VLBA ACQUISITION MEMO #273

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Subject: Magnetic Tape "Flying" Measurements vs. Model

1. Motivation

Haystack Observatory records signals received from astronomical objects on magnetic tape. It is currently desired to increase the amount of data recorded on the tape per unit time, but the density at which data is stored on the tape is already at the maximum possible, and the cost of adding extra recording equipment - so as to record data on additional tapes simultaneously - is prohibitive. A remaining strategy is to increase the speed at which the tape moves through the recorder, thereby increasing the tape-length available per unit time.

A problem with this strategy is that as the tape's speed increases, the tape tends to drag increasing amounts of air into the space between the tape and the recording head (see Figure 1) so that the tape begins to separate from, or "fly" over, the head. The strength of the signal received by the tape from the head, or by the head from the tape, diminishes in strength very rapidly with distance. Actual magnetization recorded is a nonlinear process and the record loss varies from 25 to 55 *dB* per wavelength, while the playback loss is always 55 *dB* per wavelength. A signal degradation of more than just 2 or 3 *dB* reduces the signal-to-noise ratio to unacceptable levels. At the data wavelengths typically used on the tape, 2 or 3 *dB* corresponds to a flying height on the order of tens of nanometers, a fraction of the wavelength of visible light, so it does not take much flying to cause significant signal degradation.

Rather than just "tinkering" with the equipment to try to solve the problem empirically, it was decided to develop a fluid mechanics model which predicts flying height as a function of tape velocity, tape tension, head geometry, and other relevant parameters. This model could then be used to identify acceptable operating regimes, to predict potential problems, and to serve as a tool for analyzing future problems as they arise.

The measurements described in this paper were made to test the predictions of this model, and to provide empirically-derived insights into factors affecting flying height.

2. Measurement Methodology

The flying height was measured from the signal loss observed in the playback of a short wavelength recording. A one micron wavelength recording was made on Sony D1K tape using a 2 *MHz* square wave and 80 IPS tape speed. This recording was then played back at 80, 160, and

320 IPS (at 2, 4, and 8 *MHz*) for a range of vacuum settings from 4" to 14". The playback signal strength was measured using a signal analyzer.

Because tracking shifts were observed, the signal strength recorded was always the maximum seen while scanning the headstack position to search for a peak. This scanning was done at the beginning of the tape run and after every change in tape direction for the measurements done with headstack A-26. For measurements done with the other headstacks, this scanning was done prior to each individual measurement.

The relative signal strength was converted to a flying height (see Figure 2) using the following assumptions:

1) The maximum signal observed at a particular speed over the range of vacuum settings was assumed to correspond to zero flying height.

2) The flying height was calculated assuming a spacing loss of 55 *dB*/wavelength (i.e. for the 1 micron wavelength of the recorded signal, a 5.5 *dB* signal loss corresponds to a flying height of 0.1 microns).

No attempt was made to perform any absolute calibration of signal levels owing to the complexity of such a task.

3. Chronology of Measurements

1. Tested head A-26 in the upper position, varying tension from 4" to 10" of vacuum.

2. Tested head A-26 in the upper position, varying tension from 4" to 14" of vacuum, at 320 IPS only.

3. Tested head A-26 in the lower position, varying tension from 4" to 14".

4. Repeated part 2, above, to test reproducibility.

5. Tested head A-26 in upper position at 320 IPS at various head contours, varying tension from 4" to 14".

6. Tested head D-10 in upper position, varying tension from 4" to 14".

7. Tested head D-10 in upper position at 320 IPS at various head contours, varying tension from 4" to 14".

8. Tested head D-95 in upper position at 320 IPS with aperture angle of 5 degrees, varying tension from 5" to 12" (measurements made by Alan Rogers).

9. Tested head D-95 in upper position with 7" contour and aperture angle of 15 degrees, varying tension from 4" to 14".

10. Tested head D-95 in upper position with 10" contour and aperture angle of 15 degrees, varying tension from 4" to 14".

