A Revolution in Digital Data Storage

Advanced Digital Recording White Paper

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Introduction

Despite continuing predictions that tape technology is losing momentum, 1999 has seen more new product introductions than ever before. While helical scan, data cartridge and DLT struggle to extend their existing technologies, only one technology can claim to be revolutionary: OnStream's Advanced Digital Recording™ (ADR™). ADR is the product of seven years of research on the part of electronics industry giant Philips. To provide the focus needed to successfully bring ADR to market, Philips created a spin-off company - OnStream. The first products incorporating ADR technology were launched in March 1999.

Advanced Digital Recording

What is unique about ADR that justifies its claim to be revolutionary? ADR is a collection of significant innovations, protected by 61 patents, that deliver exceptional reliability, capacity and performance at a reasonable cost. ADR's principal innovations lie in the following four areas:

– Buried servo signaling
– Multi-channel recording
– True variable transfer rate, and
– Enhanced data integrity

The combination of these innovations has enabled OnStream to redefine the price/performance benchmarks of the tape drive industry. This paper discusses each of the innovations in more detail below with special reference to how they improve the reliability, performance and value equation for tape.

Buried Servo Signaling Gives Precise Tape Position Information

The biggest innovation in ADR is buried servo signaling.The buried servo signals enable the head to track precisely the movement of the tape as it spools, thus enabling ADR to reliably incorporate high track densities. In addition, the servo signals communicate with the head to confirm media integrity as it writes data. Thisis an innovative way to avoid writing data on defective media without the added cost of dual heads and read/write circuits that most high-end competitors use.

Traditionally tape drives have had limited knowledge of where the heads were on the tape, either laterally or longitudinally. The fact that longitudinal information (knowing how far along the tape you are) was typically nonexistent meant that recording had to be done more or less in one session by starting at one end and going until either the tape or the data ended. The lack of precise lateral information limited track density. Since the head position was fixed, wider tracks were necessary to accommodate thermal expansion and tape wander. By providing a "roadmap" to the tape in both the longitudinal and lateral dimensions, buried servo signaling allows for much more exact positioning of tape versus tape head with a multitude of benefits to the ultimate application.

How Buried Servo Signaling works

Tape drives using coated media do not record data the full depth of the media. The logistics of applying a coating to the substrate dictate a thicker coating than necessary just to record the input information. Data is recorded only on the top surface of the media to a depth proportional to the wavelength of the recorded data. At the data densities used in typical tape drives, this depth is approximately 10% of the total media thickness. The remainder of the coating is essentially unused. If another signal is recorded on the tape at a much lower frequency it will be recorded far deeper in the media, effectively burying it under the data recording. This means both the low frequency "servo" signal and the high frequency data signal can co-exist without wasting any recording area. The ADR buried servo signal consists of a series of sine waves recorded across the tape at a much lower frequency than that of data - approximately 700 times lower. At the last stage of the ADR tape production process a servo-writer lays down, in a single pass, a sinusoidal servo pattern in precisely the correct location for each of the 192 data tracks across the width of the tape. The servo signals are low frequency sine waves written with 0o phase for odd tracks and 180o phase for even tracks. The boundary between these anti-phase signals defines the exact track center for the data tracks. The diagram below illustrates this concept.

