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High Data Rate Recorder Development at MIT Haystack Observatory

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Abstract

Current operational capabilities of tape recording for Very Long Baseline Interferometry (VLBI) at the Haystack Observatory allow 0.7 terabytes (12 hours at 128 Mb/s) of data to be stored in a 128 in^3 volume. On-going efforts are aimed at full time 1 Gb/s operation with two 36-channel headstacks. Applications for linear digital tape recording, with suitable development of thin-film head arrays, suggest a volume density exceeding 1 TB/in^3 to be achievable in the future.

I. Introduction

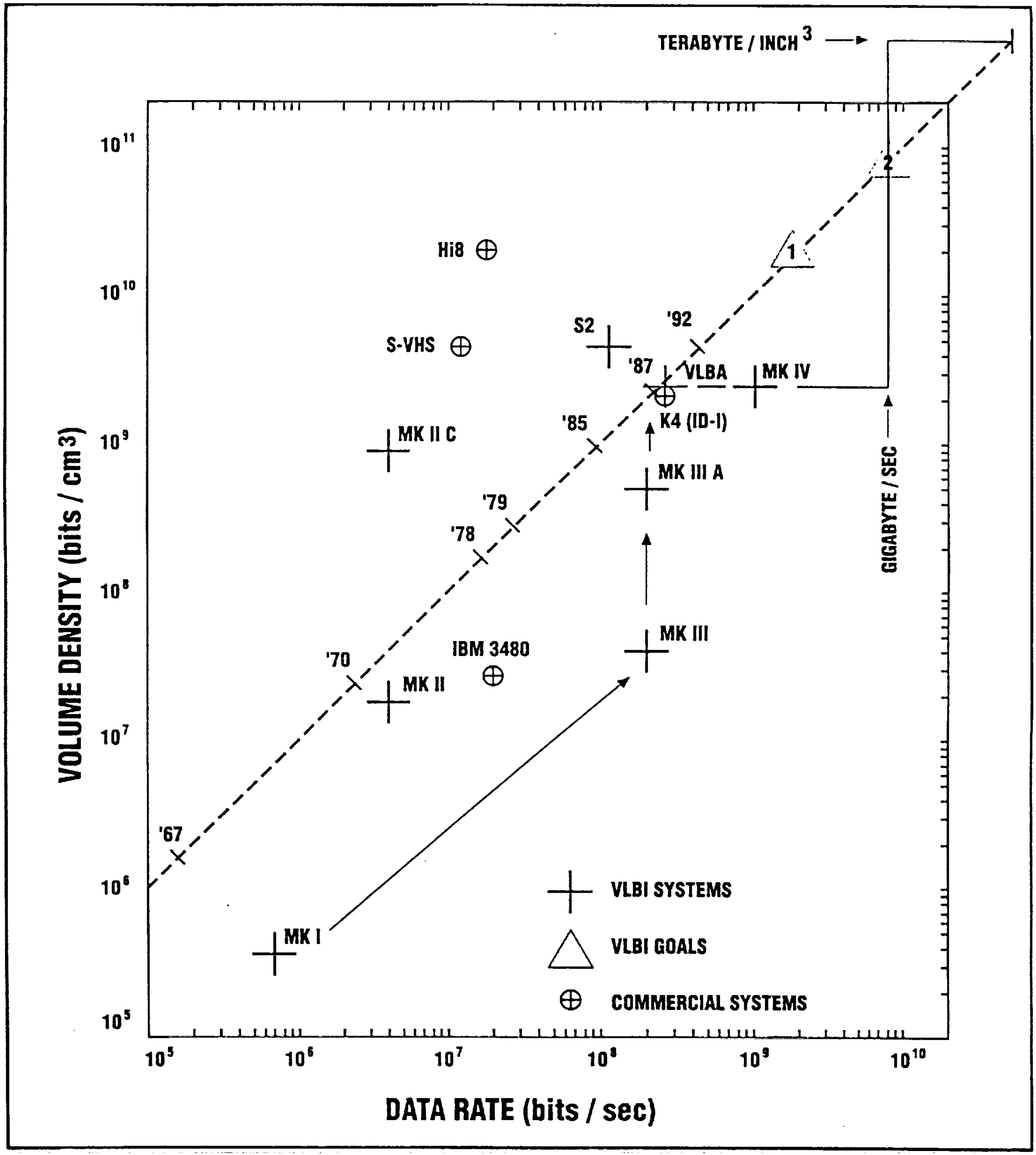
The sensitivity of Very Long Baseline Interferometry [VLBI] observations is proportional to only the square root of the number of bits recorded and processed. This fact, and the lack of affordable alternate means of sustained high-rate data transmission, continues to spur development of ever higher rate and density tape recording systems for VLBI.

