AZIMUTH AND INTERCHANNEL TIME DISPLACEMENT ERROR IN MULTI-TRACK MAGNETIC TAPE RECORDING

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Tape is often slit with a sinuous centerline ("country laning"). When this tape travels thru a transport, the recording on one track shows a varying time displacement with respect to that on another track. When the same signal is recorded on two tracks, and the reproduced signals are subsequently combined, the time displacement produces a "comb filter" frequency response. The output of a full-track head shows a response which is similar up to the first output null. This filter response is used here as a "slope detector" to measure the short-term time azimuth angle variations. Typical peak-to-peak azimuth angle variations are 600 microradians (0.03 degrees, or 2 minutes); this sets a limit to the interchannel time-displacement performance of recording systems, and to the accuracy of azimuth angle measurements.

1 INTRODUCTION

Mechanical imperfections in magnetic tape, and in the tape recorder heads and the transport cause varying high-frequency signal loss in a single-channel (mono) system, and time displacements between the signals recorded on different tracks of stereo or multi-channel systems. The variations may be seen both over a relatively short time (a number of seconds), and also over a relatively long time (a number of days or weeks). For unrelated signals in a stereo or multi-channel system, the time displacements are normally unimportant. But the same signal is sometimes recorded on two tracks, and the reproduced tracks are subsequently re-combined. In this case the time displacement modifies the frequency response, producing a "comb filter" which moves as the time displacement changes.

With a single channel (mono) system, the azimuth loss is measured using as test signal a sine wave, a swept frequency, or a random-noise signal—each has its own advantages and disadvantages. The readout method is to observe the loss of signal versus azimuth angle: zero angle gives maximum signal output. With a multi-channel system, the effect can be measured with any of the previously listed test signals. Readout methods include correlating the signals from the two channels to find the time displacement at which the correlation is maximum; or combining the two signals by either adding or subtracting them, and measuring the combination by listening, or looking at an oscilloscope or meter; or, for a periodic signal only, measuring the phase angle between the signals with an oscilloscope or a phase meter.

We will first look at the formulas for signal-level loss due to azimuth-angle loss in a single-channel (mono) system, and due to time-displacement in a two-channel system. Some numerical examples will be given. After a brief discussion of tape guiding principles, we will present data on the measured short-time azimuth angle variations on some common high-quality 6.3-mm wide mastering tapes, since the short-time errors limit the measurement of long-time errors, and also the performance of practical recording and reproducing systems.

2 AZIMUTH ANGLE ERROR CAUSES AMPLITUDE LOSS, TIME DISPLACEMENT, AND ELECTRICAL PHASE ANGLE BETWEEN CHANNELS

The azimuth was defined by Stryker [1] in 1930 for an optical (motion picture sound) system: "The azimuth is defined as the position of the axis of the image at the film plane with respect to a perpendicular to the direction of the film motion. When the image is correctly positioned the azimuth is zero." This also defines the azimuth in magnetic recording if we merely replace "axis of the image at the film plane" by "the locus of equal magnetization on the tape", and replace "film" by "tape".

An azimuth angle difference produces a frequency-dependent signal-level loss on a single-channel (mono) recording. The signal level loss L [dB] produced by azimuth angle error θ [rad] at frequency f [Hz], with track width w [m] at tape speed v [m/s] is given [1] by:

$$L = 20 \log \sin \pi x / \pi x, \qquad (1)$$

where $x = \theta wf/v$, and the table of sines is in radians.

By way of a practical example, Table 1 shows the signal loss vs azimuth angle for a 6.3-mm full-track recording.

