PAPER SURFACE ROUGHNESS MEASUREMENT

by

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ABSTRACT

By "Roughness" it is generally understood the geometrical property of the surface which may be defined as its deviation from an ideally flat plane.

The measure of the roughness of the paper surface is important, because the surface of the paper determines to a large extent its uses. Hence, it is reasonable to attempt to quantify and measure the feelings that one has, when looking at "smooth" or "rough" paper surface.

It is believed that roughness measurement would lead to improvements in the quality of paper. Surface information is of importance in the process of making the paper itself, i.e., for proper control of roll build, detection of grainy edges etc.

It is therefore of great advantage to the papermaker to have a reliable method or instrument for comparing or measuring the roughness of various papers and particularly one that would [illegible]

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experimental results of measuring the roughness with two different methods. In the first method, the "Talysurf" (T4), a sensitive stylus is following the geometry of the surface, and in the second method, the "Retro-Reflective Unit" (RRU), surface information is obtained via a combination of optical and photoelectric means.

The measurements (continuous electrical, analog, signals) from both methods are compared by treating them as stochastic processes and considering the first two moments of the probability distribution.

It is hoped to find an automatic way to classify surfaces, which would correspond to human evaluation, and be appropriate to the purpose for which the surface is intended to be used. The rational between comparing the two methods is due to the fact that the Talysurf readings require direct contact between a stylus and the surface whereas the Retro-Reflective Unit does not.

In situations where speed is a problem the T4 technique is unpracticable, hence the idea of replacing it by the RRU. Of course compatibility of the two methods must be established and this report is a step towards this goal.

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CHAPTER 1

INTRODUCTION - PAPER MANUFACTURE - PAPER SURFACE PARAMETERS

1.1 Introduction - Paper Manufacture

Paper is a complex fiber network formed from a dilute suspension of single fibers. The structural properties of the network depend upon the nature and pre-treatment of the fibers and on the processes used to form and finish the network.

We will, further, describe, very briefly, the process of paper making, so that a general idea of the dependance of paper roughness on the various materials and processes used, and of the general problems involved can be formed.

1.1.1 Preparation of the Pulp

In the making (5) of paper, the pulp (or stock as it is called) is made from a mixture of cotton, linen, hardwood, softwood etc., depending on the quality of the paper we want to obtain.

Papermaking fibers produced by the pulp mill, or partially prepared from various materials, are not suitable as such for the manufacture of paper. A sheet made from such fibers would have low strength, high bulk, an open, irregular texture, and wild uneven formation and would dis-intergrate readily when wetted by water (unless separately treated with resins to provide bonding).

The term "stock preparation" is used to cover operations such as the repulping and blending of pulps of different types, the addition of various chemicals and fillers, and the mechanical treatment necessary to make fibers suitable for forming into a sheet of paper. The terms beating and refining are commonly used interchangeably to describe various types of mechanical treatment to which the fibers are subjected. However, each term is also used in a more limited sense. Hence "beating" may refer to the operation of a beater, either in batch or continuous processing. The term "refining" is used to describe the action of various conical and disk-type pieces of equipment used almost entirely for continuous processing.

During the past decade considerable progress has been made in the understanding of the effects of mechanicl treatment on the fiber and the nature of fiber bonding in paper. Excellent reviews of present knowledge are available (6,7,8).

1.1.2 Fiber Structure (5)

Fibers are essentially long hollow cylinders. Depending upon the source, i.e., hardwoods, softwoods, plant fibers, etc., they vary primarily in lengh, diameter, wall thickness, and flexibility, and depending on the cooking process to which they have been subjected, they also vary in their rigidity, flexibility, and resistance to mechanical treatment.

Figure 1-5 is a diagrammatic representation of a cell wall in a typical wood fiber. The outermost layer of the fiber, the primary wall, is very thin, probably only a few hundred angstrom units in thickness. In this layer, the cellulose fibrils are highly individualized, somewhat

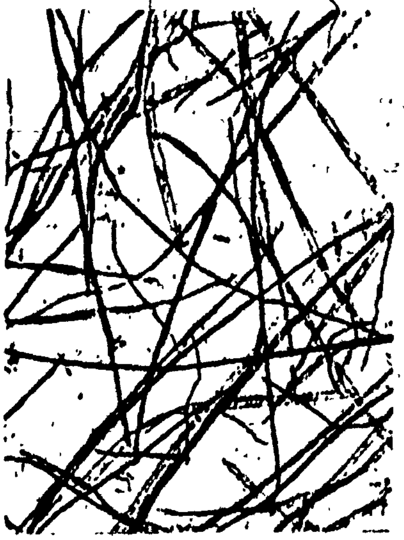


Fig. 1-1 Unbeaten softwood fibers.

Fig. 1-2 Well-beaten softwood fibers.

