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SD Department of Transportation
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Investigation and Measurement of the Ride Quality of Flexible Pavements

Study SD92-12
Final Report

Prepared by
Austin Research Engineers, Inc.
2600 Dellana Lane
Austin, Texas 78746

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16. Abstract

This project developed a draft specification for asphalt concrete pavement construction smoothness testing. The South Dakota Road Profiler, smoothness measuring equipment already owned by SDDOT, was used as the testing device. Since the objective of this testing was to assure road smoothness, automated means were devised to find localized roughness, namely bumps and dips. The cornerstone to this method lie in this project's development of the telescoped rolling straightedge statistic.

An attempt was made to economically justify implementation of this specification. Based upon existing SDDOT road profile data, these results were obtained:

- SDDOT asphalt roads are already constructed very smoothly.
- Extremely smooth asphalt concrete roads lose their edge in smoothness within seven years of construction.

Nevertheless, the assumption of a 10% smoothness increase at construction was sufficient to justify specification implementation. Based on other state's experience, specification implementation does result in smoother constructed roads and increased contractor incentive and awareness in regard to this objective. With the implementation of this specification, SDDOT will be able to assess and improve the current level of smoothness attained at construction.

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SOUTH DAKOTA DOT RESEARCH PROJECT 92-12
"INVESTIGATION AND MEASUREMENT OF THE
RIDE QUALITY OF FLEXIBLE PAVEMENTS"

OCTIBER 30, 1993

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GLOSSARY OF TERMS AND ACRONYMS

Term/Acronym	Description
AASHTO	American Association of State Highway Transportation Officials.
AC	Asphalt concrete.
ADT	ADT is the average daily traffic count at one place on a road (across all lanes).
Blanking Band	A concept and device used in the calculation of PI (see Appendix F).
California Profilograph	A particular type and brand of profilograph. The California Profilograph is used by SDDOT.
DOT	Department of Transportation.
FHWA	Federal Highway Administration.
Histogram	A representation of a frequency distribution by means of rectangles whose widths represent class intervals and whose heights represent corresponding frequencies.
IRI	The International Roughness Index (IRI) is expressed in m/km in this report and is a roughness statistic initially developed for the World Bank and adjusted by the FHWA. An IRI < 2 is smooth; IRI > 5 is rough.
MVD	Maximum vertical displacement (MVD) is the component of the TRS statistic that is summed. It is defined in Figure 10 of this report.
NCHRP	National Cooperative Highway Research Program.
PCC	Portland Cement Concrete
PI	Profile Index (PI) is the statistic used to assess roughness using profilograph data (traces plotted on paper or their digital representation) as documented in the 1993 Annual Book of ASTM

Standards, Volume 4.03 "Road and Paving Materials; Paving Management Technologies Designation: E1274-88 (see Appendix F).

Profilograph	Any of a number of smoothness measuring devices as described and illustrated in Appendix F.
Profilograph Trace	The graphic output of the profilograph a sample of which can be found in Appendix F. It is a "sine"-like wave centered around a zero line.
PSI	The roughness statistic calculated by SDDOT and reported in its Highway Needs Report. It is on a 0-5 scale, where 0 is very rough and 5 is very smooth.
RMSVA	Root mean squared vertical acceleration (RMSVA) is a smoothness statistic which is the square root of the sum of the squares of second differences using a particular base length.
second difference	A second difference at point i with base length (feet) 2*j is: $\frac{elevation_{i-j} - 2 * elevation_{i} + elevation_{i+j}}{2 * j}$
Ride Number (RN)	A roughness statistic developed during NCHRP Research Project 1-23.
SDDOT	South Dakota Department of Transportation.
SD Profiler	The South Dakota Road Profiler roughness measuring device built and used by SDDOT.
TRS Statistic	The telescoped rolling straightedge (TRS) statistic is a smoothness statistic developed on this project specifically to aid in smoothness testing at construction.

It identifies the roughness/smoothness level at any point on the road very well, but is still very correlated to standard "long distance" roughness statistics such as IRI. In fact, with an R^2 of .985:

IRI (m/km) = 1.69 TRS statistic.

This equation can be used to get a feeling for "what is rough?" and "what is smooth?" when using this TRS statistic.

The TRS statistic is really a family of statistics each with a different base length. Unless otherwise identified, in this report a 10 ft. base length is used. A detailed definition of the TRS statistic is shown in Figure 6.

VOC

Vehicle operating costs (VOC) include all the costs of operating a vehicle including: maintenance, gas, oil, major repair, and depreciation.

INTRODUCTION

PROBLEM STATEMENT

This project will develop for the South Dakota Department of Transportation (SDDOT) an asphalt concrete (AC) pavement construction smoothness specification developed, together with the assurance that the implementation of this specification will result in economic benefit to the State of South Dakota and its constituency. The impetus for the investigation of this hypothesis is the feeling that roads once constructed smoother will consequently have a longer life, and if roadway life increases then the cost of reconstruction/rehabilitation will be incurred less frequently resulting in a savings to the taxpayer. In addition smoother roads cost the motoring public less for their individual vehicle operations.

The statement of the project impetus generates questions that also must be addressed in this project:

- *Will an AC pavement construction smoothness specification improve smoothness?*

- *Does improved smoothness at construction translate into longer life for the pavement?*

- *Finally, does the benefit derived from longer pavement life exceed the additional cost to the State generated by implementation of the specification in terms of cost of testing, potential increased cost of construction, and smoothness specification payments made by the State to the contractor?*

OBJECTIVES

There are three (3) primary objectives in this project:

1. To determine if a specification will improve pavement smoothness upon construction in South Dakota.
2. To determine if improved smoothness at construction generates economic benefit to the State of South Dakota.
3. To develop and submit a proposed South Dakota AC pavement smoothness construction specification and accompanying procedures, that will both improve pavement smoothness and generate economic benefit to the State.

There are additional technical objectives that will support these primary objectives. They are:

1. to help determine if an AC pavement construction smoothness specification will improve smoothness, this research will quantify:
   - other states' smoothness improvement experience when implementing such a specification, and
   - South Dakota's current AC smoothness experience at construction and comparing it against a reasonable target smoothness expectation,
2. to determine if improved smoothness generates economic benefit other technical objectives will be met, namely:
   - quantify how improved smoothness translates into longer pavement life, and
   - quantify how this longer life translates into dollars saved,

3. to accomplish technical objectives while developing a proposed AC pavement smoothness specification this project will:
   - select and justify one or more smoothness measuring devices to be used in the test procedure,
   - select and justify rideability index to be used in the testing procedure as well as the specification, and
   - determine and illustrate that the smoothness thresholds and penalty/bonus amounts in the specification will generate an economic benefit to the state when the specification is implemented.

EXECUTIVE SUMMARY

The goal of this project was to develop an asphalt concrete pavement construction smoothness specification and justify its implementation. The key questions to be answered during the course of this project were: "What is the structure of this specification?", and "Is it worth implementing it in the State of South Dakota?".

Specification Structure

The structure of the specification is largely determined by the smoothness device selected for testing, the smoothness statistic used, the level of bonuses and penalties set, and a determination of which agency will perform the testing. The South Dakota Road Profiler, a smoothness measurement instrument, created, owned, and used by SDDOT, was recommended as the most appropriate smoothness testing device. A statistic that can identify and locate bumps and dips in the road was devised on this project and used in the specification. Dollar penalty levels were set in the specification in order to induce contractors to retain the current smooth level of asphalt concrete pavement construction in South Dakota. Bonuses were excluded

from the specification. Based upon our review of state experience, implementation of a specification alone provided sufficient incentive to contractors to construct smooth pavements. As such, the addition of bonuses was considered cost ineffective.

In summary, the decisions reached as a result of this research are as follows.

Problem	Recommendation
Select a device	SD Profiler
Select a statistic	"Telescoped" rolling straightedge statistic
Set bonus and penalties	No bonuses, and penalties as a percentage deduct adjustment to the price of asphalt placement
Perform specification testing	Performed by SDDOT personnel using software developed on this project to calculate the statistic, graph the elevation and statistic traces, and indicate where on the road the smoothness is insufficient.

The form of the draft specification will be very much like existing specifications using profilographs. In place of the PI statistic, in the wording of the specification, a statistic developed on this project, the telescoped rolling straightedge statistic (TRS) will be substituted. For bumps, in place of the PI trace deviation distance, we will substitute the maximum vertical displacement (MVD) used in calculating the telescoped rolling straightedge statistic contribution at each point. In preparation for specification drafting, the current South Dakota construction smoothness specification as well as nine other state specifications were reviewed.

Specification Justification

An attempt was made to economically justify implementation of this specification. Based upon existing SDDOT road profile data, these results were obtained:

- SDDOT asphalt roads are already constructed very smoothly.
- Extremely smooth asphalt concrete roads lose their edge in smoothness within seven years of construction.

Nevertheless, specification implementation is justified based on conservative estimates, both for the annual mileage of road whose life would be increased due specification implementation, and smoothness improvement at construction also due specification implementation. Based on other states' experience, specification implementation does result in smoother constructed roads and increased contractor incentive and awareness in regard to this objective. With the implementation of this specification, SDDOT will be able to improve pavement life and assess & improve the current level of smoothness attained for AC pavements at construction.

DEVELOPMENT OF SPECIFICATION

The primary purpose of this project is to develop an asphalt concrete pavement construction smoothness specification and justify its implementation. This chapter documents the development of the specification. A method for specification justification and recommendations relative to specification implementation is presented in the subsequent chapter.

In order to develop this specification, several decisions were necessary, including: selection of a smoothness measuring device, selection of a smoothness statistic, setting of bonuses, penalties, and threshold levels, defining the precise content of the written specification, and defining a procedure for specification testing.

To facilitate this decision making process information from several sources was obtained. Fifteen State DOT's and the FHWA were contacted and queried about their current and proposed specifications. Literature and consultant experience with smoothness measuring devices was gathered and reviewed. Profilograph and SD Profiler data was obtained from SDDOT for roads just constructed and analyzed. Finally, documents defining smoothness statistics' calculation and/or their strengths and weaknesses were reviewed. What follows is documentation of this information gathering exercise and the consequent results with respect to specification development.

BACKGROUND INFORMATION OF STATES' EXPERIENCE

Fifteen State DOTs and the FHWA were contacted and queried about their asphalt concrete pavement construction smoothness specifications, both current and proposed. The purpose was to identify the current practice across several states, as well as, learn from their experience. Specifically, inquiries were made regarding:

- Quantitative measures to justify smoothness thresholds and/or penalties and bonuses
- The specifics of the current/proposed specifications
- The evaluation of costs and benefits by State personnel based upon implementation of these specifications

Based upon the discussions, no quantitative methodology was found to either justify a specification or set penalties or bonuses and their thresholds. At best, some testing of smoothness levels achieved by construction was done to set thresholds based upon preset notions of the percentage of roadway that should be in penalty or bonus situations. Some testing was also done in cases where one roughness device was superseded by another for specification application. This testing was done solely to correlate the roughness values of the two devices in order to make a smooth transition from one device to another.

Based upon the lack of quantitative information, the benefit of this survey came from an identification of the trends in current specifications and assessment of the experience gained from implementing these specifications as communicated to us by State DOT personnel. These trends are summarized in Figures 1 and 2.

The following states were contacted and queried about their specification: Iowa, Georgia, North Dakota, Kansas, Wisconsin, Illinois, Nebraska, Wisconsin, Maryland, Idaho, Texas, Ohio, Florida, Minnesota, Virginia, Georgia, and the FHWA Denver Region. Of these agencies, written copies of current/proposed

FIGURE 1. AC CONSTRUCTION SMOOTHNESS SPECIFICATION STATE SURVEY SYNOPSIS

	Smoothness equipment basis for specification				specification parameters		
	as documented in 1987 AASHTO Chart	current (1992)	proposed (1992)	anticipated but not yet proposed	$ penalty ?	$ bonus ?	spec used*
Iowa	profilograph	profilograph	profilograph		Y	Y	P
Georgia	maysmeter	maysmeter	---	SD profiler	N	N	C
N. Dakota	---	---	---	---	--	--	--
Kansas	---	profilograph	profilograph (0"**)	---	Y	Y	C&P
Wisconsin	---	profilograph	---	---	Y	N	C
Illinois	---	---	---	---	--	--	--
Nebraska	---	profilograph	profilograph	---	Y	Y	C&P
Maryland	---	profilograph			Y	N	C
Idaho	profilograph	profilograph			N	N	C&P
Texas	---	---	profilograph	---	Y	Y	P
Ohio	---	---	profilograph	---	Y	Y	P
Florida	---	maysmeter	SD profiler	---	N***	N	C
Minnesota	---	---	---	profiling device	--	--	--
Virginia	---	profilograph	SD profiler	---	Y	Y	C

* C→ current specification used
P→ proposed (1992) specification used
** 0" blanking band
*** $ penalty is applied only on failure to repair

FIGURE 2. PENALTY/BONUS LEVELS FOR AC CONSTRUCTION SMOOTHNESS PROFILOGRAPH BASED SPECIFICATIONS

	PI range for bonus	100% payment	penalty	corrective action	$ amount penalty	bonus
Iowa (single lift)	<6"	6"-10"	>10"		$0→$200 ($800)**	$500($150)**→$0
Iowa (multi lift)	<3"	3"-10"	>10"		$0→$800 ($250)**	$150 ($20)**→$0
Kansas ****	<3"	3"-13"	>13"	>10"	$203	$152→$0
Wisconsin	--------	--------	10"-15"	>15"*	100%→60%	---------
Nebraska	<5"	5"-7"	7"-10"	>10"	100%→90%	104%→100%
Maryland	--------	--------	10"-15"	>15	100%→90%	---------
Maryland	--------	--------	7"-12"	>12"	100%→90%	---------
Idaho	--------	--------	---------	>7"	-----------	---------
Texas	<7" (prior to correction)	7"-10"	10"-15"*** (contractor elected)	>15"	100%→90%	105%→100%

* Also, if bumps are removed and PI>10", then corrective action is mandated.

** Secondary road penalty/bonuses are in parentheses.

*** At the contractor's discretion, he can accept the penalty or correct the problem and get retested (without possibility of bonus).

**** Kansas DOT uses a PI with no blanking band. These PIs were divided by 3 to approximate normal PI values (0.2" blanking band). Also, between 10" and 13" there is no dollar penalty, but grinding is required.

specifications were received from Iowa, Kansas, Nebraska, Maryland, Idaho, Virginia, Florida, and the FHWA Denver Region. The form, and many of the phrases, contained in the Kansas specification were used in the draft specification written during this project and contained in this report.

Trends In Smoothness Testing Device Usage.

Of the fifteen DOTs surveyed, 60% are using or propose to use profilographs, 25% are proposing to use profiling devices, and only 15% are using a straightedge specification. This is a great change from five years ago when, according to AASHTO, approximately 85% of those states in our current survey either did not have a specification or employed a straightedge specification. Now, only 15% are in that category. Several states have a few years of experience with a profilograph based specification. No state had any experience in a profiling device specification for asphalt pavements. Two states, Georgia and Florida which are considering profiling devices, however, had extensive experience using Maysmeters with their AC specification.

Trends In Bid Prices.

The opinion of all those surveyed was that bid prices either stayed the same or were slightly reduced because of specification implementation. The apparent explanation for much of the perceived reduction was the contractors' expectation of receiving a bonus. Where bonuses are in place, by and large, most contractors are receiving them. Georgia, however, which employs no bonuses (or penalties) but only corrective action past a certain threshold point, also noticed a decrease in bid cost. The explanation was that better attention to achieving smoothness resulted and was accompanied by an overall, continual re-evaluation by the contractor of his entire laydown operation. In the opinion of those surveyed, but not substantiated by any quantifiable data, this eventually resulted in more efficient operation and consequently lower bid prices.

Trends In Bonuses.

Of the thirteen states that have a profilograph or profiling based specification, three had no bonus or penalties, only corrective action; three had only penalties; and seven had both penalties and bonuses. Bonuses were generally limited to a maximum of 4% to 5% of cost of asphalt (and laydown). The maximum penalties were at least 10% and in two cases, went to 25% and 40% respectively. Generally, however, it was noted by those surveyed that penalties were rarely, if ever, inflicted and that instead, bonuses were widely awarded. Even for states without a bonus, it was noted that most sections tested had a PI of less than three (which is always in the bonus range). Penalties of one type or another were inflicted for PI's greater than 7 or in some cases greater than 10. Corrective measures were required at thresholds varying from greater than 7 inches to greater than 13 inches. Bonuses were paid for PI's of less than three, less than five, or less than seven depending upon the state. The consensus was, however, that the majority of the asphalt concrete roads tested were in the less than three PI range.

Trends In Use On Single Lift Overlays.

Thirty percent of the states (4 of 13) had some specific wording in the specification with respect to single lift overlays. Two of the states excluded these overlays from the specification and the other two states had a separate threshold table for single lift overlays. In addition, a few states noted that their specification was never applied to a single lift overlay project even though the specification itself did not explicitly exclude them.

Contractor Attitudes To Specification Implementation.

Only in one state was it noted that there was significant opposition by contractors to an asphalt concrete (AC) construction smoothness specification. Several states indicated that the contractors were initially somewhat anxious concerning specification implementation. However, once the specification became familiar to them, this concern generally went away. It was indicated by several states that specification implementation increased the attentiveness of the contractor to achieve smooth roads. It was also noted that this increase in attentiveness accomplished smoother constructed roads.

Measurement Inconsistencies.

At least three states surveyed indicated that they had some concern about the ability of the profilograph to adequately discern smoothness in the five to seven PI range. An example given was that one section would measure a seven PI and another five, but the seven appeared smoother. These observations were based upon experience on concrete roads, but their concern for measuring accuracy also applied to AC roads. The State of Kansas indicated that they successfully accommodated this problem by narrowing the blanking band on the profilograph (a blanking band is the area off the zero profilograph trace line outside of which PI is measured - see Appendix F for a more detailed description). Based upon their observation from field data, relatively rough roads measuring very smooth often showed significant oscillation within the two tenths inch blanking band. This oscillation accounted for no increase in roughness according to normal PI calculation procedures. By diminishing the blanking band this "roughness" was then accounted for.

The PI's of many Kansas construction projects from previous years were recalculated at the narrower band and were compared to PI results using the two inch blanking band. At that point, it was decided that the narrower blanking band resulted in a better prediction of roughness for newly constructed AC pavements.

Conclusion

Although the information obtained during this survey was largely qualitative it did provide much useful information including:

- Bid prices remain stable.
- Bonus payments are not needed to achieve contractor incentive.
- 0.2" blanking band for the PI statistic is excessive.
- Current specification thresholds are relatively lax.
- The difference in roughness on newly constructed/rehabilitated roads due to single lift vs. multiple lift needs further evaluation.
- The use of profilographs in AC smoothness specification has proliferated in the last five years.
- The use of profiling devices in place of a profilograph or a straightedge is just now emerging.

SELECTION OF A SMOOTHNESS MEASURING DEVICE

Candidate equipment

Although there are many types of smoothness measuring devices, the candidates for use with this specification were quickly reduced to just two devices, namely: the SD Profiler and the California Profilograph. Historically, the profilograph has been the device of choice for pavement smoothness construction specification testing (mostly on concrete roads). Based on our interview of 12 State DOT's, construction smoothness testing on asphalt concrete roads is also predominately being accomplished using the California Profilograph, although recently there has been a trend to investigate the use of the SD Profiler (Georgia, Florida, Virginia, and possibly Minnesota). As a result, the California Profilograph was included as a candidate device.

The SD Profiler was considered as the only other candidate because when considering all non-profilograph measuring devices, the SD Profiler was considered the best. This was concluded for the following reasons. The SD Profiler has the advantage of measuring profile directly rather than measuring vehicle response to the profile. Profiling devices, in general, have been deemed advantageous to vehicle response measuring devices by the AASHTO Subcommittee on Roughness and the World Bank. In addition, it is difficult to attribute roughness to a particular spot on the road using vehicle response measuring devices, and defining the limits of the rough area is very important for a construction specification.

Among profiling devices, the SD Profiler is considered the best device for the job because of its speed of collection, repeatability, good maintenance record, cost, and availability to SDDOT. The SD Profiler is vehicle mounted and operates at highway speed. It is preferred over manual profiling devices such as rod and level, dipstick, or rolling straightedge because these devices are prohibitively costly when considering labor time during testing. Of the automated profile measuring devices, only the KJ Law Profilometer is readily available for purchase in the United States. Its purchase cost is high with respect to the SD Profiler and its reliability and its "in the field" measurement precision has not been proven superior.

Finally, other states agree with this assessment. Of the states interviewed during this project, four are considering use the SD profiler for AC pavement construction smoothness testing. They are: Georgia, Florida, Virginia, and potentially Minnesota.

Candidate Equipment Evaluation

The major benefit of the California Profilograph over the SD Profiler is its historically widespread use in pavement construction smoothness testing. The SD Profiler is superior to profilographs with respect to ease of use, cost of use, and ability to measure smoothness. SDDOT has run tens of thousands of miles of roadway with the SD Profiler, all at highway speeds; whereas the profilograph can only be run on limited mileage because of it's slow rate of operation (two to three miles per hour). The amount of mileage involved in South Dakota's asphalt concrete annual rehabilitation program is enough to preclude the profilograph from consideration as the testing device.

The purchase price of a profilograph is considerably less than that of an SD Profiler. The cost differential for purchase is approximately $40,000. This cost spread over the life of the device, amounts to less than $4,000 per year. Considering that the SD Profiler has an alternative usage collecting network level roughness data, and that there are labor cost savings accrued from operation of a SD Profiler as compared to a profilograph, these savings counterbalance the lower initial purchase price of a profilograph.

The SD Profiler is also much better at measuring smoother roads. Based upon conversations with state transportation departments that employ profilographs, there is a widespread concern about the quality of measurement of profilographs for PI's of seven or less. Since a smooth asphalt road can easily be three or less in PI, the ability of the profilograph to measure such roads is a major concern.

Recommendation

It is our recommendation that the profiling device used in asphalt concrete pavement construction smoothness testing be the SD Profiler. It is a dependable and accurate device whose cost of use is very low. With respect to ease of use and cost of use the SD Profiler is at the top of the roughness device list. Only with respect to measurement accuracy is the SD Profiler superseded by such devices as the dipstick or rod and level. These devices are excluded from consideration due to their high cost of operation and slow speed of data collection.

SMOOTHNESS STATISTIC SELECTION

Candidate Statistics

Many smoothness statistics were considered for use in specification testing during the course of this research. Statistics already in use for construction testing such as PI at various thresholds and base lengths and RMSVA were considered. "General use" smoothness statistics such as PSI and IRI were also considered. Finally, two new statistics were developed and evaluated. These statistics were: 1) the area under the PI trace using different thresholds and base lengths and, 2) a telescoped rolling straightedge (TRS) statistic.

Statistic Evaluation

As identified in Appendix C, 128 one mile length road section profiles were made available to this research by SDDOT. These profiles consisted of elevations gathered at one foot intervals longitudinally down the road section. A single accelerometer SD Profiler was used measuring the driver side wheelpath profile. On each of the 128 one mile profiles, six PI-type statistics and six "area under the PI trace" statistics were calculated using blanking bands of .2 inches, .1 inches, and 0 inches, and base lengths (length of a two wheel profilograph) of 10 feet and 25 feet respectively. Two telescoped rolling straightedge statistics were calculated using a maximum straightedge length of ten feet and twenty feet, respectively. PSI and IRI were obtained from SDDOT at the same time that the profile data files were given to the researchers. Two RMSVA statistics were also calculated using 5 foot and 12½ foot base lengths.

The evaluation of the statistics began by calculating the correlation of each pair of statistics. Our contention is that all "quality" smoothness statistics will be highly correlated since they are measuring the same thing and measuring it well. Correspondingly, if one statistic is uncorrelated to all other statistics, then it is our contention that it is <u>not</u> a "quality" smoothness statistic. Correlations were first calculated using 13 one-mile sections. These 13 sections, all in the 1992 rehabilitation program, were measured by the SD Profiler and also the California profilograph. For these 13 cases, the results are that the profilograph based PI and the SDDOT provided PSI were not correlated to any other statistic, and that all other statistics were highly correlated to each other (see Appendix E). Our conclusion is that profilograph based on PI and SDDOT provided PSI are not "quality" smoothness statistics (for very smooth roads).

Correlations (see Appendix E) were also obtained using the entire 128 one mile profiles. Since no profilograph data was available for all 128 sections, the profilograph measured PI statistic could not be calculated and so was not available to be correlated. The correlation results were the same as for the 13 section database, namely the SDDOT provided PSI was not highly correlated with any other statistic. These results reinforced the conclusions obtained from the 13 section based correlations.

There are two consequences of this initial analysis. First, it reinforced the conclusion that the profilograph and profilograph produced PI was not adequate for this task in that the profilograph produced PI statistic had no correlation with any other statistic. Second, the SDDOT provided PSI statistic was excluded from further evaluation.

A rational and descriptive approach is used to recommend a statistic from the 16 remaining candidate smoothness statistics. A more quantitative evaluation approach, such as a comparison to a "golden" device/statistic or correlation to smoothness ratings collected by a panel of experts were not considered practical. The first approach was unfeasible because there is no "golden" statistic, so there is nothing to compare against. Use of a panel of experts was never considered as part of the scope for this project because of its expense, and the risk of unreliable ratings due to the small range of smoothness under consideration.

The recommendation for a smoothness statistic was made through a process of elimination. The first criteria for statistic acceptability is that it is locally applicable, in other words, it can identify the "rough spots". Examples of locally quantifiable statistics include the 10 foot straightedge, and the PI statistic. With the straightedge one is standing at the location measured. With the PI statistic by looking at the PI trace, one can tell where on the road there is unsatisfactory smoothness.

All of the statistics previously mentioned are locally quantifiable except for the IRI statistic. IRI simulates vehicle response through differential equations. There are two major problems with this in terms of being locally quantifiable. First, the statistic uses initial conditions. This makes the statistic perform poorly when applied to short lengths of roadway. Second, as the IRI smoothness statistic is being accumulated, each new increment accumulator is not assignable to any one point on the road, but is in fact, a composite of the influences of all of the previous elevations on the roadway. Furthermore, there is no definitive way to split each accumulator into its components on a longitudinal position-by-position basis. As a result, IRI is a good smoothness indicator for longer lengths of road, but for shorter lengths of road, or particular positions on the road, it is an inadequate statistic.

Next, let us review PI. The PI trace is primarily the elevation at the mid-point of the profilograph minus the elevation average at the ends (Note: this average elevation of the end points varies somewhat depending on the number of profilograph wheels). In its simplest form, the profilograph is duplicated by a rolling straightedge with measurement from the middle of the straightedge against the ends. Mathematically, this is called a second difference. The PI trace of a simple profilograph is a series of second differences. The PI statistic is calculated in the following manner. A blanking band is used and the PI is the sum of the maximum elevations off of the blanking band for each of the continuous areas (scallops) over or under that blanking band. The PI trace for a simple profilograph is also the basis for the calculation of the RMSVA statistic, which is calculated as the square root of the sum of the squares of the second differences.

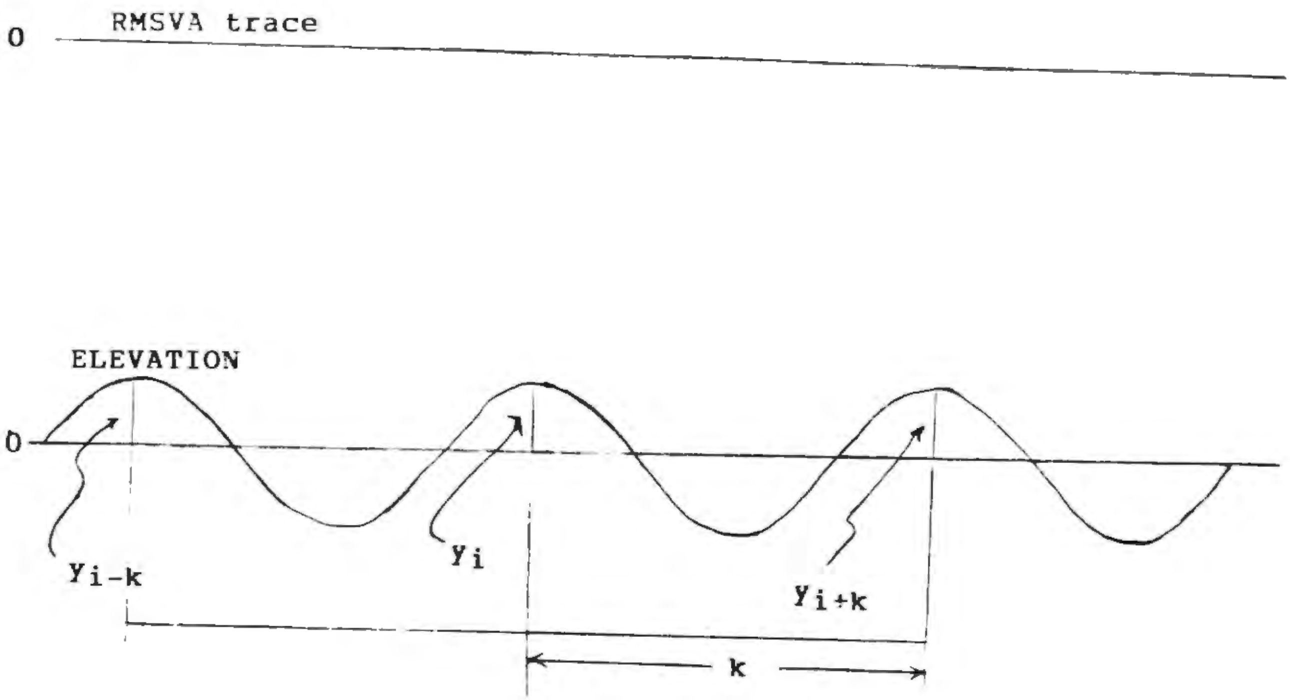
Our opinion is that the PI statistic was developed primarily for ease of calculation. A few years ago, ease of calculation was a very important criteria for statistic selection. In the age of microcomputers, however, this is no longer the case. In addition to ease of calculation, use of the blanking band may also be warranted to reduce noise in the instrument. The noise in a SD Profiler, which is the device we have recommended, is an order of magnitude smaller than that of a profilograph, and so the use of the blanking band to reduce noise is not appropriate in this situation.

Now, let us rate several PI related statistics, from worst to best. PI is an adequate statistic, but blanking band is no longer necessary. Next, instead of summing the maximum height of each PI trace scallop (PI without a blanking band), why not just sum the heights of each PI trace second difference (i.e. calculate the areas of all the PI scallops)? The advantages of summing maximum heights (PI) is that it weights large heights more than summing all heights. The advantage of summing all heights is that all deviations from perfect smoothness (a straight line) contribute something to the statistic.

These two competing statistics both have advantages. As it turns out, however, the RMSVA statistic combines the advantages of both, and so is the best statistic of the three. RMSVA is calculated by summing the squares of the PI trace heights. With this algorithm all deviations from a straight line (perfect smoothness) contributes to the statistic, and larger heights (deviations) contribute more due to the squaring of each height.

RMSVA on the other hand, which is basically the sum of squares of the differences in the average elevation of the ends of a rolling straightedge against the middle, also has a problem. This statistic performs poorly whenever there is a series of bumps or gullies placed, on average, consecutively at the distance between rolling straightedge end points and the middle. An extreme example illustrating this potential poor performance of RMSVA is shown in Figure 3 using a sine wave as the profile. In this hypothetical example, (see Figure 3), the RMSVA statistic will always be zero.

In summary, the good points of RMSVA are its sum of squares idea and its second difference idea. Its weak points are that it uses differences off the middle of the rolling straightedge and also that it uses a fixed length straightedge. This researcher came to the conclusion that instead of having a PI trace curve which is the difference of the middle elevation against the average of the end elevations it would be much better to use the difference of the current point's elevation against the average of peak elevations on either side of the current point (or trough



$y_{i-k} - 2y_i + y_{i+k} = 0$ for every i
where the base length = 2k and the sine wave frequency is k

$$RMSVA_{2k} \simeq \sqrt{\Sigma (y_{i-k} - 2y_i + y_{i+k})^2}$$

$$RMSVA_{2k} = 0$$

Figure 3. Sine Wave RMSVA Calculation.

elevations on either side of the current point). Mechanically, a device that measures such a concept would be a telescoped rolling straightedge with a maximum length.

The telescoped straightedge would start at any given point with a straightedge of two feet (one foot on either side of the current point) and measure the second difference, then would lengthen one side of the straightedge by one foot, so that one end of the straightedge was two feet away from the current point and the other one was one foot. At that point, calculate a weighted second difference, weighted by the inverse of the length away from the current point. Another way to visualize this is as the vertical difference between: 1) the line joining the two end points, and 2) the current point. By continuing to adjust the straightedge at either side of the point to all possible combinations of footage where the length of the straightedge was 10 feet or less, many vertical displacements (45) are calculated. The maximum across all of these vertical displacements is the distance from the current point to the line joining the highest neighboring peaks (or troughs, whichever is bigger). Note: as the maximum straightedge length varies the number of vertical displacement combinations varies as the square of the length.

A new statistic, the telescoped rolling straightedge (TRS) statistic can now be formulated as a variant of RMSVA. The maximum vertical distance obtained by the telescoped rolling straightedge is used to replace the second difference component in RMSVA. This new statistic is called the telescoped rolling straightedge (TRS) statistic. The telescoped straightedge combines the best of both the original straightedge and the rolling straightedge. By varying the distance of the end points away from the current point, we have simulated the best aspect of a regular 10' straightedge which is that the regular 10' straightedge will always lie on top of any peaks within 10 feet of the current point, regardless of peak placement within the 10'. By being able to measure both bumps and troughs, we have incorporated the best aspect of the rolling straightedge. And by varying base length and taking "weighted" second differences, we have avoided the RMSVA pitfall illustrated by the sine wave example and caused by "normal" second difference calculations. Figure 4 shows the ten foot telescoped rolling straightedge (TRS) profile against a sample elevation profile. This statistic makes a lot of sense. Where there are gullies, this statistic is adding the depth of the gully; where there are hills, this statistic is adding the height of the hill.

Now let us compare the TRS statistic against RMSVA. The TRS statistic will be shown to be a better statistic than RMSVA through the following three illustrations, namely:

- comparison of their respective contributions at one elevation point,
- comparison of their contributions across a profile of elevations, and
- comparison of their contributions on a sine wave profile.

Figure 5 shows a sample profile as well as what this consultant considered the desired "roughness" contribution at a given elevation point. The objective is to find the statistic that could reproduce this roughness contribution. Note, the roughness contribution shown in Figure 5 is the vertical displacement from the given point to the line joining the adjacent "peaks" (or gulleys). Figure 6 duplicates this sample profile and shows the RMSVA contribution. In this figure the RMSVA contribution, at two different base lengths, is shown in the solid lines whereas the desired contribution is shown in the dotted line. Almost always, the RMSVA contribution will be less than what is desired.

An illustration of the calculation of MVD is shown in Figure 7. MVD is the maximum of 45 different vertical displacements off of 45 different lines joining adjacent points. In Figure 7, the sample profile is illustrated 6 times and these 45 lines are shown

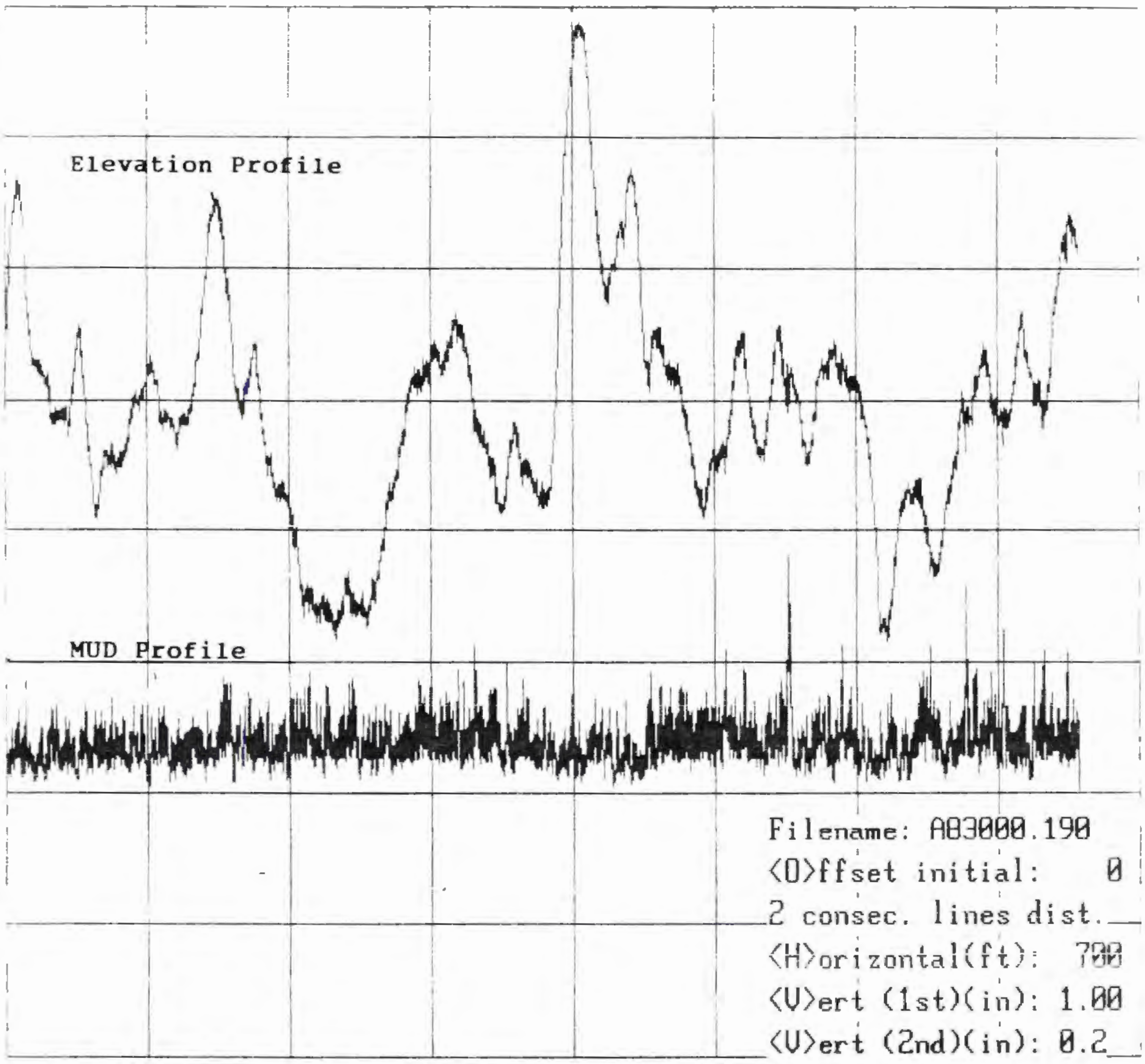


Figure 4. Typical MVD Profile for the Telescoped Rolling Straightedge.

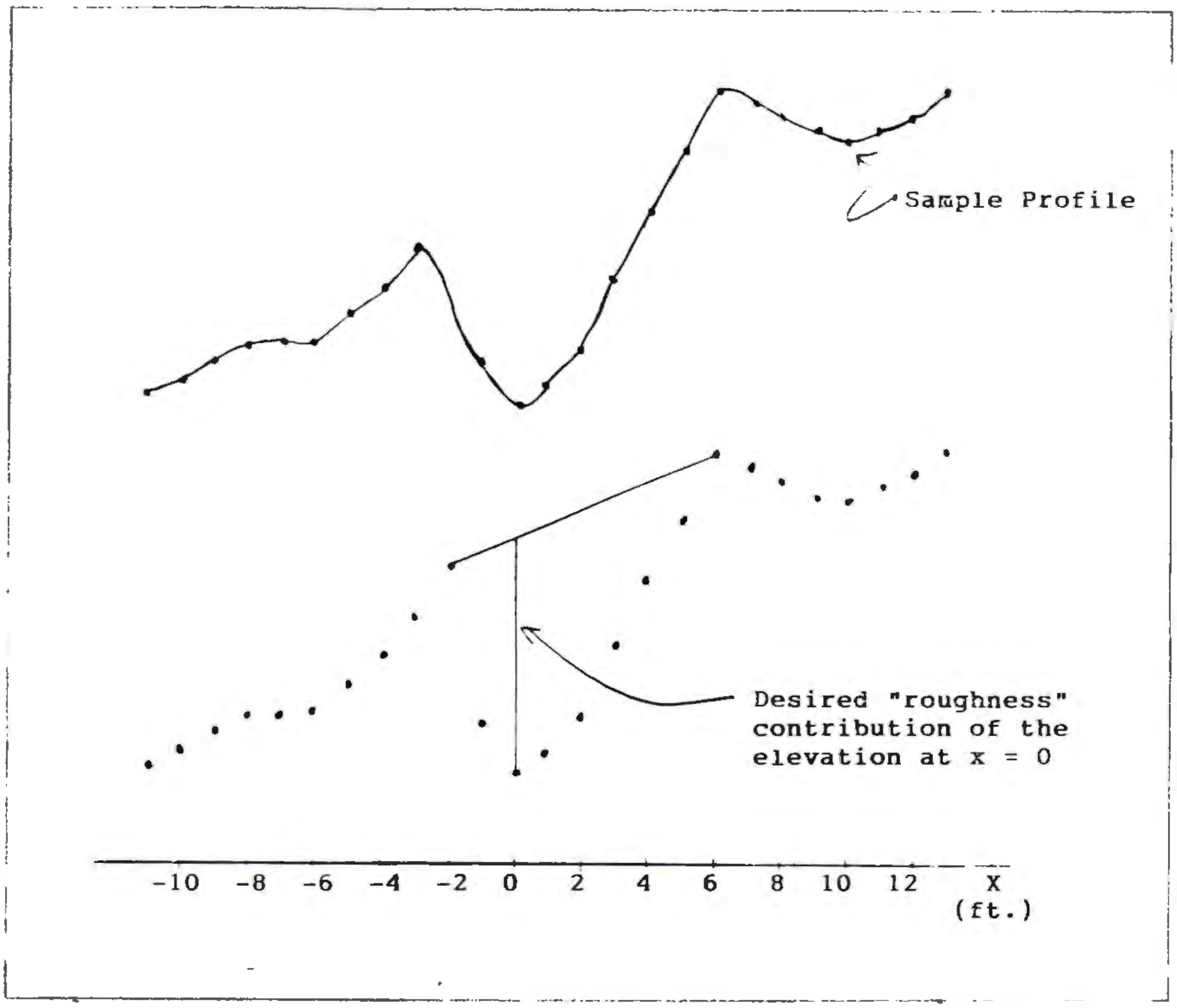


Figure 5. Desired "roughness" contribution at a point.

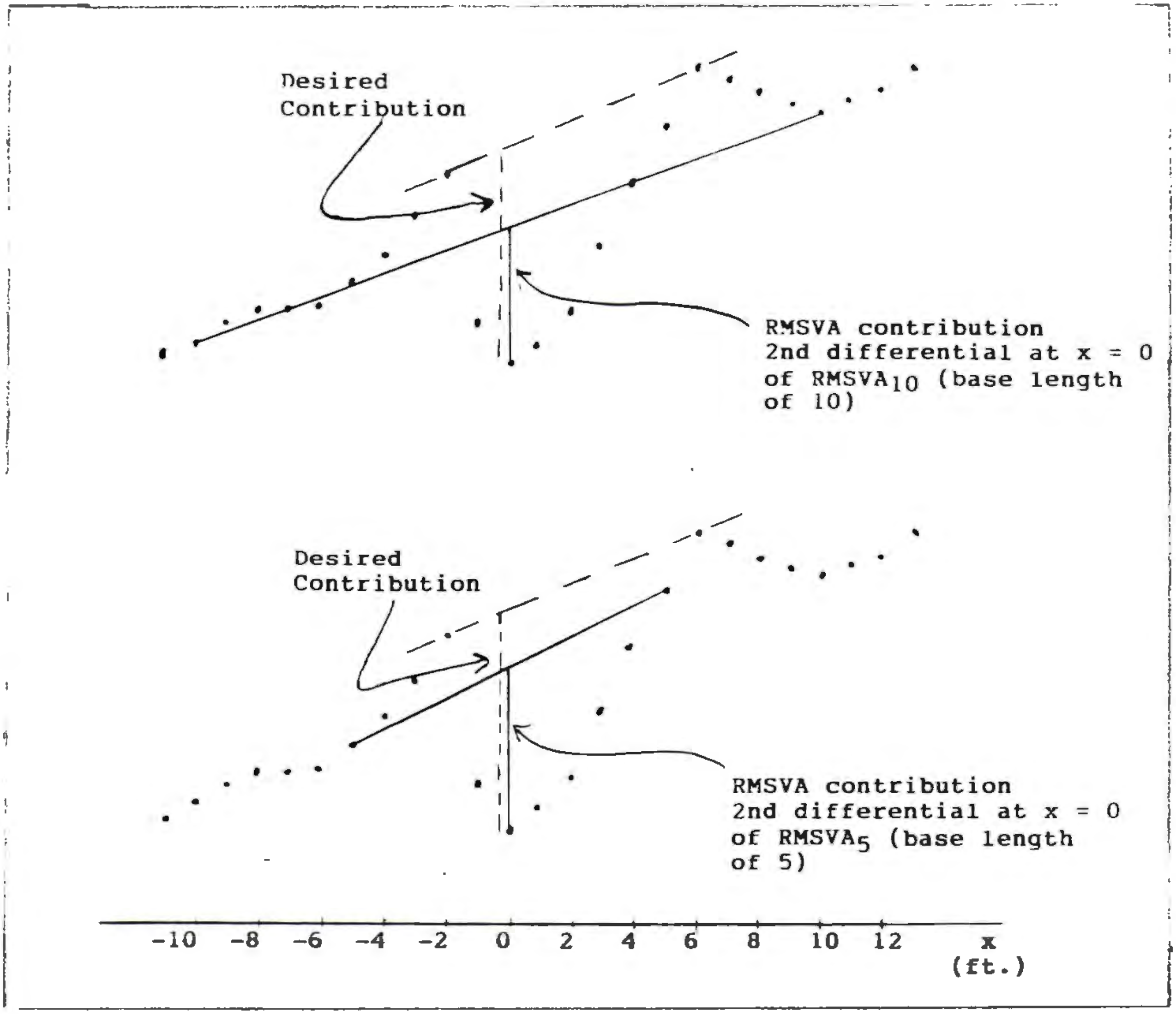
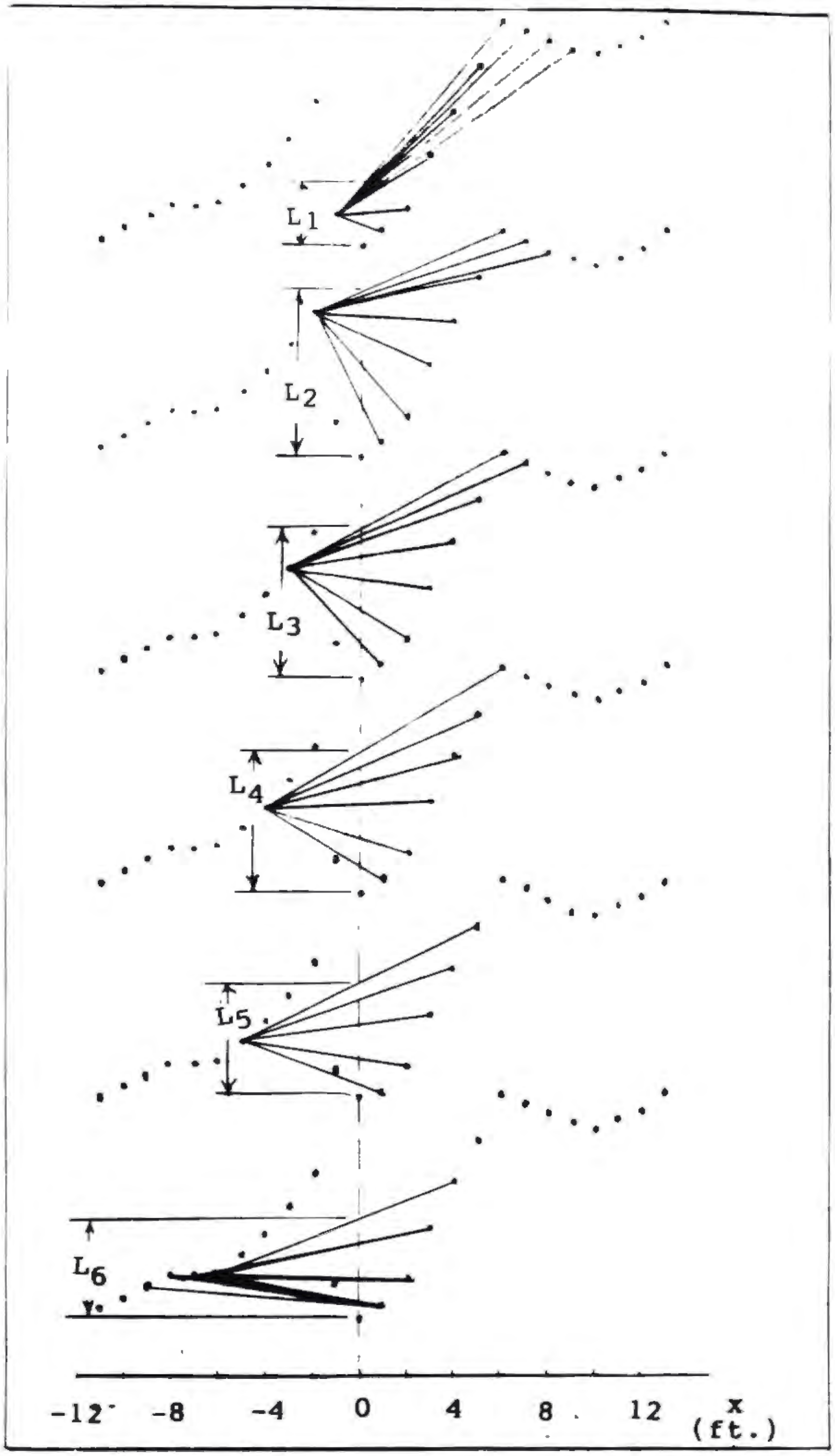


Figure 6. RMSVA "roughness" contribution at an elevation point (for two base lengths of 5 and 10 feet).



