ADVANCES IN DIGITAL AUDIO TECHNOLOGY

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1. The Birth of Digital Audio (Initial Development)

The first public experiment in digital audio was made in May 1967 by the NHK Technical Research Laboratories. NHK Tech. began research in digital recording on magnetic tape in 1965, with the goal of developing a super-high fidelity recording/replay system for audio signals. Experimental devices were perfected in 1966 for monophonic, and in 1967 for stereo signals[1]. These experimental units were rotary-head VTR (2-head, 1-inch tape), with coding configuration using a sampling frequency of 40 kHz., and a 5-segment, 12-bit quantization (Fig. 1). It is recorded that over ten million yen in research funding was utilized in this project. A master tape recorder for FM broadcasting could be purchased at that time for one tenth of that amount.

Even now I cannot forget how stunned I was when I first heard the incredible quality of digital sound. I feel that it became the driving force for the years of digital audio equipment development that followed. Nonetheless, that type of research required massive research expenditures and a long-term project time, and was faced with a variety of difficulties, some of which were related to the fact that color television was undergoing development at the same time. Fortunately, Nippon Columbia, which had been producing LP records through direct cutting, took notice of the research project and considered using a master recorder for their work. In order to fulfill industrial applications reliably, a 4-head VTR with 2-inch tape was used, with a coding configuration using a 42.25 kHz sampling frequency, and a 13-bit linear quantization[2]. Records manufactured through this process were released commercially in September 1972 as PCM records (digital master analog cutting).

The above research and application was based on the use of rotary-head VTR, but in the 1970's research into digital recording using open-reel type recorders with fixed multi-track heads was started by BBC, Sony[3], Hitachi[4], and Mitsubishi[5], among others. These were all development-level projects, and apparently primarily for intra-company experiment and audio quality evaluation applications. A variety of coding configurations were used, with sampling frequencies from 32 to 52 kHz., and quantization of 12 to 13 bits.

During this time, coding errors caused by dropouts and jitter became a major problem relative to the drive systems used, and research into correction and compensation became essential to maintain equipment reliability[6].

2. Digital Audio Tape System (DAT) - First Commercialization

The first DAT products utilized existing VTR systems, without modification, as recording devices, with the video terminal serving to handle the digital audio signals - in other words, they were combinations of VTR and PCM processors. This system was exhibited by Sony at the Audio Fair in October, 1976 in an experimental display, with product releases of the commercial PCM-1600[7] (using the U-matic VTR) and the consumer-oriented

PCM-1[8] (using the Beta-max VTR) following a year later. Signal processing was identical to video signal processing, with the same vertical synchronization and horizontal scanning times, limiting the possible sampling frequencies to 44.056 kHz for NTSC-format VTR, and 44.1 kHz for PAL- and SECAM-format VTR equipment. This fact eventually led to the establishment of the 44.1 kHz sampling frequency for consumer digital audio products. The quantization was 16-bit linear for professional use, and 3-segment 13-bit for consumer use.

For practical professional utilization, an electronic digital editor for PCM processors was developed, and the combination of this editor with the digital audio equipment was utilized in several audio production systems. This served to create a base of digital recording production technology, which was invaluable for the practical development of Compact Disc technology later.

In consumer equipment, meanwhile, standardization work began. The standardization committee for consumer PCM processors was established in April 1978, starting from a foundation of the PCM-1. Standardization took as a basic assumption that the recording equipment would be either VHS or Betamax with the same recording techniques used for video signals, and concentrated on the coding configuration to be used. Two possibilities for allocating the total number of bits that could be recorded in a single VTR horizontal scan line were evaluated, a proposal for a 14-bit LR stereo component with dropout correction signals P and Q (Fig. 2a), and a proposal for a 16-bit LR stereo component with a single dropout correction signal P (Fig. 2b). There was a great deal of discussion concerning trade-offs between improvement in dynamic range and ensuring reliability, but the planned consumer applications for VTR and tape, together with a lack of reliable technical predictions, led to the final acceptance of signal format (c). The standardization process was completed in May 1979, and the results recorded in a file of the EIAJ[9]. In October of the same year, PCM processors based on the standard. were released from seven firms, ranging in price from ¥650,000 to ¥800,000. At the same time, the integration of digital signal processing circuits and A/D and D/A convertors to LSI chips were progressing, leading to the release of devices equipped with these chips in 1981, finally cutting the price to below ¥100,000 in 1983. It must be pointed out that the experiences gained in the standardization, integration and commercialization of digital audio equipment were invaluable in the practical application of the digital audio disc later.

