

Fast DDS-2 Digital Audio Tape Drive

Running at a data transfer rate of 510 kbytes/s, the HP C1533A tape drive can record a full 4-Gbyte DDS-2 cartridge in just over two hours, almost an hour less than typical DDS-2 drives. Its development required improvements in tape material, length, and thickness, new read and write heads, a new drum design, and new methods for linearity measurement and adjustment.

by **Damon R. Ujvarosy**

Like all aspects of computing today, the face of mass storage is changing rapidly. Only a few short years ago, gigabytes of disk storage was the domain of large computer systems, housed in computer rooms with dedicated staff to look after the equipment. Personal computers that had more than 100 megabytes of disk storage were a rarity, and networks were just coming of age. The individual computer user rarely considered backup. Critical data was kept on large computer systems and backup to tape was handled by the MIS department. The odd file on the PC that was important could be saved on a diskette.

Times have changed rapidly. Individual PCs with several hundred megabytes of disk storage are common. Network servers for PCs and workstations have multiple gigabytes of disk storage. The data on these disks is critical to the company's business. High-performance, high-capacity backup solutions that fit the needs of today's computer systems are essential.

The same technologies that are propelling disk drive capacity and performance are also being applied to tape drives. Tape drives that meet the backup needs of the individual PC user are available using the DC2000 minicartridge—for example, the HP Colorado Memory Systems Jumbo 250 and Jumbo 700 tape drives. However, the backup needs of the network server are far greater. These larger backups also

require improved performance to complete the data backup in a reasonable time.

The Digital Data Storage (DDS) format standard was developed by HP and Sony in the late 1980s to establish a capacity and performance point that would serve the emerging network server market as well as the more established small multiuser systems market. The DDS format standard is based on the Digital Audio Tape (DAT) standard, which uses 4-mm-wide tape. Tape drives that employ the DDS format standard are therefore often referred to as DAT or 4-mm tape drives.

In HP DAT drives, lossless data compression was added later to the DDS format standard using an HP-developed method called DCLZ,¹ an implementation of a technique known as Lempel-Ziv data compression.² DCLZ effectively doubled the capacity and performance of the tape drive, and at the same time, longer tapes were added. Four gigabytes could then be stored on a single DDS tape. Further extensions to the DDS format standard that will allow the DDS format to serve the backup needs of network servers through the end of the 1990s have been agreed to by the DDS manufacturers group (see Fig. 1).

The HP C1533A DDS-2 tape drive (Fig. 2), introduced in 1993, stores eight gigabytes of data (typical capacity

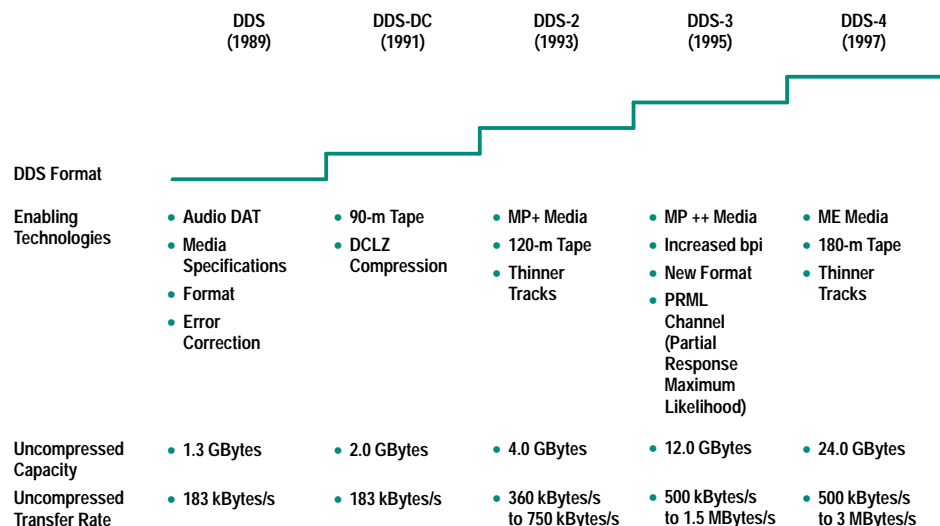


Fig. 1. Evolution of the DDS tape format.



