THE D-6 RECORDING FORMAT AND ITS IMPLEMENTATION AS A HIGH PERFORMANCE GIGA-BIT VLBI DATA STORAGE SYSTEM

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1. ABSTRACT

Significant advances have been made in high-density magnetic recording technologies since the introduction of the D-1 (4:2:2) format in 1986. The D-6 recording format, which was proposed jointly by Toshiba of Japan and BTS of Germany, is the latest advancement in tape/head technology. Based on a 19mm, 11µm thick metal particle tape format, the D-6 format is capable of recording at a data rate of 1.2Gb/s without the use of compression. This paper will explain the D-6 format, the channel coding and error correction schemes utilized within the format, a newly developed magnetic tape and head technology and the format's hardware applicability in recording high resolution video and data. Specifically, this paper will discuss the new GBR-1000 HD-Digital Video Tape Recorder (HD-DVTR) based on the D-6 format and with simple modification, as a high performance instrumentation data recorder. In addition, a new Gigabit data recording system comprising of a VLBI (Very Long Baseline Interferometry) adapter called the DRA-1000 and a modified GBR-1000 will be discussed. The DRA-1000 allows the GBR-1000 to emulate a Gigabit instrumentation recorder, which is suitable for use in the VLBI astronomical observation environment. Last, an example of how the Gigabit Instrumentation Recording system has been used to capture VLBI astronomical data from the VSOP project will be discussed.

2. THE D-6 STANDARD

In mid-1993, BTS and Toshiba jointly proposed to the Society of Motion Picture Television Engineers (SMPTE) a new digital recording format that was capable of recording high data rates up to 1.2 Gb/s. SMPTE then installed a working group and assigned the working title D-6 to the proposed format. It was recognized early on that the format may not be restricted to only one video interface standard or to conventional video signals, i.e., image or data recording. Consequently, the D-6 standards documents consist of three parts: SMPTE 226M, SMPTE 227M and SMPTE 228M. The SMPTE 226M standard specifies the dimensions for the three sizes of cassettes (S, M and L) for use with 19mm television digital recorders. SMPTE 227M specifies the format and recording method of the data blocks that form the helical records on 19mm tape. Specifically, the helical data, longitudinal index, cue and control records are specified. This part of the standard is totally independent of the nature of the recorded digital signals and need not be changed if a new image interface standard is introduced. Part two, SMPTE 278M, specifies the content of the data blocks that form the helical records. SMPTE 228M specifies the content of the helical data and the time and control code records.

3. TAPE AND CASSETTE

The D-6 S, M and L size cassettes are based on the same 19mm cassettes that are used for the D-1 and D-2 formats. However, because of the higher recording densities needed for D-6, improvements were made in two areas. Tape thickness was reduced to 11µm from 13µm to increase record time. In addition, tape coercivity of the metal particulate tape was increased from 1,500 Oe to approximately 1,700 Oe for better recording performance at smaller wavelengths. These changes result in 64, 28 and 8 minutes of recording time for the Large, Medium and Small cassettes respectively.

4. TAPE FOOTPRINT

The D-6 tape footprint was designed to be independent of the nature of the recorded digital signals and need not be changed for any new image interface standard. However, present day technology didn’t economically allow for a single channel recording system to be able to process a 1.2 Gb/s data stream. Instead, it was decided that the 1.2 Gb/s data stream would be split into eight 150 Mb/s channels, which also dictated the basic track structure. Therefore, the D-6 format uses eight heads to write a cluster of eight helical tracks with a track pitch of 21µm, as depicted in Figure 1. Within each cluster, four helical tracks record luminance while the other four record the chrominance data. To simplify processing and to make circuit implementation easier, the luminance and chrominance data are separated. Each cluster is then separated by a guard band of 6µm. The guard band improves the compatibility of different tapes because it allows for extra-wide flying erase heads to overwrite the old data completely when performing an insert edit with new data. This makes it possible to maximize track width under predetermined track pitch conditions and to reduce interference from adjacent clusters during insert editing. Additionally, an azimuth recording technique, popularized by helical based digital video recording, is used to increase the areal or data storage density on tape by reducing the spacing between tracks. The azimuth angles of the helical tracks are set at -15 and +15 degrees.

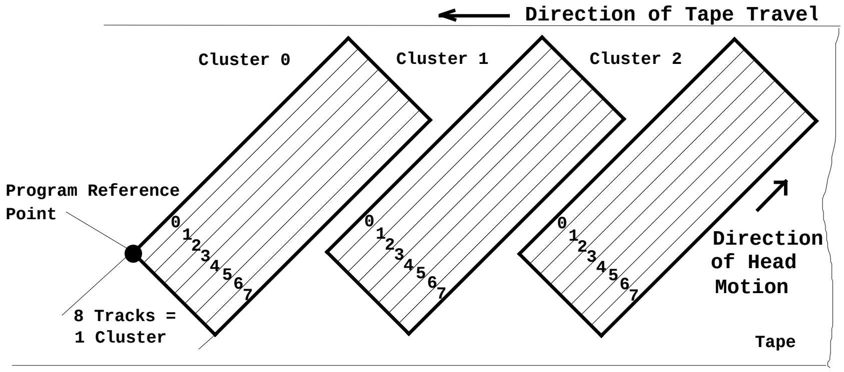


Figure 1.

View of Track Clusters for the D-6 Tape Footprint

5. HELICAL DATA CONTENT

All tracks contain 270 blocks with each block containing a packet of data comprised of the preceding synchronization and identification information. All the recorded blocks along a helical track are the same size in order to record a data pattern independent of any video, audio and edit gap parts of the track. However, two recording configurations are allowed depending upon the nature of the interface format (example: 1,035 or 1,081 active lines). The first configuration yields 229 bytes per block while the second yields 239. These blocks can be preambles/postambles or inner code blocks. As seen in Figure 2, the inner code blocks contain randomized data bytes and the preceding block identification (ID), both protected by 16 check bytes.

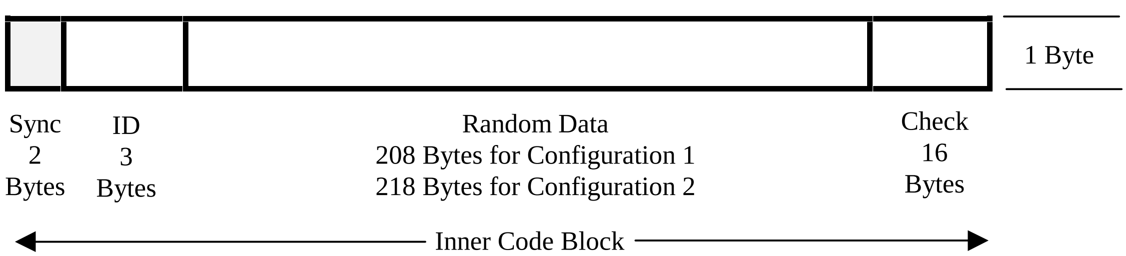
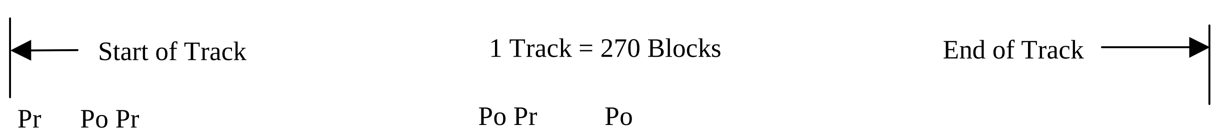


Figure 2. Structure, in bytes, of the Inner Code Block before channel modulation

As stated previously, all image standards recorded by this format employ an identical track pattern, inner and outer block structure and modulation code. Eight tracks form a cluster with each cluster divided into three sectors. The first and last sectors within a cluster contain audio data while the middle sectors contain the video data.

As can be seen in Figure 3, the audio sectors form both ends of each cluster. The number of bits per sample can be either 20 or 24 and conforms to the AES/EBU standard. Each audio sector includes the audio data for one stereo pair, corresponding to one field period of video. Therefore, audio editing is done in stereo pairs. One data field is the minimum edit distance for video and audio.



