FROM IRIG TO MICRO-TRACK

THE EVOLUTION OF MULTI-TRACK DATA RECORDING

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ABSTRACT

This paper discusses practical examples of a high capacity multi-track linear recording technique known as Micro-track Recording, showing how its performance and capabilities have evolved from its inception as a capacity up-grade for open-reel IRIG recorders to its use in a range of advanced D-1 cassette-based storage products. The technology already allows over 5 Terabits of digital information to be stored on a single 25.4 mm x 5,500 m (1 in x 18,000 ft) open reel at sustained user rates in excess of 1 Gbits/sec. Development work aimed at increasing the capacity per reel to 50 Terabits using metal particulate tape and thin film headstacks is also discussed.

INTRODUCTION

The science of magnetic tape recording is all about storing more and more information into smaller and smaller volumes. It is a game of perpetual leapfrog. First, improvements in media - generally driven by the insatiable video market - are capitalized upon by data recorder manufacturers. Then breakthroughs in head or transport design prompt further improvements in media. High coercivity tapes support narrower and more densely packed recording tracks; thinner tapes mean greater volumetric efficiency.

Linear (or longitudinal) recorders have taken full advantage of this process. As media formulations have improved over the years, the in-track packing densities of conventional 25.4 mm (1 in)[1] IRIG[2] recorders have risen from 0.197 to 1.3 kbits/mm (5 to 33.3 kbits/in) and more recently to 2.2 kbits/mm (56 kbits/in)[3]. Meanwhile track densities have increased from fourteen 1,270 µm (50 mil[4]) tracks to twenty-eight 635 µm (25 mil) and then forty-two 483 µm (19 mil) tracks. In consequence, areal packing densities have risen from 0.11 to 3.65 kbits/mm^2 (70 to 2,352 kbits/in^2).

In 1972 Penny & Giles Data Systems (then part of Thorn EMI) was the first company to develop transports with the tape guidance accuracies necessary for reliable forty-two track

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[1]Historically most standards for data recorders and media have been based on Imperial units. Conversions where given are approximate.
[2]Inter-Range Instrumentation Group.
[3]Within this paper the term 'bits/mm' (or inch) is synonymous with 'flux changes/mm' (or inch). There are digital coding schemes such as the Penny & Giles 3PM system where one flux change can represent more than one bit.
[4]1 mil = 0.001 in.

Figure 1. SIRIUS recorder.

operation. The company maintains a substantial commitment to the IRIG standards and the current *SIRIUS* range demonstrates clearly the high levels of performance which can now be achieved with 'conventional' multi-track technology. *SIRIUS* (Figure 1) features high precision tape guidance and tensioning, a long-life brushless capstan motor controlled by an adaptive capstan servo plus high stability data electronics and programmable equalization. Up to forty-two tracks of 4 MHz (direct) or 1 MHz (FM) can be recorded with excellent time base accuracies and signal fidelity. Flexible digital formatting options support rates up to 144 Mbits/sec. But as requirements for seamless data capture, computer analysis and archiving solutions intensify, it has been necessary to find even more innovative ways of increasing capacity, throughput and cost effectiveness.

MICRO-TRACK RECORDING

The term micro-track recording is used to describe 24.5 mm and 19 mm multi-track linear recording formats which use track widths narrower than 200 µm (8 mil). Two sub-divisions exist at present. One known as VLBI[5] recording is based on 24.5 mm open-reel tape drives and is used almost exclusively within the radio astronomy community. The other using the standard 19 mm D-1 cassette is found in a range of proprietary units intended for general data recording applications.

In both cases groups of narrow tracks are recorded in parallel along the tape (Figure 2). Maximum in-track packing densities are typically in the range 1.3 - 2.2 kbits/mm at present while a track rate of 18 Mbits/sec is used on high-speed open-reel systems. To maximize areal density, data is written as two or more end-to-end passes of the tape, the headstack being incremented laterally with each change of direction. Total data throughput is dependent on the number of tracks used.

[5]Very Long Baseline Interferometry.