Fig. 2. The HP C1533A DDS-2 tape drive has a native-mode data transfer rate of 510 kbytes/s, 40% faster than other designs. It records on high-capacity 4-Gbyte DDS-2 cartridges or on earlier DDS media.

achieved using the DCLZ data compression standard) and has a data transfer rate more than 2.5 times that previously available on DDS tape drives. The HP C1533A not only reads and writes tapes based on the DDS-2 format standard, but is also able to read and write tapes based on the original DDS format standard to provide compatibility with the large installed base of DDS tape drives already in existence.

The DDS-2 format standard calls for the data to be written on tracks that are nominally 9.1 μm wide as opposed to the previous DDS format standard, which used a 13.6- μm track width. The DDS-2 format standard also makes use of tapes that are 120 m long rather than the previous 90-m and 60-m tapes. These changes, defined by the DDS-2 format standard, along with a data transfer rate increase to 510 kbytes/s from 183 kbytes/s (the data transfer rate seen by the user is effectively doubled to over 1 Mbyte/s by the use of data compression) required numerous technical developments.

Media

The media used for DDS-2 are an enhancement of the existing DDS 60-m and 90-m media. Physically, all three cartridges look similar; they use the same cartridge shell and are all designed to meet the same environmental and data reliability specifications. What differentiates them, apart from the packaging, is the length of tape in the cartridge shell and the signal characteristics or recording properties of the media. The tape drive differentiates between the cartridge types by the use of recognition holes in the cartridge shell.

The longer tape length is achieved by reducing the total thickness of the tape so that the tape pack volume is the same for 120 m as for 60 m and 90 m. Fig. 3 shows the relative thicknesses of the three DDS media types and a simplified view of the construction of the tape. To provide optimal head-to-tape contact when switching between the different tape thicknesses (the drive needs to read and write DDS-1 tapes as well as DDS-2 tapes) the stiffness of the tapes needs to be matched as closely as possible. However, because the relationship between tape thickness and stiffness is a cubed law, use of the same base film material is not possible. A new base film material, polyamide or PA, has been developed. It has high stiffness, and by careful design of the

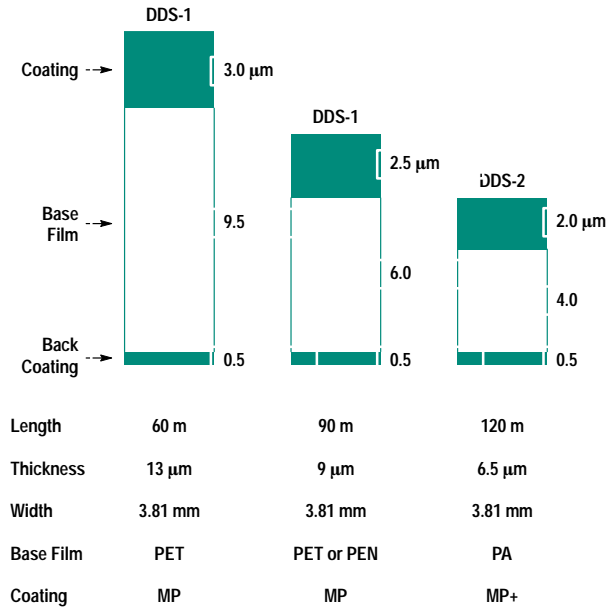


Fig. 3. DDS tape types. MP = metal particle. PET = polyethylene terephthalate. PEN = polyethylene naphthalate. PA = polyamide.

heads and drum, the ability to switch from one tape type to another can be optimized.

The 120-m tape, at 6.5- μm total thickness, offers the thinnest media currently in use in the data recording industry. This has necessitated improvements in the accuracy of the tape guidance system within the tape mechanism and in the tape motion tension control servo of the mechanism to prevent media damage.