Table 1:
SIGNAL LOSS L vs AZIMUTH ANGLE θ
FOR A 6.3-mm FULL-TRACK RECORDING

Azimuth angle θ at		Loss L at frequency of	
190 mm/s	380 mm/s	8. kHz	16. kHz
80 μrad	160 μrad	0.01 dB	0.03 dB
160 μrad	315 μrad	0.03 dB	0.10 dB
315 μrad	630 μrad	0.10 dB	0.40 dB
630 μrad	1250 μrad	0.40 dB	1.63 dB
1250 μrad	2500 μrad	1.63 dB	7.55 dB

On a multi-channel recording, there may be an inter-channel time displacement, and this time displacement produces a frequency-dependent signal level loss in the case when a signal is transmitted thru two or more channels which are then summed.

The interchannel time displacement may be caused by a *relative longitudinal mechanical* displacement (that is, down the length of the tape) d [m] between the gaps of the head cores for any two channels; this is called "gap scatter". This mechanical displacement will cause a corresponding time displacement T [s] between the reproduced signals:

$$T = d/v. \tag{2}$$

Even in a head with no gap scatter, an azimuth angle difference produces a longitudinal displacement between the tracks (in addition to the "azimuth loss" described above). Since this mechanical displacement is adjusted in a practical reproducer by the "azimuth" adjustment, it is more common to consider not the mechanical displacement itself, but rather an "effective azimuth angle" θ [rad] between the line determined by two specified recording gaps and the line of the corresponding two reproducing gaps. The longitudinal mechanical displacement d produced by this effective azimuth angle θ between tracks whose centerlines are displaced by c [m] is:

$$d = c \tan\theta. \tag{3}$$

Thus the azimuth angle error θ produces a time displacement T between channels at a tape speed v [m/s] of:

$$T = (c/v) \tan\theta \tag{4}$$

where the table of tangents is in radians.

When two equal-amplitude signals with a time displacement T between them are added, the loss of signal level relative to the addition with no time displacement is given [2] by:

$$L = 20 \log \cos \pi f T, \tag{5}$$

$$= 20 \log \cos[(\pi f c/v) \tan\theta], \tag{6}$$

where f is the signal frequency [Hz].

The time displacement between signals reproduced from two tape channels which is discussed above may also be thought of as an electrical phase angle between the signals. But the constant time displacement corresponds to an electrical phase angle which increases proportionally to the signal frequency. Thus, whereas the specification of time displacement by itself is meaningful, the specification of electrical phase angle alone is meaningless: the freqeuency must always be specified.

The electrical phase angle γ [rad] at frequency f [Hz] may be calculated from the following *formulas*:

$$\gamma = 2\pi f T, \tag{7}$$
$$= (2\pi f c/v) \tan\theta. \tag{8}$$

By way of a practical example, Table 2 shows the time displacement, electrical phase angle, and signal loss for a two-track stereo system.

Table 2: TIME DISPLACEMENT, ELECTRICAL PHASE ANGLE, AND SIGNAL LOSS
vs AZIMUTH ANGLE FOR A TWO-TRACK STEREO RECORDING ON 6.3-mm WIDTH TAPE

Azimuth angle at		Time	At frequency of 8 kHz		At frequency of 16 kHz	
190 mm/s	380 mm/s	Displacement	Loss	Elect. Phase Angle	Loss	Elect. Phase Angle
80 μrad	160 μrad	1.7 μs	0.01 dB	5°	0.03 dB	10°
160 μrad	315 μrad	3.4 μs	0.03 dB	10°	0.12 dB	19°
315 μrad	630 μrad	6.6 μs	0.12 dB	19°	0.5 dB	38°
630 μrad	1250 μrad	13.3 μs	0.5 dB	38°	2.1 dB	76°
1250 μrad	2500 μrad	26.3 μs	2.1 dB	76°	12.2 dB	151°

NOTE: *Track centerline distance c = 4 mm.*

3 TAPE GUIDANCE PRINCIPLES

The general principles of tape guiding are the same as those of web guiding in the paper industry which are given by Pfeiffer [3]. We refer you to that paper for general details, and discuss here only problems peculiar to tape and tape transports.