11. Repeated part 6, above, using new capstan to reduce slippage.

Notes:

A) Unless otherwise noted, the following held for each test:

a) Tape tension was varied from 4" to 14" of vacuum (exceptions: parts 1,8).
b) Head was in upper position (exception: part 3).
c) Aperture angle was 5 degrees (exceptions: parts 9,10).
d) Contouring tension was 10" (exceptions: parts 5,7,9).
e) Tests were done at 80, 160, and 320 IPS (exceptions: parts 2,4,5,7,8).
f) Measurements were made by Jonathan Starr (exception: part 8).

B) The head tracking position of maximum signal strength was determined at the beginning of a tape run, and each time the tape direction was changed. Beginning with part 9, the position of maximum signal strength was determined for each individual measurement.

4. Empirical Comparisons: Upper vs. Lower Position Forward vs. Reverse Tape Directions

1) Upper vs. Lower Positions (Headstack A-26 only)

A) Forward tape direction:

a) 80 IPS: Flying about the same for upper and lower head positions.
b) 160 IPS: More flying in upper position.
c) 320 IPS: More flying in lower position.

B) Reverse tape direction:

More flying in upper position at all 3 tape speeds.

2) Forward vs. Reverse Tape Directions

A) Upper head position:

More flying in Reverse tape direction at all speeds for all 4 headstacks tested

B) Lower head position:

More flying in Reverse tape direction at all speeds (only headstack A-26 was tested in lower position).

5. Flying Height as a Function of Tape Velocity and Tension

The model proposed in VLBA Acquisition Memo #264 predicts that, for a given head geometry and tape velocity, the relationship between flying height (h) and the ratio of tape velocity and tape tension (V/T) will be as shown schematically in Figure 3. There is initially a horizontal region in which there is no flying ($h=0$), followed by a linear region (h is proportional to $[V/T]$), followed by a parabolic region (h is proportional to $[V/T]^{1/2}$).

Once flying begins, the maximum possible flying height is set by the minimum of two independently determined values: 1) the size of the initial gap between the tape and the edge of the top of the head, and 2) the maximum value h can have given the load being supported by the air film of thickness h. In the linear region, the smaller value is the gap size, which is proportional to $[V/T]$. In the parabolic region, the limiting value is the maximum h for the supported load, and that h-value is proportional to $[V/T]^{1/2}$.

The plots of the measurements (see Figure 4) appear to confirm the general predicted shape. For example, the curves for headstack D-95 contoured at 7" of vacuum (third pair of graphs down) appear to have all three predicted regions. The graphs for headstack A-26 (uppermost pair) appear to have the horizontal and linear regions, and presumably if measurements were made at higher values of $[V/T]$ the parabolic region would begin to appear. On the other hand, the curves for headstack D-10 (second down) at 160 IPS and 320 IPS appear to be entirely in the parabolic region. Presumably if measurements were made at lower values of $[V/T]$, the linear and horizontal regions would appear.

This raises the point that the lowest flying height measured for each curve was arbitrarily set to be $h=0$. There can be confidence in this assumption when there is a horizontal region in the curve. However, for curves such as those for headstack D-10 in which no horizontal region appears, this assumption is probably not valid. Such curves should probably be shifted upward by some amount since there is probably some flying occurring at even the lowest $[V/T]$ value on these curves.

Further research is needed to compare particular values of h predicted by the model with those measured (as opposed to comparing just the shapes of the curves).

6. Flying Height as a Function of Head Geometry Parameters

The model proposed in VLBA Acquisition Memo #264 predicts certain relationships between flying height (h) and certain parameters characterizing the head geometry (see Figure 1), particularly head-step width (L), "aperture" angle (ϕ), and the specific tape tension (C) at which the head was contoured.

Referring to Figure 3, the model predicts that the range of $[V/T]$ values over which the horizontal ($h=0$) region extends increases with decreasing L, decreasing C, and increasing ϕ. In the linear region, the slope of h vs. $[V/T]$ is predicted to be proportional to $L([a/\phi^{1/2}] + [b(C-T)])$, where a and b are constants. In the parabolic region, h is predicted to be proportional to L (i.e. h is proportional to $L\,[V/T]^{1/2}$). Summing this up in broad terms, in the non-horizontal regions, h is predicted to be roughly directly proportional to L.