The use of thinner tracks reduces the overall system signal-to-noise ratio and the tape was called upon to make a contribution to reducing the deficit. An increase of +3 dB over the existing DDS media was needed. Existing 60-m and 90-m media use metal particle (MP) coatings. To meet the additional signal requirements an enhanced MP tape has been developed and has been designated MP+. By using a combination of magnetic particle size reduction, increased coercivity, increased remanence, and reduced surface roughness of the media, the additional signal requirements were achieved.

The higher head-to-tape speed of the HP C1533A DDS-2 tape drive compared to previous DDS drives places additional constraints on the media. Without efficient lubrication the surface of the media is damaged reducing the life of the media. There is also the possibility of the heads becoming clogged with debris from the media. To reduce this effect the lubrication has been modified for DDS-2.

Heads

The changes needed for DDS-2 also called for modifications to the heads. A DDS tape drive has four heads mounted on a rotating drum. Two heads are used for writing and two for reading. The tape is wrapped around the drum over an angle that is nominally 90 degrees (see Fig. 4) so that only one head is in contact with the tape at any given time.

During a write, the first write head (designated the A write head) contacts the tape and data is written with an azimuth angle of +20 degrees. The first read head (designated the A read head) contacts the tape next to verify the previously

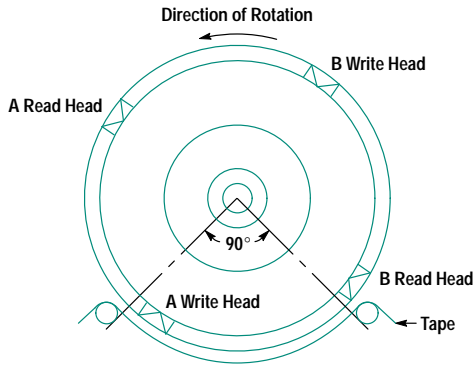


Fig. 4. The DDS tape drive has four heads mounted on a rotating drum. Only one head at a time is in contact with the media.

written data. The second write head (designated the B write head) contacts the tape next to write data with an azimuth angle of -20 degrees. The second read head (designated the B read head) contacts the tape next to verify the data previously written by the B write head. During this process the tape is moved forward to produce data on the tape as shown in Fig. 5.

To accommodate the higher coercivity of the DDS-2 tape media the write head was changed from a Sendust†-based head to a metal-in-gap (MIG) style ferrite-based head (see Fig. 6). The MIG head ensures that the magnetic coating on the tape is fully saturated during the write process. Sendust is still used in the head, but only for the gap metal and not as the bulk material.

The read head required several changes to meet the needs of the HP C1533A. The first was to change from a Sendust-based head to a ferrite-based head. This was necessary to maintain the nominal head life specification of 6000 hours. Since the HP C1533A has a data transfer rate that is 2.87 times the previous generation of DDS tape drives, the head is in contact with the tape media 2.87 times more during that 6000 hours. The ferrite-based head is harder than the Sendust-based head and meets the life requirements.

The second change to the read head was to the width. The nominal width of the read head for the DDS format standard was $20.4 \mu\text{m}$. A read head of this width on a $9.1\text{-}\mu\text{m}$ wide DDS-2 track would allow too much adjacent track noise to

† Sendust is an alloy of 85% Fe, 6% Al, and 9% Si. It was developed at the University of Sendai, Japan.

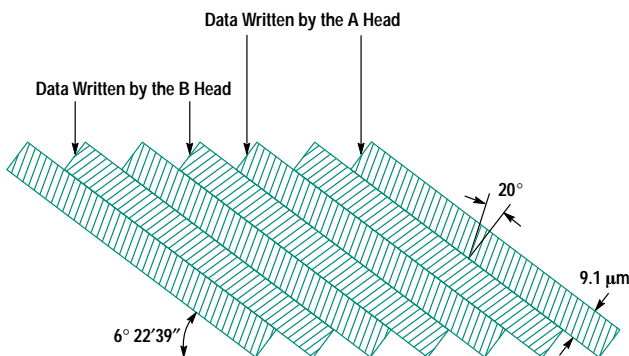


Fig. 5. DDS-2 track format on tape.