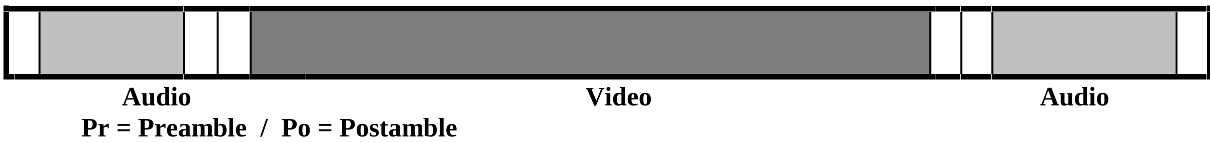


Figure 3. Track structure of Audio and Video Data

The data field is formed by a group of segments. Each segment starts with the video sector followed by the first audio sector of the same cluster and ends with the second audio sector, which is part of the next recorded cluster. The number of segments per data field is a parameter dependent upon the recorded video standard as defined in the table below. Video data are distributed over the eight tracks of a cluster and the audio data are recorded twice and placed at the beginning and at the end of each track.

No. of Active Samples/Line	No. of Active Lines/Frame	Frames/Sec	Data Fields/Frame	Segments/Data Field
1920	1035	30/29.97	2	5
1920	1080	30/29.97	2	5
1920	1152	25	2	6
1920	1080	24	2	6
1280	720	60	1	5

Table 1. Number of segments per data field as a parameter of the video standard

6. HIGH DENSITY RECORDING TECHNIQUES

The recording density chosen for the D-6 implementation is 6.6 μmm^2/bit. This recording density is twice that of existing 1-inch type Digital HDTV recorders. To achieve this, four areas of focus were addressed: (1) Magnetic Head and Tape; (2) Channel Coding Scheme; (3) Intrafield Shuffling and (4) Error Correction Format.

6.1 MAGNETIC HEAD AND TAPE

To improve the signal-to-noise (S/N) ratio of the playback signal, an improved metal particle tape formulation was developed. The new tape touts a smoother surface, a thickness of 11μm and coercivity of approximately 1,700 Oe for better recording performance at smaller wavelengths. This results in a S/N improvement of about 2.5dB. In addition, a new laminate playback head was developed that improves the S/N ratio about 3dB as compared to ordinary ferrite heads.

6.2 CHANNEL CODING SCHEME

A new channel coding scheme was also developed to ensure long minimum wavelengths and suppression of low frequency components. After careful study, an 8-12 conversion system was adopted where all data blocks would go through 8-12 modulation coding prior to recording. The minimum wavelength for this 8-12 converted sequence is 1.33 times longer than that for the original sequence. Consequently, the 8-12 mapping code not only reduces low-frequency components but also increases the minimum wavelength compared with the original data sequence by 33%. The resulting S/N ratio would be further increased by about 5dB at the highest recording frequency. This improvement is important for recording the extremely high data rates required by the D-6 format.

6.3 INFRAFIELD SHUFFLING

The final implementation of the D-6 recorder uses data shuffling over one data field to improve the recovery of random and burst errors. This intrafield shuffling sequence is created by writing to a shuffling memory array in a shuffling sequence and reading the array in a different shuffling sequence. The size of the array corresponds to 1/8 of the amount of data within one data field and there is an array for each track number. After writing to the array, outer error correction encoding is performed.

6.4 ERROR CORRECTION FORMAT

Playback errors can occur due to various processes associated with media defects, head clogging, tape path problems, environment and pre-processing errors. The resultant burst and random errors can prove problematic when the recorded data is of a sensitive nature. To increase the robustness of the format and to increase its immunity to random and burst errors, the manufacturers chose to implement an error correction system based on a Double Reed-Solomon (RS) product code formed by inner and outer code bytes. The inner error correction scheme has a minimum Hamming distance of 17 and uses 16 check bytes to correct up to 8 error words.   The outer error correction calculates 14 check bytes for every 240 data bytes and can correct up to 14 video error words and 12 audio error words. The check bytes are appended to the end of the data bytes at the bottom of the shuffling array. For off-tape error rates lower than 4×10^{-4}, an output error rate of 1×10^{-11} can be achieved. In comparison, the maximum D-1 output error rate is 1×10^{-7}.

Because of its low error rate as compared to other digital video formats, the D-6 recording format is also ideal for the recording of data. To add to its already powerful error correction scheme, the D-6 recording structure and system implementation is augmented with a method of re-recording data that can't be recovered error-free by the read-after-write method. This yields residual error rates of roughly 10^{-15}, which is ideal for the recording of data as used in instrumentation and data recording environments.

As a comparison, the following Table outlines comparative data from two of the most widely used digital formats in video. As can be seen, the high performance of the D-6 format can be utilized for both video and data recording.

TABLE 2. COMPARISON OF COMPONENT DIGITAL VTRS

	D1	D5	D6
SAMPLING FREQUENCY(MHZ)	13.5	13.5	74.25

QUANTIZING (BIT)	8	10	8
CHANNEL CODING TYPE	S-NRS	8-14	8-12
TOTAL RECORDING RATE (MBPS)	225.3	300.6	1212
ACTUAL VIDEO RECORDING RATE (MBPS)	173	250	958.5
NUMBER OF CHANNELS	4	4	8
INNER ERROR CORRECTION CHECK BYTES	4	8	16
OUTER ERROR CORRECTION CHECK BYTES	2	8	14
	D1	**D5**	**D6**
MAXIMUM RECORDING TIME (MIN)	94	123	64
VIDEO DATA RECORDING CAPACITY(GBIT)	975.7	1845	3680.6
CASSETTE SIZE (MM)	366 X 206	296 X 167	366 X 206
TAPE MATERIAL	FERRIC DIOXIDE	MP	MP
TAPE WIDTH (MM)	19.01	12.65	19.01
HC (OE)	850	1800	1700
DRUM DIAMETER (MM)	75.0	76.0	96.5
DRUM REVOLUTION (RPS)	150	90	150
TRACKS/FIELD	10	12	40
TAPE SPEED (MM/S)	286.6	167.2	497
TRACK PITCH (UM)	45	20	22
MINIMUM WAVE LENGTH (UM)	0.9	0.64	0.81

7. RECORD LOCATION AND DIMENSIONS

The record location and dimensions of the D-6 footprint are shown in Figure 4, 5 and 6. Table 3 outlines the basic specifications associated with the following figures.

