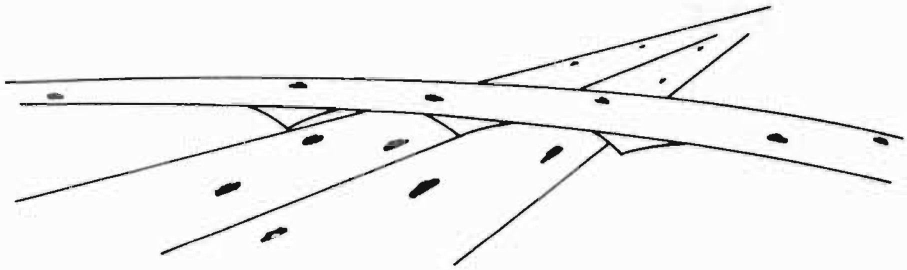

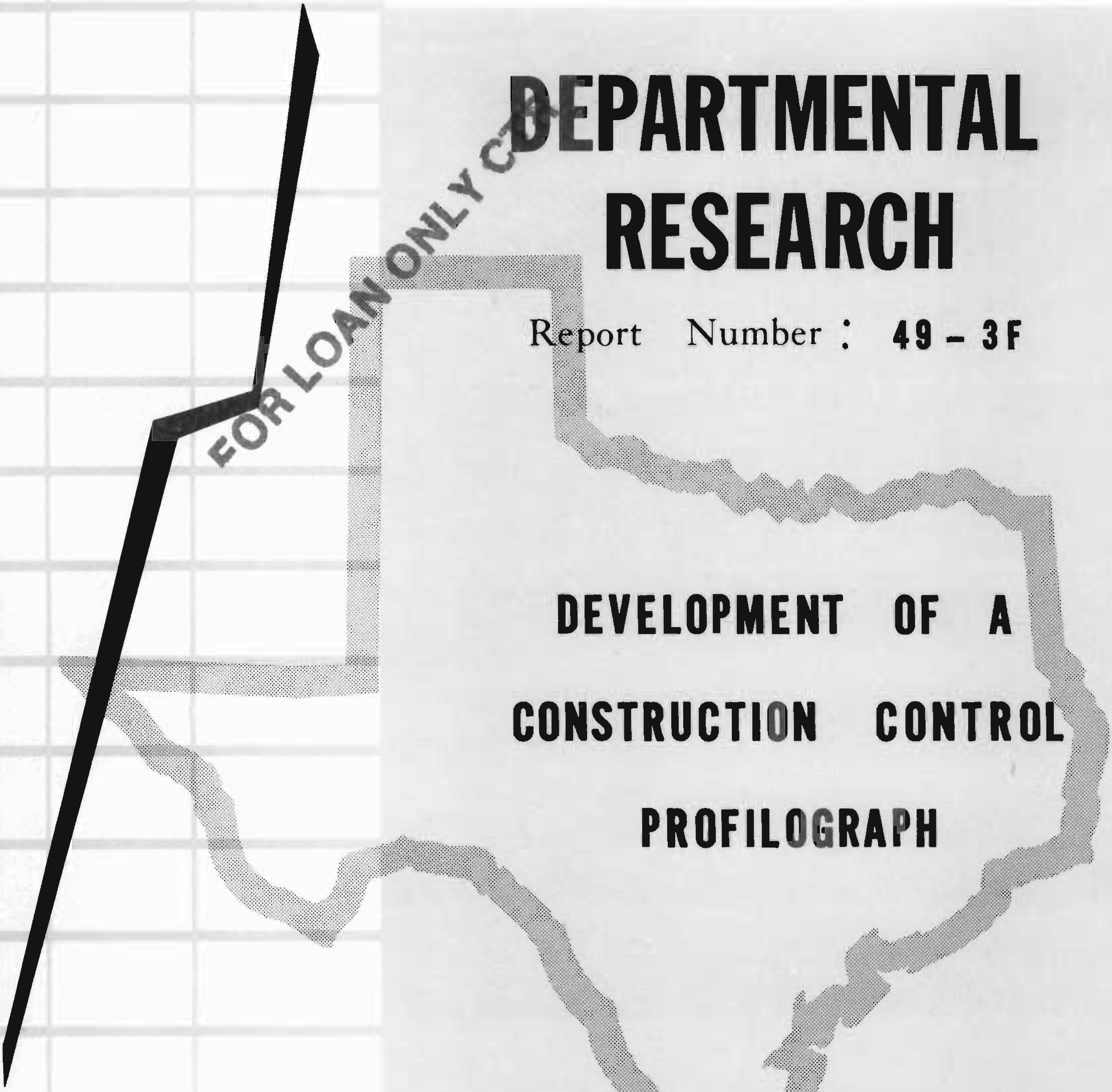

DEPARTMENTAL RESEARCH

Report Number : 49 - 3F

DEVELOPMENT OF A CONSTRUCTION CONTROL PROFILOGRAPH

TEXAS HIGHWAY DEPARTMENT

DEVELOPMENT OF A CONSTRUCTION CONTROL PROFILOGRAPH

By

Kenneth D. Hankins

and

Hugo Orellana

Research Report 49-3F

Development of a Construction Control Profilograph
Research Study 1-8-63-49

Conducted by

Highway Design Division, Research Section
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In Cooperation With The
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ABSTRACT

Due to an increasing awareness of the importance of the pavement roughness at the time of construction, a profilograph for measuring construction roughness was developed and obtained. The profilograph utilized was designed and fabricated by Rainhart Company of Austin, Texas. The profilograph featured (1) twelve averaging wheels arranged in a systematic method, (2) equally spaced averaging wheels, both longitudinally and transversely, (3) a recorder especially designed to emit both a graphical profile and a digital roughness index number, and (4) outrigger wheels allowing the profilograph to be towed to various testing locations without disassembly.

Studies of the influence of texture in pavement roughness were made leading to a modification in the profilograph recording mechanism for a filter band. A 0.1-inch filter band was utilized to reduce the influence of texture in pavement roughness measurements.

Based on field studies with the 0.1-inch filter band a "profile index" of 26 inches per mile was determined and a suggested specification was written employing a maximum "profile index" and a maximum "single peak deviation".

I. INTRODUCTION

Shortly after the AASHO Road Test, Texas embarked upon a "satellite" study intent upon applying knowledge gained at this road test to Texas conditions. To shorten the "satellite" study, a factorial composed of existing roadway sections was utilized and the initial serviceability was assumed to be about the same as the initial AASHO Road Test serviceability. However, the researchers thought it wise to check the serviceability of several newly constructed pavements. This check revealed that a wide range of initial serviceability existed in Texas. (1)*

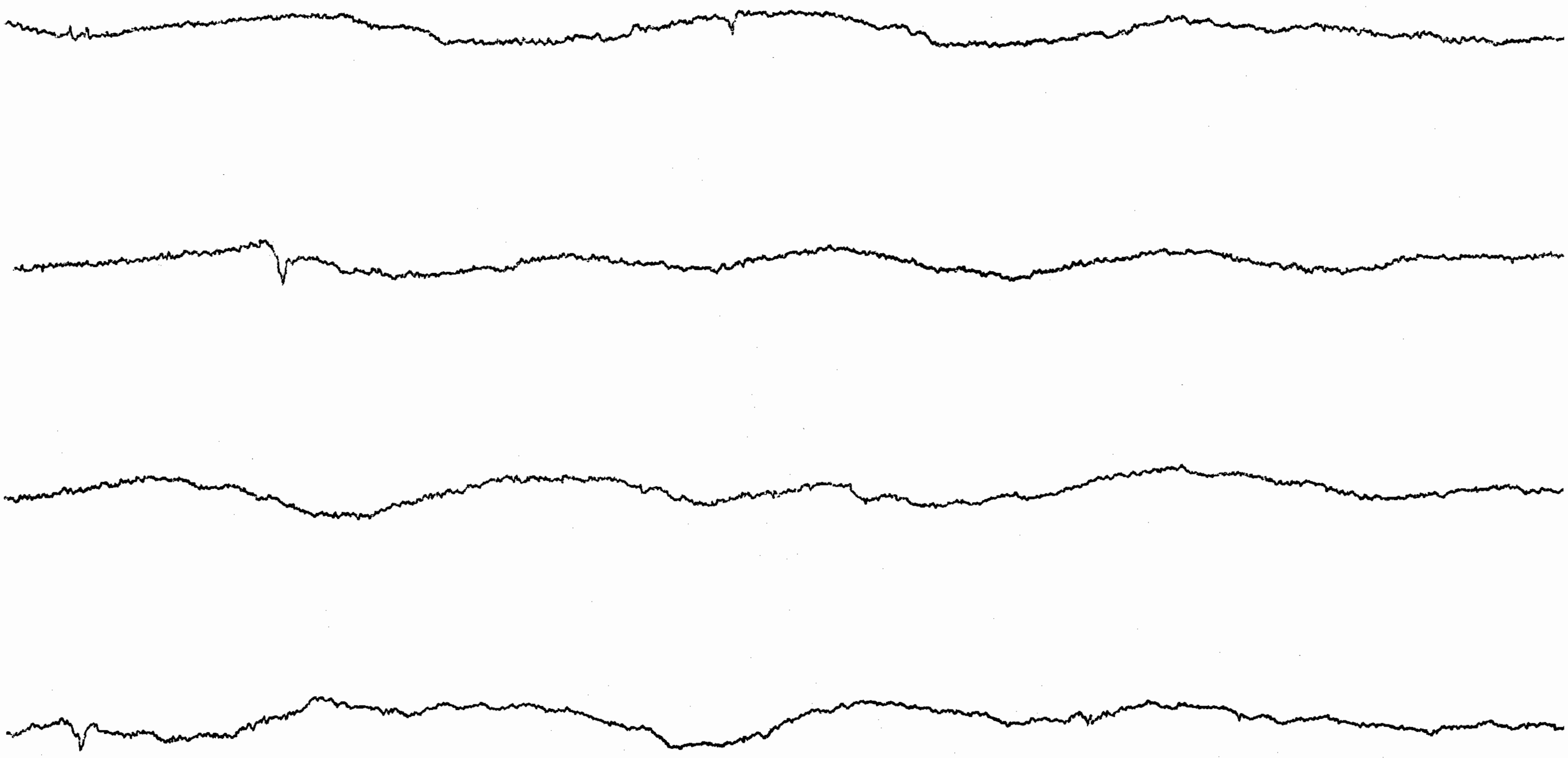
Engineers also speculated on the effect of impact loads on the pavement structure. To date, little is known about impact on highways. It is believed that impact loads can be very large. One Texas design procedure allows the design wheel load to be increased 25 percent for impact, but this amount has not been confirmed with adequate testing. It takes little postulation to realize that initial roughness could cause detrimental effects to the pavement structure.

Based on this theory and tests, it was decided to find a method to control initial roughness on the surfaces of Texas pavements. Presently, this State uses a straight edge to control the roughness of portland cement or asphaltic concrete surfaces. These specifications are as follows:

> Asphaltic Concrete Pavement Item 340.6 (6)
>
> Surface Tests. The surface of the pavement, after compression, shall be smooth and true to the established line, grade and cross section, and when tested with a 16-foot straight edge placed parallel to the centerline of the roadway, it shall have no deviation in excess of 1/16 inch per foot from the nearest point of contact. The maximum ordinate measured from the face of the straight edge shall not exceed 1/4 inch at any point. Any point in the surface not meeting these requirements shall be immediately corrected.
>
> Portland Cement Concrete Pavement Item 360.8 (3)
>
> Surface Test. After the concrete has been placed 12 hours or more, the Engineer will test the surface of the pavement with a 10-foot straight edge placed parallel to the centerline. The surface shall not vary from the straight edge by more than 1/16 inch per foot from the nearest point of contact, and in no case shall the maximum ordinate from a 10-foot straight edge to the pavement be greater than 1/8 inch. Any high spots causing a departure from the straight edge in excess of that specified shall be ground down by the Contractor to meet the surface test requirements.

It is believed that the pavement surface can meet these specifications and still result in considerable roughness. One of the first tests appears to bear out this theory. Figure 1 is

*Numbers in parenthesis refer to items in the reference.



Scale: Horiz. 1" = 10', Vert. 1" = 1"

FIGURE 1 — PROFILE OF NEWLY CONSTRUCTED CONCRETE PAVEMENT

a profile of a newly constructed concrete pavement. The horizontal scale is 1 inch equals 10 feet and the vertical scale is 1 inch equals 1 inch. Exhaustive tests on this roadway revealed that existing specifications were met with most peaks being just under 1/8 inch. However, the profile reveals considerable roughness still exists. It is possible to eliminate large isolated "bumps" with the present specification, but additional control is needed to insure against an almost continuous series of smaller irregularities in the surface.

Objectives of Study

The object of this research study was to develop the equipment necessary to measure construction roughness and to suggest additional specifications to control initial roughness.

II. INTERIM REPORTS

This report is the third and final report of this study. There have been two interim publications. A short discussion of the interim reports is outlined below.

49-1 "Construction Control Profilograph Principles"

The first interim report was concerned with the feasibility study of roughness measuring equipment. Very early in the study, State research personnel found that the Rainhart Company in Austin, Texas, was developing a profilograph and had been studying roadway profile equipment for some time. Rainhart personnel were of the opinion that:

1. Rugged, lightweight equipment could be fabricated.
2. The "averaging wheels" should be equally spaced in a longitudinal manner.
3. A "roughness index" could be incorporated through a system of mechanical counters so that the user could obtain "on the spot" results in the field.

A study was made of profilograph components and structure using a theoretical and a model approach. The results of this study were reported in the first interim report and revealed the following:

1. The even longitudinal "averaging wheel" spacing was superior to other odd spacings.
2. The number of averaging wheels and the length of the equipment were subject to economic demands with larger numbers of averaging wheels being desirable and the length being dependent on the most prevalent roughness wave length expected.

Based on the results of this study a decision was made to lease a profilograph from the Rainhart Company.

49-2 "A Study of Construction Equipment and Initial Pavement Roughness as Measured with a Profilograph"

The second interim report was concerned with studying some of the causes of construction roughness in asphaltic concrete placement. Theories were proposed as to probable detrimental events and these events were marked on the roadway during construction. Measurements were obtained with the profilograph and each event location was recorded on the output chart. The results indicated the following postulations:

1. The majority of initial roughness probably is reflected through an asphaltic concrete mat from the structure below.
2. Increased bituminous paver speeds increase roughness.
3. Areas of roughness were noted at each location in which the paver paused for a haul truck change.
4. On the construction job studied, parked rollers did not cause significant roughness in the finished mat.

III. DESCRIPTION OF EQUIPMENT

The profilograph leased from the Rainhart Company is approximately 25 feet in length, 52 inches wide and weighs 450 pounds (See Figure 2). The design of this profilograph is based on a whiffletree arrangement. The framework consist of a major truss, two minor trusses, four tripod frames and a steering assembly (See Figure 3). Each tripod frame contains three averaging wheels. A recording wheel is utilized in the exact longitudinal center of the instrument and activates a specially designed recorder. Outrigger wheels are utilized as trailer wheels for roadability.

Framework

The framework is composed of aluminum pipe and aluminum juncture castings. The end of each component is specifically marked and designated for a juncture, which has the same identifying mark. The identifying marks were incorporated for ease of shipping and assembly.

Major Truss

The major truss is centered both longitudinally and transversally. The recorder platform is centered on the major truss in the same manner and is attached near the top portion of the truss. Also attached to the major truss are the steering wheels, which will be discussed later. Stability of the major truss was accomplished by forming a double parallel truss member and providing sufficient cross bracing (See Figure 4).

In order that the minor trusses could be attached to the major truss, a bearing was provided at each end of the major truss. These bearings were placed in a horizontal position in order that the minor trusses could pivot around in a vertical manner, however, lateral or transverse stability of the minor trusses was attained. Thus, whiffle tree arrangement was established between major and minor trusses.

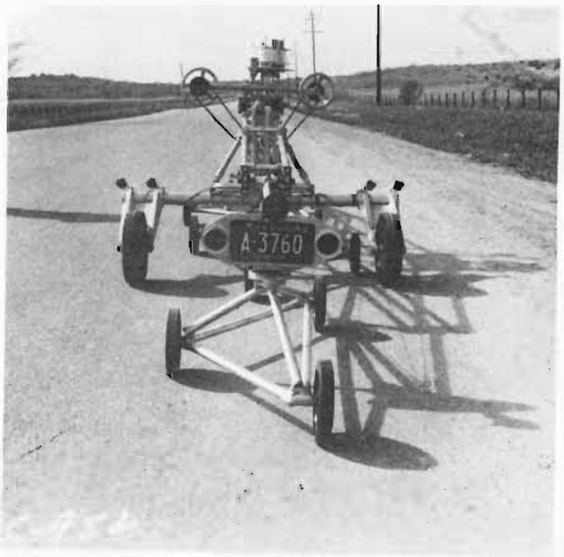
Minor Trusses

The minor trusses are not "doubled"; but are single trusses which have been braced against transverse bending by a small diamond cable truss. The two ends of each minor truss were fitted with a ball type socket and the tripod frames were joined with the minor truss at the "ball sockets". The ball sockets allow movement in any direction in approximately the lower half of the ball. That is, the tripod frame can be raised at any one of the three points and is free to rotate around the lower half of the ball.

Tripod Frame

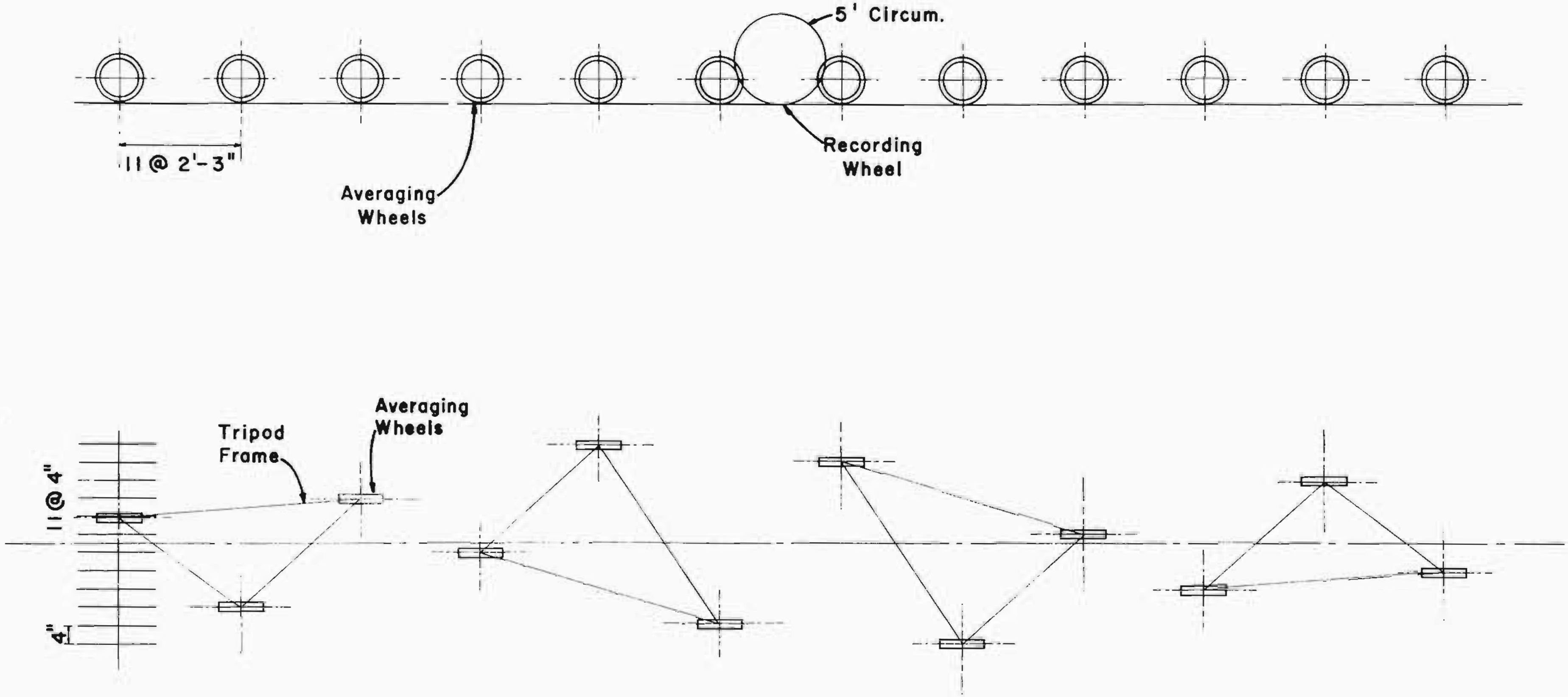
As stated previously, each tripod frame contains three averaging wheels which are parallel one to the other. There are four tripod frames and therefore 12 averaging wheels. The front and rear tripod frames are identical; so are the two center tripod frames. However, the center tripods are slightly larger in dimension that the end tripods. If the front tripod could be rotated 180° (in a horizontal plane), the front tripod would be an exact duplicate of the rear. The two center tripod frames

a - Oblique View



b - End View

Figure 2 - Rainhart Profilograph



SCHEMATIC OF PROFILOGRAPH

Figure 3

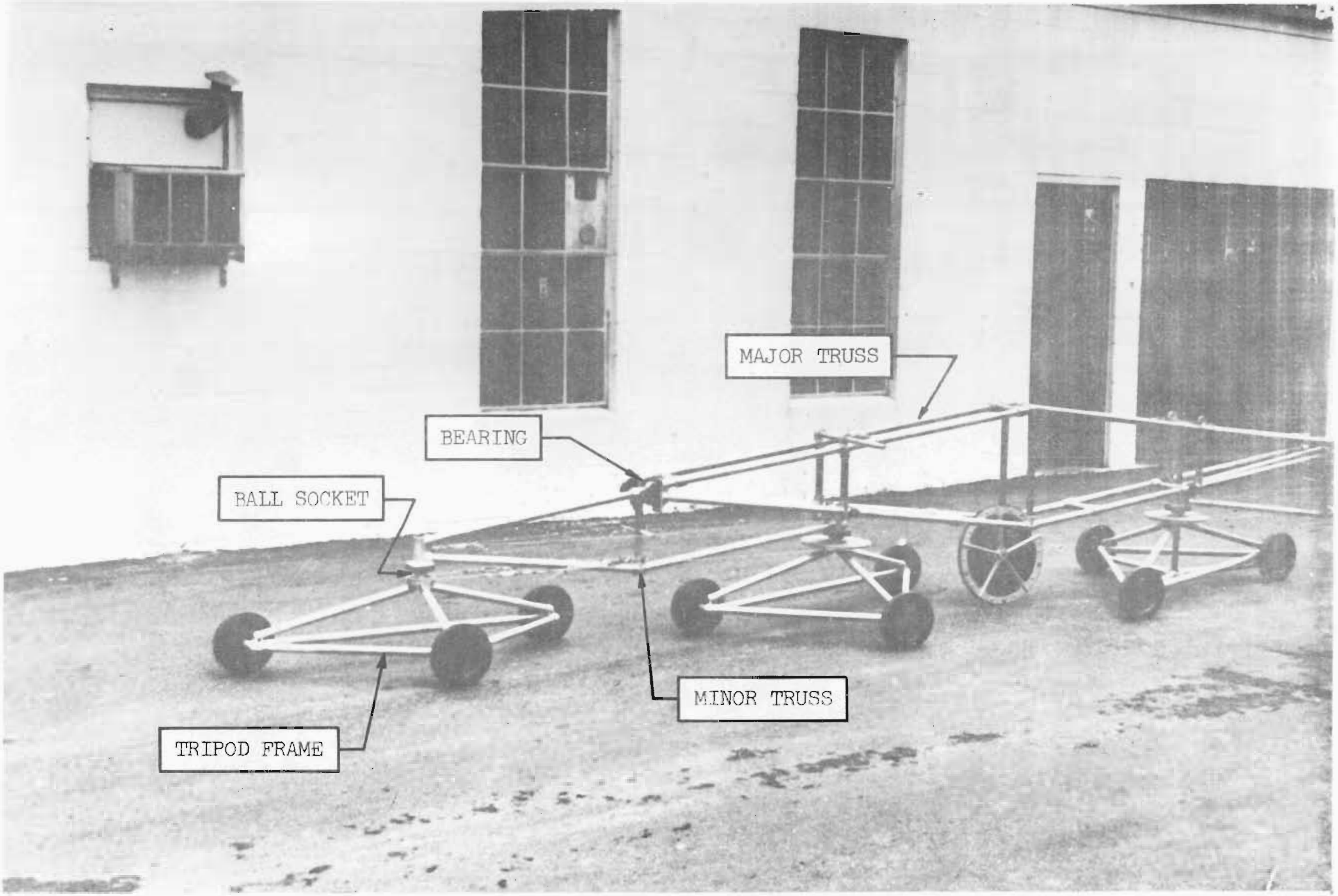


Figure 4 - Profilograph Components

could be treated in the same manner with the same result. A canoe shape is formed with this arrangement providing the system with stability.

It can be seen from this description that each averaging wheel rolls in its individual path. Also, the tripod arrangement allows the averaging wheels to be spaced at equal intervals longitudinally. Therefore, a side detail would indicate the averaging wheels to be spaced at equal 2'-3" centers longitudinally and an end detail indicates the averaging wheels to be spaced at equal 4" centers transversally. The longitudinal spacing was arbitrarily selected, however, multiples of this spacing do not match any standard repetitive highway feature such as the joints of concrete paving. A plan detail reveals the averaging wheels are distributed systematically. The plan detail also indicated the ball socket to be located at the center of the triangle formed by connecting the averaging wheel contact points. The whiffletree arrangement may be noted at this point. For an example, it is assumed that all twelve averaging wheels are in the same horizontal plane. Then, if one of the averaging wheels is lifted one inch, the ball socket (associated with the raised averaging wheel) will be lifted 1/3-inch. Assuming the other eleven averaging wheels have not moved from the horizontal plane, the ball socket raises one end of the minor truss 1/3-inch also. If one end of the minor truss is raised 1/3-inch, the end of the major truss is raised 1/6-inch and the recorder is raised 1/12-inch. Any movement is undesirable, since equipment in which the recorder remains at a constant height above the theoretical grade line is desired, but this example indicates the averaging wheels truely average out the undesirable recorder movement (See Report 49-1).

The exact diameter of the averaging wheels is not critical since this merely establishes the height of the recorder above the pavement. The concentricity of the tires is very critical since 1/12 of the total run-out would appear on the recorder as hash. The averaging wheels were therefore revolved on their own ball bearings and the tires ground to perfect concentricity.

Steering Assembly

The steering wheel is mounted on a short frame which is attached to the major truss. A sprocket and chain system is used to relay the turning movement from the steering wheel to a steering shaft running longitudinally with the trusses (See Figure 5).

To preserve constant lateral wheel tracks and to minimize off-tracking during a turn, all four tripods are steered. For example, to turn left, the front pair are revolved counterclockwise and the rear pair clockwise (plan detail). Furthermore, the end tripod must be rotated through a greater angle than the center ones to make the direction of travel of each individual tripod tangent to concentric turning circles.

The steering mechanism of the front pair of tripods duplicates that of the rear pair except for 180 rotation. A small steering quadrant (segmented pulley), is attached rigidly to the end tripods; a larger steering quadrant is rigidly attached to the inside tripods. The forward pair of tripods are connected together with a tiller cable as are the rear pair. To control each pair, a shuttle is introduced into each tiller cable; when the shuttles are moved, each tiller cable revolves its pair of tripods correct differential amounts. The shuttle movement is controlled by a sprocket-nut chain driven from the longitudinal steering shaft. Since the forward shuttle mechanism is located on the right side, and the

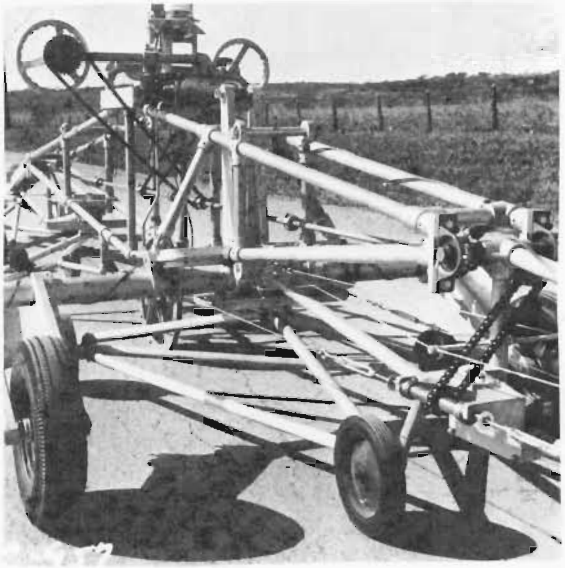


Fig. 5 - Steering Mechanism

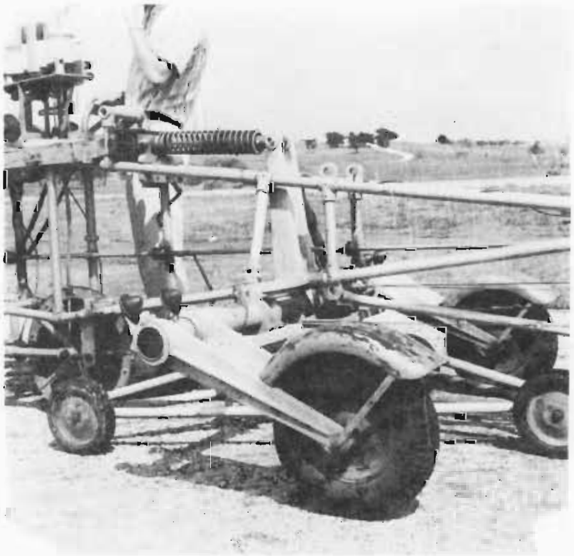


Fig. 6 - Recording and Outrigger Wheels

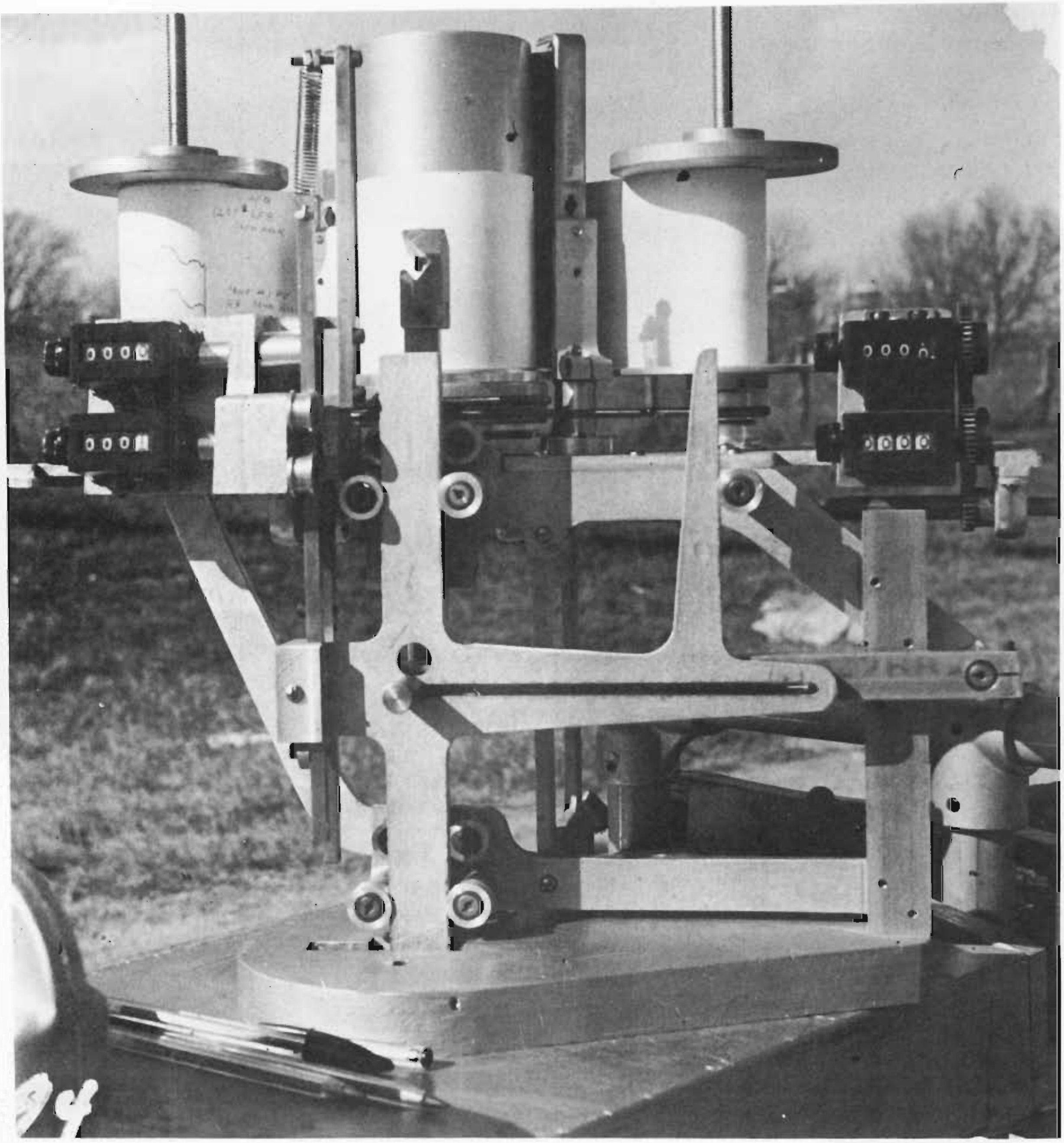


Figure 7 - Profilograph Recorder

rear mechanism on the left, synchronized counter rotation of the forward and rear pairs is accomplished.