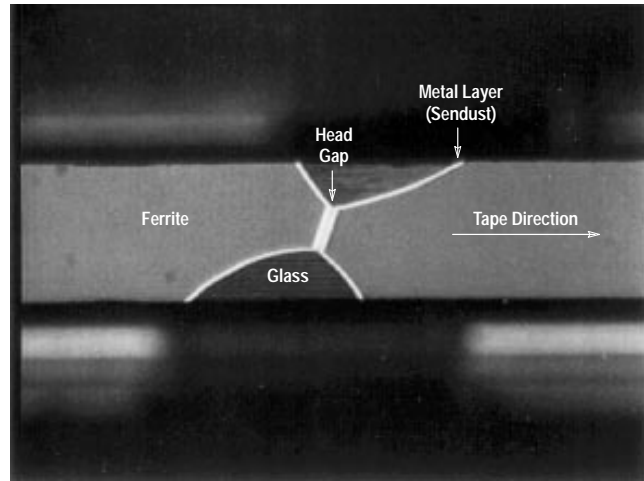


Fig. 6. The HP C1533A tape drive has metal-in-gap ferrite-based write heads.

be picked up, thereby reducing the signal-to-noise ratio below an acceptable level. At first glance it would seem that a read head width of $9.1 \mu\text{m}$ (equal to the nominal written track width) would be optimum (maximum on-track signal pickup with minimal adjacent-track noise pickup). This would be valid if the tracks were all perfectly straight. However, the DDS-2 standard calls for the tracks to be straight within $\pm 2.5 \mu\text{m}$ over the length of the track (called linearity) to allow for mechanical tolerances in the tape drive. While a $9.1\text{-}\mu\text{m}$ -wide read head would provide an excellent signal-to-noise ratio on a perfectly straight DDS-2 written track, it would not be able to read a worst-case DDS-2 written track that was written by a different drive (see Fig. 7). In this case, the read head would have a large adjacent-track noise pickup with a relatively small on-track signal pickup. Since the ability to interchange tapes between tape drives was an important consideration in the design of the HP C1533A tape

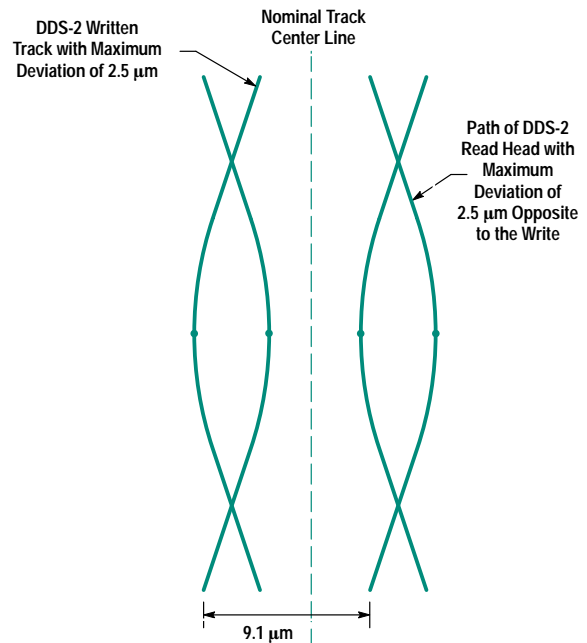


Fig. 7. Effects of tape and drive nonlinearity when a track written by one drive is read by a different drive.

drive, a balance needed to be struck to achieve the optimum read head width. A 12- μm read head width was specified through the use of computer modeling of the effect of adjacent-track noise on signal-to-noise ratio. Experiments verified the performance of the 12- μm head.