The VLBI recorders developed at Haystack for VLBI operation employ the linear [longitudinal] Metrum, formerly Honeywell, Model 96 instrumentation drive, which was selected in 1975 for its excellent tracking repeatability. These drives reliably handle 14" reels of inch-wide tape, now at speeds up to 10 m/s [420 ips], as well as with tape tension as low as 5/8 and as high as 5 N.

VLBI-qualified tapes (3M5345 and SonyD1K) can be shuttled for thousands of passes under these conditions without any noticeable edge-damage [as evidenced by the formation of a bumpy pack]. An understanding of the damage mechanisms and tape-path modifications were developed to make the drive safe for thin tape at high speed. The 15.2 mm thin, 5500 m long, SVHS-similar Co-Fe_2O_3, PET-based tapes, which we have qualified for recent VLBI systems, each store 0.7 terabytes [12 hours at 128 Mb/s] in a 128 in^3 volume.

A total of 576 [38 mm wide] tracks, for example 16 passes with 36 channels at a time, are written at a linear density of 2.25 transitions/mm [2 bits/mm with an 8/9 channel code]. A new version of the recorder (MkIV) operating at 8 m/s is capable of 1 Gb/s operation with two 36-channel headstacks and 2 Gb/s with four headstacks. The growth of the data rate and volume density in VLBI recording is illustrated in Figure 1.

Haystack's narrow-track ferrite read-or-write headstack design, illustrated in Figure 2, has been used since its introduction in 1985. It has been a 'product' manufactured by Metrum since 1989, unfortunately only in the small volumes required by its single VLBI application, which makes it increasingly less affordable. More recent recorder applications all use the same sub-mm resolution positioner [piezoelectric Inchworm actuator and LVDT sensor], one for each headstack. This positioner was developed to support narrow-track serpentine recording. It will need no significant improvement to support much narrower, even sub-mm, trackwidths since actuator resolution is about 4 nm.



In the 25-year history of VLBI, data rate has grown by more than three orders of magnitude to one gigabit/second in the Mark IV system. A further hundred-fold improvement in bandwidth and density is now a technically-realistic goal.