Recording Wheel

The recorder wheel is composed of two aluminum castings (which are graduated circumterentially in one foot and 1/2 foot intervals.) Sandwiched between these castings is a V-Belt which has been stretched over an accurately ground plywood disc. The cast aluminum sides exert a friction grip on the sides of the "V" belt. The assembled wheel is then rotated on its own sealed ball bearing pivots, ground perfectly round, and calibrated to a precise 5-ft. circumference.

The profile of the roadway surface is transmitted from the recording wheel to the recorder through a vertical shaft.

Trailer Hitch

The bow end of the frame terminates in a trailer hitch which can be attached to any vehicle. Standard trailer lights plug into the tow vehicle.

Outrigger Wheels

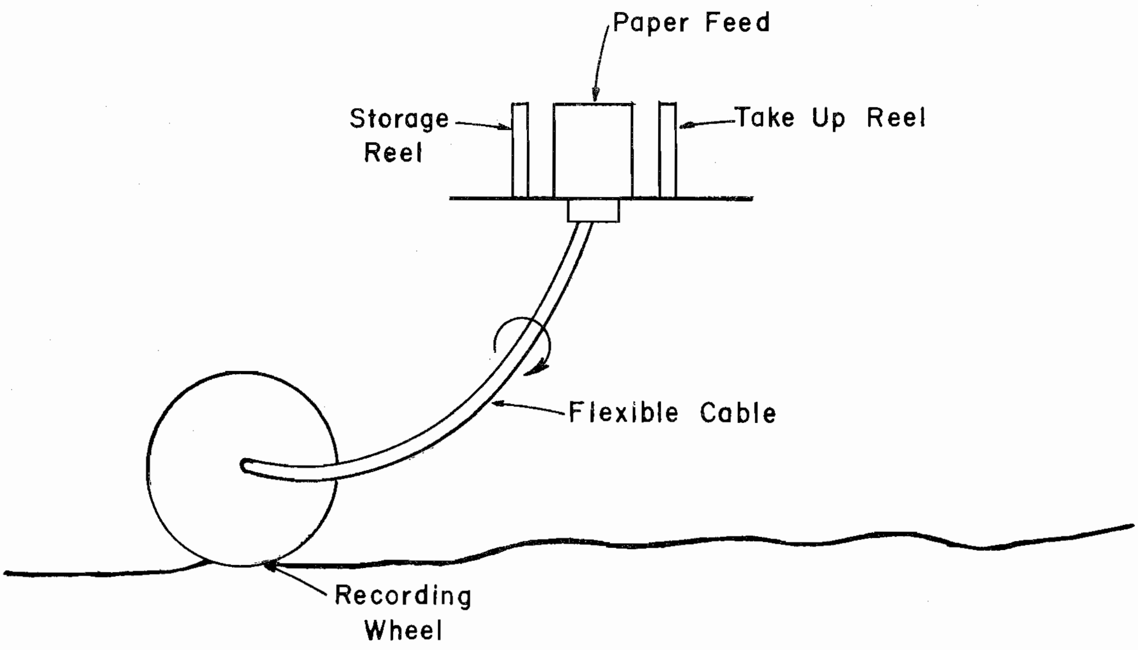
The outrigger wheels are actually small 4 x 8 pneumatic tire wheels similar to those found on many boat trailers. The wheels are mounted in a specially designed aluminum casting which is attached to an aluminum pipe axle (See Figure 6). The casting was attached to the axle at a slight vertical angle in order to activate a shock absorber system (See Figure 6). A mechanical scissor jack (between the major truss and the shock absorber) is used to rotate the outrigger wheel axle causing the profilograph to be raised or lowered in elevation. When the profilograph is raised, the entire system rests on the outrigger wheels and can be pulled behind a vehicle as a trailer. When the outrigger wheel assembly is rotated so that the profilograph is lowered, the averaging wheels, recording wheel and outrigger wheels are in contact with the roadway surface and profile measurements may be taken. The three trusses are pinned into one rigid truss for trailing.

Recorder

The recorder in its original form, was designed to accomplish the following functions:

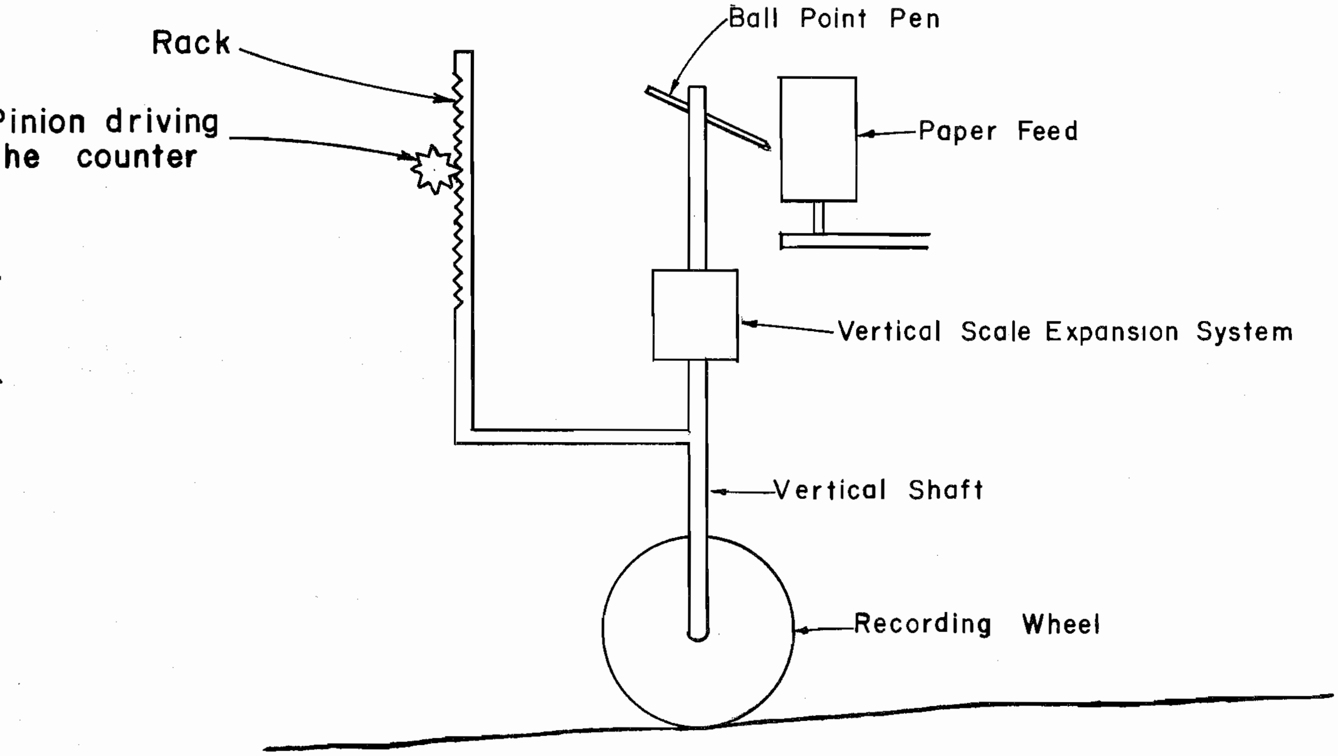
1. Produce a graphical output of the measured profile on a paper tape.
2. Produce a digital roughness index, of the measured surface, on a system of mechanical counters.
3. Provide digital output, of the longitudinal distance traversed, on a system of mechanical counters.
4. Provide a vertical scale expansion from 1:1 to 1:3 on the graphical output.
5. Produce graphic output at a horizontal scale of either 1"=10' or 1"=25'.
6. Produce the five above mentioned items while the instrument is operated either bow forward or stern forward (See Figure 7.) That is, the graphical output chart can be driven in either direction and the longitudinal distance counters record in both an ascending or descending manner.

The flexible cable attached to the recording wheel (See Figure 8a) is



SCHEMATIC OF PAPER TAPE DRIVE

Figure 8-a



SCHEMATIC OF GRAPHICAL RECORDING SYSTEM

Figure 8-b

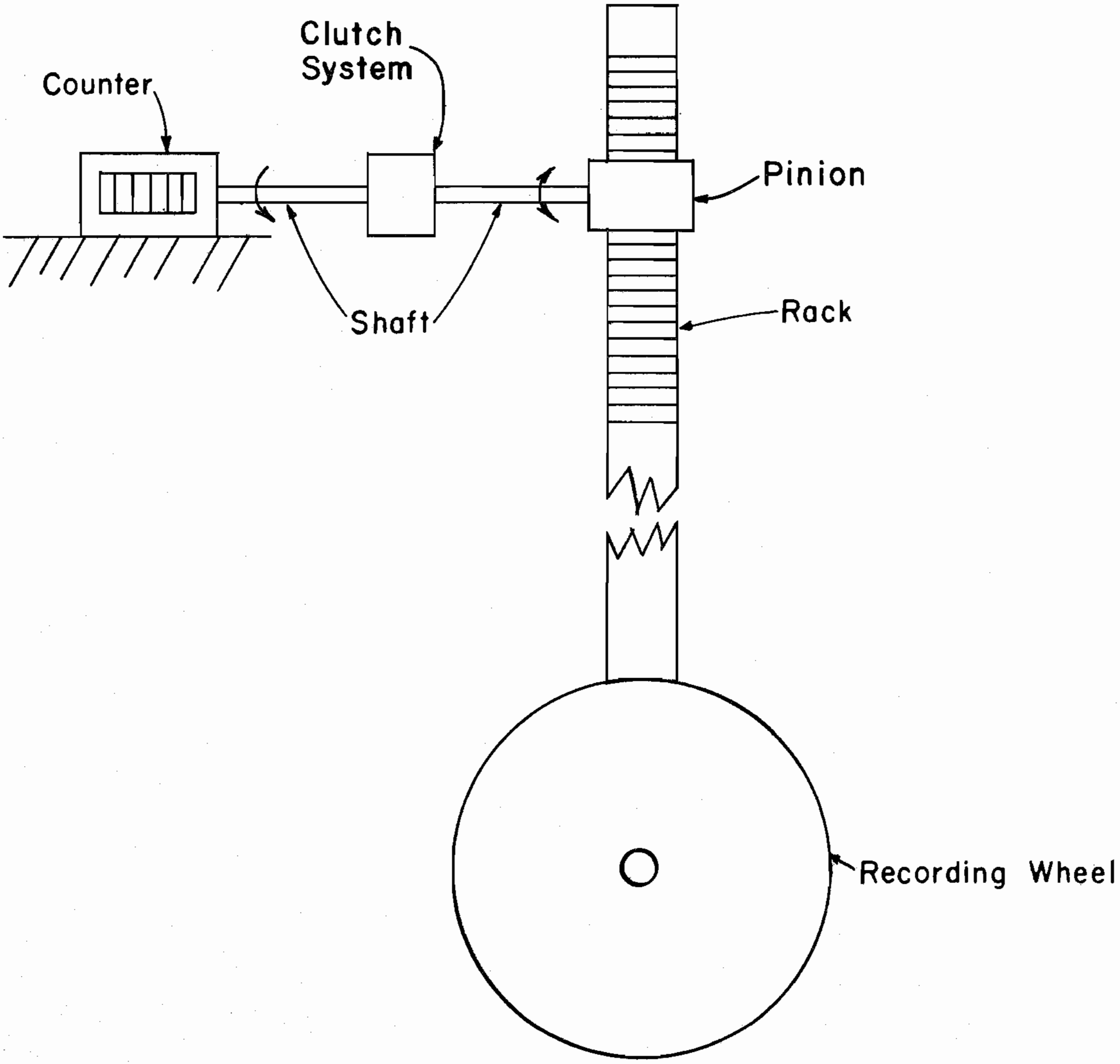
used to drive the paper tape feed at a rate proportional to the operating speed. Vertical movements of the recording wheel are transmitted through the vertical shaft (See Figure 8b) to the vertical scale expansion system which in turn activates a stylus. The stylus generally used was a ball point pen. The roughness index counters are set in motion by a rack and gear system (See Figure 8c).

The recorder was also fixed with an apparatus for blanking the digital reading. Figure 9 offers an explanation of the blanking principle. From a preset centerline a blanking width "a" is allowed as a tolerance and only the vertical excursions above "line x" or below "line y" are counted. The initial setting of the profilograph was accomplished by placing all averaging wheels and the recording wheel at the same elevation with the use of a level and rod. While in this position, the centerline was established by setting the upper vertical counter to zero and the lower vertical counter to zero. By this process, the upper vertical counter counts the vertical excursions above the centerline and the lower vertical counter counts the vertical excursions below the centerline. By inserting a known blanking tab (of any desired width) into the recorder, a blanking band (of the thickness of the tab) is established. It should be noted that the "blanking" is accomplished with the digital output and not on the graphical output.

Summary

The profilograph when pulled as a trailer has given little trouble in approximately two years of testing. During this testing period the profilograph was pulled at speeds up to 70 mph and has been trailed around 10,000 miles. Some 1800 manually operated tests were made and in general each test was 0.2-mile in length. Aside from a few changes to be discussed later in this report, the ruggedness and durability is evident.

The profilograph was designed to be fabricated, operated and maintained at a minimum cost in order that several instruments could be used in the State, possibly one in each District. Easily obtainable parts were utilized throughout the equipment. For example, the "V" belt was used as the recording wheel tire (for easy exchange in case of wear) and the flexible cable (used to drive the paper tape feed) is actually a speedometer cable, etc.



SCHEMATIC OF ORIGINAL
ROUGHNESS INDEX COUNTER

(rack and gear)

Figure 8-C

Upper Vertical Count = n + m + o + p

Lower Vertical Count = q + r + s

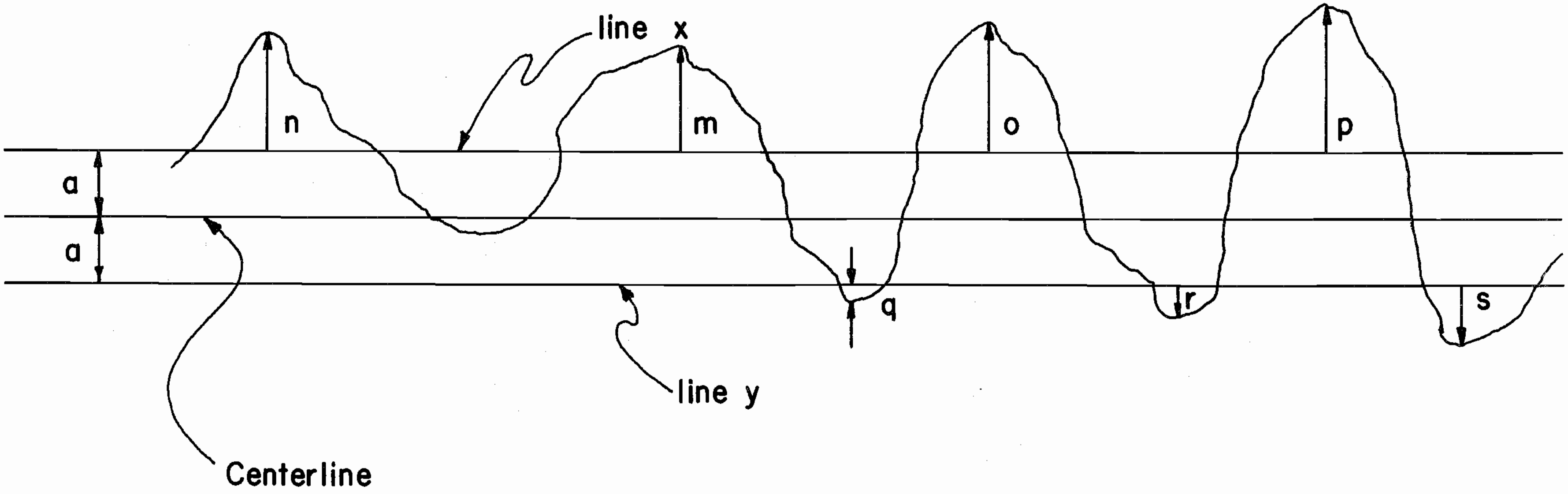


FIGURE 9 – BLANKING BAND PRINCIPLE

IV. HISTORY OF DEVELOPMENT

During the development and testing process several experiments were accomplished. In order to document the work done, each of these experiments were place in chronological order and can actually be though of as a history of development. Basically, the history consists of (1) equipment checkout, (2) awareness of the influence of texture, (3) isolation of the texture variable, and (4) development of construction roughness specifications.

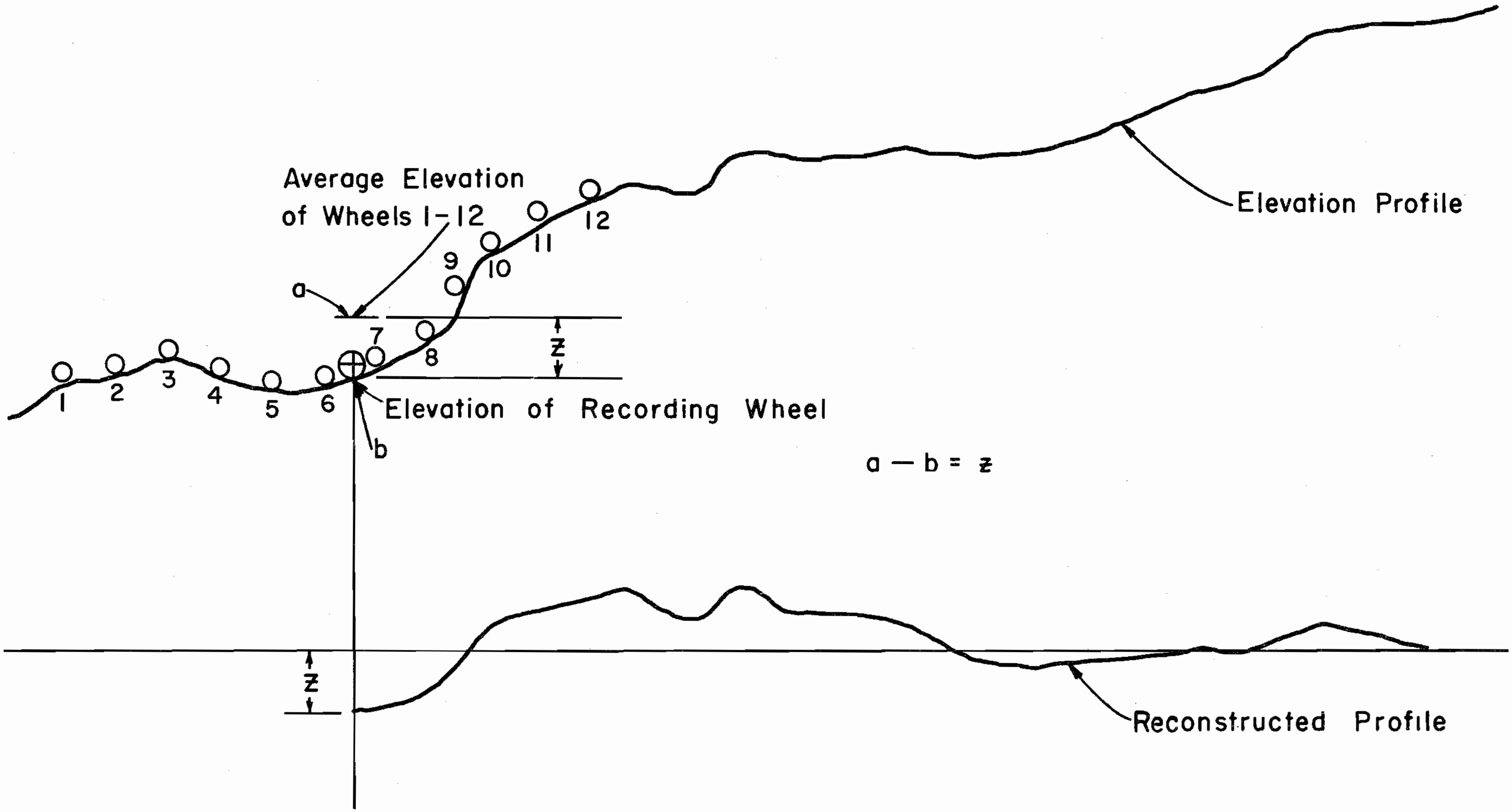
Graphical Output Compared to Rod and Level Profile

Near the beginning of the study, four pavement sections were selected to check out the equipment. Each section varied in age, roughness and location. Precise levels were obtained with a level instrument at two-foot intervals along the roadway with measurements taken to the closest 1/1000-foot. Bench marks were established at 200-ft. intervals. Four paths were located on two sections which were 2500-feet in length and one path was obtained on the remaining two sections which were approximately 300-feet in length. Small dots were painted on the pavement surface to delineate the wheel path and level elevation spacing.

The object of this work was to compare the graphical output of the profilograph with the profile produced with the level measurements obtained in the field. Level measurements cannot be easily compared to the graphical output of the profilograph since level measurements produce an elevation profile (See Figure 10). It is possible, however, to visualize the profilograph in place on the elevation profile and obtain an estimate of the roughness profile as produced by the profilograph. It has previously been shown that a vertical movement of one inch in one averaging wheel causes the recorder to move 1/12-inch. Thus, the elevation of the recorder is dependent on the elevation of the averaging wheels and the recorder elevation is actually the mean (plus a constant installation height) of the twelve averaging wheel elevations.

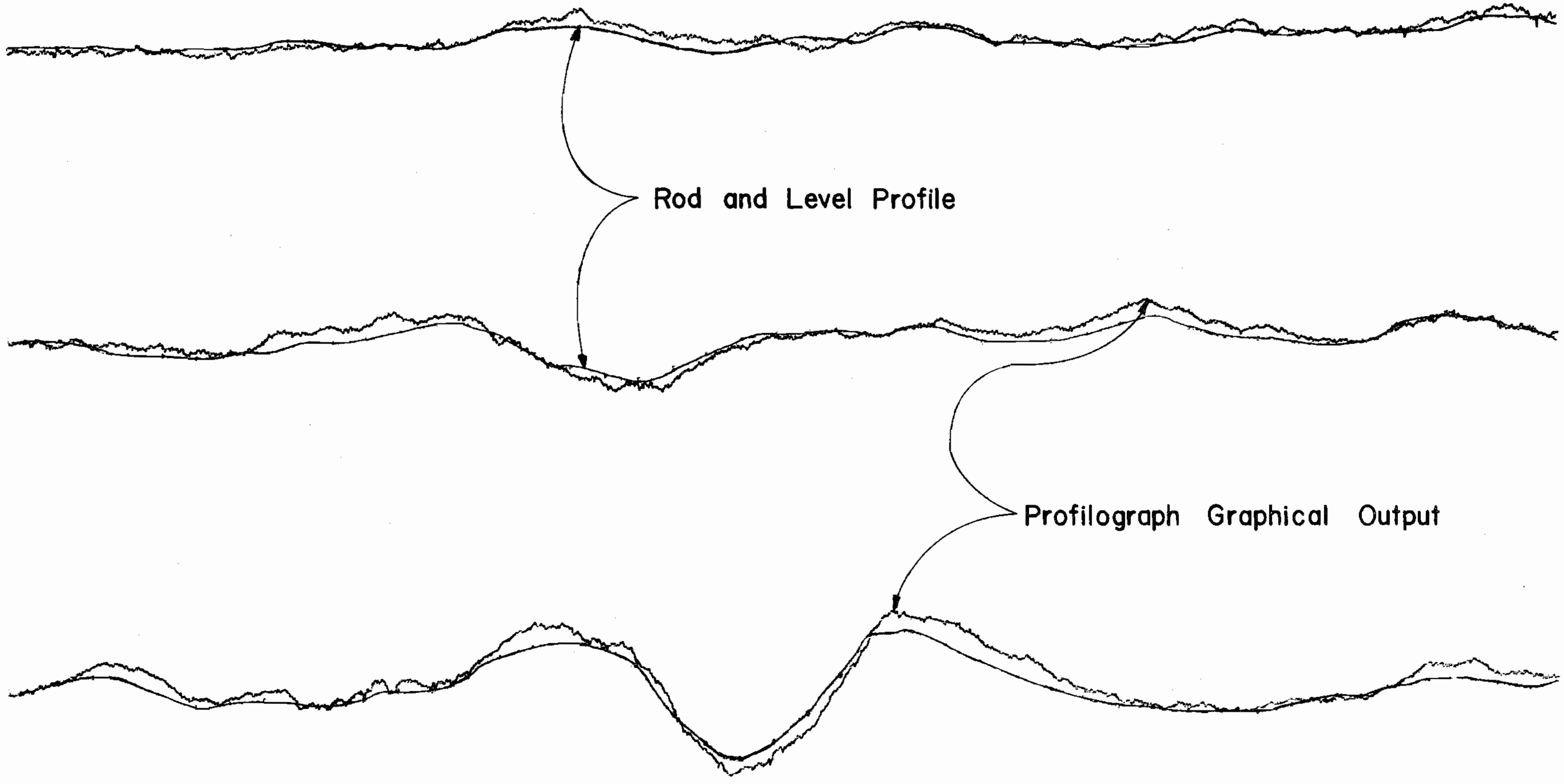
Figure 10 indicates a profilograph in place on an elevation profile. If wheels 1 through 12 are spaced at two-foot intervals and assumed to be on the elevation points which were checked with the level, the "Average Elevation" of these twelve points can be obtained. This "Average Elevation" is indicative of the profilograph recorder elevation and is termed "a" in Figure 10. Then if the mean elevation of wheels 6 and 7 is assumed to be the elevation of the recording wheel termed "b", the difference in points (a-b=z) reveals the measurement being obtained with the profilograph in this position. The profilograph is then repositioned by placing the number 1 wheel in the postion previously occupied by the number 2 wheel, the number 2 wheel in the previously occupied number 3 spot---and the number 12 wheel over the next two-foot interval and a z2 value is obtained. If this process is continued the roughness profile can be reconstructed by plotting the "z" values obtained at each interval position.

The reconstructed profile was plotted at the same scale as that used with the profilograph and the graphical output was overlaid on the reconstructed profile. Figure 11 reveals the results of these attempts. It does appear that the two profiles are compatible with the exception of minor variation in those areas of large amplitudes with respect to the wave length. Since large amplitudes are not expected on new construction, it was concluded from the experiment that the profilograph was capable of reproducing the roughness encountered on the roadway with sufficient accuracy.



SCHEMATIC OF REDUCTION OF FIELD NOTES TO ROUGHNESS PROFILE

Figure 10



Scale: Horiz. 1" = 10', Vert. 1" = 1"

FIGURE 11 — ROD AND LEVEL PROFILE COMPARED TO THE GRAPHICAL OUTPUT

It should be noted, however, that the averaging wheels are actually spaced at 2'-3" centers and level information was obtained at 2-foot intervals. This error is believed to have little influence on the results obtained.

Graphical Output Compared to Digital Output

The digital reading should be indicative of the graphic output. Therefore, it was desired to determine the relationship between the two output modes. To establish this relationship, twelve different pavement sections were selected for testing. Each section was approximately 1200 feet in length with varying characteristics as to construction materials and traffic volumes. The sections were established in various localities and were tested on various days with different operators.

The digital output was collected in the field from the counters on the recorder. These data were identified with the respective section and graphical chart. It should be noted that the digital output is a cummulative sum of the vertical excursions experienced by the recording wheel. If this sum (inches) is divided by the distance traversed (ft.) and extrapolated to a per mile basis the result is roughness in inches per mile.