Fig. 1-3 Contact between fibers of unbeaten kraft.

Fig. 1-4 Contact between fibers of beaten kraft.

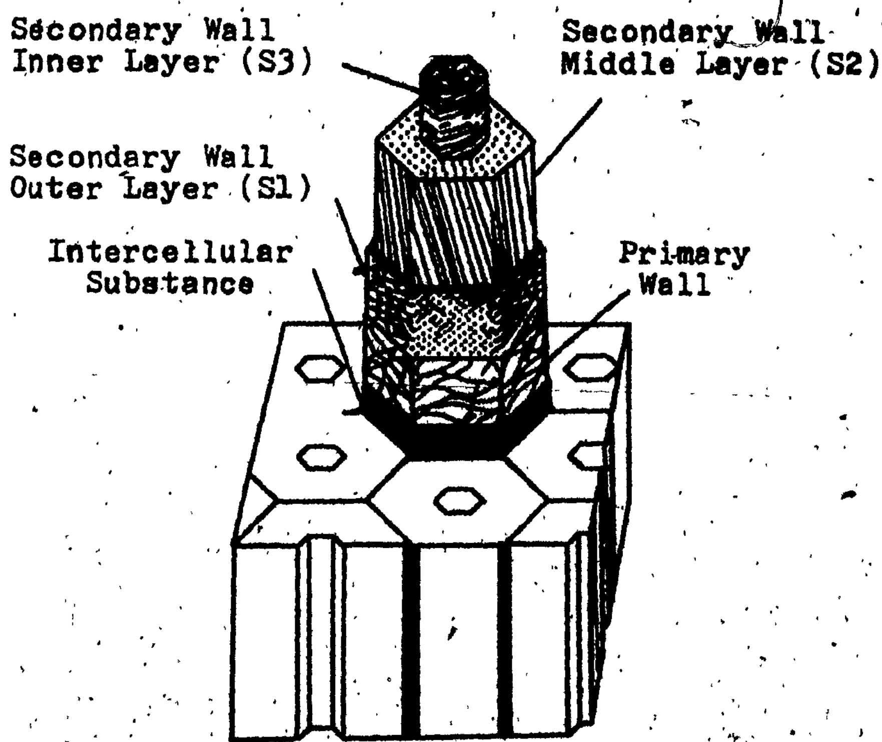


Fig. 1-5 Diagrammatic representation of the cell wall organization of a typical wood fiber.

irregularly dispersed, and to some extent interwoven. They have a preferred orientation that is mainly longitudinal on the outside of the wall but transverse on the inside.

The secondary wall is made up, usually, of three distinct layers - the outer layer (designated S1), the middle layer (designated S2), and the inner layer (designated S3). The outer layer of the secondary wall (S1) is again quite thin, of the order of 1,000 to 5,000 A in thickness. It consists of two systems of parallel fibrils which spiral in opposite senses and are symmetrically disposed about the axial direction at approximately 90^{o} to each other. The middle secondary wall (S2) consists of a series of coaxial laminae and contains the bulk of the cellulose in the mature fibers. It varies in thickness between wide limits, depending upon many factors, which include the location of the fiber within the tree, the season of the year, i.e., summerwood or springwood, climatic conditions under which the tree grows, etc. Typically, it varies from 1 to 5 μ thick. In the middle of the secondary layer the fibrils are closely packed and generally arranged in one direction at only a small angle to the longitudinal axis. The inner layer of the secondary wall (S3), again, is very thin. Here there is again predominantly one direction of fibrillar orientation, this time at a large angle to the cell axis.

The ultimate fibrous unit of the fiber has not been determined to the limit of resolution of modern microscopes. Thus, just as fibers are composed of fibrils, the fibrils in turn are composed of microfibrils, and this subdivision may extend down to the individual cellulose molecules.

The interfibrillar material consists of lignin and hemicelluloses. The hemicelluloses are hydrophylic and probably amorphous. Hemicelluloses which can be isolated from cellulose are water-soluble, and the native cellulose will have a strong tendency to dissolve, or at least to swell. This tendency to swell is partially counteracted by the bond which exists between the interfibrillar material and the fibrils and by restraint imposed by the spiral outer layer of the secondary wall.

The detailed effect that cooking and bleaching have on the fiber structure is beyond the scope of this chapter. It should be pointed out, however, that these two processes remove not only the intercellular substances (such as lignin), but also material from the fiber itself. In fact, the elimination of lignin derivatives and other highly colored compounds from the fiber is the reason for bleaching. The hemicellulosic material, which affects beating characteristics, is also affected to a greater or lesser extent by the cooking and bleaching processes. To this general well-ordered structure of a wood fiber must be added one other feature. By the time it reaches the stock preparation stages, each fiber contains a labyrinth of passageways through which the cooking and bleaching chemicals have moved in and out and which are accessible to water. Some of these correspond to structural weaknesses in the fiber, and some collapse or become blocked when the fiber is dried, and do not reopen when the fiber is rewatted.