The plots of the measurements in Figure 4 (note the parameter values listed to the right of the pair of graphs to which they apply) appear to confirm these predictions. Keeping in mind that the curves plotted for headstack D-10 (second pair down) should probably be shifted upward (as explained in the previous section), the curves show a clear direct proportionality between h and L. Referring to the graph in the lower right corner, and considering again that the curve for $\phi = 5$ degrees should probably be shifted upward, there appears to be an inverse proportionality between h and ϕ.

The model predicts that the length of the horizontal ($h=0$) region is inversely proportional to C, and that the slope of the linear region increases with increasing C. The graphs for D-95 at two different head contours (third and fourth pairs of graphs in Figure 4) show weak support for these predictions. Perhaps a larger differential in head contouring tensions will be needed to test the prediction more stringently.

The measurements in parts 5 and 7 of variation with head contour of heads A-26 and D-10 were made by contouring the heads with a separate "lapping" tape at 80 IPS. In contrast, the contouring of head D-95 was done by shuttling the Sony D1K tape (the one on which the signal was recorded) overnight at 80 IPS and at the desired contouring tape tension. The method for heads A-26 and D-10 was flawed because initially we did not realize that the abrasive contouring shape was 13 microns thick instead of 16 microns. Consequently, the results of parts 5 and 7 are not included in Figure 4. The graphs in Figure 4 are for heads with known contours.

7. Effects of Capstan Characteristics and of Ambient Humidity

While testing headstack D-10 at 320 IPS (in part 6 of the Chronology of Measurements), the signal was "lost" (i.e. became indistinguishable from noise) at tensions below 10". At first, this was attributed to a large increase in flying height.

However, while taking measurements in part 7 of the Chronology, the signal was suddenly lost again in the middle of a measurement shortly after the janitor had begun mopping the floor near the recorder. The signal could be retrieved at 80 and 160 IPS, but not at 320 IPS except at high tension values.

It was determined that the tape was actually slipping over the capstan of the tape-drive mechanism. Increased humidity may have lubricated the capstan, or increased drag on the tape where the tape touched the head or surfaces of the recorder.

The capstan was replaced by a newer, rougher capstan. The signal was not lost again, although no mopping occurred near the recording during subsequent tests.

Clearly attention needs to be given to the surface/slip characteristics of the capstan and how they are affected by wear, aging, and ambient humidity. Also the effects of humidity on capstan slippage, on drag on the tape, and on flying height should also be tested.

8. Possible Operating Points

In Figure 4, a dashed horizontal line has been drawn on each graph at about $h=0.04$ microns, the flying height corresponding to about 2.2 *dB* signal-strength degradation, which is about the maximum allowable. Points below the dashed line appear to constitute acceptable operating points subject to some important conditions:

1) As mentioned earlier, the smallest flying height measured for each curve was arbitrarily assigned the absolute flying height value of zero. There can be confidence in this assignment when there is a horizontal portion of the curve. However, some of the curves in Figure 4, - particularly those for head D-10 at 160 and 320 IPS, and those for head D-95 at aperture angle of 5 degrees - do not have horizontal portions. These curves should probably be shifted upward, since smaller values of h would probably be found for measurements taken at lower values of $[V/T]$. Therefore, these curves as currently shown probably have no acceptable operating points.

2) Since tapes may be run in both forward and reverse directions, it should be ascertained that a potential operating point is below the dashed line for both the forward and reverse direction graphs for a particular head configuration.

3) Only one point on each curve can be considered a "robust" operating point. As a tape moves over the head, it gradually wears the head into a contour

characteristic of the tension in the tape. Therefore, if a head has been contoured at one tension, but the tape is being run at a different tension, the tape will gradually change the contour of the head. For each curve in Figure 4, only one point corresponds to an operating tension which is equal to the tension at which the head was contoured. This is the "robust" point of the curve. Operating at any other tension will gradually change the contour of the head. After a while, the indicated value for *C* would no longer be valid - the operating point would have "drifted" off of the curve. The "robust" point for each curve in Figure 4 has been marked with a large solid dot.