All discussions of tape guiding and azimuth angle are based on a model of the tape and transport in which the following conditions apply: the tape is a part of a plane, with straight and parallel edges; and the tape is transported on a system in which all rotating elements have parallel axes, elements contacting the tape are parallel to those axes, and any guiding elements that touch the tape edges lie along a straight line in the plane of the tape edges as the tape is wound on the supply side.

Practical tapes and transports are of course not ideal. In order to make the system work, an "azimuth adjustment" is usually provided on the head mount, so that the azimuth angle can be set to zero for some particular test condition. But then we find in practice that the azimuth angle changes from zero to some more or less greater angle, both over a short time (a matter of seconds), and over a long time (a matter of days or weeks). The short-time changes are comparatively easy to measure; measurements and conclusions will be presented below.

Long-time changes are much more difficult, because we find that the apparent azimuth may change for almost any change of the test conditions—for the same azimuth calibration tape used at a later time; for a different azimuth calibration tape; for a different tape tension; or for a different manufacturer of blank tape. Therefore, for the long-time changes of azimuth angle we need to make "absolute" measurements of azimuth angle, not just "relative" measurements. How? Direct measurement of all guiding surfaces would be facilitated by a transport with a reference plane on which all relevant surfaces were mounted, and were accessable to measurement. But in some studio recorder transports the reference plane is not a plane, but is curved due for instance due to the weight of components mounted on it; in others the reference plane is (or is on) the <u>bottom</u> of the mounting plate, not the top; and in most studio transports the top of the transport is covered by an ornamental cover plate which is not a plane, nor is it parallel to the reference plane. Furthermore, many of the essential surfaces of the tape guiding elements are partially obscured—rollers and guides have flanges, heads have shields, etc. So the problem becomes one of measuring without a reference plane, or of gaining access to the relevant surfaces, or both.

One way to measure parallelism between surfaces (guide posts and rollers, head faces, capstan shaft, etc.) is to use a "machinist's parallel bar" of the appropriate width and length (these bars are manufactured in many sizes by Brown and Sharpe, and others). Press the bar by hand against two surfaces to be measured, then try to "rock" it. If the surfaces are parallel, you cannot rock the bar; if you can rock the bar, the surfaces are not parallel, and require adjustment to make them parallel. (I believe I first learned of this method from MCI.)

Another method of testing the guiding requires removing <u>all</u> tape guides (unfortunately this is not possible on some tape transports). The tape will then travel from the feed reel perpendicular to the capstan [3]. Adjustments must be made either to all of the edge guides so that they agree with this tape position, or to the capstan shaft so that the tape is at the guide position. This test should first be made with a medium holdback tension and the least possible takeup tension. If the surfaces that the tape contacts <u>before</u> the capstan are parallel, increasing or decreasing the holdback tension will not change the tape height. Then after this alignment is properly set, increase the takeup tension. If the surfaces <u>after</u> the capstan are parallel, changing the tension will not change the tape height. When this condition is fulfilled, the elements are aligned mechanically, and the guides can be put back.

One might well ask "What good <u>are</u> the guides, if they must be taken out to align the guiding?" Their main purpose is to help the machine operator to thread the tape! Secondarily, if the tape is properly guided to begin with, then a guide can apply the very-small force needed to hold the tape in place against the misguiding force of sinuous slitting of the tape. But if guides apply appreciable force to the tape edge, they will either fold the tape edge (the flanges on roller guides are especially able to do this), or else cause the tape to "wrinkle" out of its normal plane. In fact, wrinkles and folded edges are the sign of extreme guidance problems.

The reference direction for the azimuth given above was the "direction of [tape] motion". The reference direction is sometimes alternately defined as the centerline of the tape, or as the (reference) edge of the tape. If the tape and transport conform to the "ideal" model given above, the edge, the centerline, and the direction of motion are always parallel, so the azimuth angle can be referred to any of these lines. But in practical systems there are mechanical imperfections. We may argue differences between edge, centerline, and direction of motion, but I do not know how to measure the difference, nor what the quantitative differences are. Therefore the question of the definition of the reference direction seems academic.