The graphical charts of each profile were obtained in the field and identified for further analysis. The charts were analysed by constructing a base line through the profile which attempted to equally divide the high and low profile peaks. The base line was used as a reference line from which to measure the vertical dimensions of the peaks or depressions. An engineers' scale was used to measure these dimensions. Attempts were made to consider each minute excursion of the profile. The vertical dimensions obtained from a given chart were summed to result in a cummulative total which was divided by the test section length and extrapolated to a per mile basis.

Two statistical methods were used in analysing these data. The first method consisted of a Variance - Ratio test to determine if significant difference existed between the digital and manually processed graphical output. The second method was a Linear Regression analysis.

The Variance - Ratio test (see Table I) revealed that no significant difference existed between the data (that is 1.02 is less than 3.50-95% confidence level). The Linear Regression analysis resulted in a linear curve fit (see Figure 12) with the following equation:

$$y = -4.83 + 1.0081X$$

were y = Chart Reading
X = Digital Reading

The Correlation Coefficient (R) was 0.993 which generally indicates an excellent curve fit.

It was concluded from this experiment that the difference in the two output modes was not significant and the digital output duplicates the quantities found on the vertical excursions of the profile chart. Therefore, confidence was established in the use of the digital counter system.
Equipment "Checkout

TABLE I.

STATISTICAL COMPARISON BETWEEN CHART READING AND DIGITAL READOUT

Test #	Chart R.	Digital R.	$(Y-\bar{Y})^2$	$(X-\bar{X})^2$	(YX)
1	164.4	150.2	1,361.61	357.21	24,692.88
2	228.2	239.5	10,140.49	11,707.24	54,653.90
3	41.4	41.4	7,413.21	8,082.01	1,713.96
4	119.7	123.8	60.84	56.25	14,818.86
5	39.7	32.4	7,708.84	9,781.21	1,286.28
6	89.5	82.4	1,444.00	2,391.21	7,374.80
7	56.8	74.9	4,998.49	3,180.96	4,254.32
8	64.3	79.7	3,994.24	2,662.56	5,124.71
9	66.4	77.0	3,773.21	2,948.49	5,122.80
10	72.4	86.3	3,036.01	2,025.00	6,248.12
11	298.8	305.9	29,343.69	30,485.16	91,402.92
12	288.5	281.9	25,291.00	22,680.36	81,328.15
TOTALS	1,530.1	1,575.4	99,155.63	96,717.66	298,011.70
Mean $\frac{EY}{N}$	127.5	$\frac{EX}{N}$ 131.3			24,834.30
D.F.	11	11			

EY^2	294,256.13	EX^2	303,181.42
$(EY)^2$	2,341,296.01	$(EX)^2$	2,481,885.16
$E(Y-\bar{Y})^2$	99,155.63	$E(X-\bar{X})^2$	96,717.66

SY= 95 SX= 93.8

Rel. S. D. or
Coef. of Variance 74.5% 71.4%

F - ratio of the variance $\frac{SY^2}{SX^2} = \frac{9,025}{8,798.44} = 1.02$

Coef. of Correlation = .993
Standard Error of Estimate = 10.64
Linear Regression Equation $Y = -4.83 + 1.0081X$

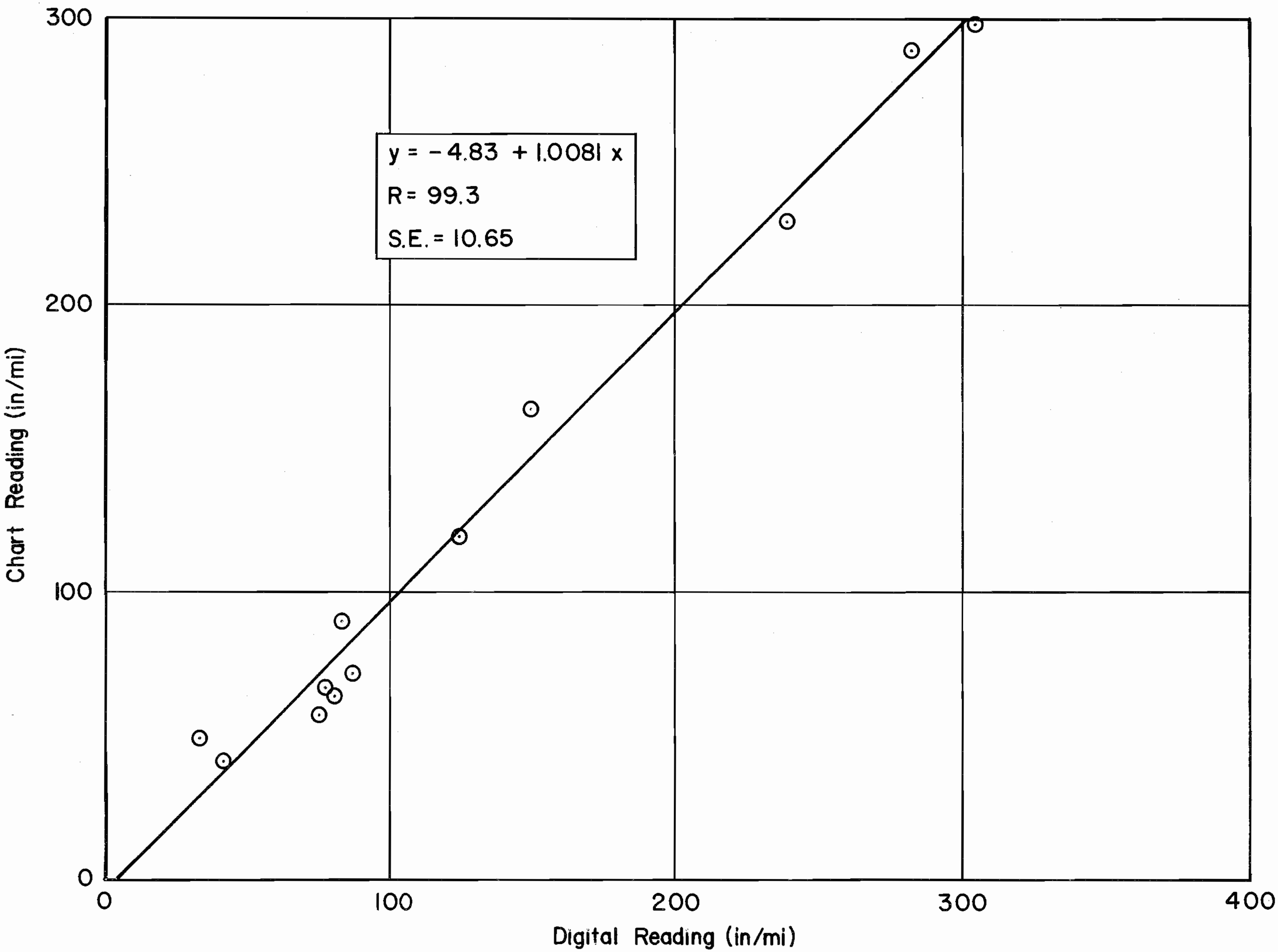


FIGURE 12 – COMPARISON OF DIGITAL AND GRAPHICAL OUTPUT

Equipment "Checkout"

Efforts were made to become more familiar with the equipment idiosyncrasies by performing three tests. These tests are reported in the following paragraphs.

Repeatability. One of the phases of the development of the profilograph was that concerned with repeatability. The repeatability characteristics of the profilograph were determined by testing the equipment several times in the same path and analysing the graphical output.

Two 2500-foot sections were selected for this study. The profilograph was operated along these sections at different times of the day and on different days. The runs were taken in the same wheel path and the machine was operated either bow forward or stern forward.

After a number of tests, the repeatability characteristics of the profilograph were evident. Figure 13 is an example of the graphical profiles obtained during these tests. An analysis of these data revealed that excellent repeatability could be obtained with the profilograph.

Speed Runs. The next step during the testing of the profilograph was the study of the influence and effects of speed in the graphical and digital systems.

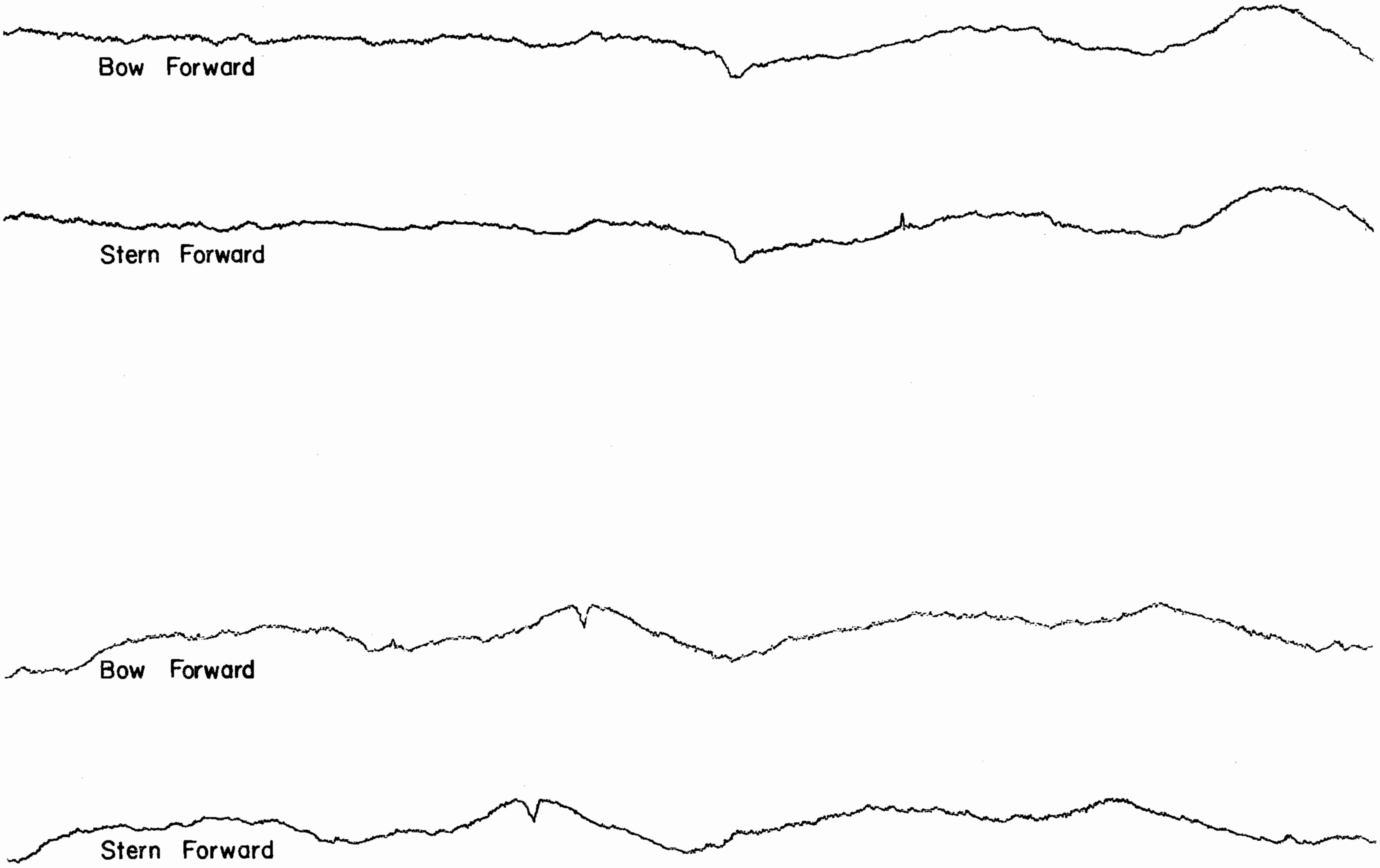
To conduct the speed study, one of the 2500-foot sections previously mentioned was selected. The selection of the test section was based on the prevailing traffic conditions and the magnitude of the roughness previously experienced.

Several tests were obtained with the profilograph over the same path on the selected section. The test speeds were varied and each test was conducted at a selected speed.

The results of the tests indicated the digital output increased as the tests speed increased (see upper curve Figure 14). Figure 15 reveals the graphical output at two of the selected speeds. It would appear from the graphical chart that the increase in digital quantities with speed is due to the small scale roughness (termed "hash"). That is, there appears to be more "hash" associated with the tests at 2.3 MPH than with the tests at 1.1 MPH. It was postulated that the small scale roughness (hash) resulted from vibrations in the equipment which were induced by the surface texture.

It should be recalled that the original design of the profilograph called for a rack and gear method of activating the mechanical counters of the digital system. Therefore, it was further postulated that the vibrations resulted in excessive movement at the rack and gear due to the operational tolerance between the rack and gear and high enertia.

To reduce the effects of vibration in the digital system, the rack and gear device was replaced by a string - system (see Figure 16). The tests previously described were again performed over the same path with the string modification. It was immediately apparent that the string modification reduced the effects of vibration (approximately 40%) in the digital system see lower curve Figure 14). As a final check, weight was added to the profilograph in an effort to dampen the vibration in the framework. The added weight was actually an operator (160#) riding on the equipment. The data obtained by adding weight did not differ from the results obtained previously with the string modification.



Scale: Horiz. 1"=10', Vert. 1"=1"

FIGURE 13 — EXAMPLE OF REPEATABILITY CHARACTERISTICS

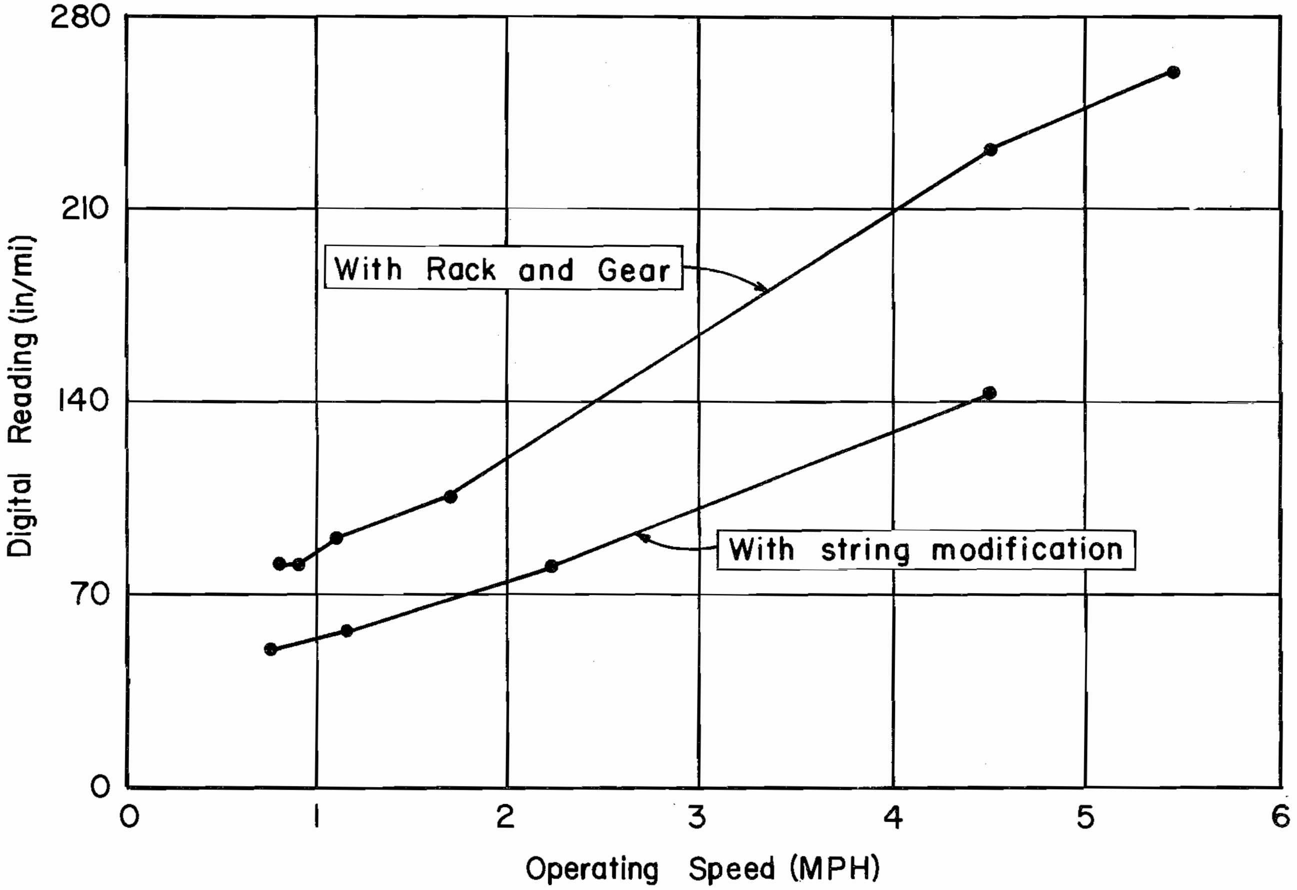
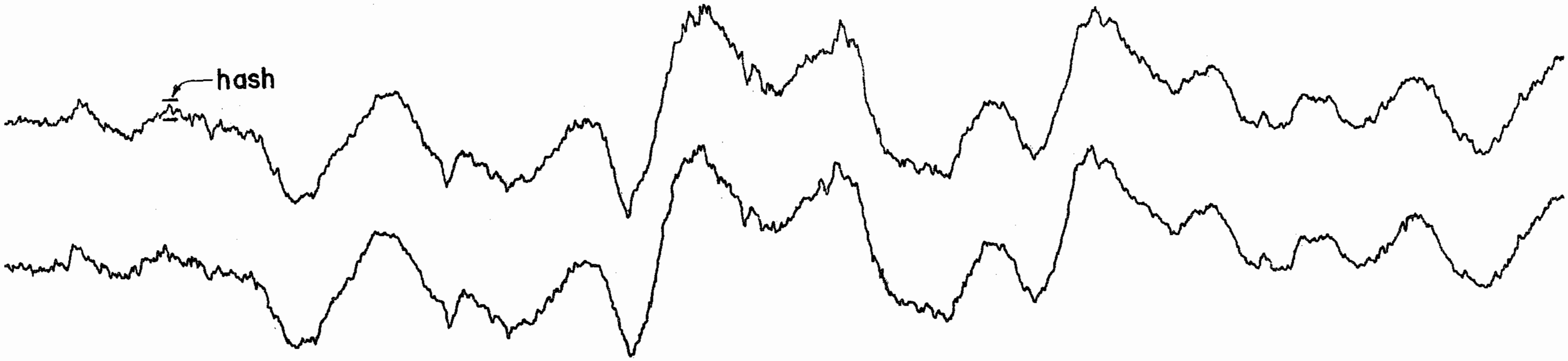
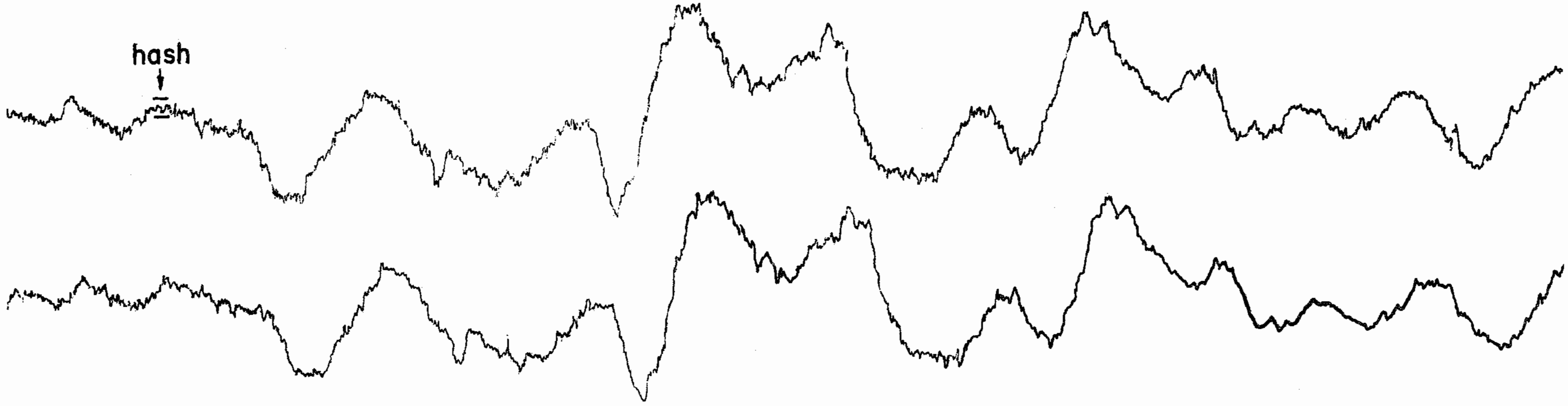


FIGURE 14 — STUDY OF DIGITAL OUTPUT AT VARIOUS TEST SPEEDS



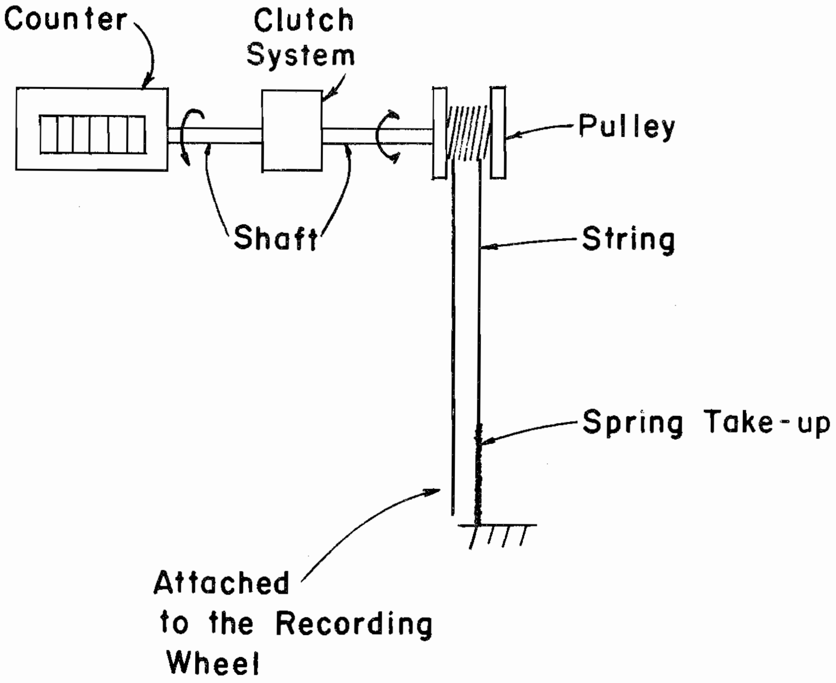
Repeat Tests at 1.1 MPH



Repeat Tests at 2.3 MPH

Scale: Horiz. 1"=10', Vert. 1"=1"

FIGURE 15 — GRAPHICAL OUTPUT AT DIFFERENT SPEEDS



SCHEMATIC OF THE DIGITAL COUNTER

(String Modification)

Figure 16

Based on this study, the string modification was retained and a speedometer was added to the profilograph. A one MPH speed was selected for use in the remainder of the study.

Treatment Study. The Treatment Study consisted of an analysis of the variance found in operators, equipment operating modes and pavement gradeline. Since the profilograph is intended to be placed in several Districts and operated by many people, variance could be induced by the operators and operating methods. Also, the instrument can be pushed either bow or stern forward with the added influence of either a positive or negative gradeline.

To study these possible error inducing variables, two repeat tests were obtained with two operators, with the profilograph in bow and stern forward positions, and on both a positive (uphill) and negative (downhill) grade. Statistically, an analysis of variance procedure was conducted using the measurements of these tests.

Measurements were obtained on each of the 2500-foot test sections and analysis were conducted on each section separately and by combining the two sections. The data sheets of this study are in Appendix A and the results are revealed in Table II.

The results of this study indicated the profilograph could be operated either bow or stern forward, uphill or downhill and with various operators without significant differences in digital readout for any one section. When the treatment combinations are studied together the more significant variations can be isolated. That is the magnitude of the Fc values in Table II are indicative of the variations expected between treatment combinations. For example, the two operators when pushing uphill or downhill on any one test section, appear to have consistently greater variation, even though it is not significatn at the 95% level (See Table II, Line 6). When this treatment combination is studied, in relation to both test sections, the variation is significant.

It is interesting to note the variation between sections (see Table II, Line 8). The "Fc" value is exceedingly large when compared to the Ft value which is correct since this value indicates significant difference between sections. This significant difference reveals the profilograph can measure difference in roughness between sections.

Based on these results, it was decided that the profilograph could be operated in any manner (with the exception of velocity) and with any operator. However, in further testing, attempts were made to operate the equipment on negative (downhill) or level sections.

TABLE II

RESULTS OF THE ANALYSIS OF VARIANCE OF THE TREATMENT STUDY

Treatment Combination Studied	Section 1		Section 2		Sections 1 and 2	
	Fc	Ft(.95)	Fc	Ft(.95)	Fc	Ft(.95)
1. Bow vs. Stern	.03	5.32	0.20	5.32	0.01	4.49
2. Uphill vs. Downhill	.26	5.32	0.50	5.32	0.00	4.49
3. Operator 1 vs. Operator 2	2.82	5.32	0.06	5.32	1.51	4.49
4. Line (1) x Line (2)	.24	5.32	1.50	5.32	1.21	4.49
5. Line (1) x Line (3)	.85	5.32	0.90	5.32	0.05	4.49
6. Line (2) x Line (3)	3.67	5.32	2.40	5.32	6.05	4.49
7. Line(1)xLine(2)xLine(3)	1.70	5.32	0.20	5.32	1.83	4.49
8. Sec. 1 vs. Sec. 2					3444.77	4.49
9. Line 1 x Line 8					0.15	4.49
10. Line 2 x Line 8					0.68	4.49
11. Line 3 x Line 8					2.32	4.49
12. Line 4 x Line 8					0.09	4.49
13. Line 5 x Line 8					1.49	4.49
14. Line 6 x Line 8					0.47	4.49
15. Line 7 x Line 8					0.61	4.49

F_c = Calculated from field data.

F_t (.95) = Obtained from Tables indicating (allowable) tolerance at the 95% level

if $F_c < F_t$ there is no significant difference between treatment combinations.

Initial Tests of New Construction

At this point, the experiments previously conducted indicated that (1) the profilograph graphical output was accurately measuring the roadway profile, (2) the digital output was accurate because the manual count from the graphical chart correlated with the digital count, (3) the graphical output repeatability of the equipment was excellent, (4) vibrations induced by varying velocities had been corrected by the string modification to the recorder and by operating at constant speed and (5) the operation mode had been established, that is generally downhill, and either bow or stern forward with any operator.

The next testing scheduled was that of obtaining a sample of tests conducted on newly constructed pavement. These test sections were located in several Districts and consisted of the following pavement types:

1. Portland Cement Concrete Pavement
2. Asphaltic Concrete Pavement
3. Penetration or Surface Treatment

Both digital and graphical output data were obtained and a partial analysis was maintained as each section was tested.

By comparing the graphical output to the digital output, it soon became evident that the surface texture of the pavement surface contributed to the digital output to a great extent. Assuming that Surface Treatments are associated with the larger surface texture, an indication of the influence of texture is found by comparing the digital outputs of the "Surface Treatment" pavements with the Portland Cement and Asphaltic Concrete pavements in Table III. It will be noted that the digital output of the "Surface Treatments" are large as compared to the digital output of pavements with smaller surface texture.

Figure 17 reveals three typical profiles obtained on different pavement types. The Asphaltic Concrete and Portland Cement Concrete pavement profiles were selected to show major roughness with small texture and the Surface Treatment was selected with minor roughness and large texture. It should be noted that the Surface Treatment profile reveals a large number of rather small vertical deviations (previously termed "hash"). Whereas, the Asphaltic Concrete and Portland Cement Concrete profiles reveal minute quantities of these small vertical deviations. Since the "hash" appears to be associated to texture and the digital output appears to increase as the "hash" increases, it was concluded that the higher digital readings resulted from the heavily textured pavement surfaces.

The sampling was halted and efforts were directed toward isolating from the digital system the vertical excursions of that portion of the profile related to texture.

Experiments with Recording and Averaging Wheels

The isolation of texture was attempted in two ways:

1. The researchers began experiments with existing equipment.
2. The fabricator began designing other adaptations for the profilograph.

TABLE III.
DIGITAL OUTPUT OF INITIAL PROFILOGRAPH TESTS

CONCRETE inches/mi.	HMAC inches/mi.	SURFACE TREAT inches/mi.
107	48.5	962
173	178.0	553
177	99.0	296
101	118.0	584
51	108	227
100	150	432
164	175	133
147	257	231
139	134	116
141	175	279
80		338
79		

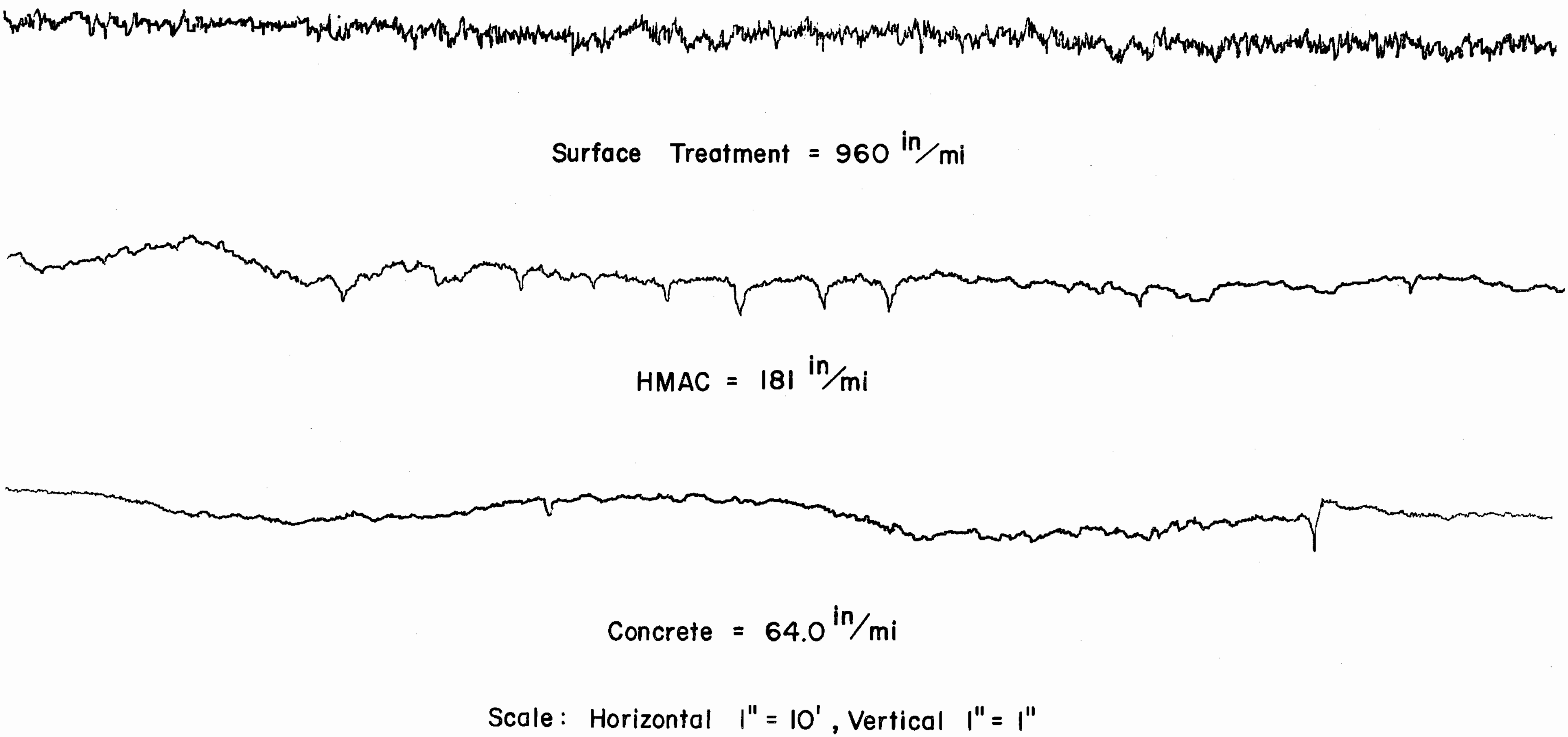


FIGURE 17 — ROUGHNESS AND TEXTURE VARIATIONS EXPERIENCED WITH THE PROFILOGRAPH

Experiments with Existing Equipment. This experiment consisted of wrapping a foam rubber around the recording wheel and averaging wheels. The rubber was 3/8-inch in thickness and approximately one inch wide. It was thought that the peaks of the aggregate would protrude into the rubber with the rubber deforming to allow a damping process for texture.