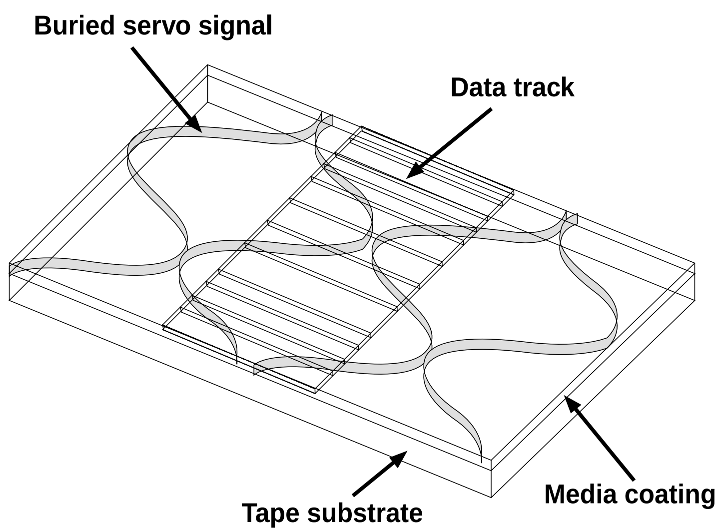

Figure 1 - Tape with Data Track and Buried Servo Signal

During the read/write processes, when the recording head is exactly at track center, the phase and anti-phase sine-waves cancel to provide a null signal. If the head is misaligned in one direction or the other, the head will read a sine wave of amplitude proportional to the misalignment. The direction of misalignment can be determined from the phase of the error signal.

With the ADR writing and recording process, eight tracks are being addressed simultaneously. With the eight active channels, the servo information is laid out such that six heads are positioned at the null-point between sine waves while two of the heads see a full width of one or the other of the phases. This allows the drive to identify the polarity of the error signal while the frequency of the sine wave provides the input signal for the tape speed servo.
The production process for the buried servo signal requires only a single pass across the servo-writing head that adds almost nothing to the manufacturing cost.

Improved Track Following Increases Track Density

Most current linear tape products do not use track-following servo technology. These drives generally locate reference bursts at one or both ends of the tape and position the heads over the desired tracks according to these reference bursts. As the tape moves across the head during the read and write processes, the positioner mechanism (typically controlled by a stepper motor) holds the head in a fixed position. It is not possible to detect or compensate for any lateral movement of the tape relative to the head due to thermal expansion or tape wander. This means track widths need to incorporate an extra margin to accommodate wander and expansion. This "wasted" space limits the track density of such drives.

A limited number of drives employ some form of track following in order to increase track density. Tandberg's MLR design uses a two-channel read/write architecture with three sets of read/write heads. Two of the head sets actively read and write data while the third head set is located over a band of dedicated servo tracks and is used as a track following transducer. This approach is not totally satisfactory for several reasons. First, about 14% of the available recording surface is dedicated to the servo tracks and is thus unavailable for data storage. Secondly, a third head (in addition to the read and write heads) is needed to read the servo information, adding both cost and the risk of 'tilt error' (the misalignment of the heads).

Quantum's SuperDLT also uses a type of track following servo: an optical transducer that follows an optical pattern laser scribed into the back-coat of the media. This avoids wasting recording surface area with dedicated servo tracks but creates significant tolerance and alignment problems between the recording heads on one surface of the tape and the optical servo transducer on the other.

The ADR servo concept avoids all these problems. As noted above, all 8 channels are used to servo: 2 channels providing polarity data and six channels providing the error signal. Thus servo noise is decreased through averaging the six error signals. Even small errors produced by tape expansion are averaged over the six channels to provide an optimum alignment between all 8 channels and tape.

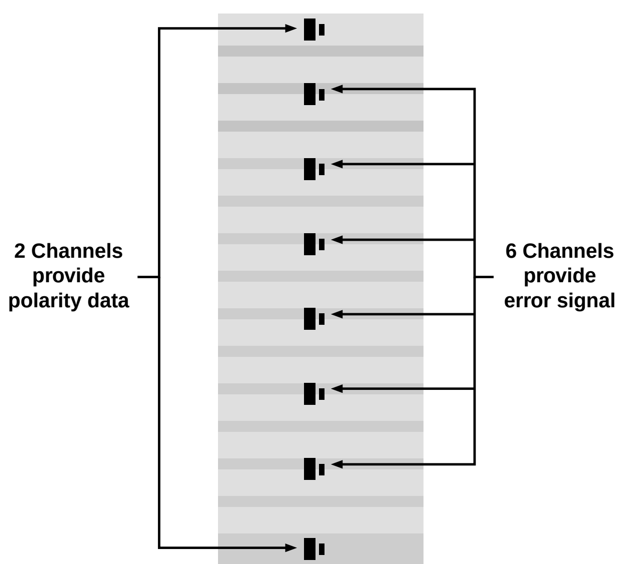

Figure 2 - Multiple Servo Inputs Reduce Errors with ADR

When reading data, the head detects a composite signal comprising the recorded data and the servo data. Since servo data is 700 times lower in frequency than recorded data, it is easy to separate the servo and data signals using simple filtering. During write, the wide frequency separation makes it equally easy to separate the low frequency servo from the high frequency cross-talk that the read head picks up from the write flux.