For the elevation at x = 0 MVD_0 is the maximum vertical distance across all drawn lines to the elevation point at x = 0. MVD_0 is equal to L_2 (Note: the same profile is drawn 6 times in order to easilty see all the lines).

Figure 7. Illustration of the TRS "roughness" contribution (MVD) at a point.

shown across these 6 duplicate profiles. The maximum vertical displacement (MVD) is found at L_2. A cross reference to Figure 5 shows that this is exactly the same vertical displacement as was initially desired. The TRS statistic has been constructed in order to obtain this desired roughness contribution at every point.

The roughness contributions for TRS and RMSVA across a profile of elevations are shown in Figure 8. As can be seen in Figure 8, TRS magnifies and discerns the local effect of gulleys and bumps much better than RMSVA.

Figure 9 shows the telescoped rolling straightedge profile against a sine wave elevation profile, whereas the second difference (PI/RMSVA) trace is always zero, the telescoped rolling straightedge profile is much more intuitively correct. As part of the project deliverables, a program called PROFILE has been created that will plot a SD Profiler elevation profile and the accompanying maximum vertical displacement (MVD) profile of the telescoped rolling straightedge. By running several profiles through this program, SDDOT personnel can convince themselves of the usefulness of this statistic.

The entire telescoped rolling straightedge (TRS) statistic definition is the square root of the sum of squares of these maximum vertical displacements, normalized to one mile in length, and also normalized to a twenty foot maximum telescoped rolling straightedge. Figure 10 is the mathematical expression that represents the TRS statistic. The computer program PROFILE calculates this statistic for any portion of any road elevation profile. Appendix D shows TRS statistic values and MVD profiles for the 13 sections in the 1992 construction program analysis during this project.

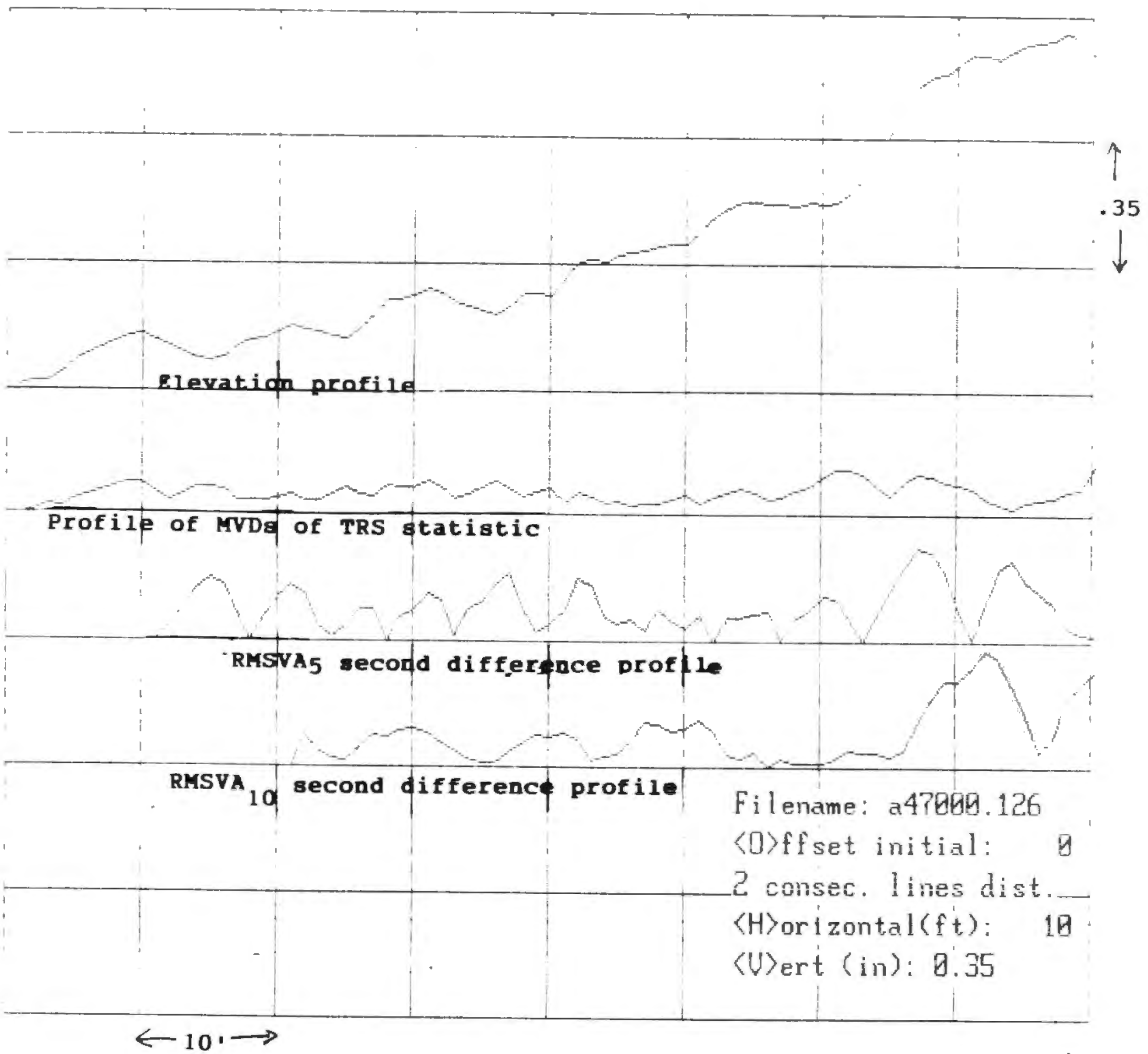
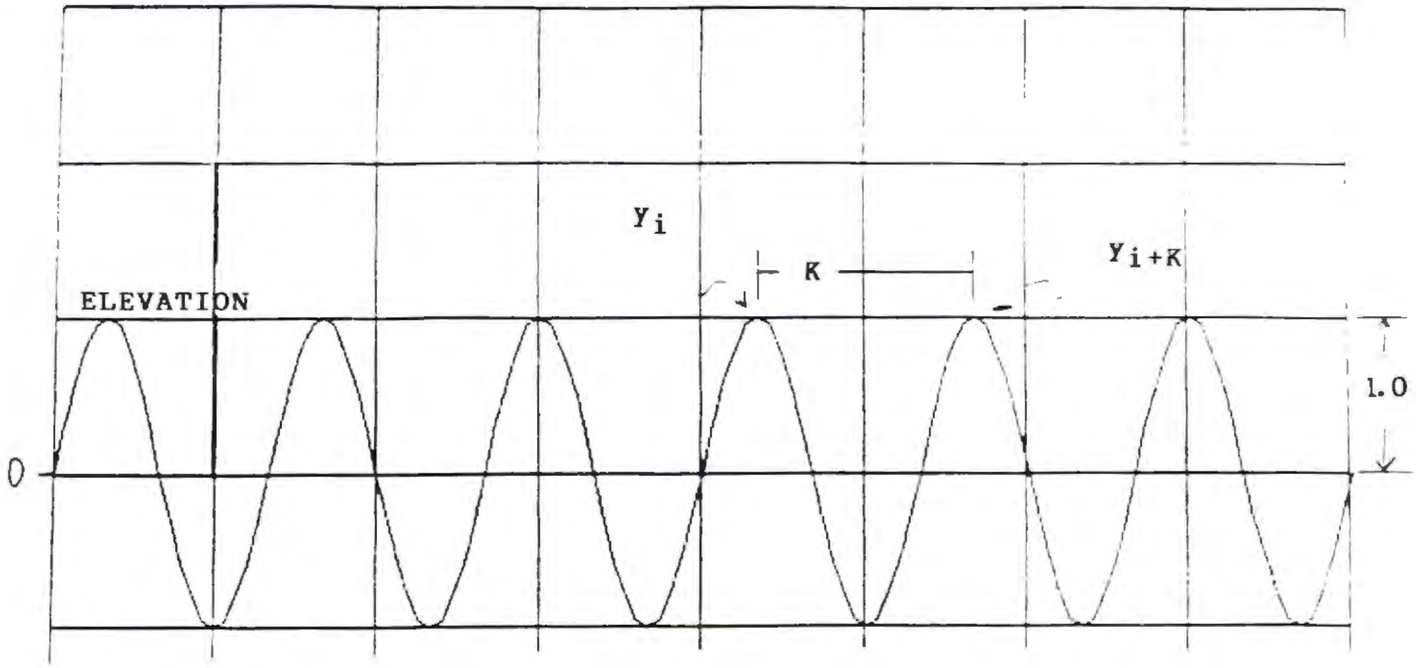


Figure 8. Roughness contribution TRS & RMSVA on an elevation profile.



$RMSVA_{2K}$ trace is always zero since $4_{ik}-2y_i-y_{i-k} = 0$ for all i (see Figure 3).

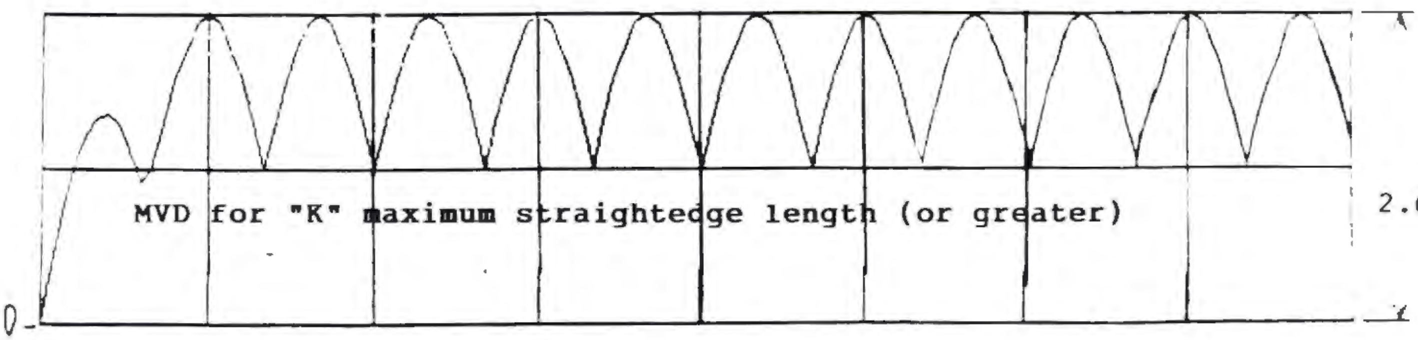


Figure 9. TRS Trace And RMSVA Trace Comparison On Sine Wave Profile.

TELESCOPED ROLLING STRAIGHTEDGE (TRS) STATISTIC

$$TRS = SQRT\left[\frac{20}{BASE} * \frac{(5280 - BASE)}{(n\text{-}BASE)} * \sum_{i=1}^{n} (MVD^2_{i,\ BASE})\right] * \frac{10{,}000}{5280*12}$$

Where

BASE = 10 feet which is the maximum length of the rolling straightedge

"n" is the number of profile values (collected at a 1 foot interval longitudinally down the road in the driver's side wheelpath).

"i" is the i^{th} consecutive profile value
[at longitudinal distance (i-1) feet assuming the starting longitudinal distance is set at zero.]

"P_i" is the i^{th} consecutive elevation, measured every 1 foot.

"$MVD_{i,\ BASE}$" is the maximum vertical displacement MVD of the TRS for the i^{th} consecutive elevation (collected at an interval of one foot).

"$MVD_{i,\ BASE}$ = MAX [(vertical distance between the line joining P_k with P_j and the point P_i) for all j, k such that $k<i$, $j>i$, $j-k \leq$ BASE and BASE = 10]

Note: TRS is dimensionless.

Figure 10. Telescope Rolling Straightedge (TRS) Statistic.

Recommendation

It is our recommendation that the telescoped rolling straightedge statistic be used for construction smoothness testing. This is a very powerful statistic. It is locally quantifiable. It is very sensitive to localized profile distortion. It measures the distance to the top of the peaks or the bottom of the troughs. It weights large vertical displacements more heavily than small ones. All maximum vertical displacements contribute to the statistics. Additionally, it could be redefined to account for the vehicle operating cost consequences of roughness. For example, if one can quantify the effect of roughness on vehicle operating costs and comfort in bumps and troughs of varying amplitude and frequency, then these effects could be included in the telescoped statistic as weights when calculating the maximum elevation differences. The result would be a (roughness or smoothness) statistic that is proportional to vehicle operating costs. This statistic would also have the advantage of being able to assign vehicle operating costs to each point on the road.

We believe that the TRS statistic has much potential. In the absence of specification implementation, we recommend that SDDOT consider further use of this statistic in their regular SD Profiler operations.

FORMULATION OF SPECIFICATION PARAMETERS

Smoothness Levels in South Dakota for AC Pavement Construction

Estimates for initial smoothness after construction were obtained from SDDOT provided SD Profiler data. Based upon the data received, South Dakota roads over the past 10 years have been constructed very smoothly. Figure 11 shows a smoothness (TRS) histogram for 453 one-tenth mile subsections taken

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HISTOGRAM OF TRS

LOW TRS	N	HIGH TRS	
0.000	0	0.100	|
0.100	0	0.200	|
0.200	7	0.300	|****
0.300	20	0.400	|*************
0.400	37	0.500	|***********************
0.500	58	0.600	|************************************
0.600	75	0.700	|**
0.700	78	0.800	|**
0.800	45	0.900	|****************************
0.900	33	1.000	|*********************
1.000	20	1.100	|*************
1.100	22	1.200	|**************
1.300	12	1.400	|********
1.400	9	1.500	|******
1.500	10	1.600	|******
1.600	6	1.700	|****
1.700	1	1.800	|*
1.800	3	1.900	|**
1.900	0	2.000	|
2.000	1	2.100	|*
2.100	0	2.200	|
2.200	0	2.300	|
2.300	0	2.400	|
2.400	0	2.500	|
2.500	0	2.600	|
2.600	0	2.700	|
2.700	0	2.800	|
2.800	0	2.900	|
2.900	1	3.000	|*

CASES INCLUDED 453 MISSING CASES 0

EXPECTED IRI(m/km)

LOW	HIGH
0	0.15
0.15	0.30
0.30	0.50
0.50	0.65
0.65	0.85
0.85	1.00
1.00	1.20
1.20	1.35
1.35	1.50
1.50	1.70
1.70	1.85
2.05	2.20
2.20	2.35
2.35	2.55
2.55	2.70
2.70	2.85
2.85	3.05
3.05	3.20
3.20	3.40
3.40	3.55
3.55	3.70
3.70	3.90
3.90	4.05
4.05	4.25
4.25	4.40
4.40	4.55
4.55	4.75
4.75	4.90
4.90	5.05

Figure 11. TRS Histogram of 0.1 mile subsections for 49 One-mile "Just Rehabilitated" Sections.

from 49 one mile road sections that have just been rehabilitated. Eighty-two percent of these subsections are considered smooth at construction (TRS <= 1.2).

Based on this histogram, TRS thresholds for the roughest "just constructed" subsections are as follows:

TRS	Expected IRI (m/km)	"Roughest" percentile
>1.2	>2.05	12%
>1.3	>2.20	9%
>1.4	>2.35	7%
>1.5	>2.55	5%
>1.6	>2.70	2%
>1.7	>2.85	1%

2nd largest TRS was 2.05 (expected IRI = 3.45 m/km)
the largest TRS was 2.95 (expected IRI = 5.00 m/km)

Specification Candidate Parameters and Their Use

Bonuses. In the draft specification, there is no provision for bonuses. Based on the high smoothness level of currently constructed South Dakota road and the eventual loss of smoothness advantage for initially very smooth roads, there seems to be little need to induce contractors to construct yet smoother roads. Additionally, states with AC pavement smoothness construction specifications without bonuses asserted that smoothness at construction increased due to specification implementation. Georgia, is one such state, with historical roughness data verifying this assertion. Finally, the bonus range, if it existed, would be between very smooth roads and extremely smooth roads. At this level of smoothness, there is little discernment and no indication of "roughness" by the casual vehicle operator. As such, it would not be apparent without the use of precision profiling machinery why some roads received bonuses and others did not.

Penalties. A provision for penalties was included in the specification in order to: 1) maintain the high level of smoothness found in newly constructed South Dakota roads, and 2) provide an incentive to construct smooth roads through both the monitoring of smoothness via specification testing and the threat of dollar penalty. Penalties were subjectively set to begin at the 10th percentile roughness level for currently constructed South Dakota roads. Penalty dollar levels were set rather low since the 10 percentile level is a TRS of 1.3 (expected IRI of 2.2 m/km) which is still a relatively smooth road. Corrective work was only required for bumps or roads in the 1% roughest range. Failure to perform corrective work results in a large dollar penalty, since the Department would be left with an unsatisfactory road. In order to avoid repeated (and possibly ineffective) corrective work, corrective work will only be allowed once, after which retesting will occur and dollar penalties applied if the problem is not corrected.

Thresholds. The initial penalty threshold was set at the 10 percentile roughest level for roads currently constructed in South Dakota. This threshold is at a TRS statistic value of 1.3. The initial penalty is set at a 1% reduction in the price of the top layer's laydown and material cost. Penalty levels are set to increase every 0.1 increase in TRS or approximately every 2 percentile. At each threshold, the penalty further reduces the top layer price by 1%. Maximum price reduction is set at 5% with two exceptions. If the contractor refuses to perform detailed corrective work, then a 20% reduction is applied. If after corrective work is performed and the resulting TRS is greater than 1.7 (expected IRI of 2.85 m/km) then a 10% penalty is assessed.

Summary. The draft specification incorporates mild dollar penalties, and requires corrective work for roads with unsatisfactory smoothness or sever bumps. In order to induce contractors to construct very smooth roads, small penalties can occur for somewhat smoothly constructed roads.

The draft specification itself and its accompanying "procedure to test" is contained in a separate document heretofore referred to as the "specification document".

SPECIFICATION JUSTIFICATION

JUSTIFICATION METHODOLOGY

Annual economic benefit due to the implementation of an asphalt concrete pavement smoothness construction specification is the sum of the following savings:

1. construction cost savings due extra pavement life, plus
2. minor maintenance cost savings due smoother roads, plus
3. vehicle operating cost savings due smoother roads, minus
4. the cost to administer the specification.

The first benefit component is directly affected by how pavement life changes due to specification implementation. Benefits 2. and 3., the minor maintenance and vehicle operating cost benefits, are affected by the decreased portion of time that the road is rough due to specification implementation.

This specification will reduce construction expenditures if pavement life is increased. As an illustration, let's consider car purchases. If one purchases a car every two years with a two year loan, monthly payments are much higher than if a new car is purchased every ten years with a ten year loan. Similarly with roadways, where the purchase price is the construction cost, if the period between construction activities increases then the consequent payment for that construction decreases. Figure 12 shows the annual and "life" construction cost savings calculations, and Figure13 provides "life" savings estimates for a one mile $70,000 rehabilitation across various expected lives and life increases.

This specification will also reduce minor maintenance and vehicle operating costs if the initial smoothness at construction increases due specification implementation. It is generally accepted, but not well quantified, that minor maintenance costs on smooth roads are much less than on rough roads. For example, the rougher a road gets, the more patching and associated patching costs there are. Savings in minor maintenance costs can be shown through this example. If the specification was implemented, a pavement might last 16 years and be constructed at an IRI of 1. In the absence of a specification, the same constructed pavement, although its life may also be 16 years, would be constructed at an IRI of 1.2. Assuming a definition of "rough" as IRI > 2.25, then this is the last 25% ([2.6-2.25]/[2.6-1.2]*100) of the road's life without specification implementation, assuming, on average, state roads in South Dakota are rehabilitated at an IRI of 2.6. If the specification had been implemented, then this would only amount to 22% of the road's life ([2.6-2.25]/[2.6-1.0]*100). This "high roughness/cost" minor maintenance time differential of 3% (25-22%), determines the minor maintenance cost savings.

The same idea that applies to minor maintenance savings also applies to vehicle operating savings. Vehicle operating costs are proportional to roughness, just as are minor maintenance costs. As such, vehicle operating savings are found during that decreased portion of time when a road exhibits a high level of roughness due to specification implementation. The difference between the minor maintenance savings equation and the vehicle operating equation, is that minor maintenance units costs are in terms of dollars per mile, whereas vehicle operating unit costs are expressed in terms of dollars per vehicle mile travelled.

Figure 14 provides "life" savings estimates due minor maintenance and vehicle operating factors for a one mile $70,000 rehabilitation across various expected lives and initial smoothnesses after construction (with and without specification implementation). Figures 15 and 16 show the annual cost savings calculations for minor maintenance and vehicle operating costs. The idea behind these calculations is that the average lifetime cost can be divided into a smooth road cost and a rough road cost and proportioned according to the time in each state. By making an assumption about: 1. the maximum roughness annual cost level, 2. the relationship between smooth road annual cost and maximum roughness annual cost (see Figure 17), and 3. the percentage of time in the rough state for roads constructed without the specification, then, the annual average cost for smooth roads can be determined. Next, for a road that is initially constructed smoother (i.e. under the specification), the percentage of life in the "rough" state decreases (see Figure 18). Since costs associated with specification implementation can also be divided into a smooth road cost and a rough road cost and proportioned according to the time in each state, and since the same maximum roughness annual cost and smooth road annual cost apply as calculated prior, then, as the percentage of life in the "rough" state decreases, so the costs associated with specification implementation also decrease.

Counterbalancing the potential savings due to specification implementation is the cost of administering the specification (see Figure 19). This cost has two components: 1) the annual cost of field testing and data processing, and 2) the annual cost to administer the specification. Administering the specification includes the cost of bonus payments minus penalties assessed as well as the staffing cost to process these accounts receivable and accounts payable.

The computer program, ECON (see Figure 20) was used to generate the results in Figures 13 and 14, and has been delivered to SDDOT. It provides SDDOT with the capability to estimate annual network benefit due to specification implementation. Using ECON, SDDOT personnel can gauge the effect of any set of input values on annual network benefit due to specification implementation.

Annual Savings(CC) = Annual construction cost savings due extended life
Annual Savings(CC) = COSTR1 - COSTR2

CC = TOT_MILES * { (MLCSTR1 / YRS_LIFE1) - (MLCSTR2 / YRS_LIFE2) }

where

COSTRi is the annualized cost of construction for the SD road network
MLCSTRi is the annualized cost to construct
YRS_LIFEi is the average years between AC pavement construction

where i = 1 is the future without a specification (current experience)
i = 2 is the future with a specification

MLCSTR2 is MLCSTR1 plus any extra rehabilitation costs due to specification implementation. These would be the net cost of any penalties/bonuses paid out, together with adjusted bid amounts due expected penalties/bonuses.
TOT_MILES is the total miles in the road network

Life Savings = CC * YRS_LIFE1

Figure 12. Construction Cost Savings From Extra Pavement Life

LIFETIME CONSTRUCTION COST SAVINGS DUE LIFE INCREASE
(AND PERCENT COST SAVINGS)

increase in life (years) due to specification implementation	average life (years) without specification implementation 10 yrs	13 yrs	16 yrs
+1 year	$ 6,363 (9%)	$ 5,000 (7%)	$ 4,117 (6%)
+2 years	$11,666 (17%)	$ 9,333 (13%)	$ 7,777 (9%)
+3 years	$16,153 (23%)	$13,125 (19%)	$ 9,130 (13%)

Note: Cost savings are proportional to rehabilitation cost.

Figure 13. Lifetime Construction Cost Savings
for rehabilitating one mile at $70,000 cost
where road life increases due specification implementation

LIFETIME MINOR MAINTENANCE AND VEHICLE OPERATING COST SAVINGS FOR ONE MILE OF ROAD WITH A 13 YEAR LIFE AND ADT OF 993

Assumes: $0.30 average VOC/mile
1% VOC increase due roughness
$1,235/mile average minor maintenance (MM) cost
50% MM cost increase due roughness

decrease in IRI at construction due to specification implementation	Smoothness at construction (IRI) without specification 0.9	1.3	1.7	2.1
-0.02	$ 41	$ 54	$ 77	$ 137
-0.05	$ 102	$ 132	$ 187	$ 324
-0.10	$ 198	$ 254	$ 356	$ 594
-0.15	$ 289	$ 369	$ 509	$ 823
-0.20	$ 375	$ 475	$ 649	$1,019
-0.30	$ 535	$ 669	$ 892	$1,338
-0.40	$ 679	$ 839	$1,098	$1,586

Note: Cost savings are proportional to life.
IRI units are m/km.

Figure 14. Lifetime Minor Maintenance and Vehicle Operating Cost Savings for one mile of road with a 13 year life and ADT of 993

Annual Savings(MM) = Savings from reduced minor maintenance costs
Annual Savings(MM) = COSTM1 - COSTM2

MM = TOT_MILES * (MLCSTM1 - MLCSTM2)

from Figure 17
MLCSTM1 = smooth_cost + (max_rough_cost - smooth_cost)*A/2

and assuming that A and B are known and are defined as:
A is the proportion of life in the rough state without the specification
B = max_rough_cost / MLCSTM1 or
max_rough_cost = B * MLCSTM1
(i.e.ratio of maximum cost to average cost (without the specification))

then
MLCSTM1 = smooth_cost + (B*MLCSTM1 - smooth_cost)*A/2

and
smooth_cost = MLCSTM1 * (1 - A*B/2) / (1 - A/2)

next, applying Figure 17 to MLCSTM2
MLCSTM2 = smooth_cost + (max_rough_cost - smooth_cost)*X/2
where X is the proportion of life in the rough state assuming the specification is implementated & is calculated (see Figure 18)
X = A - A * (RO1 - RO2) / (RT - RO2)

then substituting for smooth_cost, and max_rough_cost
(assumes these values do not vary due to specification implementation!)
and also substituting for X in the MLCSTM2 equation

MLCSTM2 = smooth_cost + {max_rough_cost - smooth_cost} * X / 2
MLCSTM2 = MLCSTM1 * (1 - A*B/2) / (1 - A/2) +
{ B * MLCSTM1 - MLCSTM1 * (1 - A*B/2) / (1 - A/2) } *
[A - A * (RO1 - RO2) / (RT - RO2)] / 2
and so now MLCSTM2, as a function of known values, can be estimated
MM = TOT_MILES * (MLCSTM1 - MLCSTM2)

TOT_MILES is the total miles in the road network
COSTMi is the annualized cost of minor maint. for the SD road network
MLCSTMi is the annualized average per mile cost to maintain a roadway
assume: MLCSTM1 is $1235 per mile
A is .25
B is 1.50
ROi is the initial roughness with or without specification implementation
where
i = 1 is the future without a specification (current experience)
i = 2 is the future with a specification

Life Savings = MM * YRS_LIFE1

Figure 15. Savings from Reduced Minor Maintenance Costs.

Annual Savings(VO) = Savings from reduced Vehicle Operating Costs (VOC)
Annual Savings(VO) = COSTV1 - COSTV2

= TOT_VEH_MILES * (MLCSTV1 - MLCSTV2)
= TOT_MILES * ADT * 365 * (MLCSTV1 - MLCSTV2)

from Figure 17
MLCSTV1 = smooth_cost + (max_rough_cost - smooth_cost)*AV/2

and assuming that AV and BV are known and are defined as:
AV is the proportion of life in the rough state without the specification
BV = max_rough_cost / MLCSTV1 or
max_rough_cost = BV * MLCSTV1
(i.e.ratio of maximum cost to average cost (without the specification))
then
MLCSTV1 = smooth_cost + (BV*MLCSTV1 - smooth_cost)*AV/2
and
smooth_cost = MLCSTV1 * (1 - AV*BV/2) / (1 - AV/2)
next, applying Figure 17 to MLCSTV2
MLCSTV2 = smooth_cost + (max_rough_cost - smooth_cost)*XV/2
where XV is the proportion of life in the rough state assuming the specification is implementated & is calculated (see Figure 18)
XV = AV - AV * (R01 - R02) / (RT - R02)
then substituting for smooth_cost, and max_rough_cost
(assumes these values do not vary due to specification implementation!)
and also substituting for XV in the MLCSTV2 equation

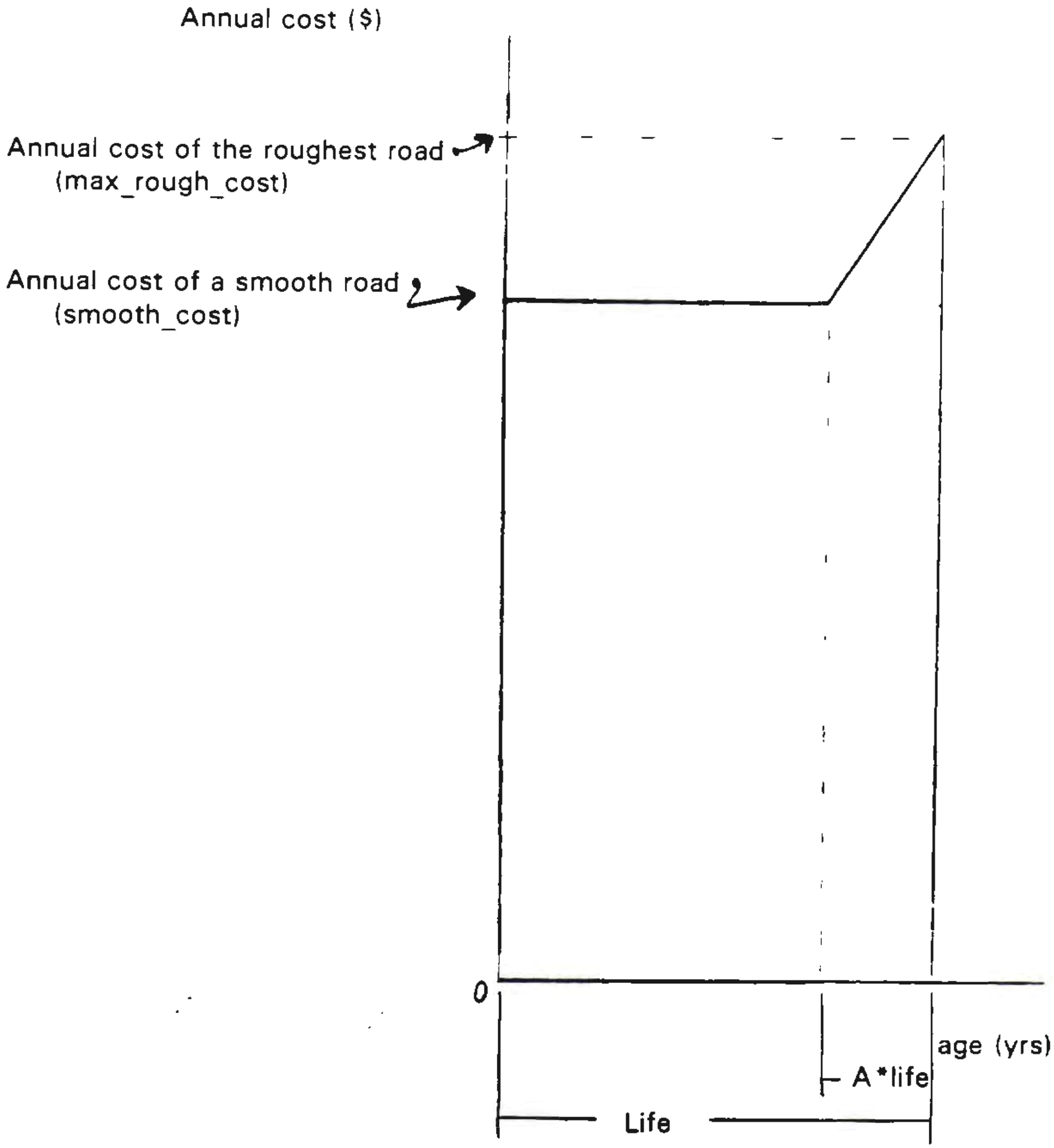
MLCSTV2 = smooth_cost + {max_rough_cost - smooth_cost} * XV / 2
MLCSTV2 = MLCSTV1 * (1 - AV*BV/2) / (1 - AV/2) +
{ BV * MLCSTV1 - MLCSTV1 * (1 - AV*BV/2) / (1 - AV/2) } *
[AV - AV * (R01 - R02) / (RT - R02)] / 2
and so now MLCSTV2, as a function of known values, can be estimated, and so

VO = TOT_MILES * ADT * 365 * (MLCSTV1 - MLCSTV2)

TOT_MILES is the total miles in the road network
TOT_VEH_MILES is the total miles driven in a year across TOT_MILES, and is calculated as TOT_MILES * ADT * 365
ADT is the average daily traffic on TOT_MILES (assume it is 973 vehicles per day)
COSTMi is the annualized cost of minor maint. for the SD road network
MLCSTVi is the average per mile cost to operate a vehicle
assume: MLCSTV1 is $0.30 per mile * 1.2 (20% VOC increase factor for trucks)
AV is .25
BV is 1.01
R0i is the initial roughness with or without specification implementation
where
i = 1 is the future without a specification (current experience)
i = 2 is the future with a specification

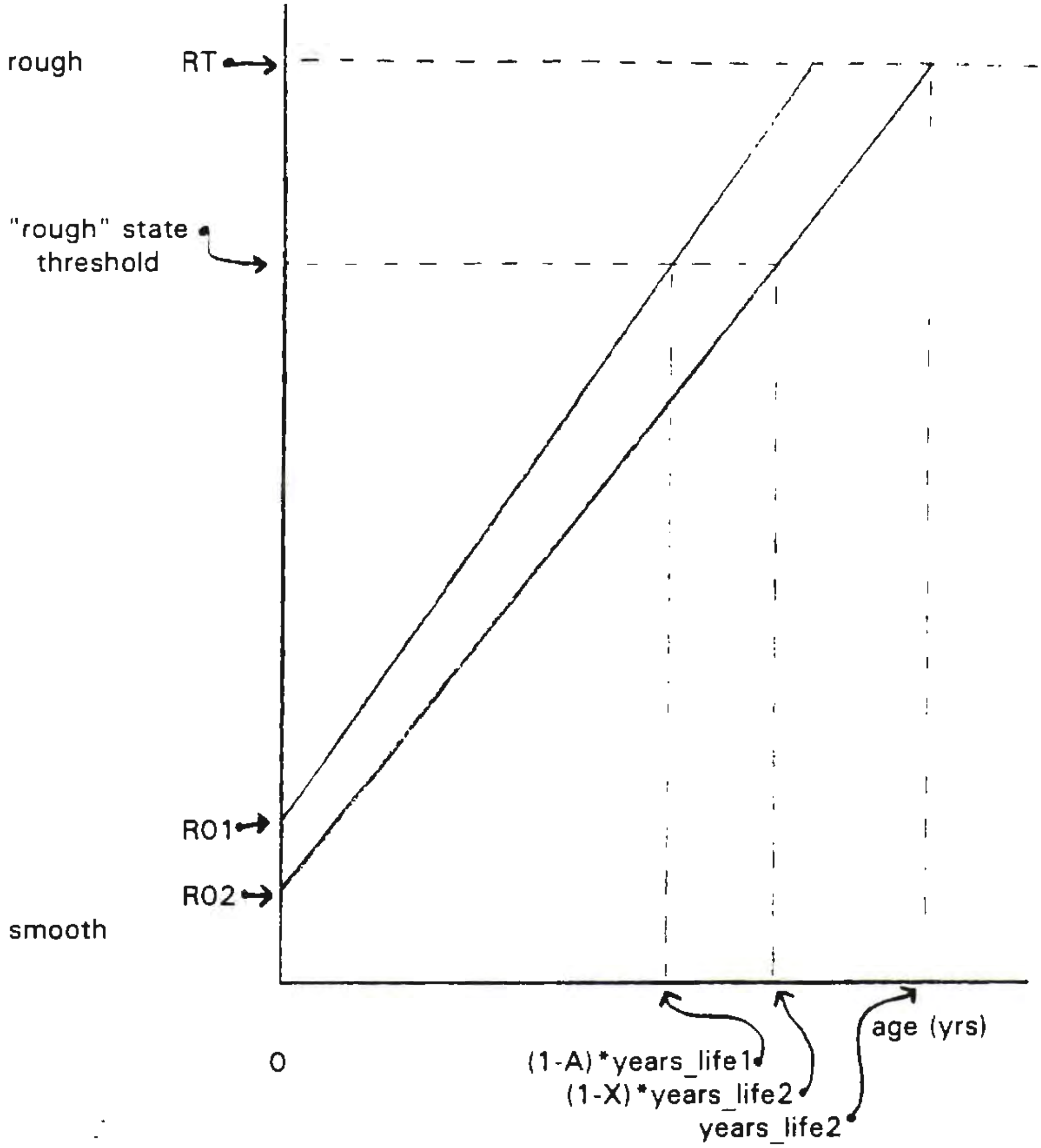
Life Savings = VO * YRS_LIFE1

Figure 16. Savings Due Reduced Vehicle Operating Costs (VOC)



Notes: "A" (or AV) is the proportion of life when the road is in the rough state
average annual cost = smooth_cost + (max_rough_cost - smooth_cost) * A/2

Figure 17. Costs Based on the Proportion of Time in the Rough State (A).



Notes: "A" (or AV) is the proportion of life when the road is in the rough state without the specification
"X" (or XV) is the proportion of life when the road is in the rough state with the specification

Figure 18. Proportion of Life in Rough State with & without the Specification

Cost = ANNUAL_SD_TESTING_COST + ANNUAL_SD_ADMIN_COST

Figure.19. Cost of Specification Administration and Justification.

APPLICATION OF METHODOLOGY

Estimates for 14 items are needed to calculate annual economic benefit using available SDDOT smoothness data (Items 1 through 14 as shown in Figure 20). Items 1 through 9 and Item 11 have been estimated in discussion with SDDOT staff as follows:

	Items	Values
1.	Total network mileage considered. (2 lane miles)	6022 miles
2.	Annual minor maintenance cost ($/mile).	$1,235
3.	% increase in minor maintenance cost for rough roads.	50%
4.	SD annual specification administrative cost to test 100mi.	$5,000
5.	SD annual cost of field testing to test 100mi.	$25,000
6.	Average ADT for SD roads.	993
7.	Avg. VOC dollars per mile.	$0.30
7a.	% increase in vehicle operating cost for rough roads.	1%
8.	Avg. IRI just prior to construction (m/km).	2.6m/km
9.	Dollars to rehabilitate a center line mile (in the absence of a specification).	$70,000
11.	Avg. life of a pavement (years) (in the absence of a specification)	13 years

Items 9 and 11 were calculated assuming overlay construction . The cost for a 2" overlay was estimated at $70,000 per 2 lane mile. Life of a 2" overlay was set at 13 years.

1. Total network mileage considered	100
2. Annual minor maintenance (MM) cost ($/mile)	1,235
3. % increase in MM cost due rough roads	50
4. SD annual specification administrative cost	5,000
5. SD annual cost of field testing	25,000
6. Average ADT for SD roads	993
7. Avg. VOC dollars per mile	0.30
7a. % increase in VO cost due rough roads	1
8. Avg. IRI just prior to construction (m/km)	2.60

	Without Specification		With Specification	
Dollars to rehabilitate a centerline mile	9.	70,000	10.	70,000
Avg. pavement life (yrs)	11.	13	12.	14
Initial IRI (m/km)	13.	1.30	14.	1.20

Annual Savings Due:

Extra pavement life	38,461
Minor maintenance cost reduction	630
Specification administration	-30,000
Vehicle operating costs reduction	1,331
Total annual savings	10,423

Figure 20. Sample ECON Cost Saving Computer Program Inputs and Results.

Economic Parameter Estimates

The cost to rehabilitate a road after specification implementation (Item 10) was set equal to the rehabilitation cost prior to specification implementation (Item 9). Based upon interviews of state DOT personnel whose states recently adopted an AC pavement construction smoothness specification, it was concluded that the average construction bid prices did not change due to specification implementation. This conclusion applied to state specifications with or without bonus clauses.

It is a project task to quantify current levels of initial smoothness after construction (Items 13 and 14) as well as subsequent smoothness deterioration from which Item 12 could be calculated.

Four different types of data as documented in Appendix A were obtained from SDDOT.

1. SD Profiler data for 12 one mile sections in the 1992 rehabilitation program collected just after rehabilitation.
2. Profilograph data on the same 1992 program 12 sections.
3. SD Profiler data for 22 one mile sections collected within the last 10 years, just after those sections were rehabilitated/constructed.
4. The entire history of SD Profiler data for 10 one mile sections collected over the last 10 years.

Initial Smoothness Estimates and Consequent Pavement Life

Using this data, estimates for initial smoothness after construction and subsequent smoothness deterioration were obtained. Based upon the data received, it was observed that South Dakota roads over the past 10 years have been constructed relatively smoothly. Figure 21 shows a smoothness (IRI) histogram for 49 one mile road sections shortly after they had been rehabilitated. Eighty-eight percent of these sections are considered very smooth at construction (IRI < = 2.1 m/km). For the economic analysis a median IRI of 1.3 m/km was used for smoothness just after construction in the absence of a specification (Item 13). For initial smoothness in the presence of a specification (Item 14), the 80th percentile IRI value of 1.05 m/km was used.

Smoothness Deterioration Estimates

Smoothness deterioration was analyzed using multi-year data for 10 one mile South Dakota road sections. For each one mile section, elevation traces for each year's data were plotted side-by-side (see Appendix B). Adjustments to longitudinal distance were made in order to align data for the same section across time. Once aligned, section data was broken up into 1/10 mile lengths. Then, statistical analyses were performed to determine if initially smoother subsections (1/10 mile) retained their smoothness over time better than those initially rougher. Regression formulas set up to quantify deterioration rate, as a function of initial smoothness, were run under various circumstances. Initially, all subsections were included. Then, only the 20% initially smoothest and the 20% initially roughest were included. Finally, in order to compensate for possible heaving effects in selected sections, a "within section" analysis was performed that, in effect, removed the average heaving effect on a section-by-section basis before performing the regression analysis. In most cases, the results show that initially rougher roads deteriorate slower than the initially smoother sections and on average, after 7 years, the 20% smoothest sections were on the same deterioration curve as the 20% initially roughest sections.

Note 1: It is conjectured that loss of initial extreme smoothness may be due to settling, or heaving.

HISTOGRAM OF IRI (mm/km)

	IRI (m/km)		expected TRS	
COUNT	LOW	HIGH	LOW	HIGH
1	0.1	0.5	0.1	0.3
5	0.5	0.9	0.3	0.5
17	0.9	1.3	0.5	0.75
14	1.3	1.7	0.75	1.0
6	1.7	2.1	1.0	1.25
5	2.1	2.5	1.25	1.5
1	2.5	2.9	1.5	1.7

CASES INCLUDED 49

Figure 21. Smoothness (IRI) Histogram of Just Rehabilitated/Constructed Road Sections.

Note 2: All of the sections reviewed were initially very smooth. The difference between the smoothest and the roughest was small. As such, the inference just made does not apply to roads that were constructed very rough. In our sample, initial roughness for all but one section was valued at IRI <2.5 m/km.

Analysis

Based upon the information already presented, there are two ways to justify specification implementation: 1. by extending the life of a sufficient number of rehabilitated miles of road, or 2. by sufficiently improving the roadway smoothness at construction for a large number of miles of rehabilitated roadway.

Extending roadway life. A typical annual rehabilitation program for South Dakota covers 400 miles. If 100 miles were tested annually at a cost of $30,000, then, according to the calculations in Figure 13, if for at least 10 of these miles the contractor improved his construction methods enough to extend life by one year, then the savings due extended life would exceed $30,000 for those 10 miles (see Figure 13). In the researcher's opinion SDDOT can get one year of extra life out of 10 miles of constructed roadway annually through selective testing. Using this reasoning, specification implementation is justified. NOTE: Figure 22 shows an ECON program run for the $5,000 cost savings shown in Figure 13. Other Figure 13 cost values were calculated setting Item 1. equal to Item 11. and then changing the value of Item 12. Item 1. is set equal to Item 11. in order to simulate one mile of roadway for a "lifetime" number of years.

Improving initial smoothness at construction. Using an approximate current construction experience (no specification) IRI distribution as obtained from Figure 21, applying cost savings from Figure 14, and hypothesizing conservative smoothness improvements due to specification implementation, a cost savings due smoothness increase at construction for 100 miles of roadway tested per year is calculated at $20,700 per year.

Initial IRI distribution (see Fig 21)	Initial IRI without spec. distribution	Percent IRI improvement (hypotheses)	Initial IRI with spec. distribution	Savings for one mile of rehabilitated roadway ($ from Fig 14)
10%	0.5	0%	0.50	$ 0
20%	0.9	2%	0.88	$ 41 * .2
30%	1.3	4%	1.25	$132 * .3
25%	1.7	4%	1.63	$280 * .25
15%	2.1	5%	2.00	$594 * .15

				$207/mile is saved or $20,700 / 100mi.

The $20,700 does not cover the $30,000 annual cost to administer 100 miles of testing annually. However, the assumptions made, in the opinion of this researcher, are very conservative. The percent IRI improvement at construction could easily double, and that would justify specification implementation on IRI at construction improvement alone. Also, if the entire 400 miles annual rehabilitation program were tested, then it would be difficult to justify an annual cost to administer of greater than $100,000 (unit cost decrease due the size of the testing program), while the savings would exceed $100,00 ($20,700 * 5). NOTE: Figure 23 shows an ECON program run for the $187 cost savings shown in Figure 14. Other Figure 14 cost values were calculated by resetting Items 11. and 12, accordingly. Item 1. is set to 13 to simulate one mile of roadway for 13 years of "lifetime" savings.