The testing was conducted on a 264-foot Surface Treatment section with coarse texture. All tests were obtained over the same path at a constant one MPH speed.

The foam rubber was premeasured to fit each wheel and attached by the use of an adhesive. The testing was divided into four steps as follows:

1. All wheels were unwrapped
2. Only the averaging wheels were wrapped
3. Only the recording wheel was wrapped
4. All wheels were wrapped

Figure 18 indicates the results of these tests. It may be noted that there is a reduction in digital output by wrapping the wheels. The graphical output appears to have been affected in like manner. The greatest single reduction appeared when the recording wheel was wrapped. However, the digital readout was still over 600 inches per mile. Since several smooth textured pavements (which were considered rough) had been measured with readings around 100 inches per mile, it was decided that no significant accomplishment had resulted from wrapping the wheels. A decision was made to retain the tire design on the recording and averaging wheels rather than obtaining a softer tire for the wheels.

Fabricator Adaptations. Rainhart Company developed a spring-type shock absorber system which was incorporated on the shaft between the recording wheel and the recorder. It was found that this system resulted in an even greater digital output. That is, the spring, which was used as a damper in the shock absorber, seemed to have induced a greater frequency of vertical movement at the recorder. After the above facts were known the spring-type shock absorber was removed.

All Wheels Wrapped — D_0 = 665 Inches / Mile

Averaging Wheels Wrapped — D_0 = 1063 Inches / Mile

Recording Wheel Wrapped — D_0 = 720 Inches / Mile

All Wheels Unwrapped — D_0 = 1218 Inches / Mile

Scale: Horiz. 1" = 10', Vert. 1" = 1"

FIGURE 18 — EXPERIMENT WITH PADDED WHEELS

Blanking Band Study

The Blanking Band Study was an effort to eliminate the influence of texture from the digital output. A general description of the blanking principle was given in Chapter III in the description of the recorder (See Figure 9). It was conceived that the blanking principle could be used as a texture correction factor in the digital output. That is, the blanking band would "blank out" the digital reading produced by the texture but would allow the large scale roughness to be recorded.

Procedure. Twenty three test pavements were selected for this study. In selecting the test pavements, attempts were made to obtain surfaces with a wide range of roughness and texture. Each test pavement was 0.2-mile in length and digital readings were recorded at 0.1 mile intervals. The test pavements were divided into two equal parts to produce forty six 0.1-mile sections.

The profilograph was used to evaluate each section. Utilizing the blanking band feature of the digital output, each section was tested using four blanking bands. Digital readings were obtained using a zero or no blanking band, a 0.05 inch, a 0.10 inch and a 0.15 inch blanking band. Graphical output was also obtained on each section. A texturemeter developed under Research Project 2-8-62-32 was used to obtain a measure of surface texture by taking the average of 20 texturemeter readings spaced at 100-foot intervals along the section. The results of the measurements are shown in Table IV.

Basis of the Digital Study. A visual graphical rating was arbitrarily selected as the best estimate of pavement roughness and was used as the basis for further digital study. It should be recalled that the influence of texture was noted on the graphical output by viewing the small consistent variations (hash) occuring within the larger undulations as shown in Figure 17. However, by visually discounting the texture variations of the graphical output a comparison of roughness may be determined between pavements (See Figure 19).

The graphical output was rated by visually comparing each chart. That is, each of the 46 charts was placed side by side and so ordered as to result in a rating from the roughest to the smoothest. The average ratings of three people were used to provide the final order.

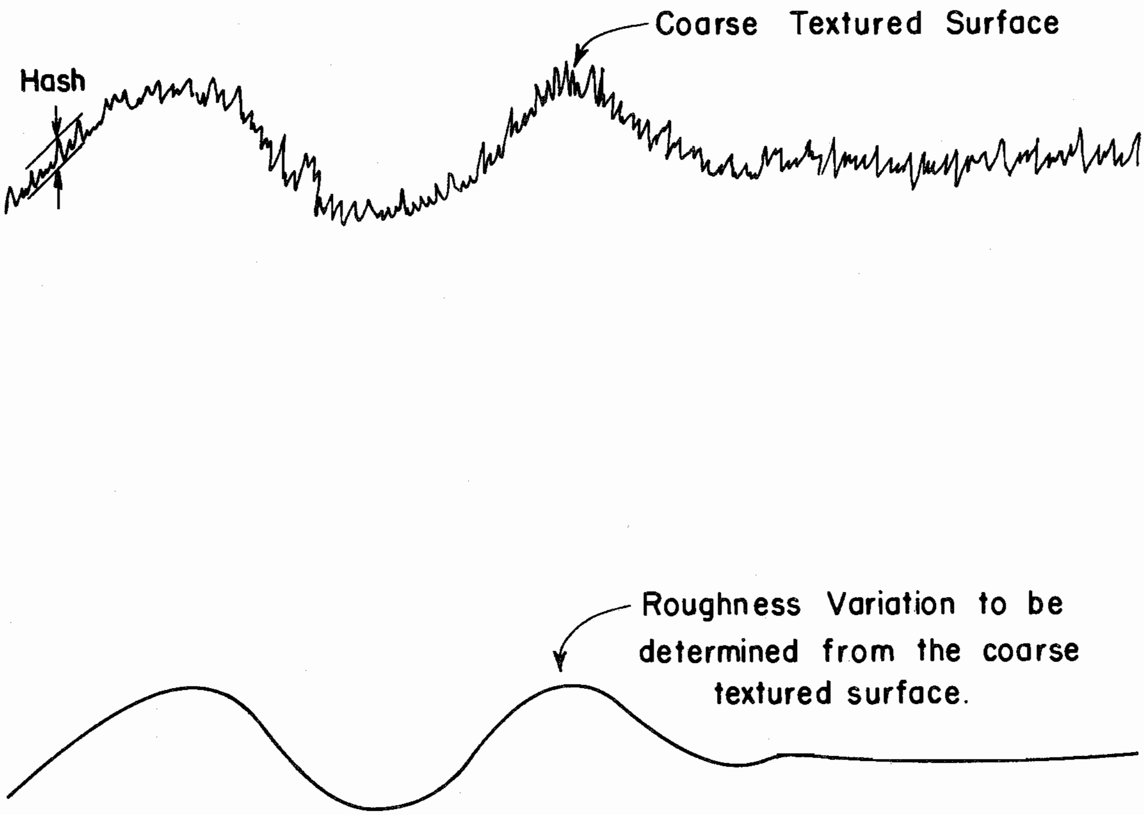
Since the authors feel that the acceptance of the studies performed on the digital output hinges on the acceptance of the visual graphical rating, the rated profiles (explained in the preceding paragraph) are given in Appendix B for perusal. Data pertinent to each numbered profile may be found in Table IV.

Analysis. The digital reading was studied at each blanking band setting for each section tested. Typical plots are presented in Figure 20. The plots revealed that the magnitude of the slope of the curve of any section was associated with the texture as measured with the texturemeter. Rather than determining an equation for each curve, the digital reading with the 0.10-inch blanking band (D_{10}) was subtracted from the digital reading with zero blanking band (D_0) and used as an estimate of the slope. Figure 21 is a plot of the D_0-D_{10} differential (slope) and the texturemeter reading (T_r).

TABLE IV.

BLANKED DIGITAL DATA AND TEXTURE MEASUREMENTS ON 23 SELECTED SECTIONS.

SECTION	TEXTURE	D_0	D.05	D.10	D.15
12	14.87	405.0	361.5	296.5	266.5
2	0.06	214.3	144.5	101.0	59.0
1	0.46	165.5	120.3	84.0	51.3
7	139.10	1072.5	656.0	310.0	105.5
9	2.25	158.0	76.0	34.0	8.5
11	11.22	392.0	225.5	113.8	35.0
A	67.00	775.5	257.3	185.0	15.0
13	3.23	354.5	181.5	85.0	19.0
8	30.00	621.0	380.5	172.0	69.5
13F	20.60	229.8	116.8	50.3	15.0
16	6.50	239.5	60.8	20.0	4.9
10	6.87	137.8	63.5	27.0	0.5
5	5.20	284.0	142.5	46.8	13.8
3	3.58	168.5	29.5	14.0	5.3
4A	3.00	89.5	36.0	8.5	0.0
14	4.15	86.5	11.5	3.0	0.0
17	1.25	62.8	6.0	0.0	0.0
18	1.60	65.0	8.5	0.0	0.0
4	15.90	321.0	77.5	6.0	0.8
17E	2.80	97.0	3.5	0.0	0.0
3C	6.00	172.5	23.5	0.0	0.0
1C	7.00	162.8	23.5	3.5	0.0
6	12.70	92.5	7.0	0.5	0.0



SCHEMATIC OF ROUGHNESS AND TEXTURE VARIATIONS

FIGURE 19

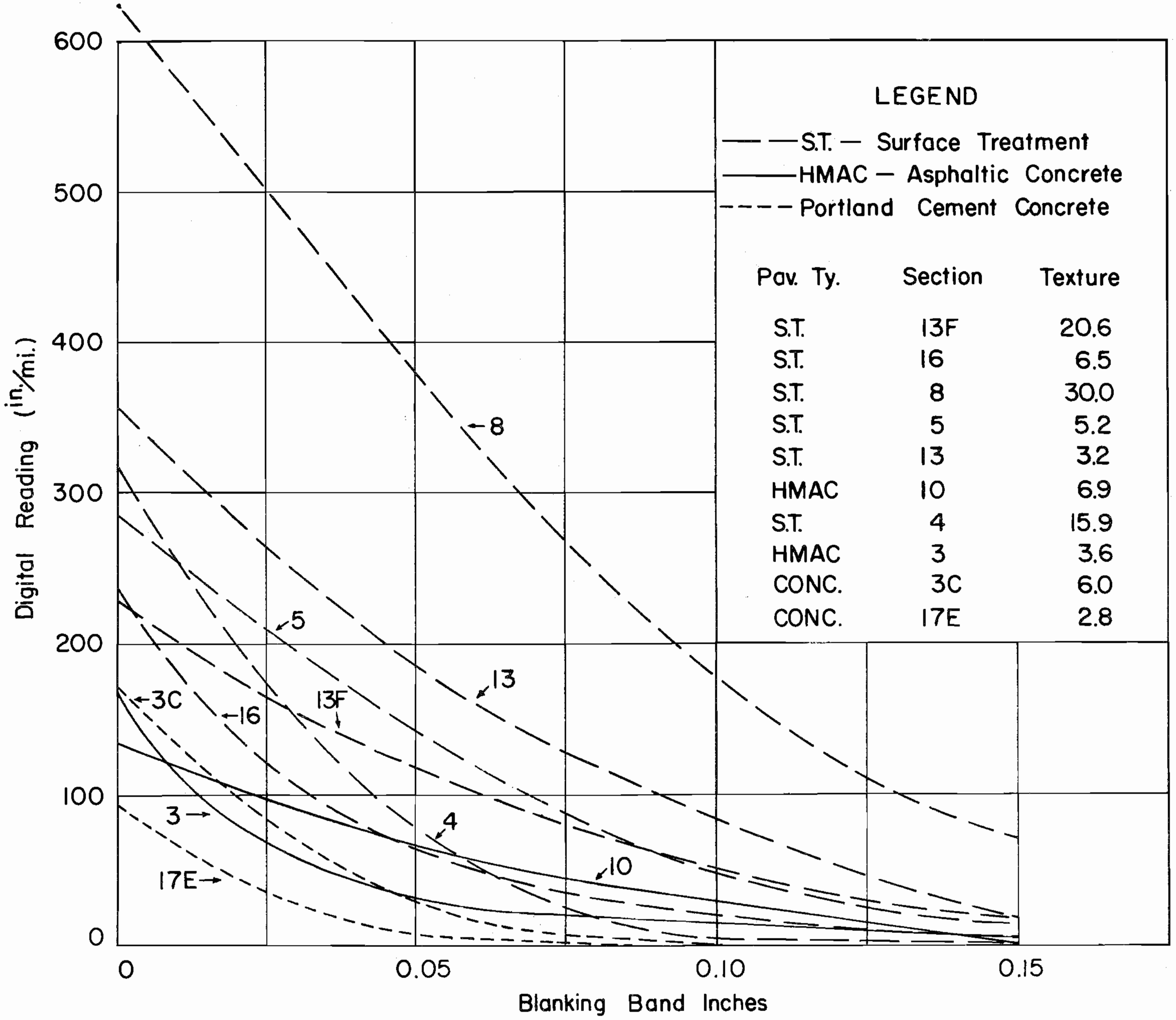


FIGURE 20 — STUDY OF DIGITAL OUTPUT AT SELECTED BLANKING BANDS

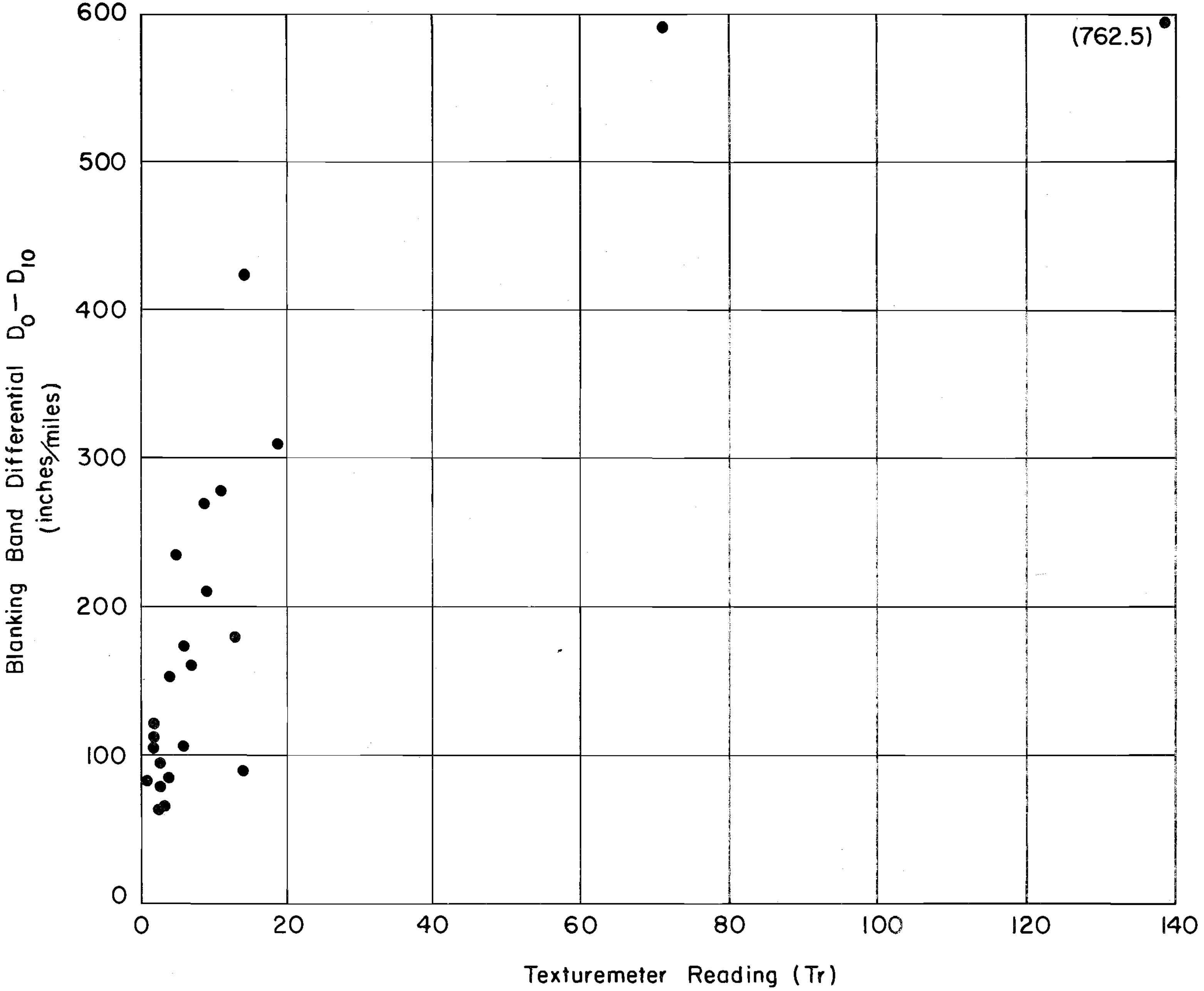


FIGURE 21 — CORRELATION OF BLANKING BAND DIFFERENTIAL AND TEXTURE

The digital reading at each blanking band setting was compared with the visual graphical rating. It was concluded from this comparison that no apparent relation existed between the digital reading at a certain blanking tolerance and the visual rating. That is, no one blanking tolerance can be used to blank out or correct for texture. It was postulated, however, that the influence of texture could be separated from pavement roughness by selecting an appropriate blanking tolerance for any given pavement. This means that for a given texture a specific blanking tolerance would be permitted.

Footnote:

The texturementer is a small instrument approximately 18"x8"x1" in dimension. The instrument contains several probes which contact the surface when the instrument is forced certically downward. Texture measurements are formed by the probes contacting the surface in various vertical positions causing indicator movement on a dial gage by a string running transversally through the probes.

Based on the above postulation, it appeared that there were available four methods to correct for texture, explained as follows:

A. From Measurements of Texture Using Texturementer Readings

1. A chart could be prepared in which the blanking band size could be selected from the texturemeter reading on a given test section. If a tab corresponding to the selected blanking band size was inserted in the profilograph recorder, it would be assumed that the digital output obtained from the profilograph using the selected blanking tab would be corrected for texture.

2. A correction factor could be obtained from a chart using the texturemeter reading. It would be assumed that the digital output would be corrected for texture by subtracting (or adding) the correction factor from the digital reading obtained with a zero blanking band.

B. Measurements of Texture Using the Slope ($D_0 - D_{10}$)

1. A short repeat test could be performed on any selected test section using both a zero blanking band and a 0.10-inch blanking band. A differential obtained from these readings could be used to select a blanking band size from a chart. As in A-1 above a tab corresponding to the selected blanking band could be inserted in the recorder. Tests could then be performed on the section using the selected blanking tab. It would be assumed that the digital output obtained from the profilograph using the selected blanking tab would be corrected for texture.

2. From the $D_0 - D_{10}$ differential explained in B-1 above, a correction factor could be selected from a chart. This correction factor could be subtracted from (or added to) the digital reading after tests were obtained on the section with a zero blanking band. It was assumed that a texture corrected reading would result.

The methods and correction charts explained in "B" above were developed because the measurements necessary for the texture corrections could be produced by the profilograph, thus eliminating the additional cost of the texturemeter. The methods and charts in "A" above were included because it was believed that the texturemeter produced measurements of texture more accurately than those produced by the D_0- D_{10} slope.

Four charts (relating to Methods A1, A2, B1 and B2) were prepared. Method A1 was used as an example for explaining the preparation of the charts.

In general, the chart for Method A1 was prepared by ordering the sections (roughest to smoothest) based on the visual graphical rating. The ordering is given in Column (1) of Table V. Minimum and maximum blanking bands were selected so that the digital readings ranked in the same order as the visual readings. More specifically, Table V was formed as follows:

Minimum Blanking Band

1. The second roughest section (number 2 in Column 1) was compared to the roughest section (number 1 in Column 1).

2. Using plots similar to that found on Figure 20 the minimum blanking band (Column 3) was selected so that the digital readings (Column 4) ordered the two sections the same as the visual rating. That is, the blanking band size was found that would cause the digital reading of the second roughest pavement to be equal to or smaller than the digital reading of the roughest pavement.

3. The third roughest pavement was compared to the second roughest pavement and the minimum blanking band was found so that the digital readings of the two sections were ordered similar to that explained in steps 1 and 2 above.

4. This process was repeated for all 46 sections to obtain a minimum blanking band for each. It may be noted that the values in Column 4 are in a general decending order, however, the item of importance is the minimum blanking band permitted to keep the digital order like the visual order.

Maximum Blanking Band

5. The second smoothest section (number 45 in Column 1) was compared to the smoothest section (number 46 in Column 1).

6. Again using plots similar to Figure 20, the maximum blanking band Column 5) was selected so that the digital readings (Column 6) ordered the two sections the same as the visual rating.

7. The third smoothest section was compared to the second smoothest as was done in steps 5 and 6 above.

TABLE V.

ANALYSIS OF TEXTURE CORRECTIONS BY METHOD A1

Col. 1 Roughness Order	Col. 2 Section No.	Col. 3 Min. Blank Band	Col. 4 Dig. Rd. Min. Band	Col. 5 Max. Blank Band	Col. 6 Dig. Rd. Max. Band	Col. 7 Texture Reading
1	12	0	432	0.150	295	14.9
2	12X	0	379	0.150	238	14.9
3	2X	0	226	0.095	117	0.06
4	1	0	167	0.053	117	0.5
5	2	0.024	167	0.069	117	0.06
6	1X	0	164	0.058	117	0.5
7	7	0.134	164	0.150	117	139.1
8	9	0.001	164	0.034	97	2.3
9	9X	0	151	0.038	97	2.3
10	11X	0.103	151	0.128	97	11.2
11	7X	0.133	151	0.150	97	139.1
12	11	0.061	151	0.088	97	11.2
13	AX	0.121	151	0.134	97	67.0
14	13	0.061	151	0.088	97	3.2
15	13X	0.690	151	0.102	97	3.2
16	8	0.104	151	.127	97	30.0
17	13F	0.062	151	.090	97	20.6
18	16	0.019	151	.038	97	6.5
19	10	0	138	.025	97	6.9
20	8X	0.126	138	.150	97	30.0
21	10X	0	128	.125	18	6.9
22	5X	0.063	128	.150	18	5.2
23	16X	0.019	128	.120	11	6.5
24	5	0.051	128	.150	11	5.2

TABLE V Continued:

Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7
25	4AX	0	104	.116	11	2.5
26	3X	0.029	104	.150	11	3.6
27	A	0.110	104	.150	4	67.0
28	13FX	0.032	104	.150	4	5.3
29	4A	0	75	.117	2	2.5
30	14	0.008	75	.125	2	4.2
31	14X	0.005	75	.092	2	4.2
32	3	0.014	75	.085	2	3.6
33	17	0	57	.080	2	1.3
34	18	0.004	57	.067	2	1.6
35	17X	0.008	57	.090	2	1.3
36	4X	0.068	57	0.150	2	15.9
37	18X	0.006	57	0.150	0	1.6
38	4	0.048	57	0.150	0	15.9
39	17E	0.013	57	0.150	0	3.0
40	3C	0.029	57	0.150	0	6.0
41	1C	0.032	57	0.150	0	7.0
42	1CX	0.019	57	0.150	0	7.0
43	17EX	0.008	57	0.150	0	3.0
44	3CX	0.031	57	0.150	0	6.0
45	6X	0.018	57	0.150	0	12.7
46	6	0.006	57	0.150	0	12.7

8. This process was repeated for all 46 sections to obtain a maximum blanking band for each. Again, the item of importance was the maximum blanking band (Column 5) permitted to keep the digital order like the visual order.

It would appear that the correct criteria would select blanking bands for various textured pavements that would lie within the blanking band range shown in Columns 3 and 5 of Table V.

Figure 22 reveals a plot of the texture readings and the minimum blanking bands. Curve I was established along the leading edge of the data points.

Figure 23 reveals a plot of the texture readings and the maximum blanking bands and Curve J was placed along the trailing edge of the data points. Figure 24 indicates a plot of both curves. It had been postulated that Curve I would have been above and to the left of Curve J in Figure 24 in order that the criteria could be established between the curves with no overlap. However, the curves crossed as shown in Figure 24. The data points shown between the curves indicate of measure of error encountered by using this method. The stepped line reveals the criteria established for further study. In seven cases the blanking band selected using the criteria was to small and in two cases the criteria was too large. Additional blanking tabs were fabricated as indicated in the Blanking Size criteria on Figure 24.

As stated previously, each of the four texture correction methods was analysed in a manner similar to Method A1. The correction charts are given in Figure 25 (Method A-2), Figure 26 (Method B-1), and Figure 27 (Method B-2).

Results. The results of applying the correction methods to the data obtained are given in Figures 28 through 31. In these plots, the corrected roughness reading (index) is studied in relation to the visual graphical rating. Even though Methods A-1 and B-1 appear to result in a close relation with the visual graphical rating, erratic points were noted in the roadways with larger texture measurements.

Applying the Results. To select one desirable method from the four proposed and to insure adequate results, further testing of newly constructed pavements was accomplished.

Forty eight test sections were selected consisting of 5 Surface Treatment or Penetration Surfaces, 14 Portland Cement Concrete surfaces and 29 Asphaltic Concrete pavements. Measurements were made as described in the "procedure" paragraph above. That is, each 0.2-mile section was tested with the progilograph using a zero blanking band, a 0.05 blanking band, a 0.10 blanking band and a 0.15 blanking band. In addition, texture measurements were made with the texturemeter previously described and from these texture measurements Method A-1 was followed in which a blanking band was selected and a blanking tab inserted into the profilograph. One additional test was made with this blanking band. Digital and graphical output were collected on each run of each section. Data was not collected using Method B-1 because of the time required to perform the test. A list of the measurements are given in Table VI.