1.1.3 Fiber Geometry (5)

The status of the relationship between fiber characteristics and paper properties, from the fundamental point of view, can be best appreciated by comparing the two paragraphs below:

The length of the fiber in the original wood from which the pulp is derived is of particular importance for tearing resistance.... Pulp strength properties such as burst, tensile, and particularly folding endurance, are adversely affected by an increase in wall thickness (6).

Fiber length, which varied from 0.6 to 3.2 mm, had no significant influence on paper properties, not even on tearing strength.... The relative length (length over diameter ratio) seemed to be the most important factor for tearing strength, the flexibility coefficient (lumen width to fiber width ratio) for tensile strength, and somewhat less so far for bursting strength (6).

From the standpoint of papermaking, it must be remembered that fiber population, even in a furnish using a single type of pulp, is probably as heterogeneous in size, shape, or any other physical characteristics as is the human race. When this is extended to include pulps from various types of trees and prepared by various cooking processes, the difference in extremes of individual fibers is at least as great as that between the elephant and the mouse. In stock preparation systems, there is less interest in absolute numerical values than in relative data which can be correlated, through experience, to the end result in the finished sheet of paper. This generalization has resulted in considerable misunderstanding by those involved in fundamental research, as evidenced by the amount of "debunking" of "established theories" which they find necessary to include in their published articles.

Again, in discussing fiber geometry, we are faced with the incompatibility of tests which are simple enough for control purposes, yet indicative of the complexities of sizes and shapes of the fibers in the mixed stock.

1.1.4 The Fourdrinier Paper Machine (5)

Two standard types of paper machines are used to manufacture the many and varied grades of paper, the "fourdrinier" and the "cylinder" machine. In addition, there is a number of special types, or are specially designed to make a particular product. Further, we will, briefly, describe the fourdrinier machine (see Fig. 1-6).

The general method of making paper is essentially the same for all types of machines. The paper is made by depositing fibers from a very low consistency aqueous suspension onto a relatively fine woven screen (wire). More than 95% of the water is removed by drainage through the wire. As the fibers are deposited on the wire, they interlace in a generally random manner, and in doing so, they themselves become part of the filter medium. The fiber

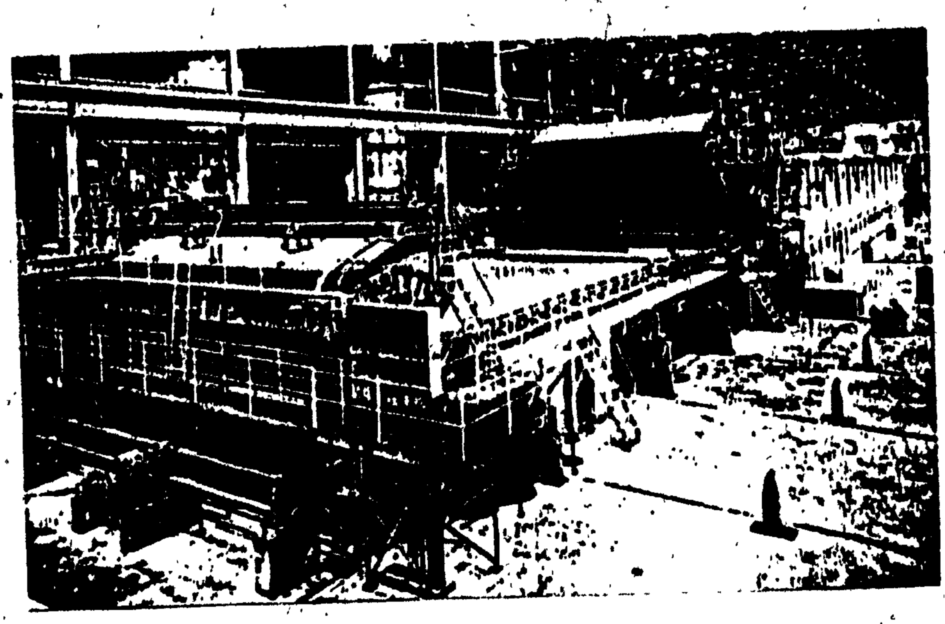


Fig. 1-6 A modern fourdrinier.

length is of the same size as the openings in the screen, so that a lot of fibers pass through the wire during the initial stages of drainage. As the fiber mat begins to form, the retention rate increases progressively.

The varying retention rate leads to a gradual variation of the sheet characteristics from one side to the other. Even as a very wet mat, the forming sheet has considerable strength. This is due to the frictional and interlocking forces which occur between the fibers, and its strength increases as the web consistency is increased. At a later stage during drying, the fibers begin to bond to one another chemically, until this type of bond predominates in the fully dried state.