Finally, even if the IRI improvement at construction did <u>not</u> justify specification implementation, then the combination of savings due: 1. life increase, and 2. initial IRI improvement, would justify implementation.

1.	Total network mileage considered	13
2.	Annual minor maintenance (MM) cost ($/mile)	1,235
3.	% increase in MM cost due rough roads	50
4.	SD annual specification administrative cost	0
5.	SD annual cost of field testing	0
6.	Average ADT for SD roads	993
7.	Avg. VOC dollars per mile	0.30
7a.	% increase in VO cost due rough roads	1
8.	Avg. IRI just prior to construction (m/km)	2.60

		Without Specification		With Specification
Dollars to rehabilitate a centerline mile	9.	70,000	10.	70,000
Avg. pavement life (yrs)	11.	13	12.	14
Initial IRI (m/km)	13.	1.30	14.	1.30

Annual Savings Due:

Extra pavement life	5,000
Minor maintenance cost reduction	0
Specification administration	0
Vehicle operating costs reduction	0
Total annual savings	5,000

Figure 22. Sample ECON Cost Saving Computer Program Inputs and Results. (to obtain Figure 13 values)

APPENDIX A

INFORMATION GATHERED FOR THIS PROJECT

The information gathered for this project falls into three categories.

1. Smoothness statistic and/or smoothness measuring device literature.

2. State DOT specification and background information.

3. Information obtained from SDDOT.

    a) The current concrete specification.
    b) The 1992 highway needs analysis report.
    c) Estimates for parameters needed in the economic analysis.
    d) One mile sections of SD profiler elevation and, at times, profilograph PIs and PI traces.

Background smoothness related literature included reports on procedure development of the calibration of profilographs, sensitivity analysis of the IRI variable, RMSVA documentation, and a draft memo on the Ride Number statistic produced by NCHRP Project 1-23. These documents were used to calculate and evaluate already existing smoothness statistics. These documents also provided information on how other agencies develop and justify similar specifications.

During the course of this project, 13 state DOTs were interviewed with respect to their current or planned asphalt concrete construction smoothness specifications. Nine of the states sent their written specifications. A synopsis of this state survey is available in the main body of this report.

During the course of this project and at the request of the researchers, SDDOT provided: 1) their current pavement construction smoothness specification for Portland Cement to concrete roads, 2) 1992 highway needs analysis report, 3) many of the inputs that are needed for the economic analysis of the specification that was performed during this project, and 4) all of the profile and profilograph data used on this project. One hundred and twenty-eight (128) one-mile profiles were obtained. The first 13 profiles belonged to 13 one-mile sections that had just been constructed in the 1992 construction program. For these 13 sections, SD profiler data was obtained. A profilograph was also run on these 13 miles of road, the PI trace was obtained, and SDDOT estimated PIs provided. The next 21 profiles were obtained from SDDOT archives. They represented 21 different one-mile sections that had been constructed/rehabilitated not more than two years prior to the date that the profile was collected. The remaining profiles were obtained from 10 different one-mile sections. These 94 profiles obtained from SDDOT archives provided a multiple year perspective on each of these ten sections. Eight of the ten sections' data was obtained in two lanes. As a result, there were 18 different multi-year perspectives to analyze. Figure A.1 documents all sections analyzed on this project. Figure A.1 can also be used to cross reference between sections and computer file names.

Figure A.2 shows several profile statistics calculated for each of the 128 one-mile profiles.

One hundred twenty-eight profiles/statistic trace files are provided to SDDOT on this project. The record layout for these files is shown in Figure A.3. Three more files are also provided to SDDOT including; 1) statistic file where each record contains statistics of the entire one-mile profile length (documentation for this file is shown in Figure A.4) 2) 1/10 mile statistics file (documented in Figure A.5) and 3) a file containing histogram information for each one-mile profiles (documented in Figure A.6). These histograms are counts of the maximum number of vertical displacements of the 10 foot telescoped rolling straightedge broken into .01 of an inch increments.

FILE NAME	LANE NO.	SECTION NAME	START MILEAGE	YEAR(S) COLLECTED	constr./ overlaid	chip sealed
MULTI-YEAR HISTORICAL SECTIONS						
A12000.1*	1	US 12	127.00	1982 - 1990	1984	1990
A12000.2*	2	US 12	127.00	1987 - 1992	1984	1990
A12001.0*	1	US 212	60.00	1983 - 1990	1977	1984
A12002.0*	2	US 212	60.00	1987 - 1989	1977	1984
A37000.1*	1	SD 37	54.00	1986 - 1992	1980	--
A37000.2*	2	SD 37	54.00	1985 - 1992	1980	--
A37001.0*	1	SD 37	55.00	1986 - 1991	1980	--
A37002.0*	2	SD 37	55.00	1983 - 1991	1980	--
A38A01.0*	1	SD 38A	364.57	1983 - 1990	1985 (30%)	--
A44000.1*	1	SD 44	296.00	1982 - 1992	1983	1988
A44000.2*	2	SD 44	296.00	1983 - 1991	1983	1988
A45000.1*	1	SD 45	76.00	1982 - 1992	1982	1987
A45000.2*	2	SD 45	76.00	1983 - 1992	1982	1987
A63000.1*	1	SD 63	143.00	1983 - 1989	1982	1988
A63000.2*	2	SD 63	143.00	1986 - 1992	1982	1988
A63001.0*	1	SD 63	145.00	1983 - 1989	1985 (40%)	1989 (40%)
A63002.0*	2	SD 63	145.00	1986 - 1991	1985 (40%)	1989 (40%)
A83000.1*	1	US 83	214.00	1984 - 1992	1982	1987 (sand)
A83000.2*	2	US 83	214.00	1987 - 1989	1982	1987 (sand)
1992 PROGRAM SECTIONS						
A12000.002		Route 212	4.00	1993		
A12000.314		Route 212	317.00	1993		
A12000.315		Route 12	315.00	1993		
A18000.311		Route 18	314.00	1993		
A34000.002		Route 34	3.00	1993		
A38000.358		Route 38	358.00	1993		
A47000.126		Route 47	127.00	1993		
A81000.001		Route 281	0.00	1993		
A81000.075		Route 81	76.00	1993		
A81000.086		Route 281	87.00	1993		
A83000.096		Route 83	100.00	1993		
A83000.097		Route 83	111.00	1993		
AENN00.000		Route 88	0.00	1993		
ONE TIME HISTORICAL SECTIONS (just constructed/rehabilitated)						
A07000.000		SD 407	0.50	1990		
A12000.103		US 12	127.00	1986		
A12000.160		US 12	168.00	1986		
A15000.107		SD 115	106.00	1987		
A16000.044		US 16	17.00	1990		
A17000.024		SD 17	29.00	1989		
A19000.032		SD 19	35.00	1990		
A39000.195		SD 239	189.00	1988		
A44000.172		SD 44	179.00	1988		
A44000.240		SD 44	211.00	1988		
A44000.298		SD 44	296.00	1985		
A45000.080		SD 45	76.00	1984		
A45000.177		SD 45	160.00	1987		
A46000.318		SD 46	314.00	1986		
A49000.053		SD 49	44.00	1986		
A63000.167		SD 63	150.00	1986		
A73000.061		SD 273	70.00	1989		
A73000.146		SD 73	147.00	1990		
A73000.161		SD 73	166.00	1989		
A83000.019		US 183	8.00	1987		
A83000.213		US 83	214.00	1984		
A15000.106		SD 115	97.00	1989		

(A15000.106 was not used -- it is a concrete road)

*** -> THAT THERE ARE MANY PROFILES FOR THE SECTION/LANE ACROSS MANY YEARS (1982 - 1992)**

Figure A.1. Information on AC sections analyzed on this project.

Figure A.2 Statistics' Values for each of the 128 1-mile road section profiles

FILENAME	SECTION TYPE	JUST REHBD?	PI	IRI	PSI	TRS10 10 ft	TRS20 20 ft
A12000.182	H			3.46	2.48	2.160	2.259
A12000.185	H			3.01	1.55	1.189	1.223
A12000.186	H	Y		1.19	4.58	0.688	0.806
A12000.190	H			3.46	3.71	1.945	1.770
A12000.287	H	Y		1.23	4.58	0.699	0.813
A12000.288	H			1.29	4.53	0.704	0.859
A12000.289	H			1.42	4.46	0.825	0.935
A12000.292	H			2.22	4.16	1.276	1.276
A12001.083	H	Y		1.50	4.08	0.954	1.156
A12001.084	H			2.27	3.16	1.294	1.491
A12001.085	H			2.43	3.07	1.355	1.550
A12001.086	H			2.50	3.02	1.388	1.559
A12001.090	H			2.17	3.13	1.181	1.378
A12002.087	H			2.44	3.15	1.423	1.561
A12002.088	H			1.69	3.40	0.945	1.189
A12002.089	H			2.17	3.29	1.254	1.386
A37000.186	H	Y		2.52	4.01	1.403	1.354
A37000.187	H			2.21	4.08	1.245	1.244
A37000.191	H			2.46	3.97	1.425	1.387
A37000.192	H			2.67	3.93	1.462	1.407
A37000.285	H	Y		0.76	4.92	0.556	0.614
A37000.288	H			1.92	4.41	1.086	1.082
A37000.289	H			2.51	4.18	1.384	1.308
A37000.290	H			2.38	4.20	1.318	1.277
A37000.291	H			2.66	4.09	1.513	1.414
A37000.292	H			2.67	4.06	1.489	1.419
A37001.086	H			2.30	3.82	1.382	1.486
A37001.087	H			2.17	3.97	1.267	1.347
A37001.091	H			2.48	3.76	1.483	1.558
A37002.083	H	Y		0.61	4.96	0.478	0.572
A37002.084	H			0.84	4.87	0.591	0.691
A37002.085	H			0.63	4.93	0.526	0.643
A37002.088	H			2.05	4.08	1.189	1.283
A37002.089	H			2.42	3.94	1.388	1.413
A37002.090	H			2.30	3.97	1.321	1.376
A37002.091	H			2.61	3.82	1.505	1.534
A38A01.083	H			2.00	2.62	1.258	1.916
A38A01.084	H			2.71	3.14	1.578	1.844
A38A01.085	H			1.74	3.77	1.153	1.433
A38A01.086	H			1.73	3.38	1.084	1.503
A38A01.088	H			1.93	3.27	1.142	1.581
A38A01.089	H			1.96	3.15	1.244	1.683
A38A01.090	H			1.95	3.32	1.245	1.572

· section type

H -> multi-year historical data
O -> one-time historical data (just after construction)
N -> newly rehabilitated in 1992 program

Figure A.1 Statistics' Values for each of the 128 1-mile road section profiles

FILENAME	SECTION TYPE	JUST REHBD?	PI	IRI	PSI	TRS10 10 ft	TRS20 20 ft
A44000.182	H			2.58	3.60	1.551	1.685
A44000.186	H	Y		1.27	4.36	0.695	0.947
A44000.187	H			1.42	4.32	0.784	1.013
A44000.188	H			1.41	4.29	0.775	1.033
A44000.189	H			2.50	4.01	1.380	1.384
A44000.190	H			2.21	4.07	1.244	1.317
A44000.191	H			2.58	3.93	1.419	1.454
A44000.192	H			2.57	3.91	1.442	1.469
A44000.283	H	Y		0.51	4.95	0.433	0.565
A44000.285	H			1.60	3.26	0.861	1.038
A44000.291	H			2.11	4.06	1.217	1.286
A45000.182	H	Y		0.59	4.91	0.454	0.556
A45000.185	H			1.43	4.31	0.891	0.978
A45000.187	H			1.94	4.10	1.144	1.138
A45000.188	H			1.97	4.07	1.149	1.171
A45000.189	H			2.28	4.02	1.276	1.233
A45000.191	H			2.36	3.92	1.355	1.315
A45000.192	H			2.14	3.86	1.220	1.262
A45000.283	H	Y		0.51	4.97	0.441	0.551
A45000.284	H			2.16	3.19	1.127	1.204
A45000.290	H			2.32	3.94	1.353	1.313
A45000.291	H			2.66	3.84	1.509	1.425
A45000.292	H			1.89	4.05	1.103	1.175
A63000.183	H	Y		0.48	4.96	0.396	0.466
A63000.184	H			2.78	3.59	1.573	1.577
A63000.185	H			2.41	3.55	1.316	1.429
A63000.189	H			2.26	3.33	1.270	1.482
A63000.286	H			1.78	3.53	1.049	1.375
A63000.287	H			2.08	3.39	1.243	1.506
A63000.288	H			1.88	3.46	1.051	1.383
A63000.290	H			2.63	3.22	1.535	1.706
A63000.291	H			3.64	2.91	2.122	2.187
A63000.292	H			3.00	3.02	1.429	1.590
A63001.083	H	Y		1.07	4.37	0.745	1.002
A63001.084	H			3.04	3.02	1.730	2.013
A63001.085	H			2.54	3.06	1.560	1.932
A63001.089	H			1.89	3.67	1.091	1.324
A63002.086	H			1.65	3.83	1.026	1.168
A63002.087	H			2.28	3.69	1.334	1.338
A63002.088	H			1.69	3.80	1.011	1.177
A63002.090	H			2.96	3.40	1.796	1.707
A63002.091	H			3.02	3.41	1.752	1.687

\- section type
\- ---

H -> multi-year historical data
O -> one-time historical data (just after construction)
N -> newly rehabilitated in 1992 program

Figure A.2 Statistics' Values for each of the 128 1-mile road section profiles

FILENAME	SECTION TYPE	JUST REHBD?	PI	IRI	PSI	TRS10 10 ft	TRS20 20 ft
A83000.184	H			2.13	3.88	1.454	1.469
A83000.186	H	Y		1.24	4.42	0.724	0.776
A83000.188	H			2.80	3.85	1.589	1.468
A83000.190	H			2.41	4.00	1.362	1.281
A83000.191	H			2.19	4.05	1.308	1.233
A83000.192	H			2.62	3.91	1.493	1.378
A83000.287	H	Y		2.26	4.01	1.285	1.196
A83000.289	H			2.39	3.93	1.366	1.291
A12000.002	N	Y	3.80	1.09	4.45	0.574	0.722
A12000.314	N	Y	0.90	1.42	3.63	0.894	1.023
A12000.315	N	Y	6.60	1.67	4.30	1.002	1.572
A18000.311	N	Y	3.40	1.74	3.56	1.099	1.039
A34000.002	N	Y	2.30	1.16	4.35	0.636	0.767
A38000.358	N	Y	1.40	1.81	3.95	1.376	1.424
A47000.126	N	Y	1.20	1.96	3.58	1.694	1.788
A81000.001	N	Y	2.60	0.96	4.58	0.642	0.744
A81000.075	N	Y	0.70	1.74	4.21	1.051	1.212
A81000.086	N	Y	1.10	1.44	4.40	0.799	0.955
A83000.096	N	Y	3.20	1.43	4.11	0.826	0.952
A83000.097	N	Y	1.40	1.34	4.13	0.769	0.811
AENN00.000	N	Y	4.20	1.74	3.43	1.147	1.074
A07000.000	O	Y		1.85	4.02	1.135	1.233
A12000.103	O	Y		1.19	4.58	0.688	0.806
A12000.160	O	Y		1.42	4.48	0.846	0.854
A15000.107	O	Y		1.44	4.14	0.775	0.948
A16000.044	O	Y		1.69	4.58	0.914	0.970
A17000.024	O	Y		1.00	4.61	0.527	0.710
A19000.032	O	Y		1.40	4.07	0.755	0.931
A39000.195	O	Y		1.25	4.24	0.711	0.851
A44000.172	O	Y		2.44	4.02	1.404	1.310
A44000.240	O	Y		1.43	4.22	0.822	0.969
A44000.298	O	Y		1.40	4.37	0.860	1.035
A45000.080	O	Y		2.16	3.19	2.367	2.343
A45000.177	O	Y		1.03	4.54	0.607	0.694
A46000.318	O	Y		0.98	4.67	0.526	0.693
A49000.053	O	Y		1.23	3.59	0.679	0.914
A63000.167	O	Y		1.35	3.55	0.649	1.060
A73000.061	O	Y		1.10	4.30	0.600	0.828
A73000.146	O	Y		0.91	4.62	0.493	0.650
A73000.161	O	Y		1.31	4.75	0.722	0.735
A83000.019	O	Y		1.29	4.71	0.724	0.763
A83000.213	O	Y		2.13	3.88	1.454	1.469
A15000.106	X	y		2.16	4.50	1.220	1.148

section type

H -> multi-year historical data
O -> one-time historical data (just after construction)
N -> newly rehabilitated in 1992 program

These PI values were obtained using the California Profilograph

Structure for database: ALL PROFILE FILES

Field	Field Name	Type	Width	Dec	
1	ELEVATION	Numeric	7	3	SD Profiler elevations (in)
2	DISTANCE	Numeric	4		Longitudinal distance (ft). When the first record's distance is not equal to 0, then adjustments were made to align multi-year profiles for the same 1-mile section.
3	S1	Numeric	8	6	10' Rolling Straightedge (PI) trace
4	S2	Numeric	8	6	25' Rolling Straightedge (PI) trace (simple profilograph)
5	S3	Numeric	8	6	10' TRS Maximum Vertical Disp. (MVD) trace
6	S4	Numeric	8	6	20' TRS Maximum Vertical Disp. (MVD) trace
7	S5	Numeric	8	6	Ride Number trace

Figure A.3 SD Profiler Elevation Profile and Maximum Vertical Displacement (MVD) Profile File Description.

```
Structure for database: STAT.DBF
Number of data records:      128

Field Field Name  Type        Width Dec.

   1  FILENAME    Character     15      Profile file name
   2  SECT_TYPE   Character      1      Section type (H,N,O)(see Figure B)
   3  JUST_REHBD  Character      1      Yes/No if just constructed/rehab'd
   4  HISTORICAL  Character      1      Yes/No if multi-year historical

SDDOT PROVIDED STATISTICS
   5  PI          Numeric        5   2  Profilograph PI
   6  IRI         Numeric        5   2  SDDOT IRI (mm/km)
   7  PSI         Numeric        5   2  SDDOT PSI

PROJECT CALCULATED STATISTICS
   8  RN          Numeric        8   3  NCHRP 1-23 Ride Number (RN)
   9  STRAEDGE10  Numeric        8   3  10 ft max TRS
  10  PI2_10      Numeric        8   3  10' profilograph PI +/-.1"  blanking
  11  PI1_10      Numeric        8   3  10' profilograph PI +/-.05" blanking
  12  PI0_10      Numeric        8   3  10' profilograph PI      no blanking
  13  PIAREA2_10  Numeric        8   3  10' prflgrph trace area +/-.1"  blanking
  14  PIAREA1_10  Numeric        8   3  10' prflgrph trace area +/-.05" blanking
  15  PIAREA0_10  Numeric        8   3  10' prflgrph trace area     no  blanking
  16  STRAEDGE20  Numeric        8   3  20 ft max TRS
  17  RMSVA2_25   Numeric        8   3  25' RMSVA with +/-.2" blanking
  18  RMSVA1_25   Numeric        8   3  25' RMSVA with +/-.1" blanking
  19  RMSVA0_25   Numeric        8   3  25' RMSVA with     no blanking
  20  PI2_25      Numeric        8   3  25' profilograph PI +/-.2"  blanking
  21  PI1_25      Numeric        8   3  25' profilograph PI +/-.1"  blanking
  22  PI0_25      Numeric        8   3  25' profilograph PI     no  blanking
  23  PIAREA2_25  Numeric        8   3  25' prflgrph trace area +/-.2"  blanking
  24  PIAREA1_25  Numeric        8   3  25' prflgrph trace area +/-.1"  blanking
  25  PIAREA0_25  Numeric        8   3  25' prflgrph trace area     no  blanking
  26  RMSVA2_10   Numeric        8   3  10' RMSVA with +/-.1"  blanking
  27  RMSVA1_10   Numeric        8   3  10' RMSVA with +/-.05" blanking
  28  RMSVA0_10   Numeric        8   3  10' RMSVA with      no blanking
```

Figure A.4 Statistics File Description for One hundred Twenth-eight (128) 1-mile Sections.

Structure for database: STATTNTH.DBF
Number of data records: 1280

Field	Field Name	Type	Width	Dec	
1	FILENAME	Character	15		File name
2	MILE_PT	Numeric	3	1	Mile point
3	DELTASTR10	Numeric	8	3	1 year change in 10' TRS
4	DELTAYEAR	Numeric	3		Age of pavement when change calculated
5	LEVEL	Numeric	3		-2 -> initial roughness < .4 (TRS) -1 -> .4 <= initial roughness < .6 (TRS) 0 -> .6 <= initial roughness < .8 (TRS) 1 -> .8 <= initial roughness < 1. (TRS) 2 -> 1. <= initial roughness (TRS)
6	MAXMIN	Numeric	3		-1 -> 20% smoothest initial roughness 1 -> 20% roughest initial roughness
8	IGNORE	Character	1		Y -> ignore for regression calculation
9	SECT_TYPE	Character	1		(see STAT.DBF record layout)
10	JUST_REHBD	Character	1		Y -> section was just rehabilitated
11	HISTORICAL	Character	1		Y -> section with multiple year profiles
SDDOT PROVIDED STATISTICS					
12	PI	Numeric	5	2	Profilograph PI
13	IRI	Numeric	5	2	SDDOT IRI (mm/km)
14	PSI	Numeric	5	2	SDDOT PSI
PROJECT CALCULATED STATISTICS					
15	RN	Numeric	8	3	NCHRP 1-23 Ride Number (RN)
7	STRAEDGE10	Numeric	8	3	10 ft max TRS
16	PI2_10	Numeric	8	3	10' profilograph PI +/-.1" blanking
17	PI1_10	Numeric	8	3	10' profilograph PI +/-.05" blanking
18	PI0_10	Numeric	8	3	10' profilograph PI no blanking
19	PIAREA2_10	Numeric	8	3	10' prflgrph trace area +/-.1" blanking
20	PIAREA1_10	Numeric	8	3	10' prflgrph trace area +/-.05" blanking
21	PIAREA0_10	Numeric	8	3	10' prflgrph trace area no blanking
22	STRAEDGE20	Numeric	8	3	20 ft max TRS
23	RMSVA2_25	Numeric	8	3	25' RMSVA with +/-.2" blanking
24	RMSVA1_25	Numeric	8	3	25' RMSVA with +/-.1" blanking
25	RMSVA0_25	Numeric	8	3	25' RMSVA with no blanking
26	PI2_25	Numeric	8	3	25' profilograph PI +/-.2" blanking
27	PI1_25	Numeric	8	3	25' profilograph PI +/-.1" blanking
28	PI0_25	Numeric	8	3	25' profilograph PI no blanking
29	PIAREA2_25	Numeric	8	3	25' prflgrph trace area +/-.2" blanking
30	PIAREA1_25	Numeric	8	3	25' prflgrph trace area +/-.1" blanking
31	PIAREA0_25	Numeric	8	3	25' prflgrph trace area no blanking
32	RMSVA2_10	Numeric	8	3	10' RMSVA with +/-.1" blanking
33	RMSVA1_10	Numeric	8	3	10' RMSVA with +/-.05" blanking
34	RMSVA0_10	Numeric	8	3	10' RMSVA with no blanking

Figure A.5 Statistics File Description For All One-tenth Mile Subsections of the One hundred Twenty-eight (128) 1-mile Sections.

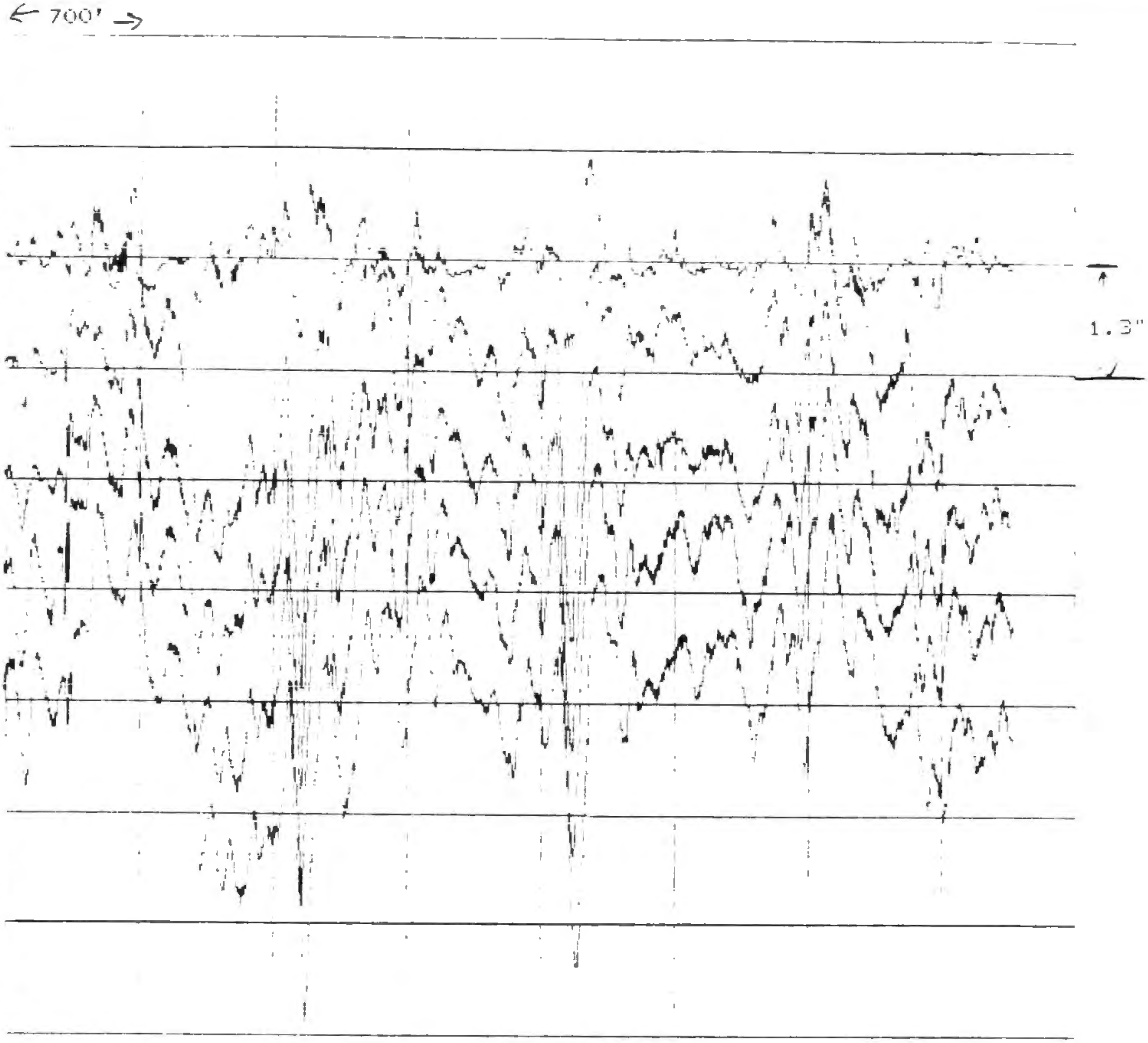
```
Structure for database: E:\SDROUGH\PRG\DISTRIB.DBF
Number of data records:      128

Field    Field Name    Type       Width

1 - 51   A1 - A51      Numeric     4      For field "i", a count of all TRSs
                                            between .01*(i-1) <= TRS < .01*i
                                            for the 1 mile profile identified
                                            by FILENAME
  52     FILENAME      Character 15       Profile file name
```

Figure A.6 Maximum Vertical Displacement (MVD) Histogram File Description for One hundred Twenth-eight (128) 1-mile Sections.

APPENDIX B

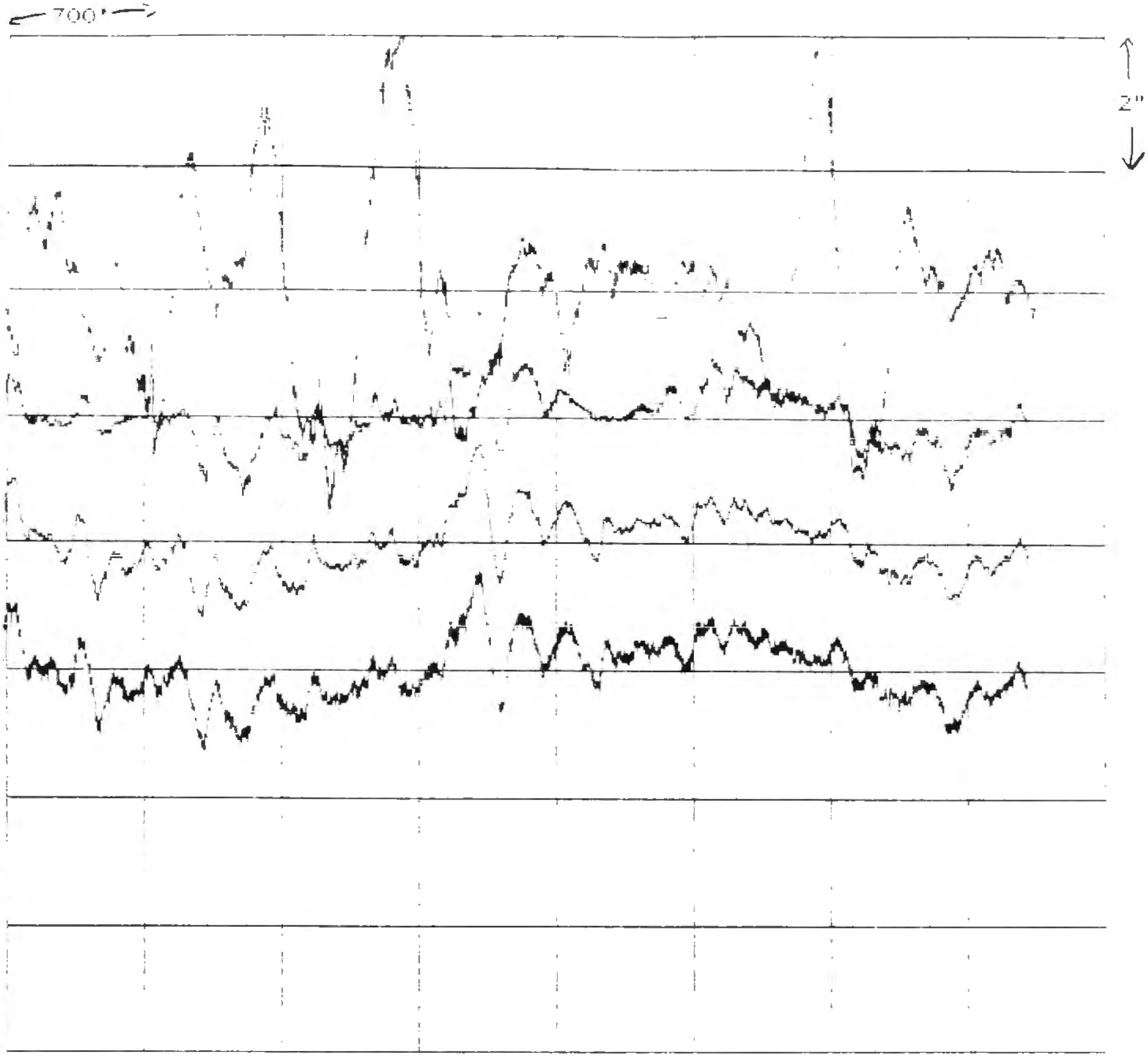
MULTI-YEAR ELEVATION PROFILES FOR TEN 1-MILE ROAD SECTIONS

This appendix contains plots of elevation profiles for all of the multi-year historical sections (10) analyzed in this project. Each plot contains all years' profiles for each one one-mile section/lane. When adjustments were made to the horizontal off-set to align these multi-year profiles, it is indicated on the plot. File names for each plot are also indicated on the plot. Distance between consecutive vertical lines on the plot is 700 feet. Distance between consecutive horizontal lines on the plot is either 1.3 inches or 2 inches and is documented on each plot. The consistency of these profiles for one section across time supports the hypothesis that the SD profiler collects repeatable data. The identification of construction (or even heaving) is evident from these profiles. Histograms of the maximum vertical displacement of the TRS for these 10 sections across all years can be found in Appendix C. These are also useful in identifying roadway smoothness changes.



path name: e:\scrough\august14\

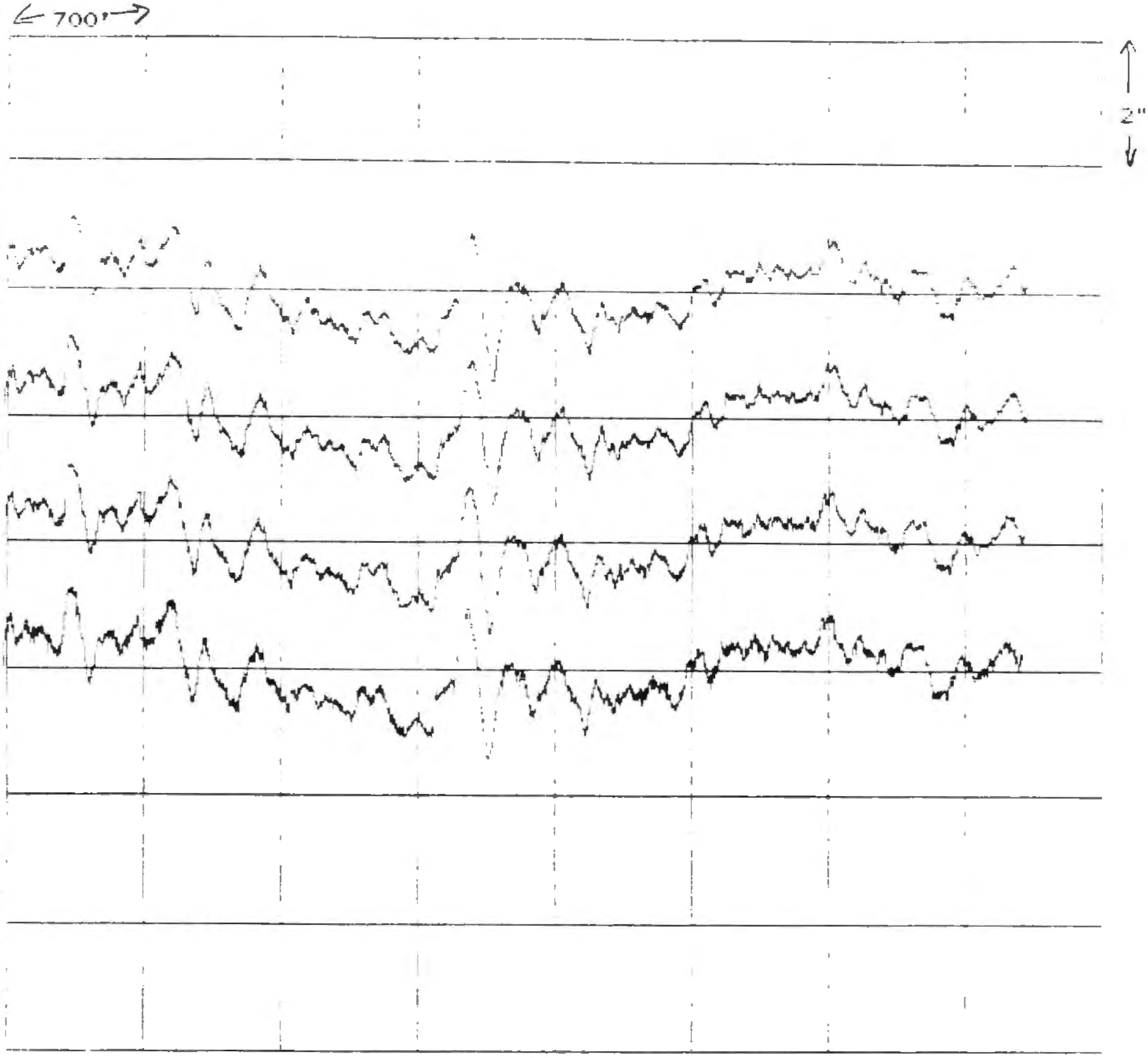
	file names		offset
1.	A12001.083	1.	0
2.	A12001.084	2.	0
3.	A12001.085	3.	0
4.	A12001.086	4.	-10
5.	A12001.090	5.	-25
6.		6.	0
7.		7.	0
8.		8.	0



path is: e:\sdrough\analysis\\\\\

	file names	offset	
1.	a12000.182	1.	0
2.	a12000.195	2.	0
3.	a12000.186	3.	0
4.	a12000.190	4.	0
5.		5.	0
6.		6.	0
7.		7.	0
8.		8.	0

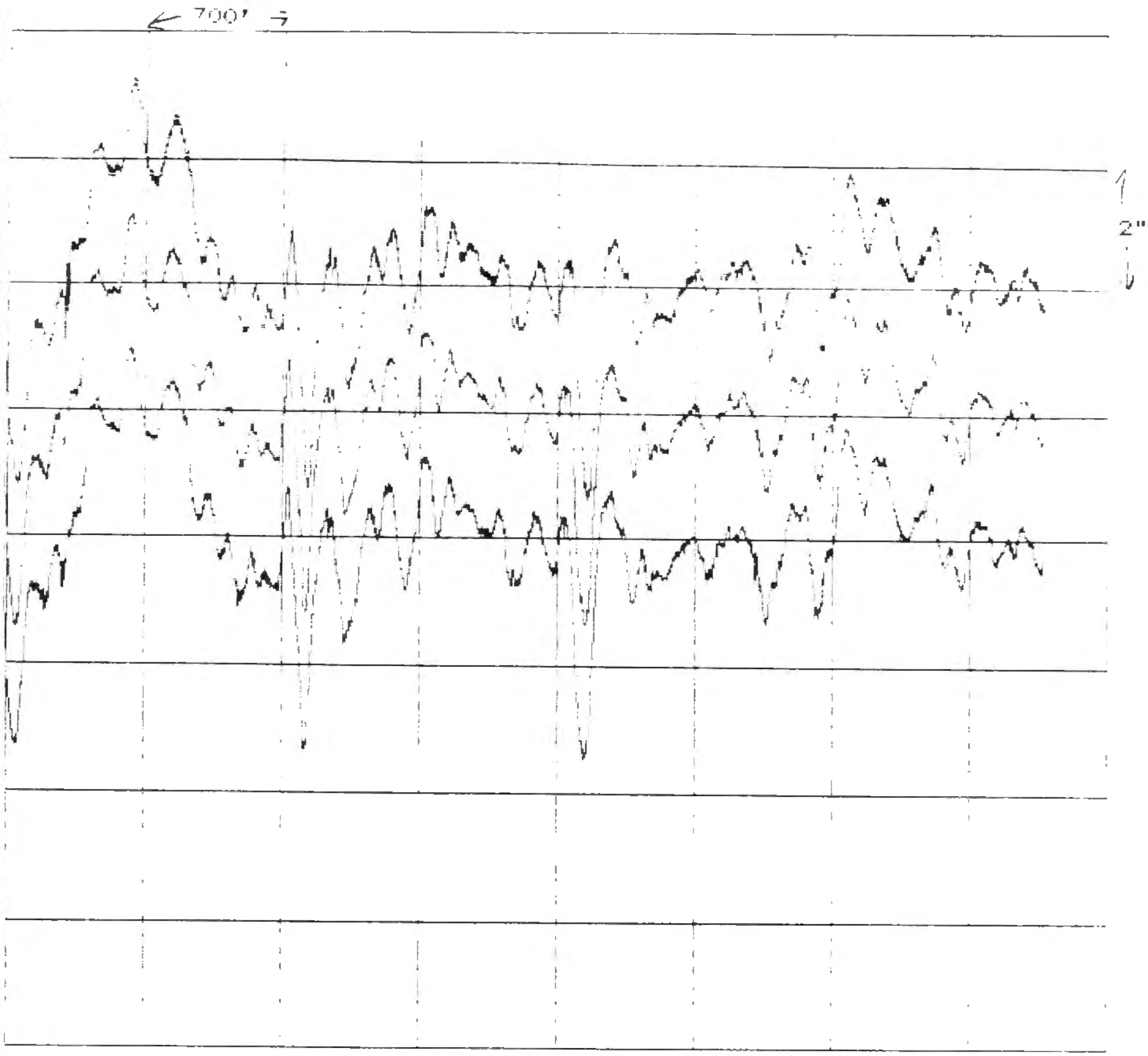
to exit press ESC



path is: e:\sdrough\analysis\\\\\

file names		offset	
1.	a12000.287	1.	0
2.	a12000.288	2.	0
3.	a12000.289	3.	0
4.	a12000.292	4.	0
5.		5.	0
6.		6.	0
7.		7.	0
8.		8.	0

to exit press <ESC>

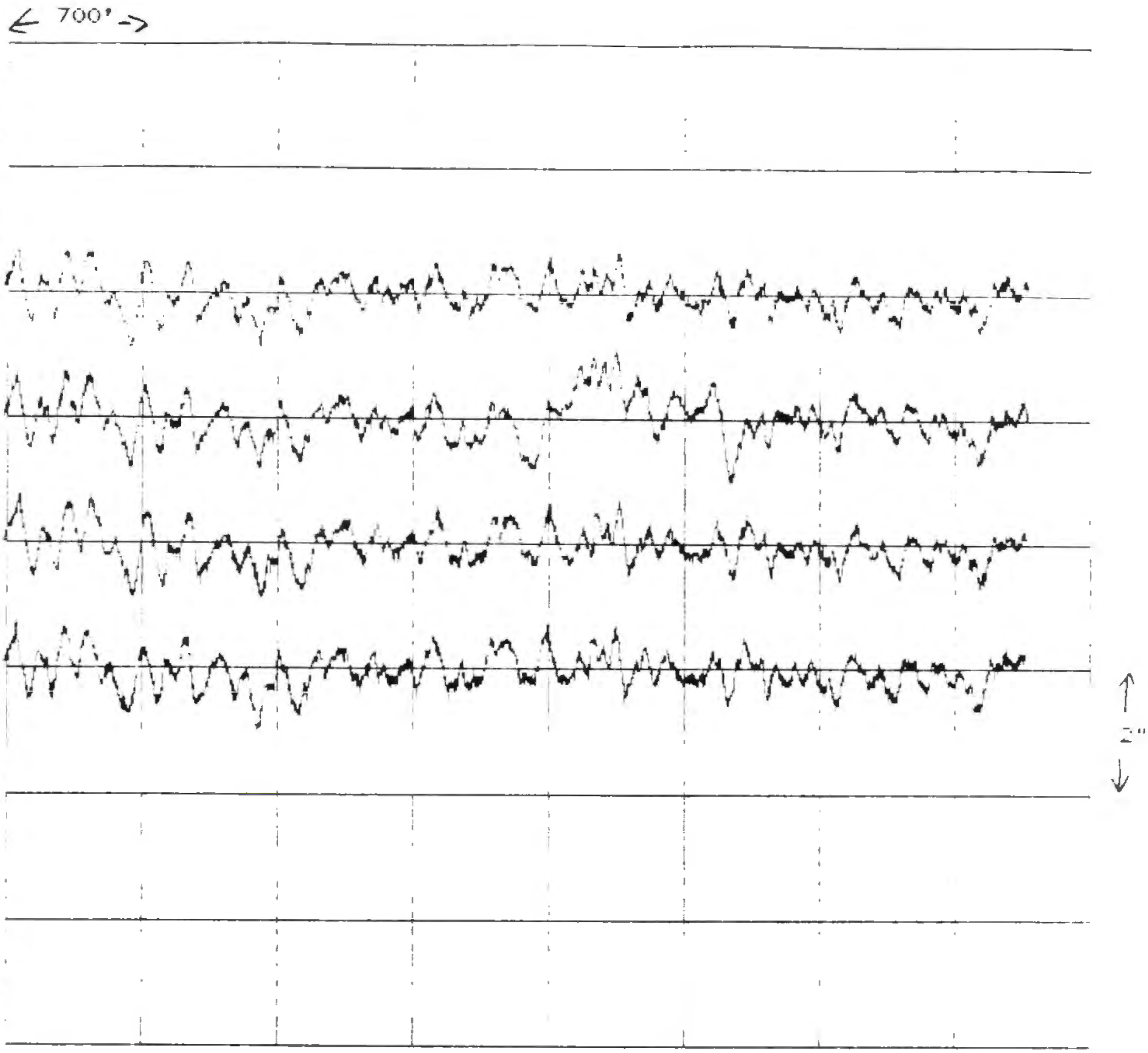


path is: e:\sdrough\analysis\\\

file names		offset
1. a12001.087	1.	0
2. a12001.088	2.	0
3. a12001.089	3.	0
4.	4.	0
5.	5.	0
6.	6.	0
7.	7.	0
8.	8.	0

LOM

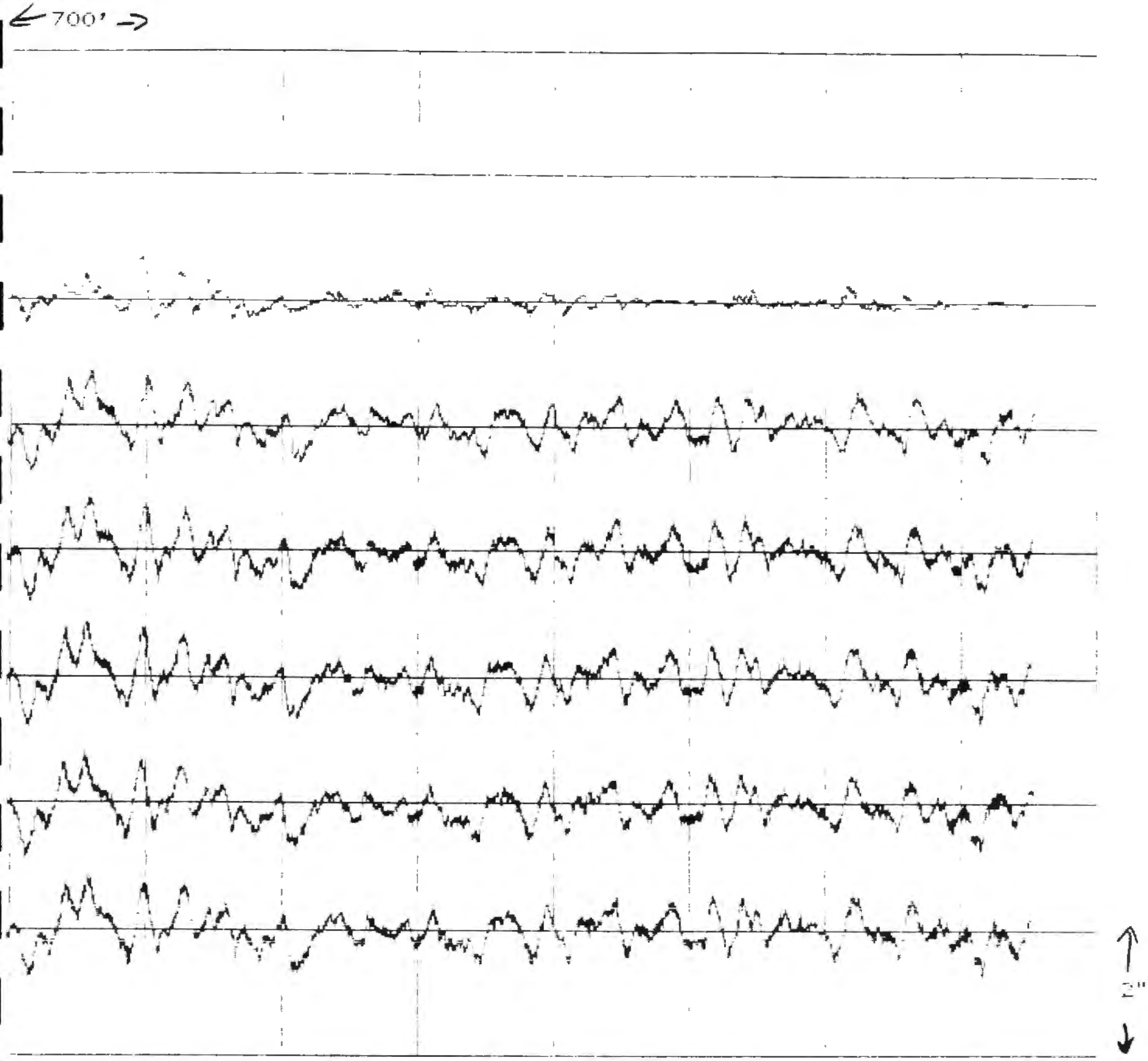
to exit press (ESC)



path is: e:\sdrough\analysis\\

file names		offset	
1.	a37000.186	1.	0
2.	a37000.187	2.	0
3.	a37000.191	3.	0
4.	a37000.192	4.	0
5.		5.	0
6.		6.	0
7.		7.	0
8.		8.	0