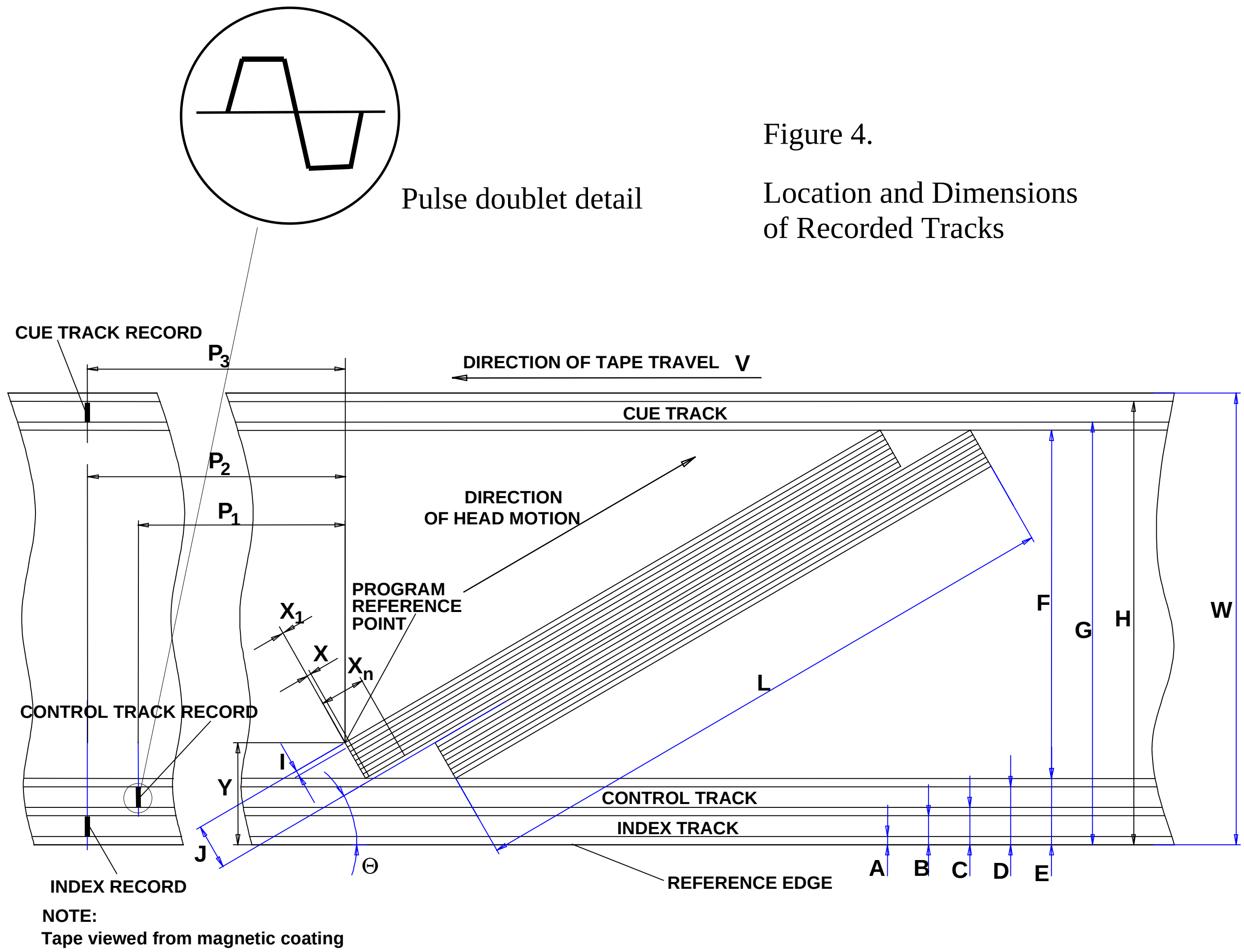


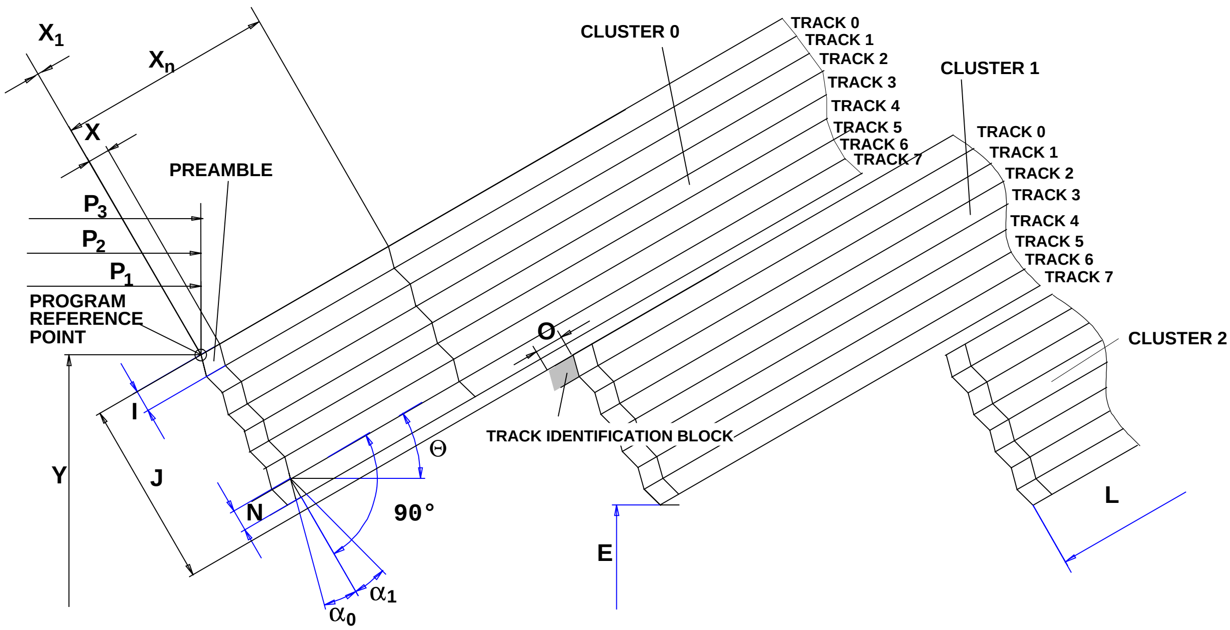
Figure 4.

Location and Dimensions of Recorded Tracks

	Dimensions		Tolerance	Dimen.
A	Index track lower edge	0.200	+-0.100	mm
B	Index track upper edge	0.700	+-0.100	mm
C	Control track lower edge	1.000	+-0.100	mm
D	Control track upper edge	1.500	+0.050 -0.100	mm
E	Program area lower edge	1.761	Derived	mm
F	Program area width	16.098	Derived	mm
G	CUE track lower edge	18.200	+-0.100	mm
H	CUE track upper edge	18.900	+-0.100	mm
I	Helical track pitch	0.021	Basic	mm
J	Helical cluster pitch	0.176	Basic	mm
L	Helical cluster length	150	+-0.300	mm
M	Number of blocks per track	270	Basic	
N	Record head track width	0.023	+-0.0015	mm
O	Length of TID pattern	0.700	+-0.200	mm
P1	Control track pulse	0	+-0.060	mm
P2	Index code information	99.500	+-0.300	mm
P3	CUE information	99.500	+-0.500	mm

V	Tape speed	497.418	+-0.05%	mm/s
W	Tape width	19.010	+-0.010	mm
X	Block length	0.55587	Basic	mm
X1	Loc. of start of block 1	0	+-0.200	mm
Xn	Loc. of start of block n	n*0.55587	+-0.300	mm
Y	Program reference point	1.930	Basic	mm
Zo	Tolerance zone track 0	0.006	Basic	mm
Z	Tolerance zone other tracks	0.010	Basic	mm
Θ	Dynamic track angle	6.0903	Basic	°
α0	Azimuth angle (track 0)	14.93	+-0.17	°
α1	Azimuth angle (track 1)	15.07	+-0.17	°

Table 3. Record location and Dimensions



NOTES: i) The program reference point is defined by the intersection of the upper edge of track 0 of Cluster 0 of the even numbered Data Fields with a parallel at distance Y to the reference edge.

ii) For easier identification of the track to head relation the track 0 of Cluster 1 of the even numbered Data Fields is extended by a track identification (TID) pattern.

Figure 5. Detail of Recorded Tracks for Field 0

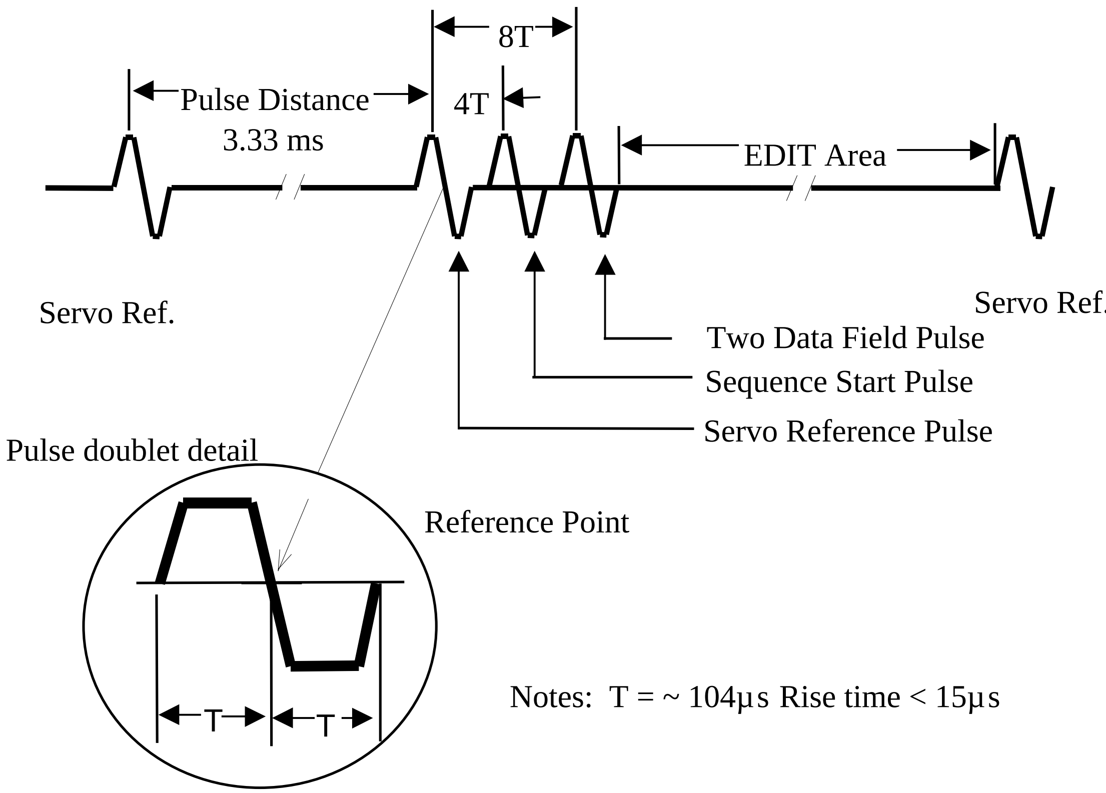


Figure 6. Control Track Waveform Timing

8. DESIGN IMPLEMENTATION OF THE D-6 FORMAT: THE GBR-1000 HD-DVTR

The joint efforts of BTS and Toshiba combined with SMPTE's quick response in establishing the D-6 format standard has resulted in the development of the first commercially available D-6 cassette based High Definition Digital Video Tape Recorder (HD-DVTR). In addition to the HiVision format in Japan (1125 video scanning lines and 60 Hz field frequency), the GBR-1000 can also be used with 1125/59.94 and with the format for the European HDTV standard (1250 video scanning lines and 50 Hz field frequency). Two HDTV formats can be selected for the GBR-1000 according to the application. The resultant GBR-1000 HD-DVTR as depicted in Figure 7 is capable of recording at 1.2Gb/s.