The principal parts of the modern fourdrinier machine are shown diagrammatically in Figure 1-7. The course of the paper through the machine is also indicated. Details of the several sections differ in various types of machines.

The stock, which is about 0.5% fiber, depending on the grade of paper being made, enters the flowbox, or headbox, through the inlet, whence it is forced by its own weight, or plus air pressure, out through the slice on to the endless fourdrinier wire. This wire is driven by the couch roll, or sometimes by the wire drive roll, and is supported by the breast roll, the table rolls, and the wire rolls. Much water drains through the wire at the table rolls; more is taken out by the flat suction boxes and the suction couch roll. Many modern machines are equipped with several wire-

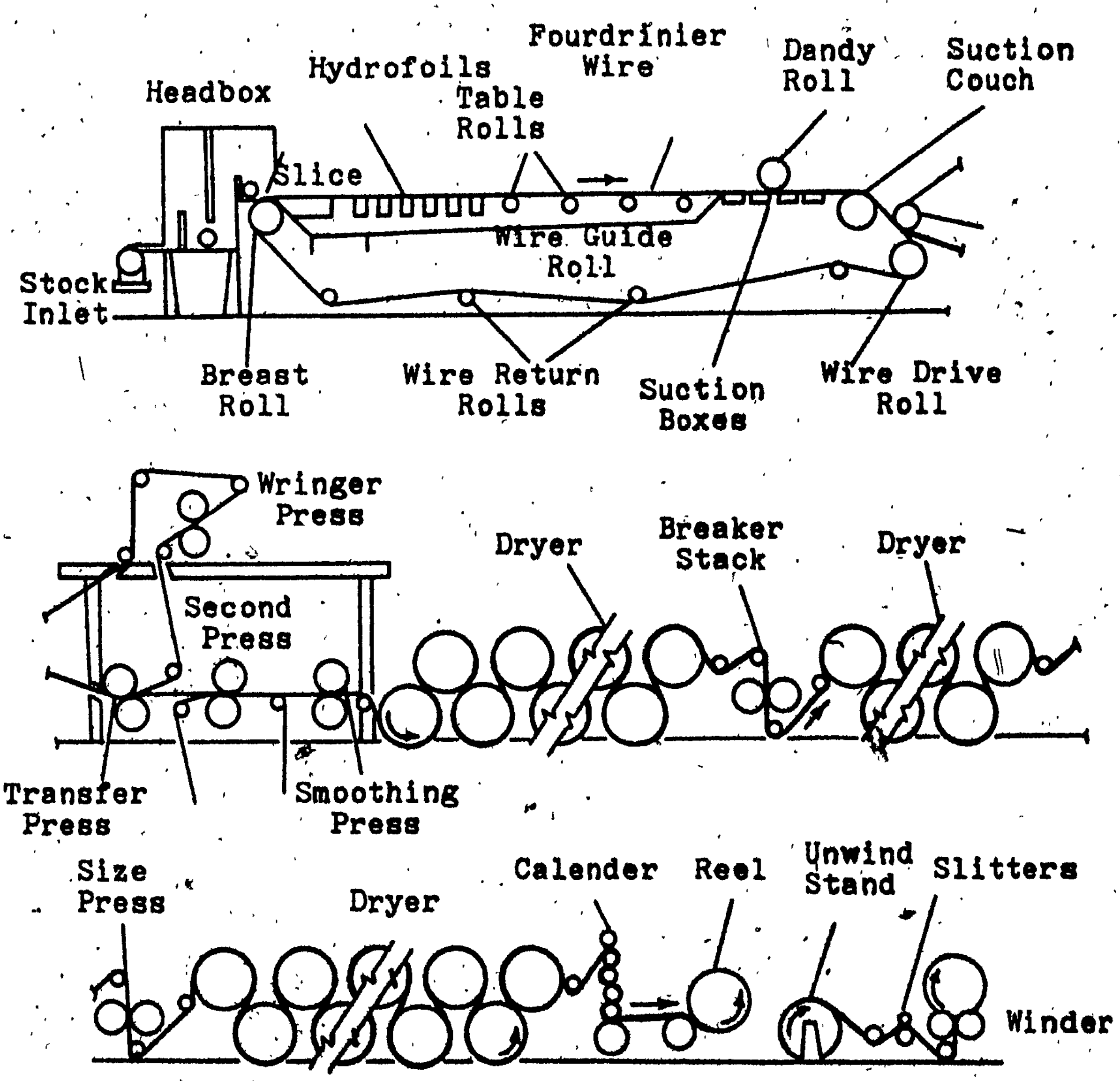


Fig. 1-7 Parts of a fourdrinier paper machine.

carrying deflectors, sometimes called "hydrofoils", whose purpose is to increase dewatering rates, improve fines retention, and reduce headbox consistencies. A dandy roll is sometimes used to improve sheet formation by smoothing the top surface and imparting a wire design to make the paper alike on both sides. Some of the older paper machines making special papers have used a plain bottom couch roll with a jacketed top couch roll; however, the plain bottom couch roll is practically obsolete.

