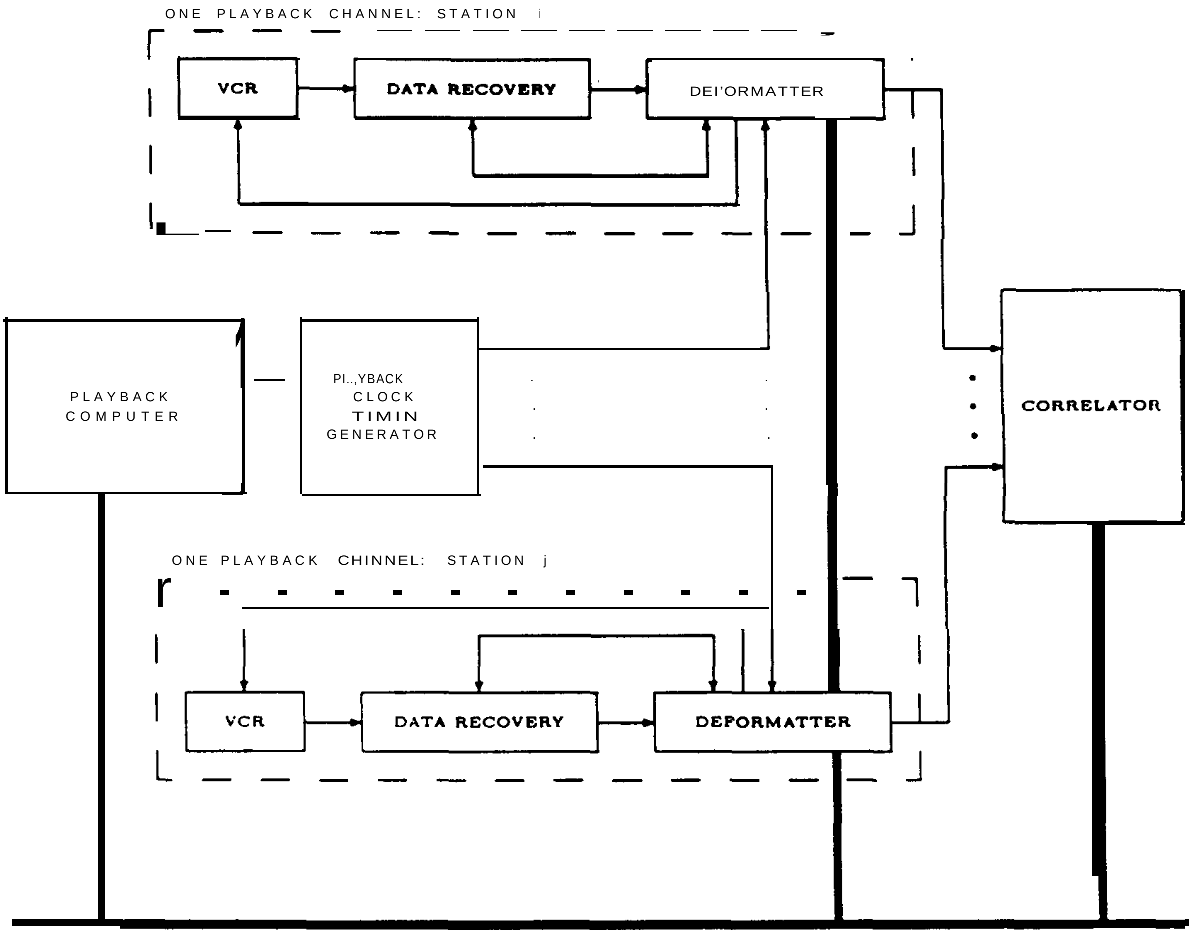


Fig. 6. Wave front clock implementation.



CGLBI PLAYBACK SYSTEM SCHEMATIC

Fig. 7. The playback correlator system.

sampling epoch is +5 ns, and the resolution in local oscillator phase is +/- 3.5” in the present implementation.

The operation of the observing terminal is controlled by an IBM personal computer host computer which contains data files governing the observation schedule and a model for the computation of delay between wave front clock and universal time [Muthieu, 19861. The data files contain a radio source catalog, an observing schedule, the a priori station geodetic coordinates or geocentric Cartesian coordinates, and the observing frequency. In preparation for the start of an observation, the host computer passes all parameters required to track the source to the wave front clock, which sets the appropriate value of delay relative to the universal time for the observation start time. At start time the wave front clock drive is initiated, and the wave front clock simulates a clock attached to the source reference position of observation with epoch set at the Earth center. At the end of an observation the wave front clock is stopped, setup for the initial delay for the next observation, and the drive disabled until the next observation. Real-time monitoring of the system performance during an observation is possible by comparing the hardware generated delay and Doppler frequency against the model values.