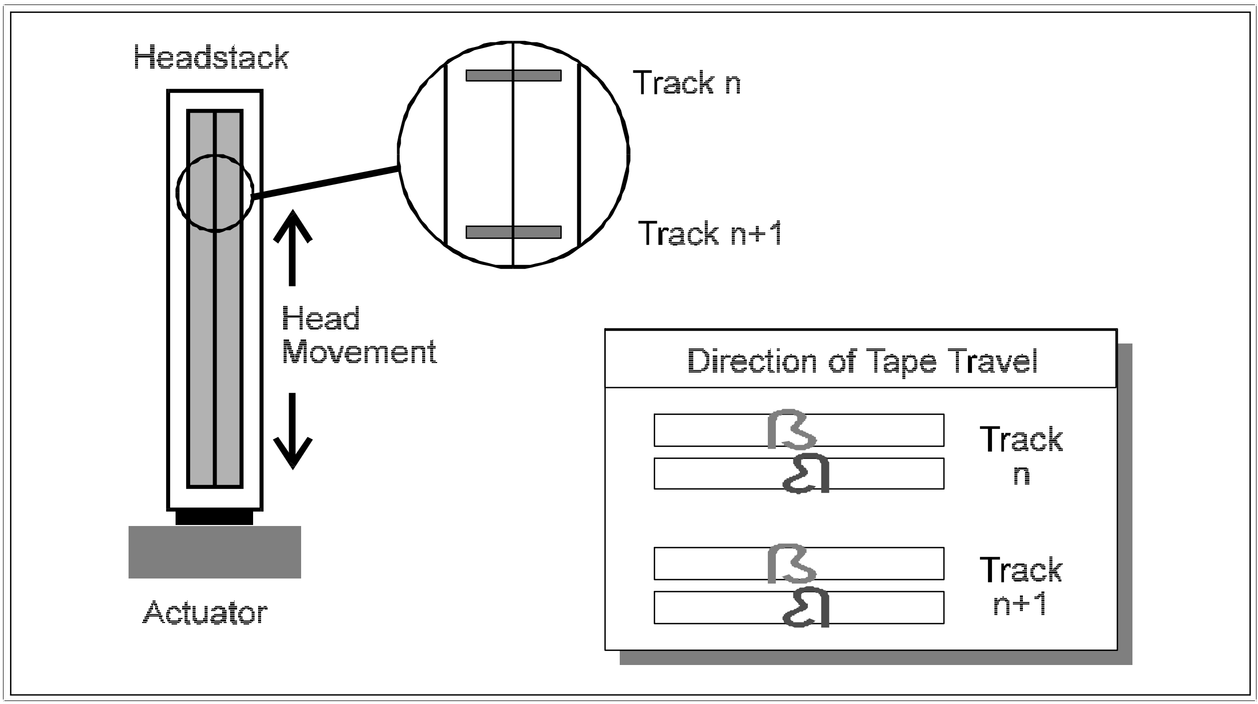

Figure 2. Micro-track recording.

MECHANICAL CONSIDERATIONS

Figure 3 shows a standard VLBI 36-track 1 inch micro-track headstack mounted on its precision actuator. The assembly is designed for easy field replacement without special tooling. Recording and (more importantly) reading narrow track requires accurate and consistent tape guidance. Here the tight slitting tolerance of current video tapes is of considerable assistance, allowing repeatability to better than +/- 4 µm (0.16 mil) to be achieved without difficulty on the *SIRIUS* transport.

Correct lateral positioning of the headstacks is more critical. In the case of open-reel formats where 38 µm (1.5 mil) track widths and up to sixteen separate recording passes may be used, it is essential that the recording headstack be positioned accurately. This is achieved by a conventional LVDT servo loop. When the same track group is to be replayed, the headstack is first moved to the nominal lateral position to read header information from the tape which is used to verify that the correct track group has been located. Residual write/read track positioning errors can then be removed both statically and dynamically by a 'dither' servo which moves the headstack small amounts to peak up the output of a reference track. The necessary electronics are housed in a VME chassis within the *SIRIUS* unit (Figure 4). Where more than one headstack is used, each is capable of independent movement. On the D-1 cassette formats, slightly wider tracks are used with mechanical dimensions and tolerances chosen to guarantee peak output without this fine tuning process.