To record at this high data rate, the GBR-1000 utilizes a unique head drum scanner employing 16 recording heads, 16 playback heads and 2 erase heads, for a total of 34 heads. These heads are mounted onto a high-density head wheel, along with recording and playback amplifiers. To facilitate high speed data recording, the 96mm diameter drum rotates at 9,000 rpm, which corresponds to a longitudinal head to tape speed of 46 meters/second. Confidence playback of both video and audio is also integrated into the recorder to ensure that there is no deterioration in picture or sound quality during recording or repeated dubbing.

To facilitate the interchange of different tapes from various HD-DVTRs, the GBR-1000 employs automatic playback equalization. This equalization can take place automatically with a minimum rate of error in the data stream and with concealment-free video and audio signals.

Figure 7. Toshiba GBR-1000 HD-DVTR Tape Deck and Processor

For video, the GBR-1000 conforms to the BTA S001/S002 (SMPTE 240M/260M) (1125/60) and EU95 HDI (1250/50) standards. The sampling frequency is 74.25 MHz (1125/60) or 72 MHz (1250/50) for the luminance signal and 37.125 MHz (1125/60) or 36 MHz (1250/50) for the Pb and Pr color difference signals. The quantization is 8-bit.

For audio, the GBR-1000 conforms to the AES/EBU standard. A total of 10 channels (12 channels in the case of 1250/50) or 5 stereo pairs (6 pairs in the case of 1250/50) are available for the digital recording of audio signals. This recording uses a sampling frequency of 48 kHz and 20/24-bit linear quantization. The frequency response is flat from 20 Hz to 20 kHz, and the dynamic range is more than 90 dB.

Since the overall intent of this paper is targeted at data recording applications, the specific video and audio performance features and attributes of the GBR-1000 will not be discussed further. However, a cursory overview of the system are outlined in Figures 8 and 9 and Table 4; which outlines the general specifications of the GBR-1000.

The following two diagrams depict the system flow of the GBR-1000. Figure 8 depicts the Input/Encoding System Flow diagram while Figure 9 depicts the Output/Decoding System

Flow Diagram. As can be seen, the video signals are first digitized. Then, after shuffling, encoding of error correction, and digital modulation, the signals are divided into eight channels in parallel and recorded on tape. With the GBR-1000, the highest level of picture quality is achieved with the absolute minimum of non-correctable errors thanks to strengthened error correction encoding using a double Reed-Solomon code.

Model Name	GBR-1000 HD-DVTR	
Video Signals	1125/60, 1125/59.64 specifications BTA S-001, S-002 SMPTE 240M, 260M	1250/50 specifications EU95 HDI
Recording Time	64 min. (L cassette)	
Tape	3/4-inch (19mm) metal particle (MP) type	
Cassette Housing	D-6 type	
Video Bandwidth	Y : 30 MHz, Pb/Pr : 15 MHz	
Video Sampling Frequency	1125/60 specifications Y : 74.25 MHz Pb/Pr: 37.125 MHz	1250/50 specifications Y : 72 MHz Pb/Pr: 36 MHz
Video Quantization	8 Bits	
Recording Data Rate	1.188 Gbits/sec	
Audio Signal	AES/EBU Standard	
No. Of Channels	10 (5 stereo pairs)	12 (6 stereo pairs)
Sampling Frequency	48 kHz	
Audio Quantization	24 Bits Max.	
Dimensions	Tape deck: 700mm L X 447mm W X 397mm H Processor: 692mm L X 447mm W X 397mm H	
Weight	Tape deck: Approx. 55 kg Processor: Approx. 55 kg	
Power Consumption	Approx. 1 kW	