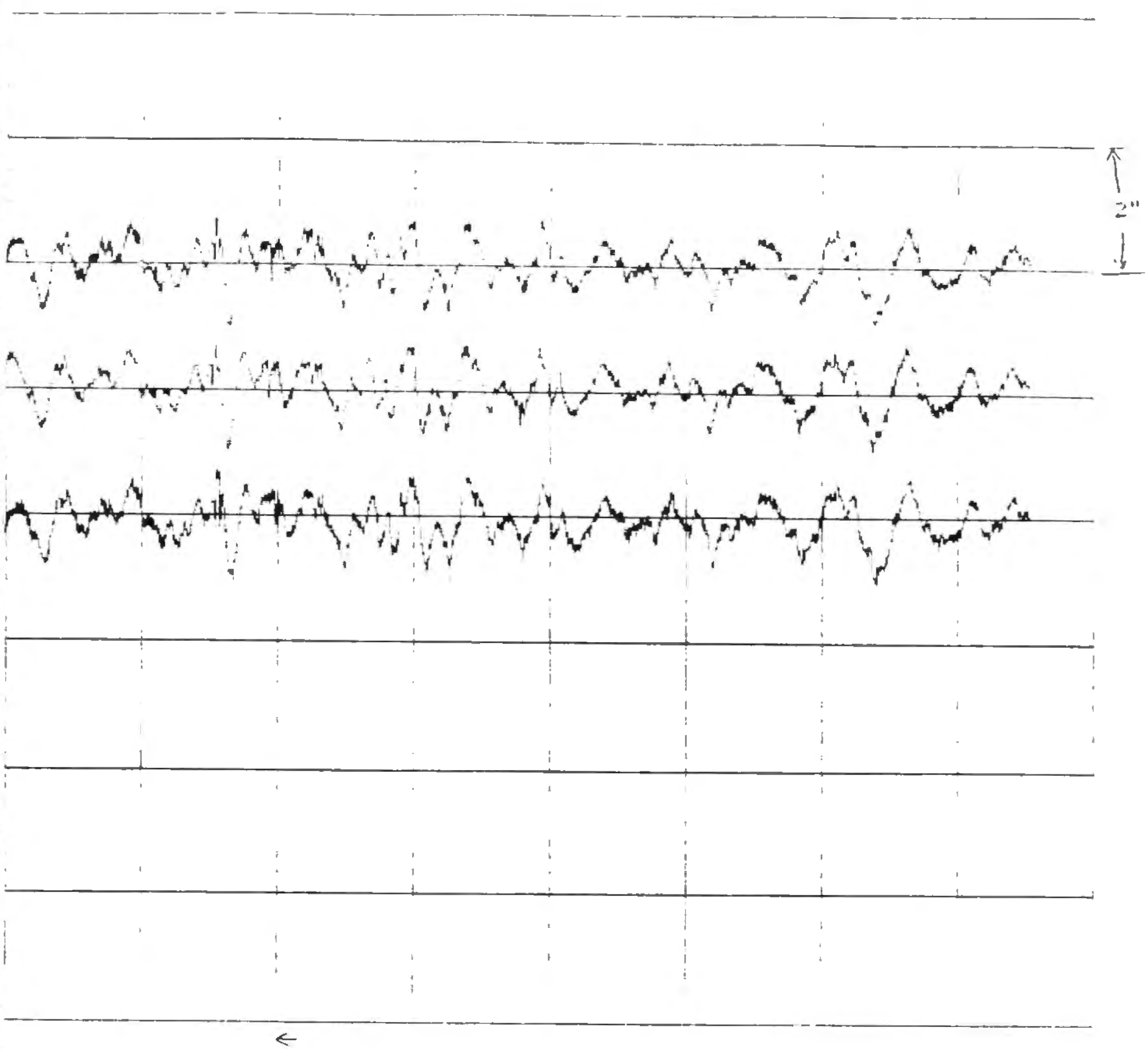
to exit press (ESC)



path is: e:\srough\analysis\\\

file names		offset	
1.	a37000.285	1.	0
2.	a37000.288	2.	0
3.	a37000.289	3.	0
4.	a37000.290	4.	0
5.	a37000.291	5.	0
6.	a37000.292	6.	0
7.		7.	0
8.		8.	0

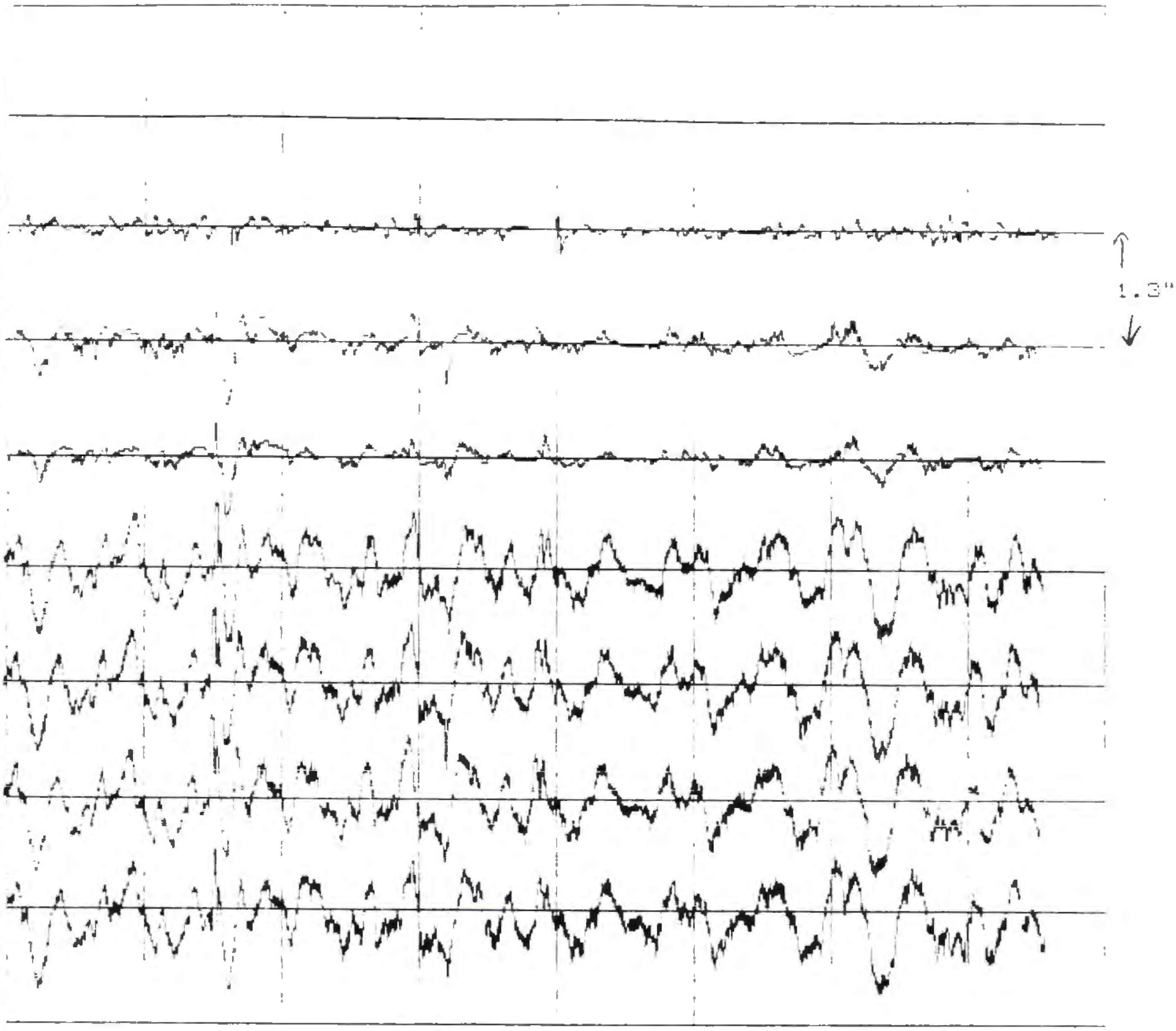
to exit press <ESC>



data in: e:\sdrough\analysis\\\\

file names		offset	
1.	a37001.093	1.	0
2.	a37001.087	2.	0
3.	a37001.091	3.	0
4.		4.	0
5.		5.	0
6.		6.	0
7.		7.	0
8.		8.	0

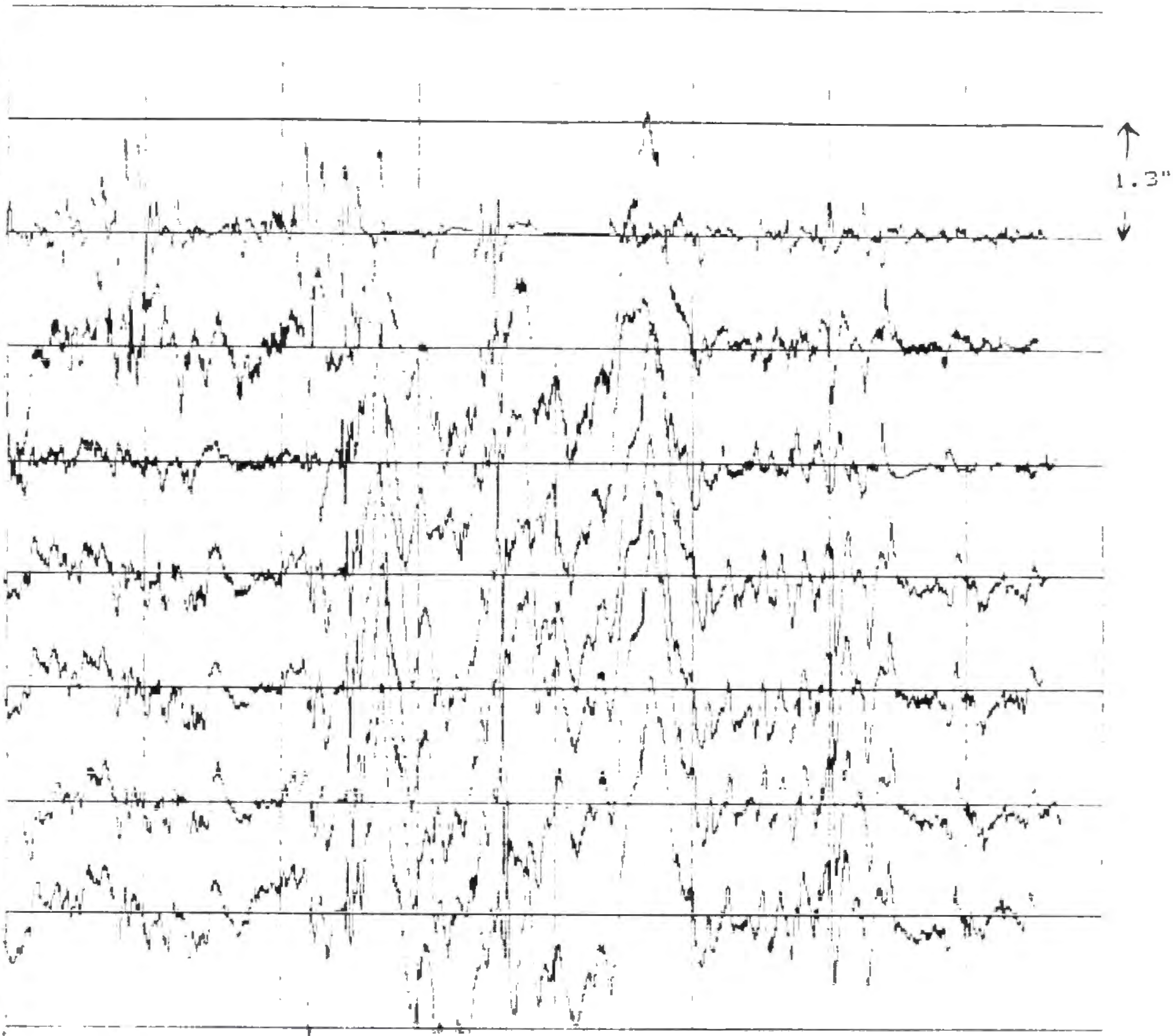
to exit press <ESC>



edrough\august14\

file names		offset	
1.	A37002.083	1.	[illegible]
2.	A37002.084	2.	0
3.	A37002.085	3.	25
4.	A37002.088	4.	0
5.	A37002.089	5.	0
6.	A37002.090	6.	0
7.	A37002.091	7.	25
8.		8.	0

to exit press ESC



PCC?

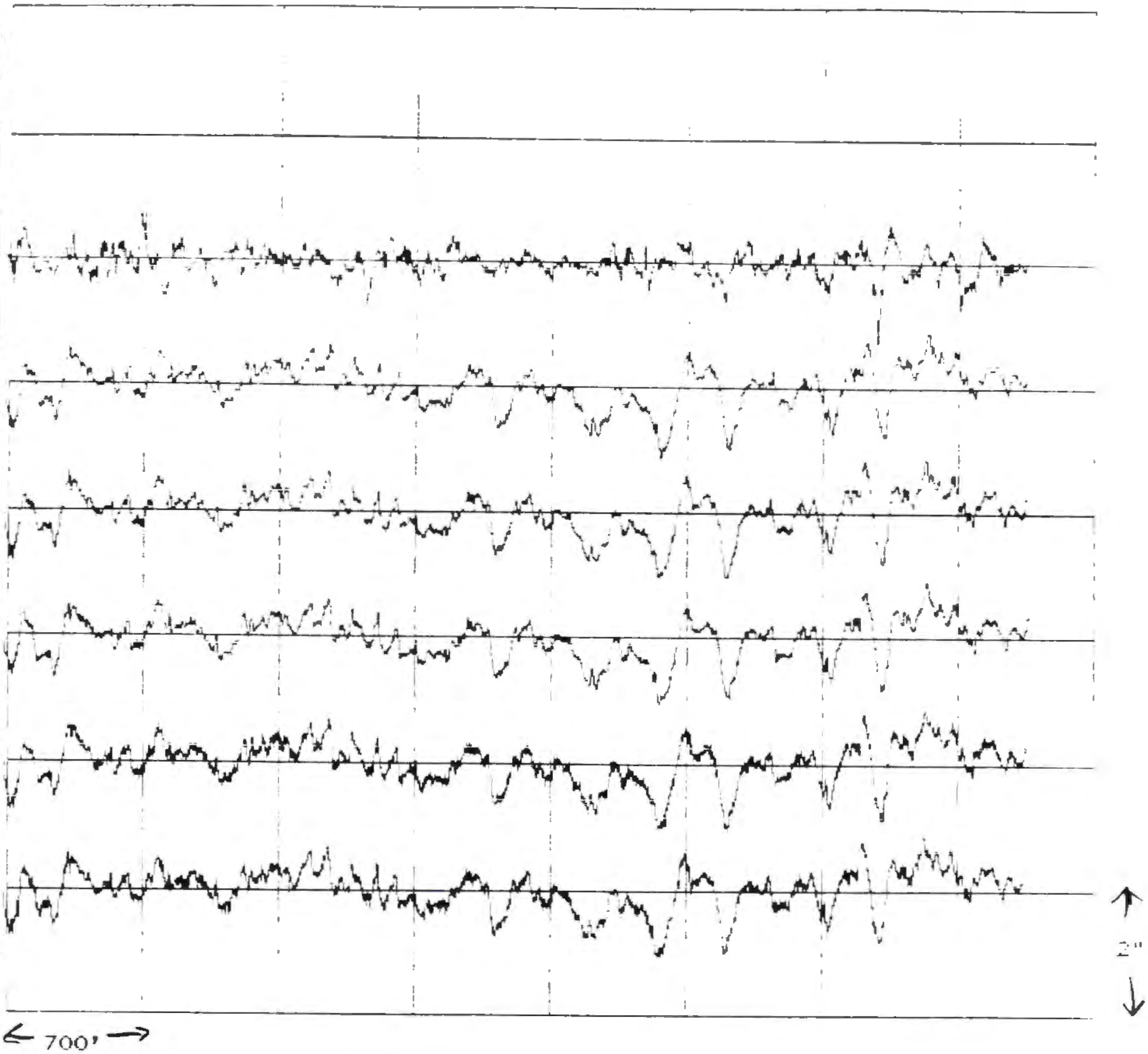
[illegible] edrough\august14

file names		offset	
1.	A38a01.083	1.	[illegible]
2.	A38a01.084	2.	[illegible]
3.	A38a01.085	3.	50
4.	A38a01.086	4.	[illegible]
5.	A38a01.088	5.	0
6.	A38a01.089	6.	100
7.	A38a01.090	7.	0
8.		8.	0

LOM

MAR 3

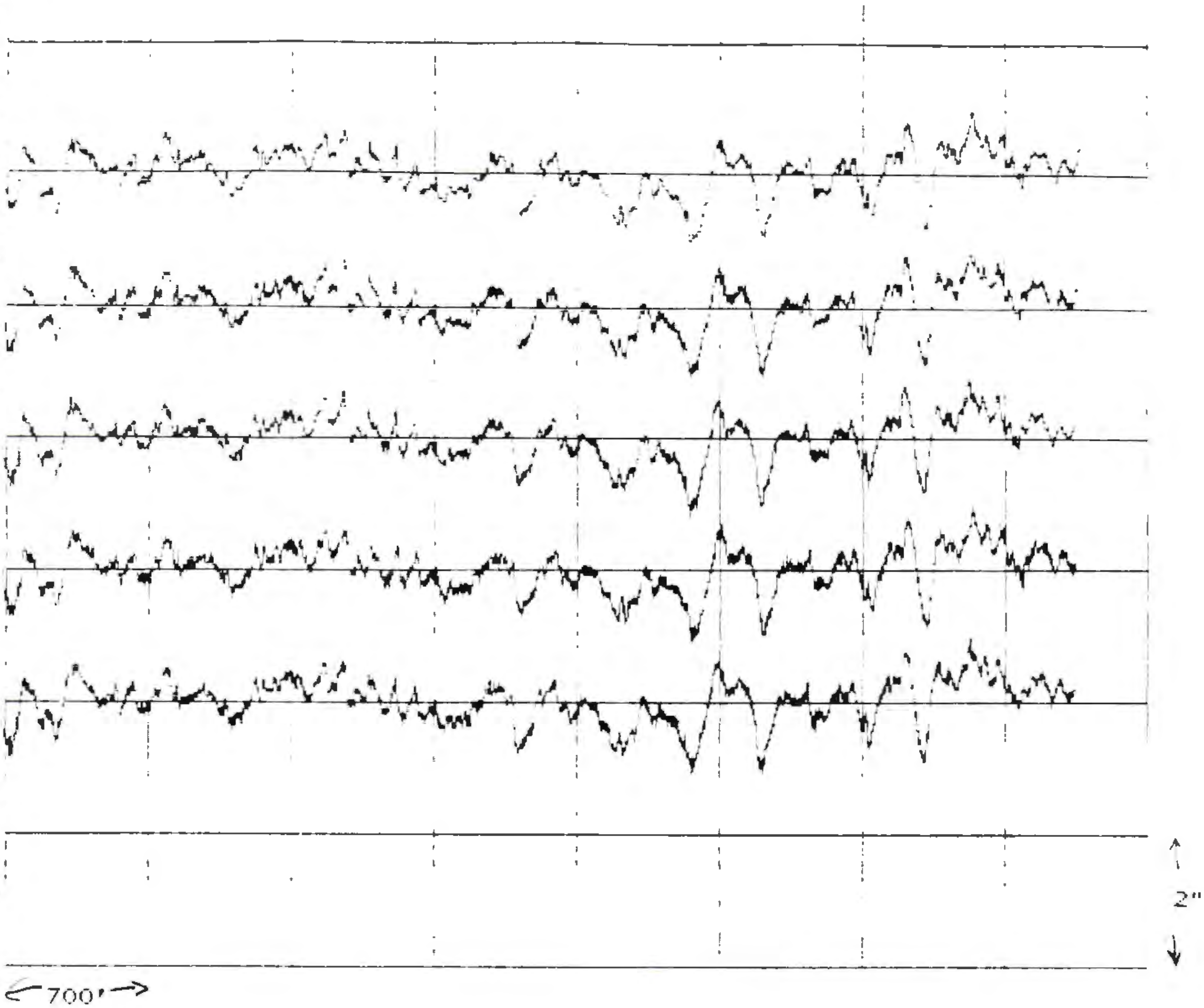
to exit press "ESC"



path is: e: sgrough\analysis \

file names		offset	
1.	[illegible]	1.	40
2.	a44000.186	2.	[illegible]
3.	a44000.187	3.	0
4.	[illegible]	4.	0
5.	a44000.189	5.	0
6.	a44000.190	6.	0
7.		7.	0
8.		8.	0

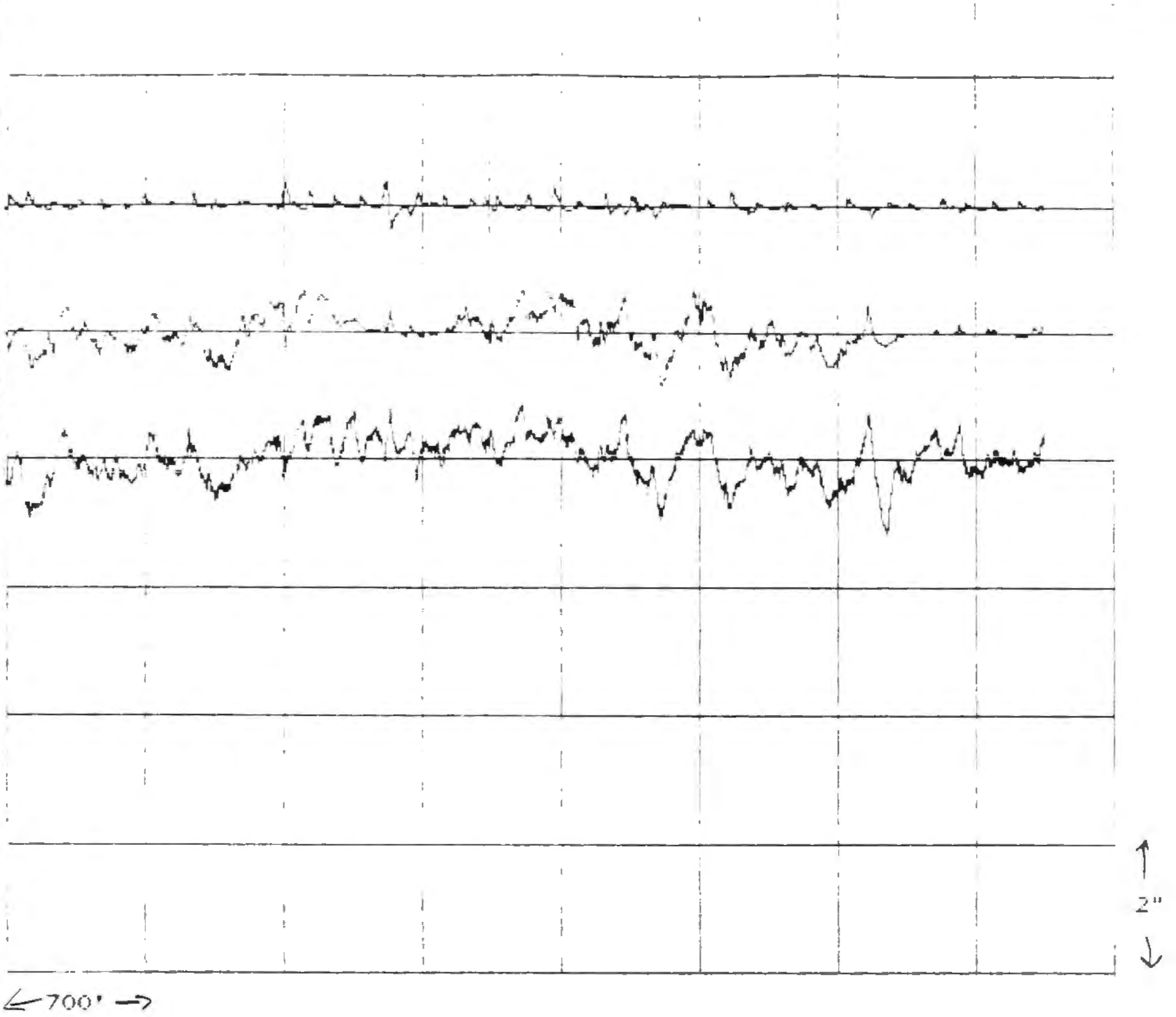
to exit press ESC



[illegible] e: edrough\analysis\\\\

	file names		
1.	a44000.188	1.	0
2.	a44000.189	2.	0
3.	a44000.190	3.	0
4.	a44000.191	4.	0
5.	a44000.192	5.	0
6.		6.	0
7.		7.	0
8.		8.	0

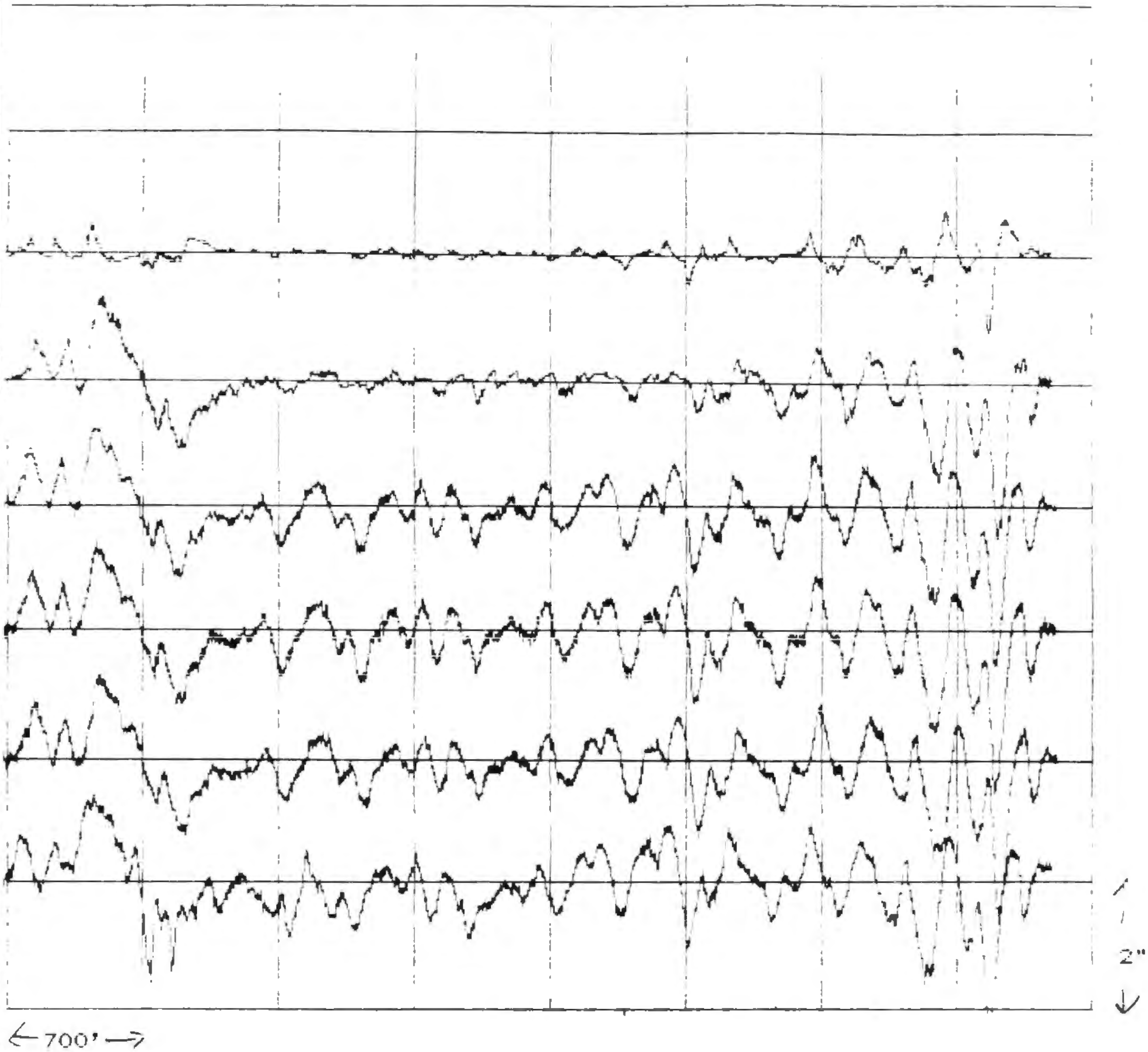
to exit press ESC>



[illegible] sdrough\analysis\\

file names		offset	
1.	a44000.283	1.	0
2.	a44000.285	2.	0
3.	a44000.291	3.	0
4.		4.	0
5.		5.	0
6.		6.	0
7.		7.	0
8.		8.	0

to exit press <ESC>



path is: e:\edrough\analysis\\\

file names:		offset	
1.	a45000.182	1.	40
2.	a45000.185	2.	
3.	a45000.187	3.	[illegible]
4.	a45000.189	4.	0
5.	a45000.191	5.	0
6.	a45000.192	6.	60
7.		7.	0
8.		8.	0

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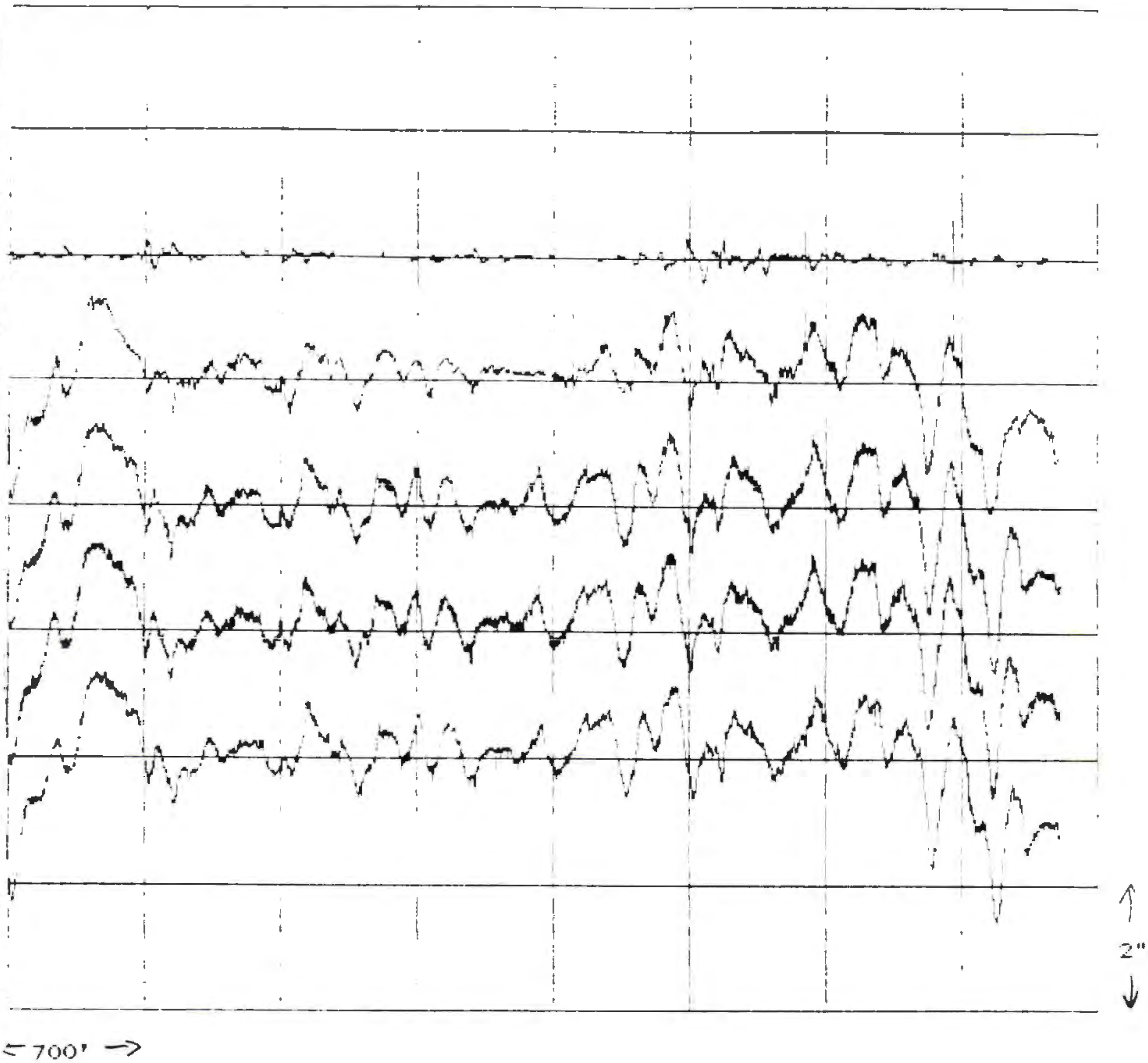
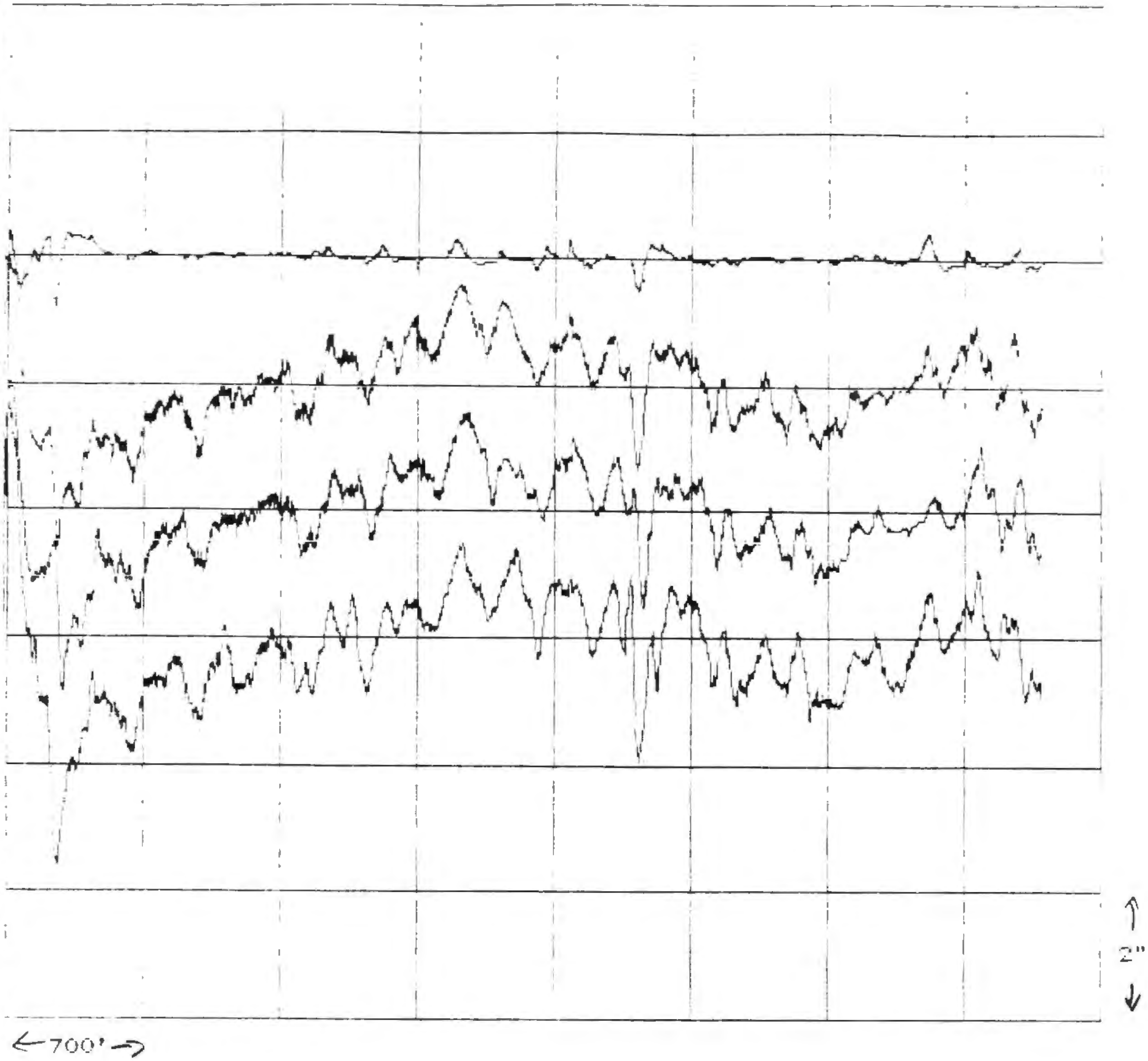


path is: e:\sdrough\analysis\\\\

file names		offset	
1.	a45000.283	1.	0
2.	a45000.284	2.	0
3.	a45000.290	3.	0
4.	a45000.291	4.	0
5.	a45000.292	5.	0
6.		6.	0
7.		7.	0
8.		8.	0

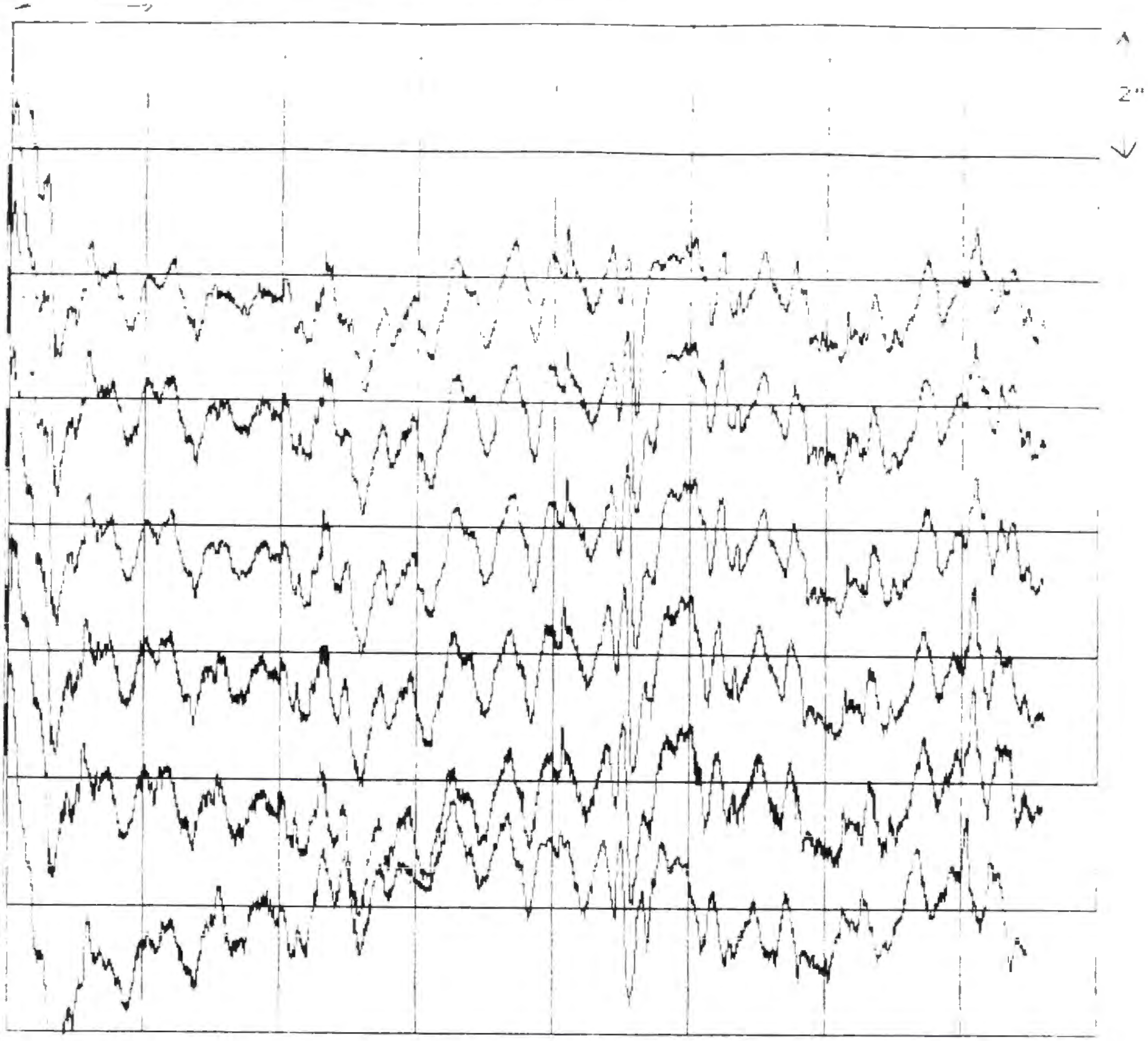
to exit press <ESC>



[illegible] e:\sdrough\analysis\

file names		offset	
1.	a63000.183	1.	0
2.	a62000.184	2.	0
3.	a63000.185	3.	0
4.	a63000.189	4.	0
5.		5.	0
6.		6.	0
7.		7.	0
8.		8.	0

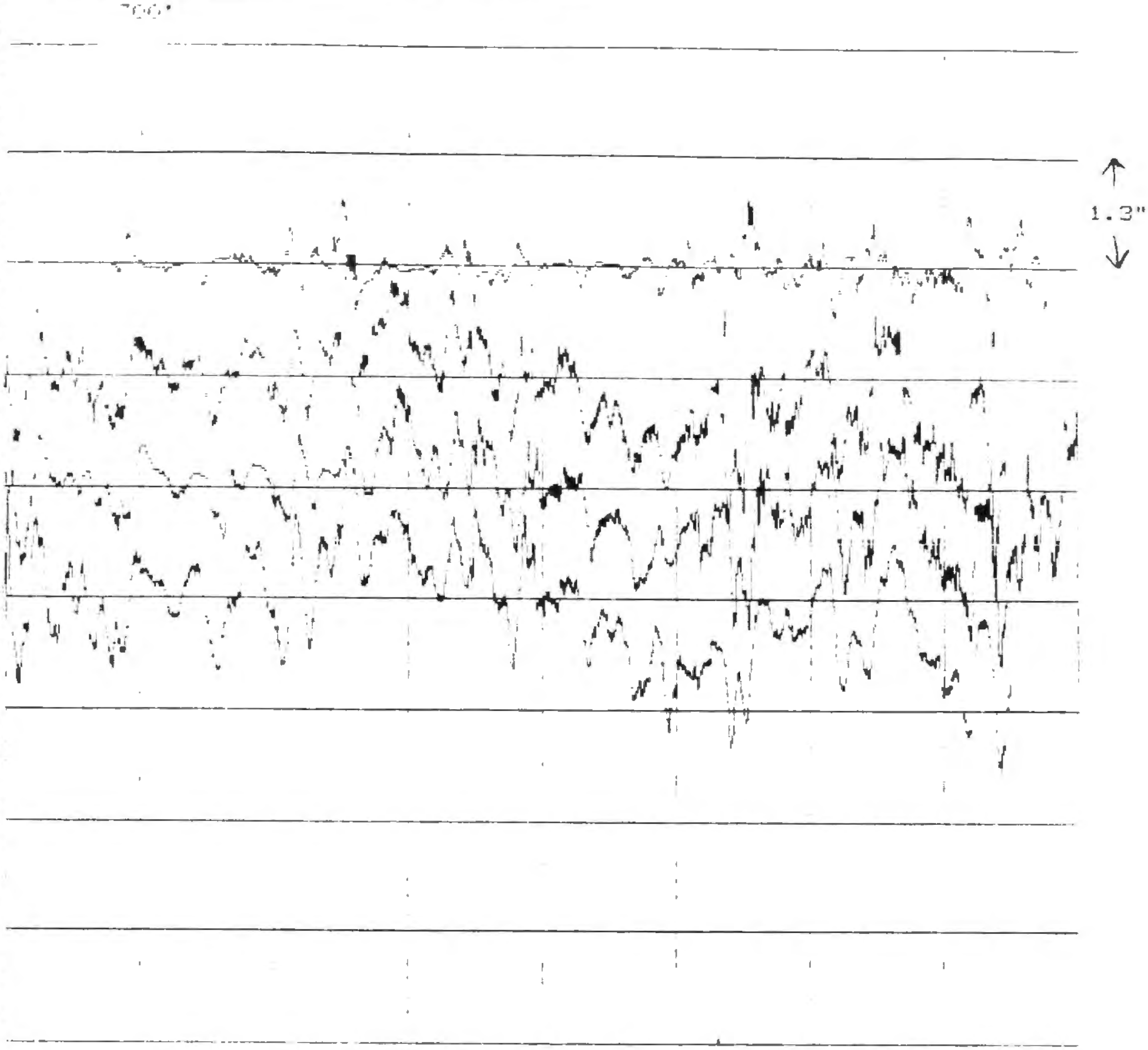
to exit press <ESC>



path is: e:\sdrough\analysis \\\\

file names		offset	
1.	a63000.286	1.	[illegible]
2.	a63000.287	2.	0
3.	a63000.288	3.	0
4.	a63000.290	4.	[illegible]
5.	a63000.291	5.	0
6.	a63000.292	6.	0
7.		7.	0
8.		8.	0

to exit press <ESC>

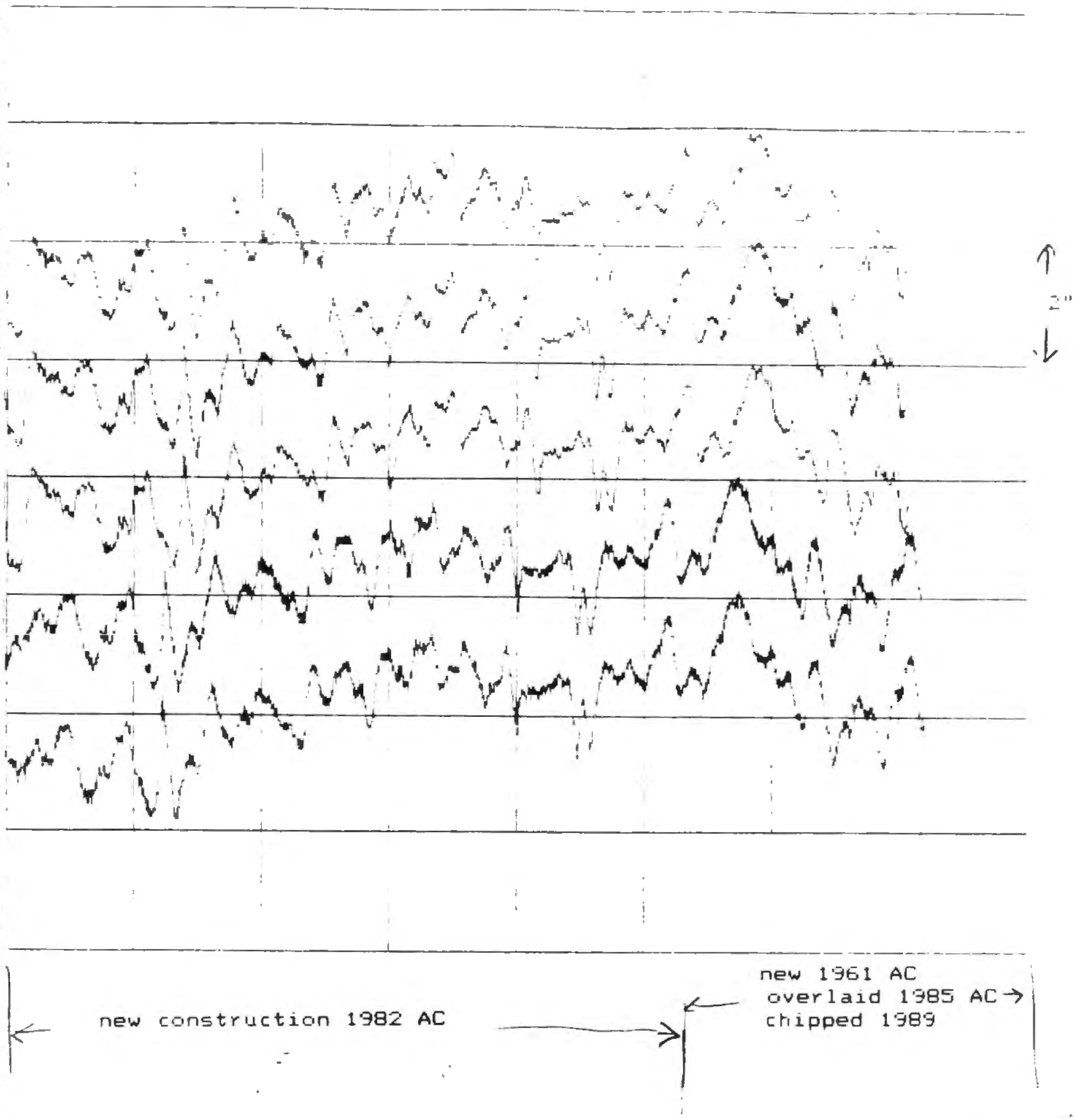


new construction 1982 AC

new 1961 AC
overlaid 1985 AC
chipped 1989

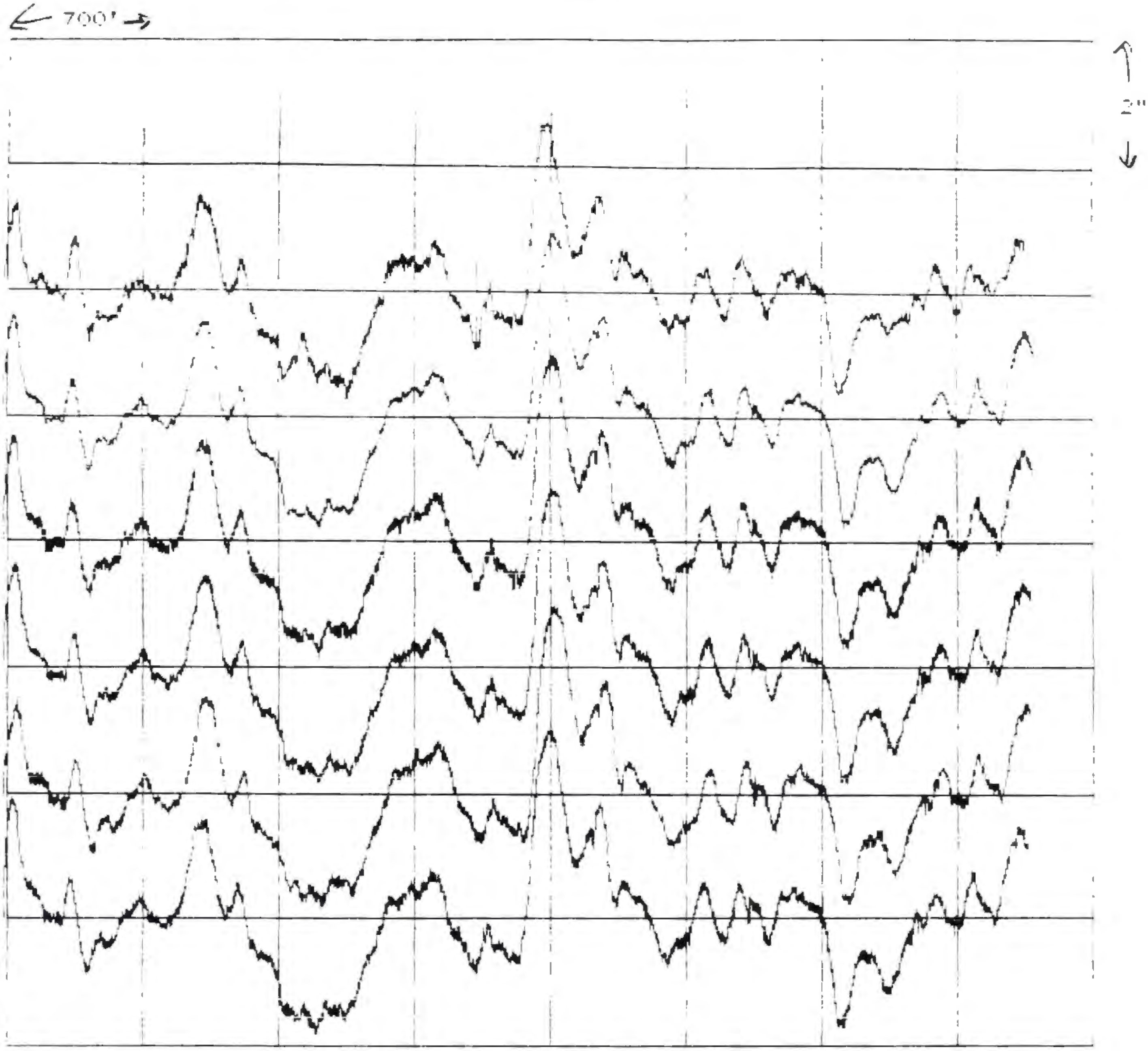
file names		offset
1.	A63001.083	550
2.	A63001.084	0
3.	A63001.085	0
4.	A63001.089	0
5.		0

to exit press <ESC>



path is: e:\scrough\analysis\\

	file names		offset
1.	a63002.086	1.	0
2.	a63002.087	2.	0
3.	a63002.088	3.	0
4.	a63002.090	4.	+100
5.	a63002.091	5.	+100
6.		6.	0
7.		7.	0
8.		8.	0



path is: e:\sdrough\analysis\ \

file names		offset	
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2.	a83000.186	2.	0
3.	a83000.189	3.	0
4.	a83000.190	4.	0
5.	a83000.191	5.	0
6.	a83000.192	6.	0
7.		7.	0
8.		8.	0

to exit press <ESC>

APPENDIX C
HISTOGRAMS OF MAXIMUM VERTICAL DISPLACEMENTS FOR MULTI-YEAR PROFILES FOR THE TELESCOPED ROLLING STRAIGHTEDGE STATISTIC

This appendix shows plots of the maximum vertical displacement profiles for the telescoped rolling straightedge statistic for each of the ten multi-year historical sections. Plots shown are histograms of the maximum vertical displacement (MVD) values used by the telescoped rolling straightedge statistic. MVDs were grouped in .01 inch increments starting at 0 inches, and the number of MVDs in each group were counted for each one-mile profile.