For fixed-head DAT, meanwhile, professional use master stereo recorders and 8 to 48 channel recorders aimed to record different music instruments on each channel were developed. The standardization of the involved signal format was initiated at the October 1977 AES Conference, but was halted temporarily by suspicion of violation of the monopoly law in 1978. It reformed rapidly, and the DASH[10] standard, covering 2 to 48 channel professional fixed-head signal formats, was formalized in 1983. There were three tape speeds in the format, corresponding to 1, 2 and 4 recording tracks. The sampling frequencies were 48 and 44.1 kHz., and a 16-bit linear quantization was recommended (Table 1).

In this way, as professional multi-track recorders and master recorders were gradually commercialized, the digitalization of mixing circuits used to process audio signals and link the equipment together became essential. Digital technology was applied to mixers, tone adjustment circuits, and reverberation circuitry and so on, leading to the overall creation of a digital audio processing system.

3. Digital Audio Disc System (DAD) - The Audio System Revolution

At the September 1977 Audio Fair, experimental DAD systems utilizing optical signal detection technology was displayed by three groups: Mitsubishi - Teac - Todenka, Sony, and Hitachi - Columbia. An outline of the exhibits is given in Table 2, and while there was a considerable density difference between them, they were, in general, highly similar. In 1978, research into even higher densities for optical signal detection was increased, and the utilization of modulation systems such as MFM and 3PM made the recording/replay of 1.5 to 2.5 hours of information by a 30-cm diameter disc possible. Matsushita released a mechanical signal detection DAD system, while JVC and Toshiba released DAD systems using electrostatic principles. This meant that all three of the conventional video disc signal detection techniques had been applied to DAD. In 1979, Philips exhibited an experimental 11.5-cm disc using optical signal detection which could record/replay 1 hour of information.

29 Japanese and foreign companies co-operated in the standardization of the digital audio disc, with the formal committee named as the DAD Conference being established in September, 1978. In June, 1980 various techniques were suggested: the optical signal detection method (CD system) by Sony and Philips, the electrostatic detection system by JVC (AHD system), and the mechanical detection system by Telefunken and Teldec (MD system) (see Table 3). Evaluation of the three systems and experimental confirmation of their compatibility was completed in April 1981[11]. By this time, the number of firms participating in the standardization process had grown to 51. At the Audio Fair in October 1981, there were 14 firms exhibiting experimental CD systems and 2 firms exhibiting experimental AHD systems.

After the evaluation of the CD system[12], mass production technology was established for discs and semiconductor lasers, digital processing LSI chips were developed, and several firms released products in October 1982 with discs ranging from ¥3,500 to 3,800, and players from ¥160,000 to 200,000. By the fall of 1984, discs had dropped to ¥3,000 and players to ¥60,000 to 70,000, with not only audio component players, but also portables and in-car-use systems developed, leading to significant enlargement of the utilization range. The number of disc titles reached 3,000 to 4,000, and the production of players reached over 600,000 units per year. The advanced features of the CD player, including audio quality, compactness and light weight, high reliability (non-contact) and easy operation, are expected to lead to production figures for players and discs exceeding those for conventional record players and LP records in 1986.

In compact discs, about 3% of the total signal recording area is assigned as a sub-code area, and is used to store signals other than audio digital signals. This sub-code is composed of eight codes named from P through W, with P indicating the presence/absence of information in the track, Q the start and end of the track, the track title and number, and the time from start to finish of the track. Codes R-W were determined in May 1984 to hold characters and graphics. This procedure allows one picture image (about 280 x 192 pixels) in roughly 2 seconds, and discs and players utilizing this technology are expected in the middle of 1985. In addition, standards to apply this technology to CD-ROM read-only storage devices have also been adopted, with discs and players expected to be released soon.

Throughout the research and development process, the information recording onto the media has left the regions of conventional audio digital signals, and now includes information utilizing the characteristics of digital technology successfully, such as control signals, image signals, and data signals.

Developments into discs are now concentrating on increased random access speeds and higher recording densities. Non-erasable DRAW disks and erasable EDRAW disks are both made possible through laser-based read and write technology, and both have entered the realm of practical commercial application. For consumer use, however, even though the former has the density of CD discs, standardization is essential. The latter still requires improvement in both density and price before being acceptable in the consumer market.

4. Digital Audio Transmission - Diversity in Media

Digital transmission for telephone quality audio signals entered practical application over 30 years ago, but the first practical use of audio signal digital transmission was the FM stereo programs broadcast in September 1979 by NTT in the Tokyo-Nagoya-Osaka region[13]. With a sampling frequency of 32 kHz , and a 10-bit non-linear quantization, the transmission rate was about half of the coding method utilized for conventional digital audio record/replay equipment. Nonetheless, compared to the quality of analog signals broadcast through the 19 cm/sec tape recorder, there was a major improvement in quality. The PCM transmission network was expanded in the following year from Sapporo to Fukuoka, and eventually spanned the entire nation.