Figure 1

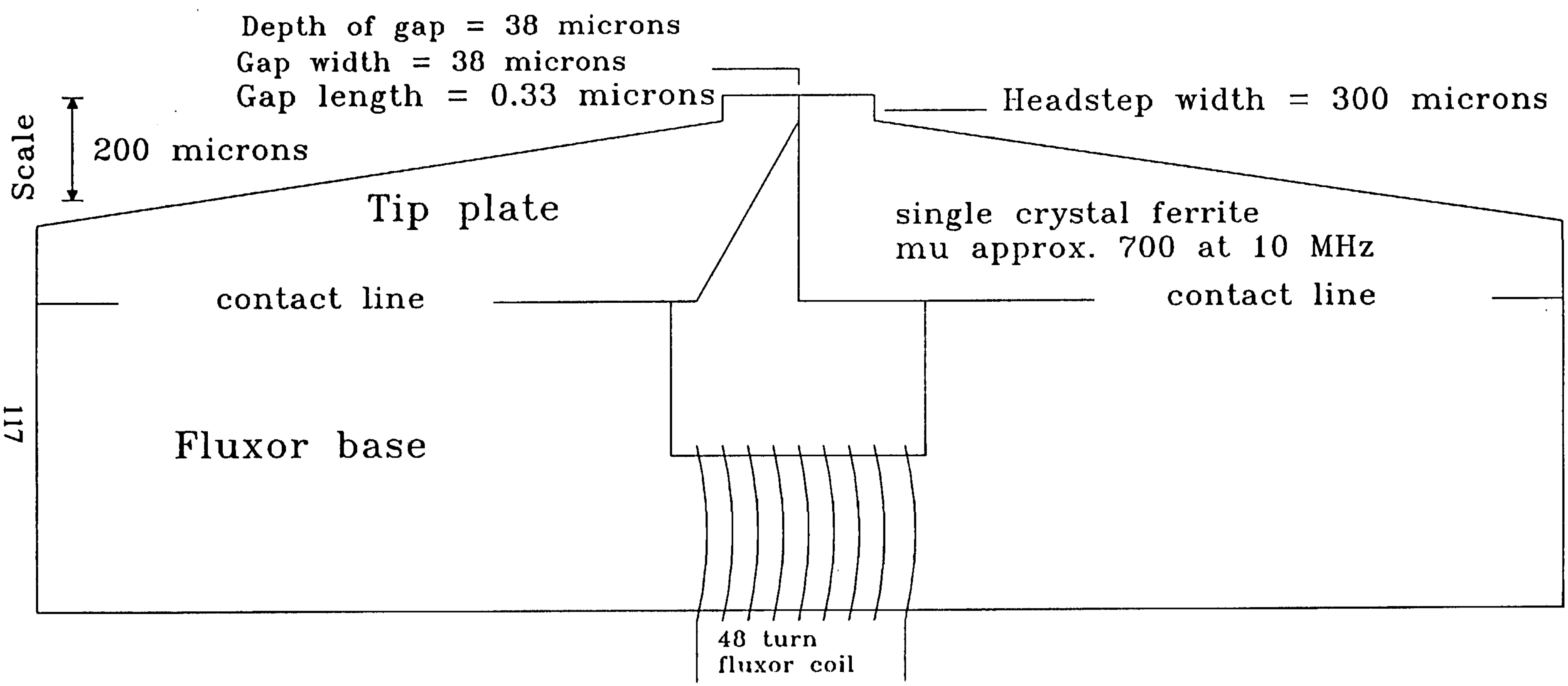

Depth of gap = 38 microns
Gap width = 38 microns
Gap length = 0.33 microns
Headstep width = 300 microns
Scale
200 microns
Tip plate
single crystal ferrite
mu approx. 700 at 10 MHz
contact line
contact line
Fluxor base
48 turn
fluxor coil

Figure 2

II. Goals for Future Developments

The more recent version of our VLBI tape recorder developed for the NRAO VLBA system is designed to operate full-time at 128 Mb/s at 2 m/s. With a 10-station array, the VLBA collects 14 TB/day and could process 56 TB/day with its 20-station 4 m/s correlator. A new correlator (MkIV) under development at Haystack will be configurable to keep up with 4 Gb/s per station; another iteration could easily raise that to 4 GB/s. Processing hardware will therefore soon cease to be the chief limit on VLBI bandwidth, hence sensitivity.

Thus there is a need to provide affordable full-time VLBI recording soon at Gb/s, and not much later at GB/s, rates. The first goal, achieving Gb/s rates, requires only new thin-film head-arrays. The second goal, achieving GB/s rates, requires new tape as well. Both these goals are discussed below.

The highly repeatable tracking of the Model 96 drive has been modeled and is now well understood. It is good enough to permit trackwidth reduction from 38 to 7-10 mm without, and probably less than 2 mm with, possibly only minor modifications. Short-term nonrepeatability is about 1 mm p/p and is due to wobble of the capstan, which is in close proximity to the head. The 'perfect' edge-guide [bearing point] in the slanted-wall vacuum pocket is much further away. The desired modifications under development should have the effect of bringing head and edge-guide very much closer together. They must also increase the along-tape distance from head to capstan, and/or isolate it with another sliding edge-guide between head and capstan.

The principle of tilted-wall vacuum-pocket edge-guiding can be applied to vacuum-less guides such as tilted posts or flexible conical-foil air-bearings. Long-term nonrepeatability and sensitivity to pack imperfections which produce a reel once-around 'bump' signature is also eliminated by bringing head and edge guide together. Much more robust, pack-imperfection-tolerant passive tracking should result.

a. *Thin-Film Head-Arrays*

Haystack is seeking support to collaborate with Seagate Tape Technology Inc. to further develop thin-film head-arrays for linear multichannel drives. Thin-film head-arrays, with inductive write (IW) and magnetoresistive (MR) read elements, are key to achieving both high data rate and density at the lowest cost. Sensitive MR heads will allow a 4-fold increase in track density with the present tapes. A read-width of 9 mm and write width of 11 mm can therefore now be targeted. More conservative specifications for VLBI thin-film head-arrays proposed in 1993 (not funded) are given in Table 1.

Current processes for thin-film IW-MR disk heads allow increasing channel density from 36 to at least 144 per inch. Channel densities of 1000 per inch or so are not far off for MR and 1-2 turn IW heads. With a mature high-yield process, if chips are of comparable size, the cost of a dense head-array should eventually become comparable to that of a single-channel disk slider. This will happen only when and if a comparably large linear tape head market develops. Commonality at the wafer level with a high volume PC/consumer product is therefore highly desirable. The manufacturability of dense arrays is the central issue for this kind of product.

b. *The Promise of Advanced Tapes*

Advanced high-SNR, high-resolution, super-smooth, ultrathin (3-7 mm) metal-evaporated, metal-particle, and barium ferrite tapes promise further 4-fold density increases in each dimension and continue to be evaluated. TB/in^3 volume density is technically within reach with products like WVHS and Hi8Master tape.