We have tried to measure the long-time azimuth angle variations, but we find that the same factors that cause the short-time variations (as discussed below) seem to cause long-term variations—so the short-time variation problem must first be attacked.

4 MEASURING THE SHORT-TIME VARIATIONS IN AZIMUTH ANGLE

Short-time variations in the azimuth angle can be measured in several ways. One simple way is to record a medium-wavelength signal (to minimize dropout problems inherent at short wavelengths), and intentionally offset the reproducing head azimuth to get a level loss of about 10 dB from either a single (mono) head, or the sum of two (stereo) heads. In either case, the loss function given in (1) or (6) results in an angle-to-loss conversion, analogous to a "slope detector". We have here used a full-track head, and offset the azimuth angle for a 10 dB loss of a 1700 Hz signal at a tape speed of 380 mm/s, with a 6.25 mm track width. (MRL also uses a similar set of conditions in a "difference method" azimuth adjustment tape). Under this condition, the calculated mechanical azimuth angle difference between recording and reproducing is 26 milliradians (1.5 degrees), and the slope of the level change per unit azimuth angle change is 1044 dB/rad. Thus if we plot the reproduced level versus time as the tape travels thru the transport, the level variations are a direct measure of the effective short-time azimuth angle variation due to the combination of tape and transport. A 1 dB level change corresponds to a 833 µrad azimuth angle change.

In this experiment, a number of rolls of professional mastering tape of 6.3 mm width were measured. These were tapes commonly available in the USA: Ampex 456, Agfa PEM 468, and 3M "Scotch" 250.* They were random samples from our stockroom: they were not in any way selected, but they do seem to be typical of the tape manufacturers' production. Two tape transports were used: One was a stock MCI Model JH 110A-1, whose tape path is shown in Fig. 1(a). The other was a special transport used by MRL for making calibration tapes and "difference-method" azimuth tapes; it is an Ampex Model 300, with an MRL-designed multiple edge-loading guide, as shown in Fig. 1 (b).

We first measured the Ampex 456 on the MCI transport: Fig. 2 (a) shows the level variations for simultaneously recording and reproducing. The peak-to-peak level variation ΔL was 0.6 dB, corresponding to a peak-to-peak angle shift $\Delta\theta$ of 500 µrad. Next this recording was rewound and reproduced again, Fig. 2 (b). Now ΔL was 1.2 dB, for $\Delta\theta$ of 1000 µrad. We again rewound and reproduced this same recording, Fig. 2 (c), and so on thru Fig. 2 (e). The patterns from different reproductions of the same recording are usually random, but show some coherence in some places. This indicates that the motion over the recording and reproducing heads is somewhat coherent during a given pass, but rather random from pass to pass. We have no theory to explain this. It does, however, agree with the fact that the angle shift for separate reproduction is about twice that for simultaneous recording and reproduction. The guiding on the MCI transport [Fig. 1 (a)] would allow $\Delta\theta$ to be 800 µrad, which agrees fairly well with the measured 500 µrad to 1000 µrad for the two level-variation measurements.

This same experiment was repeated using the same roll of tape on the MRL-modified transport. This transport uses 4 edge-loading guides, one on each side of each of the three heads, as shown in Fig. 1 (b), so that—in principle—the tape is held in a straight line as it passes over the heads. The data of Fig. 2 (f) and (g) were obtained for simultaneous recording and reproducing, and separate reproducing, respectively. Here ΔL is less than 0.1 dB, for $\Delta\theta$ less than 80 µrad, for both (g) and (g). This suggests two possibilities: 1) that the tape is slit straight, and that the azimuth angle variation is due entirely to some defect in the MCI transport; or (2) that the tape centerline is sinuous, but the edge-loading guides are working as hoped for, and holding the tape in a straight line. When this recording was reproduced on the MCI transport, as shown in Fig. 2 (h)...(j), ΔL was 0.8 dB, for $\Delta\theta$ of 660 µrad, which is about half the value for