The first experiments into the direct broadcasting of digital audio were performed by Sony in co-operation with the German IRT under commission to the German DFVER, with the resultant experimental equipment displayed at the Berlin Messe in September 1981[14]. The DFVER concept at that time was to make one of the three channels of the broadcast satellite to be launched in 1984 digital by multiplexing 12 channels of stereo programs supplied by 12 digital FM broadcasting stations scattered across Germany. The experimental device used a PCM processor as the source simulator, for which reason the sampling frequency was 44.1 kHz , with a linear 16-bit quantization. Modulation was 4ø PSK, with a BCH error correction code and parity checking, and practical performance was verified. The original plan was to broadcast with a 32 kHz sampling frequency and a 14-bit quantization for 16 stereo channels, but the project still has not been realized due to causes not related to the digital technology involved.

In Japan, the use of digital technology for audio and television audio broadcasting for the broadcasting satellite BS-2 was officially approved in March 1983[15]. As indicated in Table 4, two modes (A and B) were set, and the A mode was utilized for the BS-2a satellite launched in January 1984, for television audio signal broadcasting.

From the above process, the coding congifuration for audio signals linked with images was effectively fixed at 32 kHz , with a non-linear 8 to 10-bit quantization. The transmission rate is roughly half that of the Compact Disc system.

5. Digital Audio Tape System (DAT) - Digital Audio Systems

The consumer VTR, which matches the PCM processor approved by the EIAJ, was later standardized into an 8-mm video format[16], and the camera industry released equipment based on this standard in America in 1983. The notable point about 8-mm video is that a PCM stereo audio signal recording system is available as an option. The sampling rate for the coding configuration is 31.5 kHz , with a non-linear 8-bit quantization. In addition to the normal application of 8-mm video technology, an examination of its application to audio uses shows that the image recording section can record digital signals in EIAJ format, and that combination with the optional PCM stereo signal allows 4-channel digital signal recording. Assuming that a PCM stereo signal is also recorded onto the image recording portion, 6-channel stereo signal recording (90-minute recording time), or 9 hours of record/replay time for 2-channel stereo signals, become possible. These audio recording systems were standardized in April 1985, and commercial application is expected soon.

At the October 1981 Audio Fair, equipment to record digital signals onto compact cassettes was exhibited by JVC, Sanyo, Sony, Sharp, and Pioneer. The equipment used multi-track fixed-head systems with 8 to 16 tracks, a sampling frequency of 44.1 kHz , 14 to 16-bit quantization, and 30 to 60-minute recording times. At the October 1982 Audio Fair, several other firms also exhibited experimental models, raising the total number of firms involved in development to ten[17-23]. In November 1982, Sony announced a rotary-head DAT (30-mm drum diameter) capable of recording 1 hour of digital audio signals on a cassette approximately half the size of a compact cassette[23].

The DAD Conference was formed in June 1983 to standardize digital audio tape systems utilizing compact cassettes. In September 1984 experimental formats were established for both fixed-head and rotary head systems, and experiments to investigate compatibility were initiated. Experimental work was mostly completed by April, 1985, and currently the detailed technical standards are being drafted. Specifications for the experimental format are listed in Table 5.

By the time this has passed through the same procedure as the Compact Disc and entered practical application, a digital audio transmission via broadcast satellite should be in orbit, leading to the total digitalization of audio media. Together with these media and the digital processing in the area of acoustic adjustment controlling them, it cannot be too far in the future before A/D and D/A converters can handle sound recording and playback, or input and output in a digital system.