The drive controller monitors the integrity of the servo signal. If, during writing, there is a perturbation in the servo signals due to an off-track condition or degradation of the servo signals (possibly due to a loss of head tape contact or to damage to the media surface) the drive will immediately stop writing to ensure that data on adjacent tracks is not overwritten. This is a protection feature that is only available with a track-following servo. When the drive detects this condition, it initiates a re-write operation to ensure that data is written correctly. These two features provide better data protection than traditional read-while-write and eliminate the need for the redundant head structure necessary with the read-while-write architecture.

Multi-Channel Recording Head Allows Slower Tape Speeds

The second significant ADR innovation is the thin-film, magneto-resistive 8 channel recording head used in all ADR devices along with the sophisticated electronics that support the head. The head's ability to simultaneously read or write eight channels of data significantly improves tape life and reliability, while the construction of the head itself improves head reliability as well as reduces cost.

Multi-Channel Read/Write Improves Tape Life and Reliability

By increasing the simultaneous read-write functions from one track to eight, the speed of the tape under the head may be reduced by a factor of eight. For example, single channel drives must move tape at 120 inches per second to provide a data transfer rate of 1MByte/second. With 8 channels transferring data simultaneously, ADR transfers data at 2MBytes/second at a tape speed of only 44 inches per second. This has many advantages:

– Lower tape speeds result in less frictional heat generation and thus lower temperatures in the cartridge.
– Lower tape speeds result in lower power demand from the host.
– Lower tape speeds result in significantly lower acoustic noise levels. Running tape at 120ips generates noise levels >54db, which is unacceptable in an office environment, while running tape at 44ips results in noise levels in the mid 40db range that are barely detectable.
– Lower tape speeds result in more gentle tape handling and improve cartridge and drive reliability and life.

A single channel drive with 106 tracks needs 106 end-to-end passes to read the whole tape. An ADR drive with its 192 tracks can be entirely read in 24 end-to-end passes. This gives ADR media a significantly longer life expectancy since tape life is typically specified in terms of total end-to-end passes (10,000 passes in a normal office environment).

Yoke Inductive Read Heads are More Rugged and Easier to Manufacture

The read and write heads for all 8 channels are contained on a single thin-film chip. The write heads are a conventional thin-film inductive design while the read heads are a yoke thin-film magneto-resistive (MR) design. Virtually all other magneto-resistive heads used in tape drives use the so-called "Sensor-in-Gap" construction (SIG). Such heads are notoriously fragile and difficult to fabricate. By contrast the yoke head is relatively rugged and easier to both build and use.

Variable Transfer Rate Optimizes Throughput And Reduces Tape Stress

ADR's variable transfer rate represents the third significant innovation. Unlike almost all other tape technologies, the ADR architecture permits the drive to vary its tape speed and transfer rate to match the data rate that the host system can tolerate. ADR drives today employ continuously variable speeds between 0.5 and 2MB/second (native). This is a very important performance feature since it means users always get the fastest possible transfer rates.

With conventional tape drives, both linear and helical scan, optimum performance is obtained in the streaming mode where the host can always provide or accept data from the drive. That means in practice, that the host must always be capable of transferring data at a higher rate than the drive can write or read to the media. This was not a problem in the past where tape drives had low transfer rates and were used in applications where performance was not critical. As tape technology advanced, drive transfer rates outpaced the ability of computers to supply data. Virtually all tape technologies operate at fixed or stepped tape speed and transfer rate. If the host transfers data at slower than the drive rate, the drive must continually stop until the host catches up. For example, if the drive transfers data at 1MByte/sec and the host can only supply data at 0.5MByte/sec, the drive will read and write to tape only 50% of the time and will be stopped and waiting for the host for the remaining 50%.