Figure 1-7 shows the sheet transferred to the first press felt, which is an endless woolen blanket, by means of the suction pickup roll. Then the sheet passes between the top and bottom rolls of a transfer press, where more water is removed and the sheet further pressed. Most modern machines use a perforated bottom suction press roll to facilitate the removal of water from the sheet. The press felt is supported and kept tight by felt and stretch rolls (not shown). The next step is to transfer the sheet to the felted second press, which is sometimes similar to the first press, and then to the third press, in case the machine is so equipped. Many machines use a reverse last press instead of a straight-through press; also a smoothing press, as shown in Figure 1-7. A reverse-press arrangement may also be found in first- and second-press locations. The primary function of the smoothing press is to impart smoothness to the wet sheet immediately ahead of the first dryer. Wire and felt marks are reduced by this press, and no felts are required at this stage of manufacture.

After the paper leaves the press part, it contains about 60 to 70% water, and it then goes over the steam-heated dryers, which evaporate additional water and make the sheet 90 to 94% dry. In its passage through the dryer part, the paper (unless very thick and strong) is carried through and kept in contact with the dryers by canvas or fabric felts.

A fabric-felt-and-paper sandwich passes through the nip of the rubber-covered press rolls. The ability of the open-mesh fabric to store water pressed from the felt simplifies removal of water out of the press section entirely.

The machine shown in Figure 1-7 is equipped with a breaker stack, which is generally located about two-thirds of the way down the main dryer section. The primary function of the breaker stack is to compact and smooth the sheet while it still has a fairly high moisture content. Also shown is a size press installed after the main dryer section and prior to the last dryer section, where the sheet is submerged in or flooded with size and other solutions, i.e., starch, etc., to impart to the paper not only resistance to penetration of liquids, but other characteristics as well. In actual practice, the paper is thoroughly dried (3 to 8%), run through the size press, and then further dried out. The dried sheet then goes through the calender stack, which consists of a series of smooth, heavy iron rolls, and the paper is calendered, i.e., given a smooth surface. The sheet is now wound on the reel as rapidly as formed on the machine. When one of the reels is full, a new reel is started, and the sheet is transferred to the unwind stand, from which it is run through the slitters to the winder. The winder part then slits the full-width wheel and winds it into rolls of proper width and diameter on desired core size to suit the customer, or for further processing. In some cases the full-width roll is further processed before slitting.

1.1.5 Calendering and Effect of Calendering on the Paper Quality (5)

After drying, the paper surface is still rough and its caliper not completely uniform. Both properties can be controlled, within certain limits, by calendering.

The calendering of paper is the action involved in subjecting the viscoelastic paper web to the nip pressure of a set of two or more adjacent and revolving rolls; this action compacts the web and changes its surface properties through pressure and friction. The mechanism by which the changes in the paper properties are produced is very important, since more emphasis is being placed on better paper quality.

The changes which have been introduced in the design of the steel roll calender stack since it first appeared as an integral part of the papermaking operation have been mainly refinements in bearing design, roll strength, surface finish, and improved control of nip pressure. These changes have been important in improving both the quality of the paper and the operation and maintenance problems of this part of the paper machine. But since the fundamentals are largely intuitively, rather than quantitatively, known, no theory has been evolved on which basic designs can be made.

The distribution of the power input to the stack is one of the important factors in determining both the mechanism of calendering and the efficiency of the utilization of the power available. The variables which affect it are bearing friction, nip stress hysteresis, rolling friction, the belt effect, and roll-to-roll slip both for the bare rolls and for the case when paper is in the stack.

The function of the calender stack is studied here as it applies to production, i.e., to provide caliper control across the width of the sheet to build even reels and to produce a smooth well-finished sheet to meet printability requirements of the publisher. There are other functions; e.g., in certain grades of kraft paper and board, the chemical, as well as the mechanical, finish is applied at the stack, using wet boxes to stack-finish the sheet with various additives; these additional uses are not included, since they are fields of investigation quite separate from the consideration of the basic mechanical action of the steel roll stack.

The calender stack is the one part of the paper machine devoted exclusively to the quality aspect of papermaking, but it is important to point out at the beginning that the final paper quality depends on other causes as well, i.e., the basic properties of the fibers used, the uniformity of distribution and drainage at the wet end, and the pressing and drying operations which subsequently occur. The surface finish of newsprint is mainly due to calendering, although altering the wet-end drainage to retain different fines fractions would probably have some effect on the ultimate surface finish; the absolute caliper and the caliper uniformity are mainly effects of the fiber properties and the stock distribution system, respectively, although the absolute caliper can be changed at the stack by controlling the total nip pressure; and caliper nonuniformities can be partially corrected through good localized nip pressure control.