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* DISCLAIMER: The tapes and transports are identified for the reader's information so that he can verify the measurements for himself. The tests here are to demonstrate general principles and practical problems of tape guiding and sources of azimuth-angle variations: they are not complete evaluations of the tapes and transports, and therefore must not be taken as general recommendations or criticisms by MRL of any of the products mentioned. Tape slitting is important, but only one factor in judging a tape; similarly, transport guiding. Complete evaluation requires judging many other properties of a tape or transport.

separately recording and reproducing on this transport. This would be consistent with either of the hypotheses above.

Several different rolls of the Ampex 456 were next measured; the level changes were all similar, altho the periods of the changes were sometimes different [Fig. 2 (k)...(n)]. Several rolls of 3M 250 were measured; the level changes were again similar, with periods in the same range [Fig. 2 (o)...(r)]. From this data, one would be tempted to conclude that, since all of the tapes would not likely be sinuously slit, the tapes must have all been slit straight, and the observed azimuth angle variation must be caused by the MCI transport.

But then we measured the Agfa PEM 468 on the MCI transport, with the results shown in Fig. 2 (s) and (t), for the same test conditions as above. These measurements show very small azimuth variations (less than 80 μrad) for simultaneous recording and reproducing, or separate reproducing. The test was repeated on about 25 different rolls of this tape, with the same results for all rolls. Thus it appears that the Agfa PEM 468 tape is slit straight, and nothing is "wrong" with the MCI transport except that the other tapes are slit sinuously, and the MCI guiding allows those tapes to move within its guides.

Could there be some other explanation? Suppose there were a difference in width: a wider tape might guide better in a given width of guide. But no—a number of samples of all three kinds of the tapes was measured using a microscope with a micrometer stage, and all of the tapes showed the same width down their lengths in several places, and that width was always in the range of 6.25 mm to 6.27 mm. Compared to the MCI guide width of 6.38 mm, this would not make a significant difference.

From this, we conclude that the angle variations seen for the Ampex 456 and 3M 250 tapes are the result of slitting which produces a sinuous centerline. The basic period for the Ampex 456 [from Fig. 2 (i)] seems to correspond to a length of 0.8 seconds at 380 mm/s, or 300 mm; this corresponds to a 100 mm diameter cutting blade, which I believe is in the range of typically used slitter blades. Other lengths are seen in Fig. 2, but we have no explanation for them—they may be "beat" patterns, or they may even be random variations. The amplitude of the angle change seems to be "peak limited", and corresponds to the angular variation that the guides on this MCI transport would allow with this tape width.

The elegant solution to this tape slitting problem would be to use only tape which is slit straight. In practice we (and you!) don't have that luxury, since we must use more than one kind of commercially-available tape. Therefore we need to minimize the angular changes due to the sinuous slitting. The multiple edge-loading guides of the MRL-modified head assembly hold the tape into a straight line, despite the sinuous slitting. (These guides probably cause scrape flutter, however, and may not be desirable on a studio recorder.) Changing the MCI guides to a "tight fit" (say 6.28 mm width) might reduce the angular variations, if one were willing to accept the chance of the tape's jamming in the guides. It is likely, however, that one would need to add several more guides between the heads, in order to have several guides per half-wavelength; since the length of the slitting wave is about 300 mm, the half-wave is 150 mm, and guides should be perhaps about 50- to 60-mm apart, as on the MRL-modified head assembly. This is an experiment we plan to do, in order to be able to use the MCI transport with sinuously-slit tapes.