TABLE VI.
BLANKED DIGITAL DATA AND TEXTURE MEASUREMENTS ON NEWLY CONSTRUCTED PAVEMENTS

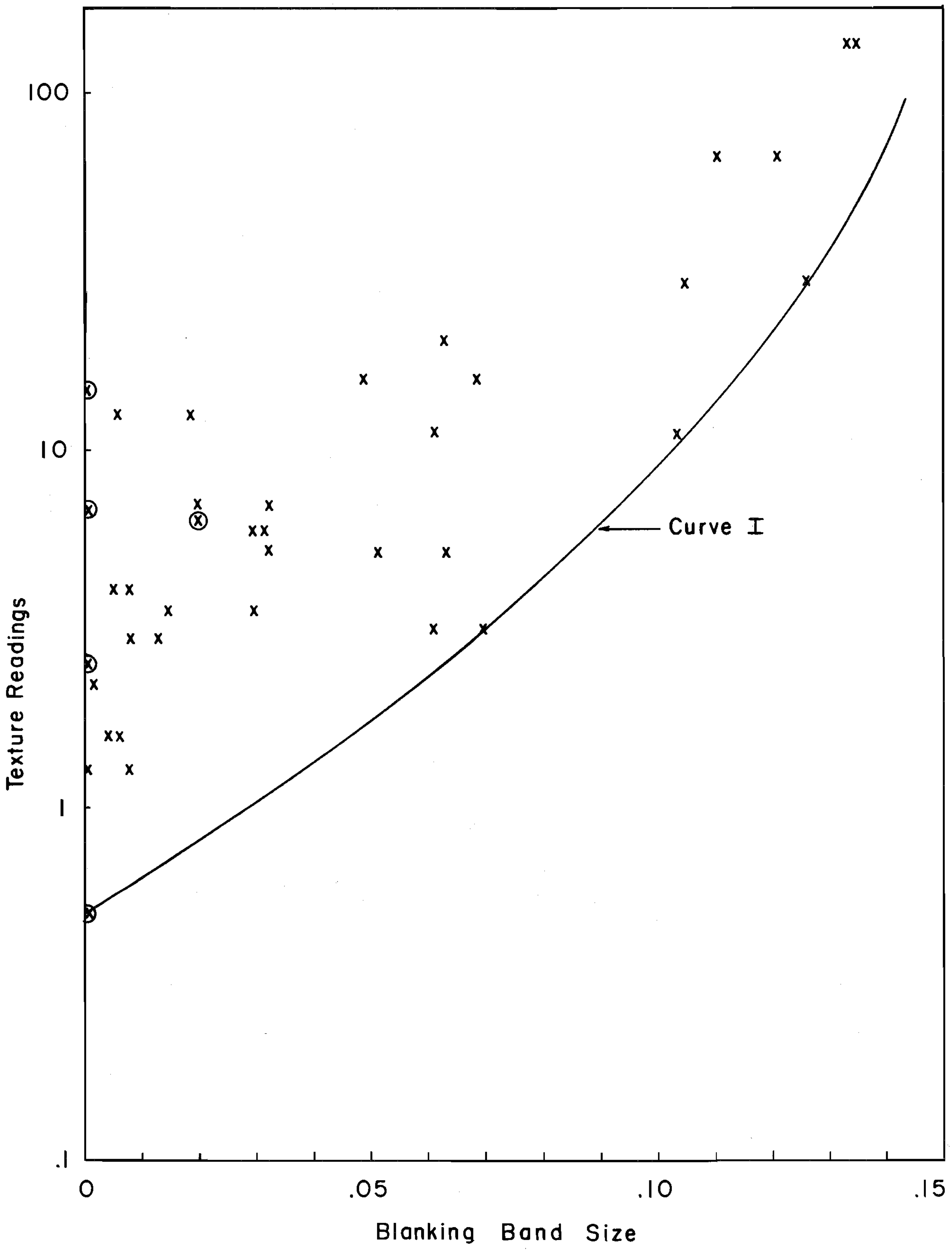
SECTION	TEXTURE	D.0	D.05	D.10	D.15	METHOD A1	METHOD B2	METHOD A2
17-7	2.15	211.5	116.0	63.0	38.5	123.0	151.5	261.5
12-13	1.55	173.0	-	37.5	13.5	79.8	123.0	233.0
17-6	2.35	219.0	126.5	50.0	24.0	123.0	134.0	269.0
17-3	1.15	144.0	140.5	39.0	18.5	159.5	122.5	224.0
12-11	2.45	233.5	93.0	25.0	3.5	95.0	107.5	273.5
9-1	3.25	189.0	-	79.5	5.0	17.80	163.0	219.0
17-14	2.75	90.5	35.0	6.0	-	46.5	80.0	120.5
12-26	9.95	65.5	33.5	9.0	-	9.0	80.0	65.5
12-5	1.48	131.0	47.0	12.0	3.5	90.5	91.0	191.0
17-2	1.05	202.0	136.0	66.0	6.0	131.3	152.0	282.0
17-1	0.83	67.0	55.0	12.0	-	35.5	82.0	137.0
12-28	88.40	1133.0	995.0	148.0	38.0	30.0	0.0	833.0
17-5	1.65	144.5	96.0	47.0	15.0	87.5	124.0	214.5
12-3	0.53	97.5	87.0	10.5	1.0	55.5	83.0	197.5
9-4	61.50	297.5	170.0	127.0	21.5	36.5	212.0	107.5
12-4	87.0	87.0	79.0	8.5	1.0	53.8	82.0	167.0
24-1	1.55	136.0	116.0	20.0	4.0	101.0	100.0	206.0
9-2	12.30	713.0	543.0	170.0	-	166.5	123.0	703.0
17-8	3.95	133.5	111.0	22.5	10.0	44.0	104.0	163.5

TABLE VI. CONTINUED

SECTION	TEXTURE	D.0	D.05	D.10	D.15	METHOD A1	METHOD B2	METHOD A2
17-8	3.95	133.5	111.0	22.5	10.0	44.0	104.0	163.5
12-29	82.10	1779.5	1232.0	547.5	155.0	188.5	284.0	1509.5
9-3	3.05	87.5	66.0	21.0	-	46.3	97.0	117.5
17-12	0.20	50.0	46.0	4.0	-	50.5	85.0	160.0
14-2	3.30	77.0	67.0	10.0	-	13.3	87.0	107.0
17-4	2.95	167.0	156.0	11.0	1.5	8.65	97.0	197.0
9-8	4.60	107.5	-	-	-	10.3	78.5	127.5
8-7	8.85	34.5	21.0	-	-	13.5	87.7	34.5
9-7	6.20	84.5	-	-	-	4.8	76.5	99.5
17-10	0.00	43.0	37.0	6.0	-	45.0	83.0	163.0
14-1	8.43	114.0	107.0	7.0	2.0	49.8	89.0	114.0
17-9	0.45	36.0	25.0	11.0	-	40.0	75.0	136.0
17-17	2.65	65.0	53.0	12.0	-	28.8	84.5	110.0
17-18	5.00	97.0	52.0	45.0	8.5	53.0	95.0	117.0
8-12	5.50	112.0	106.0	6.0	-	19.8	84.3	132.0
12-27	0.80	70.0	70.0	6.0	-	40.5	72.0	156.0
9-10	51.45	734.5	620.0	115.5	68.0	42.0	0.0	574.5
8-11	6.40	114.5	72.0	42.0	-	28.8	84.5	124.5
14-3	6.55	168.0	166.0	1.5	-	5.8	87.5	178.0

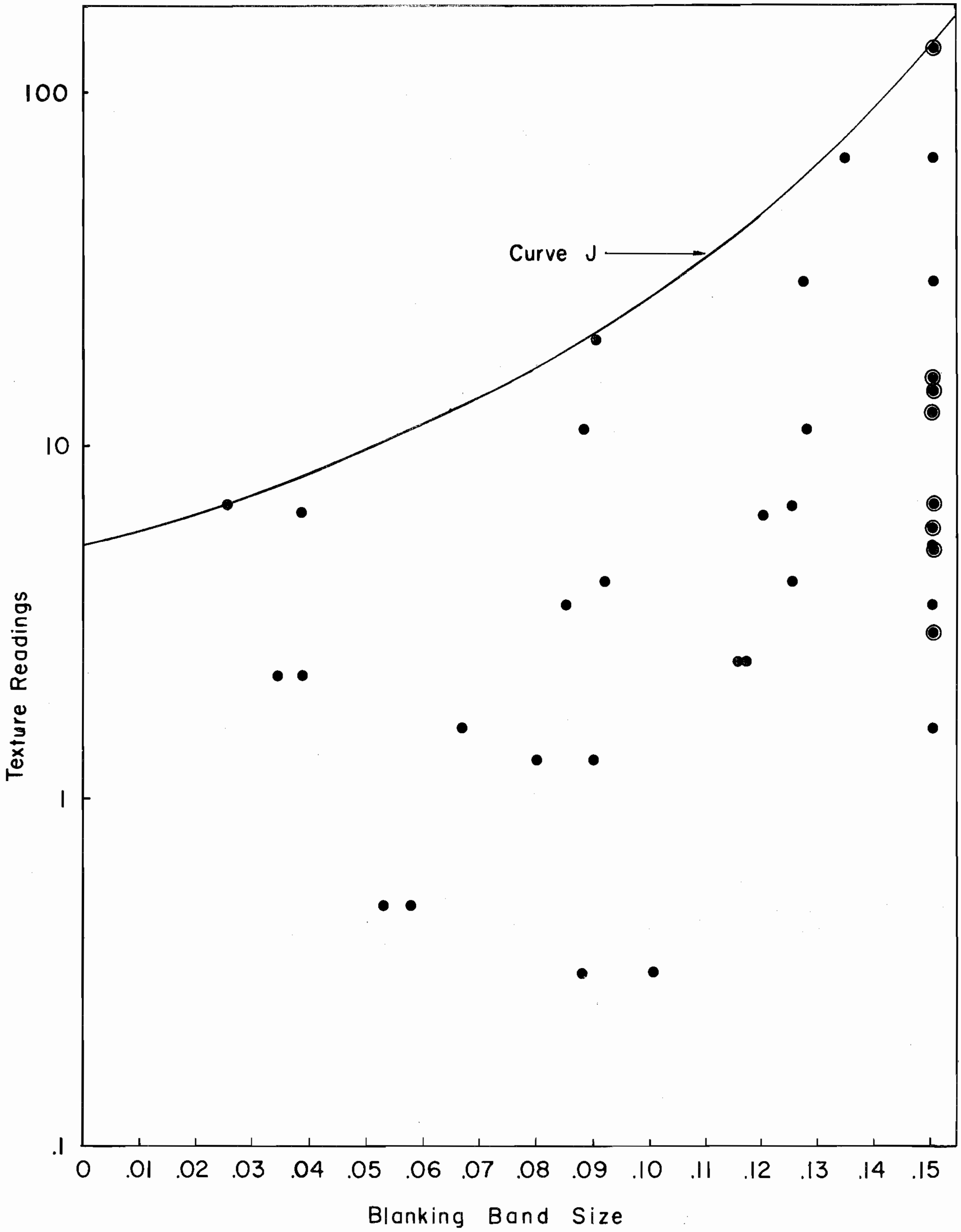
TABLE VI. CONTINUED

SECTION	TEXTURE	D.0	D.05	D.10	D.15	METHOD A1	METHOD B2	METHOD A2
8-2	13.10	169.0	166.0	3.0	-	0.0	93.0	159.0
8-5	6.20	34.5	33.0	2.0	-	13.5	77.5	44.5
14-5	7.90	88.0	86.0	2.0	-	2.3	72.0	93.0
8-9	9.15	49.0	34.0	15.0	-	17.5	91.3	49.0
8-10	9.55	50.5	39.0	12.0	-	12.0	85.5	50.5
8-8	8.50	-	43.0	42.0	-	36.0	112.8	62.8
9-9	8.65	53.5	53.0	0.5	-	0.5	81.3	58.5
8-1	6.35	-	63.0	10.0	-	2.0	75.5	90.5
8-13	11.40	77.0	76.0	1.0	-	2.0	100.0	72.0
9-6	5.10	60.5	30.0	-	-	6.3	76.0	80.5
9-5	4.50	49.0	48.0	1.0	-	6.5	78.0	69.0



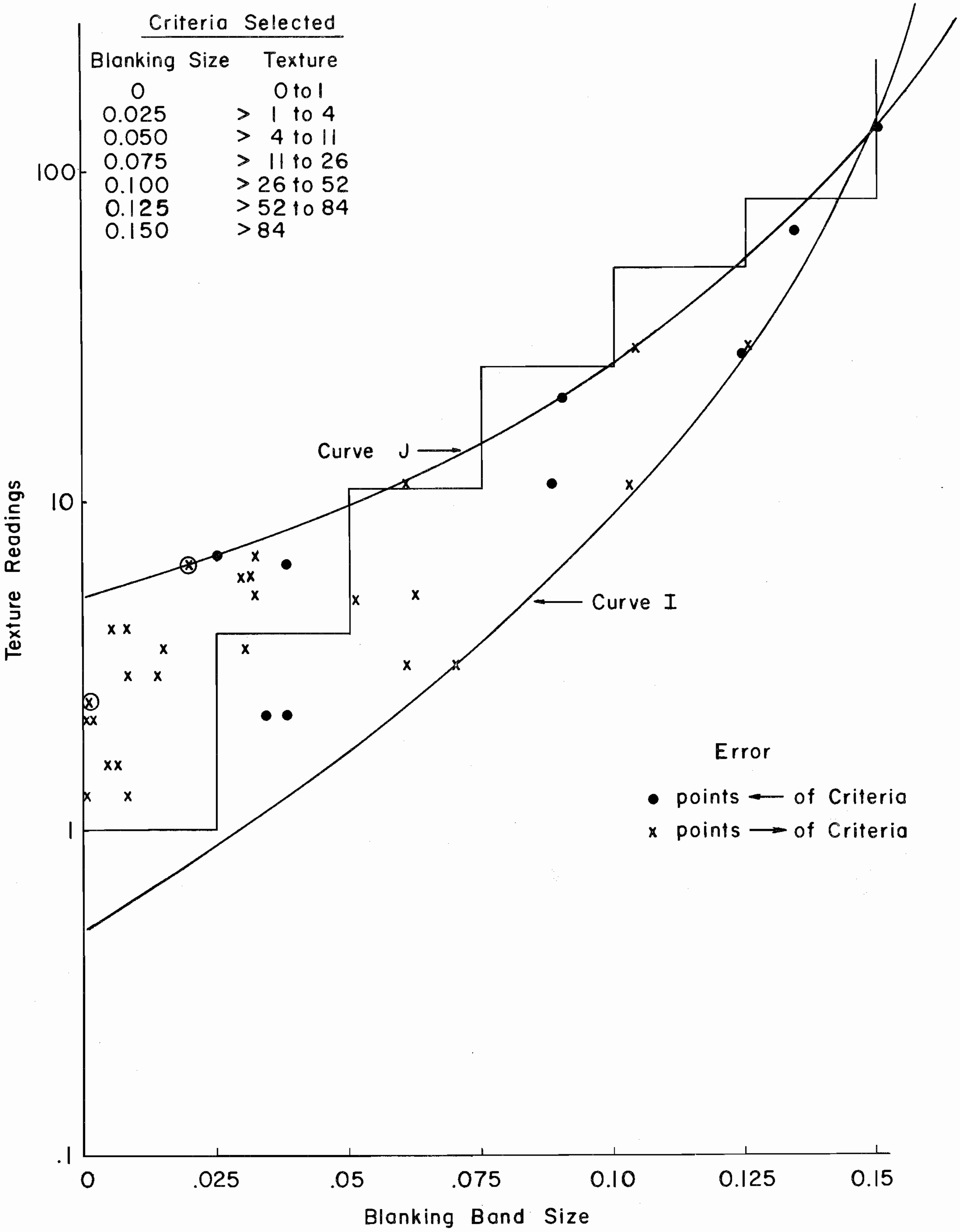
ANALYSIS OF THE MINIMUM BLANKING BAND SIZES

Figure 22



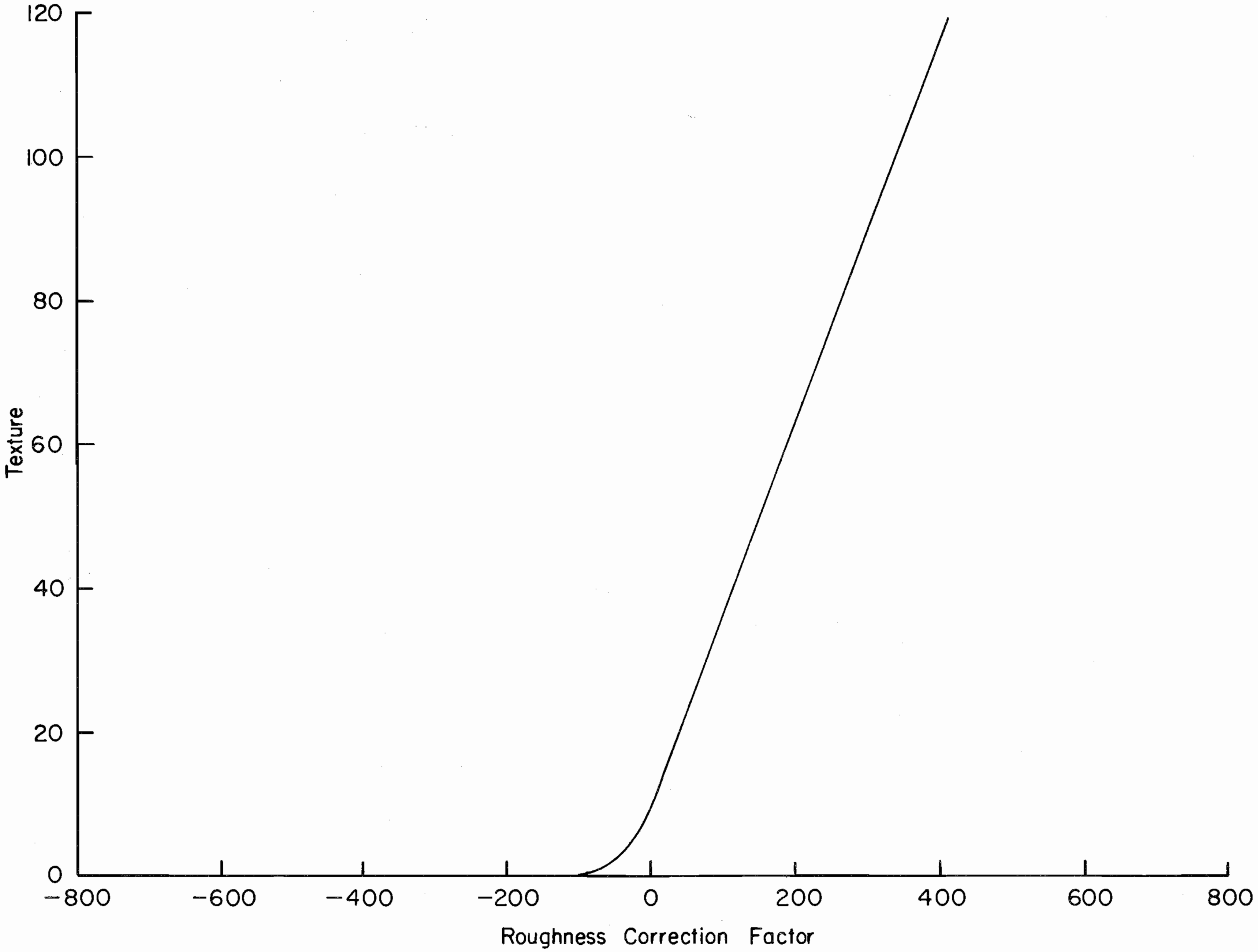
ANALYSIS OF THE MAXIMUM BLANKING BAND SIZES

Figure 23



BLANKING BAND CRITERIA FOR METHOD A-I

Figure 24



CORRECTION FACTOR CHART USING THE TEXTUREMETER

Figure 25

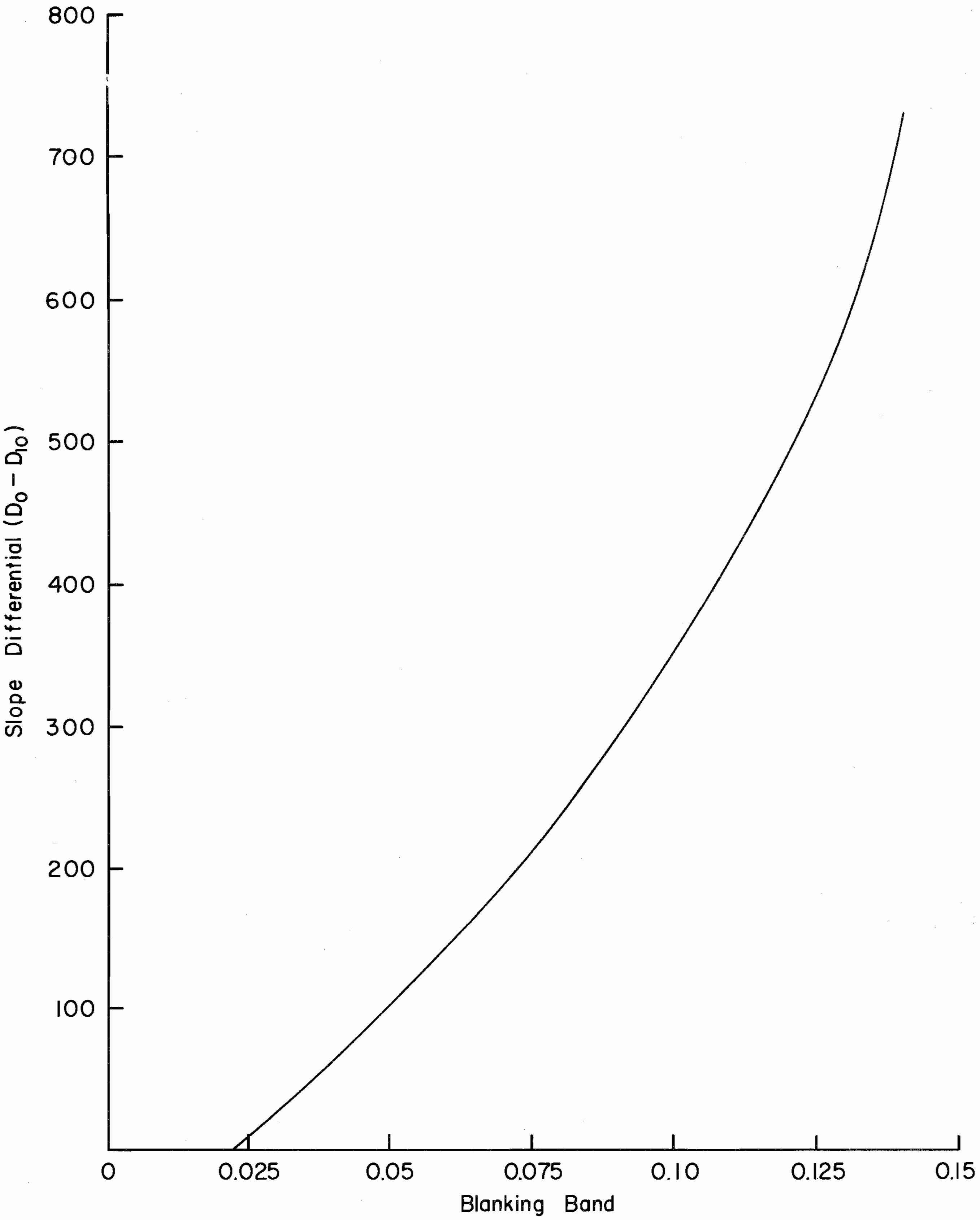
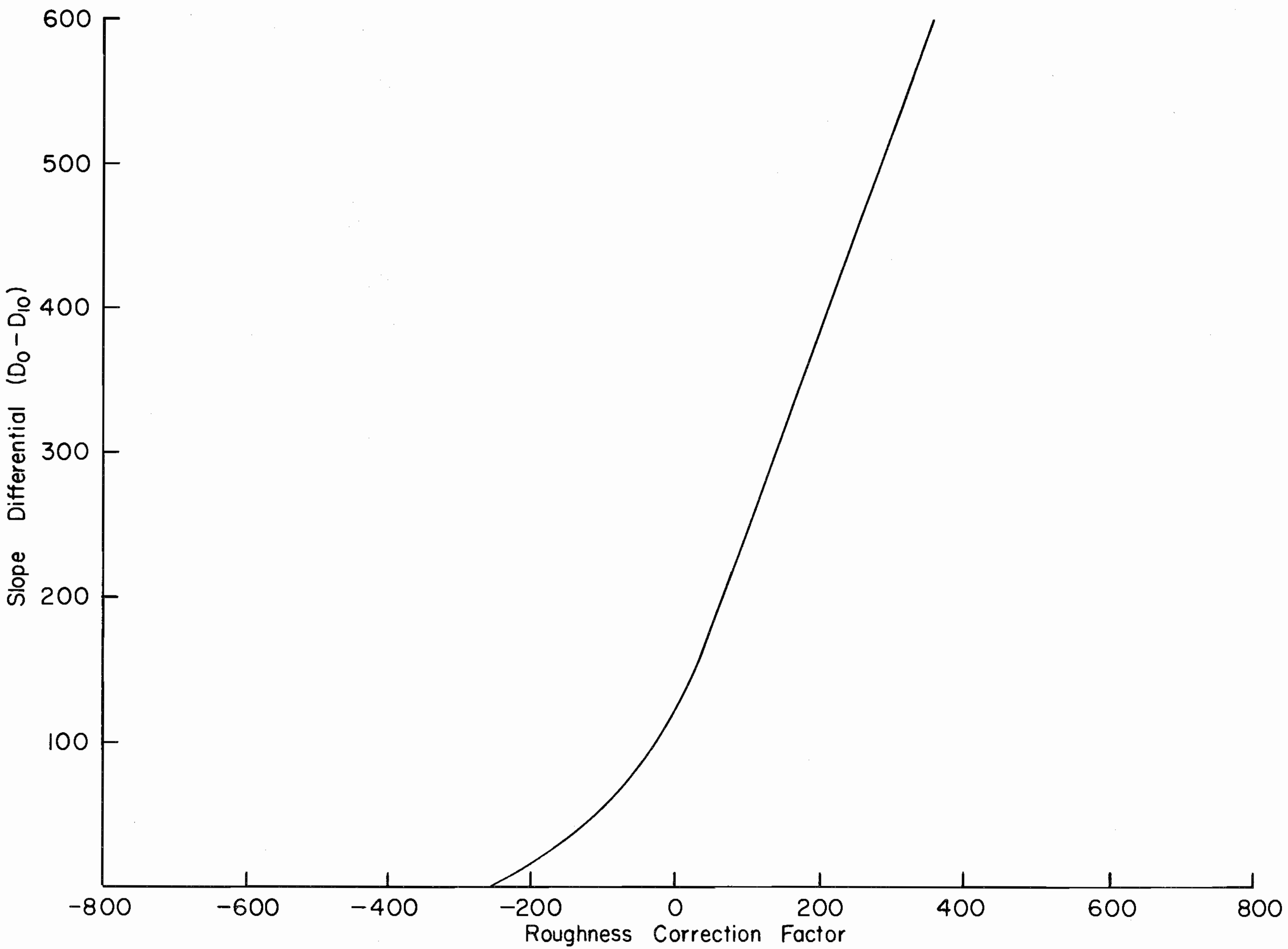


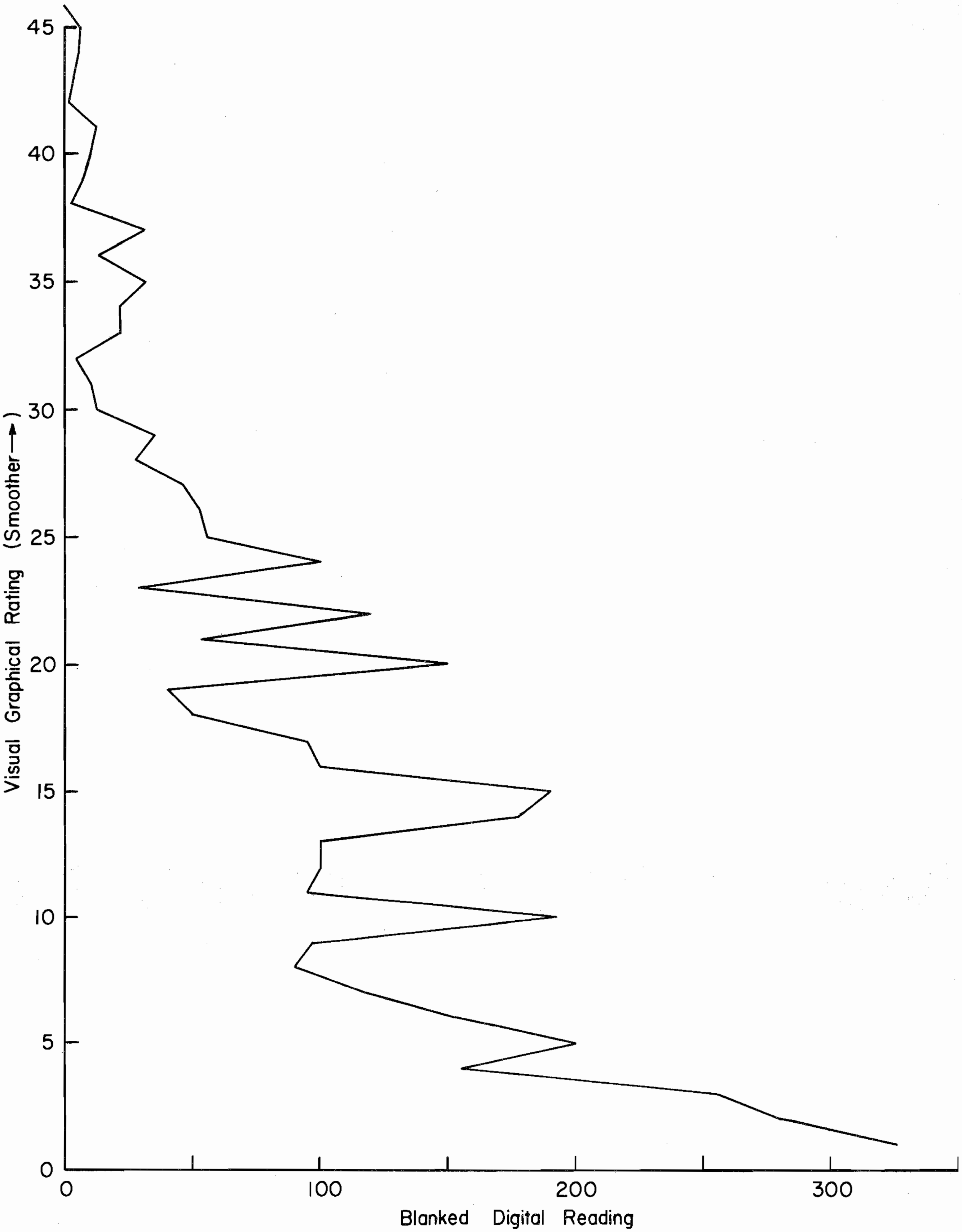
CHART FOR SELECTING A BLANKING BAND USING $D_0 - D_{10}$ DIFFERENTIAL

Figure 26



CORRECTION FACTOR CHART USING THE $D_0 - D_{10}$ DIFFERENTIAL

Figure 27



STUDY OF APPLICATIONS OF METHOD A-I (DIGITAL READING FROM SELECTED BLANKING BANDS BY USING THE TEXTUREMETER)

Figure 28

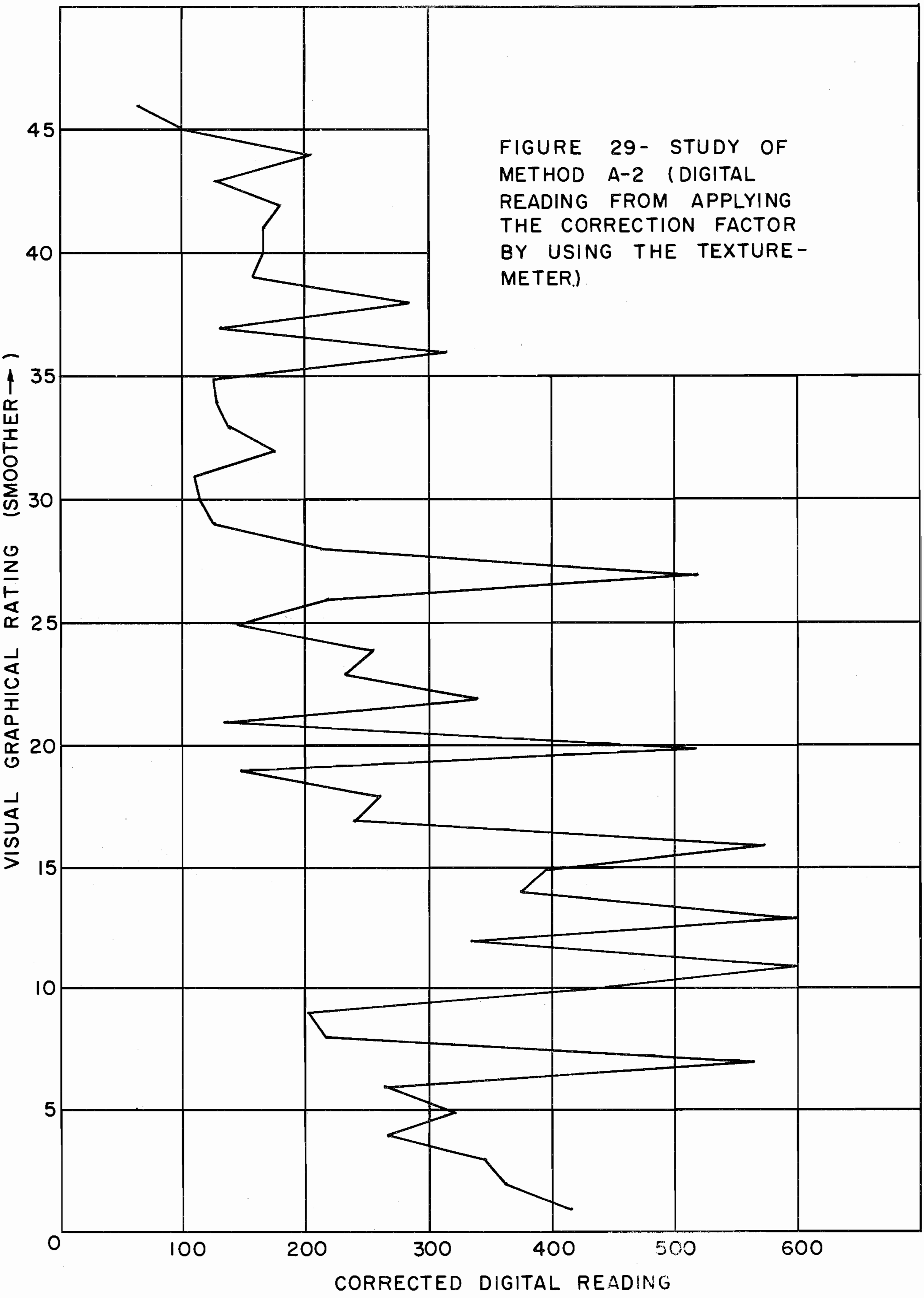


FIGURE 29- STUDY OF METHOD A-2 (DIGITAL READING FROM APPLYING THE CORRECTION FACTOR BY USING THE TEXTURE-METER.)