Table 4. GBR-1000 General Specifications

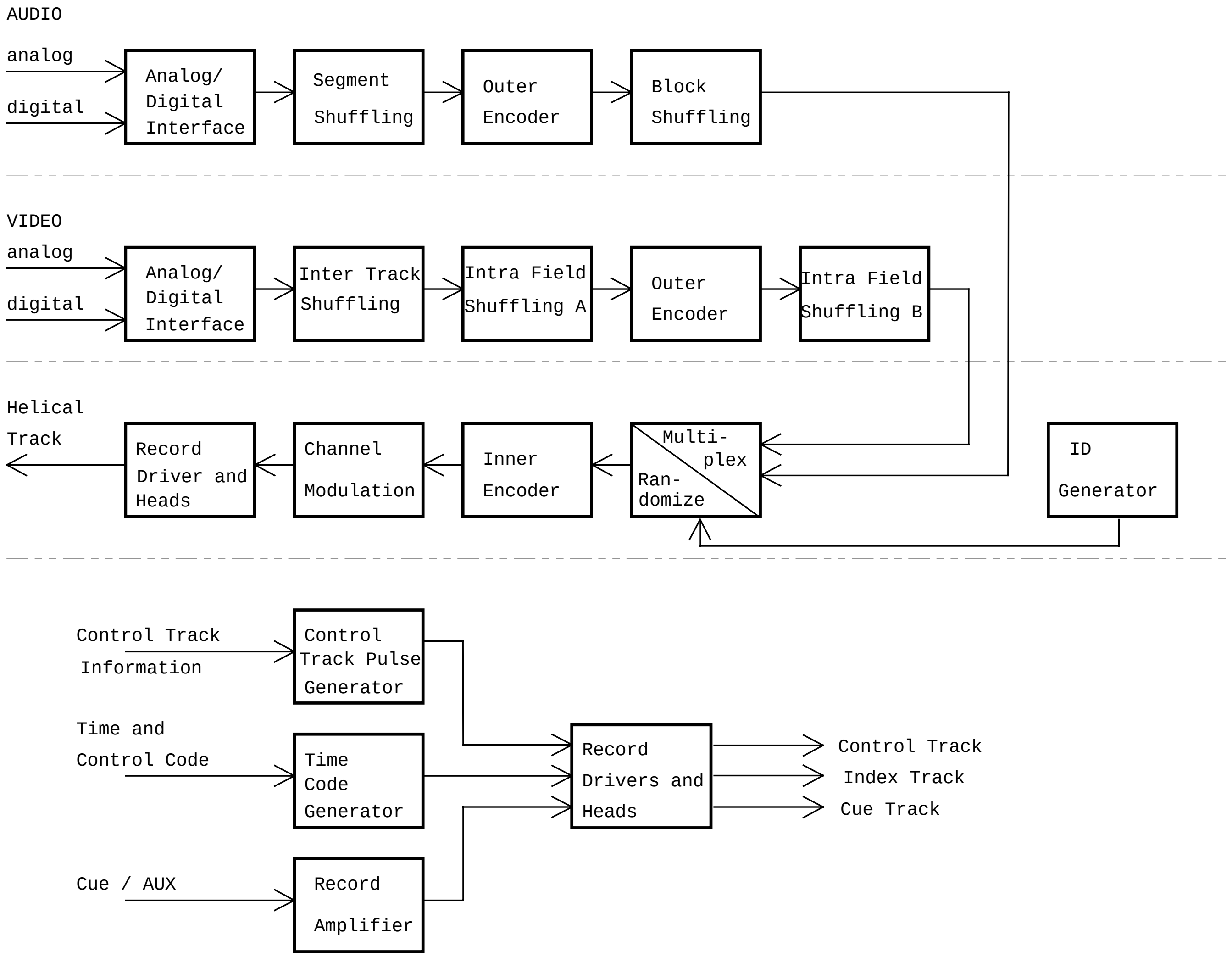


Figure 8. Input/Encoding System Flow of GBR-1000

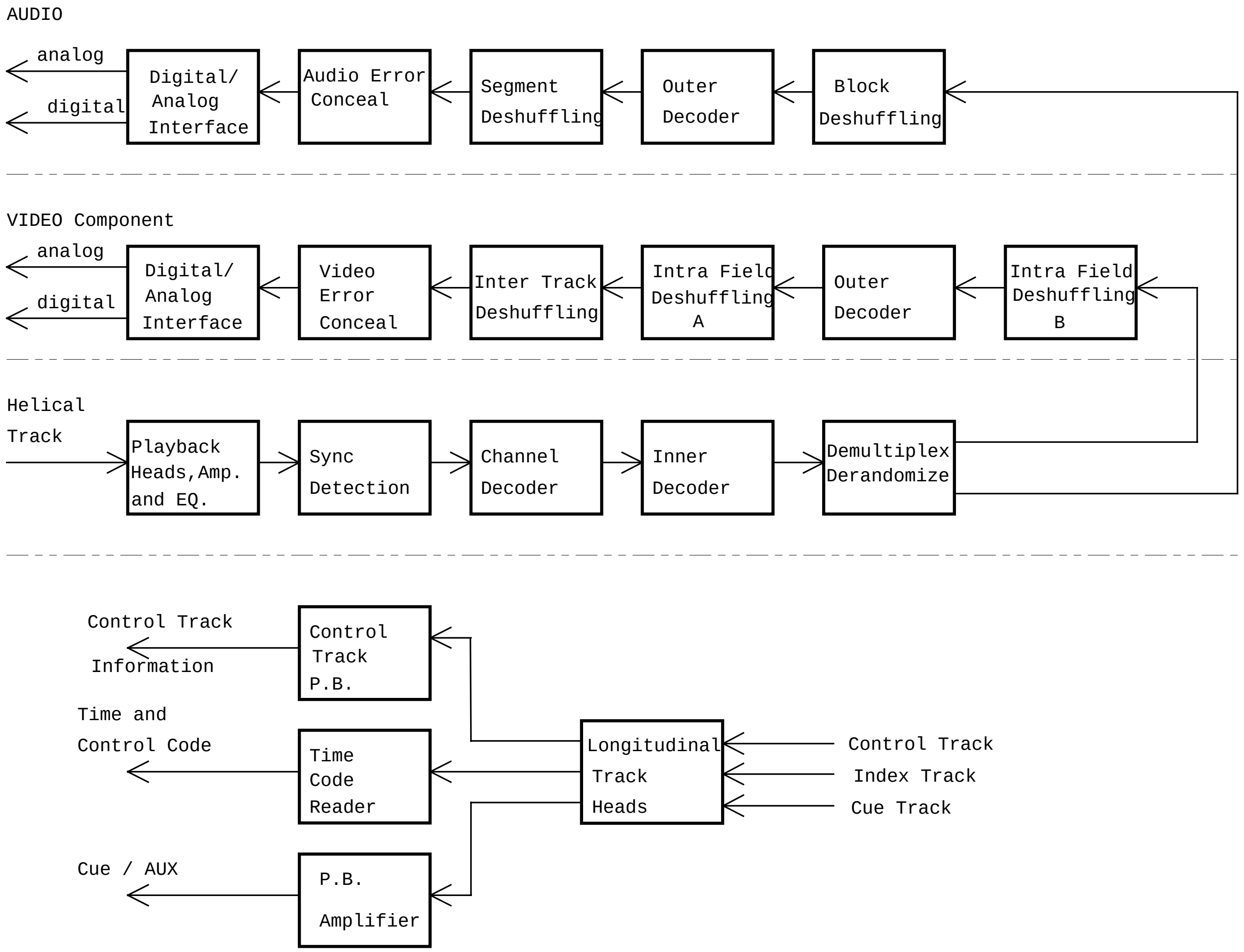


Figure 9. Output/Decoding System Flow of GBR-1000

9. SCIENTIFIC TARGET FOR GIGABIT VLBI STORAGE

One of the main research areas in the astronomical observation environment is the study of gravitational lensed objects, such as quasars. The quasars that are hidden behind galaxies can be revealed by utilizing VLBI analysis techniques. General relativity theory suggests that a quasar image will split into 3 or 5 images. However, in observing the magnified components of such a phenomenon, some of the weaker components are not detected by conventional techniques. These weak components contain information about the path of nearby lensing galaxies and its mass distribution. Thus, any technique that will aid in increasing the sensitivity of the data collected will contribute to the study of lensing mass and dark matter.

Figure 10 depicts the principle behind VLBI observation. As can be seen in Figure 10, during VLBI measurements, two or more separate antennas are set up to receive a radio wave which comes from a single radio star. The received signals are then recorded onto high-bandwidth storage mediums (magnetic tape) together with a timing signal from the atomic standard and their cross correlation function is calculated. As a result, one can establish the precise distance between the antennas from the delay of the signal and also establish the structure of the radio star from its phase and amplitude. The system described in this paper can determine the delay time with a precision of less than 0.05 ns, which corresponds to a 1-2 cm measurement of length.

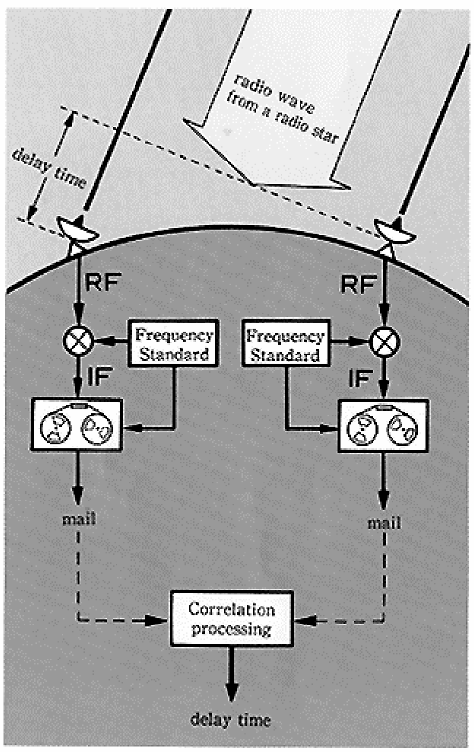


Figure 10. Principle behind VLBI observation.

Although VLBI observations have achieved remarkable progress in resolution, the minimum sensitivity has stayed around 1 Jy. By making better use of a receiver's bandwidth by the use of digital storage and processing technologies, better high-sensitivity VLBI measurements can be made, which allows detection of weak distant QSO continuum emission.

Until recently, the only attempt so far has been made by the Mark-IV group (Whitney 1991). From the minimum VLBI sensitivity $S \alpha (T_{sys1}T_{sys2})^{1/2} / (A_1A_2 \; B \; \tau)^{1/2}$, the receiver temperatures T have drastically improved in this decade and high-sensitivity observations have been dependent on receiver performance. It is also difficult to increase the radio telescope size A. Also, the integration time τ is limited, especially in mm-wave observations. One improvement area that was both economically and technologically viable to pursue was in the area of bandwidth (B). To maximize the bandwidth B, it was essential to develop a Gigabit VLBI Data Storage device and a High-Speed Sampler.

10. D6 - FORMAT OF CHOICE FOR VLBI

It was decided that the D6 format was the ideal choice after researching the different tape formats available for the recording of high bandwidth data. The D-6 based Gigabit VLBI recorder has many performance attributes that exceed existing implementations. Of the most notable are the Mark-IV and the K-4 which uses the ID-1 format. Table 5 below shows a comparison between the ID-1 and the D-6 formats while Table 6 shows a comparison between the various recorders used to-date for the recording of astronomical data.

	ID-1	**D-6**
Data Rate	256 Mb/s	1024 Mb/s (4 times faster)
Recording Capacity/Cassette	770 Gbits	3680 Gbits (4.8 times higher)
Tape Width	19mm	19mm
Cassette Size	S/M/L	S/M/L
Tape Material	Oxide	Metal Particle
Channel Coding	8-9	8-12
Error Check Words: Inner	8 bytes	16 bytes
Error Check Words: Outer	10 bytes	14 bytes
Residual Error	Less than 10^{-10}	Less than 10^{-11}

Table 5. Comparison between the ID-1 and D-6 formats

Table 6. Comparison of Mark-IV, K-4 and GBR-1000 Recorders.