Figures 3 and 4 below illustrate what happens during such a start-stop operation. Consider a write operation (a similar argument applies to read) and assume that the drive buffer has run out of data. At this point, the tape motion stops. The stopping process is not instantaneous; the driveoverruns the point at which the last data bit is written. If the drive started writing just where the tape finally came to rest, there would be a "blank" spot on the tape. To prevent this, the drive reverses the tape and repositions it to a point where it is ready to start writing again so that the data on the tape is written in a continuous stream. This backhitch operation takes time. Meanwhile, during the backhitch the host continues to supply data to the drive buffer and the buffer starts to fill. At slow interface rates (slower than the tape write speed), the buffer will never completely fill. When the backhitch is complete, the buffer will start emptying to tape at the drive transfer rate while data continues to flow in over the interface. Since the tape write rate is higher than the interface transfer rate, the buffer will gradually empty and the process will start over.

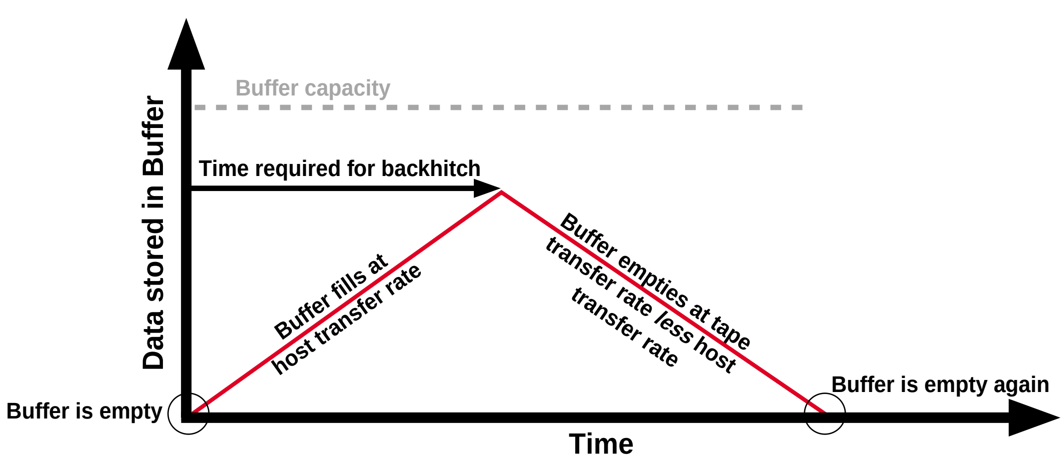

Figure 3 - Schematic of Data Transfer Process When Buffer Is Partially Filled During Backhitch

At higher interface rates, the buffer will fill before the backhitch is complete and the drive must stop accepting data from the host - this is the shaded area in the Figure 4 below. When the backhitch is complete, the buffer will empty to tape as in the previous case.

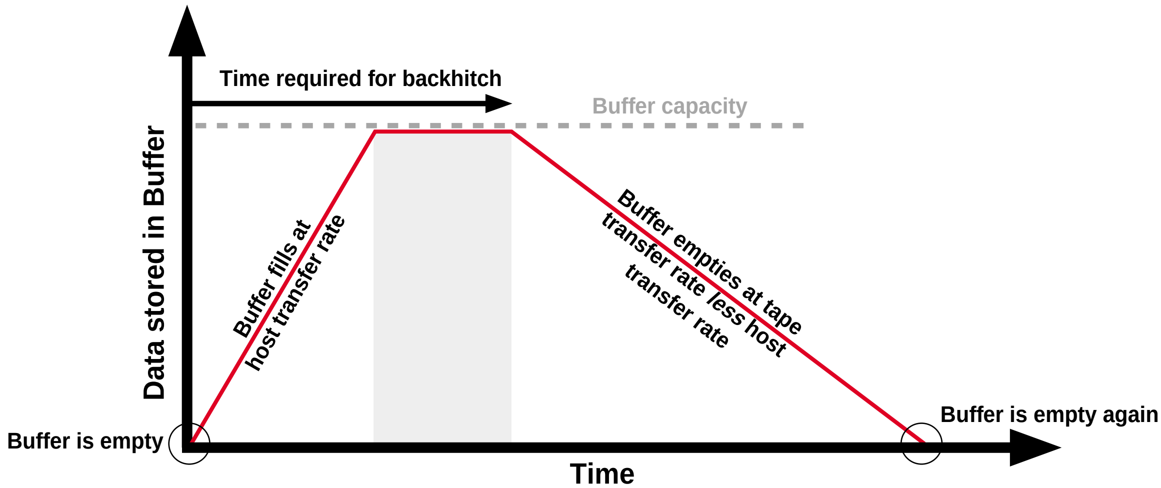

Figure 4 - Schematic of Data Transfer Process When Buffer Is Fully Filled During Backhitch