Efforts to guarantee more nearly ideally robust edges for ultrathin tape must be pursued with the

Specifications for VLBI Head Array Prototypes

Read-Only Array	
Technology Thin Film	MR
Track Width	19 Microns
Head Pitch	349.25 microns
Number of Heads in Array	72
Equivalent Spacing	<0.05 microns
Write/Read-Verify Array	
Technology Thin Film	Inductive
Track Width	22 microns
Head Pitch	349.25 microns
Number of Heads in Array	72
Equivalent Spacing	<0.1 microns
For Both Arrays	
Minimum Record Density	56,000 kfci
Tape Speeds Up To	8 m/s (320 IPS)
Media	3M 5345 (16-micron thick) Similar to S-VHS)

Table 1

collaboration of manufacturers. A degree of rounding of the corners of order 10% of thickness and comparably small edge asperities are needed to guarantee that plastic deformation of these asperities does not lead to edge-thickening which results in a bumpy pack.

Since the stiffness of tape goes as thickness cubed there may be a more fundamental problem with winding much thinner than 15 mm tapes on large self-packing reels. These were invented for VLBI in 1978 and the design was improved in 1994 explicitly to suppress scatter-wind so as to make the tape directly shippable. Self-packing reels intentionally use close spacing and curvature of the flanges to guide the tape into a smooth-faced pack. This does not damage the edge even under extreme high-speed [8 m/s], high-tension [4.4 N], long-term [1000 pass] running conditions. Both 3M5345 and SonyD1K typically pass such 'torture' tests with no evidence of damage [a bumpy pack when wound at 2 m/s]. With 9-mm tape samples similar to 3M5354 the tape edge tends occasionally to hang up slightly on the flange and voids are formed because subsequent turns yield too easily. Even without this problem, unreasonable thickness uniformity requirements may be placed on ultrathin tape wound into a 14" diameter pack. Ultrathin tapes are likely to be much better suited for formats where the pack diameter is kept under about 3" [VHS, 3480, DLT, QIC, etc.].

III. Longer Term Potential of Tape Recording Applications

Tape recording is and for the foreseeable future will remain by far the densest and most economical form of data storage. Applications that must sustain high data rates in the 0.1 to 10 Gb/s neighborhood or that require convenient access to enormous [of order 10**15 bytes (petabyte)] data libraries will continue to rely on tape.

The overwhelming volume density and capacity advantage of tape is due entirely to its high relative thickness-density. The areal density of tape recording can keep up with the advances in disk recording. Though track densities on tape [especially in linear systems] have traditionally been lower than on disk, simple passive edge-guides can provide essentially perfectly repeatable tracking; active track-following should not be needed to at least 10,000 tpi.

The two fundamental advantages of linear [compared to helical-scan] tape drives are: (1) its mechanical simplicity, and (2) its ability to support many parallel channels, hence very high aggregate data rates, without added complexity.

A low-cost high-rate linear digital VCR is possible in the future. Given the 4 in^3 capacity of a VHS cassette or 3480 cartridge for example, a 250 Mb/s machine could operate for two hours at a volume density of only 1/16 terabyte/in^3, a density that can be achieved with some of today's tape and head components. The 'effective density' of the Hi8 analog consumer video tape recording format in long play mode is about 1/20 TB/in^3 for example. This density is already so high that the use of so-called data-compression [redundancy reduction, especially the lossy varieties used for video] for tape-storage seems counter-productive, an unnecessary added special-purpose complexity. Rather, with more than an order of magnitude higher TB/in^3 density on the horizon, the highest-volume market for such high capacity storage should be cultivated. There should be no doubt that the all-purpose high-rate capability of the linear recorder can be made attractive to the consumer/PCuser.

The key prerequisite for this development is the availability of mass-production processes for (1) dense thin-film narrow-track head-arrays as discussed above, and (2) simple, low-power, multi-channel ICs.

The thin-film head and integrated channel technologies are ones in which the U.S. maintains a strong leadership. These provide a major opportunity for the U.S. storage industry to take the initiative to reenter the consumer market with native drive, head, channel, and tape component technologies, each of which has substantial technical and/or manufacturability advantages.

Author's VLBI-Related Work Background

Hans F. Hinteregger received B.A. and Ph.D. degrees in physics from MIT in 1964 and 1972 respectively and has been at Haystack Observatory since 1967 at the time of the first very long baseline interferometry (VLBI) experiments. He pioneered the geodetic/astrometric applications of VLBI by introducing means to accurately measure group delay (by coherently sampling a wide spanned bandwidth). Since 1975 his work within the Haystack VLBI Group has focused on the development of the extreme wideband digital tape systems required by VLBI. The latest version of this system (Mark IV) has demonstrated 1 Gb/s operation with sixty-four 16 Mb/s channels [using two headstacks of the author's 1985 design].