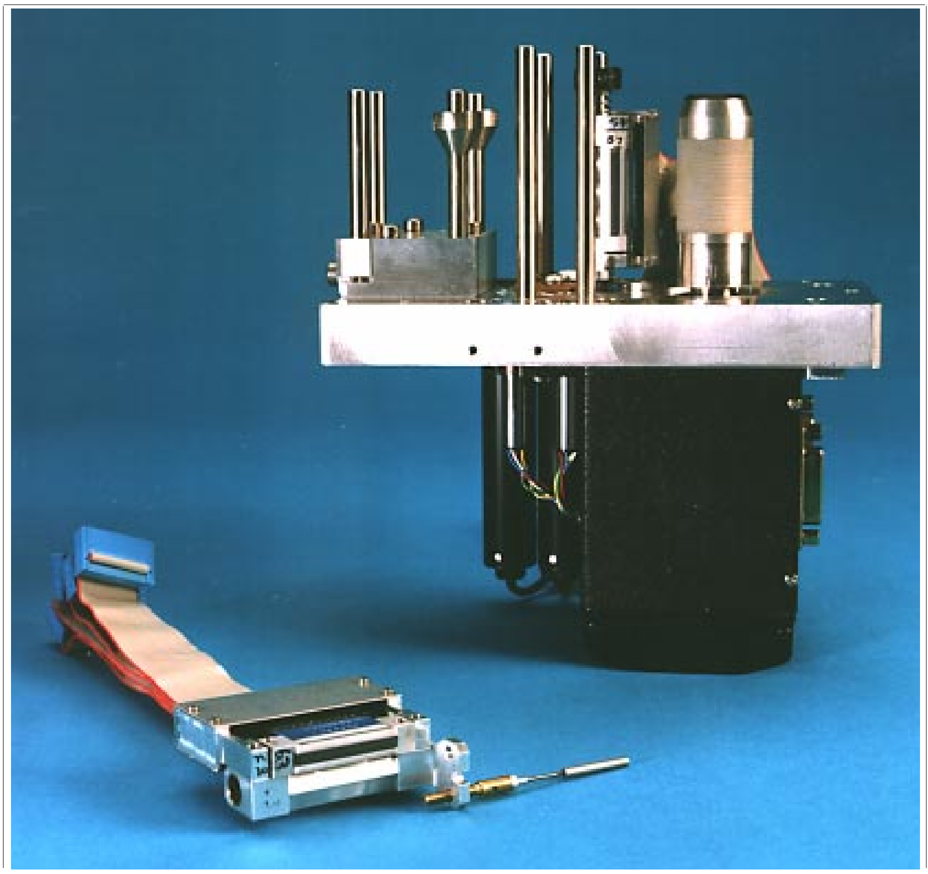

Figure 3. SIRIUS precision plate showing brushless capstan motor, actuators, LVDTs and two headstacks (one removed).