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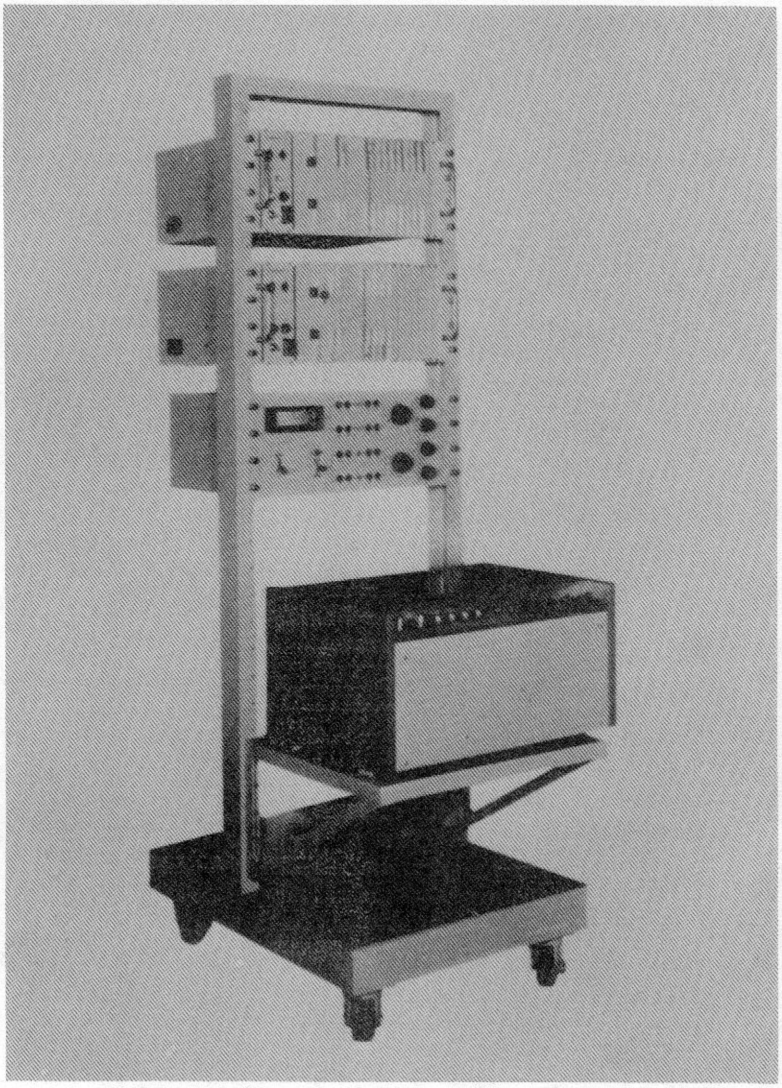
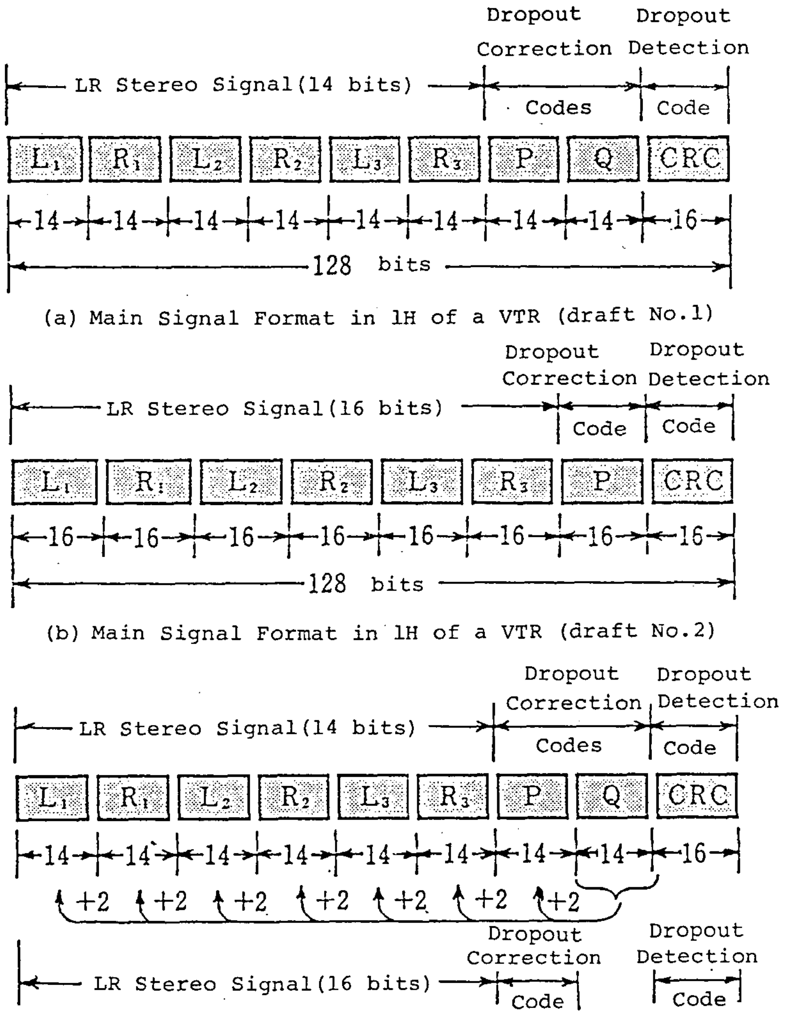