When the buffer never fills, data is always flowing over the interface at the host system's transfer rate so system throughput will not be degraded, but the problem of continuous start-stops will remain. In all drives, this creates unnecessary wear on the drive and on the media. In some drives these start-stops create a very annoying acoustic noise pattern and cause severe degradation of tape tension that can lead to catastrophic data loss. Several manufacturers attempt to avoid this issue by detecting the start-stop condition and switching tape speed to a lower value to reduce drive transfer rate. This will avoid reliability issues but creates a very severe performance degradation as indicated in the figure below. In the case where the buffer does fill up and interface transfers are interrupted, system throughput is degraded by the proportion of time the interface is idle.

The OnStream ADR drives provide, for the first time in tape technology, a means of avoiding this start-stop phenomenon. The ADR drive has a true continuously variable transfer rate that tracks the host interface rate and adjusts the tape transfer rate to match.

Each time the conventional drive detects a backhitch, it reduces its transfer rate and can respond quickly to a reduction in host transfer rate. This algorithm is very ineffective, however, in reacting to increases in host rate. Typically such a drive cannot return to a faster transfer until it reverses direction at the end of the tape. The shaded area in figure 5 shows the loss in performance this scheme creates. The OnStream ADR drive, with its 4:1 continuously variable transfer rate will follow the host transfer rate accurately and result in optimum performance.

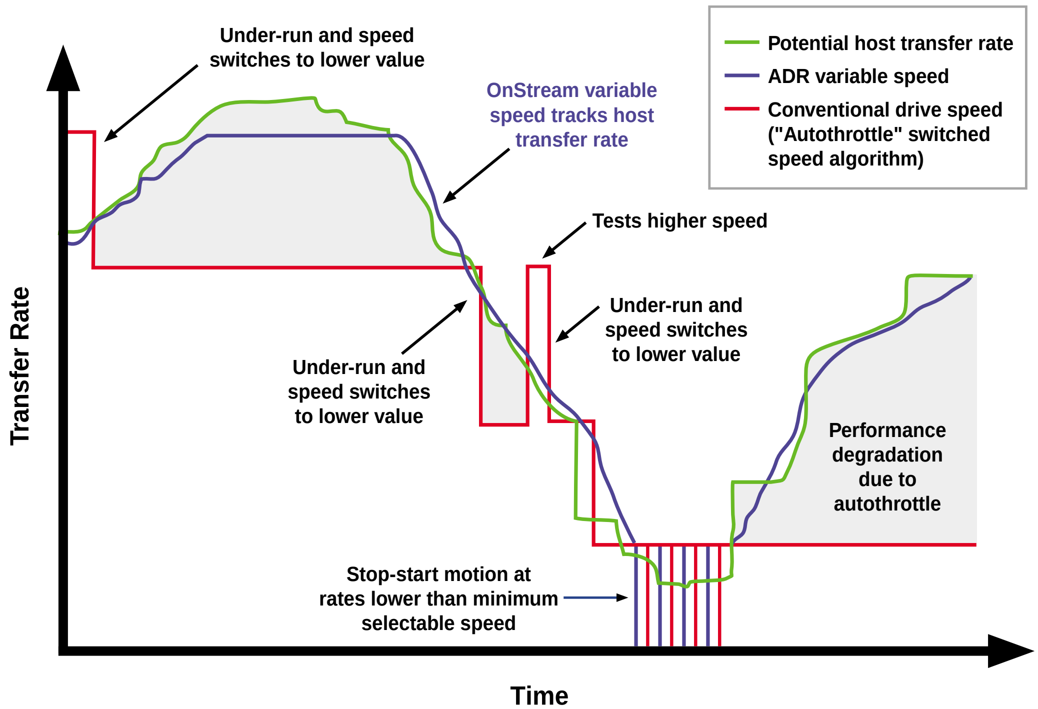

Figure 5 - Comparison of ADR variable transfer rate with that of a conventional tape drive