Format	**Data Rate (Mb/s)**	**Duration (Min.)**	**Number of Heads**	**Mag. Tape Thickness (μ)**	**Recording Time ID**
Mark-IV	1024	67.5	64 fixed	16	TC(a)
K-4	256	50/61	4 rotary	16/13	TC/TSS(b)
GBR-1000	1024	52/64	16 rotary	13/11	TSS

TC(a) - indicates the Time Code replaces VLBI data.
TSS(b) - indicates the time is replaced to Track Set Sync code ID in the tape track.
Conventional K-4s are compatible to Mark-IIIA and have time code in data.
New K-4s employed in VSOP terminals use TSS ID.

11. THE GBR-1000 AS A 1024 Mb/s VLBI DATA RECORDER

The GBR-1000's ability to record and playback at 1.2 Gb/s makes it an ideal candidate for the recording of high bandwidth data, such as that used in the astronomical observation environment. In 1995, the Communications Research laboratory, the National Astronomical Observatory and the Institute Space and Astronautical Science of Japan set out to develop a high performance VLBI (Very Long Baseline Interferometry) recording system using the GBR-1000 as its baseline recording system. Their development efforts resulted in significant advancement toward the field of VLBI measurement techniques and the establishment of a Gigabit instrumentation recording system comprising of a modified GBR-1000 (Tape Transport and Processing Unit) HD-DVTR and a VLBI interface (DRA-1000). The original tape transport and drum scanner are made by BTS in Germany, the processing unit by Toshiba and the VLBI Interface is made by YEM respectively. The recording system has been successfully utilized in the recording of radio astronomical data. The following discusses the theory behind the VLBI measurement system and its success in the measurement of distant quasars.

12. GIGABIT RECORDER OVERVIEW

In designing the Gigabit VLBI recorder, two approaches were examined to increase the corrected data rate to 1,024 Gb/s: (1) Increase the clock frequency by 7% to increase the recorder speed and (2) Change the error collection logic. The latter approach would have meant both hardware and VLSI logic redesign. As a result, the former approach was implemented with a target error rate of at least 10^{-11}. Also, since only the internal clock of the GBR-1000 is changed, commercial hardware compatibility and support are maintained. Commands to the GBR-1000 are handled by the DRA-1000 VLBI Interface via GPIB protocols. The GPIB commands can be issued from a PC locally or at a remote site.

The GBR-1000 Gigabit VLBI recorder also touts unique functions that are not possible with former VLBI recorders. As an example, using read-after-write techniques, self-diagnostic of the flying head wheel (16 heads) is possible. Error logging of each tape can be performed to ensure tape quality and consistent error performance. Since the recorder can insert an electronic ID into the header block, no tape labels is needed to identify the recording unit. In addition, the physical size of the SMPTE defined D-6 L cassette is the same as that of the K4 (ID-1) cassette used in previous VLBI systems, thus ensuring media exchange compatibility.

The GBR system has 32MHz 32 parallel ECL interfaces. The 32 parallel interfaces are divided into four cables with each having compatibility to the K4 256Mb/s cable, i.e., 32MHz clock 8 parallel. This clock speed with differential ECL drive allows cable extensions to more than 20m. Also, compatibility to the MK-IV recorder being developed in Haystack (Whitney et al.) is possible when copying a GBR tape to the MK-IV format, but difficult in the reverse direction. Table 7 outlines the Gigabit recorder specifications.

Table 7. Gigabit Instrumentation Recording System Specifications

Configuration	GBR1000 + DRA1000
Recording tape format	SMPTE Type D6
Cassette tape	D6 L, M, S
Data Transfer Rate	1024.000 Mbps
Recording capacity	L: 3.68 Terabits (460 GB) M: 1.61 Terabits (201 GB) S: 460 Gigabits (57.5 GB)
Error rate	10^{-11} to 10^{-10}
Servo lock time	Standby on: < 2 sec Standby off: < 4sec
Tape loading time	< 10 sec
FF REW speed	10 m max
Power requirements	100-120/200-240 VAC 10%
Power consumption	GBR1000: Approx. 1.1 kW DRA1000: Approx. 150W

Operating Temperature	+5 - +35
Storage temperature	-25 - +70
Humidity	10 - 85 % (Non condensing)
Weight	GBR1000: Tape deck=Approx. 55 Processor=Approx. 55 kg DRA1000: Approx. 15 kg
Dimensions	GBR1000: Tape deck=447(W)700(D)397(H) Processor =447(W)692(D)397(H) DRA1000: 483(W)434.5(D132.5(H))
Audio in/out	Analog: 8 channels IN: -16-28 dbm, 600/10k OUT: -3,0,+4,+8 dbm switchable, low Z Digital: AES/EBU 10 channels
CUE (Annotation) audio	Analog: 1 channel (LINE or MIC) IN: -16-28 dbm, 600/10k OUT: -3,0,+4,+8 dbm switchable, low Z
Headphone out	8 unbalanced
Head Configuration	Rotary 16 Channels
Head Life	More than 1000 hrs.
Track Pitch	22um
Tape Speed	531.43 mm/s
Drum rps	160 rps or 9,600 rpm
Azimuth Angle	+/- 15 degrees

13. DRA-1000 VLBI GIGABIT DATA RECORDING ADAPTER

The DRA-1000 VLBI interface allows the GBR-1000 to emulate an instrumentation recorder that is suitable for use in the VLBI astronomical observation environment. The developed adapter has four ID-1 compatible inputs and outputs so that the current VLBI recording data rate of 256Mb/s is easily upgraded up to 4X of 1,024 Mb/s. Synchronized multi-machine recording and playback operation is possible with the DRA-1000 to aggregate multiple data rates. Communications from a host computer including the Timeline control, a time control and many other VTR functions are done through the GBIP interface.

The main features of the DRA-1000 are the following while Table 8 outlines the specifications of the DRA-1000 VLBI Adapter.

- Recording and playback at 1,024Mb/s (32MHz, 32 bits parallel)
- Synchronized playback
- Slow-motion playback (32Mb/s)
- VTR control, Timeline control, and many other front panel functions
- 19-inch rack mountable

Data Input	8 line ECL differential NRZ (with clock, sync, parity) 32Mbps 8bit 4 inputs 1024Mbps (128MB) in total	D-SUB 25 pin4 (DIR-1000 Compatible)
Data Output	8 line ECL differential NRZ	D-SUB 25 pin4

	(with clock, sync, parity) 32Mbps 8bit 4 outputs 1024Mbps (128MB) in total	(DIR-1000 Compatible)
Control in/out	GPIB	
Time reference	UTC 1 pps signal (ECL/TTL)	
Data start timing (for correlation)	TTL	
Time code	Year, day, hour, minute, second, frame	YY DDD HH MM SS FF

Table 8. Specification of DRA-1000 VLBI Gigabit Recording Adapter

Figures 11 and 12 outline the front and back views of the DRA-1000.