What one expects is that, over the years, the "peak" of the histograms move to the right (the "median" MVD gets larger) and that the histograms flatten out a bit. When the peak moves significantly to the left (lower MVDs), or the shape of the curve changes significantly, then either major maintenance has occurred, the SD profiler is measuring overly smooth, or the section collected has been misidentified. Several incongruent histograms are noted in Figure C.1.

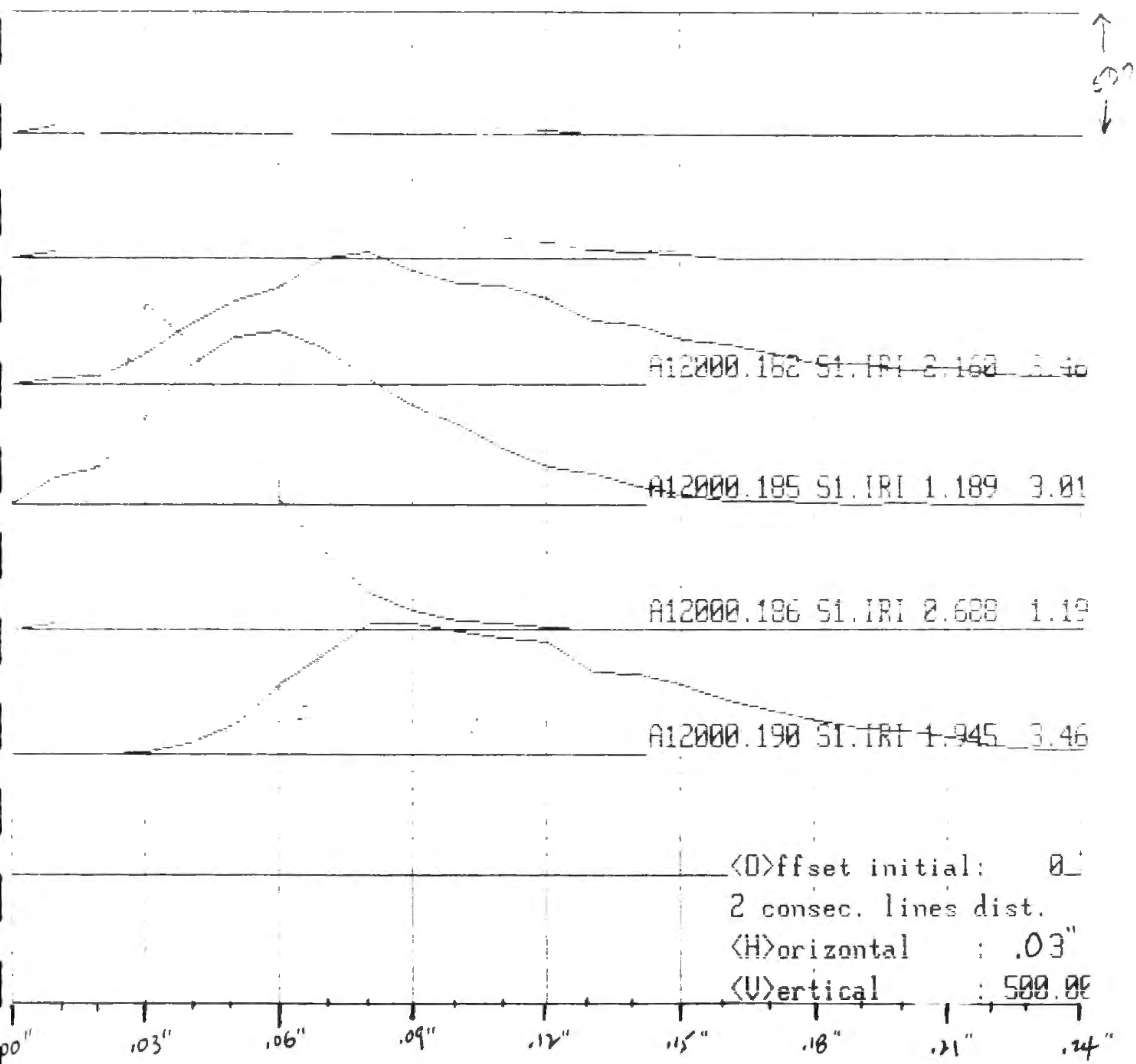
By viewing the histograms across time for the same section, it becomes evident when something happens to the profile of the section. These happenings can either be rehabilitation, maintenance such as a chip seal, uncalibrated smoothness collection machinery, or plotting of the wrong section.

For the attached plot, the counts are indicated on the Y axis where the number of counts between consecutive horizontal lines is 500. On the X axis, there are three histogram groups within two consecutive vertical lines. As an example, the count at X access value 0.09 is the count of all MVDs greater than or equal to .09 inches and less than 0.10 inches.

Note: The S1 value shown on the plot is the 10 foot TRS statistic value for the entire one-mile profile.

File	Route # and Milepoint	Lane	Between Years	Comments
A12000.1*	US12 127.	1	1982&1985	
A12000.1*	US12 127.	1	1985&1986	
A12001.0*	US212 60.	1	1986&1990	
A12002.0*	US212 60.	2	1987&1988	
A38A01.0*	SD38A 364.57	1	1984&1985	
A38A01.0*	SD38A 364.57	1	1985&1986	
A44000.1*	SD44 296.	1	1982&1986	
A44000.1*	SD44 296.	1	1989&1990	
A45000.1*	SD45 76.	1	1991&1992	
A45000.2*	SD45 76.	1	1991&1992	
A63000.1*	SD63 143.	1	1984&1985	
A63000.2*	SD63 143.	2	1987&1988	
A63000.2*	SD63 143.	2	1991&1992	
A63001.0*	SD63 145.	1	1984&1985	
A63002.0*	SD63 145.	2	1987&1988	
A63002.0*	SD63 145.	2	1990&1991	
A83000.1*	SD83 214.	1	1984&1986	
A83000.1*	SD83 214.	1	1988&1990	
A83000.1*	SD83 214.	1	1990&1991	

Figure C.1. Sections with Incongruent Histograms.


A12000.182 S1.IRI 2.160
A12000.185 S1.IRI 1.189 3.01
A12000.186 S1.IRI 0.688 1.19
A12000.190 S1.IRI 1.945 3.46
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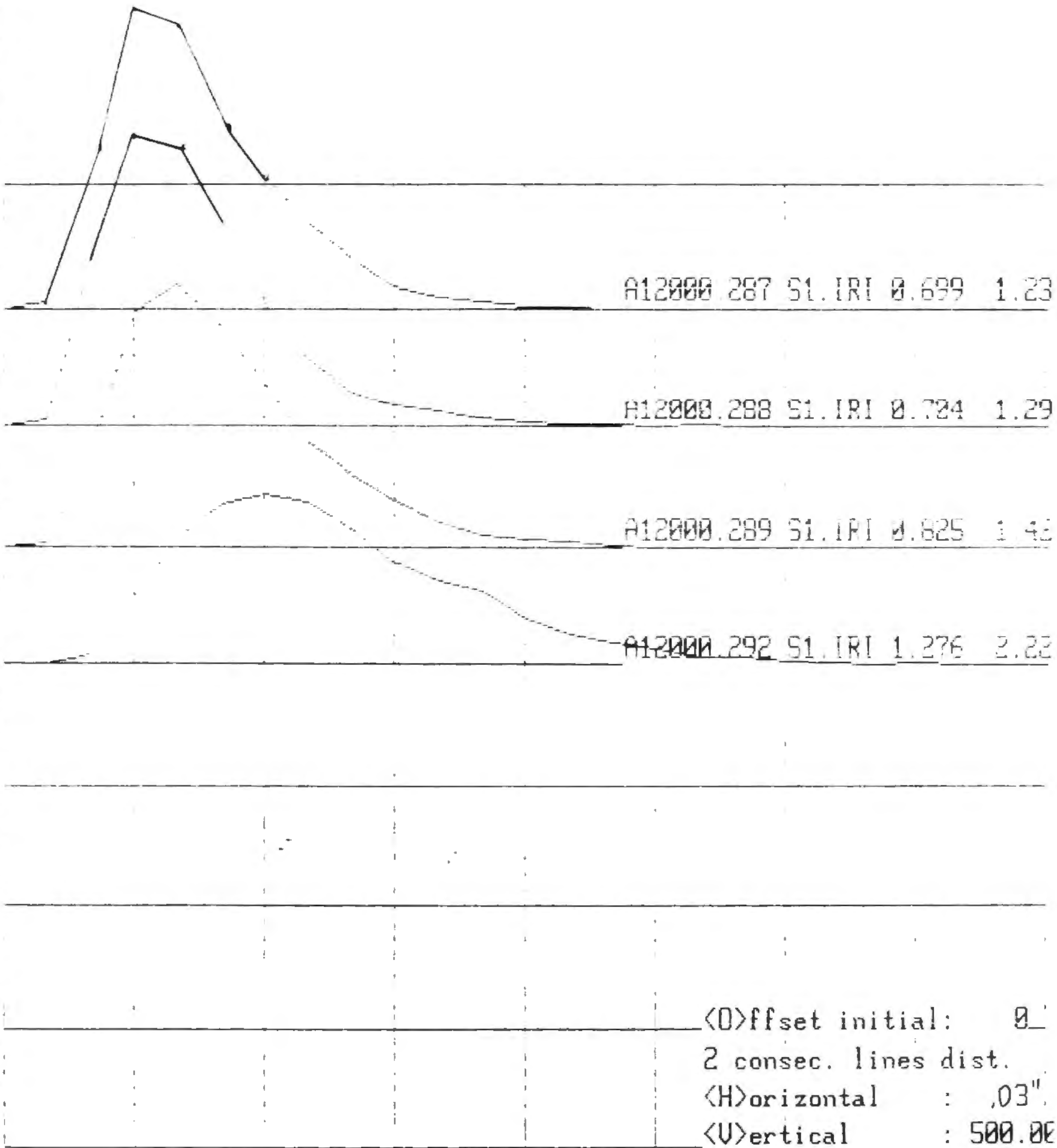
2 consec. lines dist.
<H>orizontal : .03"
<V>ertical : 500.00
.00"
.03"
.06"
.09"
.12"
.15"
.18"
.21"
.24"


A12000.287 S1.IRI 0.699 1.23
A12000.288 S1.IRI 0.724 1.29
A12000.289 S1.IRI 0.825
A12000.292 S1.IRI 1.276
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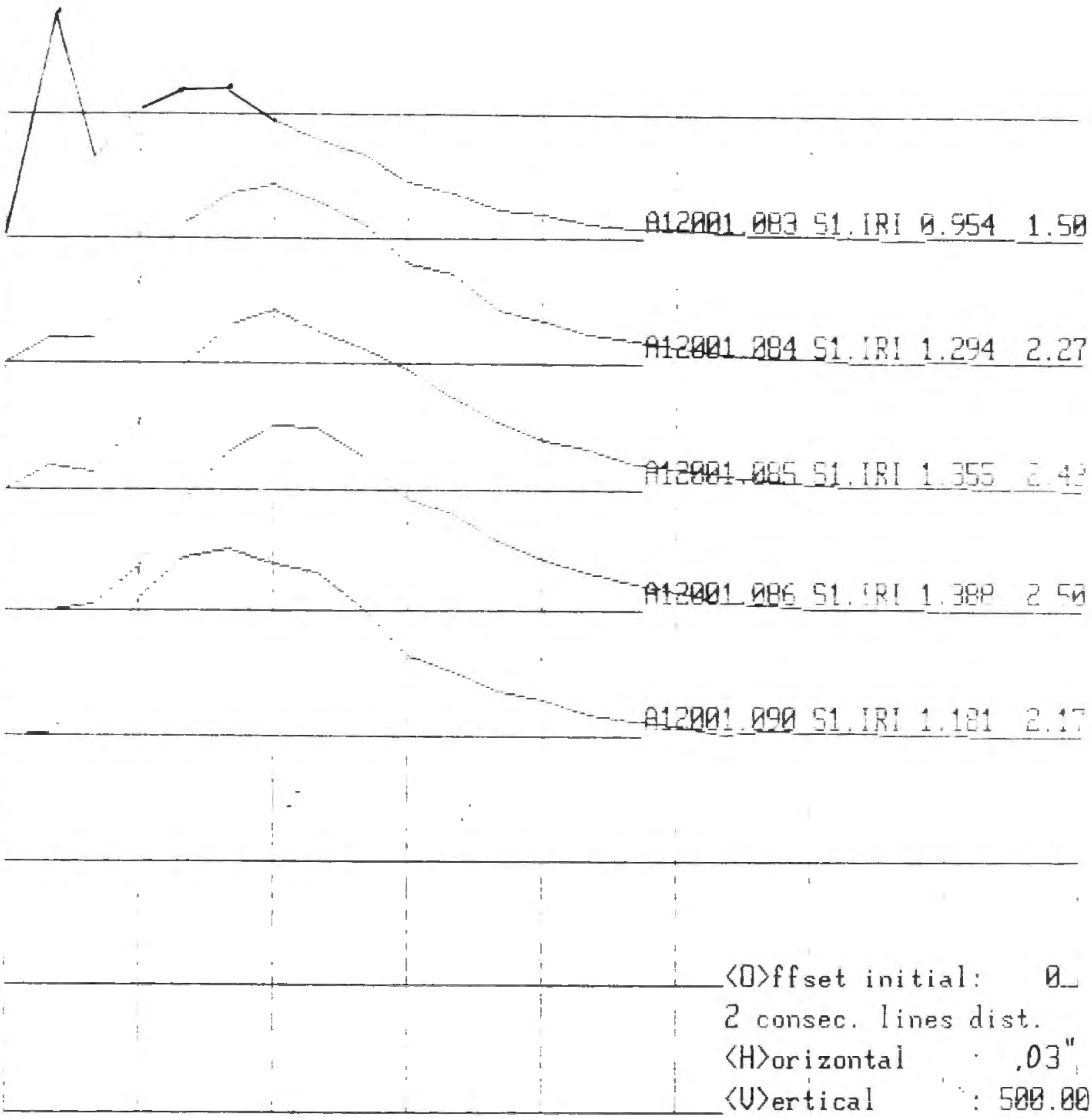
A12001.083 S1.IRI 0.954 1.50
A12001.084 S1.IRI 1.294 2.27
A12001.085 S1.IRI 1.355
A12001.086 S1.IRI 1.388 2.50
A12001.090 S1.IRI 1.181
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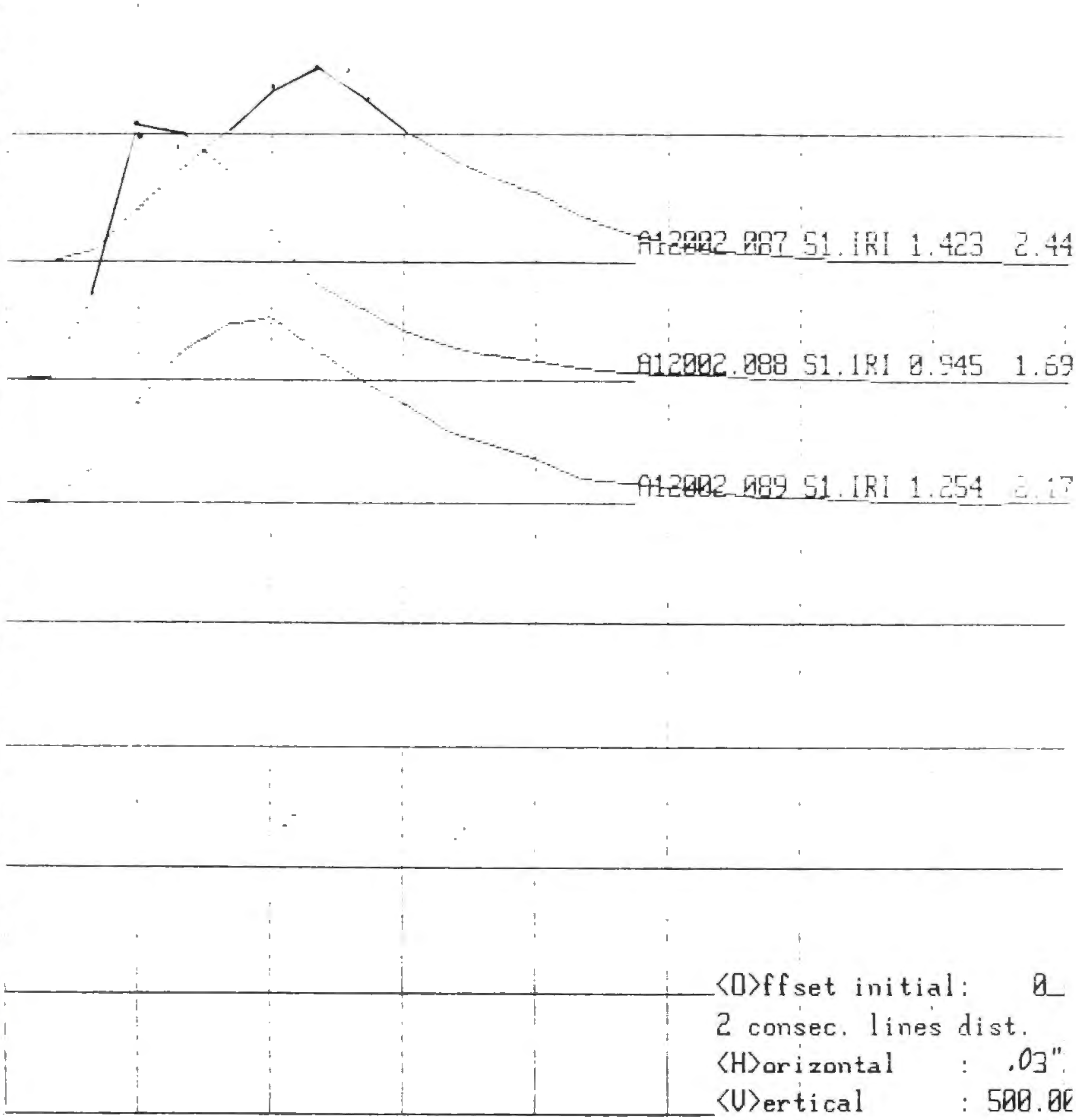
A12002.087 S1.IRI 1.423 2.44
A12002.088 S1.IRI 0.945 1.69
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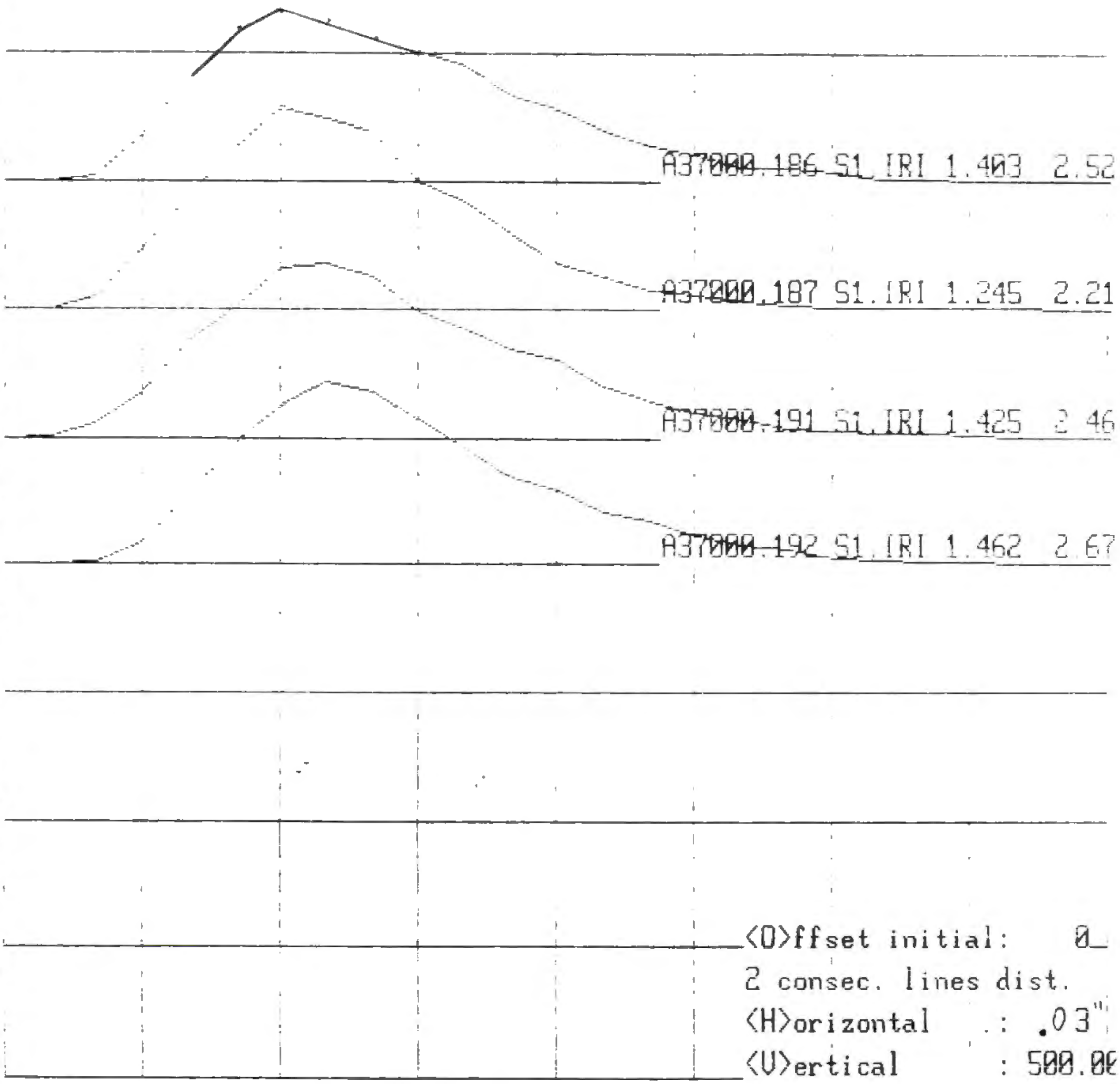
A37000.186 S1 IRI 1.403 2.52
A37000.187 S1 IRI 1.245 2.21
A37000.191 S1 IRI 1.425 2.46
A37000.192 S1 IRI 1.462 2.67
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2 consec. lines dist.
<H>orizontal .: .03"
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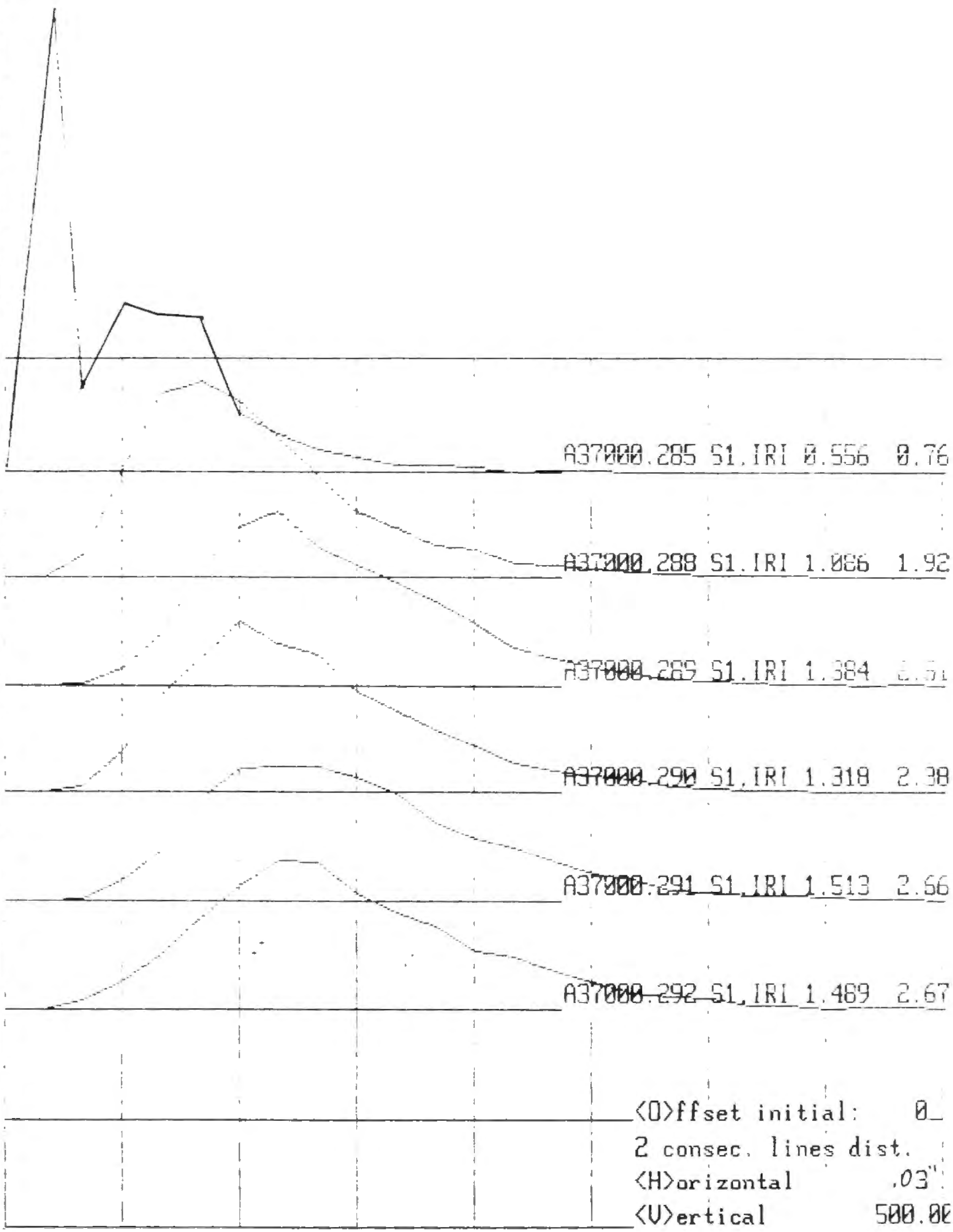
A37000.285 S1.IRI 0.556 0.76
A37000.288 S1.IRI 1.086 1.92
A37000.289 S1.IRI 1.384
A37000.290 S1.IRI 1.318 2.38
A37000.291 S1.IRI 1.513 2.66
A37000.292 S1.IRI 1.469 2.67
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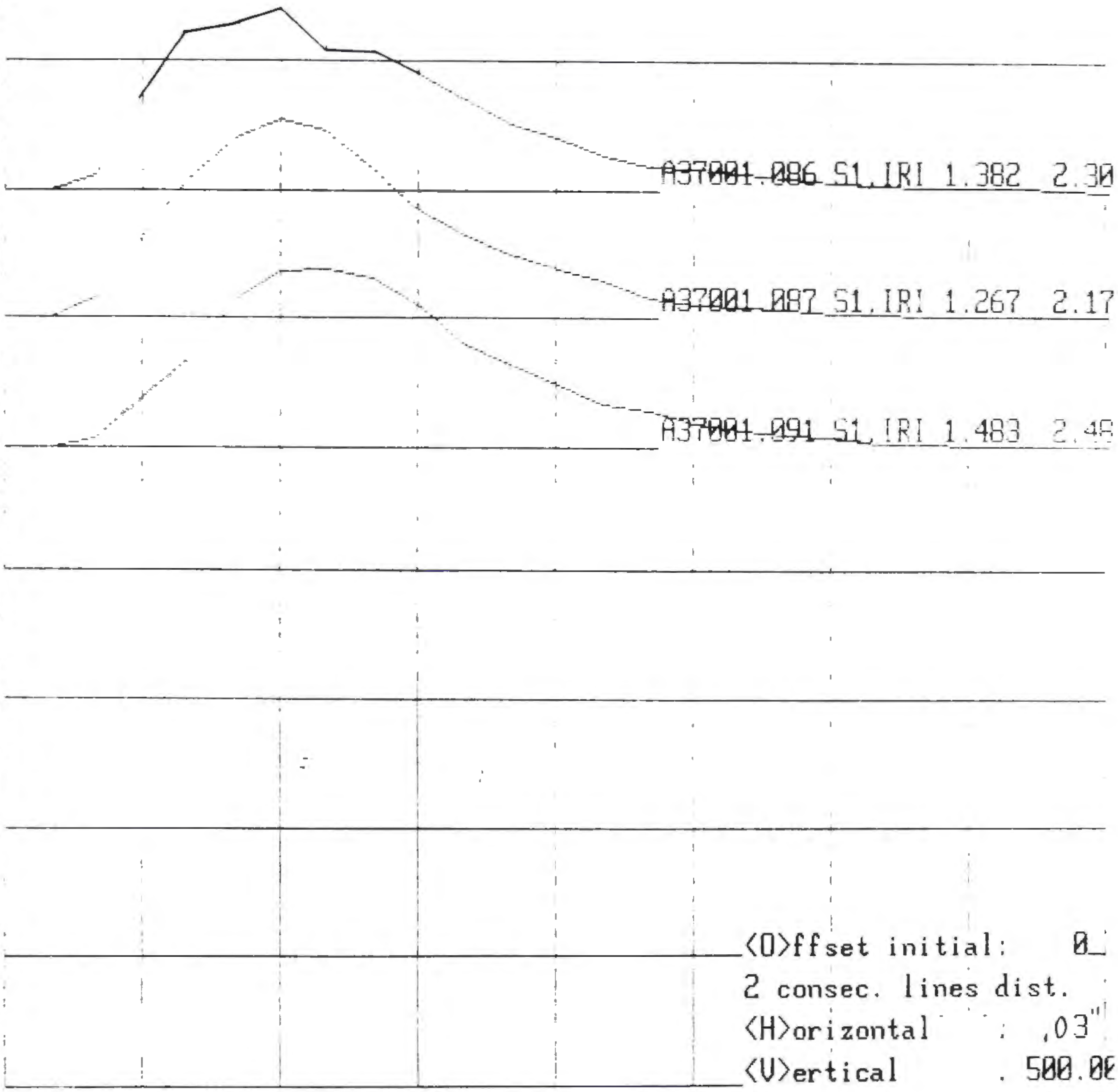
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A37001.087 S1.IRI 1.267 2.17
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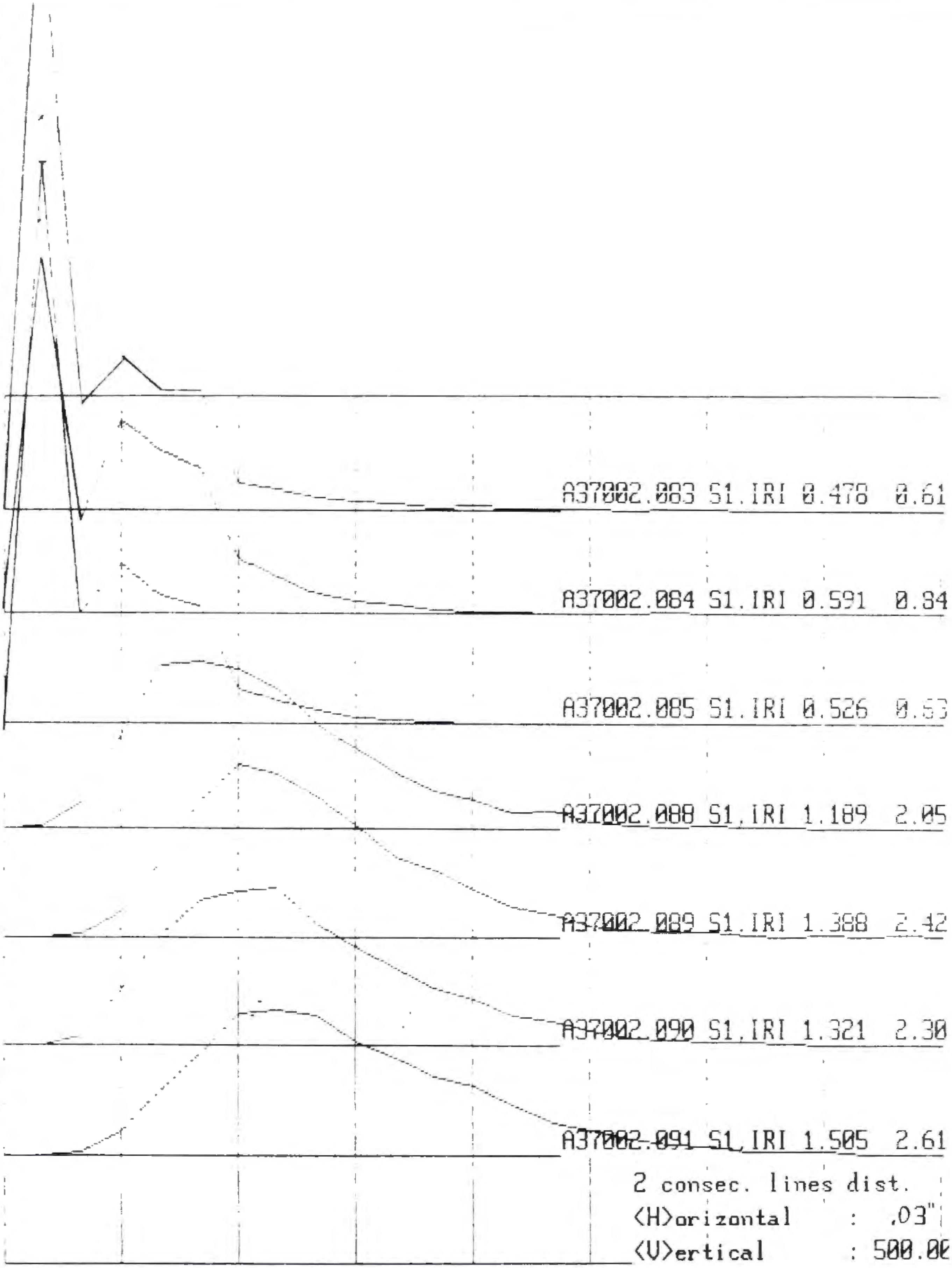

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A37002.084 S1.IRI 0.591 0.84
A37002.085 S1.IRI 0.526 0.53
A37002.088 S1.IRI 1.189 2.05
A37002.089 S1.IRI 1.388 2.42
A37002.090 S1.IRI 1.321 2.30
A37002.091 S1.IRI 1.505 2.61
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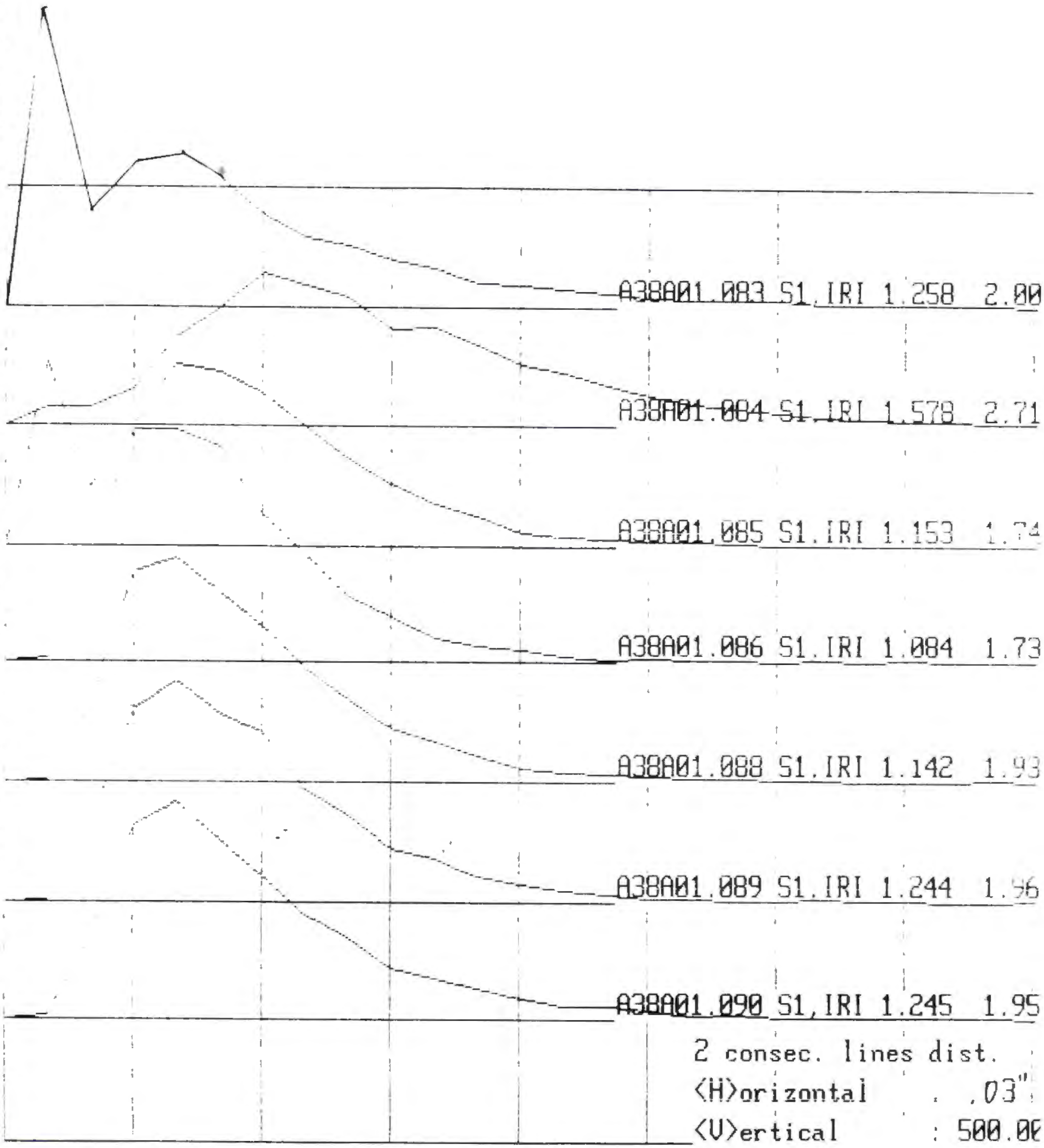