Figure 4 indicates that head A-26 with a headstep width of 217 microns, a contouring tension of 10", and an aperture angle of 5 degrees has "robust" operating points at all three tape speeds in both tape directions. So does head D-95 with headstep width of 315 microns, contouring tension of 10", and aperture angle of 15 degrees.

As described elsewhere, the reliability of these operating points may be severely affected by such factors as surface/slip characteristics of the tape-drive's capstan, and by ambient humidity. More testing is needed to assure the reliability of these operating points under a variety of operating conditions.

9. Future Research

1. Testing the robustness of possible operating points.

2. Further testing of the variation of flying height with head contour.

3. Comparing specific values of flying height predicted by the model with those actually measured (as opposed to just comparing the shapes of the curves).

4. Testing capstan surface/slip characteristics and their relationship to: tape speed, capstan wear and aging, ambient humidity.

5. Testing the effect of ambient humidity on flying height and on drag on the tape at points of contact of the tape with other surfaces.

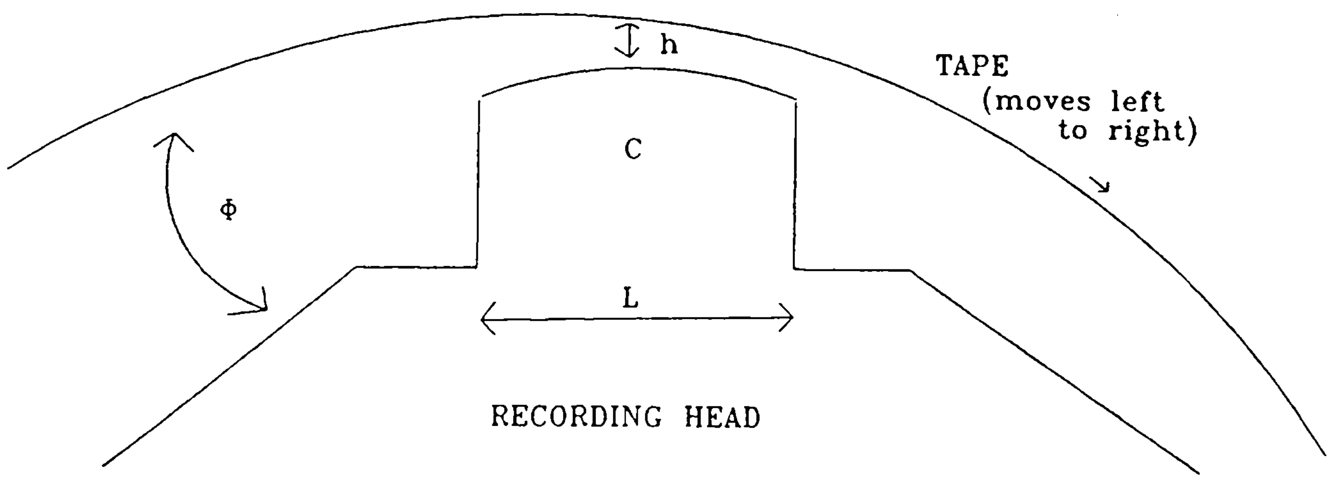
6. Testing novel head designs:

   a) Cutting channels in the head to allow air to flow through.
   b) Blocking air flow with the "Tri-Cap" head design.

Note: The model should set some limits on the range of parameter values to be tested, thereby reducing the number of experiments required.