The effect of the calendering mechanism on paper properties must also be considered, and since the stack is essentially two-dimensional in its effect (as are all other parts of the paper machine), the action of each nip on the machine-direction quality, as well as the effect of localized nip pressures on cross-machine-direction paper quality, must be examined. The action of the stack on machine-direction and on cross-machine-direction properties of paper can be visualized by splitting them into two separate, but related, spheres; in the first case, the average quality improvement which takes place is due to the number, size, speed, and weight of the rolls in the stack, as well as their limits by changing any one of the variables (for existing stacks, the only variable which can be effectively controlled is the number of rolls); the second case, that of the cross-machine-direction effect of the stack on paper quality, is quite separate. With any stack it is possible to correct partially for cross-direction variations in the sheet (which may be uniform in the machine-direction) through the control of localized nip pressure by the calender cooling system.

In Figure 1-8 two paper samples are shown before and after calendering.

Table 1-1 shows a typical set of results for newsprint quality changes through successive nips of the machine calender.

Table 1-2 shows the relation between Bendtsen roughness (B ml/min) and absolute units (G μm).

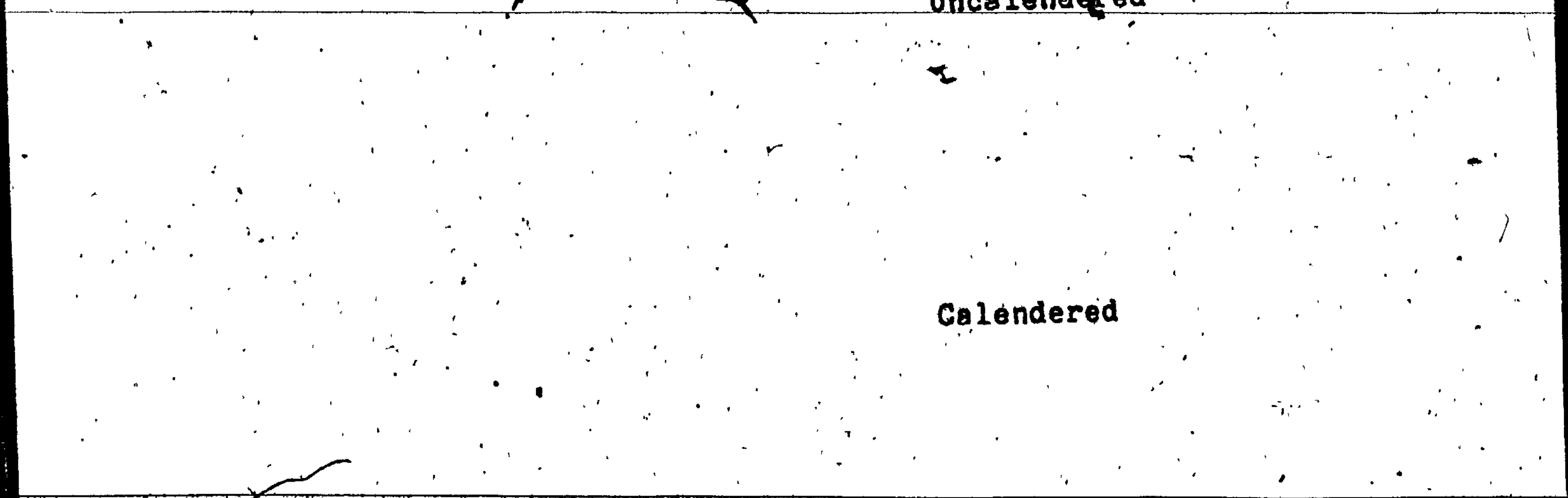
The Bendtsen is an air flow instrument for measuring smoothness and is used for industrial quality control. It determines the rate of air flow at 0.25 psi over an area 0.006 in wide. Between B and G the following (2) relation holds:

$$G = 1.545 \times B^{1/3}$$

Figure 1-9 shows the rate of change of newsprint caliper through the six nips in the stack.

Figure 1-10 shows the change in Bendtsen roughness through the nips of the stack; in contrast to the change in caliper, surface roughness of the sheet develops linearly, with each successive nip, contributing nearly equal amounts.

Uncalendered



Calendered

Fig. 1-8 Uncalendered and calendered paper samples.

TABLE 1-1. Change in paper quality under normal operating conditions.