A38A01.083 S1.IRI 1.258 2.00
A38A01.084 S1.IRI 1.578 2.71
A38A01.085 S1.IRI 1.153
A38A01.086 S1.IRI 1.084 1.73
A38A01.088 S1.IRI 1.142
A38A01.089 S1.IRI 1.244
A38A01.090 S1.IRI 1.245 1.95
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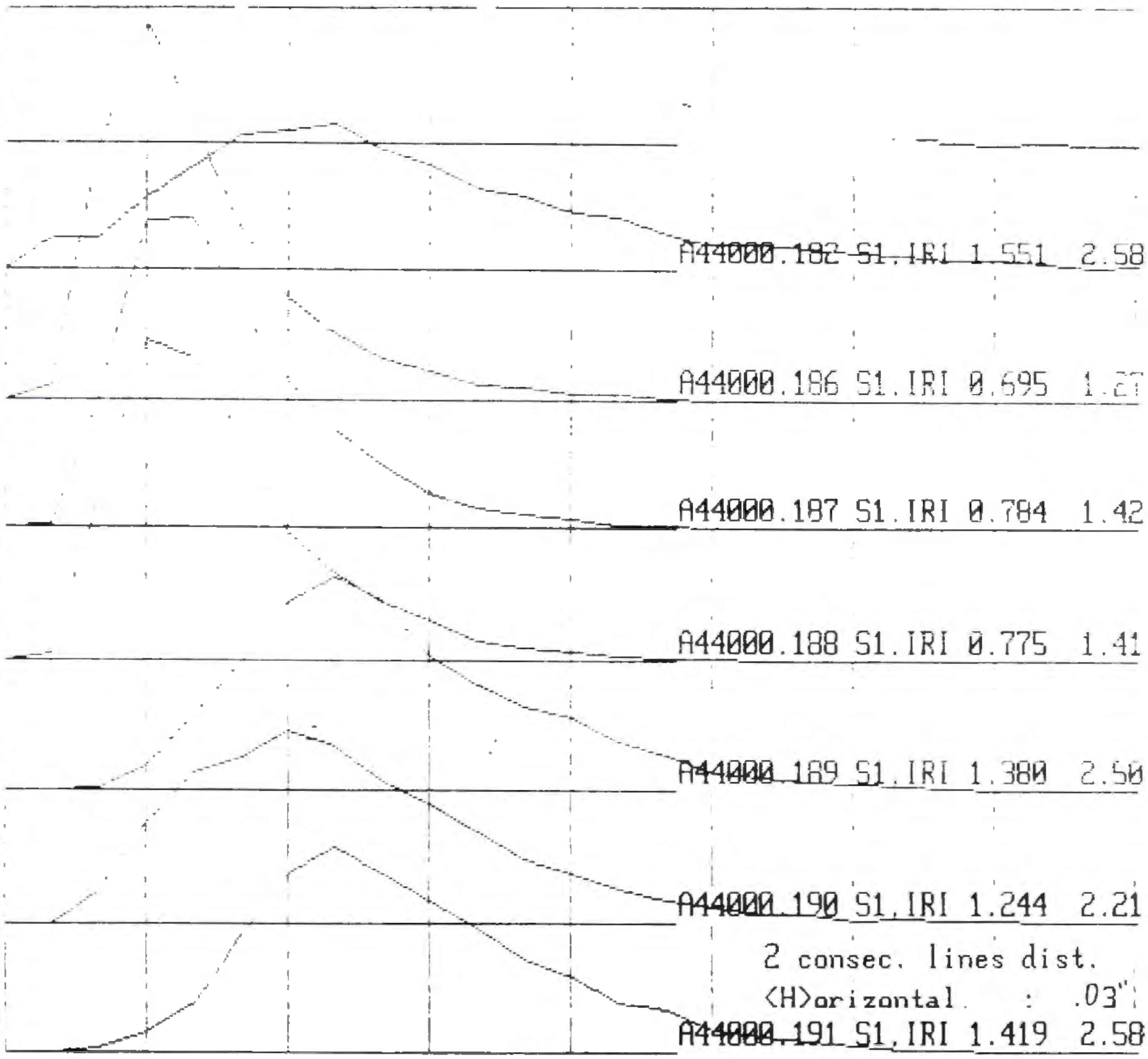
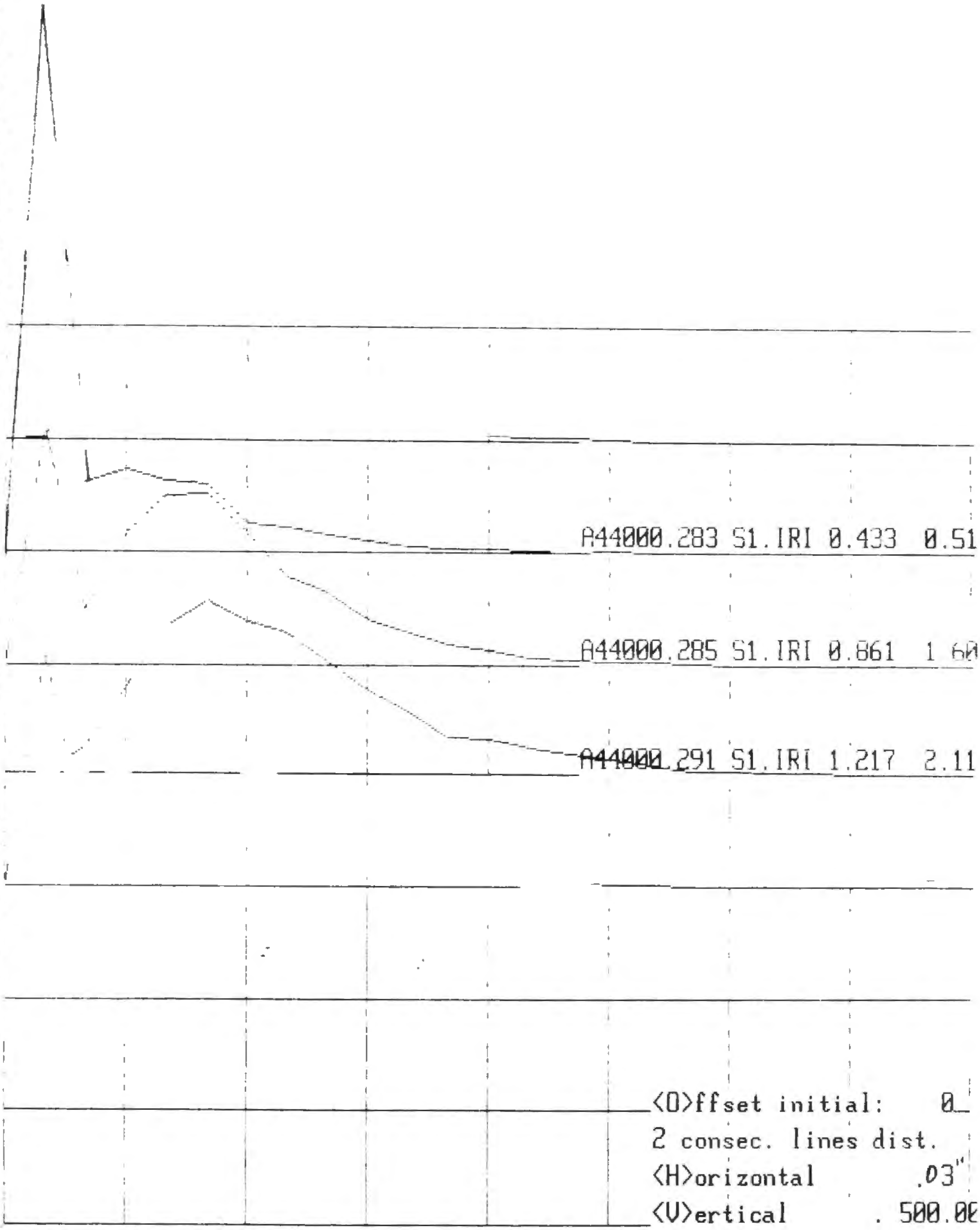
<V>ertical : 500.00


A44000.182 S1.IRI 1.551 2.58
A44000.186 S1.IRI 0.695 1.2
A44000.187 S1.IRI 0.784 1.42
A44000.188 S1.IRI 0.775 1.41
A44000.189 S1.IRI 1.380 2.50
A44000.190 S1.IRI 1.244 2.21
2 consec. lines dist.
<H>orizontal : .03"
A44000.191 S1.IRI 1.419 2.58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A44000.285 S1.IRI 0.861 1.60
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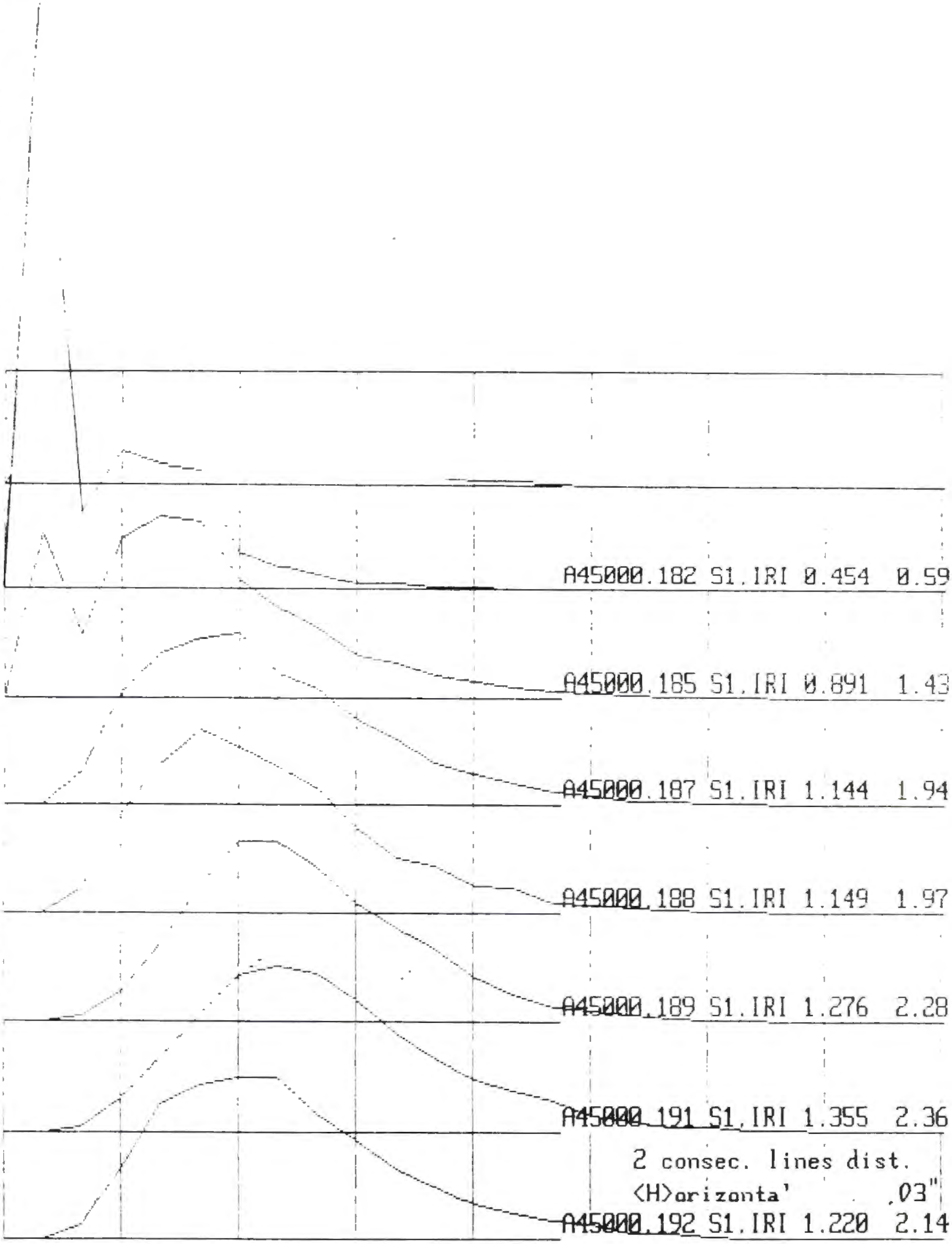
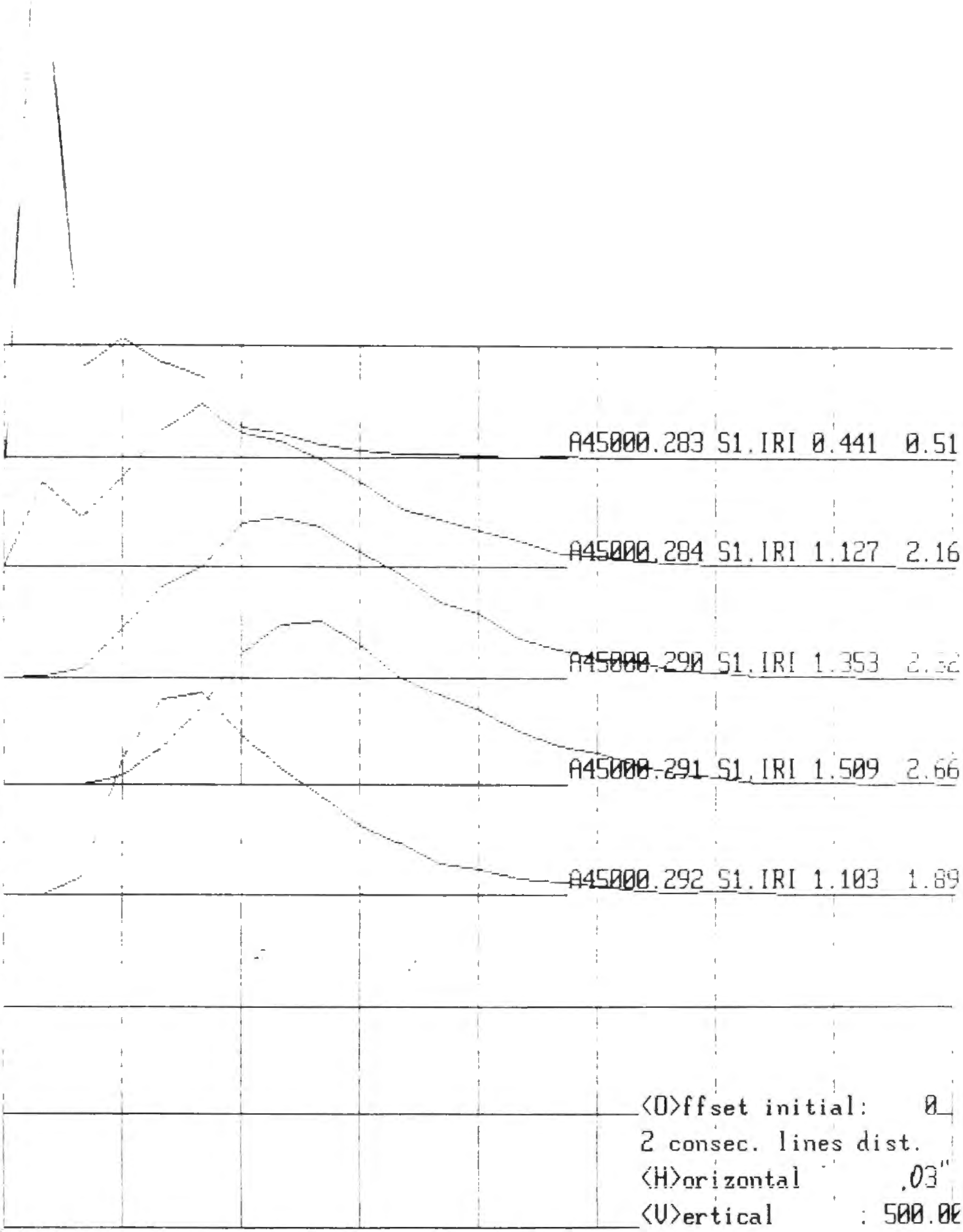

A45000.182 S1.IRI 0.454 0.59
A45000.185 S1.IRI 0.891 1.43
A45000.187 S1.IRI 1.144 1.94
A45000.188 S1.IRI 1.149 1.97
A45000.189 S1.IRI 1.276 2.28
A45000.191 S1.IRI 1.355 2.36
2 consec. lines dist.
<H>orizonta' .03"
A45000.192 S1.IRI 1.220 2.14


A45000.283 S1.IRI 0.441 0.51
A45000.284 S1.IRI 1.127 2.16
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A45000.291 S1.IRI 1.509 2.66
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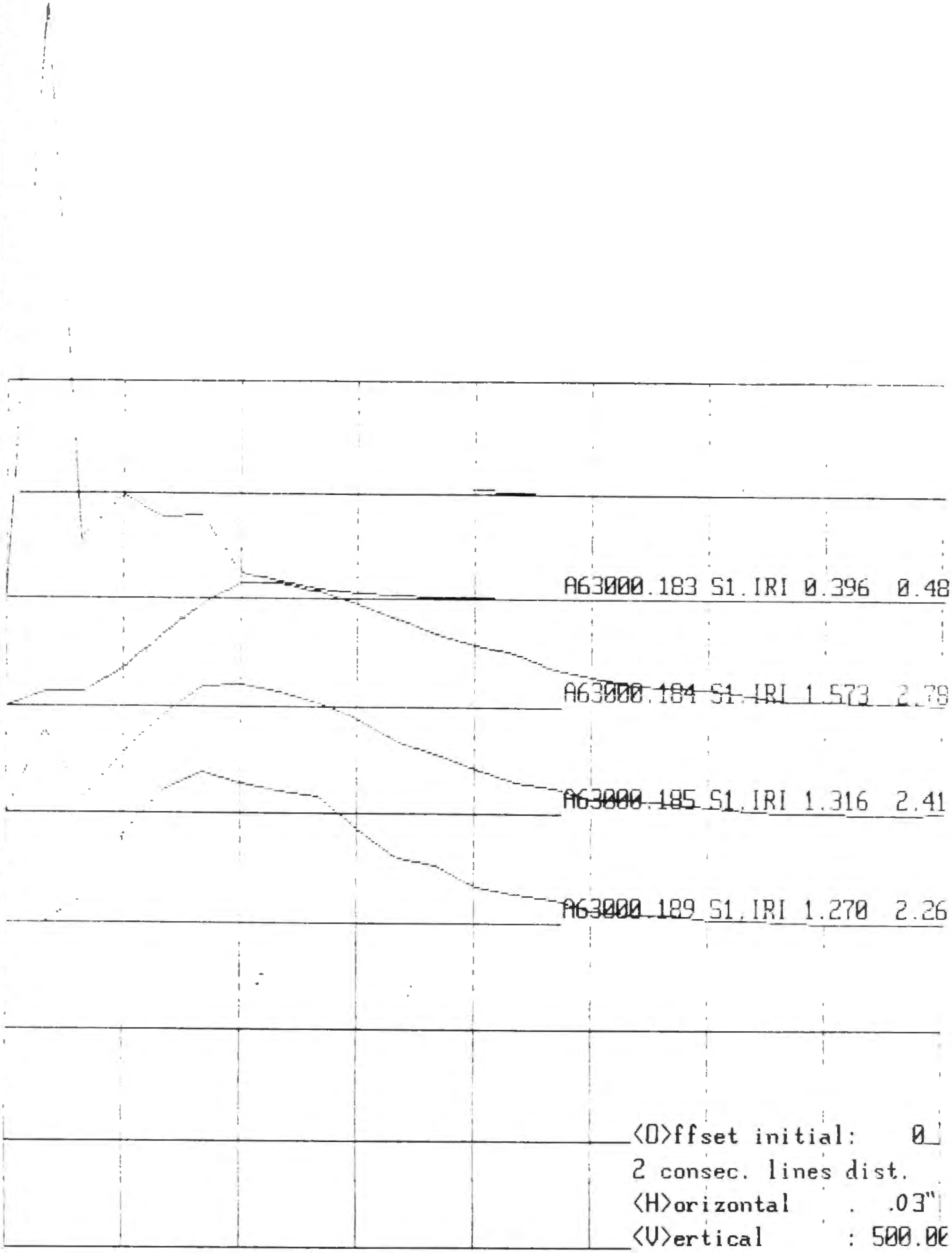
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A63000.185 S1.IRI 1.316 2.41
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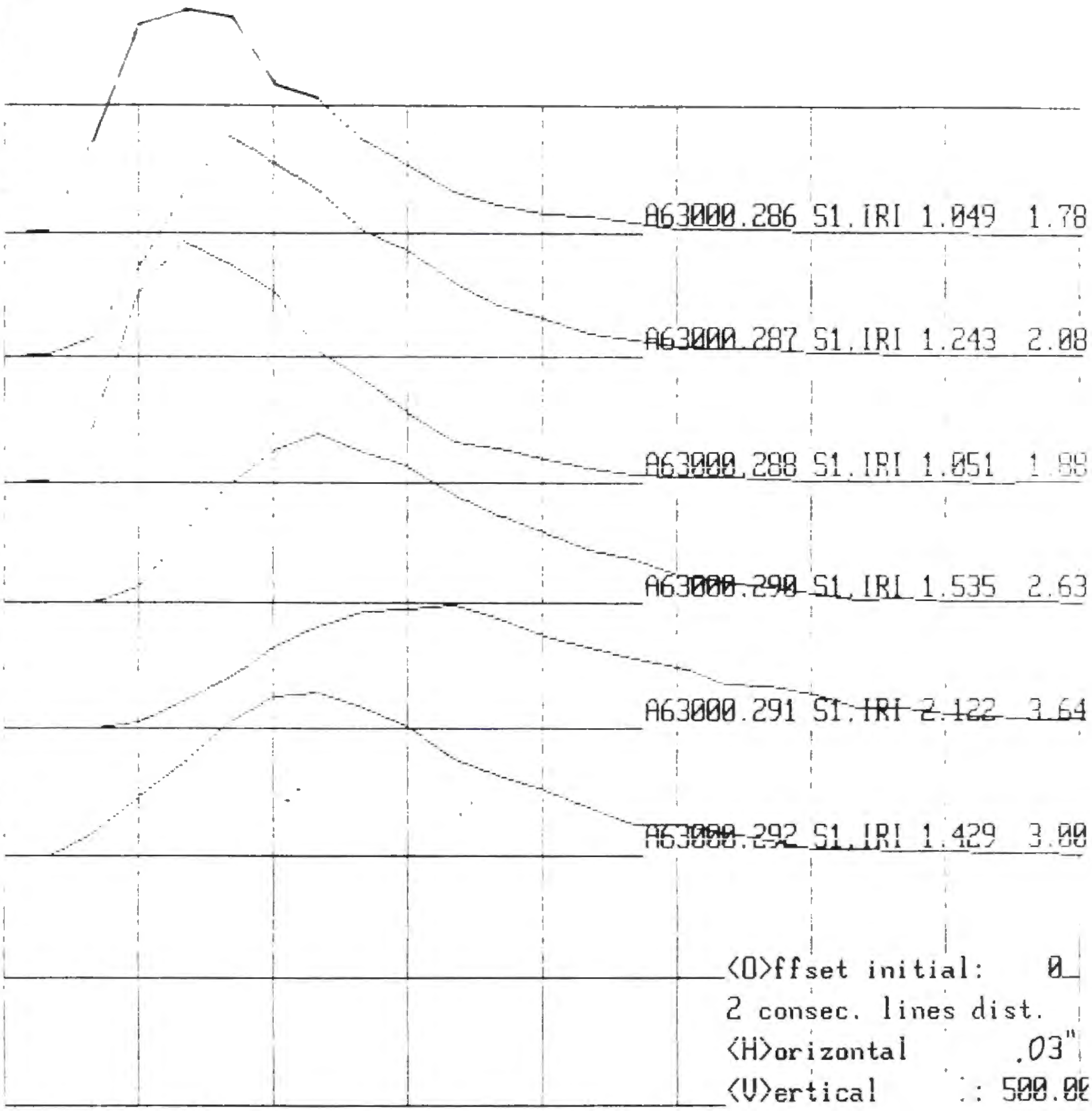
A63000.286 S1.IRI 1.049 1.78
A63000.287 S1.IRI 1.243 2.08
A63000.288 S1.IRI 1.051 1.88
A63000.290 S1.IRI 1.535 2.63
A63000.291 S1.IRI 2.122 3.64
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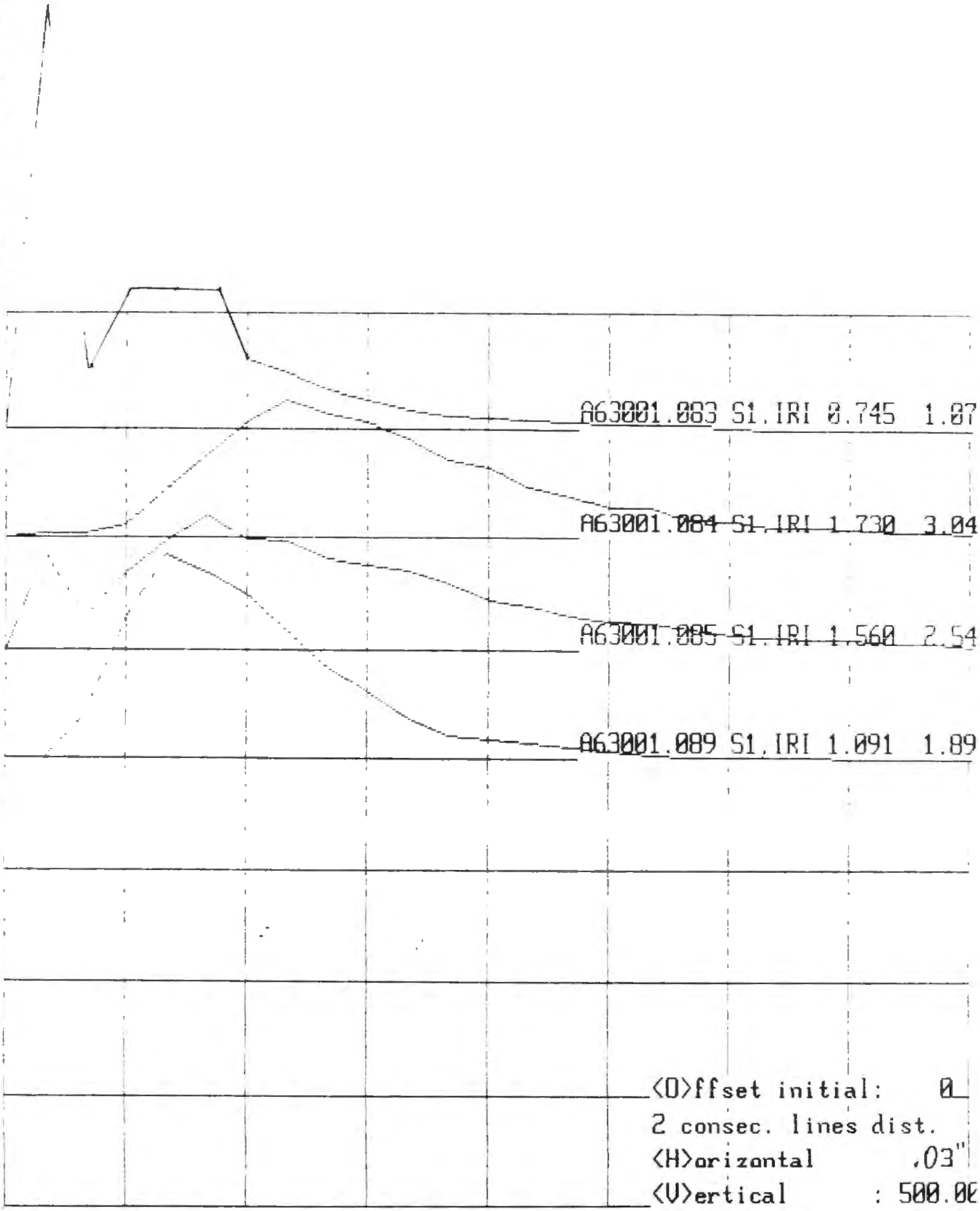
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A63001.085 S1.IRI 1.560 2.54
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2 consec. lines dist.
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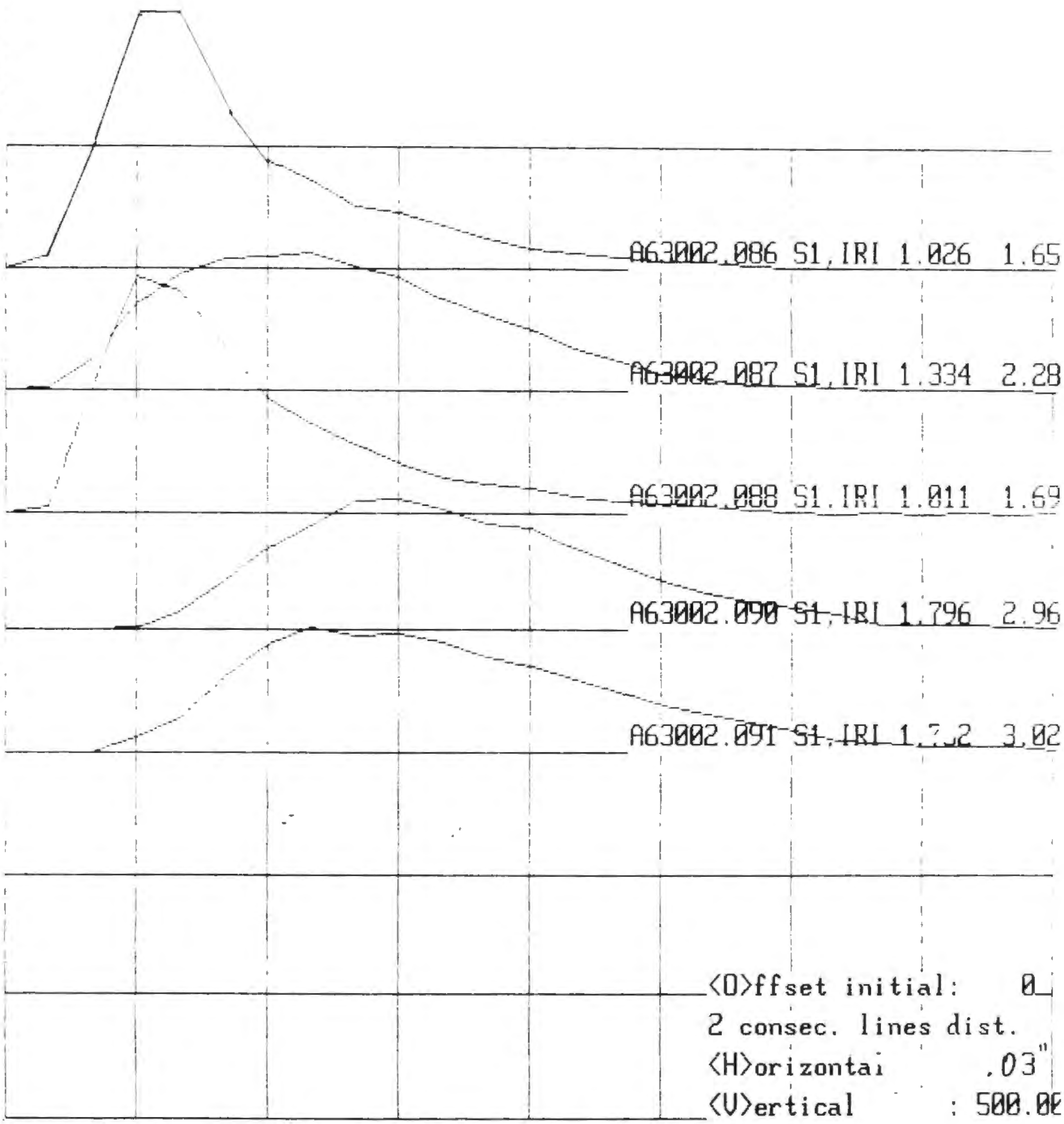
<V>ertical : 500.00


A63002.086 S1,IRI 1.026 1.65
A63002.087 S1,IRI 1.334 2.28
A63002.088 S1,IRI 1.011 1.69
A63002.090 S1,IRI 1.796 2.96
A63002.091 S1,IRI
3.02
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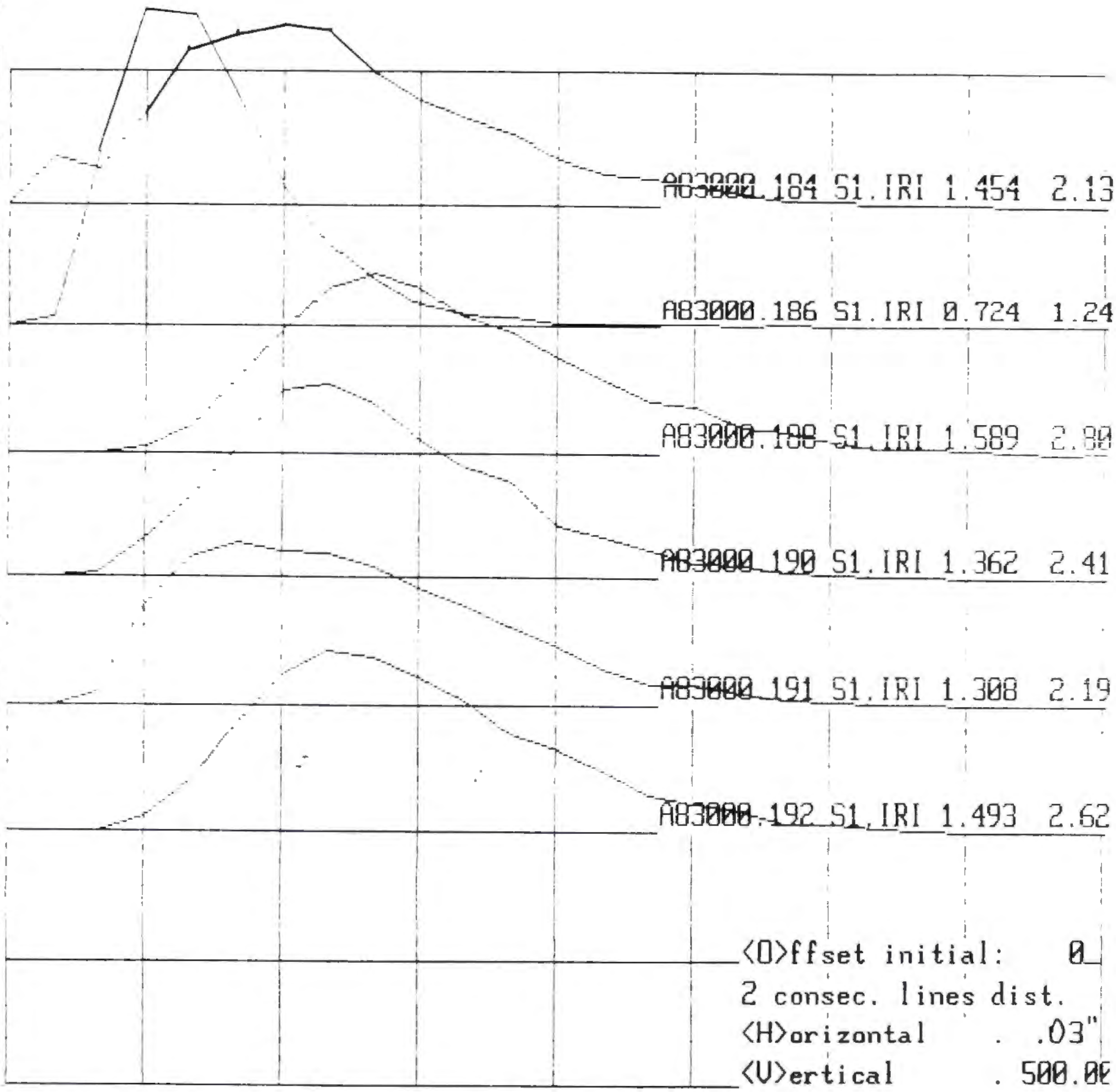
<V>ertical : 500.0


A83000.184 S1.IRI 1.454 2.13
A83000.186 S1.IRI 0.724 1.24
A83000.188 S1.IRI 1.589 2.80
A83000.190 S1.IRI 1.362 2.41
A83000.191 S1.IRI 1.308 2.19
A83000.192 S1.IRI 1.493 2.62
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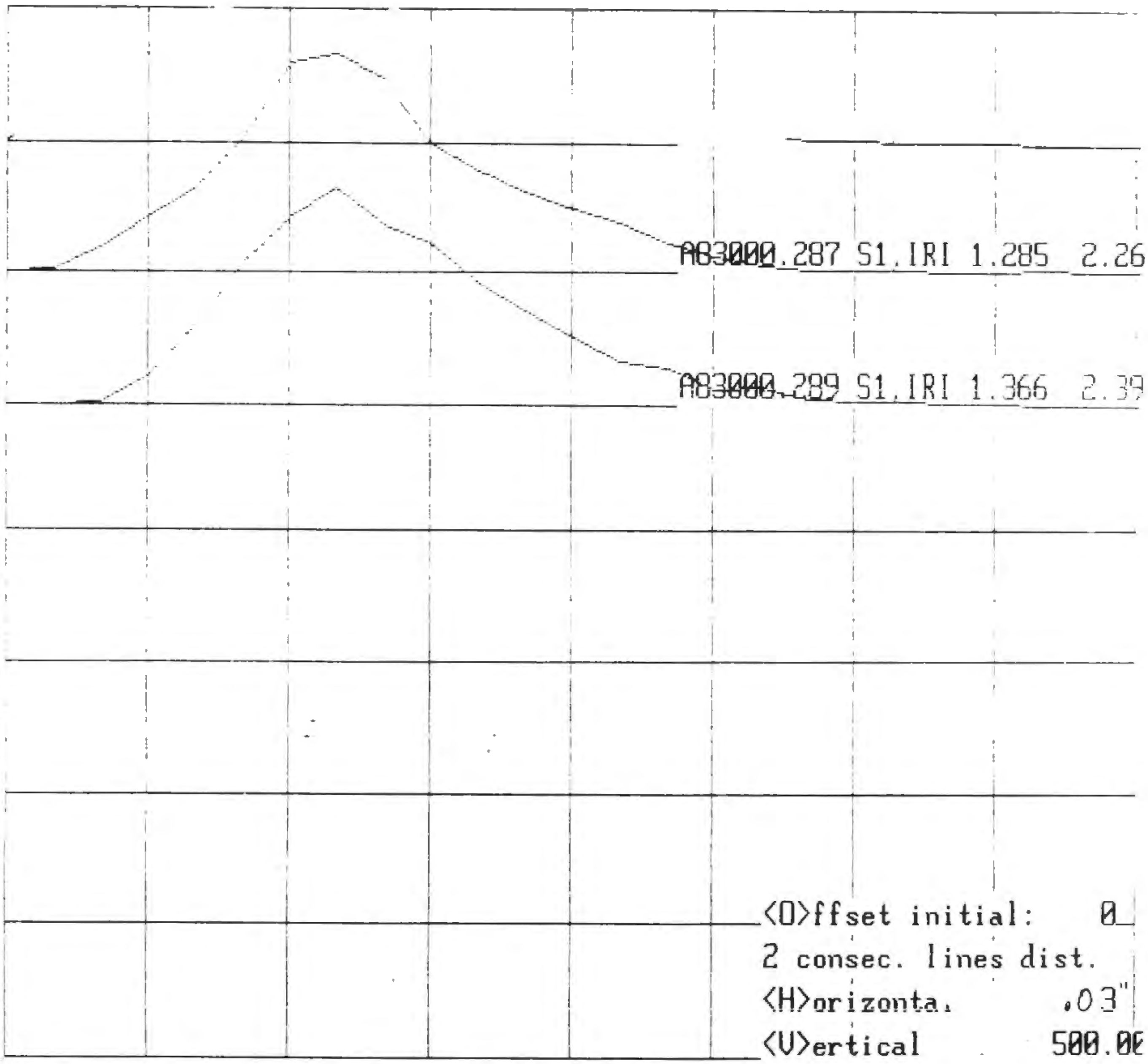
2 consec. lines dist.
<H>orizontal . .03"
<V>ertical . 500.00


A83000.287 S1.IRI 1.285 2.26
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<V>ertical 500.00

APPENDIX D

SD PROFILER ELEVATION AND TRS STATISTIC PROFILES FOR 13 ONE-MILE SECTIONS IN THE 1992 CONSTRUCTION PROGRAM (COLLECTED JUST AFTER CONSTRUCTION)

Elevation profile and maximum vertical displacements of the telescoped rolling straightedge statistic profile are shown for each of the 13 one-mile sections in the 1992 Construction Program and analyzed in this project. For these plots, horizontal distance is set at 700 feet between consecutive vertical lines. Elevation height, which is the profile at the top of each plot, is set at one inch between consecutive horizontal lines. Maximum vertical displacement (MVD), profiled at the bottom of each plot, vertical scale is set at 0.2 inches between consecutive horizontal lines. This scale applies for all plots in this appendix.

Although many of the elevation profiles look very rough, it must be remembered that the horizontal scale of the entire plot covers one mile in length, and that the vertical scale is only 1" between horizontal lines. The telescoped rolling straightedge statistic was devised to find peaks and gullies within 10 feet of any given point. As such, in order to get a good feeling for how the statistic acts relative to the elevation profile, it is recommended that SDDOT personnel use the PROFILE computer program to review a sample of these profiles and set the horizontal scale at 10 or 20 feet between consecutive vertical lines.

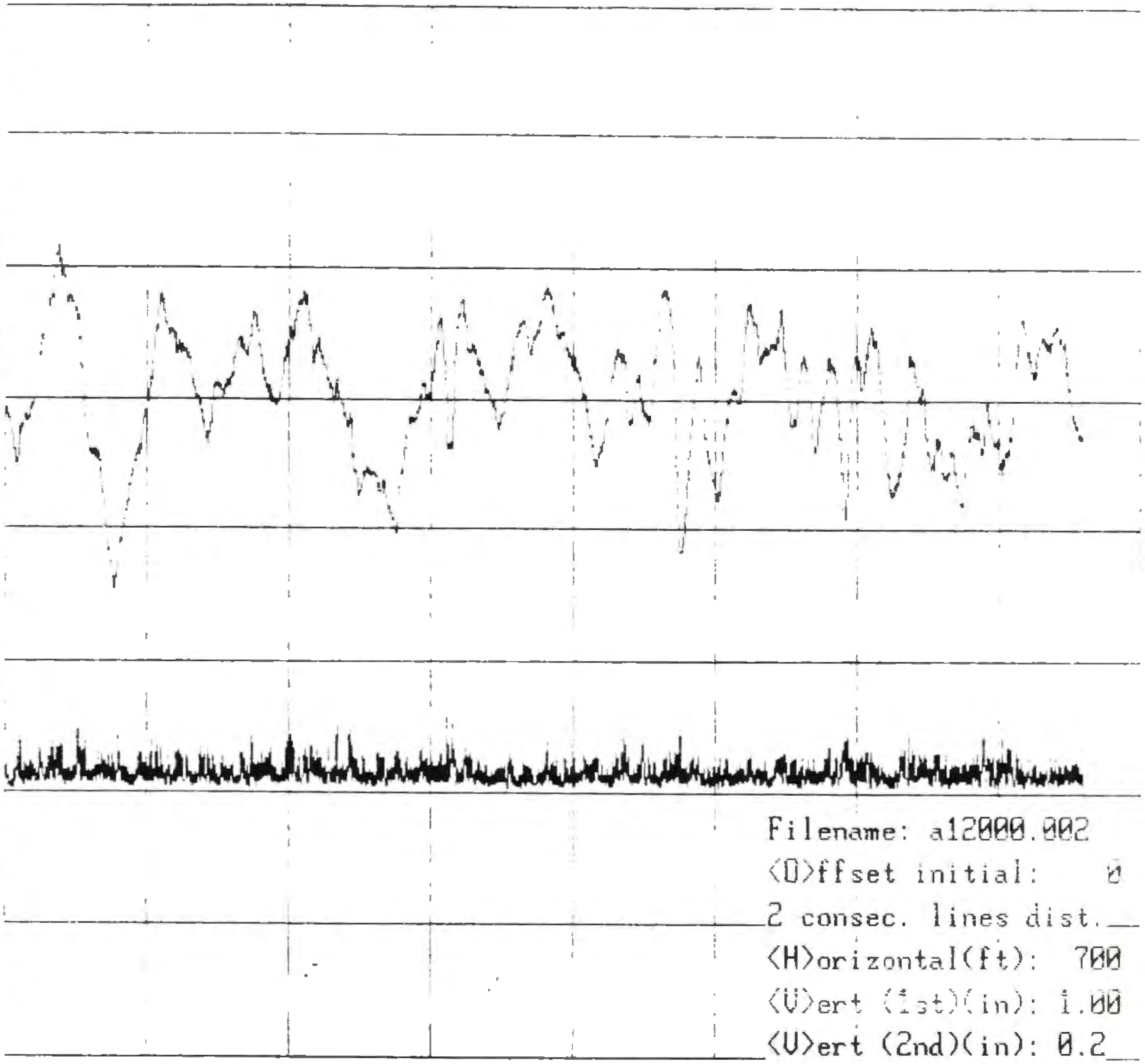
A review of these plots shows that bumps can easily be found (see File A38000.358, A47000.126, and A81000.001). Also, long range changes in the smoothness capability of the laydown operation can be seen by viewing files A83000.096, A83000.097, and AENN00.000.

Figure D.1 provides a synopsis of statistic values for the 13 sections plotted in this appendix.