Atch: Figures 1-4

Close-up View of Tape/Head Interface



h = Flying Height

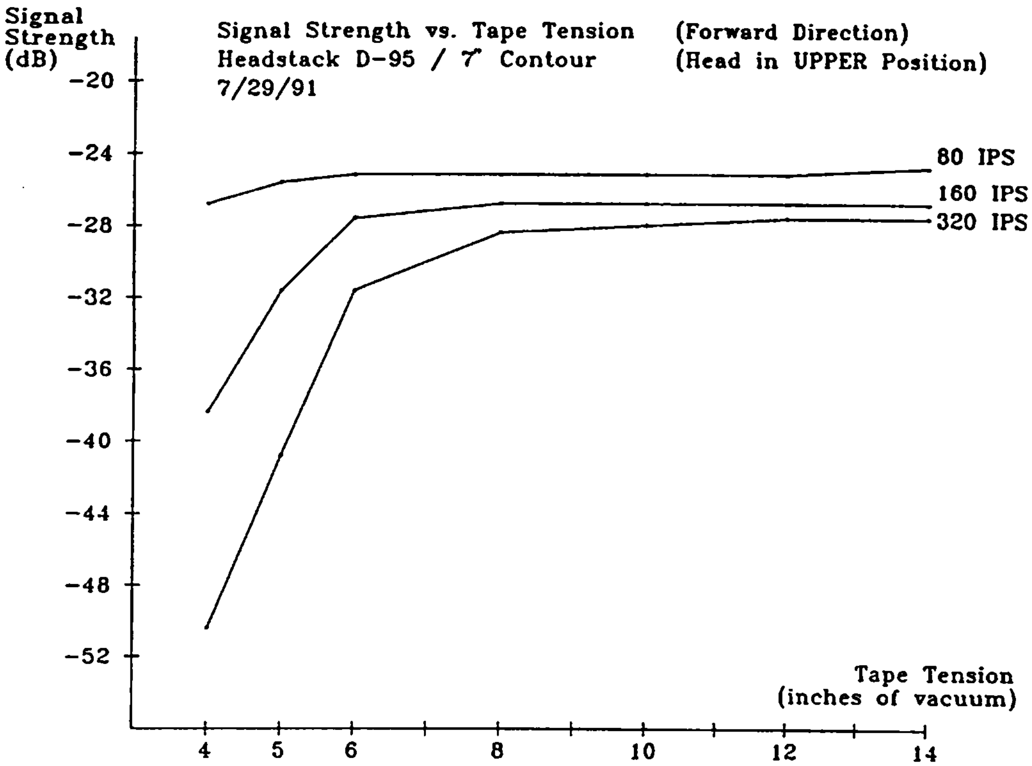
Head Geometry Parameters: L = Headstep Width*
C = Tension at which Head was Contoured
Φ = Aperture Angle