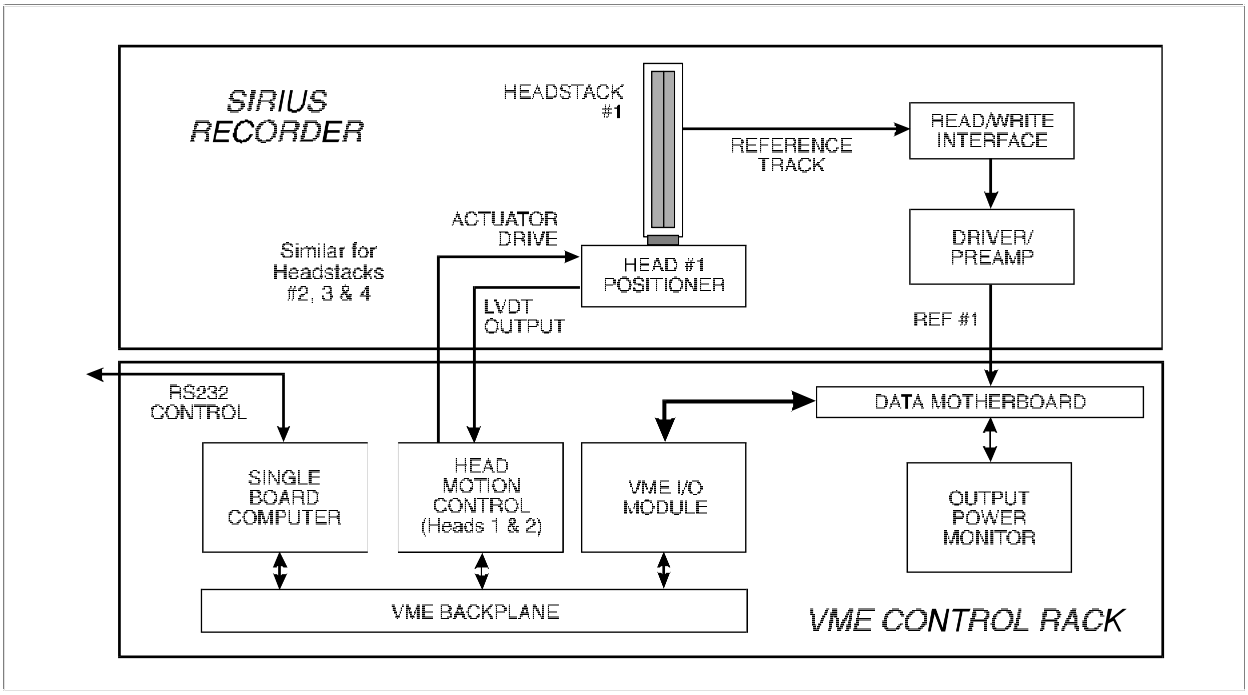

Figure 4. VLBI headstack movement.

TERABIT STORAGE - FIRST APPLICATIONS

The origins of narrow track data recording can be traced to a need within the radio astronomy community to increase the capacity of 25.4 mm x 2,830 m (1 in x 9,200 ft) tapes used to record data captured by radio telescopes. A technique used by astronomers and known as Very Long Baseline Interferometry (VLBI) involves transporting this data in considerable volumes to central sites for correlation to produce images and other information on distant radio sources (Figure 5). The driving force at the time (the early 1980s) was essentially economic. There were already more than fifty field systems based on conventional 28-track IRIG transports recording digital data at up to 256 Mbits/sec for observation periods lasting days or even weeks. The cost of buying and shipping tapes was enormous.

MIT Haystack Observatory near Boston, funded by NASA to support the geodetic applications of VLBI, calculated that if the capacity of each reel could be increased by a factor of ten, this could be translated to savings of hundreds of thousands of dollars in annual operating costs. To achieve this, the engineers at Haystack proposed the use of a format with a 38 µm track width, writing twelve separate passes of 28 data tracks each. There was no requirement at the time to increase throughput so recording duration and tape consumption could be improved by more than 10:1 immediately. The change was intended as a bolt-on upgrade to all existing recorders and reproducers (designated the MKIII-to-MKIIIA format upgrade).