FIGURE D.1 13 SECTIONS (1 MILE)
1992 REHABILITATION PROGRAM
SD PROFILER & PROFILOGRAPH RESULTS

Route	Mile Pt.	File Name	Profilograph PI	m/km SDDOT IRI	10' Telescoped Rolling Straightedge Statistic
Route 12	315	A12000.315	6.5	1.67	1.002
Route 18	314	A18000.311	3.4	1.74	1.099
Route 34	3	A34000.002	2.3	1.16	0.636
Route 38	358	A38000.358	1.4	1.81	1.376
Route 47	127	A47000.126	1.2	1.96	1.694
Route 81	76	A81000.075	0.7	1.74	1.051
Route 83	100	A83000.096	3.2	1.43	0.826
Route 83	111	A83000.097	1.4	1.34	0.769
Route 88	0	AENN00.000	4.2	1.74	1.147
Route 212	317	A12000.314	0.9	1.42	0.894
Route 281	0	A81000.001	2.6	0.96	0.642
Route 281	87	A81000.086	1.1	1.44	0.799
Route 212	4	A12000.002	3.8	1.09	0.574

Note: 10'
Telescoped
Rolling = .6 * IRI approximately
Straightedge
Edge
Statistic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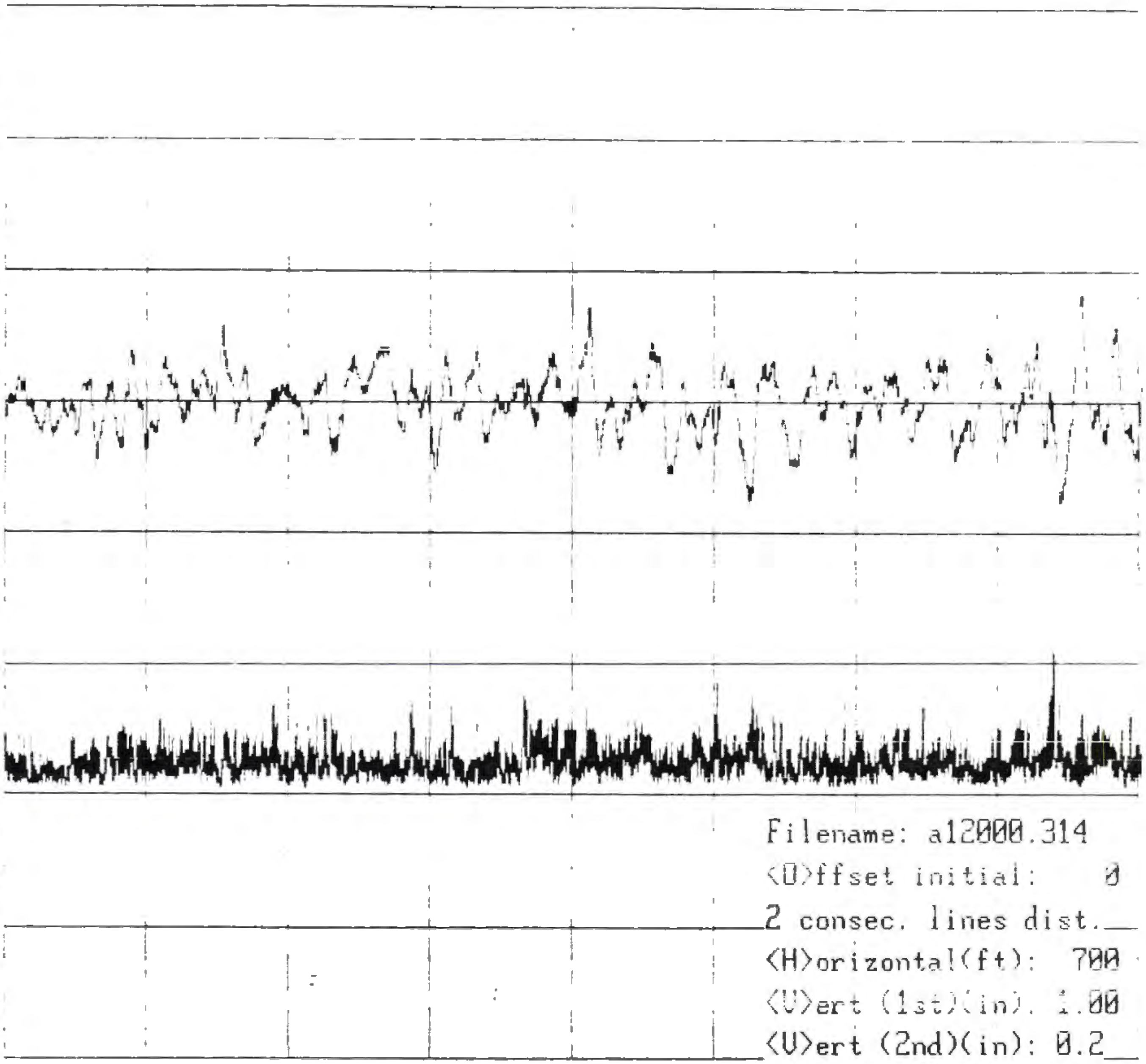
<V>ert (2nd)(in): 0.2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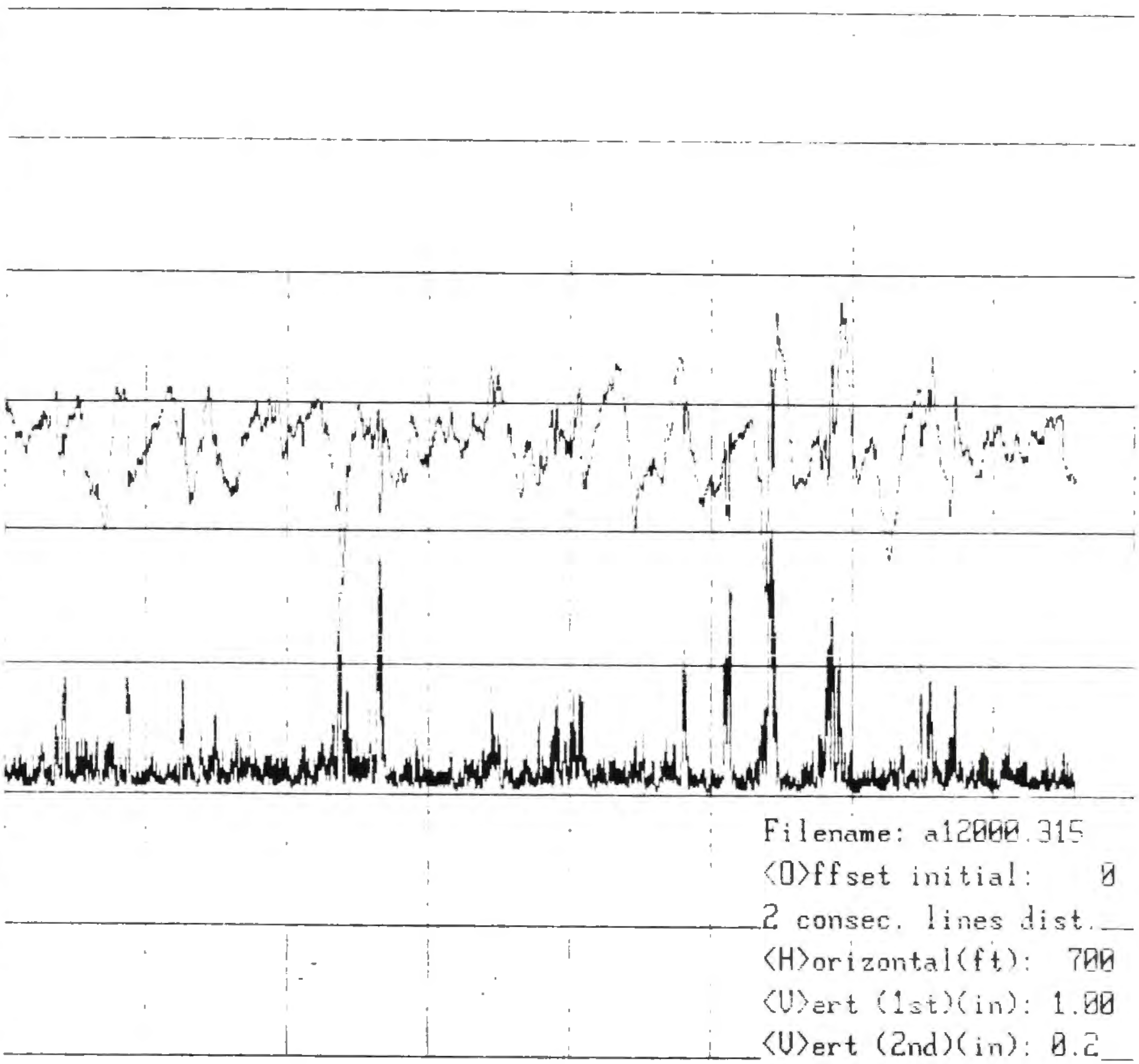

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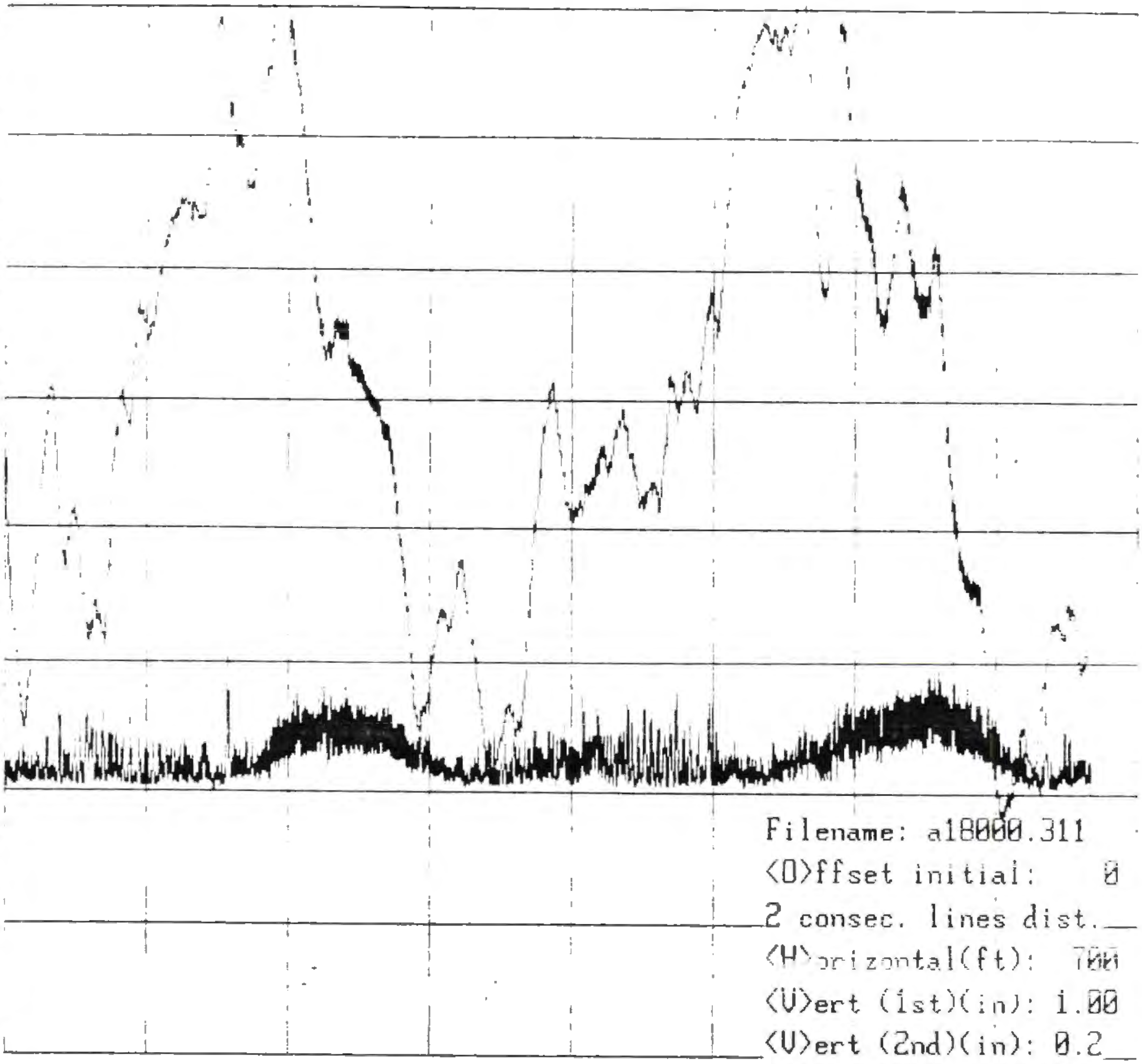

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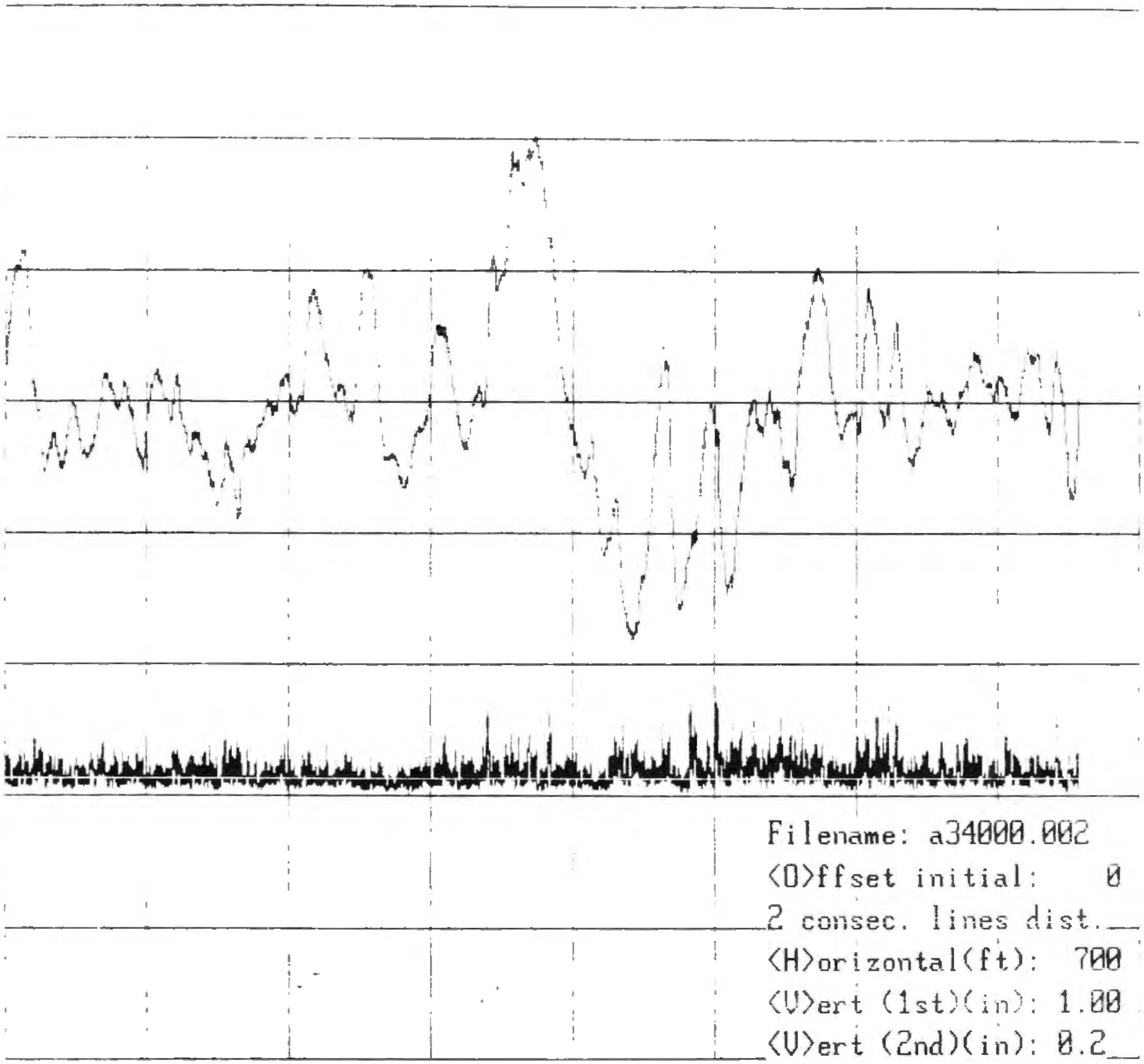
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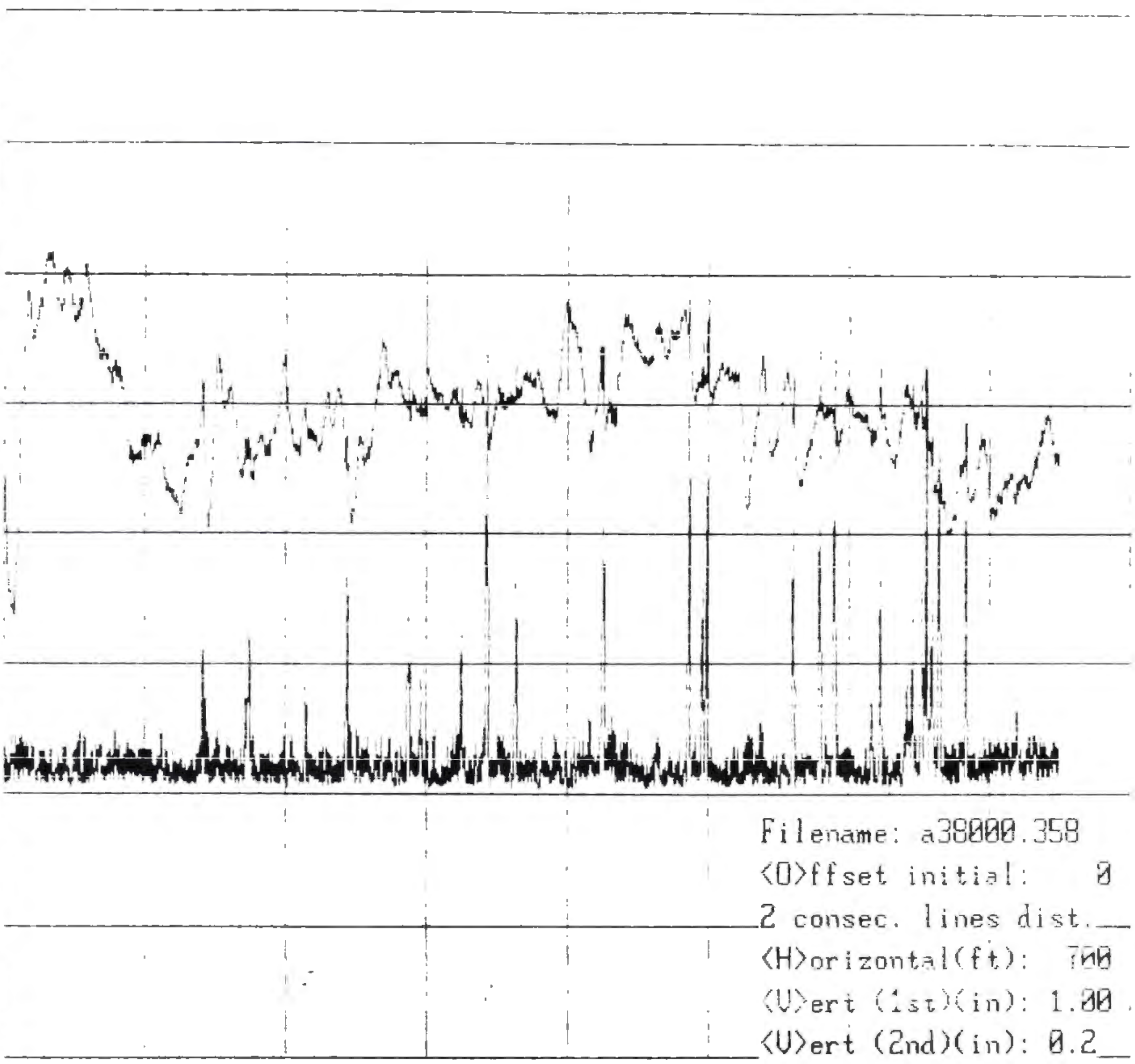
<V>ert (1st)(in): 1.00
<V>ert (2nd)(in): 0.2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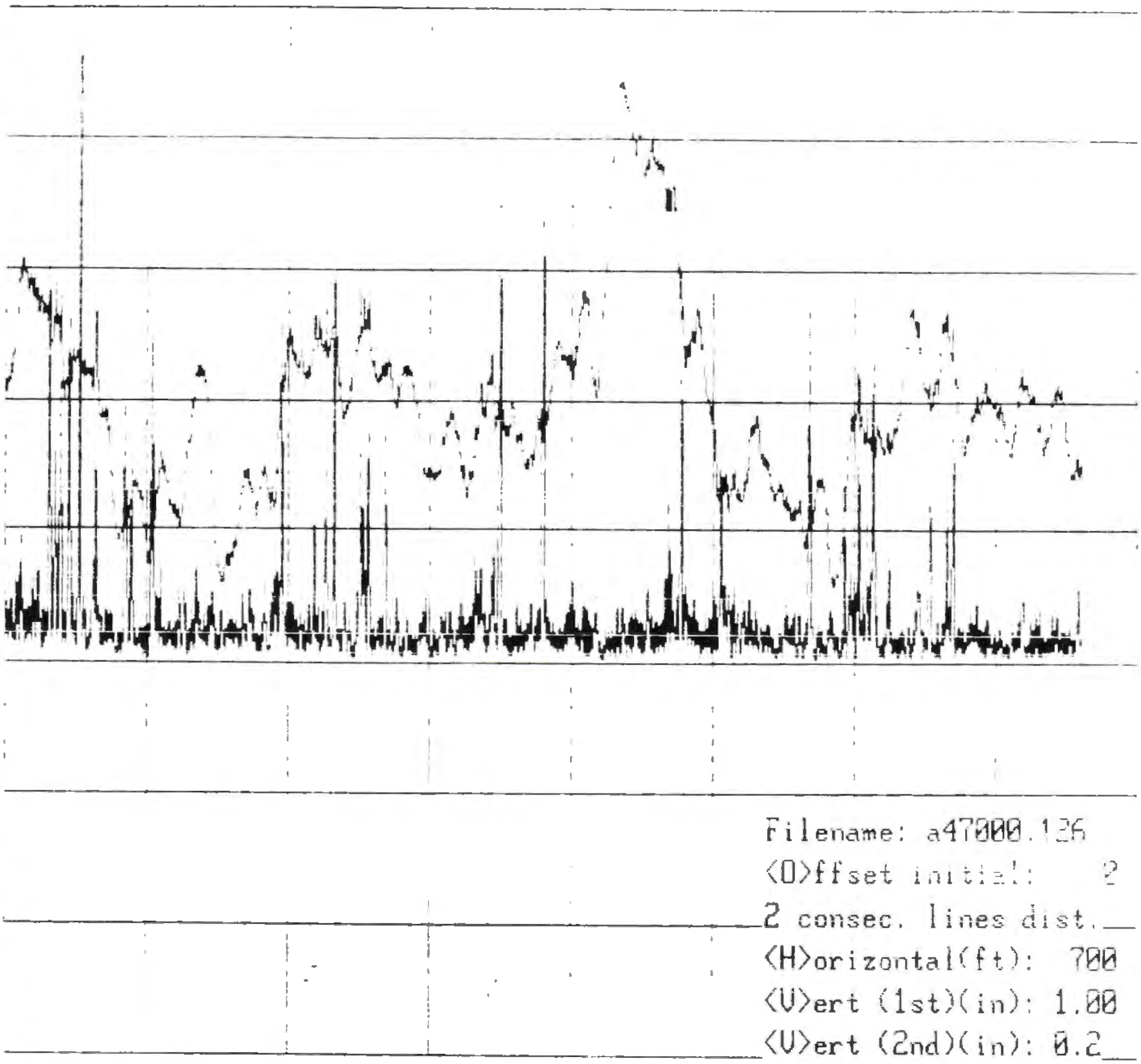
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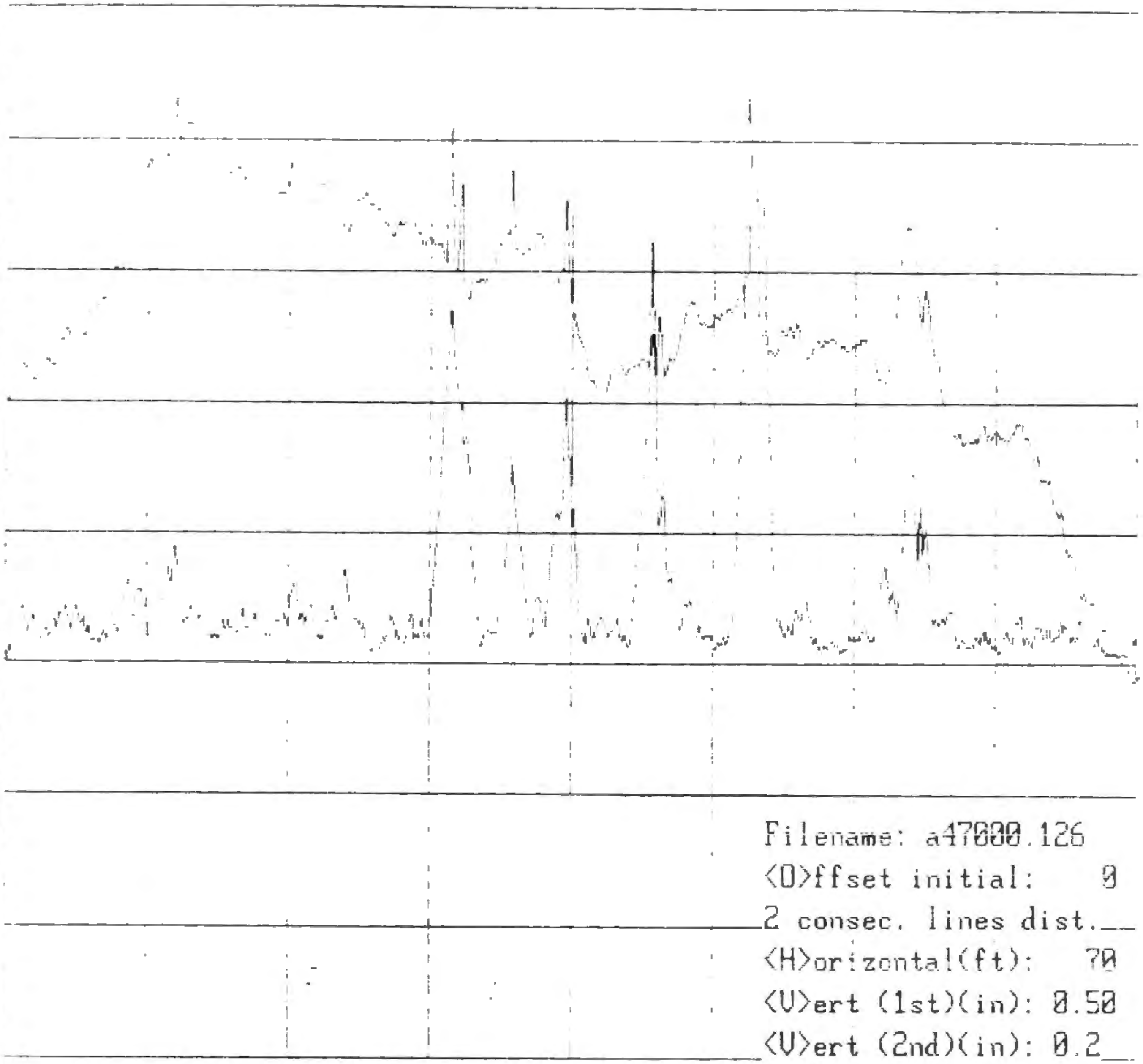
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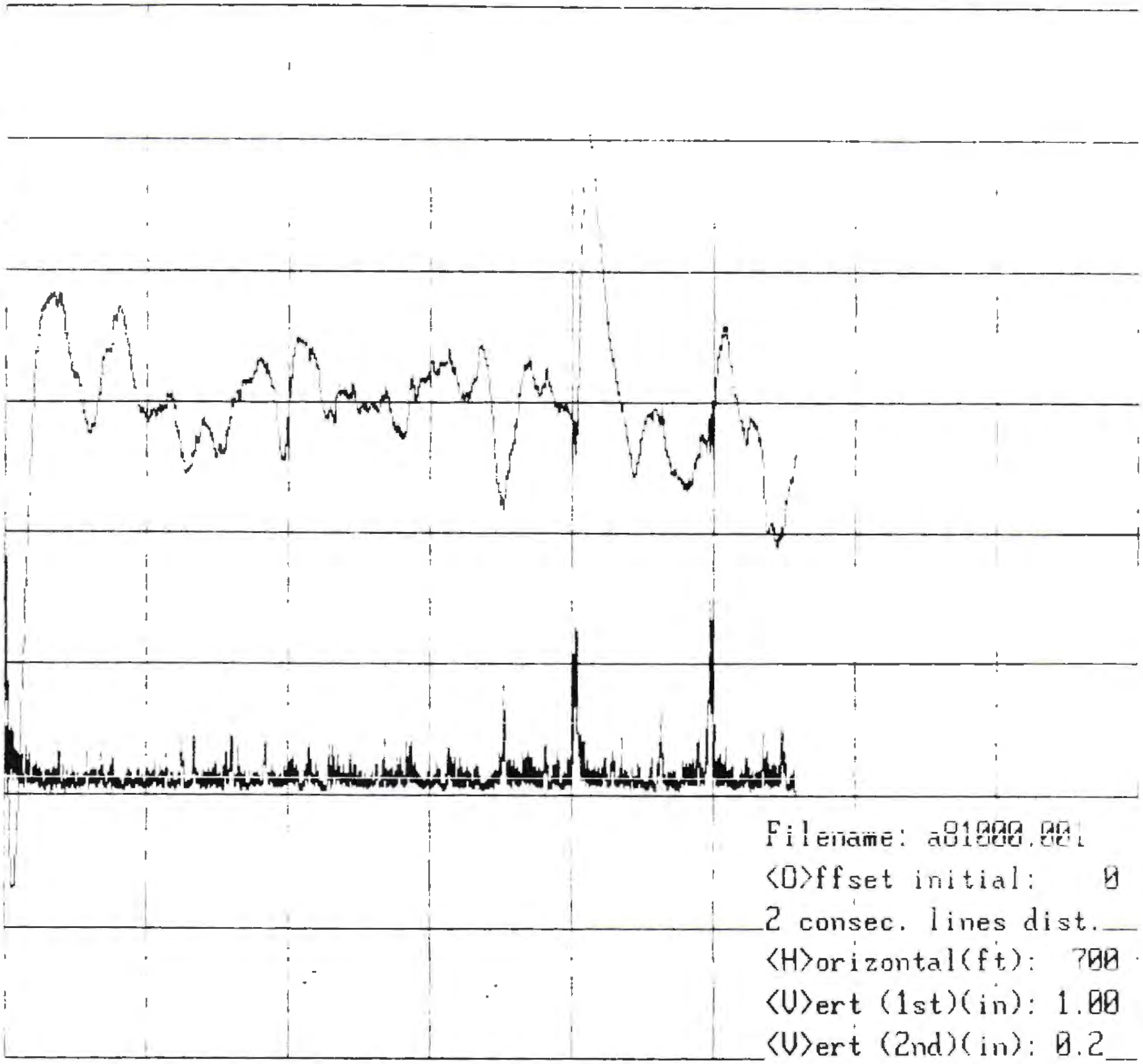
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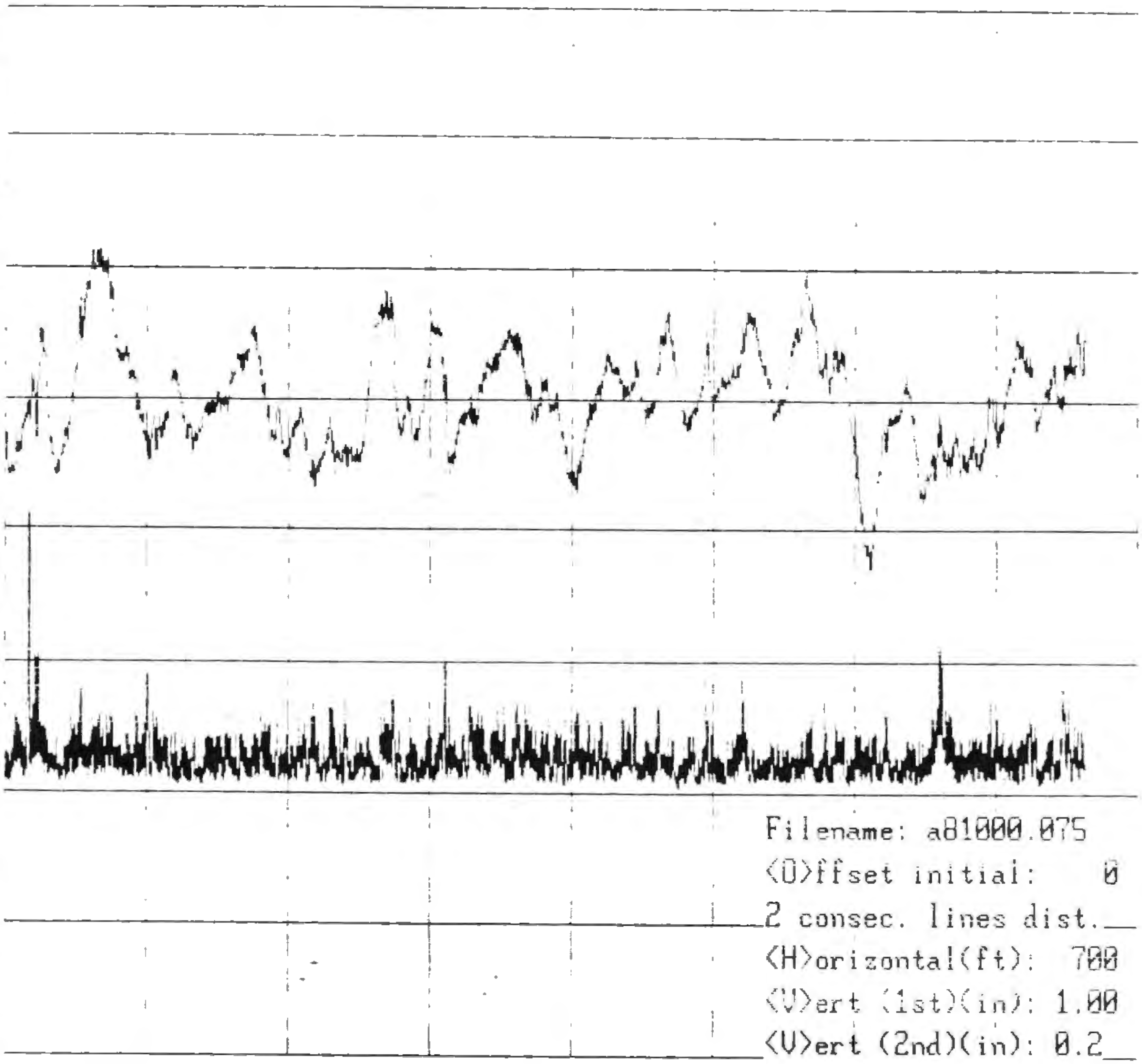
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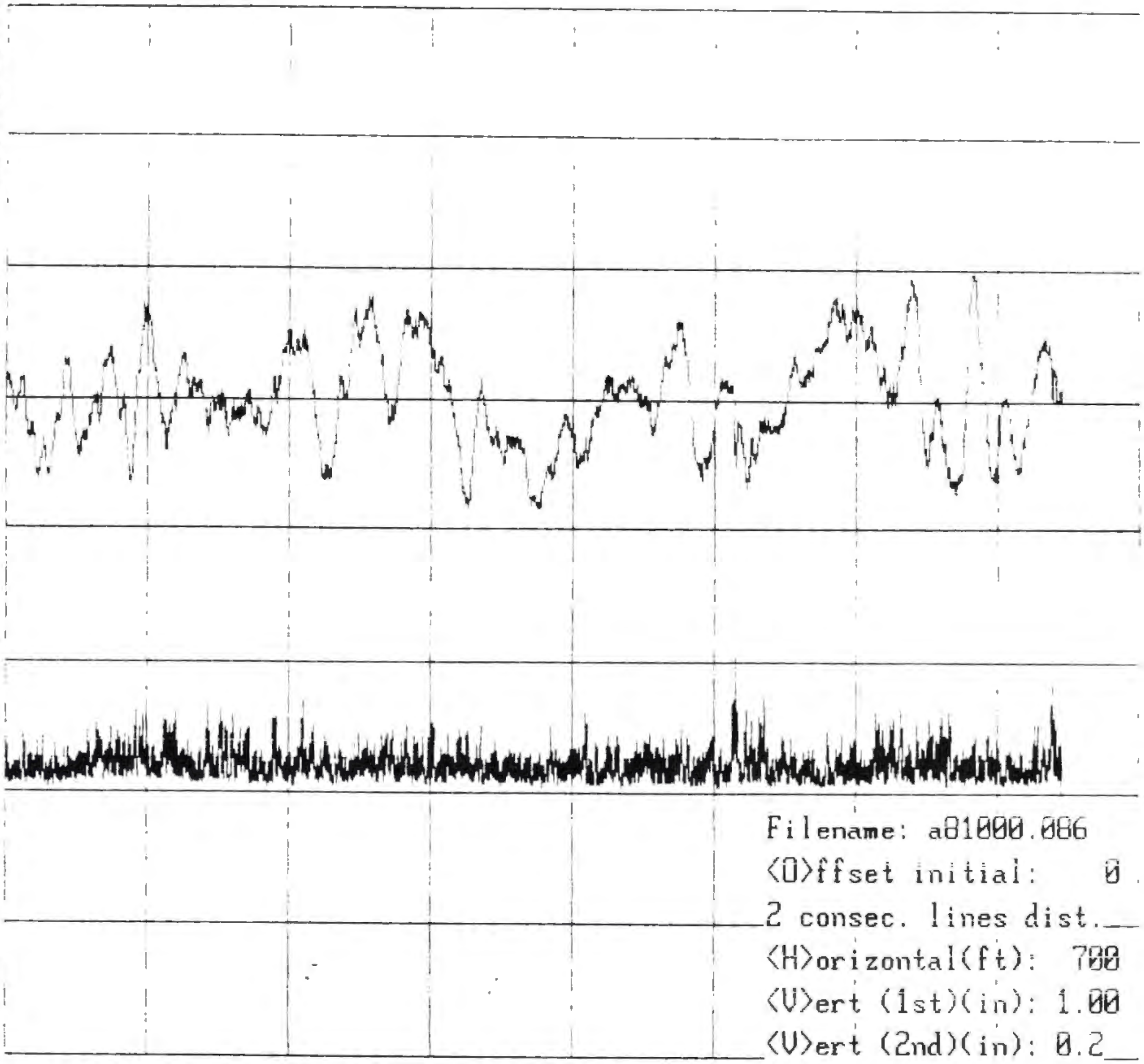
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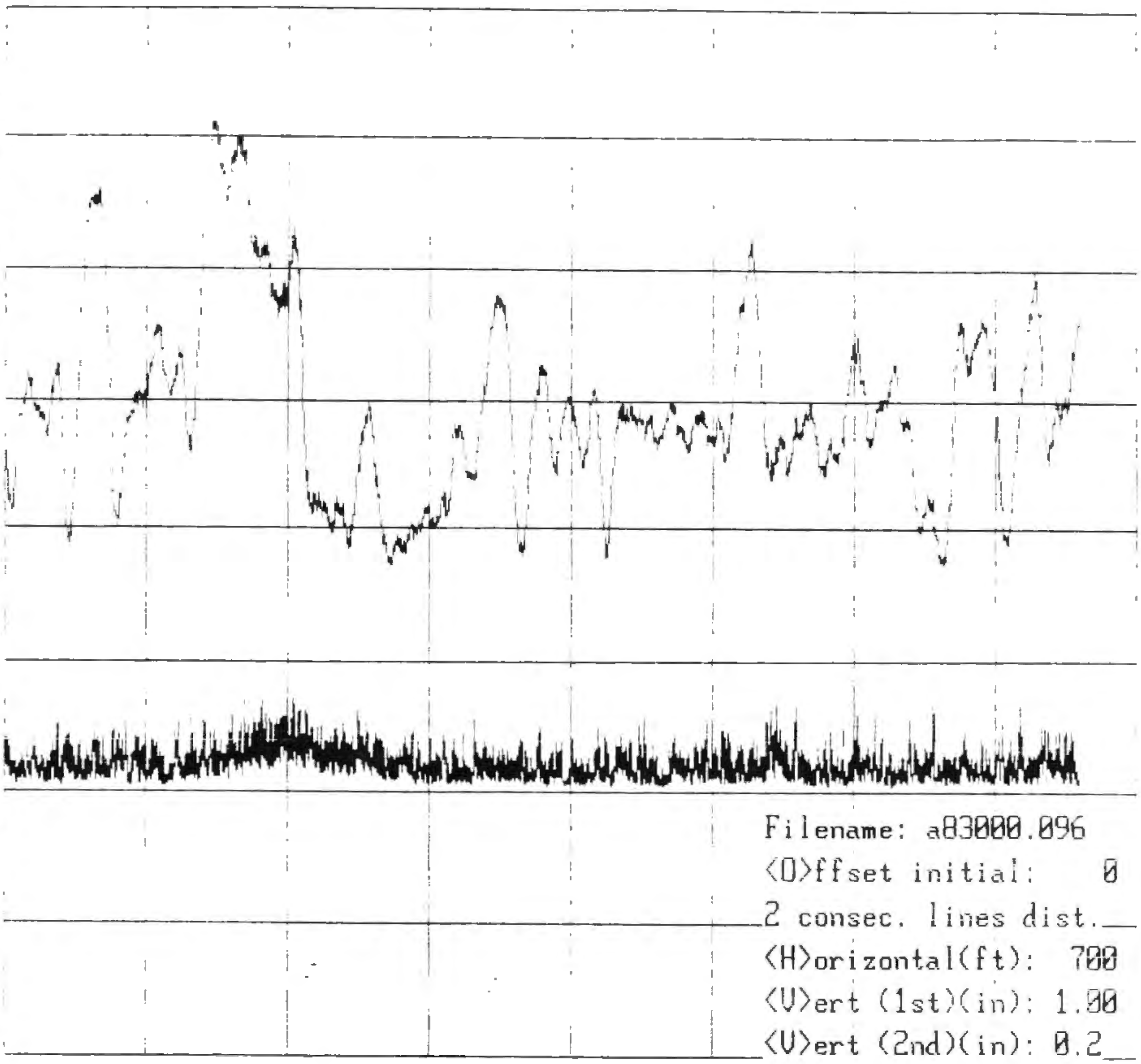
Filename: a83000.096
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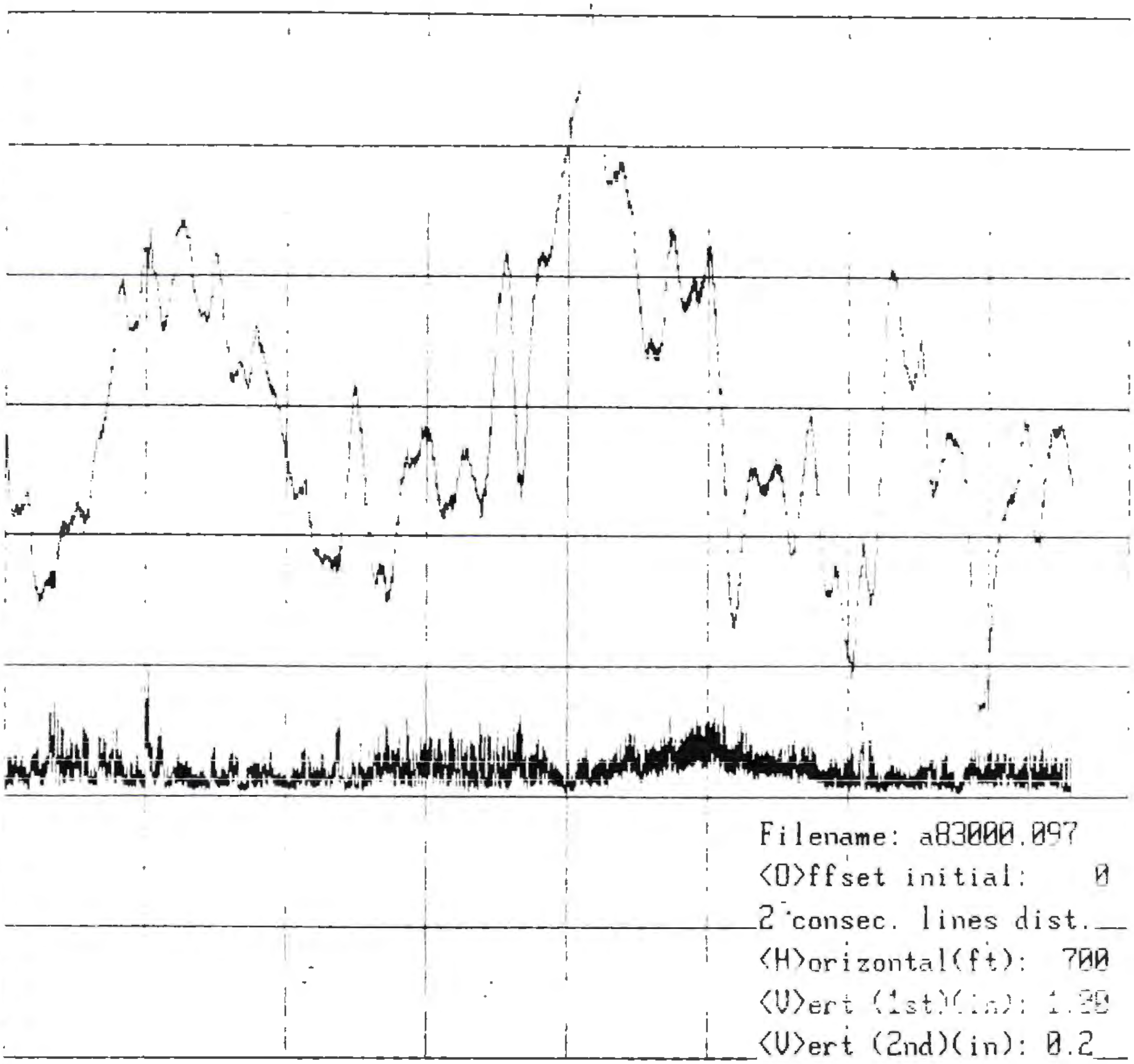
2 consec. lines dist.
<H>orizontal(ft): 700
<V>ert (1st)(in): 1.00
<V>ert (2nd)(in): 0.2



Filename: a83000.097
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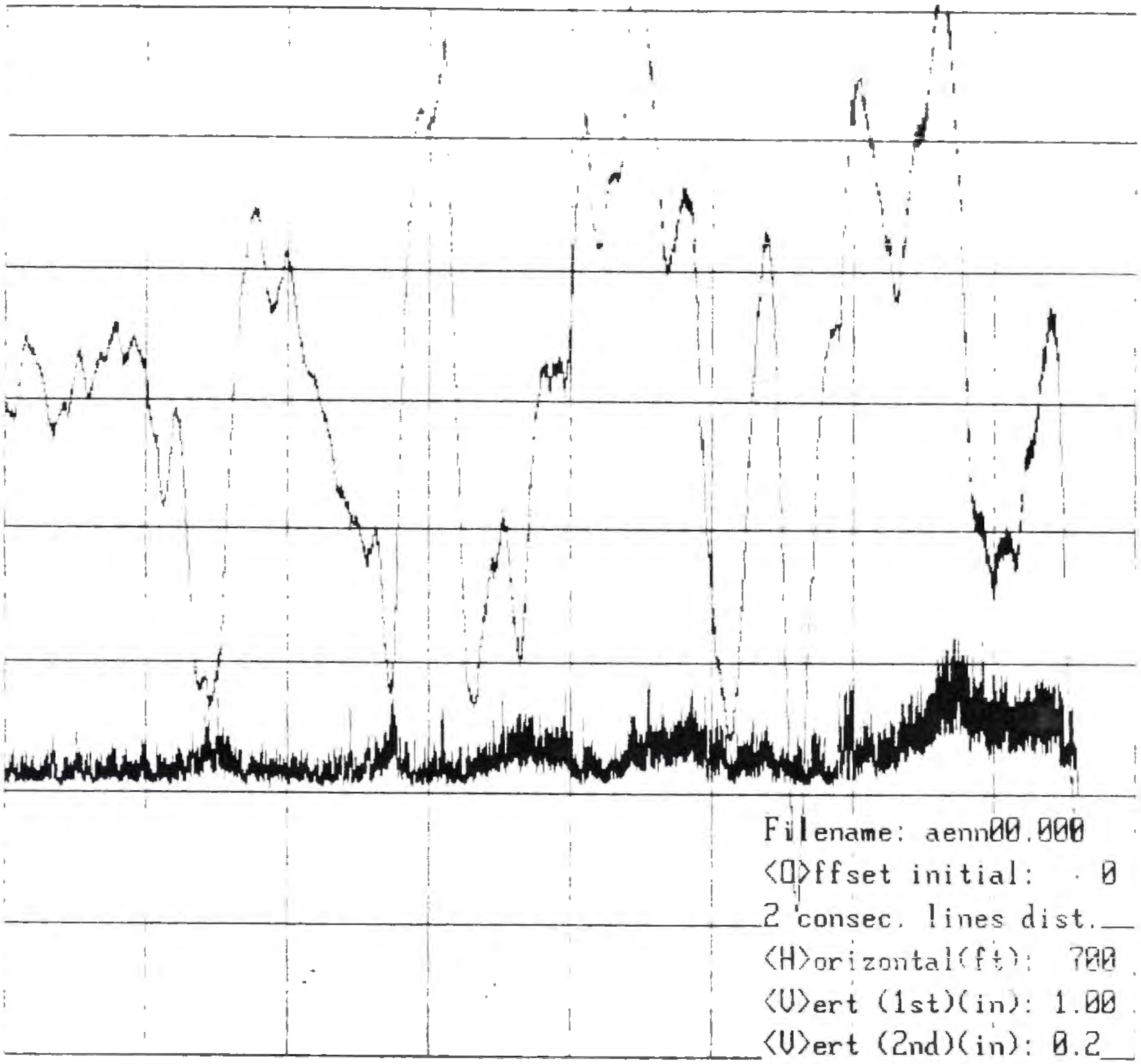
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APPENDIX E
CORRELATIONS OF DIFFERENT ROUGHNESS STATISTICS

Figure E1 shows correlations of 24 different roughness statistics based on data from 13 one-mile sections (one profile per section) that were in the 1992 AC construction program. Figure E2 shows correlations of 23 different roughness statistics (all but PI from profilograph data) obtained from the entire 128 one-mile sections (1 profile per section) where each profile was collected within 2 years after construction. Figure E3 is a legend describing each statistic acronym.