Drum Design

The next major challenge came in the drum design. The increase in the data transfer rate to 510 kbytes/s from 183 kbytes/s required an increase in the drum rotation speed, to 5737 r/min from 2000 r/min. The major issues to contend with were drum bearing life, acoustic noise at the higher rotation speed, and excessive air between the drum and the tape. Excessive air would force the tape too far away from the drum, resulting in reduced signal levels because of loss of contact between the head and the tape.

A great deal of work has already gone into bearing life and acoustic noise in high-rotation-rate spindle motors for disk drives. The key to bearing life is the proper choice of lubricants. By using the same high-performance lubricants that are found in disk drive spindle motors, we were quickly able to meet the bearing life requirements of the HP C1533A tape drive.

The acoustic noise generated by the drum is largely a function of the control system. The control algorithm used in the HP C1533A tape drive reduces the high-frequency content of the control signals so that the acoustic noise of the HP C1533A is comparable to previous-generation DDS tape drives.

The problem of excess air between the drum and the tape required the development of techniques to bleed away the excess air to ensure that proper head-to-tape contact was maintained. Several techniques were prototyped and carefully measured by HP Laboratories for their impact on tape deformation. Among the techniques prototyped was a "windowless" drum, in which there is a gap between the lower, stationary section of the drum and the upper, rotating section of the drum. The gap provides a path for the air to bleed away and eliminates the need for a "window" around the head. A second technique prototyped was a standard window style drum with a small chamfer along the bottom edge of the upper rotating section of the drum to provide the necessary air bleed (see Fig. 8).

In the end, the window style drum using a chamfer on the lower edge of the rotating section of the drum was found to be the best solution, ensuring that the tape was not damaged while providing an easily manufacturable solution to the problem of excess air between the drum and the tape.

Linearity

As previously mentioned, the DDS-2 specification calls for a maximum deviation from a straight line of $\pm 2.5 \mu\text{m}$ for a written track. This specification is referred to as linearity. The linearity of the previous generation of DDS tape drives was measured and found to have a mean value of $3.7 \mu\text{m}$ and a standard deviation of $0.74 \mu\text{m}$. To meet the DDS-2 specifications, an intensive research activity was undertaken at HP Laboratories. That research determined that the linearity measurement and adjustment process would have to be changed to meet the DDS-2 specifications consistently.

Previously, linearity was measured by writing a tape, physically cutting out a section of that tape, developing the tape using ferrofluids to be able to see the written tracks, and then measuring the tracks under a microscope. This technique suffers from two problems. First, the measurement error associated with the technique was found to be up to $2 \mu\text{m}$. Second, the technique did not allow the linearity to be measured in real time while adjustments to the guides were being made on the production line.

The problem of measurement error was tackled by developing an automated optical measurement system. Using optical pattern recognition software, the system automatically finds special written patterns on the tape. A precision coordinate measurement system measures the track position relative to the edge of the tape. The system is calibrated with a chrome optical standard and a measurement accuracy of $\pm 0.15 \mu\text{m}$ is achieved.

This optical measurement system is used to measure the absolute linearity of tapes. These tapes are then used as a reference for a real-time measurement system in production. Special patterns written on the tape are used by the tape drive under test to measure its own deviation along the track relative to the tape in the drive. By subtracting out the measured linearity deviation of the tape in software, an accurate real-time measurement of the linearity of the drive under test is achieved. It is then possible for a production operator to adjust the tape guides for minimum linearity deviation as part of the standard production process. The use of these linearity measurement and adjustment methods has allowed HP to reduce the mean linearity deviation in production to $1.4 \mu\text{m}$ with a standard deviation of $0.33 \mu\text{m}$, well within the DDS-2 specifications.