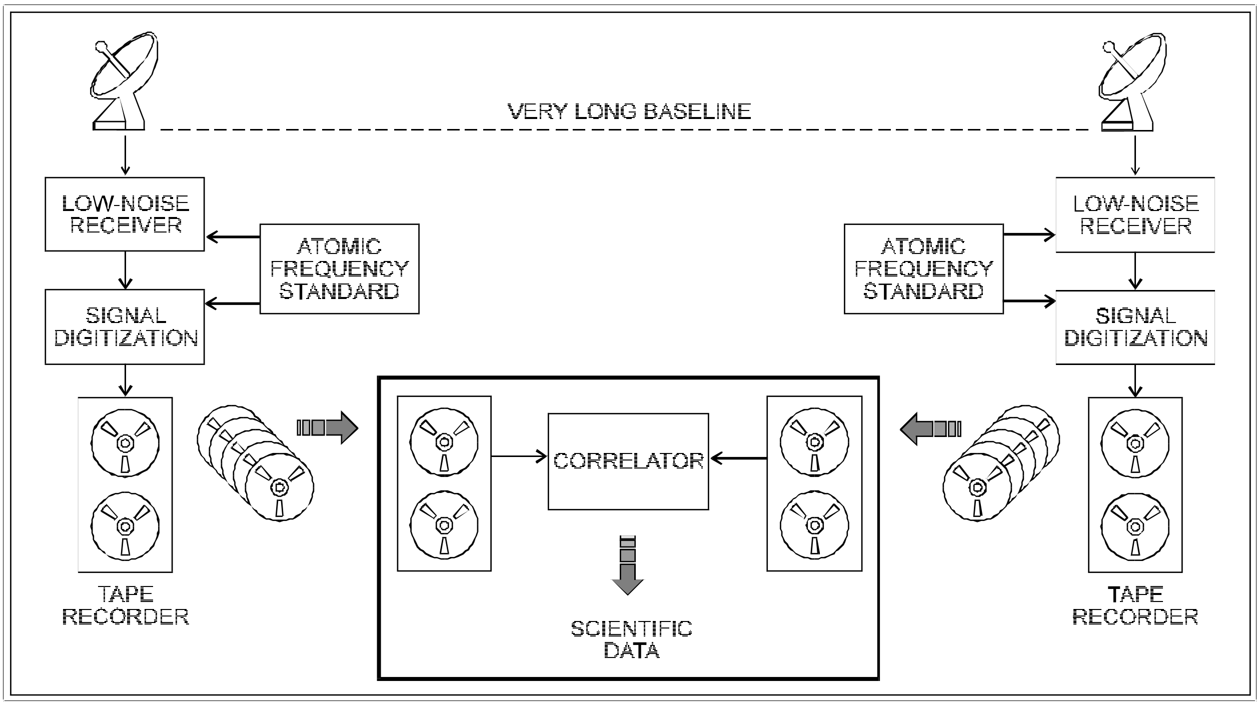

Figure 5. Data recorded on tape at up to twenty radio telescope sites is transported to a correlator facility for processing.

The MKIIIA upgrade was duly developed by Haystack and integrated across the world. Standard MKIIIA tape speeds are 3,429 and 6,858 mm/sec (135 and 270 in/sec) at a packing density of 1.3 kbits/mm (33.3 kbits/in). The capacity of the 2,830 m reel is approximately 1.3 Terabits (compared with the 100 Gbit figure achieved with the 28-track IRIG format). The standard MKIIIA headstack has 36 tracks (28 data, 4 system and 4 spare).

INCREASED CAPACITY AND THROUGHPUT - VLBA

Around 1993, the MKIIIA concept was developed further to support another radio astronomy program known as the Very Long Baseline Array (VLBA), a dedicated US network of sixteen telescopes spanning a line from Hawaii to the Virgin Islands. From the recording standpoint, the improvements of note are that the maximum tape speed was increased to 12.6 m/sec (320 ips) raising the maximum data transfer rate to 512 Mbits/sec (Figure 6). The number of passes was increased from twelve to sixteen, increasing the capacity of the 2,830 m reel to more than 1.5 Terabits. At the same time a 'thin tape' capability was added allowing 5,500 m (18,000 ft) tapes to be used, doubling the capacity per reel to 3 Terabits. Thirty-two tracks are used in the VLBA implementation.

GIGABIT RECORDING

Under a contract from the Joint Institute for VLBI in Europe (JIVE) Penny & Giles Data Systems has developed a VLBI micro-track recorder/reproducer on which the throughput of the basic MKIIIA/VLBA formats has been increased to 1 Gbits/sec without loss of compatibility with existing operating modes (Figure 6). This has been achieved by adding a second headstack to give sixty-four data tracks in all. At the same time the per-track packing density has been increased from 1.3 kbits/mm to 2.2 kbits/mm (33.3 to 56 kbits/in) and the data rate from 9 Mbits/sec to 18 Mbits/sec. Penny & Giles was selected for this project following the successful installation of a VLBA/MKIIIA system at the Max Planck Institute for Radio Astronomy, Bonn in 1992 and a subsequent demonstration of the tape handling characteristics of its latest *SIRIUS* recorder on which the development has been based.

Note that the track width of the new system - designated MKIV - is the same as before, the major technical advances concerning the ability to crossplay tapes reliably at the higher packing density and channel rate. When two heads are in use, the maximum number of passes is reduced from sixteen to eight but the increased linear packing raises the capacity of a 5,500 m reel to over 5 Terabits. The MKIV design allows for the addition of a third and fourth headstack and additional electronic channels to extend the user data rate beyond 2 Gbits/sec (the proposed MKIVA format).

	1975	**1985**	**1993**	**1995**	**1996**
Format	MkIII	MkIIIA	VLBA	MkIV	MkIVA
Mbits/sec (max.)	256	256	512	1024	2048
Data Tracks	28	28	32	64	128
Packing Density (kbits/in)	33.3	33.3	33.3	56	56
Tape Length (ft)	9,200	9,200	18,000	18,000	18,000
Capacity per Reel (Terabits)	0.1	1.3	3.0	5.0	5.0

Figure 6. Evolution of VLBI recording formats.

FROM VLBI TO A GENERAL PURPOSE PRODUCT

Clearly, micro-track recording has much to offer in terms of throughput and capacity, but radio astronomers have one advantage over the rest of the data recording world (with the possible exception of the users of sonar systems). Radio sources emit what is effectively white noise, so a few lost or corrupted bits here and there are not a problem. The *SIRIUS* VLBI MKIV recorder demonstrates parity error rates typically better than 1 x 10-5 - around two orders of magnitude better than that necessary for successful correlation. Even so, this figure is several orders of magnitude below that required by many other applications, so when Penny & Giles Data Systems decided to use its micro-track experience as the basis of a general purpose data recorder some changes to the detailed implementation were required. It was also decided to take advantage of the convenience of large-format cassettes.