Fig.1 The NHK Technical Research Center
Experimental DAT



(a) Main Signal Format in 1H of a VTR (draft No.1)

(b) Main Signal Format in 1H of a VTR (draft No.2)

(c) Format agreed upon

Fig.2 Signal Formats for VTR Horizontal Scan Line

Table 1. Outline of DASH Format

1.Sampling frequencies and tape speeds

Sampling frequencies (kHz)	Tape speeds (cm/sec)		
	HIGH SPEED	MEDIUM SPEED	LOW SPEED
48	76.20	38.10	19.05
44.1	70.01	35.00	17.50

2.Number of channels dependent on tape width and tape speed

Tape width		1/4"		1/2"	
Track density (Number of Digital audio track)		8 (Normal)	16 (Double)	24 (Normal)	48 (Double)
Number of Digital Audio Channels	High S.	8	16	24	48
	Med. S.		8		24
	Low S.	2	4		
Number of AUX Tracks		4	4	4	4

Table 2. Experimental DAD Systems Exhibited in October,1977

Demonstrators	Mitsubishi.Teac Todenka	Sony	Hitachi.Nippon Columbia
Disc Diameter (mmØ)	300	300	300
Signal Detection Method	Optical	Optical	Optical
Rotational Speed(rpm)	1,800	900	1,800
Playing Time (hours)	0.5	1.0	0.5
Number of Channels	2	2	2
Sampling Frequency (kHz)	46.08	44.056	47.25
Quantization (bits)	12 Non-linear	13 Non-linear	14 Linear

Table 3. Outlines of the Three Proposed DAD Systems

Proposer Company		Sony.Philips	JVC	Telefunken.Teldec
Nomenclature		CD (Compact Disc)	AHD (Audio High Density Disc)	MD: (Mini Disc) / (Micro Disc)
Signal Detection Method		Optical	Capacitive	Mechanical(piezo-electric)
Mastering Method		Optical	Optical	Mechanical
Audio Spec.	Number of Channels	2	2 / 3 / 4	2
Audio Spec.	Playing Time (min)	60	60x2 / 60	60 / 10
Audio Spec.	Frequency Response (Hz)	20 ～ 20,000	20 ～ 20,000	20～20,000
Audio Spec.	Dynamic Range (dB)	>90	>90	>85
Disc Specification	Diameter (mmØ)	120	260	135 / 75
Disc Specification	Recorded Area (mmØ)	50～116	98.2～244	60 ～132 / 60～72
Disc Specification	Rotational Speed (rpm)	500～200 (CLV)	900	250
Disc Specification	Tracking Method	Dynamic Tracking	Tracking Signal	Trapezoid Guiding Groove
Disc Specification	Material	Polycarbonate	Conductive PVC	PVC
Signal Format	Sampling Frequency (kHz)	44.1	47.25	48
Signal Format	Quantization (bits)	16 linear	16 linear	14
Signal Format	Modulation	EFM	MFM-FM	IDM
Signal Format	ECC	CIRC	CRC+Biparity	CRC+Parity
Signal Format	Redundancy (%)	Approx. 30	Approx. 50	Approx. 26

Table 4. Audio Signal Format of a Japanese Broadcasting Satellite

Transmission Mode	A	B
Audio Bandwidth (kHz)	15	20
Sampling Freq. (kHz)	32	48
Quantization Law	14/10 bit quasi-instantaneous companding (5 ranges)	16 bit linear (with 5 range bit)
Transmission Rate	2,048 Mb/s(±10b/s)	
Number of Channels	4	2
Notes	Multi-channel proper	High quality Audio

Table 5. Outline of Experimental DAT Specifications

Items	S-DAT	R-DAT
Number of Channels	2	2
Sampling Frequencies (kHz)	48/44.1	48
Quantization (bits)	16 linear	16 linear
Linear Recording Density (KBPI)	64	61
Transmission Rate (MBPS)	2.4/2.205	2.46
Cassette Size (mm)	86x55.5x9.5	73x53.5x10.5
Tape Width (mm)	3.81(Bi-directional)	3.81(Uni-directional)
Tape Speeds (cm/s)	4.76/4.37	0.815
Track Pitch (μm)	80	13.6
Number of Data Tracks	20	
Relative Tape Speed (m/s)		3.133
Drum Diameter (mm)		30
Wrapping Angle (°)		90
Recording Time (min.)	35x2(with 13 μm tape) 45x2(with 10 μm tape)	120 (13 μm tape) 150 or more