THE PLAYBACK SYSTEM

The playback system consists of a bank of VCRs, each with its own data recovery module and deformatter, a delay controller, and an interface to the correlator. Figure 7 shows a block diagram of the playback and the correlator system. The data recovery module recovers the composite data together with its clock from the magnetic tape. The deformatter [Wietfefdt, 1984] takes the composite data recovered from a VCR, detects the beginning of frame and 1-s frame group from the synchronizing word, decodes the message, and sends the information to the playback correlation controller.

To achieve robustness in the presence of tape errors, soft decision is used to detect the three synchronizing words to prevent missed detection of the beginning of frame. Detection of one out of the three is taken as frame detection. In addition, to avoid false alarm, only detection falling within a window bracketing the expected position of the synchronizing word is accepted. Following detection of the synch words in the deformatter, the data overhead (including the header, the message character, the commas, and the locking sequence) is stripped off from the composite data and the 12 mbar/s astronomy data is reconstituted in a buffer RAM synchronized to a common cot-relator clock. Bit slip errors are monitored by detecting the presence of a comma in the proper location within a 7-bit window. On detection of an error condition such as a missed frame synch or a bit slip, the deformatter flags the controller by raising a “data invalid” flag to instruct the correlator to ignore the incoming data until the data invalid condition is removed. Small-bit slips detected within a frame will trigger resynchronization to minimize data loss.

To align the astronomy data on the magnetic tapes for correlation, the cot-relator controller first starts the VCRs, reads the tape time recorded on each magnetic tape, then stops each VCR at a prescribed common tape time. The correlator then starts all the VCRs simultaneously and synchronizes the tape times to the nearest second. Each tape is then slewed individually until the frame groups are synchronized with the correlator clock.

THE CORRELATOR

Since delay tracking and fringe rotation are performed during observation by the wave front clock in the CGLBI system, a simple “delay line” correlator with a search range in delay sufficient to allow for errors in the a priori station coordinates, source position, and station clock synchronization is all that is necessary to process the data. In the present system a two-station dual channel 16-lag cot-relator for continuum observations has been implemented. Each channel accepts a pair of 1-bit astronomy data at 12 mbar/s together with a pair of data valid lines. The accumulators in the 16 channels can be read at a maximum rate of 60 Hz corresponding to a minimum dump interval of 16.67 ms for a maximum fringe frequency of 30 Hz. For reasonable uncertainties in the a priori parameters governing the operation of the wave front clock the residual delay and residual fringe frequency are well within acceptable limits and a fast ASIC implementation of a correlator of this type is a straightforward task.

As shown in Figure 7, the cot-relator and the playback system are controlled by a 68000 based microcomputer using a real-time multitasking operating system built around the Versatile Real-Time Executive (VRTX) kernel that allows flexibility in a user friendly manner. Pertinent parameters for processing such as tape times, tape offset, coherent integration time, and dump time are set by the controller. Various modes and options of correlator operation including fringe search and estimates of delay, delay rate, fringe amplitude, and phase during correlation can also be executed.

SOME SAMPLE OBSERVATION RESULTS

The CGLBI system has been put into operation at 1668 MHz on the 3100-km baseline between the 46-m radio telescope of the Algonquin Radio Observatory and the 26-m radio telescope of the Dominion Radio Astrophysical Observatory in Penticton British Columbia. Rubidium frequency standards are used in both observatories. Figure 8 shows the results in a 6-hour segment of an observation carried out in April 1988. Six sources were observed in succession at 30-min intervals. In Figure 8a the residual delays are shown as they appeared directly from the cot-relator from processing of a single 12 mbar/s channel without any selection or removal of outliers, and exhibits an rms scatter of 5 ns. Figure 8b shows the corresponding fringe frequency data. In the data shown the fringe frequency residuals are clustered around 100 MHz, an offset introduced to avoid zero frequency fringe during the observation, with an rms scatter of about 2 mHz on each source or one part in 10^{12} of the observing frequency. This is consistent with the use of Rubidium oscillators as the frequency standard at each station. The relative amplitudes of the fringes are shown in Figure 8c.