The new system, called *PEGASUS*, uses the 19 mm D-1(L) cassette, being readily available from a number of international sources (Figure 7). *PEGASUS* headstacks are essentially similar to those used for VLBI, the main difference being that the tracks are approximately five times wider for improved output and less reliance on precise tape guidance for guaranteed data interchange. A balance between data throughput and areal density has been achieved by recording with a pair of interleaved 20-track headstacks (Figure 8). Limiting the number of passes to two initially permits a simpler head movement mechanism to be used and the wider tracks make the dynamic 'track following' described earlier unnecessary. Two additional issues arise concerning one of our key markets - satellite remote sensing. Users require both real-time off-tape data validation and the ability to reproduce data in both forward and reverse directions. The first is satisfied by flanking the interleaved reproduce headstacks with two pairs of similar record headstacks. The format accommodates the bi-directional play feature simply by selecting the required direction of tape movement.

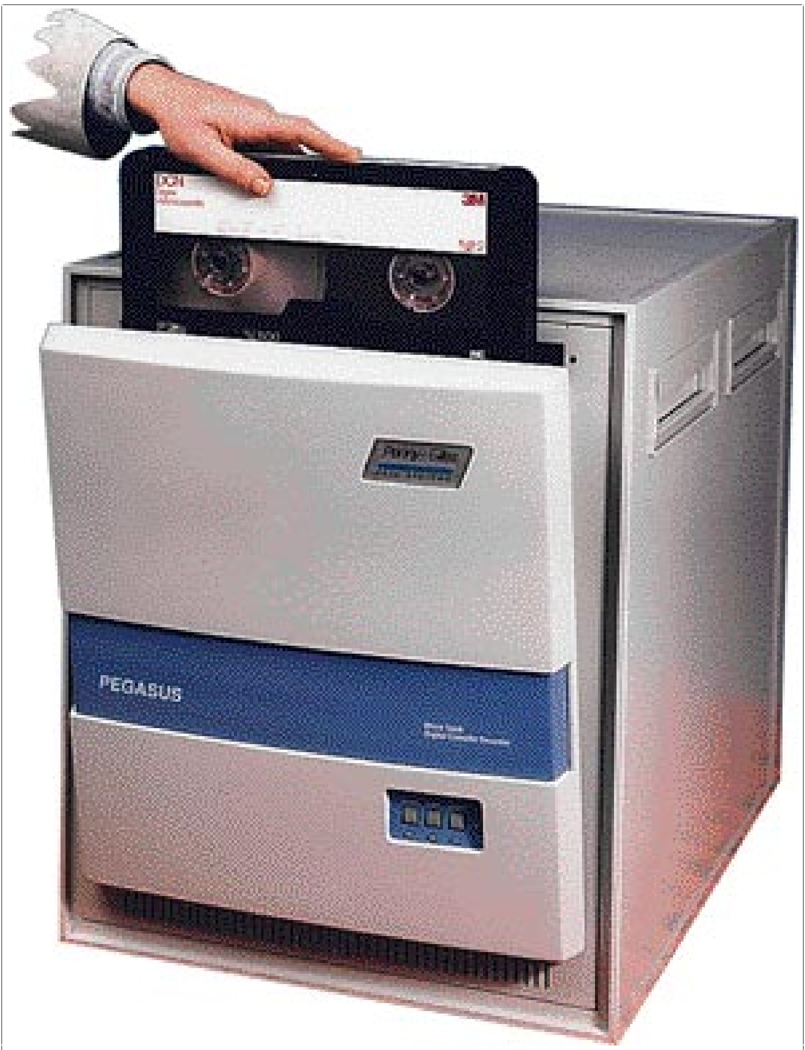

Figure 7. PEGASUS D1 Micro-track digital cassette recorder.