Performance

The network server market that the HP C1533A tape drive is designed to serve requires high performance as well as high capacity. The data transfer rate of 510 kbytes/s is an important factor in the performance of the HP C1533A tape drive since it defines the maximum rate at which data (after compression) can be written to or read from the tape. The actual

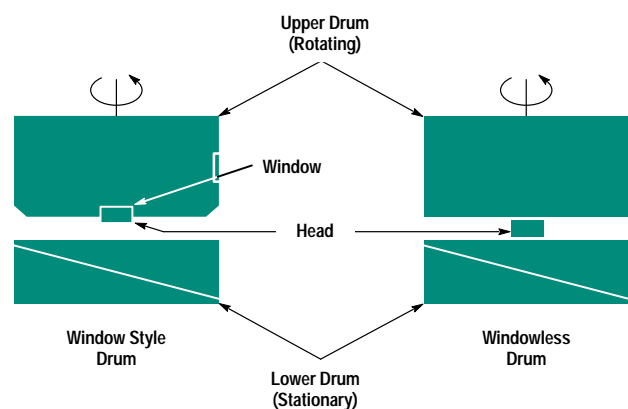


Fig. 8. Two styles of drums with gaps to bleed off excess air between the drum and the tape. In each case, four heads are spaced evenly around the drum, but only the one nearest the observer is shown in this drawing. The diagonal line on the lower drum is the path of the lower edge of the tape in this helical scan system.

performance the user will see in a system is a function of at least thirteen factors. Some of these factors are a function of the tape drive, but many are dictated by the system using the tape drive. The major performance factors, along with the corresponding controlling functions, are listed below.

Performance Factor	Controlling Function
Data transfer rate	Tape drive if desired data transfer rate is greater than maximum tape drive transfer rate Computer system if desired data transfer rate is less than maximum tape drive transfer rate
Maximum data compression ratio that maintains maximum tape drive transfer rate	Tape drive
Data compression ratio	Data
Main buffer size	Tape drive
SCSI transfer rate	Limited to the maximum SCSI transfer rate that both the tape drive and the computer system can achieve
Data transfer size	Computer system

The architecture of the HP C1533A controller is outlined in Fig. 9.

An examination of the write process is instructive in understanding the potential performance limiters. The following are the major steps in the write process.

1. Computer system negotiates SCSI transfer rate with the tape drive.
2. Computer system establishes transfer size.
3. Computer system transfers data to the tape drive.
4. Tape drive compresses the data through the data compression processor and moves the data into the main buffer.

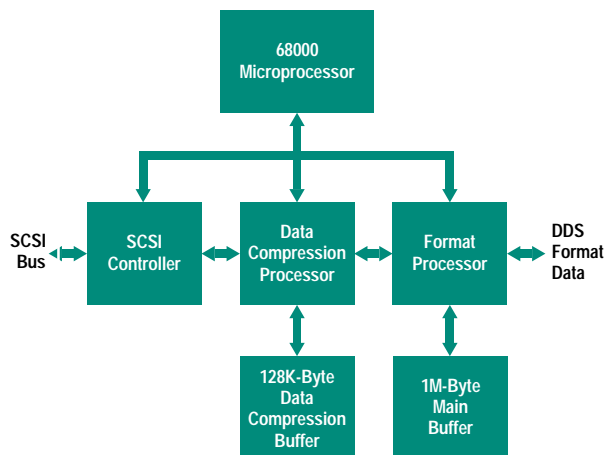


Fig. 9. Block diagram of the HP C1533A tape drive controller.

5. Format processor divides the data into DDS format standard groups and adds access and indexing data to enable high-speed search and retrieval and error correction fields to maintain data integrity on reads.

6. DDS format data is written onto the tape.

To achieve maximum performance, it is essential that DDS format data is available to write onto the tape at all times. If no data is available, the tape drive will have to stop writing data and wait until data is available before restarting the write process. The tape will also have to be repositioned before the next write can begin. The format processor must of course have the ability to take the data from the main buffer, convert the data into the DDS format and compute the error correction values in real time or the tape drive will never achieve its full performance.

The main buffer performs a speed matching function, giving the data compression processor the necessary freedom to output data at a varying rate while keeping the tape drive streaming. Modeling demonstrated that a buffer size of 1M bytes is sufficient to maintain the performance of the HP C1533A tape drive in most applications.