There are actually clues to tape slitting that can be seen without even recording on the tape: namely, the way a tape "fast winds", and the way the face of a "pancake" of tape looks as received from the manufacturer. Almost all tape packs wound at slow speed have a smooth face; but when they are fast wound, the tape which is straight-slit shows a very-nearly smooth face on the tape pack, whereas the sinuously-slit tape shows "ridges", and even single turns thrown up from the face. This is a test you can easily perform on any roll of tape. Different studio recorders wind differently—some "fast wind" at a medium speed, and generally produce good-looking tape packs. Others wind very fast, and generally produce poor-looking tape packs. But the differences between straight-slit and sinuously-slit tape will still be visible on any given transport. Since the tape manufacturer usually winds the pancakes at a fairly high speed, these same qualities are also often visible on tape pancakes as received from the tape manufacturer: the sinuously-slit tape has an uneven looking face, while the straight-slit tape has a face of the pack that looks almost like a mirror. (Sometimes, however, if tape has been badly slit, a tape manufacturer may rewind it slowly to make the pancake look good—so watch out!)

At one time only German-made tapes were available with "back coating". We noticed how much better these tapes would fast wind, and assumed the secret was the back coating. Now we see that altho the back coating may help any tape to wind better, the real secret is in the slitting!

5 REFERENCES

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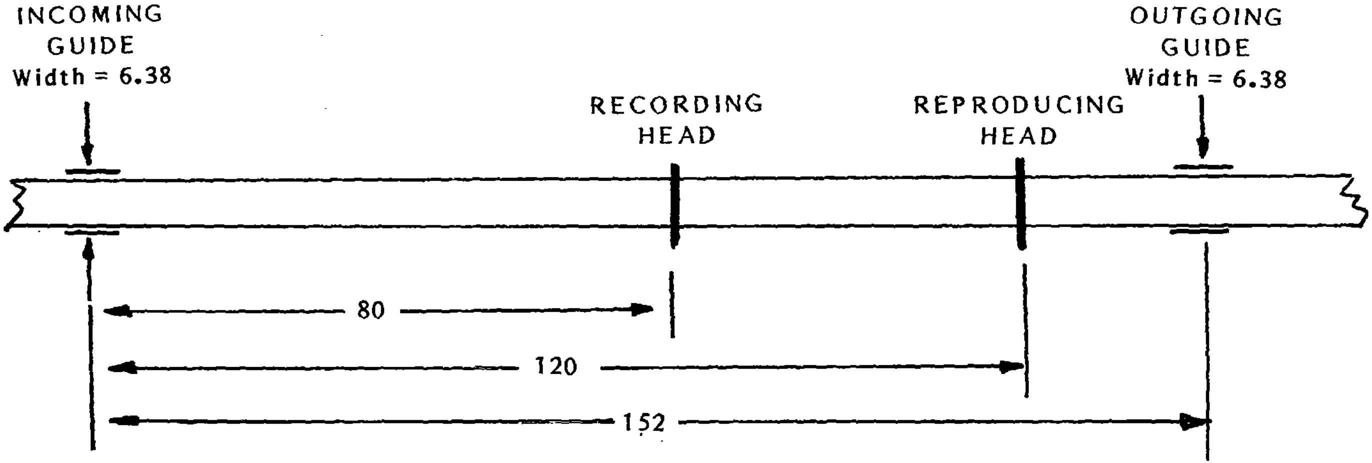
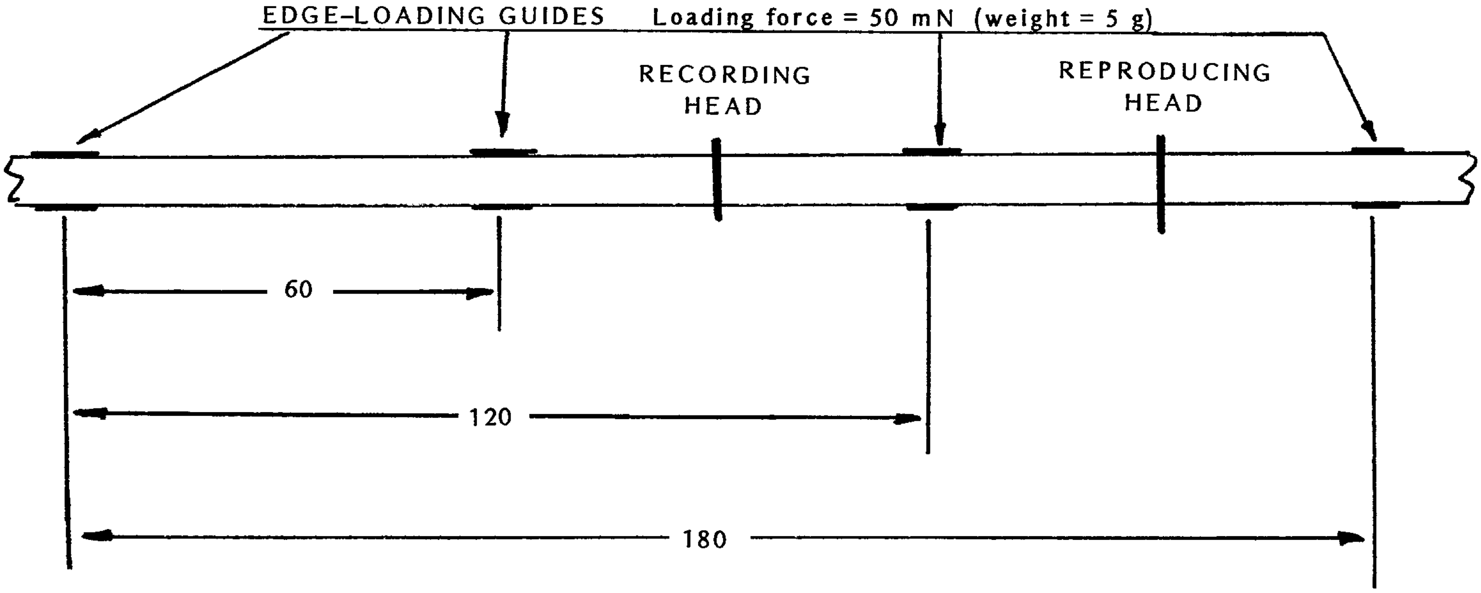