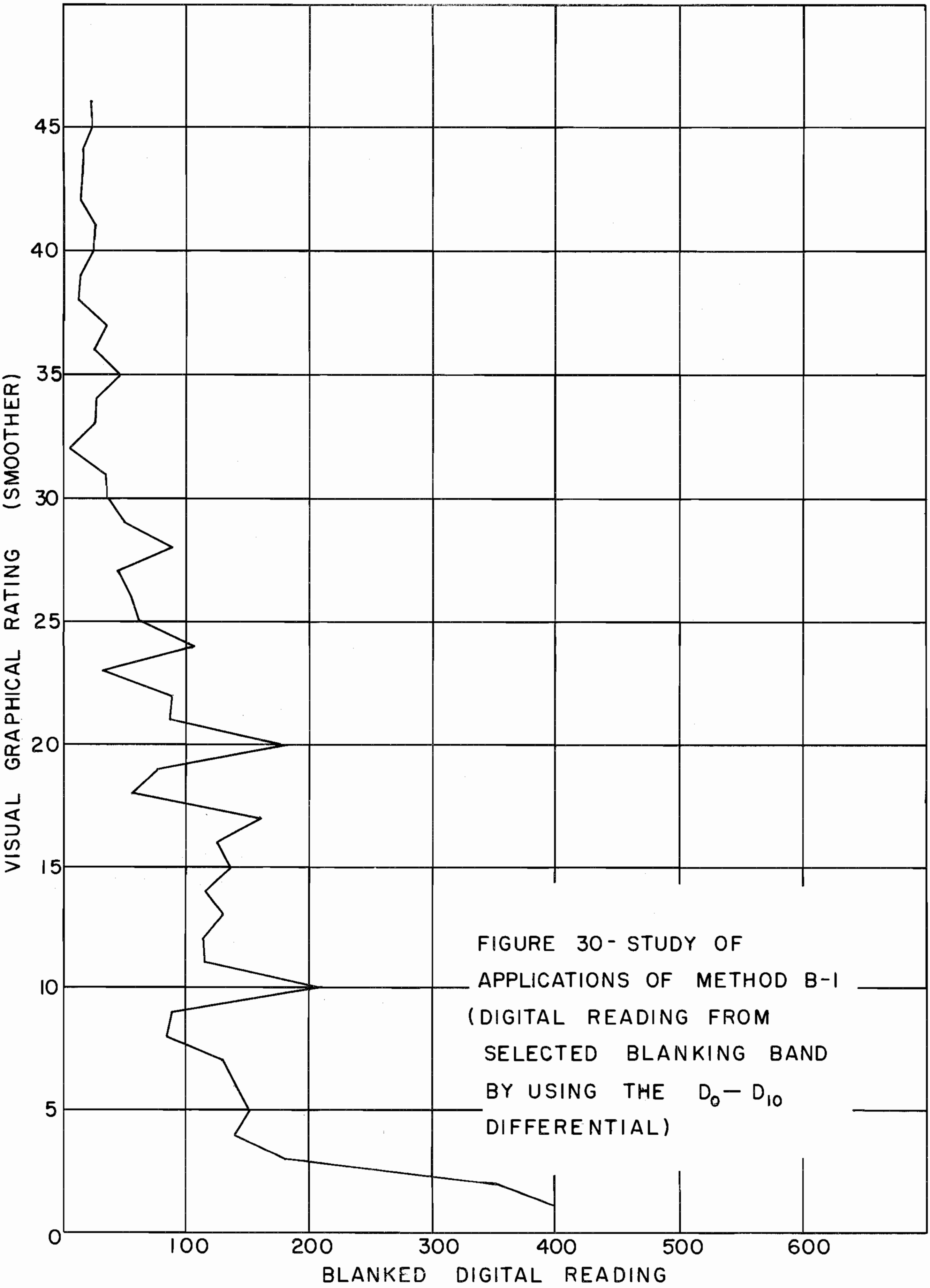


FIGURE 30 - STUDY OF APPLICATIONS OF METHOD B-1 (DIGITAL READING FROM SELECTED BLANKING BAND BY USING THE $D_0 - D_{10}$ DIFFERENTIAL)

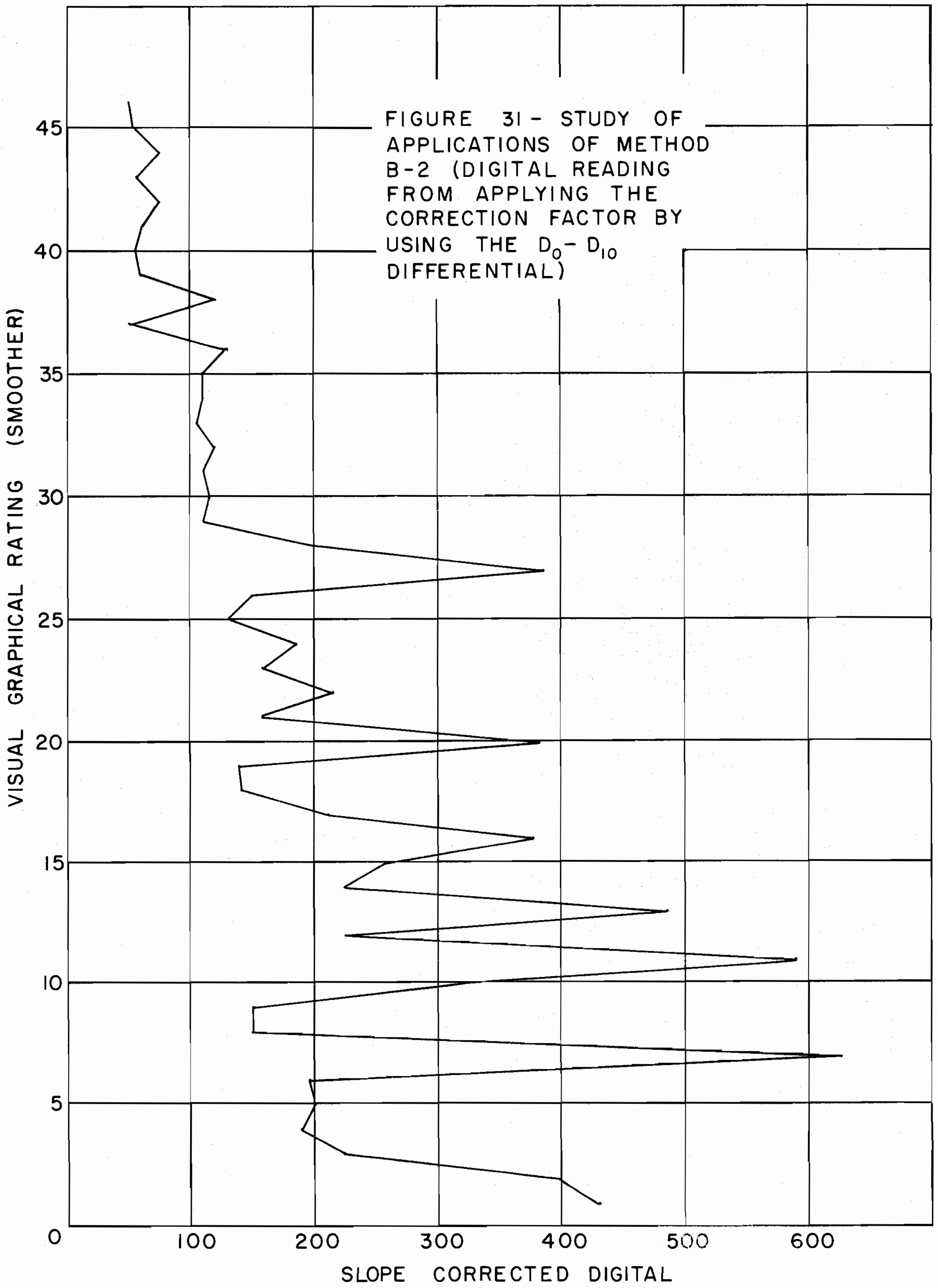


FIGURE 31 - STUDY OF APPLICATIONS OF METHOD B-2 (DIGITAL READING FROM APPLYING THE CORRECTION FACTOR BY USING THE $D_0 - D_{10}$ DIFFERENTIAL)

Visual ratings were performed by a three man panel on the graphical output. These ratings were analyzed in connection with Method A-1, A-2 and B-2, (as shown in Figures 32, 33, and 34. It appeared from this analysis that Methods A-1 and A-2 resulted in a large data scatter. Method B-2 resulted in the lowest variation. The exceptional variation in each of the three methods was experienced on the surface treatment pavements, indicating that texture still influenced the values obtained. Even though Method B-2 had the smallest variation, it appeared that readings around 70 to 100 inches per mile resulted in ratings from 10 to 48. It was postulated that the chart reading resulting from the D_0- D_{10} slope corrections (Method B-2) blanked out not only texture influences but desirable roughness measurements. By comparison, Method A-1 and A-2 reveals a desirable range in digital reading. It was noted that feasible texture corrections were obtained on the Surface Treatment pavements by the use of Method A-1.

Filter Band Study

Near completion of the "Blanking Band Study" Rainhart Company advised the Highway Department that a Ratchet Filter System had been devised for use with the digital output. In this system a ratchet was placed on the shaft activating the digital counters (See Figure 35). In general, the ratchet allowed vertical movements of a selected amount to be induced by the recorder wheel without movement of the digital counters. Upon close inspection it was noted that a band may be established around the peaks of the profile by using the ratchet system. The band was termed a Filter Band (see Figure 36). This system seemed feasible in that vertical movements induced by texture would result in small or no movements of the digital counters; however, if vertical movements greater than the Filter Band Size were found, the counter would move in relation to the roughness experienced. After this movement, the ratchet would again allow the small texture movements to be filtered.

It should be noted that the ratchet only permits the measurement of the upward vertical movements of the recording wheel. It must be assumed that a given profile will produce an equal amount of upward and downward excursions. However, both the blanking and filtering systems are similar in this respect. The reader is again reminded that the graphical output has not been affected by the changes made to the digital system.

The ratchet filter system was installed in the recorder of the profilograph and the first Filter Band was arbitrarily set at 0.10-inch. The 0.10-inch width was selected based on previous experience, especially with the use of various blanking bands, and after measuring the "hash" on several graphical charts.

Procedure. For an analysis of the filtered digital output, thirty one newly-constructed test sections were selected for study. The 0.2-mile sections consisted of 2 Surface Treatment, 6 Portland Cement Concrete and 23 Asphaltic Concrete surfaces. The profilograph was tested on each section and both digital and graphical data were collected. A tabulation of the digital measurements is given in Table VII.

As described previously visual ratings were performed on the graphical output by a three man panel. The rated profiles are revealed in Appendix C and the ratings are given in Table VII.

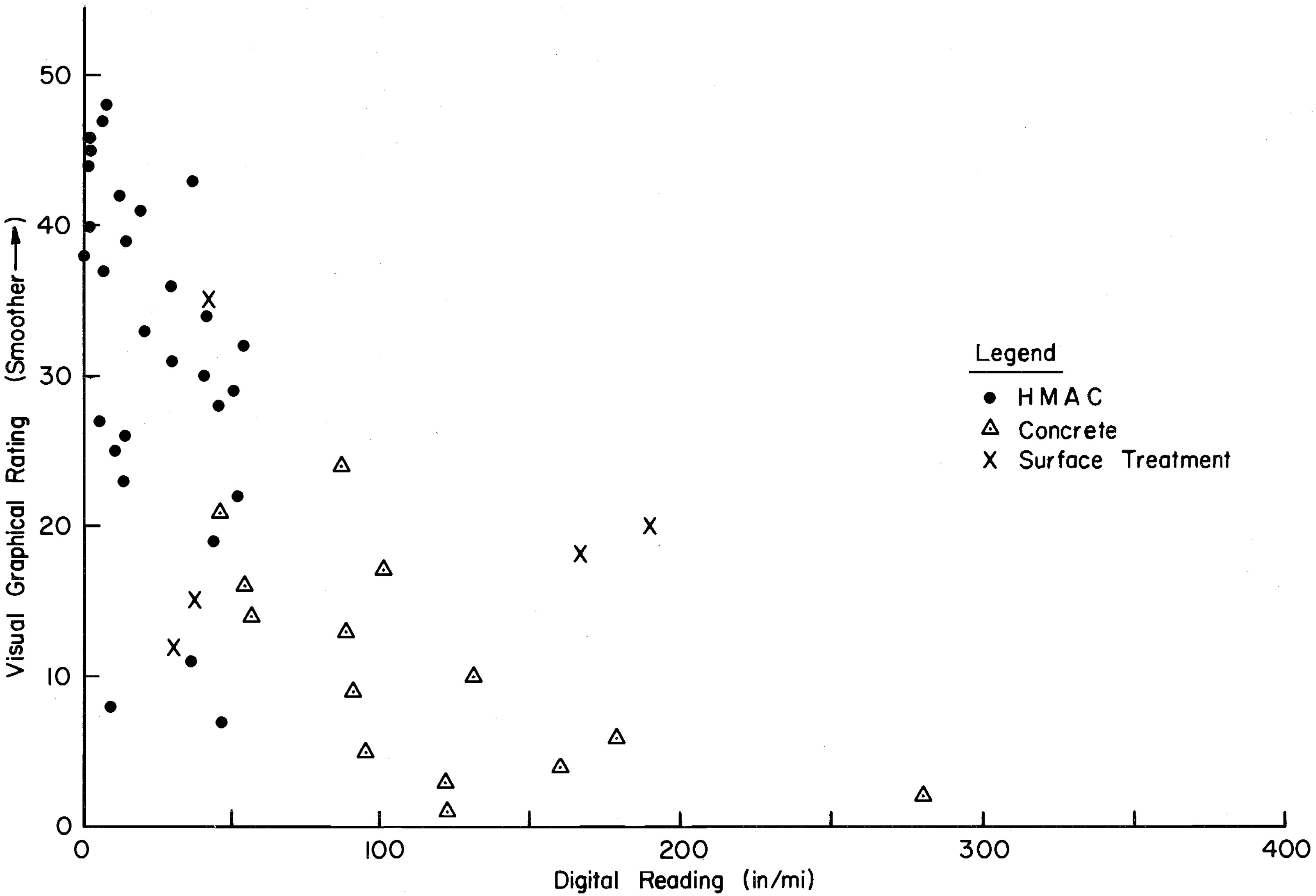
TABLE VII.

MEASUREMENTS ON NEWLY CONSTRUCTED PAVEMENTS USING THE FILTER BAND

	SECTION	READING	PAVEMENT TYPE
1	17-7	56.50	Conc.
2	17-6	60.50	Conc.
3	17-5	39.50	Conc.
4	17-2	30.50	Conc.
5	14-7	501.00	S.T.
6	17-3	33.00	Conc.
7	17-4	33.25	Conc.
8	17-1	17.00	Conc.
9	17-10	25.00	HMAC
10	8-7	23.75	HMAC
11	14-6	389.50	S.T.
12	17-12	19.50	HMAC
13	17-9	15.00	HMAC
14	8-6	14.25	HMAC
15	8-12	12.50	HMAC
16	8-14	15.00	HMAC
17	17-11	16.50	HMAC
18	8-5	17.50	HMAC
19	8-11	13.00	HMAC
20	14-2	10.75	HMAC
21	8-17	16.50	HMAC
22	8-8	16.50	HMAC
23	8-15	17.50	HMAC

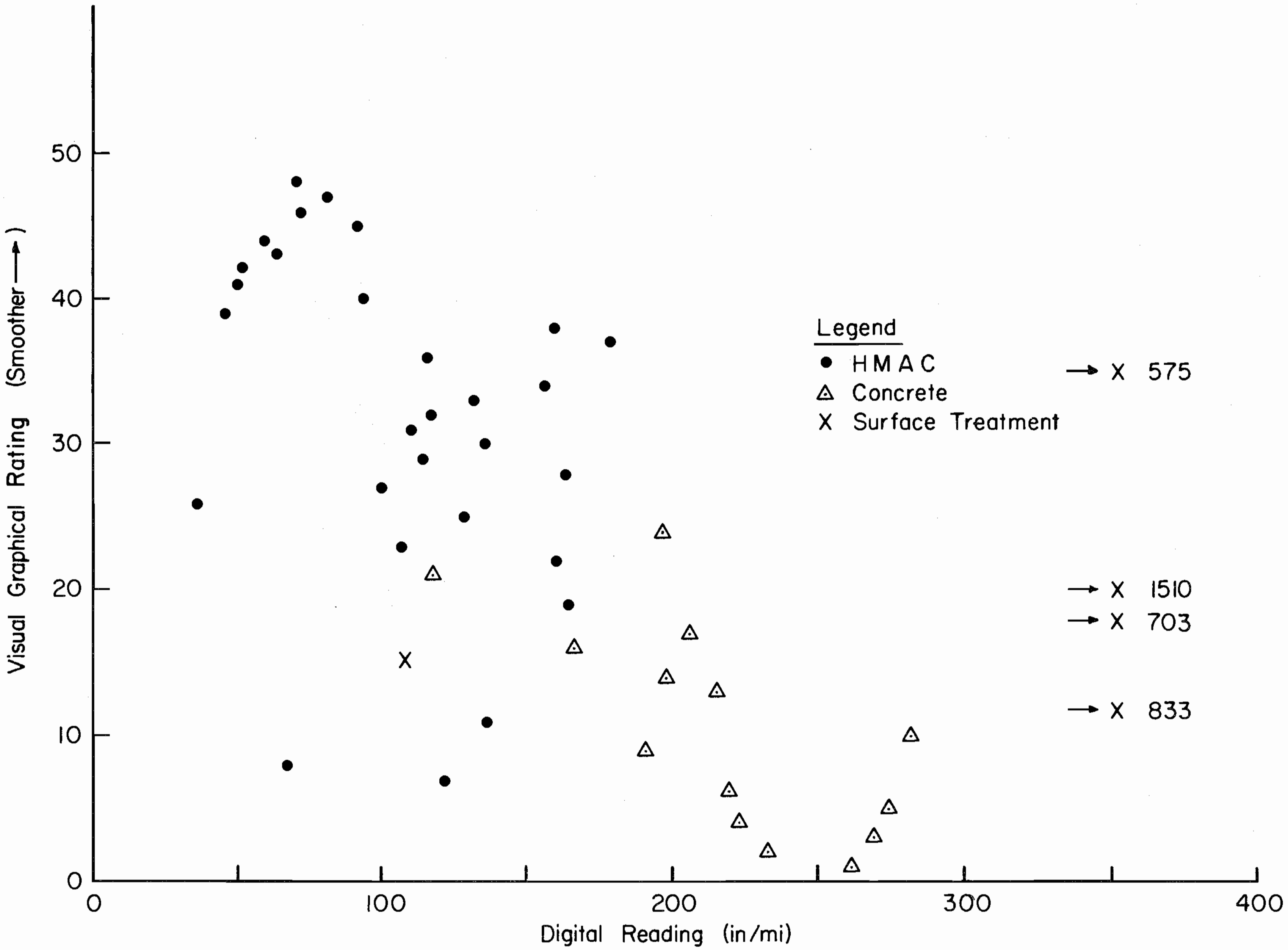
TABLE VII.
CONTINUED

	SECTION	READING	PAVEMENT TYPE
24	8-9	14.25	HMAC
25	14-3	23.00	HMAC
26	14-1	11.75	HMAC
27	8-13	14.25	HMAC
28	14-4	13.50	HMAC
29	8-10	18.50	HMAC
30	8-16	9.50	HMAC
31	8-1	10.75	HMAC



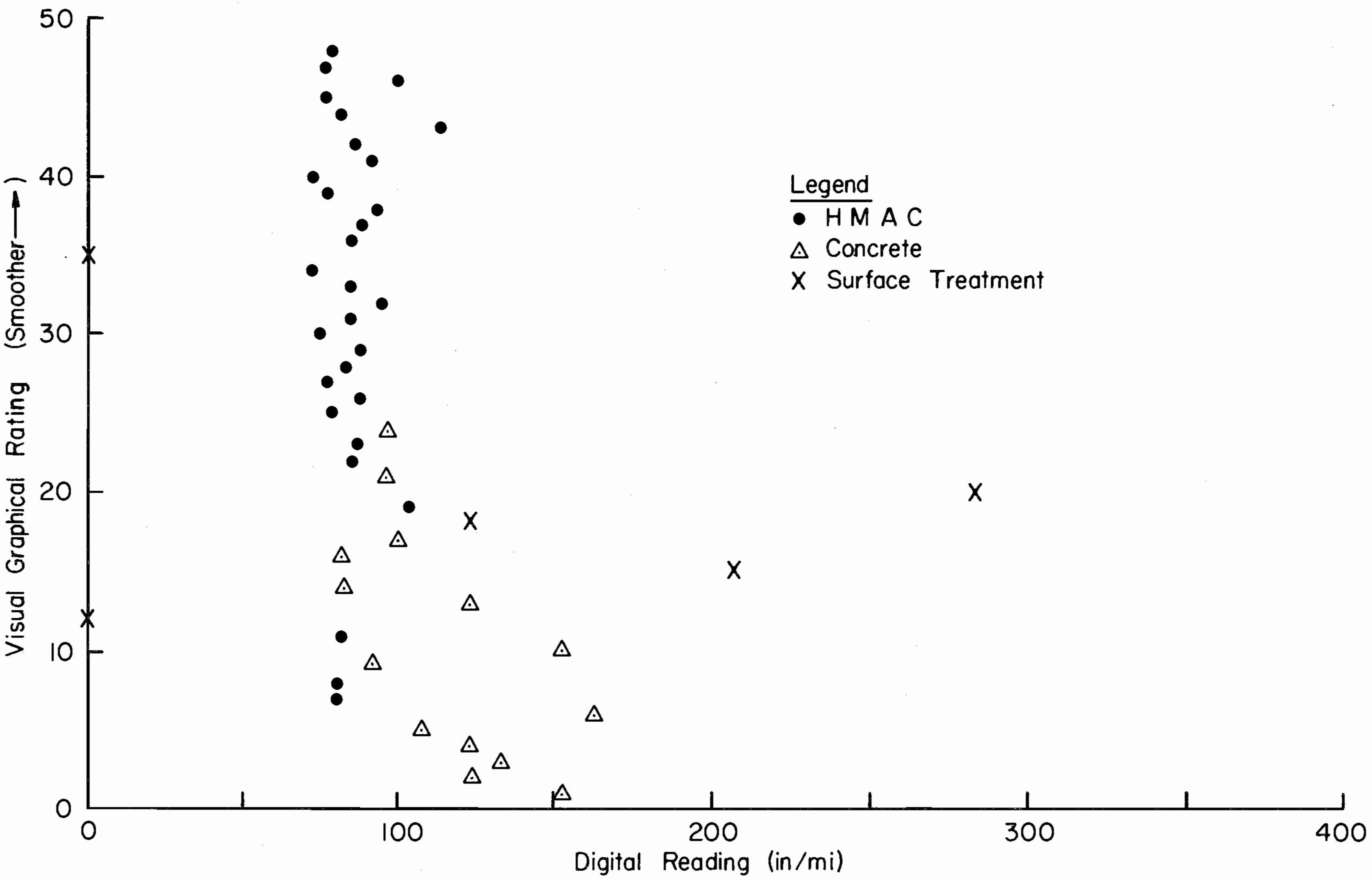
STUDY OF METHOD A-I ON NEWLY CONSTRUCTED PAVEMENTS

Figure 32



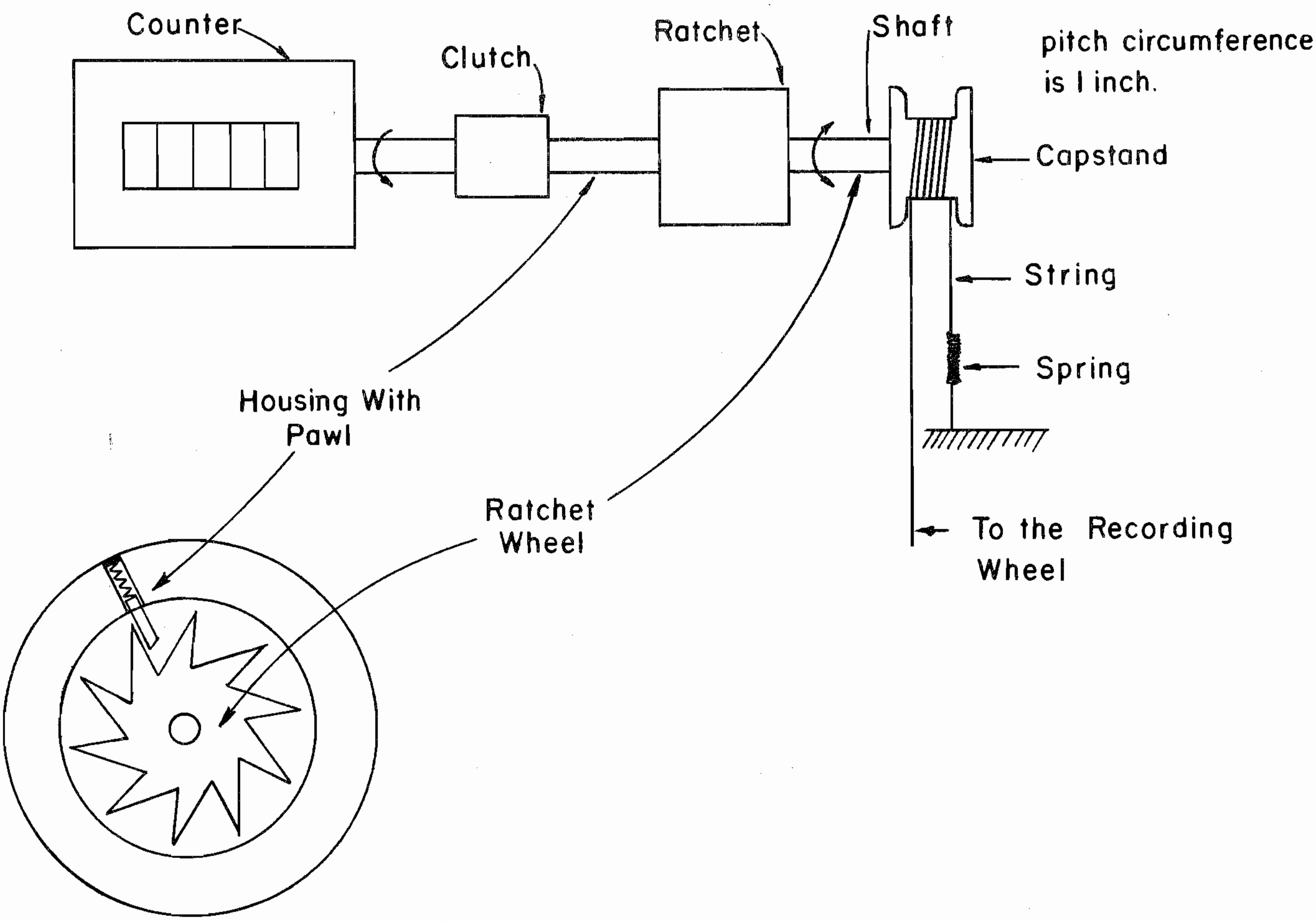
STUDY OF METHOD A-2 ON NEWLY CONSTRUCTED PAVEMENTS

Figure 33



STUDY OF METHOD B-2 ON NEWLY CONSTRUCTED PAVEMENTS

Figure 34

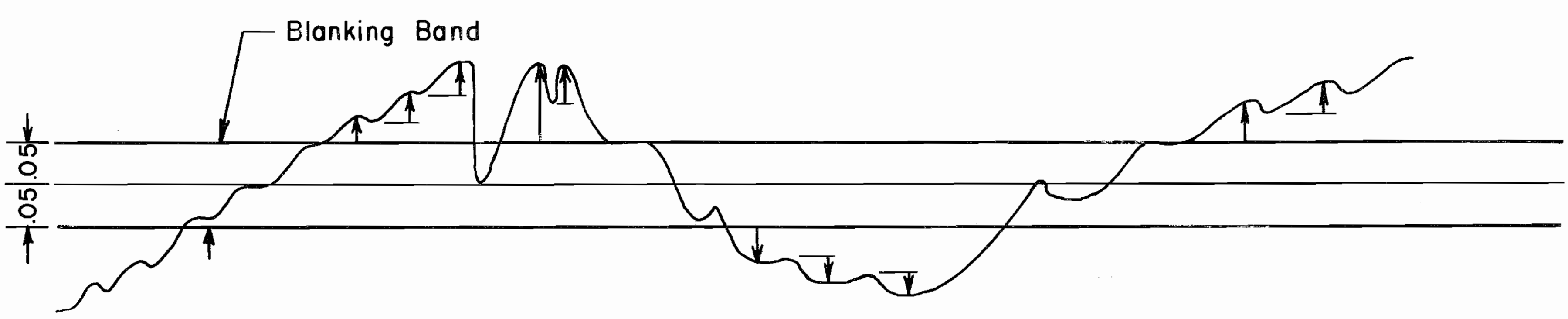


1 rev. = 1 inch. vertical motion
with 10 Teeth

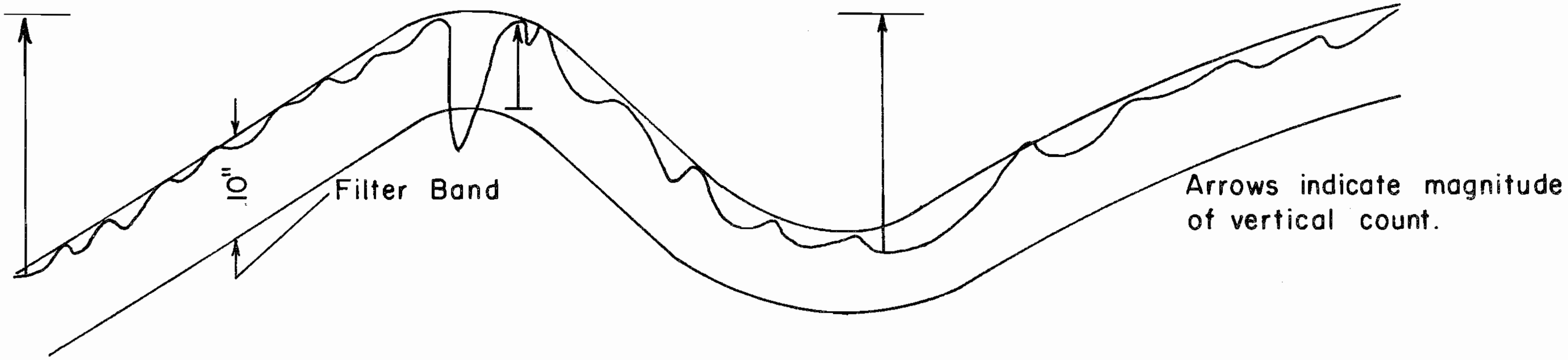
teeth Diff. = 0.1 in.