The maximum speed at which the data compression processor can take uncompressed input data and output it as compressed data is another factor in the performance picture. The more compressible the data, the faster the data compression processor needs to be to maintain an output rate that is fast enough to keep the tape drive streaming. An average compression ratio of 2 to 1 is the accepted industry norm for typical computer data. However, within a large backup, the compression ratio of individual files will vary tremendously. By studying a large number of backups, we were able to establish that the data compression processor needs to be capable of about 4-to-1 compression at full output rate to maintain an overall 2-to-1 compression rate. We therefore designed the data compression processor for the HP C1533A to meet this requirement.

The last major piece in the performance picture has to do with the ability of the computer system to move data to the tape drive. To get the maximum performance from the tape drive, it is important that the computer system provide the data as fast as the tape drive needs it. The maximum rate at which the data can then be transferred to the tape drive is determined by the negotiated SCSI transfer rate and the transfer size that the computer system establishes. The SCSI transfer rate is the lower of the computer system and tape drive maximum rates. If the computer system's maximum SCSI transfer rate is less than the tape drive's maximum SCSI transfer rate, the SCSI transfer rate used will be that of the computer system. The slower the transfer rate, the less time there is to cover any system overhead. Additionally, if the computer system establishes a small transfer size, the data transfer will occur in small increments. Since each transfer has overhead associated with it, small transfer sizes will have relatively more overhead which will likely reduce the performance of the tape backup (see Fig. 10).

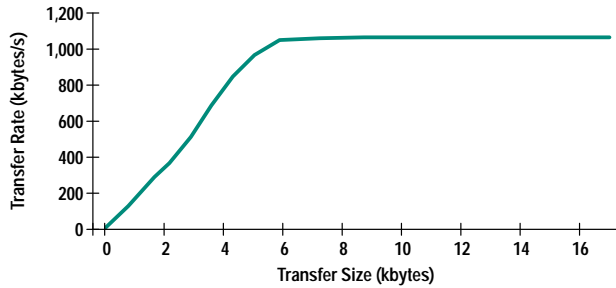


Fig. 10. Maximum data transfer rate of the HP C1533A tape drive at 2:1 data compression ratio (variable mode, writing from memory on an HP 9000 Model 720 computer).

Acknowledgments

I would like to acknowledge Hugh Rattray for mechanism and media development management, Peter Steven for tape path development, John Hardwick and Phil Connor for head and drum development, Ian Russell for media development, Simon Gittens for servo and data channel development management, Rob Morling for data channel development, Ben Willcocks for servo code development, Julian Potter for prototype and tool development, Tom Conway for servo IC development, Steve Krupa for controller development management, Tim Phipps, Andy Hana, Steve Langford, Pete Walsh,

and Dave Dewar for controller IC development, Richard Bickers, Paul Bartlett, Simon Rae, and Jon Buckingham for controller firmware development, Pete Bramhall for technology and standardization management, Chris Williams and Simon Chandler for data channel modeling, Bryan Magain for interchange test development, Richard Vincent for integration management, Dave Tuckett, Simon Southwell, and Jon Rushton for integration engineering, Greg Trezise and John Rich for printed circuit board development, Gary Marriner for project coordination, Mike Padfield, Malcolm Grimwood, and Jonathan Lord for testing, Carl Tausig of HP Labs, Palo Alto for linearity measurement tools, Albert Jeans of HP Labs, Palo Alto for tape path modeling, and many others. I would like to thank Ian Russell, Peter Steven, and Richard Bickers for their help in preparing the material for this article. I would also like to thank Jo Dursley for her efforts in typing and editing the article.

References

1. M.J. Bianchi, et al, "Data Compression in a Half-Inch Reel-to-Reel Tape Drive," *Hewlett-Packard Journal*, Vol. 40, no. 3, June 1989, pp. 26-31. This paper discusses the HP-DC algorithm, a precursor of the DCLZ algorithm.
2. J. Ziv and A. Lempel, "A Universal Algorithm for Sequential Data Compression," *IEEE Transactions on Information Theory*, Vol. IT-23, no. 3, May 1977, pp. 337-343.