SIMPLE CORRELATIONS

	PI0	IRI	PSI	RN	S1	PI1	PI2
PI0	1.0000						
IRI	-0.0369	1.0000					
PSI	0.0778	-0.6984	1.0000				
RN	0.2468	-0.6869	0.6793	1.0000			
S1	-0.1515	0.9138	-0.6912	-0.8334	1.0000		
PI1	-0.1672	0.6554	-0.3141	-0.6622	0.8683	1.0000	
PI2	-0.2329	0.8913	-0.6709	-0.8088	0.9798	0.8479	1.0000
PI3	-0.2231	0.8184	-0.8407	-0.7899	0.8043	0.4785	0.8391
PA1	0.0454	0.6572	-0.2239	-0.4907	0.8066	0.9543	0.7710
PA2	-0.0347	0.8761	-0.4929	-0.5704	0.9074	0.8450	0.9020
PA3	-0.2163	0.9129	-0.6399	-0.5161	0.8333	0.6107	0.8525
S2	0.0692	0.8470	-0.4313	-0.5189	0.8875	0.8739	0.8642
R1	0.3914	0.3746	0.1226	-0.0408	0.4236	0.6266	0.4050
R2	0.3243	0.5273	-0.0379	-0.0444	0.5178	0.6340	0.5088
R3	0.1936	0.6995	-0.2551	-0.0802	0.5970	0.5616	0.5905
PI4	0.1717	0.5931	-0.1558	-0.3611	0.7229	0.8928	0.6791
PI5	0.0380	0.7840	-0.3889	-0.4971	0.8705	0.9123	0.8490
PI6	-0.0568	0.9715	-0.7382	-0.6841	0.9350	0.6985	0.9309
PA4	0.6301	0.2750	0.1418	0.1818	0.2217	0.3608	0.1657
PA5	0.5791	0.3245	0.1162	0.1348	0.2847	0.4287	0.2363
PA6	0.4696	0.4676	-0.0005	0.0640	0.4104	0.5071	0.3758
R4	-0.0647	0.6601	-0.2371	-0.5707	0.8343	0.9822	0.8075
R5	-0.0442	0.7560	-0.3389	-0.5961	0.8864	0.9620	0.8647
R6	-0.1085	0.8852	-0.5103	-0.6074	0.9324	0.8786	0.9208

	PI3	PA1	PA2	PA3	S2	R1	R2
PI3	1.0000						
PA1	0.3613	1.0000					
PA2	0.5960	0.8847	1.0000				
PA3	0.7051	0.6185	0.8952	1.0000			
S2	0.5503	0.9376	0.9740	0.8229	1.0000		
R1	0.0007	0.8115	0.6795	0.3624	0.7545	1.0000	
R2	0.1319	0.8206	0.7850	0.5646	0.8448	0.9561	1.0000
R3	0.3065	0.7271	0.8345	0.7822	0.8660	0.7561	0.9101
PI4	0.2566	0.9847	0.8502	0.5615	0.9202	0.8803	0.8830
PI5	0.5002	0.9648	0.9542	0.7712	0.9898	0.7698	0.8479
PI6	0.8250	0.6988	0.9215	0.9262	0.8775	0.4377	0.5853
PA4	-0.1443	0.6187	0.5113	0.2521	0.6101	0.9145	0.8893
PA5	-0.0953	0.6755	0.5725	0.3091	0.6664	0.9428	0.9253
PA6	0.0367	0.7368	0.6968	0.4869	0.7734	0.9351	0.9730
R4	0.4074	0.9889	0.8732	0.6175	0.9151	0.7497	0.7518
R5	0.4915	0.9809	0.9387	0.7264	0.9635	0.7510	0.7866
R6	0.6223	0.8955	0.9874	0.8992	0.9754	0.6298	0.7435

	R3	PI4	PI5	PI6	PA4	PA5	PA6
R3	1.0000						
PI4	0.7698	1.0000					
PI5	0.8399	0.9484	1.0000				
PI6	0.7235	0.6424	0.8307	1.0000			
PA4	0.7411	0.7360	0.6003	0.3068	1.0000		
PA5	0.7784	0.7832	0.6604	0.3625	0.9960	1.0000	
PA6	0.8938	0.8267	0.7623	0.5057	0.9599	0.9769	1.0000
R4	0.6580	0.9501	0.9453	0.6975	0.5138	0.5770	0.6446
R5	0.7380	0.9425	0.9758	0.7948	0.5339	0.5972	0.6846
R6	0.8141	0.8480	0.9604	0.9133	0.4537	0.5172	0.6502

	R4	R5	R6
R4	1.0000		
R5	0.9857	1.0000	
R6	0.8955	0.9526	1.0000

CASES INCLUDED 13 MISSING CASES 0

Figure E1. Simple Correlations of Many Smoothness Statistic on 13 One-mile Road Sections in the 1992 Rehabilitated Programs Measured With Profilograph & SD Profiler Soom After Construction.

SIMPLE CORRELATIONS

	IRI	PSI	RN	S1	PI1	PI2	PI3
IRI	1.0000						
PSI	-0.6988	1.0000					
RN	-0.8773	0.5932	1.0000				
S1	0.9323	-0.6630	-0.8962	1.0000			
PI1	0.7895	-0.6148	-0.7293	0.8480	1.0000		
PI2	0.9341	-0.5973	-0.8566	0.9261	0.9120	1.0000	
PI3	0.9535	-0.5489	-0.8996	0.9130	0.7839	0.9606	1.0000
PA1	0.7205	-0.6735	-0.6311	0.7960	0.9570	0.8091	0.6571
PA2	0.9152	-0.6890	-0.7918	0.9222	0.9413	0.9583	0.8776
PA3	0.9727	-0.6955	-0.8512	0.9386	0.8250	0.9356	0.9378
S2	0.8589	-0.7790	-0.7574	0.9321	0.8358	0.8335	0.7735
R1	0.4232	-0.7134	-0.2818	0.4700	0.5722	0.4144	0.2714
R2	0.5978	-0.7990	-0.4182	0.6038	0.6394	0.5591	0.4493
R3	0.7308	-0.8219	-0.5448	0.6948	0.6315	0.6332	0.5964
PI4	0.4826	-0.7088	-0.4154	0.5788	0.7367	0.5202	0.3551
PI5	0.8232	-0.7900	-0.6953	0.8475	0.8972	0.8423	0.7337
PI6	0.9755	-0.6287	-0.8911	0.9501	0.8342	0.9584	0.9654
PA4	0.2111	-0.5514	-0.1845	0.2917	0.3959	0.2041	0.0761
PA5	0.3292	-0.6505	-0.2243	0.3870	0.5006	0.3188	0.1775
PA6	0.5206	-0.7730	-0.3567	0.5430	0.6132	0.4870	0.3635
R4	0.4447	-0.5893	-0.6231	0.5902	0.6683	0.4999	0.3864
R5	0.6663	-0.6885	-0.7723	0.7732	0.8074	0.7086	0.6099
R6	0.8468	-0.7439	-0.8753	0.8984	0.8592	0.8516	0.7961

	PA1	PA2	PA3	S2	R1	R2	R3
PA1	1.0000						
PA2	0.9145	1.0000					
PA3	0.7762	0.9446	1.0000				
S2	0.8687	0.9122	0.8987	1.0000			
R1	0.7366	0.6050	0.4947	0.7361	1.0000		
R2	0.7577	0.7188	0.6669	0.8339	0.9470	1.0000	
R3	0.7051	0.7499	0.7979	0.8649	0.8023	0.9336	1.0000
PI4	0.8791	0.6993	0.5561	0.7856	0.9197	0.8662	0.7397
PI5	0.9319	0.9373	0.8686	0.9428	0.8000	0.8889	0.8738
PI6	0.7557	0.9318	0.9728	0.8684	0.4123	0.5777	0.7016
PA4	0.5815	0.3811	0.2546	0.5364	0.8121	0.6823	0.5222
PA5	0.6861	0.5133	0.3874	0.6531	0.9267	0.8339	0.6802
PA6	0.7669	0.6693	0.5884	0.7945	0.9683	0.9604	0.8675
R4	0.7309	0.5849	0.4858	0.6631	0.6054	0.5660	0.4922
R5	0.8397	0.7795	0.7036	0.8179	0.6493	0.6703	0.6359
R6	0.8562	0.8972	0.8808	0.9055	0.6145	0.7066	0.7469

	PI4	PI5	PI6	PA4	PA5	PA6	R4
PI4	1.0000						
PI5	0.8573	1.0000					
PI6	0.4988	0.8303	1.0000				
PA4	0.8085	0.5444	0.2223	1.0000			
PA5	0.8973	0.6908	0.3287	0.9632	1.0000		
PA6	0.9188	0.8418	0.5066	0.8411	0.9479	1.0000	
R4	0.7685	0.6738	0.4915	0.6578	0.6260	0.6049	1.0000
R5	0.7967	0.8210	0.7055	0.6196	0.6351	0.6760	0.9582
R6	0.7385	0.8891	0.8714	0.5092	0.5682	0.6779	0.8335

	R5	R6
R5	1.0000	
R6	0.9531	1.0000

CASES INCLUDED 128 MISSING CASES 0

Figure E2. Simple Correlations of All Smoothness Statistics Using All 128 One-mile Road Section Profiles.

PI0 PI calculated by SDDOT from traces produced by a profilograph

All statistics below are calculated using SD profiler data

IRI IRI as calculated by SDDOT (m/km)
PSI PSI as calculated by SDDOT (0-5: rough to smooth scale)

All statistics below have been calculated by the Consultant using SD profiler data

RN	Ride number as documented in NCHRP Project 1-23 (same scale as PSI)
S1	TRS with a 10 ft. maximum straightedge.
S2	TRS with a 20 ft. maximum straightedge.
PI1	Simulated 10' profilograph PI with a ± 0.1" blanking band
PI2	Simulated 10' profilograph PI with a ± 0.05" blanking band
PI3	Simulated 10' profilograph PI with no blanking band
PI4	Simulated 25' profilograph PI with a ± 0.2" blanking band
PI5	Simulated 25' profilograph PI with a ± 0.1" blanking band
PI6	Simulated 25' profilograph PI with no blanking band
PA1	Simulated 10' profilograph area under the profilograph trace rectified with a ± 0.1" blanking band
PA2	Simulated 10' profilograph area under the profilograph trace rectified with a ± 0.05" blanking band
PA3	Simulated 10' profilograph area under the profilograph trace using no blanking band
PA4	Simulated 25' profilograph area under the profilograph trace rectified with a ± 0.2" blanking band
PA5	Simulated 25' profilograph area under the profilograph trace rectified with a ± 0.1" blanking band
PA6	Simulated 25' profilograph area under the profilograph trace using no blanking band
R1	RMSVA using a 5' base length and with a ± 0.1" blanking band used on the second difference.
R2	RMSVA using a 5' base length and with a ± 0.05" blanking band used on the second difference.
R3	RMSVA using a 5' base length and with no blanking band used on the second difference.
R4	RMSVA using a 12.5' base length and with a ± 0.2" blanking band used on the second difference.
R5	RMSVA using a 12.5' base length and with a ± 0.1" blanking band used on the second difference.
R6	RMSVA using a 12.5' base length and with no blanking band used on the second difference.

Figure E3. Statistic (Acronym) Descriptions

APPENDIX F

STANDARD TEST METHOD FOR MEASURING ROUGHNESS USING A PROFILOGRAPH

Standard Test Method for Measuring Pavement Roughness Using a Profilograph[1]

This standard is issued under the fixed designation E 1274; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the measurement of pavement roughness using an articulated multi-wheeled profilograph at least 23 ft (7 m) long (Fig. 1 is typical).

1.2 This test method utilizes a surface record made by moving the profilograph longitudinally over the pavement at less than 3 mph (5 km/hr). The record is analyzed to determine the rate of roughness and to identify bumps that exceed a specified threshold.

1.3 The values stated in inch-pound units are to be regarded as the standard.

1.4 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* See Section 6 for specific hazard statement.

2. Referenced Document

2.1 *ASTM Adjunct:*

E 1274 Test Method for Measuring Pavement Roughness Using a Profilograph[2]

3. Terminology

3.1 *Description of Terms Specific to This Standard:*

3.1.1 *blanking band*—a band of uniform height with its longitudinal center positioned optimally between the highs and lows of the surface record depicting at least 100 ft (30 m) of pavement (see Fig. 2).

3.1.2 *cutoff height*—a specified distance of a high on the surface record from a chord representing 25 ft (7.5 m) on the longitudinal scale. The chord may represent less than 25 ft (7.5 m) if it is from the lows on each side of the high (see Fig. 2).

3.1.3 *rate of roughness*—sum of the roughness divided by the longitudinal distance covered by the blanking band.

3.1.4 *roughness*—height of each continuous scallop rounded to the nearest 0.05 in. (1 mm), except those less than 0.03 in. (0.8 mm) vertically and 2 ft (0.6 m) longitudinally.

3.1.5 *scallops*—excursions of the surface record above and below the blanking band (see Fig. 2).

4. Significance and Use

4.1 This test method provides a means for measuring the roughness of new or rehabilitated pavements. Results may differ between profilographs of different designs and therefore will not necessarily agree with roughness measurements by other profilographs or other roughness-measuring equipment.

5. Apparatus

5.1 *Profilographs:*

5.1.1 *With Uniformly Spaced Wheels*—a reference platform comprised of dollies articulated by rigid members or trusses so that all the wheels are supporting the profilograph. There must be at least twelve reference platform wheels, and the axes of these wheels must be uniformly spaced throughout the effective length of the profilograph.[3] The effective length must be at least 23 ft (7 m) long. A surface sensing wheel and recorder shall be located at the center of the reference platform. The diameter of the surface sensing wheel shall be at least 6 in. (150 mm). If the recorder is graphic, its scales shall be 1:1 vertically and 1:300 longitudinally (1 in. = 25 ft). If the recorder is digital (optional analog display must have the same scales as the graphic recorder), it must sample 5 times/longitudinal inch of travel and record the relative height of the surface to at least the nearest 0.01 in. (0.25 mm).

5.1.2 *With Non-Uniformly Spaced Wheels*—It shall be as described in 5.1.1, except the axes of the reference-platform wheels are not uniformly spaced but are at least 1 ft (0.3 m) apart so no two wheels cross the same bump at the same time. The recorder can be located elsewhere, but surface sensing equipment must be located at the center of the reference platform. A common apparatus with non-uniformly spaced wheels is the California profilograph (see 2.1).

5.1.3 There are differences in frequency responses between profilographs with uniformly spaced wheels and profilographs with non-uniformly spaced wheels (see Fig. 3).

5.2 *Blanking Band Template* (optional)—Approximately 2-in. (50-mm) wide clear plastic strip at least 4 in. (100 mm) long. A common length is 21.12 in. The center of the template is marked with an opaque strip the width of the stipulated blanking band throughout its length and with lines every 0.1 in. (2 mm) above and below the blanking band.

5.3 *Excessive Height Template* (optional)—Clear plastic piece marked with a 1.00 ± 0.02-in. (25.0 ± 0.5-mm) line that is the stipulated cutoff height distance from a straight edge on the template. Two small holes may be drilled to fix

[1] This test method is under the jurisdiction of ASTM Committee E-17 on Pavement Management Technologies and is the direct responsibility of Subcommittee E17.32 on Measurement and Control of Roughness in Construction and Rehabilitation of Pavements.

Current edition approved Oct. 31, 1988. Published December 1988.

[2] *Annual Book of ASTM Standards*, Vol 04.03.

[3] Hankins, Kenneth D., "Construction Control Profilograph Principles," *Research Report 49-1*, Texas Highway Department, June 1967.

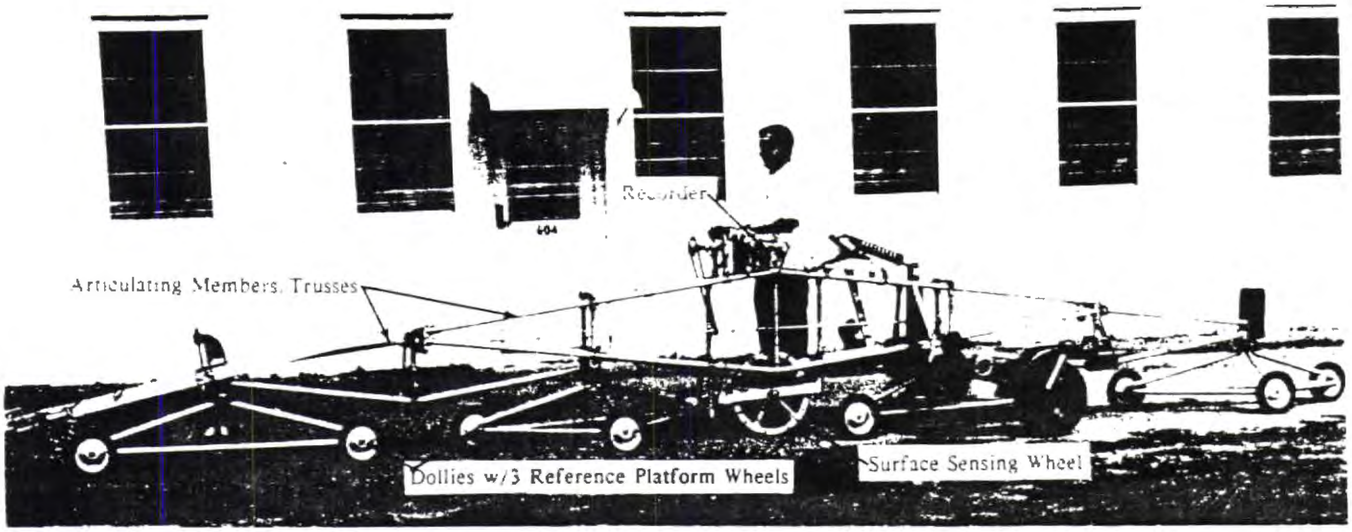
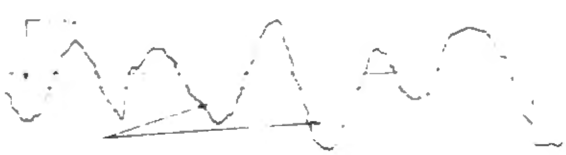


FIG. 1 Typical Profilograph



NOTE—Fig. 2 is graphic for visual reading; it can be data for computer input

FIG. 2 Surface Record

the ends of the line (see Fig. 2).

6. Hazards

6.1 Since profilographs in the testing mode are moved no faster than 3 mph (5 km/hr), do not operate near traffic without proper traffic control devices and use procedures that assure the safety of testing personnel and the public.

7. Sampling

7.1 Take profilograph recordings 3.5 ± 0.5 ft (1.0 ± 0.2 m) from and parallel to both edges of the pavement and to both sides of each planned longitudinal joint or in each planned wheel path.

7.2 Any exceptions to these sampling requirements (for example, 25 ft from each bridge) must be stipulated.

8. Calibration

8.1 *Height recording*

8.1.1 Place gage blocks of 0.5 in. (10 mm) and 1.5 in. (60 mm) under the surface sensing wheel. The record must indicate the actual height of each platform within ±0.02 in. (0.5 mm).

8.1.2 Verify the standardization of the height recording before any week of use, whenever the profilograph is re-assembled and whenever there is evidence of possible inaccuracy.

8.2 *Distance recording*

8.2.1 Mark a distance of 100.00 ft (30.00 m) on reasonably even pavement. Move the profilograph forward until a particular point is at the first mark and make the recorder mark the event on the record. Move the profilograph forward again until the point is at the second mark and make the recorder to mark this event, too. The record must indicate 100 ± 1 ft (30.0 ± 0.3 m) between the two events (... 4 in. on graphic record).

8.2.2 Verify the standardization of the distance recording before any month of use and whenever there is evidence of possible inaccuracy.

9. Procedure

9.1 Clear the intended profilograph path of all loose material and foreign objects.

9.2 If possible, move the profilograph about 30 ft ... forward to the starting point. Once there, initialize the recorder and make beginning notations.

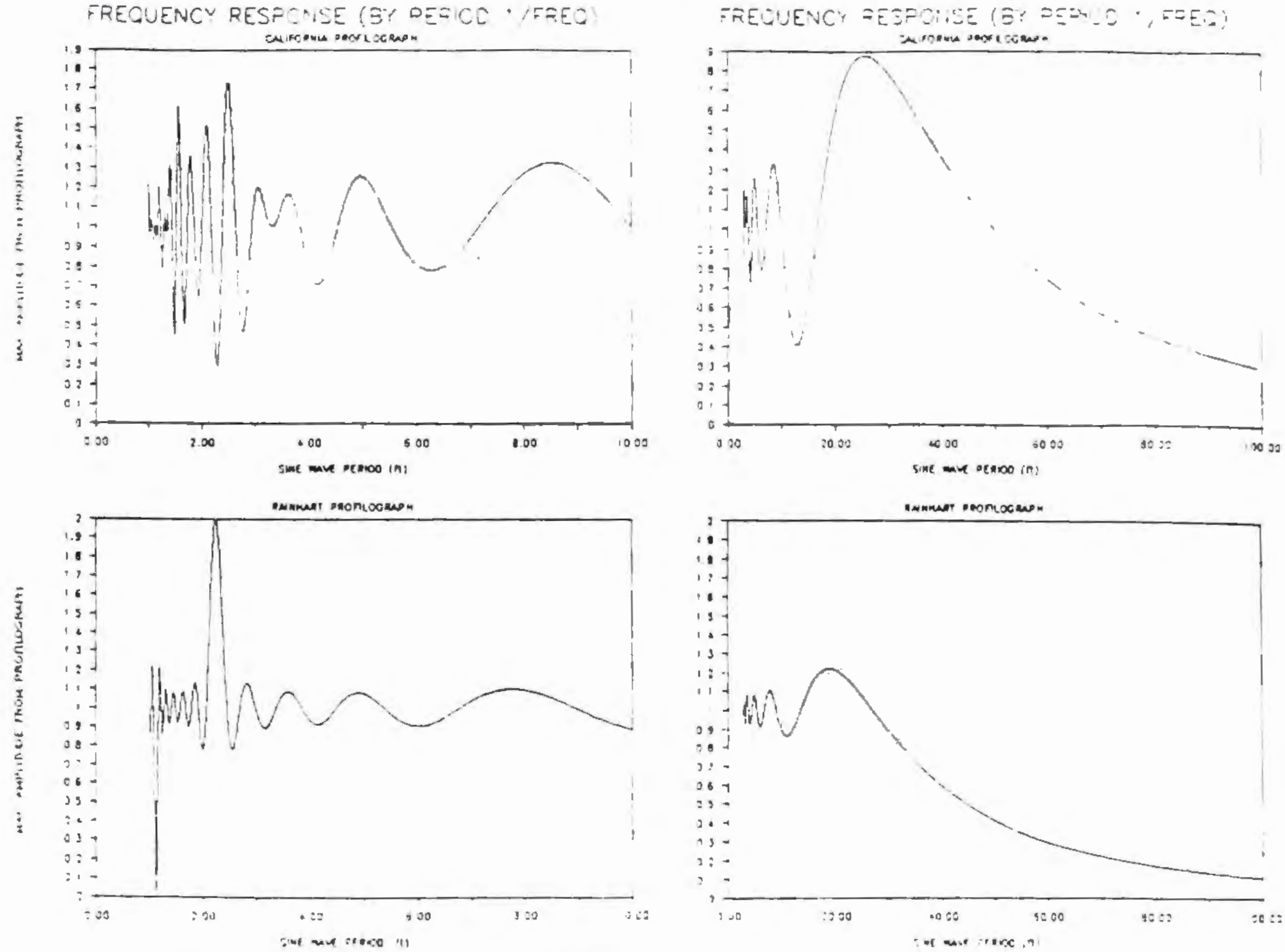
9.3 Move the profilograph forward no faster than 3 mph (5 km/hr), steering it to stay within that prescribed sampling path. Pertinent observation about surveyed location or unusual conditions may be made on the record only as they occur. Observe the recorder for any unusual operation.

9.4 Upon completion of a sampling path, make ending notations and review the recording for reasonableness. Repeat the procedure for successive sampling paths.

10. Calculation

NOTE 1—Calculations can be done manually with the blanking band and excessive height templates or electronically with routines in a computer.

10.1 Apply the blanking band to successive lengths of the surface record. Determine the roughness from each scallop. Add all roughness for each stipulated segment. From the surface record, determine the longitudinal distance between the farthest points of the beginning and ending scallops or absence thereof. Divide the result of the addition by the



NOTE—This figure comes from Walker, Roger S., and H.-T. Lin, The University of Texas at Arlington, Research Project 8-10-87-569 "Correlation of California and Rainhart Profilographs with PSI," conducted for Texas State Department of Highways and Public Transportation in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

FIG. 3 Computer Simulation of Profilograph Responses to Sinusoidal Inputs of Different Periods (wave lengths)

corresponding longitudinal distance to calculate the rate of roughness for that segment of that path.

10.2 Apply the excessive height chord to the top of each wave on the surface record. Identify all bumps that are excessively high by their locations.

11. Report

11.1 The following information shall be given for each specific application:

11.1.1 Height of blanking band to nearest 0.05 in. (1 mm), (for example, 0.1 or 0.2 in.).

11.1.2 Cutoff height to the nearest 0.05 in. (1 mm), (for example, 0.3 in.).

11.1.3 Profilograph with or without uniformly spaced reference platform wheels, and

11.1.4 Length of each segment for which the rate of roughness is calculated.

12. Precision and Bias

12.1 The precision and bias of this test method are being determined.

APPENDIX G

PROPOSED CONSTRUCTION SPECIFICATION DOCUMENT

CONSTRUCTION SPECIFICATION FOR BITUMINOUS CONCRETE PAVEMENT SMOOTHNESS

1.0 GENERAL

(A) The department shall determine the smoothness of pavement by operating a South Dakota (SD) Profiler over the finished surface of the mainline pavement, sideroads, auxiliary lanes, and ramps.

(B) This entire specification applies to all bituminous roadways receiving more than two (2.0) inches in plan thickness of new or recycled pavement.

(C) The following surfaces are specifically excluded from the terms of this provision:

1. Bridge decks unless to be overlaid;
2. Acceleration and deceleration lanes for at grade intersections;
3. Side roads less than one section (528 ft) in length;
4. Shoulders;
5. Pavement on horizontal curves which have a 1,000 foot or less center-line radius of curvature and pavement within the super-elevation transition of such curves;
6. County secondary and federal aid urban projects with posted speeds 40 MPH or less unless specified otherwise on the plans;
7. Projects less than one-half mile in length (excluding bridge lengths).

(D) Bituminous concrete pavement surfaces not subject to SD Profiler will be tested with a straightedge or profilograph in accordance with subsection 380.3(0)(1.) of the Standard Specifications.

2.0 EQUIPMENT

The pavement profile shall be determined using a South Dakota Profiler (SD Profiler) or other style of machine that yields compatible results and has been approved for use by the Office of Materials & Surfacing. The equipment shall be furnished and operated by the department in accordance with the requirements of SD-xxx (South Dakota Test Method for Determination of Asphalt Concrete Pavement Smoothness with the South Dakota Profiler).

3.0 SURFACE TEST

Pavement profile testing will be performed only on the final surface of the pavement. The testing may be performed by the Department in accordance with the procedures for testing one lane paving operations shown in SD-xxx and one pass shall be made for each lane. The pass shall be made after final rolling and within 30 days of the surface being opened to traffic. Failure to test during this time period will result in pavement acceptance for smoothness. Just prior to testing, the contractor shall be responsible for the removal of all objects and foreign materials on the pavement surface, provided that paving for the project is still in operation.

Each lane will be divided into approximately 0.1 mile, sections beginning at the project limits in the direction of traffic. Partial sections may result at either end of the project or when an exception occurs within a section. The length considered to be part of the exception shall be excluded from the length of the section and the length remaining shall form a partial section. An exception for purposes of this specification is defined at any break in continuous paving, such as a bridge or railroad crossing or any area unable to be tested with the SD profiler.

For paving operations shorter than 0.1 mile inspection and testing will be performed with a straightedge or profilograph in accordance with subsection 380.3(0.)(1.) of the Standard Specifications.

4.0 SMOOTHNESS EVALUATION

Each section will be tested by the Department and an evaluation report shall be provided to the contractor. The evaluation shall be performed in accordance with the SD-xxx procedures. A profile index in inches per lane mile shall be determined that represents each section or portion thereof, of the finished pavement surface.

A daily average profile index shall also be determined for the surface of each day's placement of the final surface lift. If the smoothness evaluation occurs while the paving operation is still in production and the daily average profile index exceeds 3.0 inches per mile per lane for any single day's production, the paving operation will be suspended and paving shall not resume until corrective action is taken by the contractor. For the purposes of determining a day's production the following shall apply:

1. A days production is defined as the placement of a minimum of one full section of pavement in a day.

2. If less than one section is paved, that day's production will be grouped with the next day's production.

5.0 CORRECTIVE ACTIONS

Each section of pavement will be evaluated using the SD Profiler to determine if corrective actions are necessary. Each individual section will be evaluated to determine areas where corrective action is needed.

All areas within each section having high points (bumps) or low points (dips) with deviations in excess of 0.3 inches in a length of 10 feet or less shall be corrected regardless of the profile index value.

Any section initially tested at a profile index of greater than 2.5 inches per lane mile per section shall be corrected to reduce the profile index to 2.0 inches or less per lane mile.

When profile corrections are required, the contractor shall use one or more of the following corrective methods:

1. Diamond grinding or use of other profiling devices;
2. Removing and replacing the entire pavement thickness;
3. Removing the surface by milling and applying a lift(s) of the specified surface course;
4. Overlaying (not patching) with the specified surface course;
5. Use of other methods that will provide the desired results.

The corrective method(s) chosen by the contractor shall be subject to the approval of the Engineer and shall be performed at the contractor's expense. The Department may retest any section where corrections were made. The Department shall furnish an evaluation report to the contractor within forty-five working days after any corrections are made. Failure to furnish the evaluation report within the designated time period will result in section acceptance without further penalty.

This specification, its testing, and its associated pay adjustments will then be applied to the corrected pavement sections. In the case that a corrected pavement section exceeds 2.5 inches per lane mile, no further corrective action will be allowed, and instead, a pay adjustment will be made.

6.0 PAY ADJUSTMENTS

Pay adjustments will be based on the profile index determined for the section as shown in Table 1. In the event that the contractor performs corrective methods listed above in 5.0 then the contractor will be paid the contract price minus the price that corresponds to the profile index obtained on the pavement section after correction. Areas excluded from testing under 1.0 (C) will not be subject to price adjustments.

TABLE 1

SCHEDULE FOR ADJUSTED PAYMENT

The accepted quantity of asphalt cement and asphaltic concrete corresponding to the mix design and plan thickness of the top layer of the pavement of the driving lanes will be adjusted according to the following schedule and payment criteria for each pavement section.

TRS Statistics	Percent of Contract Prices to be paid by the Department
0.0 to 1.3	100.
1.3 to 1.4	99.
1.4 to 1.5	98.
1.5 to 1.6	97.
1.6 to 1.7	96.
1.7 to 1.8	95.
Greater than 1.8 at initial testing	Corrective work required
Greater than 1.8 after corrective work performed	90.
Failure to perform corrective work	80.

A payment reduction of $100.00 will be made for each bump over 0.3 inch remaining in the top layer.

SOUTH DAKOTA TEST METHOD SD-xxx

A DETERMINATION OF ASPHALT CONCRETE PAVEMENT SMOOTHNESS AT CONSTRUCTION USING THE SOUTH DAKOTA PROFILER

SCOPE

This method of test covers the procedure for determining the smoothness of the bituminous pavements at construction using the South Dakota (SD) Profiler or equivalent.

TERMINOLOGY

Elevation Point - the vertical displacements that are the output of the South Dakota Profiler.

Elevation Profile - consecutive series of elevation points obtained from the South Dakota Profiler at one foot intervals longitudinally down the roadway.

Bump - a bump is said to exist if the difference between any two adjacent TRS statistic contributions is greater than 0.3 inches.

Telescoped Rolling Straightedge (TRS) Statistic

$$TRS = SQRT\left[\frac{20}{BASE} * \frac{(5280 - BASE)}{(n\text{-}BASE)} * \sum_{i=1}^{n} \left(MVD^2_{i,\ BASE}\right)\right] * \frac{10{,}000}{5280*12}$$

Where,

BASE = 10 feet - which is the maximum length of the telescoped rolling straightedge

"n" is the number of profile values (collected at a 1 foot interval longitudinally down the road in the driver's side wheelpath).

"i" is the i^{th} consecutive profile value
[at longitudinal distance (i-1) feet assuming the starting longitudinal distance is set at zero.]

"P_i" is the i^{th} consecutive elevation.

"$MVD_{i,\ BASE}$" is the maximum vertical displacement (MVD) of the TRS for the i^{th} consecutive elevation (collected at an interval of one foot).

"$MVD_{i,\ BASE}$ = MAX [(vertical distance between the line joining P_k with P_j and the point P_i) for all j, k such that $k<i$, $j>i$, $j-k \leq$ BASE and BASE = 10]

MVD profile - consecutive series of maximum vertical displacements (MVDs) of the telescoped rolling straightedge (TRS).

APPARATUS

A South Dakota Profiler capable of collecting road profile in the driver's side roadway wheelpath.

Any device capable of 1) plotting elevation profile, 2) plotting the MVD profile, 3) calculating the TRS statistic.

TEST PROCEDURE

The South Dakota Profiler will be operated at highway speeds and record data at one foot intervals in the driver side wheelpath for each section of pavement as defined in the appropriate specification.

A plot of both elevation profile and MVD profile, preferably, for an entire mile of roadway, will be reviewed for elevation spikes and MVD spikes. Elevation spikes are defined as points where consecutive elevation differences are greater than 1 inch. MVD spikes are defined as consecutive MVD differences of more than .4 inches. A sample of spikes, not to exceed 2 per section tested, will be investigated to determine if these spikes actually reflect the condition on the pavement. If not, the Engineer can either rerun the SD Profiler on these sections or substitute, for the spurious elevations the distance weighted average of its neighboring elevations.

STATISTIC TRACE REDUCTION AND BUMP LOCATING PROCEDURE

Obtain the elevation profile and MVD profile for the appropriate section or consecutive sections of roadway on a per lane basis. This can be done with the PROFILE software or any equivalent means.

Identify any elevations that are greater than one inch different than the adjacent elevations. Also identify any MVDs that are more than .4 inches different than the adjacent MVDs.

Locate the positions on the road for a maximum of 2 of these "spikes" per section tested and determine if they accurately represent the condition of the pavement.

If any of the spikes tested do not represent the condition of the pavement, then the Engineer must take the following action.

1. If there are more than 2 spikes on a section, then the elevation profile must be recollected with the South Dakota Profiler and the new profile used for testing. Provided that the paving operation for the project is still in operation, just prior to testing, the contractor shall be responsible for the removal of all objects and foreign materials on the pavement surface.

2. If there are less than 2 spikes per section, the elevations represented by the spikes can be replaced by the average of neighboring elevations not associated with the spike itself. (Note: if several elevations are influenced by the spike, then the two elevations adjacent to this set of "spike influenced" elevations will be used for averaging. Each "spike influenced" elevation is replaced by the horizontal distance weighted average of the adjacent elevations).

The TRS statistic, elevation profile, and MVD profile are then produced from the adjusted elevations. Failure to produce a satisfactory elevation profile within three runs of the South Dakota Profiler will lead to either further retesting or a waiver of the specification for that section under the discretion and written approval of the Department Engineer.

Once a satisfactory profile has been produced for each section, then the program PROFILE or any equivalent method can be used for each section to calculate the TRS statistic and identify and count the bumps.

Figure 1 shows a sample output of the PROFILE computer program. The elevation profile is at the top and the MVD profile is at the bottom. Horizontal displacement is set at 700 feet between consecutive vertical lines and can be changed by the operator. Vertical displacement for the elevation profile is set at 1 inch between adjacent horizontal lines and also can be modified by the operator. Vertical displacement for the MVD profile is set at .2 inches between adjacent horizontal lines, and that value is fixed. Finally, to get to the beginning of any given section, the initial horizontal offset can be varied by the operator. All .1 mile TRS statistics starting from the initial horizontal offset (see Figure 2) can be reviewed by pressing the letter R on the computer keyboard.

REPORT

For each road section to be tested, the Department will furnish to the contractor the graphs and the reports shown in Figures 1 and 2 or their equivalent. The need for corrective action and the amount of penalty will also be provided to the contractor at this time. Should corrective action be deemed necessary, the maximum length of time to perform such actions and to retest the corrected pavement are stipulated in the specification.

Attachment A documents the PROFILE computer program which is used in application of this procedure. Attachment B shows a sample specification test summary report.

Figure 1. PROFILE Software Profiles' Plots.

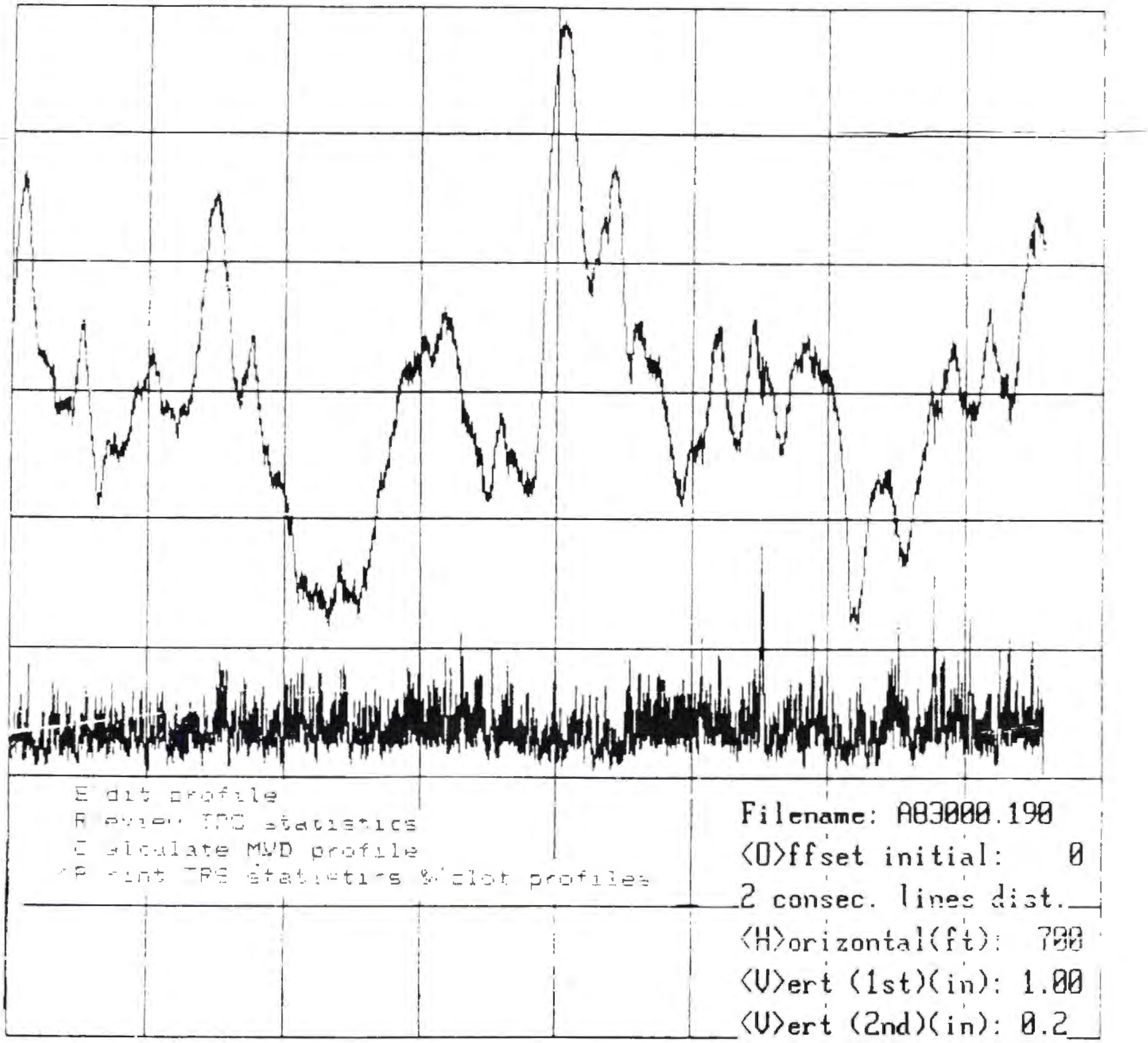


Figure 2. PROFILE Software Evaluate Report.

The TRS statistic for the entire plotted distance of 5280 ft

starting at offset 0 ft
& ending at offset 5280 ft
is 2.14 mm/km

The TRS statistic for each 0.1 mile starting at offset 0 ft

starting offset (ft)	TRS statistic
0	0.45
528	0.43
1056	0.57
1584	1.21
2112	1.06

ending at 2300 ft.

Bumps greater than 0.3" are located as follows.

Offset (ft)	Bump height (in)
456	0.45
1256	3.12
1452	0.77
2036	1.21

ATTACHMENT A

"PROFILE" COMPUTER PROGRAM DOCUMENTATION

The PROFILE suite of computer programs consists of the UPLOAD program, and the PROFILE program. The purpose of each of these programs is as follows.

UPLOAD translates SD Profiler output into a database file.

In PROFILE, for any database file created by the UPLOAD program, an elevation profile and MVD profile is plotted. PROFILE calculates the maximum vertical displacement (MVD) values for the telescoped rolling straightedge (TRS). TRS statistics are also produced. Finally, the elevations, themselves, can be edited to remove spurious elevation spikes.

The UPLOAD program requests the SD Profiler output file name. It produces a DBASE formatted file with elevation, distance, substitute elevation, and MVD as the four data items. Elevation values are received from the SD Profiler output. All SD profiler "header" type output and MRM output should be removed by the UPLOAD program. The distance field is calculated starting at zero and incremented by one for each successive elevation. Substitute elevations and MVD are left blank. Substitute elevations can be set using the PROFILE name program when the actual elevations are to be excluded from the calculation of the TRS statistic (when spurious spikes are found). The output file of the UPLOAD program retains the SD Profiler output file name, except that its file name extension is changed to DBF.

The UPLOAD program is not a deliverable on this project because the input file format (data coming from the SD Profiler) has not yet been determined by SDDOT. When this file format is known, SDDOT will make this software program.

The PROFILE program produces the results that are required for the asphalt pavement construction smoothness specification, namely: the elevation and MVD profile plots, and the smoothness evaluation report.

Figure A.1 shows the PROFILE input screen. Of the five input values on this screen, usually only the directory path and the file name need to be entered. The other values are usually left at their default values, and changed from the graphics screen shown in Figure A.2. Elevation data is ordered in the PROFILE input file by longitudinal distance at one foot spacings. The graphics screen shows the elevation and MVD profiles. Horizontal and vertical scales are documented in the bottom right hand corner of the screen. These can be changed by pressing the letters H and V, respectively. The initial horizontal offset plotted is varied by pressing the letter O. The vertical scale for the MVD profile is fixed, only the elevation vertical scale is adjustable.

From the graphics screen, the ability to edit elevation data, review TRS statistics, and print results are available by pressing the letters E, R, and P, respectively. Editing of data is to be done in order to remove spikes from the elevations. This is done by entering a "substitute" elevation from the edit screen as shown in Figure A.3. When a "substitute" is entered, then the TRS statistic and the elevation and the MVD profiles are adjusted using the substitute elevation value.

Statistics' results take the form shown in Figure A.4. The TRS statistic is shown for the entire plotted elevation as well as for each consecutive 0.1 mile length of the plotted elevations. The height and position of all bumps is also reported. Profiles and statistic values can be printed by pressing the letter P. The printed results are then used to calculate the price adjustment, a copy of all of which is then sent to the contractor (under the terms of the proposed specification).

All software programs delivered on this project (PROFILE and ECON) were created with FoxPro 2.0 which is a database language employing DBASE file structures. Compiled versions of these programs with a runtime module have been delivered to SDDOT.

The directory path is: e:\sdrough\analysis\

file name	initial offset (ft)
----------	-----------
A83000.190	0

The distance between consecutive plot lines

on the x-axis is 700 ft.

on the y-axis is 1.00 in. for the elevation profile (on top)

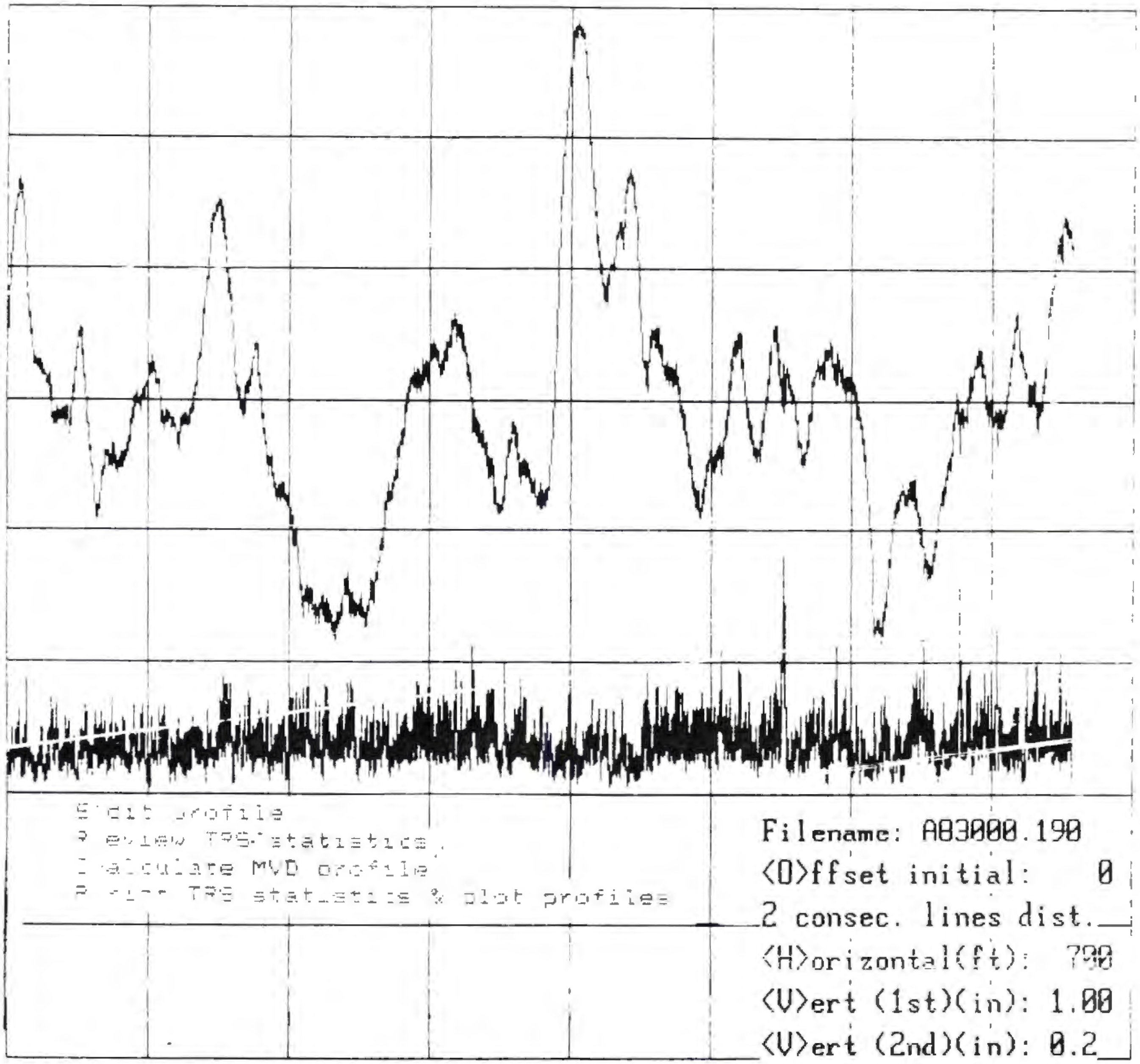
on the y-axis is 0.20 in. for the MVD profile (on bottom)

The entire plotted range is eight times the distance between consecutive plot lines.

To exit press <ESC>

Figure A.1 PROFILE Input Screen.

Figure A.2. PROFILE Graphics Screen.



ELEVATION	SUBSTITUTE
0.071	
0.173	
0.225	
0.298	
0.379	
0.457	
0.520	
0.568	
2.714	0.589
0.611	
0.667	
0.755	
0.792	
0.839	
0.872	
0.904	
0.922	

Figure A.3. PROFILE Browse Screen.

The TRS statistic for the entire plotted distance of 5280 ft

starting at offset 0 ft
& ending at offset 5280 ft
is 2.14

The TRS statistic for each 0.1 mile starting at offset 0 ft

starting offset (ft)	TRS statistic
0	0.45
528	0.43
1056	0.57
1584	1.21
2112	1.06

ending at 2300 ft.

Bumps greater than 0.3" are located as follows.

Offset (ft)	Bump height (in)
456	0.45
1256	3.12
1452	0.77
2036	1.21

Figure A.4. PROFILE Evaluation Report.

ATTACHMENT B
SPECIFICATION TEST SUMMARY REPORT

Project name:____

Length of road evaluated:

Route #:______ start milepoint:_____ end milepoint:_____ lane#:_____

Date placed:____________________

Date profiled:____________________

Date profile evaluated:__________________________

Date evaluation received by contractor:____________________________

Contractor signature____

Contractor name:____

Department engineer signature__________________________________

Department engineer name:___________________________________

Section results

(1) Start Milepoint	(2) End Milepoint	(3) TRS Statistic	(4) # of Bumps	(5) % Deduct	(6) AC Top Layer $/lane mile	(7) Dollars deducted from full price

Columns 1, 2, 3, and 4 are obtained from the PROFILE evaluation report. Column 4 is obtained by counting the bumps documented in this report for the appropriate mileage. Column 5 is obtained by comparing the TRS statistic value in Column 3 against the Price Adjustment Table in the specification, and transcribing the appropriate deduct percentage. Column 6 is set in the contract and is the same for all sections.

Column 7 is calculated as follows:

Column 7 = (col2 - col1)* col6 x col5/100 + col4 * 100