SCHEMATIC OF FINAL MODIFICATION
OF THE ROUGHNESS INDEX COUNTER

Figure 35



Blanking Principle



Arrows indicate magnitude of vertical count.

Filtering Principle

FIGURE 36 — COMPARISON OF BLANKING AND FILTERING PRINCIPLES

Analysis. Figure 37 is a plot of the visual graphical rating and the filtered digital reading. From this plot it appeared that the texture induced by the Surface Treatments still influenced the digital output. However, more consistent data was obtained on the Asphaltic and Portland Cement Concrete pavements. That is, the scatter or variation of points using the Filter Band was much less as compared to the scatter of points in the Blanking Band studies. The Surface Treatment pavements were omitted and a curve was placed through the remaining data points.

Assuming that a 50% improvement in construction roughness was desired, a horizontal line (M) was drawn through the midpoint of the visual graphical rating (15) to intersect the curve. A vertical line (N) was established at this intersection and a digital reading of 18 was found.

It must be assumed that the variation of data about the curve resulted from equipment and operational effects. It was believed that the contractor and contracting agency would eventually be concerned about this variation in data points. This problem was studied by analysing the four quadrants formed by lines M and N on Figure 37 as follows:

N

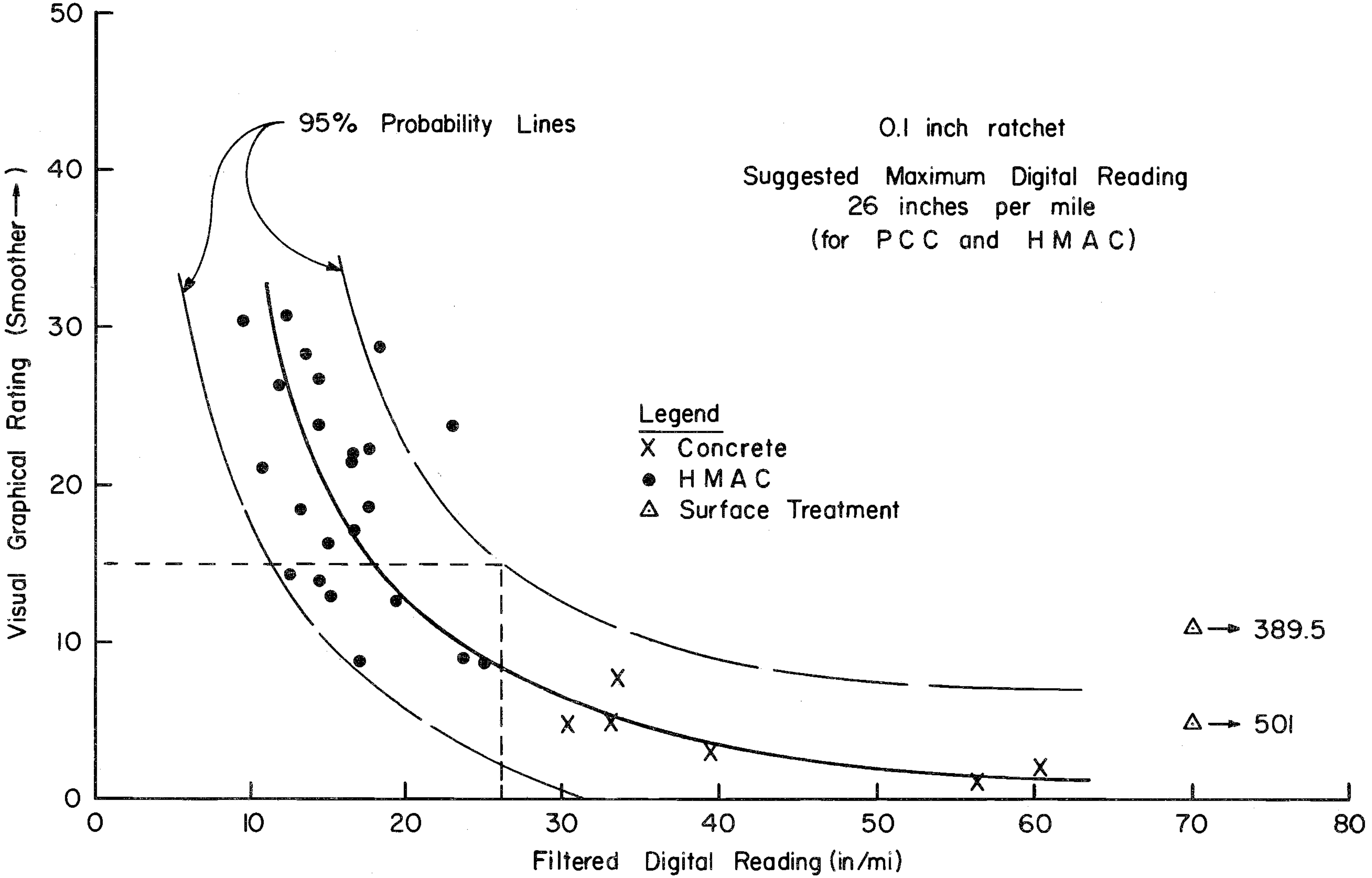
Satisfactory Low Digital Readings (Smooth) Large Visual Ratings (Smooth)	Contractor Penalized Large Digital Readings (Rough) Large Visual Rating (Smooth)
Low Digital Readings (Smooth) Low Visual Rating (Rough) Contracting Agency Penalized	Large Digital Readings (Rough) Low Visual Rating (Rough) Unsatisfactory

M

A close study of Figure 37 indicated that of the twenty nine sections tested, three sections fell in the lower left quadrant and two sections in the upper right quadrant.

Assuming that the contracting agency is responsible for the equipment and operating effects and to be sure that the contractor would not be penalized unnecessarily, a 95% confidence limit was established around the curve. That is, the "Standard Error" was calculated, 95% confidence limits were established, and the two curves drawn in at these confidence limits. Line M was extended to intercept the right most curve and Line P was constructed in a vertical manner at this point. The digital reading at Line P was found to be 26 inches per mile.

Therefore assuming that 50% improvement is desired, and the contractor will be penalized for the equipment and operating effect only 5% of the time, a specification could be based around a digital reading of 26 inches/mi.



0.1 inch ratchet

Suggested Maximum Digital Reading
26 inches per mile
(for PCC and HMAC)

STUDY OF VISUAL RATING AND DIGITAL OUTPUT USING FILTER BAND
Figure 37

Modifications to the Profilograph

Most of the testing with the profilograph had established a routine pattern at this point. Several features originally incorporated in the instrument had not been used or had been revised. It may be recalled that the recorder was fabricated with a vertical scale expansion for use with the graphical output. However, the three-to-one vertical scale expansion had not been used at this point primarily because the one to one graphical output is easier to visualize when observing the charts. Also the horizontal scale expansion had received little use since the 1"=10 ft had been used rather that the 1"=25 ft position.

The profilograph had originally been fabricated to operate bow or stern forward by reversing the recording mechanism with a clutch arrangement. By reversing the recording mechanism and steering the equipment in the opposite direction, repeat test could be obtained in the same path. But the operators found that when a repeat test was desired, the easiest method was to raise the profilograph to the road wheels, pick up the bow (hitch end), swing the instrument 180 degrees, lower the profilograph to the testing mode and begin the repeat test.

It was also found that the trailer hitch was very desirable for spot sampling. On one occasion, 0.2-mile tests were required every 2 miles. Testing was acomplished as follows: (1) at the completion of one spot test, the automobile was backed into position while the profilograph was being placed in the roading mode. (2) The instrument was hitched to the vehicle, (3) driven 1.8 miles to the beginning of the next test, (4) unhitched, (5) placed in the testing mode while the vehicle was removed and (6) testing again started. The time for a test was 15 minutes.

Because of these resulting work patterns the profilograph was modified as follows:

1. The graphical vertical scale expansion was removed and a one-to-one graphical output was utilized.
2. The graphical horizontal scale expansion was locked in the one inch to 10-foot position.
3. The recorder reversing mechanism was locked in the bow forward mode.
4. The stern forward steering wheel was removed.

As explained previously, a speedometer had been attached to the profilograph, the recorder had received the string modification, and the recorder had been modified with a ratchet system for use with the Filter Band. The profilograph had also been modified slightly to allow the instrument to be moved to different locations with the recorder in place. Previously, the recorder had been removed and stored in the tow vehicle when moving from one location to another. But by slinging the recording wheel to the frame, moves to various test locations was accomplished with the recorder in place. In fact, the recorder was mounted in the morning and not removed until evening.

Testing after this period was conducted with the bow forwarded, with one to one vertical output, and with one inch to 10-foot horizontal output.

V. Development of Suggested Specifications

At the time of this study, Texas Engineers were particularly impressed with the studies the California Division of Highways had accomplished with various profile measuring equipment. It should be stated that the background for much of this study and particularly the specifications was provided by reports from California. 2&3.

Attempts were made to develop a suggested specification for the control of construction roughness and this study is reported in this chapter. The specifications include (1) a maximum roughness index number, thereafter termed Profile Index (0.1 inch Filter Band), and (2) a maximum single deviation value per prescribed length.

Review of Current Specifications

A close review of the present "straight edge" specifications reveals the following:

Item	Portland Cement	Asphaltic Concrete
Straightedge length	10'	16'
The maximum ordinate from the straight edge	1/8"	1/4"
Maximum Deviation of the Surface From the Nearest Point of Straightedge Contact	1/16" per foot	1/16" per foot
Correction Specified	Any high spots causing a departure from the straightedge in excess of that specified shall be gound down by the Contractor to meet the surface test re-requirements.	Any point in the surface not meeting these requirements shall be immediately corrected.

One interesting point in the present specifications is Item 3 - the "Maximum Deviation of the Surface". If the interpretation of the specification is that the surface will not contain a deviation (slope) from the straight edge in excess of 1/16-inch per foot, a study would indicate that a "roughness index" is presently imposed. Calculations would reveal that roughness can be cumulated up to 165 inches per mile for both Portland Cement and Asphaltic Concrete Pavements. This assumes a maximum 1/8" deviation every 4 feet (1/16" per ft.) for concrete pavements and a maximum 1/4" deviation every 8 feet (1/16" per ft.) for ACP.

It is also interesting to note that only high spots are ground down on Portland Cement Concrete Paving because of the difficulty of treating low areas, where as, all deviations (not meeting the requirements) of asphaltic concrete are treated. However, rigid pavement appears to be subjected to a slightly greater restriction with the maximum ordinate from the straight edge.

Suggested Specifications

Based on information obtained in this study, the following suggested specification is offered for use with Portland Cement Concrete Pavements and Asphaltic Concrete Pavements:

Surface Test.

The Profile Index (0.1-inch Filter Band) as measured by the Construction Control Profilograph for any section of one-tenth mile, or less, shall not exceed the rate of 26 inches per mile along any path parallel to the edge of the pavement. If on any path of a section of one-tenth mile or less the Profile Index (0.1-inch Filter Band) exceeds 26 inches per mile, correction shall be made by the Contractor to provide the required Profile Index. The profile chart which has been appropriately designated as to location shall be made available to the Contractor for study before remedial procedures are attempted. Any deviation of the paved surface greater than 0.30-inch, within a 25-foot length of pavement, as measured from the profile chart, shall be corrected by the Contractor. If the daily average of the profile indexes, measured along paths approximately 3.0 feet from the edges of each traffic lane, before correction, exceed the rate of 26 inches per mile for any 3 consecutive working days, the paving operations shall be discontinued until suitable equipment and methods are provided by the contractor and approved by the Engineer.

Suggested Test Method

This test method describes the procedure for determining the roughness tolerance for newly constructed asphaltic concrete and Portland Cement concrete pavements.

Apparatus

Construction Control Profilograph

Test Sections

The test sections shall consist of the surfaces of Portland Cement Concrete pavement or Asphaltic Concrete pavement. The surfaces shall be tested as soon as practicable after placement and before opening to traffic.

Procedure

After the profilograph has been placed in the testing mode and correctly positioned in any path parallel to the edge of the roadway, the beginning point shall be noted on the graph along with pertinent location and identification information. The digital counters shall be set to zero and the profilograph shall be operated along the chosen path. The digital output shall be recorded on the "Test Record Form" at each 0.1-mile interval, or portion thereof, and an identifying mark shall be recorded on the graph at 0.1-mile intervals.

Digital Output.

An example of the recorded digital output for a 0.35-mile section is as follows:

Section Length (miles)	Digital Counter Reading (inches)	Profile Index (0.1-inch Filter Band) (inches/mile)
0.10	2.0	20
0.10	2.8	28
0.10	2.3	23
0.05	1.1	22

Graphical Output

Each prominent peak or high point of the profile shall be studied by positioning a 2-1/2-inch straight edge (25 feet) along the profile line (not neccessarily horizontally) at the base of the peak. Each end of the straight edge should touch the profile line on each side of the peak. Furthermore, one end could touch the profile on one side of the peak and the other contact with the profile may be at any point along the straight edge. The straight edge shall be positioned such that the maximum perpendicular distance from the straight edge to the peak is obtained. The station number, as scaled from the graph, of any perpendicular distance in excess of 0.3-inch shall be recorded on the Test Record Form.

Calculation

The Profile Index (0.1-inch Filter Band) is determined from the digital output as follows:

$$\text{Profile Length (Miles)} = \frac{\text{Distance Tested (Feet)}}{5280\left(\frac{\text{Feet}}{\text{Mile}}\right)}$$

$$\text{Profile Index (0.1-inch Filter Band)} = \frac{\text{Digital Output (Inches)}}{\text{Profile Length (Miles)}} \times 1 \text{ (Mile)}$$

Test Record Form

District________ County________ Project No.________ Hwy.________

Contractor________ Date of Test________ Operator________

Lane Tested________

Path______

Beginning Station Number______

Section (feet)	Length (miles)	Digital Counter Reading (inches)	Profile Index 0.1-inch Filter Band (inches/mile)

Ending Station Number______

Path______

Beginning Station Number______

Section (feet)	Length (miles)	Digital Counter Reading (inches)	Profile Index 0.1-inch Filter Band (inches/mile)

Ending Station Number______

Station Numbers of Deviations Greater than 1/8 Inch

Path____ ______ ______ ______ ______ ______ ______ ______

Path____ ______ ______ ______ ______ ______ ______ ______

Sheet____ of____

Discussion of Suggested Test Method

Several comments should be made concerning the suggested test method:

1. The intent of the Specification and test procedure was to obtain at least two profiles in each traffic lane, preferably in the wheel paths.
2. It was intended that the full length of each construction job be tested.
3. It was found that the curing compound used on Portland Cement Concrete Pavements clings to the profilograph wheels when these pavements are tested on the day after placement. The cumulation of curing compound on the profilograph wheels could cause distorted roughness output. It is suggested that some time period be allowed before testing, in order that the curing compound may dry.
4. Loose aggregate or pebbles on the surface have been found to alter the roughness output. It was suggested that the profilograph be tested on a surface free of debris.
5. It is suggested that an average Profile Index, (after correction, if any) for the whole construction job be obtained for the project files.

VI. SUMMARY OF RESULTS

The results of this research study may be summarized as follows:

1. The Rainhart Profilograph has been found to be well designed, rugged equipment which is well adapted for field use.
2. In addition to the proposed use, benefit has been and is expected from special studies which may be conducted by design, construction and maintenance personnel.
3. The profilograph graphical output has been compared with a rod and level profile with excellent results.
4. The graphical and digital output have been correlated and the following linear equation produced.

   $Y = 4.83 + 1.0081\ X$
   Where Y is the Chart Reading and X is the digital reading.
   The correlation coefficient was 0.993.

5. The equipment produces repeatable graphic output, both on different days and on the same day. However, little work was accomplished on the repeatability of the digital output and no work was done with the repeatability of the digital output in the final design. Since the graphic output was repeatable and correlation was found between the graphic output and the digital output (Do) it is assumed that the filtered digital output has approximately the same repeatibility characteristics as the graphic output.
6. It was found that there is no difference in operators (that is, any personnel may operate the equipment), the equipment may be operated bow or stern forward without correction factors (in the final design the equipment was operated only bow forward), and the equipment may be operated uphill or downhill without correction factors.
7. Operating speed was found to affect the digital output. A string modification and a speedometer were installed in the equipment. A constant speed of one mph was selected as the test speed.
8. Efforts were made to eliminate the influence of surface texture in the roughness results and reasonable success was found.
9. Data was collected on three pavement types and a suggested specification of the control of construction roughness resulted.

VII. DISCUSSION AND CONCLUSIONS

The primary objective of this study was to develop suitable equipment for the control of construction roughness. It is believed that suitable equipment has been developed. As in almost every case, there are needed features which cannot be included in singular equipment. Therefore, the following features are listed for review.

The profilograph should fulfill the requirements for field use since:

1. Repair parts may be found locally.
2. The unit may be stored in the open (with the exception of the recorder which may be detached if necessary).
3. The unit may be moved from site to site quickly and be made ready for testing in a short time period.
4. The output is either a graphical trace (which may be maintained for reference) or digital (which provides a quick field answer).
5. Areas of the surface which are to be treated may be found on the graphic output by referencing the initial point on the trace to ground control. Improvements may be noted by retesting in the same path.
6. The equipment cannot detect roughness with wave lengths greater than around 25 feet.
7. The equipment is operated manually and is therefore slow in comparison to other equipment. (Several Districts have made inquiry about motorization of the unit.)

Considerable time has been devoted in this project in the study of an item which the authors refer to as "surface texture". Partial redesign of the equipment was made in order to eliminate surface texture from other roadway roughness. This attempt was not completely successful because it was found that the influence of texture still exists in Surface Treatments or penetration pavement types. However, it was found that the influence of the smaller texture was eliminated by using the filter band. Therefore it was assumed that test conducted on surfaces such as Asphaltic Concrete and Portland Cement Concrete are virtually texture free.

Attempts were made to analyze the texture of Surface Treatment Pavements by counting the number of smaller (texture) peaks in a given length. In almost every case it was found that some 3 to 4 peaks were present in a one-foot interval of profile length. Since Surface Treatments in Texas use aggregates of 3/4 - inch size or less (most are around 3/8 - 1/2 inch), theory would suggest the profile of the texture should contain some 16 to 24 peaks per inch. There was, therefore a difference in the test and in the expected. It was postulated that this difference was caused by the averaging wheels. That is, at one increment of time the averaging wheels averaged out the texture and at another increment of time the averaging wheels caused vertical movement at the recorder (in the form of a texture peak). The vertical displacement of texture varied from zero to approximately 1/8-inch. Thus the implication is-whether or not vertical excursions of up to 1/8-inch at longitudinal cycles of 3 to 4 inches should be included as pavement roughness. Based on this study, it must be stated that:

1. Texture does influence pavement roughness measurements and can be noted on the profile charts in various amplitudes which are dependent on the size of texture encountered.
2. It is not known whether the texture influence should be included in roughness measurements, but attempts have been made to eliminate this influence in the final design of the equipment (for Asphaltic Concrete and Portland Cement Concrete pavements).

A suggested specification has been developed which is believed to be based on sufficient testing. The problem becomes one of estimating the degree of improvement sought and establishing a specification which is dependent on this estimation. A specification should be dependent on pavement structure performance data (with particular emphasis on the performance of pavement structures which are subjected to impact loads). Such information is not available. Therefore, the specification which is suggested is based on a 50% improvement in the existing surfaces (See Figure 37). It should be recalled that the rating in Figure 37 was from a visual inspection of the graphical output. To protect the contractor a 95% confidence level was used in connection with the data scatter. It could be assumed that in only 5% of the cases would the profilograph indicate axcessive digital readings when the actual condition of the surface was above tolerance.

It also should be noted that the specification is for Asphaltic Concrete and Portland Cement Concrete. It is believed that further study would reveal a filter band size which could be used for Surface Treatments and even for the prepared base material.

VIII. RECOMMENDATIONS FOR CONTINUATION AND APPLICATION

During the course of this project opportunity was presented to talk to personnel from several Districts concerning the use of this equipment. It was somewhat surprising to learn that most field personnel desired to use the profilometer to assist contractors in the improvement of construction. That is, rather than imposing a roughness tolerance, most field personnel desired (1) information which would allow them to determine a tolerable roughness level, but (2) use the profilograph to assist the contractor in meeting this level. For example, the Construction Control Profilograph would be tested on the flexible base before the seal or asphaltic concrete pavement and rough areas would be worked out before the application of the wearing surface. In concrete paving, continuous checks would be made of the previous days placement, and the State Construction Staff would set down with the contractor's personnel and decide methods of improving the surface roughness if applicable.

Based on this information and discussions with other administrative personnel the following recommendations for the continuation and application of this project are offered:

1. At least three profilographs be placed in three various Districts.
2. The equipment will be used by each District and tests with sufficient records be performed and maintained.
3. Depending on District desires a roughness specification may (or may not) be used and changed with each construction job as knowledge is gained.
4. At the completion of a certain time period (suggested as two years) the recommendations for the use of equipment and specifications of each District will be forwarded to all Districts for comment. Further recommendations will be based on these comments.

BIBLIOGRAPHY

(1) Scrivner, F.H. and Moore, W.A., "A Tentative Flexible Pavement Design Formula and Its Research Background" Research Report 32-7, Research Study 2-8-62-32, Texas Transportation Institute, February 1966.

(2) Materials and Research Department, "Evaluation of Profiles", Test Method No. Calif. 526-C, California Division of Highway, July 1963.

(3) Hveem, F.M., "Devices for Recording and Evaluating Pavement Roughness", January 1960.

APPENDIX A

Analysis of Variance of the Treatment Study

ANALYSIS OF VARIANCE
STUDY OF OPERATORS, EQUIPMENT AND PAVEMENT GRADE
SECTION P

Treatment Combination	Reading #1	Reading #2	Diff.	Diff.^2	Treatment	$(\text{Treatment Total})^2$	Col. 1 B. vs. S.	Col. 2 U. vs. D	Col. 3 1. vs. 2.	Col. 4 is Col. 1 x Col. 2	Col. 5 is Col. 1 x Col. 3	Col. 6 is Col. 2 vs. Col. 3	Col. 7 is Col. 1 vs. Col. 2 vs. Col. 3
BU1	64.90	68.50	3.60	12.96	133.40	17,795.56	1	1	1	1	1	1	1
BU2	64.20	64.20	0.00	0.00	128.40	16,486.56	1	1	-1	1	-1	-1	-1
BD1	67.20	67.70	0.50	0.25	134.90	18,198.01	1	-1	1	-1	1	-1	-1
BD2	67.00	62.80	1.20	1.44	126.80	16,078.24	1	-1	-1	-1	-1	1	1
SU1	64.40	64.20	0.20	0.04	128.60	16,537.96	-1	1	1	-1	-1	1	-1
SU2	64.10	70.70	6.60	43.56	134.80	18,171.04	-1	-1	1	-1	1	-1	1
SD1	69.70	64.50	5.20	27.04	134.20	18,009.64	-1	-1	1	1	-1	-1	1
SD2	64.10	60.10	4.00	16.00	124.20	15,425.64	-1	-1	-1	1	1	1	-1
				101.29	1045.3	136,702.65	Fc = .03	Fc = .26	Fc = 2.82	Fc = .24	Fc = .85	Fc = 3.67	Fc = 1.70

$$\text{Total } R_{error} = \frac{\text{Sum. Diff.}^2}{2} = \frac{101.29}{2} = 50.645$$

Number of Treatment Combinations = 8

$$\text{M.S.} = \frac{50.645}{8} = 6.33$$

$$\text{SSBT} = \frac{\text{Sum } (\text{TT}^2)}{2} - \frac{(\text{Sum TT})^2}{2\text{N}}$$

$$\text{SSBT} = \frac{136{,}702.65}{2} - \frac{(1045.3)^2}{16} = 60.57$$

$$\text{MSBT} = \frac{\text{SSBT}}{\text{DF}} = \frac{60.57}{7} = 8.65$$

$$\text{Fc} = \frac{8.65}{6.33} = 1.37$$ (Overall Variation)

$$\text{F}_t = \frac{7\ \text{DF}}{8\ \text{DF}} = 3.50$$ at a = 0.05

$\text{F}_c \quad \text{F}_t$ No Significance

B - Bow Forward
S - Stern Forward
U - Positive Grade
D - Negative Grade
1 - Operator 1
2 - Operator 2

$$\text{SSBT}_{(\text{Col. 1})} = (133.4 + 128.4 + 134.9 + 126.8 - 128.6 - 134.8 - 134.2 - 124.2)^2 + 16$$

$$= (1.7)^2 \div 16$$

SSBT = .18

$$\text{Fc} = \frac{.18}{6.33} = .03$$

$$\text{SSBT}_{(\text{Col. 2})} = (133.40 + 128.40 - 134.90 - 126.80 + 128.60 + 134.80 - 134.20 - 124.20)^2/16$$

$$= (5.1)^2 \div 16$$

SSBT = 1.63

$$\text{Fc} = \frac{.26}{6.33} = .26$$

$\text{SSBT}_{(\text{Col. 3})} = 17.85$

$\text{SSBT}_{(\text{Col. 4})} = 1.50$

$\text{SSBT}_{(\text{Col. 5})} = 5.41$

$\text{SSBT}_{(\text{Col. 6})} = 23.28$

$\text{SSBT}_{(\text{Col. 7})} = 10.73$

$\text{SSBT} = \text{SSBT}_{(\text{Col. 1-7})}$

SSBT = .18 + 1.63 + 17.85 + 1.50 + 5.41 + 23.28 + 10.78

SSBT = 60.57

$$\text{F}_t = \frac{1\text{DF}}{8\text{DF}} = 5.32$$

ANALYSIS OF VARIANCE
STUDY OF OPERATORS, EQUIPMENT AND PAVEMENT GRADE
SECTION I

Treatment Combination	Reading #1	Reading #2	Diff.	Diff.^2	Treatment Total	$(\text{Treatment Total})^2$	Col. 1 B. vs. S.	Col. 2 U. vs. D.	Col. 3 1. vs. 2	Col. 4 is Col. 1 vs. Col. 2	Col. 5 is Col. 1 vs. Col. 3	Col. 6 is Col. 1 vs. Col. 3	Col. 7 is Col. 1 x Col. 2 x Col. 3
BU1	19.55	17.00	2.55	6.50	36.55	1,335.90	1	1	-1	1	1	1	1
BU2	22.80	17.70	5.10	26.01	40.50	1,640.25	1	1	-1	1	-1	-1	-1
BD1	21.00	20.80	0.20	0.04	41.80	1,747.24	1	-1	1	-1	1	-1	-1
BD2	22.75	19.30	3.45	11.80	42.05	1,768.20	1	-1	-1	-1	-1	1	1
SU1	19.70	20.55	0.85	0.72	40.25	1,620.06	-1	1	1	-1	-1	1	-1
SU2	22.15	20.50	1.65	2.62	42.65	1,819.02	-1	1	-1	-1	1	-1	1
SD1	21.85	21.10	0.75	0.56	42.95	1,844.70	-1	-1	1	1	-1	-1	1
SD2	18.55	19.60	1.05	1.11	38.15	1,455.42	-1	-1	-1	1	1	1	-1
				49.36	324.90	13,230.79	Fc = 0.20	Fc = 0.50	Fc = 0.06	Fc = 1.50	Fc = 0.90	Fc = 2.40	Fc = 0.20

$$\text{Total } R_{error} = \frac{\text{Sum }(\text{Diff}^2)}{2} = \frac{49.36}{2} = 24.68$$