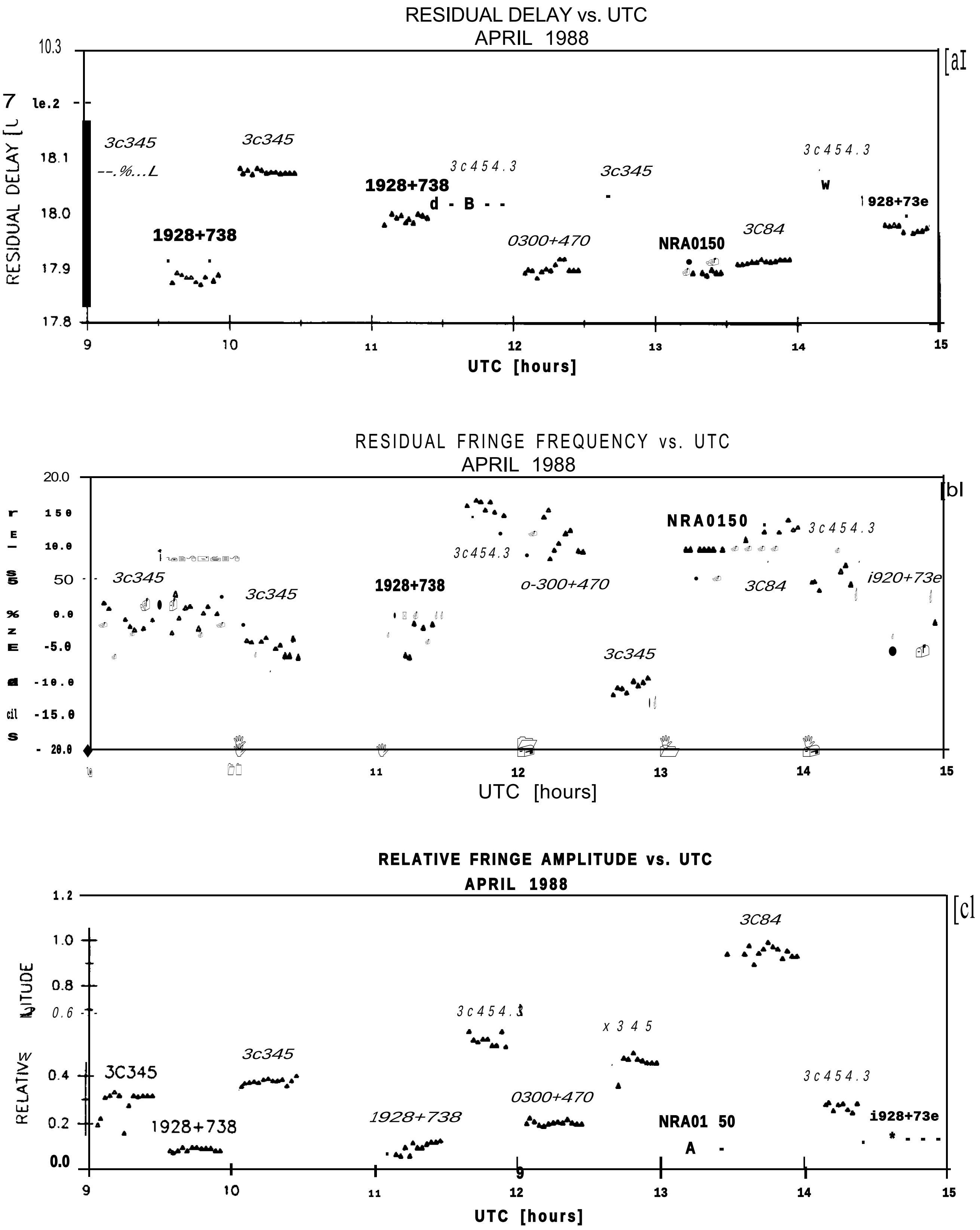


Fig. 8. Sample results of a 6-hour observation: (a) residual delay, (b) residual fringe frequency, and (c) relative fringe amplitude.

CONCLUSIONS

A new VLBI system has been developed. The system is characterized by the use of simple VCRs for high data rate recording. The system, named the Canadian geophysical long baseline interferometer (CGLBI), incorporates real-time delay and fringe correction on recording using a wave front clock, thereby greatly simplifying the correlator, and enabling the use of a wideband burst mode operation which may prove advantageous for high-precision geodetic measurements.

Prototype system observations have been carried out at 1668 MHz on the 3100-km baseline between the Algonquin Radio Observatory in Ontario and the Dominion Radio Astrophysical Observatory in Penticton, British Columbia. The system is simple and easily upgradable to larger bandwidths by replication of channels. It offers a simple VLBI alternative to the large dedicated Mk IIIA or VLBA data acquisition systems for special purpose and exploratory observations. Finally, with an appropriate data buffer and a recorder controller, astronomy data recorded on the system with the wave front clock turned off can be made compatible with the MK IIIA or VLBA correlator, either directly or through transcription, to accommodate joint observations with the VLBA system.

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W. H. Cannon, Institute of Space and Terrestrial Science, Space Geodynamics Lab, 2700 Steeles Avenue West, Concord, Ontario L4K 3C8 Canada.

G. Feil, W. T. Petrachenko, and J. Popelar, Geophysics Division, Geological Survey of Canada, Ottawa, KlA OY3 Canada.

J. A. Gait, Dominion Radio Astrophysical Observatory, Penticton, British Columbia, V2A 6K3 Canada.

P. Leone, G. A. Watson, J. L. Yen, and J. K. Zao, Department of Electrical Engineering, University of Toronto, Toronto, M5S 1A4 Canada.

P. Mathieu, P. Newby, H. Tan, and R. D. Wietfeldt, Institute of Space and Terrestrial Science, York University, Toronto, L4K 3C8 Canada.