(a) Head assembly and guiding of the MCI JH-110A. Tape can shift by the angle due to the spacing between the tape (width 6.27 mm) and the guides (width 6.38 mm):
Peak-to-peak Angle = 2 arctan [(6.37 mm – 6.27 mm)/152 mm)] = 1320 microradians.



(b) Head assembly and guiding of the MRL special transports. The special edge-loading guides prevent angular motion of the tape. The guide width without tape is 6.22 mm.

Fig. 1 Guiding dimensions on the head assemblies used in these measurements of short-time azimuth angle variations. All dimensions in millimeters.

TAPE	TRANSPORT	TEST	Δθ/[µrad]
AMPEX 456 ROLL 1	MCI	a) Rec/rep	500
		b) Rew a), rep	1000
		c) Rew a), rep	
		d) Rew a), rep	
		e) Rew a), rep	
	MRL SPCL	f) Rec/rep	<80
		g) Rew f), rep	<80
	MCI	h) Rew f), rep	660
		i) Rew f), rep	
		j) Rew f), rep	
AMPEX 456 ROLL 3	MCI	k) Rec/rep	160
		l) Rew k), rep	1000
		m) Rew k), rep	
		n) Rew k), rep	
3M 250 ROLL 7	MCI	o) Rec/rep	160
		p) Rew o), rep	1000
		q) Rew o), rep	
		r) Rew o), rep	
AGFA PEM468 ROLL 21	MCI	s) Rec/rep	<80
		t) Rew s), rep	<80