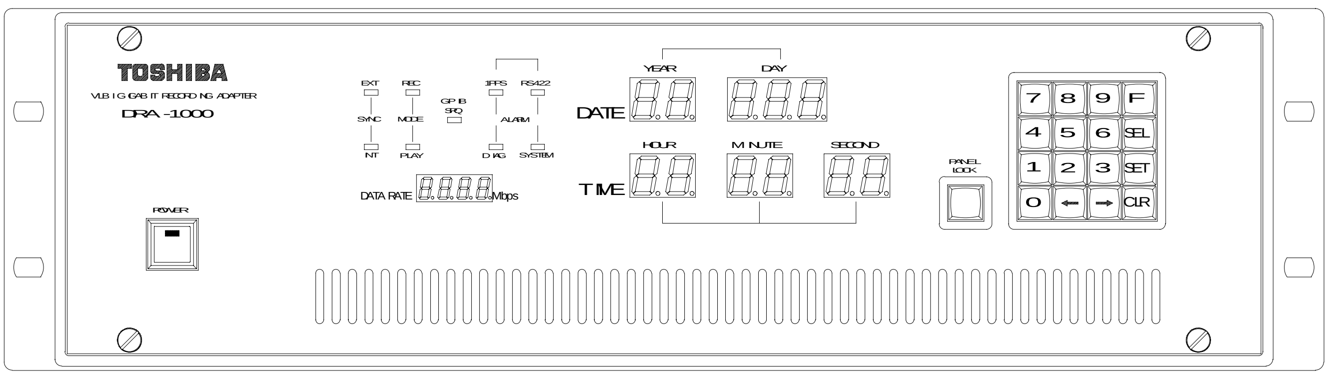


Figure 11. DRA-1000 Front Panel

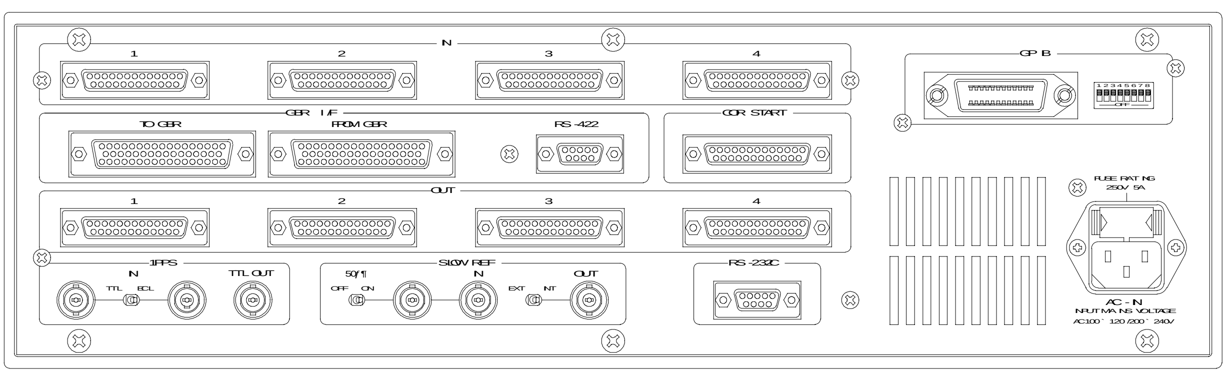


Figure 12. DRA-1000 Back Panel

14. HIGH SPEED A/D SAMPLER AND MM-RECEIVER

The high-speed sampler (DRA-1000) is designed to sample a data rate of 1,024/512/256MHz over 1/2/4ch with 1/2-bit selection. The total output data rate is limited by the VLBI sampler interface to 2,048Mb/s. The wideband acquisition was achieved with the compact 7mm-wave SIS VLBI receiver at Kashima. The receiver 5-7 GHz IF is also used for the K-4 burst sampling mode. The optically connected IF is converted with a VLBI wide-band video converter, and is fed to the high-speed sampler at the acquisition site.

Figure 13 shows the developed VLBI terminal; both modified devices have a multiple 32MHz 8 parallel interface. This is similar to ID-1 and partially compatible with other K4 equipment. For the sampler part, a Tektronix TDS784 (DSO) Digital Storage Oscilloscope A/D head-end was modified. The DSO as a feature of 1G/4ch continuous data sampling. The 4 channel 1/2 bit VLBI data are picked up at the DSO buffer memory MSB side and transferred to the VLBI interface with the 128MHz clock bus. The sampling clock is generated from an external hydrogen maser reference. At the interface, 1G/4ch data are selected and slowed down to the 32 MHz cycle by de-multiplexing. The VLBI interface has 8 ID-1 (8 x 256 Mb/s) connector outputs.

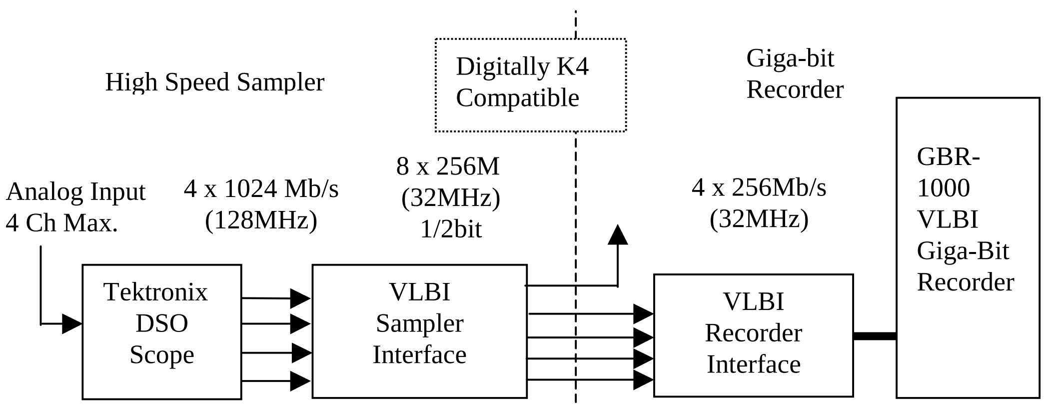


Figure 13. Configuration of VLBI Terminal

15. SYSTEM CONFIGURATION

The simplified system configuration of the VLBI adapter and recorder is straightforward and is depicted in Figure 14. The data from the VLBI sampler interface are connected to the VLBI recorder interface via the 4 ID-1 like (32MHz, 8 parallel) cables. The interface keeps the UTC clock. In comparison, the single unit system takes the place of 4 parallel K-4 ID-1 recorders with an aggregate data rate of 1.2Gb/s. The VLBI data from the sampler are recorded without a time code. During observations, the recorders in each VLBI station record UTC (Universal Time Code) keeping an interface with 1PPS input. Since every station participating in an observation records the same-numbered data frame simultaneously at a certain time, there’s no need to refer to the timecode on tape to achieve the playback synchronization during subsequent correlation processing. The buffer in the front end of the correlator removes lag within the frame. Through GPIB, the recorder actions are programmable with time definition. A control program of the observation site and multi-baseline correlation becomes easy using this function. Tape for the GBR-1000 is a D-6 SMPTE standard cassette.

Another benefit of helical scan recorders is the ability to perform variable playback. The GBR-1000 is capable of playback speeds of 1/1, 1/4, 1/8, 1/16 and 1/32 and the system can be adapted to the new K-4 machines out in the field.

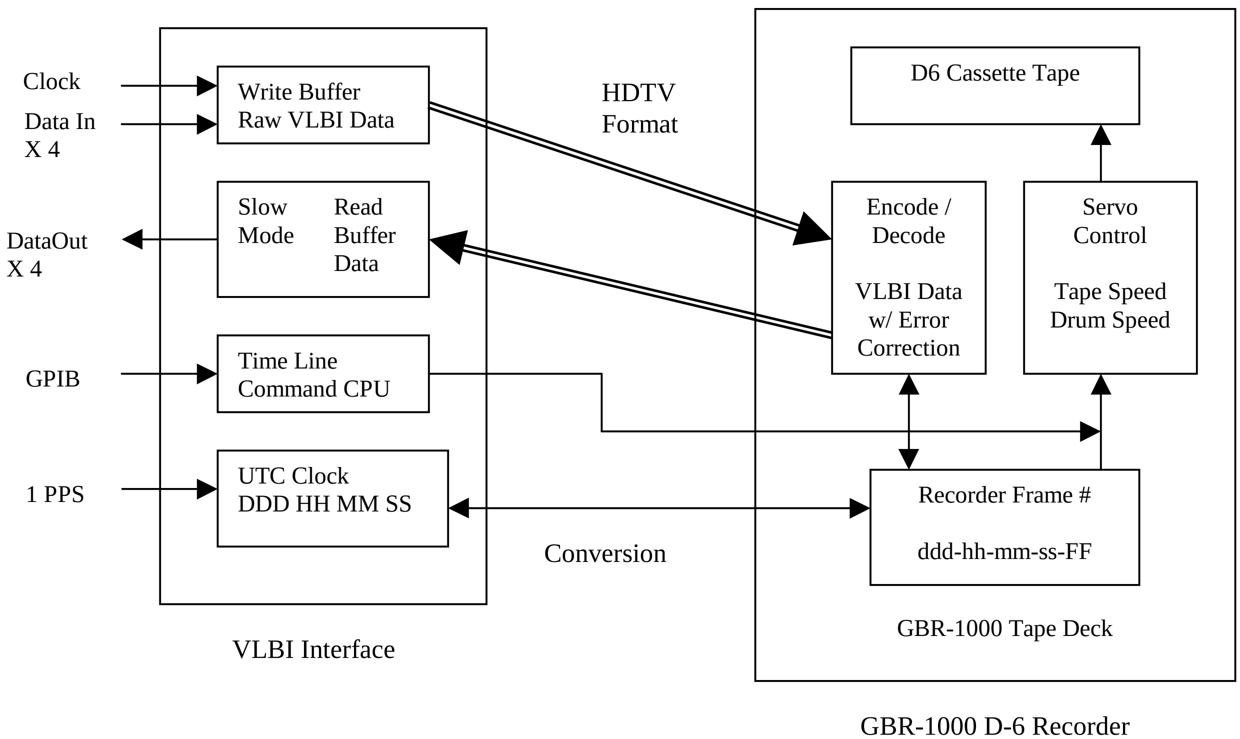


Figure 14. Gigabit VLBI Recorder System

Since multiple devices can be connected with the DRA-1000, the following Figure (15) outlines the system for the recording and correlation of data. In addition, since the GBR-1000 can be cascaded in a parallel fashion, cartridge based systems similar to that used in broadcast systems can be utilized to increase its storage and performance capacity.