	Caliper	Smoothness Top	Smoothness Wire
Entering first	0.00570	208	252
Leaving first	0.00460	178	207
Leaving second	0.00380	150	177
Leaving third	0.00350	108	124
Leaving fourth	0.00330	102	114
Leaving fifth	0.00319	76	88
Leaving sixth	0.00307	58	62

TABLE 1-2. Bendtsen (B) to absolute (G) units conversion.

B ml/min	G µm
10	3.3
30	4.8
100	7.2
300	10.3
1000	15.5

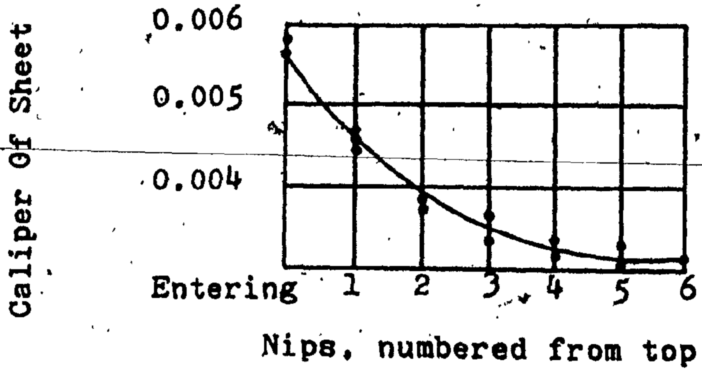


Fig. 1-9 Change in newsprint caliper through six nips.

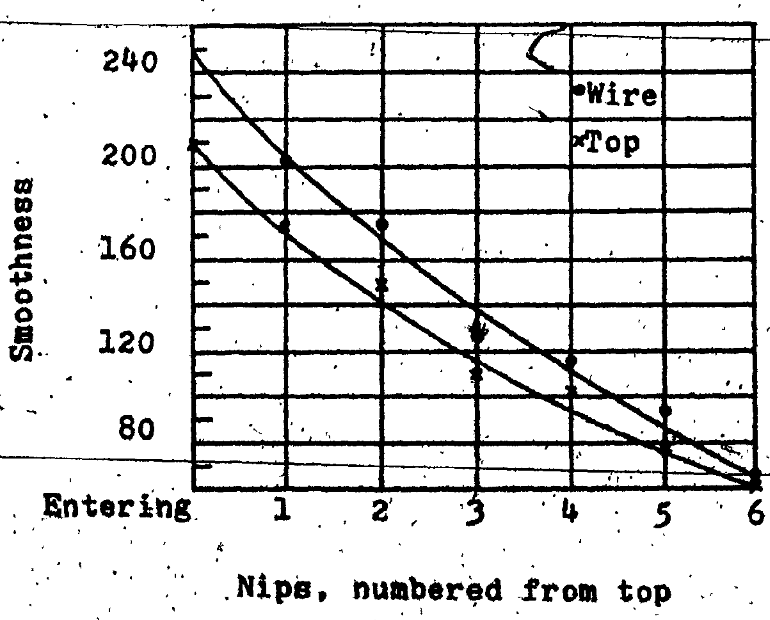


Fig. 1-10 Change in Bendsten roughness through six nips.

1.2 Characteristics of a Paper Surface - Statistical Surface Parameters

1.2.1 Roughness of Paper

By roughness (or its opposite, smoothness) is generally understood the geometrical property of the surface which may be defined as its deviation from (or in the opposite case, closeness to) an ideally flat plane. In the case of paper or board, the deviations that are perceived as roughness are on a very small scale, and occur as "topographic" features on the surface (peaks or valleys) having dimensions of the order of 0.01 - 2.0 mm in the plane of the paper, and about .01 - 0.1 in the direction normal to the plane.

Deviations of lower frequency and larger dimensions no longer contribute to roughness but may come under the designation of "waviness", or indicate variations in thickness, etc.

Consider a simplified paper surface (or any surface in general), Fig. 1-11, and let us make some definitions which will be useful.

- a is the direction of lay or machine-direction, i.e., the direction along which the paper is manufactured.
- b is the direction vertical to the machine direction, or cross direction
- c is the profile
- d is the waviness spacing

e is the waviness

f is the roughness, and

g is the roughness spacing

1.2.2 Statistical Surface Parameters

The paper surface can be studied by statistical analysis by considering the measurement signal from either T4 or RRU as a stochastic process. It is important to note that this process is related to the surface geometry but, due to measurement distortions or errors, it is not possible in general to reconstruct the surface geometry from the measurements.

The study of certain statistical parameters calculated from the stochastic process will give a possible description of the qualities of the surface and the means to compare different types of paper samples or the same paper for different production runs. It is of course desirable that the parameters (10) to be considered describe adequately the roughness heightwise and lengthwise (the roughness spacing).

Consider, Fig. 1-12, a paper surface profile signal in continuous form, as it is recorded on the magnetic tape, or as it can be seen on an oscilloscope, from the measuring devices.