Enhanced Data Integrity Improved Error Correction Enhances Data Integrity

ADR's fourth significant innovation is the innovative way in which it maintains data integrity. In many applications, tape is used as the storage medium for mission critical backup or archived data. It is vital, therefore, that the user has 100% confidence that data can be recovered error free in a subsequent read. Building confidence in data reliability has two aspects: 1) maintaining a low-stress environment for both tape and drive to minimize physical issues such as tape stretch, and 2) using a proactive aggressive strategy to uncover write errors and repair them. The previous sections have described some of the ways that the ADR drives reduce the strain on the media. For example the eight-channel heads reduce requisite tape speeds for real-world transfer rates and variable transfer rates reduce the wear and tear of frequent stops and starts. In this section, the advantages of ADR, especially with buried servo signaling, in detecting and overcoming write errors will be discussed.

The most certain way of ensuring that data has been written correctly is to perform a read verify pass following a backup. This option is provided as standard in all backup software applications. The only downsides are that it effectively doubles the time required for a backup and it requires another pass of the tape through the drive.

Many of the existing higher performance tape drives provide a feature known as Read-While-Write (RWW). This feature is implemented by adding a second set of heads so that data can be read simultaneously as it is being written. The controller verifies the error detection information in the data and will automatically rewrite blocks it detects in error. With present-day sophisticated Error Correction Code (ECC) algorithms, small defects have no effect on system performance and many drives with RWW ignore such small defects.

ADR architecture intrinsically performs a Read-While-Write function since each head monitors the servo signal during a write operation. The low frequency servo data is not affected by very small media defects so it is not possible to detect these by monitoring the servo signal. While the servo itself is tolerant of errors in the readback signal, the circuitry includes a very sensitive monitor that can detect minor perturbations in one or more of the individual servo signals and report this to the drive controller.

The main value of RWW is detecting catastrophic error conditions that would overwhelm the ECC algorithm and the table below lists error situations and compares the response of conventional RWW and ADR technology. It can be seen that the features of ADR provide equal or better performance than RWW and ADR does not incur any added cost for this feature.

Feature	RWW	ADR	Comment
Detects Small Media Defects	some		ECC will recover errors from small defects
Detects Media Damage	•	•	Potential Unrecoverable Error
Detects Poor Tape Contact	•	•	Potential Unrecoverable Error
Detects Positioner Malfunction		•	Potential Unrecoverable Error, damages adjacent tracks
Detects Off-track Errors (Shock and Vibration)		•	Potential Unrecoverable Error, damages adjacent tracks
Detects Head Contamination	•	•	Potential Unrecoverable Error
Detects Write Head Failure	some		Low probability of occurrence
Optimizes Head/Media Contact		•	Improves System Performance
Optimizes Head Widths		•	Improves System Performance
Avoids Unnecessary Product Cost		•	RWW doubles cost of head and adds electronics

Table 1- Comparison of Traditional RWW Error Correction with ADR-Based Error Correction

Small Media Defects: These will not affect system performance due to the powerful ECC algorithms. ADR has the advantage of having more advanced ECC than other linear tape drives.

Media Damage: This is a potential source of an unrecoverable error. Both RWW and the ADR servo circuitry can detect media scratches and damage.

Poor Tape Contact: This is a potential source of an unrecoverable error. Both RWW and the ADR servo circuitry can detect poor head/tape contact

Positioner Malfunction: This is a potential source of an unrecoverable error. Since RWW heads are part of the head assembly, the Positioner could be totally inoperative, write the same piece of tape over and over again and RWW can never detect this condition. The ADR servo automatically verifies that the heads are correctly positioned.

Off-track Errors: This is a potential source of an unrecoverable error. Non-track-following tape drives have no way of detecting if the head is knocked off-track due to shock or vibration. When this happens, adjacent track data is overwritten and RWW can not detect that condition. The ADR servo sets tight limits to detect an off-track error and stops writing when the heads go off-track. The drive will then automatically rewrite the missing data when the perturbation stops.