Number of Treatment Combinations = 8

$$MS = \frac{24.68}{8} = 3.09$$

$$SSBT = \frac{\text{Sum}(TT^2)}{2} - \frac{(\text{Sum } TT)^2}{2n}$$

$$SSBT = \frac{13230.79}{2} - \frac{(324.9)^2}{16} = 17.89$$

$$NSBS = \frac{SSBT}{DF} = \frac{17.89}{7} = 2.56$$

$$F_c = \frac{2.56}{3.09} = .83 \text{ (Overall Variation)}$$

$$F_t = \frac{7 \text{ DF}}{8 \text{ DF}} = 3.50 \quad \text{at } a = 0.05$$

F_c F_t No significance

B - Bow Forward
S - Stern Forward
U - Positive Grade
D - Negative Grade
1 - Operator 1
2 - Operator 2

$$SSBT_{(\text{Col. } 1)} = (36.55 + 40.50 + 41.80 + 42.05 - 40.25 - 42.65 - 42.65 - 42.95 - 38.15)^2 \div 16$$

$$= (-3.10)^2 \div 16$$

$$SSBT_{(\text{Col. } 1)} = .60$$

$$F_c = \frac{.60}{3.09} = 0.19$$

$$SSBT_{(\text{Col. } 2)} = 1.56$$

$$SSBT_{(\text{Col. } 3)} = 0.20$$

$$SSBT_{(\text{Col. } 4)} = 4.62$$

$$SSBT_{(\text{Col. } 5)} = 2.72$$

$$SSBT_{(\text{Col. } 6)} = 7.42$$

$$SSBT_{(\text{Col. } 7)} = 0.76$$

$$SSBT = SSBT_{(\text{Col. } 1\text{-}7)}$$

$$SSBT = .60 + 1.56 + 0.20 + 4.62 + 2.72 + 7.42 + 0.76$$

$$SSBT = 17.88$$

$$F_t = \frac{1 \text{ DF}}{8 \text{ DF}} = 5.32$$

ANALYSIS OF VARIANCE
STUDY OF OPERATORS, EQUIPMENT AND PAVEMENT GRADE
SECTIONS P AND I

Treatment Combination	Reading #1	Reading #2	Diff.	Diff.^{2}	Treatment Total	(Treatment Total)^2 #1	Col. 8 B. vs. S.	Col. 9 U. vs. D.	Col. 10 1. vs. 2.	Col. 11 B. vs. S. x U. vs. d.	Col. 12 B. vs. S. x 1. vs. 2	Col. 13 U. vs. D x 1. vs. 2.	Col. 14 B vs. S. x U vs. D x 1 vs. 2	Col. 15 P vs. I	Col. 16 P vs. I x B vs S	Col. 17 P vs. I x U vs D	Col. 18 P vs. I x 1 vs 2	Col. 19 P vs. I x B vs S x U vs D	Col. 20 P vs I x b vs S x 1 vs 2	Col. 21 P vs I x U vs D x 1 vs 2	Col. 22 P vs I x U vs D x 1 vs 2
PBU1	64.90	68.50	3.60	12.96	133.40	17,795.56	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
PBU2	64.20	64.20	0.00	0.00	128.40	16,486.56	1	1	-1	1	-1	-1	-1	1	1	1	-1	1	-1	-1	-1
PBD1	67.20	67.70	0.50	0.25	134.90	18,198.01	1	-1	1	-1	1	-1	-1	1	1	-1	1	-1	1	-1	-1
PBD2	64.00	62.80	1.20	1.44	126.80	16,078.24	1	-1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1	1	1
PSU1	64.40	64.20	0.20	0.04	128.60	16,537.96	-1	1	1	-1	-1	1	-1	1	-1	1	1	-1	-1	1	-1
PSU2	64.10	70.70	6.60	43.56	134.80	18,171.04	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
PSD1	69.50	64.50	5.20	27.04	134.20	18,009.64	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1
PSD2	64.10	60.10	4.00	16.00	124.20	15,425.64	-1	-1	-1	1	1	1	-1	1	-1	-1	-1	1	1	1	-1
IBU1	19.55	17.00	2.55	6.50	36.55	1,335.90	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1
IBU2	22.80	17.70	5.10	26.01	40.50	1,640.25	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	1	1	1
IBD1	21.00	20.80	0.20	0.04	41.80	1,747.24	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	1	-1	1	1
IBD2	22.75	19.30	3.45	11.80	42.05	1,768.20	1	-1	-1	-1	-1	1	1	-1	-1	1	1	1	1	-1	-1
ISU1	19.70	20.55	0.85	0.72	40.25	1,620.06	-1	1	1	-1	-1	1	-1	-1	1	-1	-1	1	1	-1	1
ISU2	22.15	20.50	1.65	2.62	42.65	1,819.02	-1	1	-1	-1	1	-1	1	-1	1	-1	1	1	-1	1	-1
ISD1	21.85	21.10	0.75	0.56	42.95	1,844.70	-1	-1	1	1	-1	-1	1	-1	1	1	-1	-1	1	1	-1
ISD2	18.55	19.60	1.05	1.11	38.15	1,455.42	-1	-1	-1	1	1	1	-1	-1	1	1	1	-1	-1	-1	1
				150.65	1370.20	149,933.44	Fc = 0.01	Fc = 0.00	Fc = 1.51	Fc = 1.21	Fc = 0.05	Fc = 6.05	Fc = 1.83	Fc=3,444.77	Fc = 0.15	Fc = 0.68	Fc = 2.32	Fc = 0.09	Fc = 1.49	Fc = 0.47	Fc=0.61

Total $R_{error} = \frac{\text{Sum (Diff}^2)}{2} = \frac{150.65}{2} = 75.325$

Number of treatment Combinations = 16

$$MS = \frac{75.325}{16} = 4.708$$

$$SSBT = \frac{\text{Sum }(TT^2)}{2} - \frac{(\text{Sum }TT)^2}{2n}$$

$$SSBT = \frac{149{,}933.44}{2} - \frac{(1370.20)^2}{32}$$

$$SSBT = 74{,}966.72 - 58{,}670.25 = 16{,}296.47$$

$$MSBT = \frac{SSBT}{DF} = \frac{16{,}296.47}{15} = 1086.43$$

$$Fc = \frac{MSTB}{MS} = \frac{1086.43}{4.71} = 230.66$$

$$F_t = \frac{15D^F}{16DF} = 2.35 \quad \text{at } a = 0.05$$

$Fc. = F_t$ Highly Significant

B - Bow Forward
S - Stern Forward
U - Positive Grade
D - Negative Grade
1 - Operator 1
2 - Operator 2

$$SSBT_{(Col.\ 8)} = (133.40 + 128.40 + 134.90 + 126.80 - 128.60 - 134.80 - 134.20 - 124.20 + 36.55 + 40.50 + 41.80 + 42.05 - 40.25 + 42.65 - 49.95 - 38.15)^2 \div 32$$

$$SSBT_{(Col.\ 8)} = (1.40)^2/32 = 0.06$$

$$Fc = 0.06/4.708 = 0.01$$

$SSBT_{Col.\ 9} = 0.00$
$SSBT_{Col.\ 10} = 7.13$
$SSBT_{Col.\ 11} = 5.70$
$SSBT_{Col.\ 12} = 0.23$
$SSBT_{Col.\ 13} = 28.50$
$SSBT_{Col.\ 14} = 8.61$
$SSBT_{Col.\ 15} = 16{,}218.00$
$SSBT_{Col.\ 16} = 0.72$
$SSBT_{Col.\ 17} = 3.19$
$SSBT_{Col.\ 18} = 10.93$
$SSBT_{Col.\ 19} = 0.43$
$SSBT_{Col.\ 20} = 7.00$
$SSBT_{Col.\ 21} = 2.21$
$SSBT_{Col.\ 22} = 2.88$

$$SSBT = SSBT_{(Col.\ 8\text{-}22)}$$

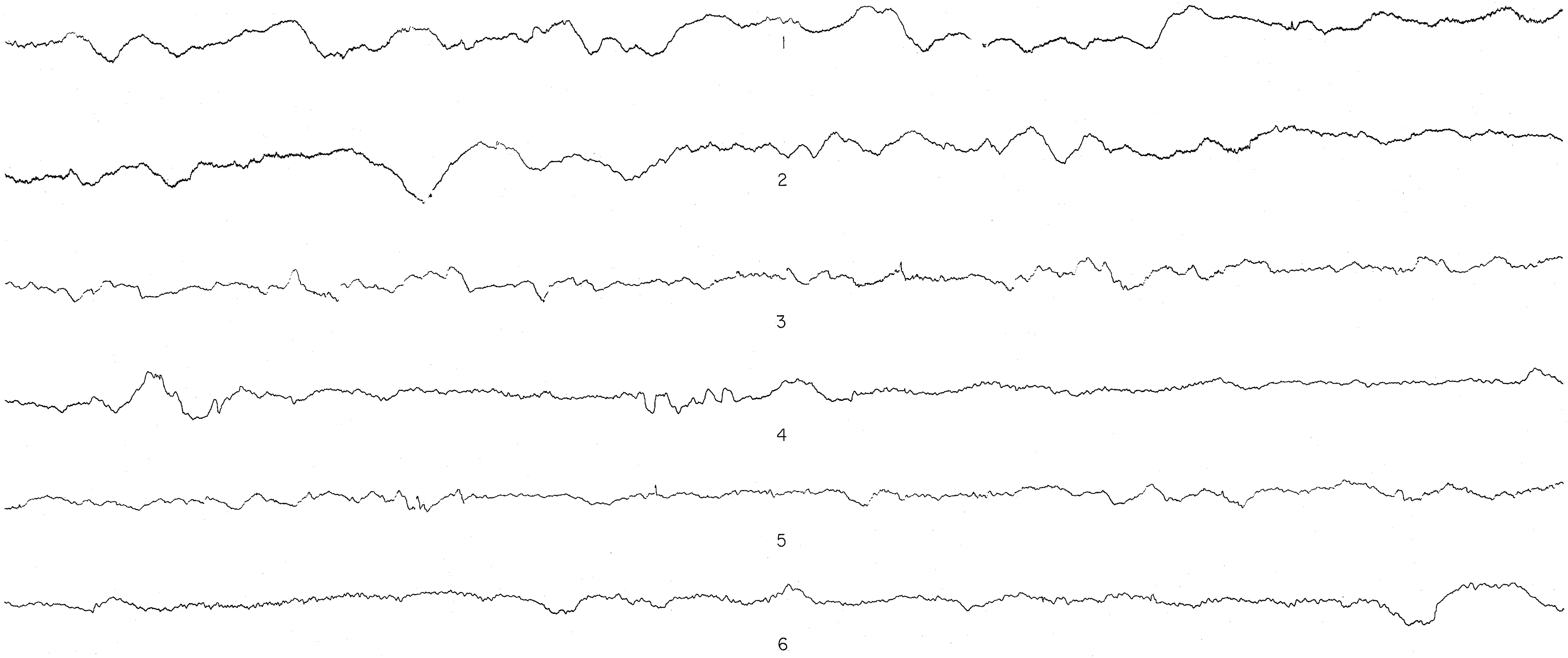
$$SSBT = 16{,}295.59$$

$$Ft = \frac{1DF}{16\ DF} = 4.49$$

APPENDIX B

Visually Rated Profiles

Blanking Band Study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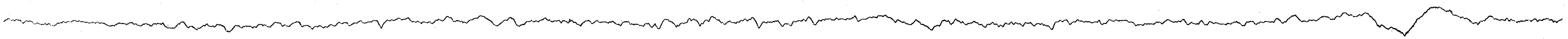

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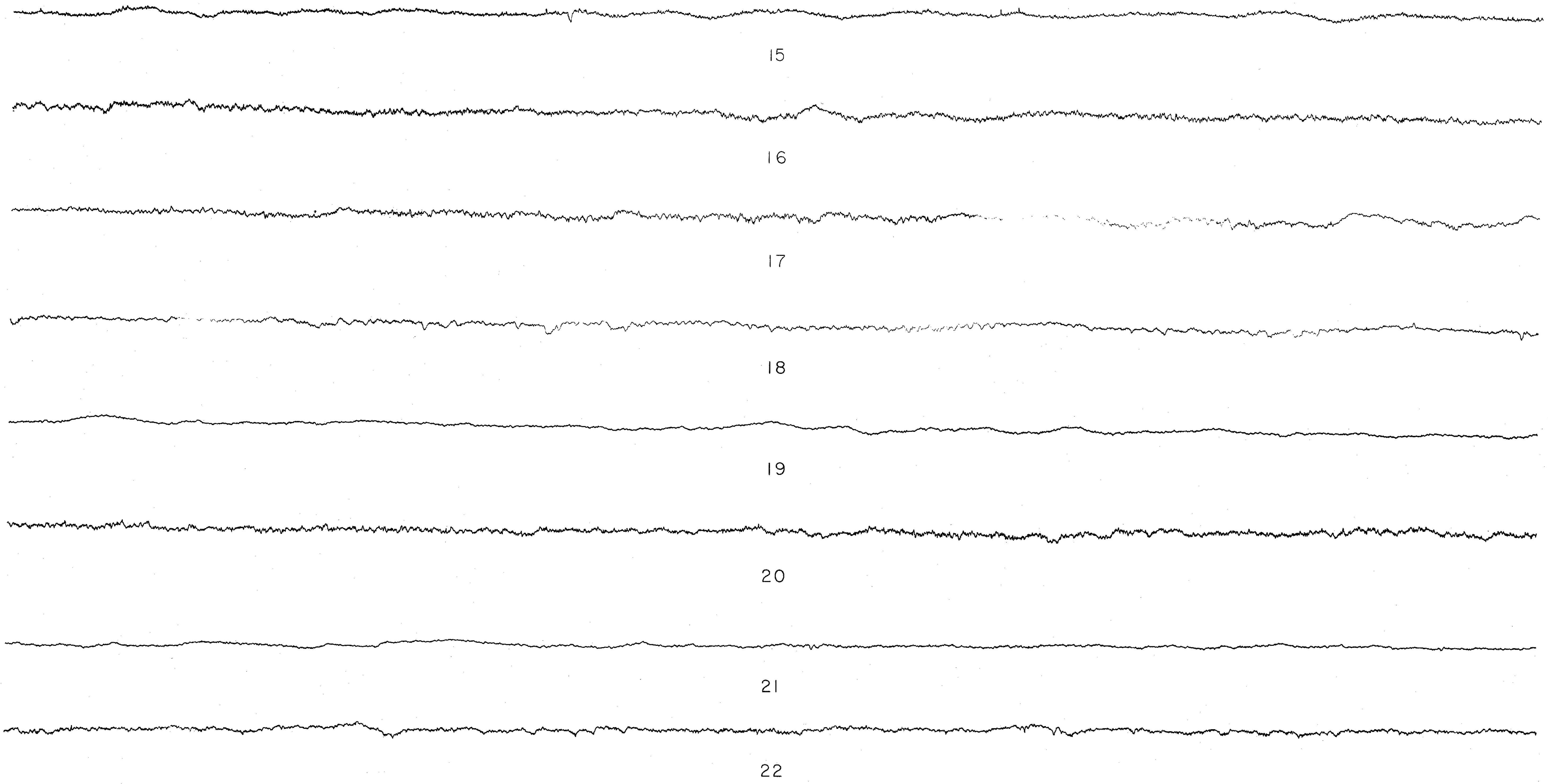
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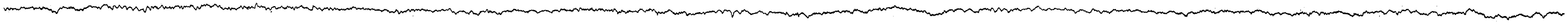

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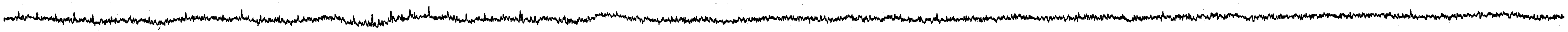

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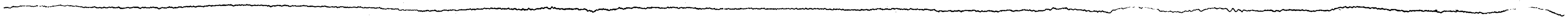

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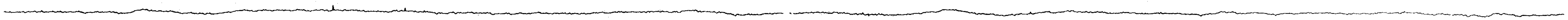

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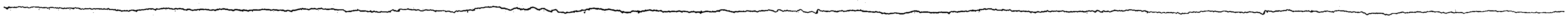

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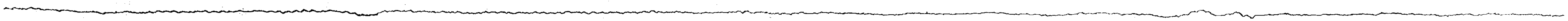

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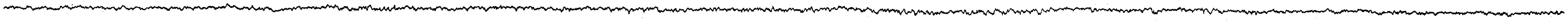

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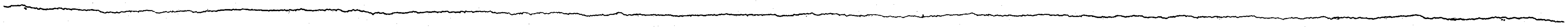

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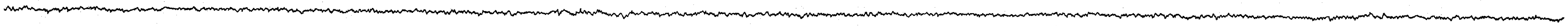

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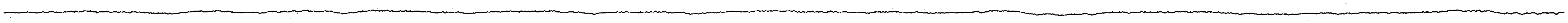

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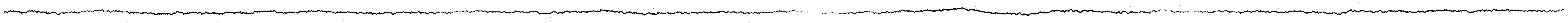

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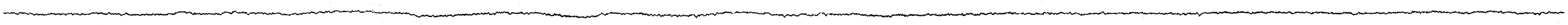

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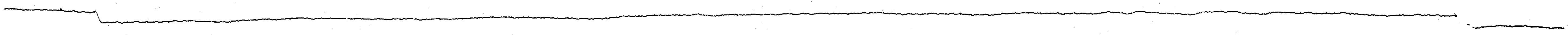

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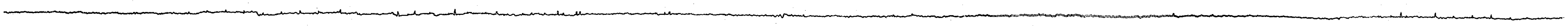

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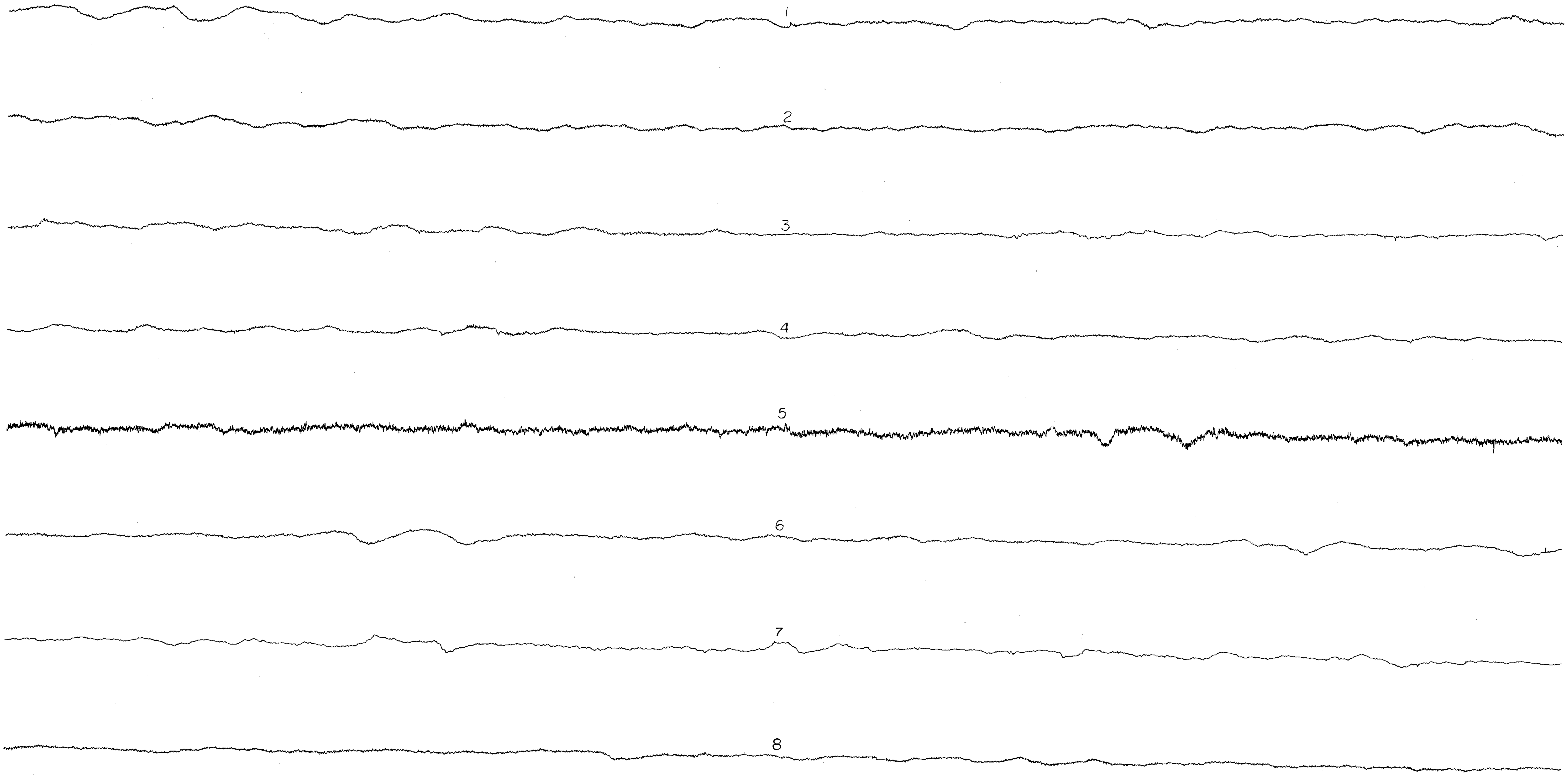
APPENDIX C

Visually Rated Profiles

Filter Band Study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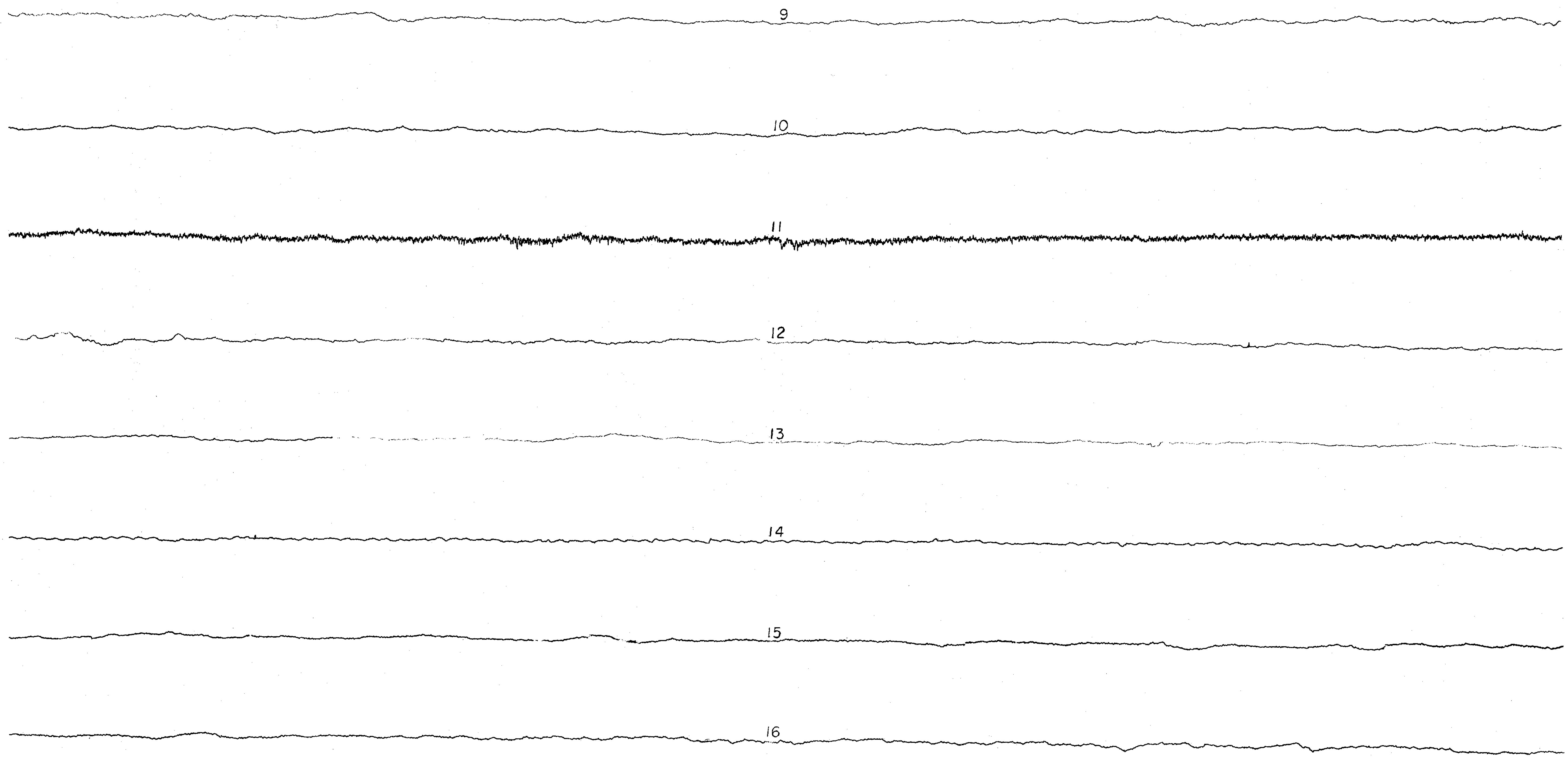
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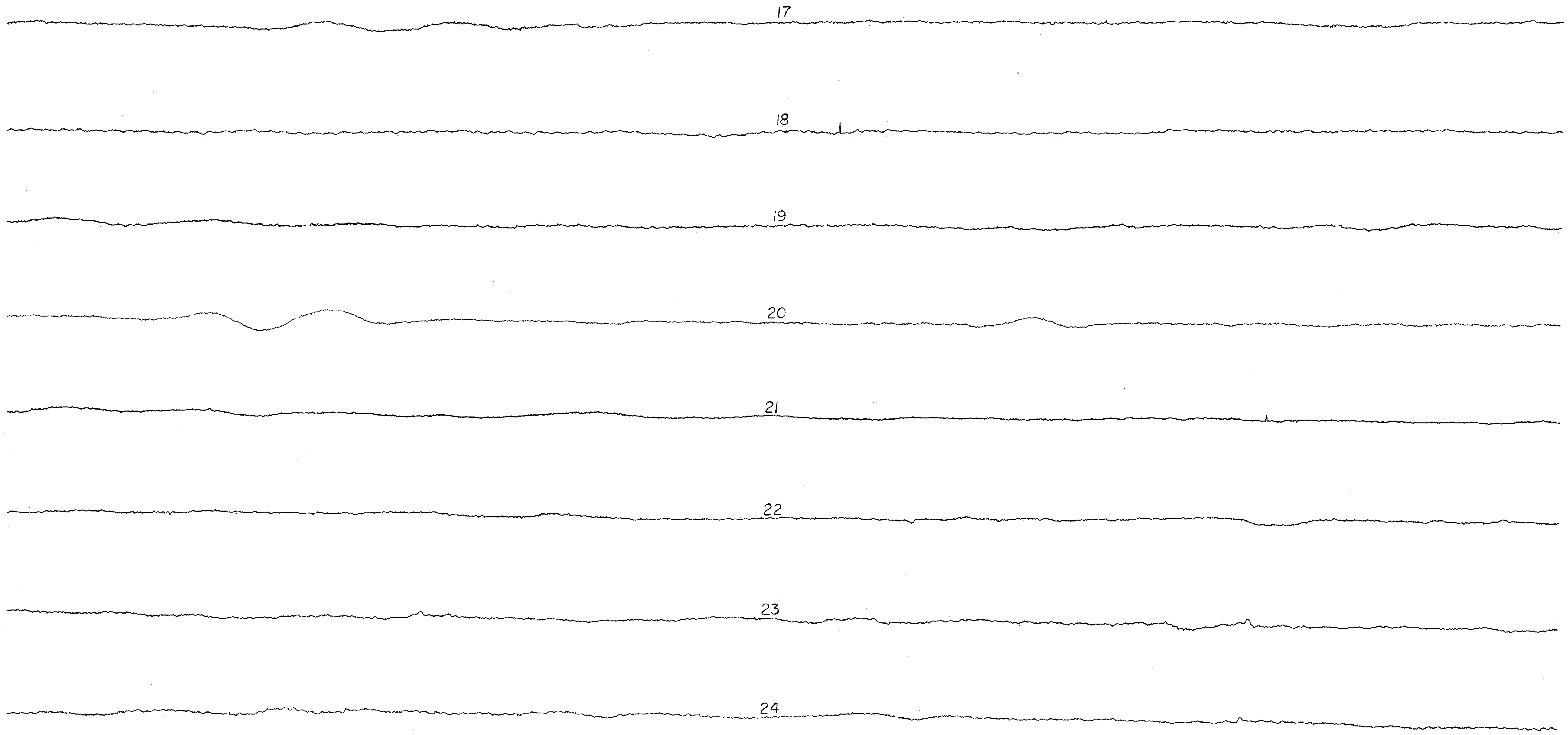
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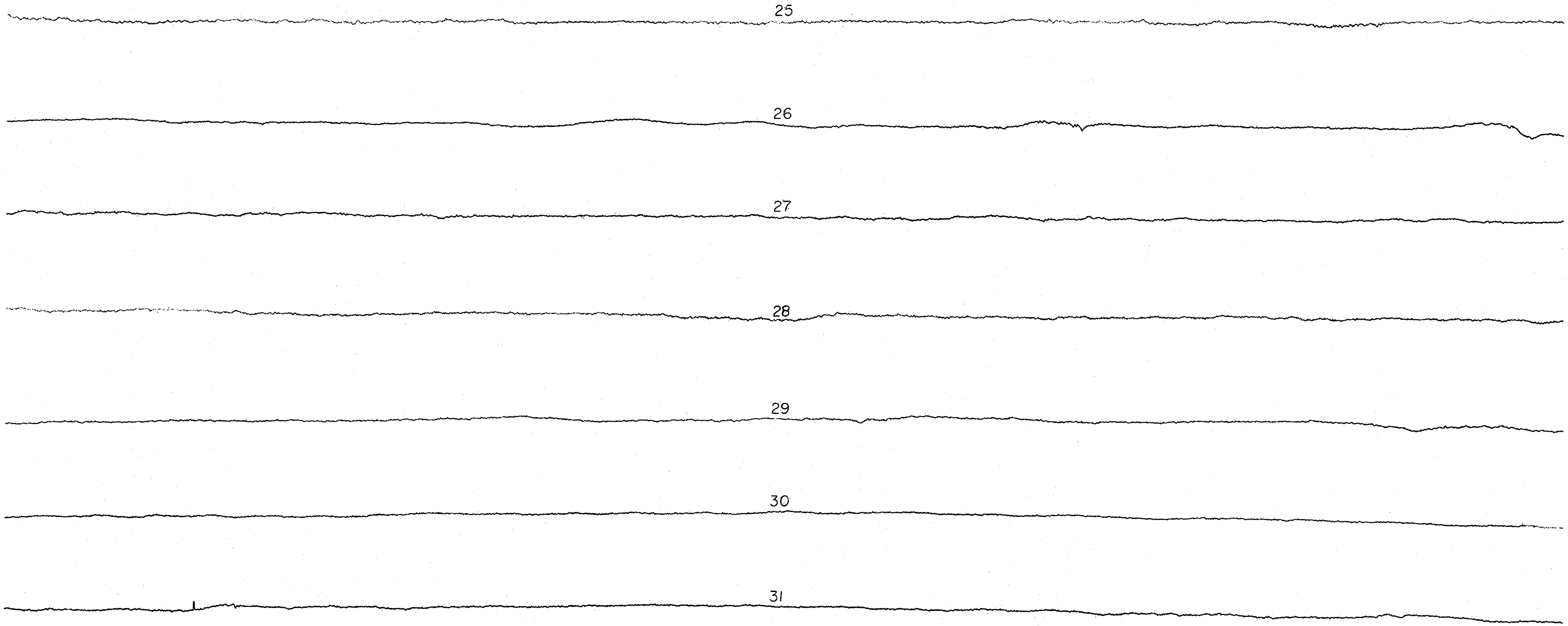
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