The other major departure from the VLBI implementations discussed earlier concerns the way the tape is moved. VLBI data is recorded continuously in the conventional IRIG way in that there are only a small number of fixed data rates to consider and so a few fixed tape speeds can cover all operating modes. However, for a recorder to be easy to integrate and use in general applications it is essential that it should be able to operate without adjustment over a wide range of data rates. The solution adopted for *PEGASUS* is to record and reproduce incrementally (as a series of ramp up/write to tape/ramp down sequences); using an internal buffer to smooth out differences between the recorder's fixed internal write/read clock and user's continuous (or intermittent) data rate.

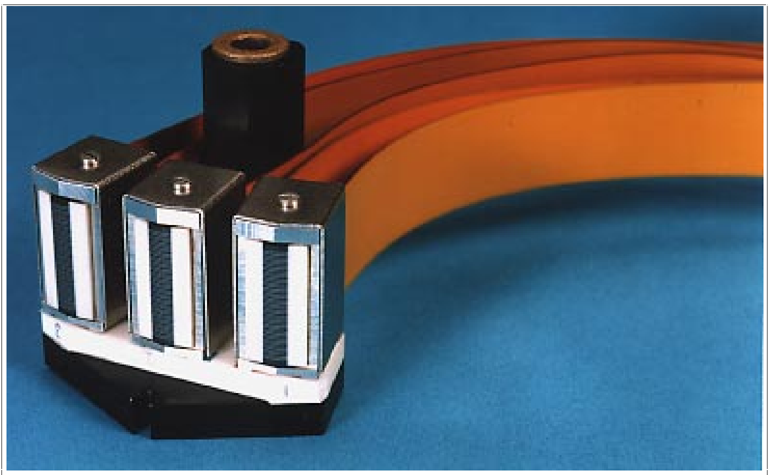

Figure 8. PEGASUS headstacks.

Incremental recording has other important advantages. It is not necessary to run the tape in anticipation of data being received at the input. Hand-shaking lines can be used to ensure that recording only starts when valid data is received at the input. This in turn avoids unnecessary head-wear, allowing the life of micro-track heads typically to exceed 8,000 hours. Also, since writing and reading take place at a single fixed tape speed, there are none of the traditional speed-related equalizer circuits to calibrate. A single D1(L) cassette holds up to 240 Gbits of user data regardless of user input rate. Future models will double this capacity by increasing the number of passes from two to four.

Three versions of the Penny & Giles *PEGASUS* recorder have been released to-date.. *PEGASUS 100* records sustained data rates up to 100 Mbits/sec and is intended for aerospace, sonar, electronic warfare and similar high rate data capture, analysis and archiving applications. *PEGASUS 110* is the only large format cassette recorder designed specifically for remote sensing applications. This unit supports all current and planned platforms up to a maximum rate of 110 Mbits/sec and includes a bi-directional replay capability as standard. *PEGASUS 64* is an entry level variant which records up to 64 Mbits/sec and fills the gap between 'high-end' S-VHS products and high rate large format products. Further details of the application and interfacing of *PEGASUS* can be found in Reference [1].

THE WAY FORWARD - 50 TERABITS ON A SINGLE REEL?

While the design of the VLBI MKIV allows for the deployment of two additional headstacks to raise the user data rate from 1 to 2 Gbits/sec (with the same total capacity), it seems that it may be possible to extend both throughput and capacity still further using magneto-resistive (MR) heads made with thin film technology. As with earlier advances, these intriguing possibilities result from fundamental advances in other areas. Experiments using MR heads to reproduce waveforms recorded by thin film and metal-in-gap heads on a metal particulate tape have indicated that it is possible to achieve excellent signal-noise ratios with tracks as narrow as 3.8 µm (0.15 mil) - just one-tenth of the current VLBI design. The tape currently under investigation is designated W-VHS with a formulation popularly known as MP++. The tape delivers an output 6-8 dB higher than a S-VHS tape and it is projected that it may be possible to record and reproduce wavelengths as short as 6 kbits/mm (152 kbits/in) - about three times the MKIV standard.

Clearly, using tracks of these widths presents significant challenges in the tape guidance and track registration areas, and work is on-going to establish suitable operating strategies and techniques. Even so, the implications of this research are significant particularly as it may be possible to reduce the track width to as little as 0.5 µm. Taken together, a ten-fold increase in lateral track density and a trebling of linear packing density mean that it is not unreasonable to think of storing 50 or even 100 Terabits in the volume of a 25.4 x 355.6 mm reel using linear recording in due course.

REFERENCE

[1] Engineering handbook *Micro-track Digital Cassette Recording* published by Penny & Giles Data Systems Ltd.
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