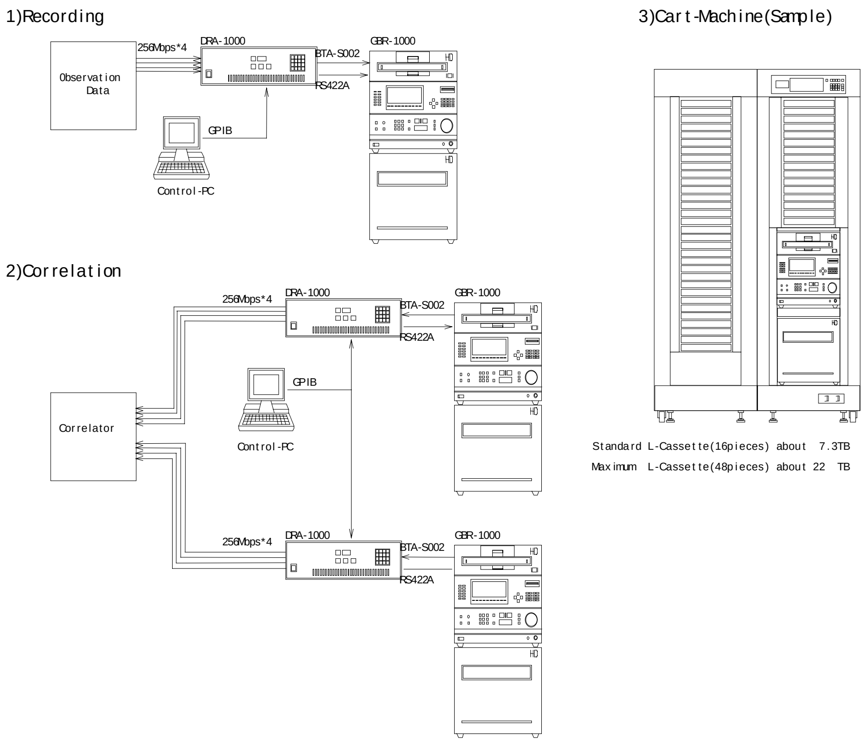


Figure 15. Gigabit recording systems used for recording & correlating VLBI data

2. APPLICATION OF VLBI USING DESCRIBED SYSTEM

Using the system described, several observations have succeeded in reconstructing the ratio absorption line by overlapping VLBI video converter channels combined with precise phase/amplitude calibration. The measurement of these ratio absorption observations behind clusters of galaxies have become possible when a wide-band recording system as described is used with a small number of channels.

As a recent example, the VLBI Gigabit recording system was used in the VSOP (VLBI Space Observatory Program) project for space VLBI. The VSOP satellite is the first satellite dedicated to VLBI from space. The rocket housing the satellite Muses-B was successfully launched into space using the new ISAS M-V rocket from Japan's Kagoshima Space Center (KSC) at 13:50 JST on February 12th of this year. Following the launch, the satellite was given the name HALCA, an acronym for Highly Advanced Laboratory for Communications and Astronomy.

HALCA is an eight meter diameter antenna for space VLBI and interferometric tests. Combing the radio signals detected by the satellite with those detected by radio telescopes on the ground allows a telescope about 30,000km to be synthesized. This enables an angular resolution as fine as 60 micro-arcseconds to be achieved, which is equal to being able to see a grain of rice in Tokyo, Japan from Sydney, Australia. VSOP uses this high angular resolution to probe maser sources in our galaxy, the cores of galaxies, and distant quasars.

The satellite, HALCA, has been observing radio sources in concert with ground based radio telescopes throughout the world. Telescopes operated by the National Radio Astronomy Observatory (USA), the European VLBI Network, and the Australia Telescope National Facility have been participating. Five ground-based satellite tracking stations are used to record data from the satellite. The most important combination of the radio signals - correlation (Figure 15) - are being carried out at correlators operated by the National Astronomical Observatory (Japan) and the National Radio Astronomy Observatory (USA).

17. HALCA ANTENNA DEPLOYING TEST

The first tests of the 15 giga-Hertz telemetry link between the Usuda tracking station and HALCA took place during the second week of March. Since then the other real-time telemetry stations in Green Bank (Virginia, operated by NRAO), and the three NASA-DSN stations at Goldstone (California), Tidbinbilla (Australia) and Madrid (Spain) have been slowly brought on-line.

The first successful interferometric tests between HALCA and a ground radio telescope were conducted between the satellite and the Usuda 64m telescope on May 7th. Observations of the bright, compact quasar PKS1519-273 at a wavelength of 18cm were made by HALCA's antenna elements, and the data recorded on magnetic tape (Giga-Bit Recording System). Data from the satellite were down-linked to the Usuda 10m tracking station antenna. The data were correlated at the Mitaka correlator, and first fringes were found on 13th May.

Fringes to HALCA were in a second 18cm experiment using the Usuda 64m telescope, the Kashima (CRL) 34m telescope and HALCA, on May 13th. Fringes were found on all three baselines, allowing a quantity known as the "closure phase" to be obtained. This was found to be stable and distributed around zero, as expected. Combining HALCA's technology with high-speed, high bandwidth VLBI test instrumentation as described in this paper was an important step towards the viability of full space VLBI observations.

18. IMAGES FROM SPACE

Recent testing of the VSOP project combined with the D6 based high speed, high capacity archiving system have been a success. The following pictures captured by HALCA and other radio observatories in the US is one million times better than one taken by HUBBLE telescope. Figure 16 depicts captured data from HALCA.

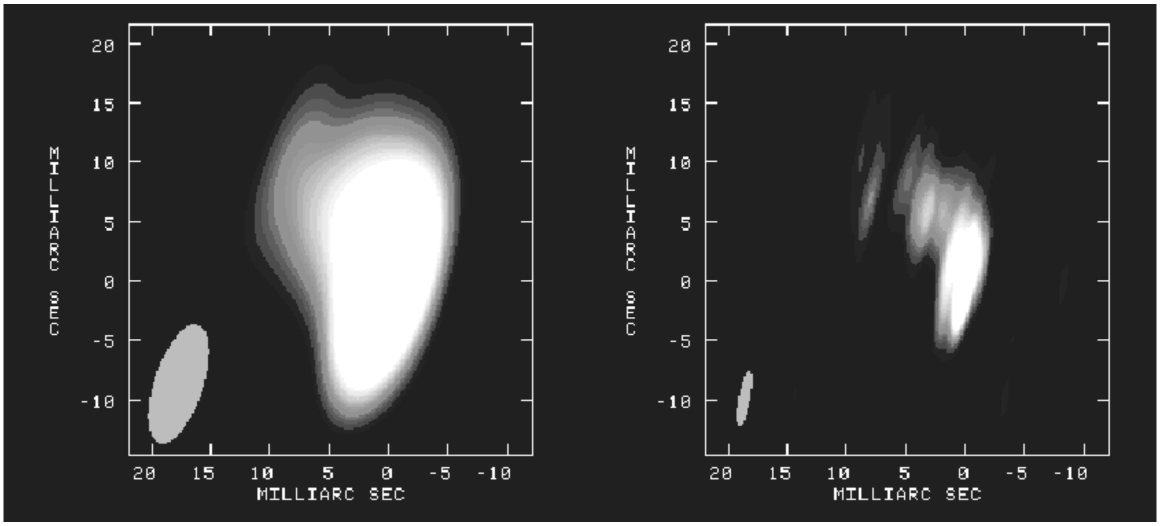


Figure 16.

The quasar 1156+295, at left, as imaged with VLBA data only. At right, with the addition of data from the HALCA satellite and correlated with the Giga-bit recording system.

Components in the 'jet' are clearly visible. The green ellipses (lower left ellipses) indicate the size of the beam of the synthesized telescope. Observations with the satellite result in a smaller beam and correspondingly better resolution.

19. CONCLUSION

The D-6 format and its application as a high-performance video and data (instrumentation) recorder have been discussed. A high-speed Sampler/VLBI interface have been developed and integrated with a modified GBR-1000 for the measurement and storage of VLBI data. The outcome of these tests combined with the modification of the VLBI interface will create possibilities for application to other astronomical purposes, remote sensing and other data measurement fields where high data throughput and capacity are priorities.

20. ACKNOWLEDGMENT

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