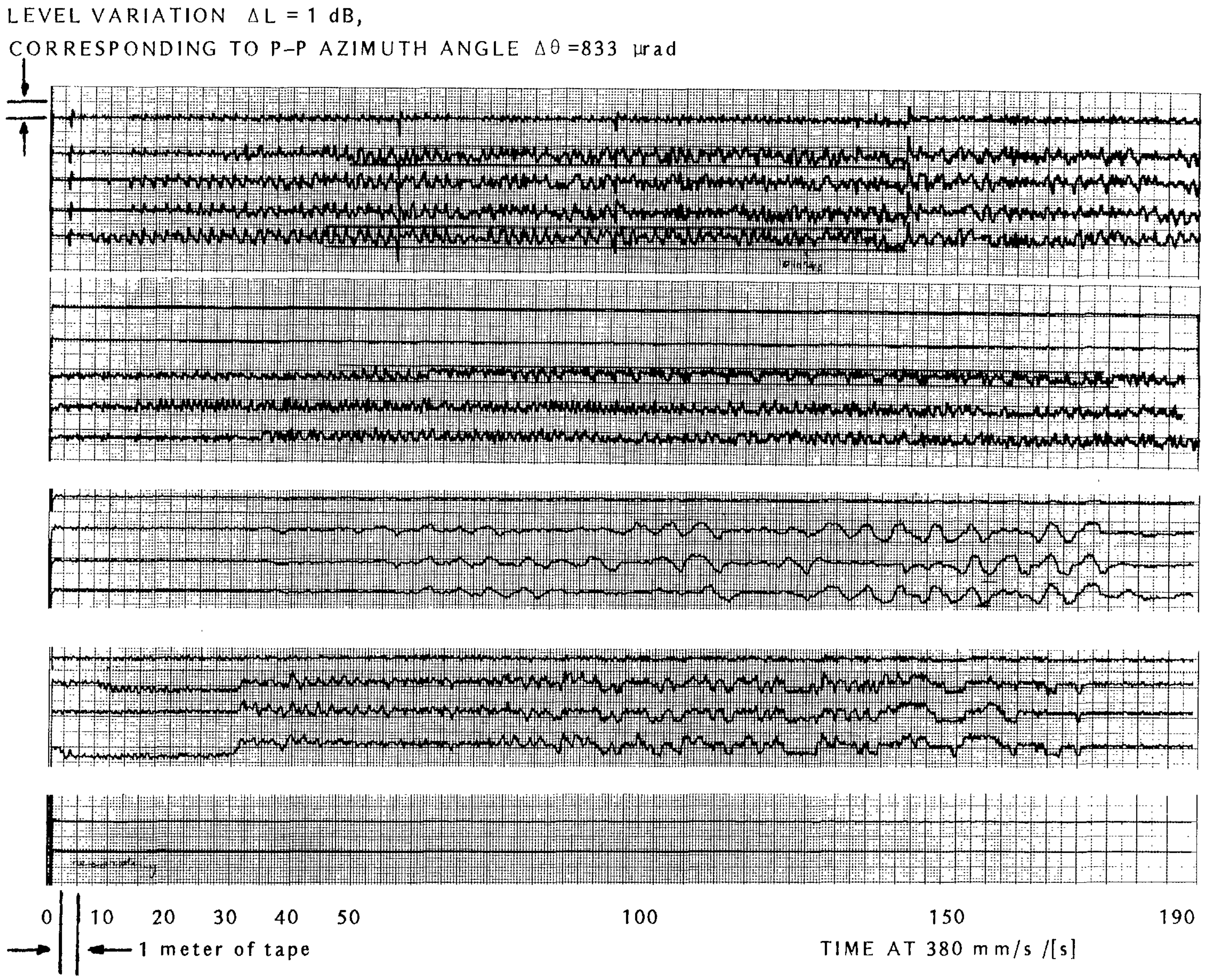


Fig. 1 Level variations, corresponding to azimuth angle variations, versus time, for several tapes and test conditions.
Rec/rep = reproduce while recording. Rew a), rep = rewind the recording of a) and reproduce it again.