Head Contamination: This is a potential source of an unrecoverable error. Contamination build-up on the tape bearing surface can degrade head/tape contact. Both RWW and the ADR servo circuitry can detect this condition.

Write Head Failure: This is a potential source of an unrecoverable error although, given the simplicity of the write head and circuitry, it has a very low probability of occurrence. RWW does not check the content of written data, only checks for valid CRC. In most cases when old data is being overwritten, valid CRC will be present from that old data and RWW will not report an error.

Optimized Head/Media Contact: The best contact between head and tape is ensured when the head forms a single contact edge touching the tape. RWW requires two such contact surfaces in close proximity and this degrades the quality of head to tape contact. Ironically, by using RWW a source of error is introduced.

Optimized Head Widths: For a non-RWW configuration, the width of the read head can be optimized from the tolerance calculation using all sources of off-track error. For RWW, further terms are added to this tolerance calculation to take account of the tilt error between the writing and reading head. This generally requires that the read head be made narrower and this reduces the signal amplitude and degrades the error rate.

Product Cost: The head assembly is typically one of the major component costs in a drive, often accounting for 20-30% of the component cost. RWW can double the cost of the head and increase drive cost by around 25% with no improvement in performance.

ADR's raw error rates are the best in the industry

ADR provides a two layer ECC scheme similar to that used in DAT and 8mm, but ADR has a raw error rate three orders of magnitude better than these helical scan drives. Looking at it from a different angle, ADR has raw error rates that are better than, or equivalent to any other data cartridge drive and ADR has an ECC correction power that is many orders of magnitude better that these other linear drives. ADR uses "Spatially distributed ECC" that interleaves the ECC data across all 8 tracks and makes ADR technology virtually immune to media defects and scratches.

On single channel drives, no matter how powerful the ECC, a single short scratch can damage a sufficient number of blocks to overwhelm the ECC. For TR4 for example, a narrow scratch 0.7" long will create an unrecoverable error.

With ADR, data can be recovered error free with a single track wiped out for the entire length of the tape. ADR can also recover data with wide scratches across the width of the tape – data will be recovered error free when the entire width of tape is erased for lengths up to 0.11."

Format	Error Rate		ECC Structure	Redundancy
	Raw	Unrecoverable		
TR4/NS8	≈1 in 10^8	1 in 10^{15}	Single level, interleaved, single track	6 ECC bytes for 26 data bytes
TR5/NS2	<1 in 10^8	1 in 10^{15}	Single level, interleaved, single track	10 ECC bytes for 54 data bytes
MLR	<1 in 10^8	1 in 10^{17}	Single level interleaved, across 2 tracks	6 ECC bytes for 26 data bytes
DAT	≈1 in 10^5	1 in 10^{15}	Two level, interleaved, single track; third level, non-interleaved on extra track pair	C1 4 ECC bytes for 28 data bytes C2 6 ECC bytes for 26 data bytes C3 1 ECC frame for 22 data frames
8mm	≈1 in 10^6	1 in 10^{17}	Two level, interleaved, single track	C1 16 ECC bytes for 144 data bytes C2 24 ECC bytes for 144 data bytes
DLT	≈1 in 10^8	1 in 10^{17}	Multilevel, interleaved, across 4 tracks	16 ECC bytes for 64 data bytes
ADR	≈1 in 10^8	1 in 10^{19}	Two level interleaved across 8 tracks	C1 6 ECC bytes for 66 data bytes C2 12 ECC bytes for 64 data bytes

Table 2- Comparison of Error Correction in Typical Tape Products

Conclusion

In selecting a tape drive technology, a user needs to consider Reliability, Performance, and Value for future enhancements. In most cases, this requires considerable thought since no traditional tape technology can satisfy all these requirements simultaneously. Now this choice is made very simple: ADR leads the field in all of these categories and is the natural choice for next generation tape systems.

	ADR	QIC/Travan	DAT	8mm	DLT
Capacity	•			•	•
Performance	•			•	•
Reliability	•	•		•	•
Cost	•	•		•	
Potential	•	?	?	?	?