Tape Parameters: V = Tape Velocity
T = Tape Tension

*Important: In VLBA Acquisition Memo #264, L = HALF Headstep Width

Figure 1

Equivalent Data-Plots



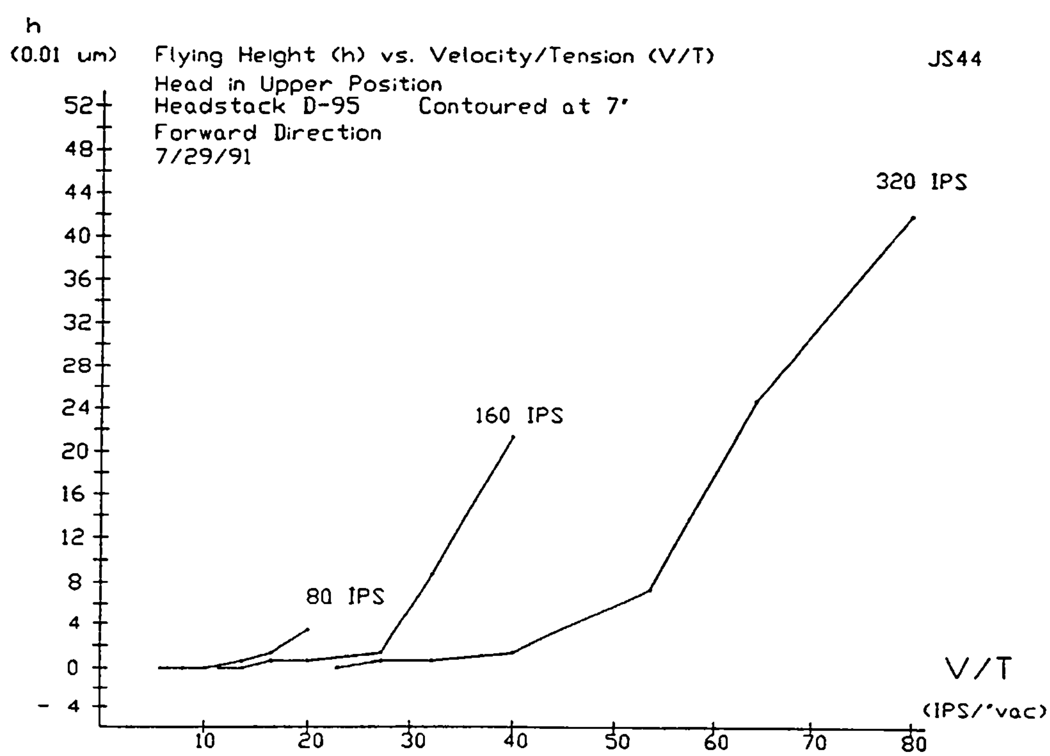
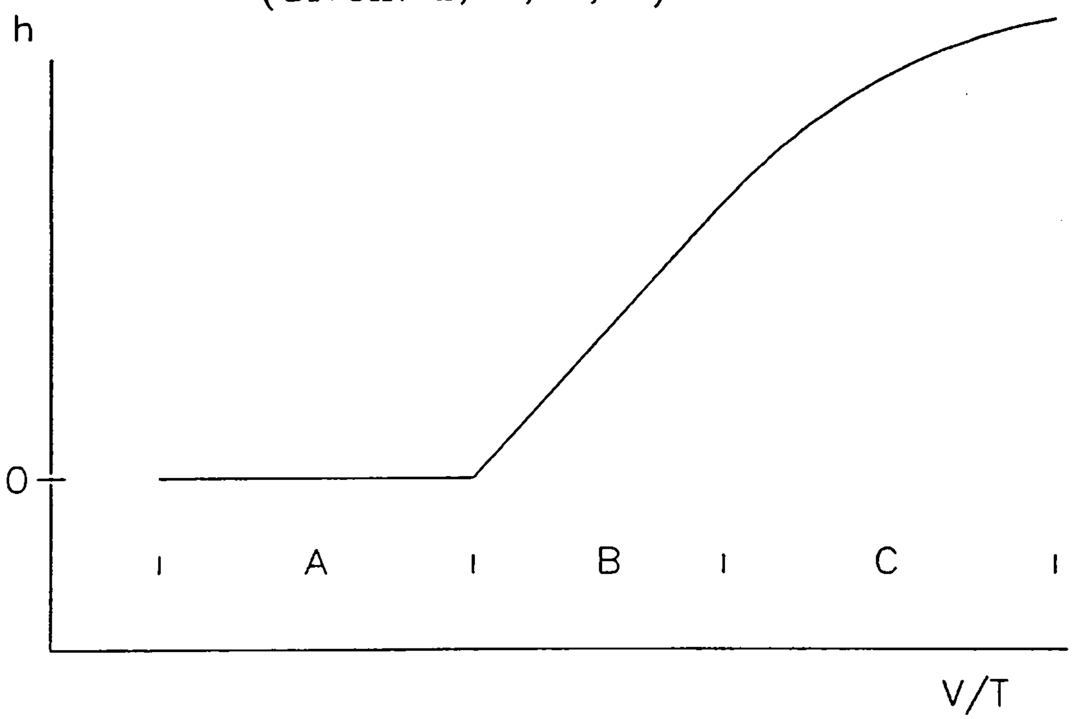


Figure 2

Predicted Shape of h vs. (V/T)

(Given: L, Φ, C, V)



Region A:	$h = 0$		No flying
Region B:	$h \propto$	(V/T)	Linear
Region C:	$h \propto$	$(V/T)^{1/2}$	Parabolic

OTHER PREDICTED DEPENDENCIES:

Flying Threshold: $f(V, C, L, \Phi)$

Linear Region: slope $\propto L[(a/_{\phi}2) + b(C - T)]$

with a,b constants

Parabolic Region: $h \propto L$

Figure 3

Flying Height Measurements

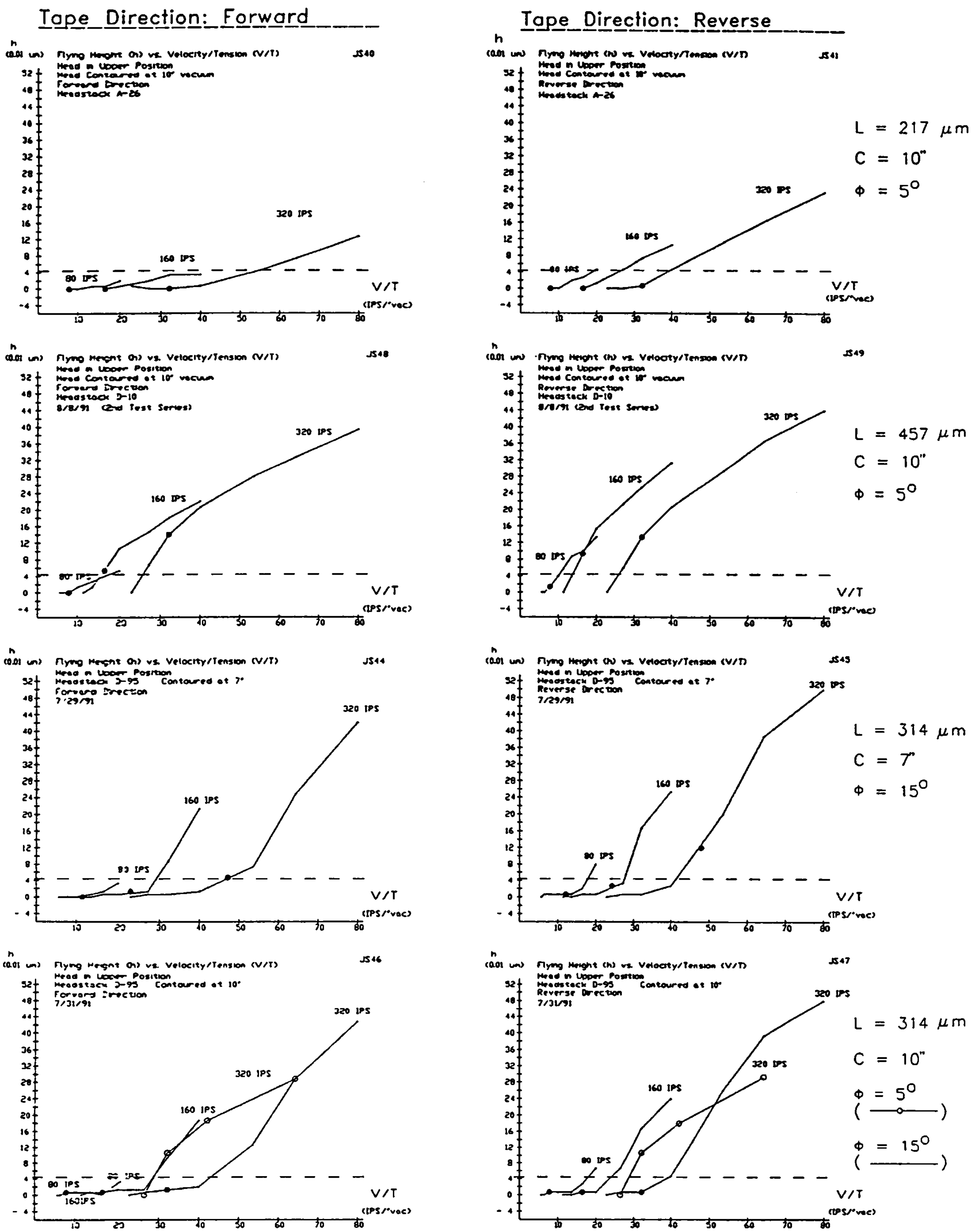


Figure 4