After the Analog to Digital conversion we get a data set of points representing the amplitude of the signal sampled at regular intervals.

We define:

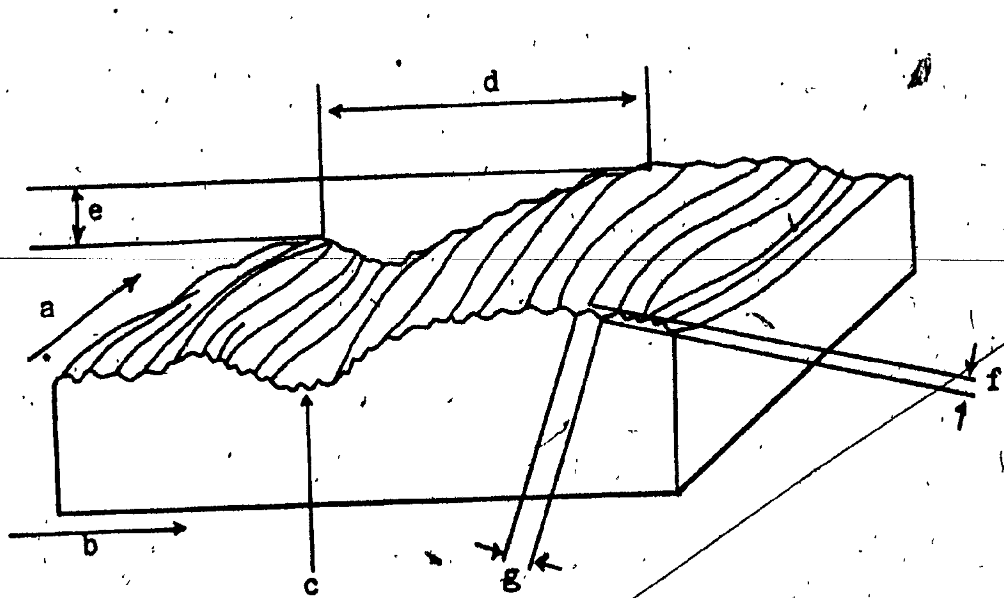


Fig. 1-11 Simplified paper surface profile.

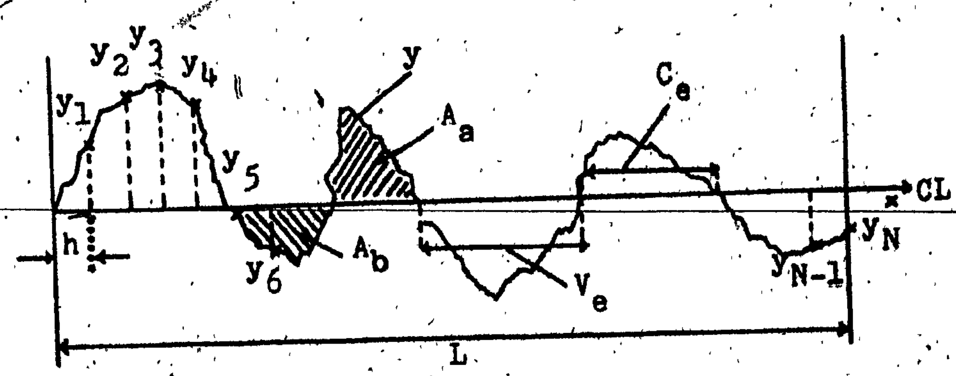


Fig. 1-12 Paper profile signal.

y is the continuous signal

y_i is the value of the i^{th} data point of our discrete signal

L is the "Sampling Length"

h is the "Sampling Interval" (constant)

N is the total "Number of Samples"

C_e is the "Crest Excursion" (duration of)

V_e is the "Valley Excursion" (interval between excursions)

Consider the areas A_a and A_b and suppose that we can find such a line that:

$$\sum \text{areas above the line} = \sum \text{areas below the line}.$$

Such a line will be called "Center Line".

In the discrete case, let us define as y_j and y_k the values of y_i that satisfy:

$$\sum_{1}^{j} y_j = \sum_{1}^{k} y_k, \quad y_j \neq y_k, \quad j+k = N$$

The values y_j are above the "Center Line" (CL) and the values y_k are below the "Center Line".

The "Center Line" is used as reference for defining the roughness of the paper (see definition of roughness in section 1.2.1).

Further, we will describe the statistical parameters that were examined in this report. Some of these parameters (or their intermediate values) are used within the computer program for further estimations.

1.2.3 Mean Value (of a Sample)

Let y_i, i = 1, N, be the discrete signal values, then:

$$\text{Mean Value } \bar{y} = \frac{1}{N} \sum_{1}^{N} y_i \quad (1.2\text{-}1)$$

1.2.4 Center Line Average

As CLA value is defined:

$$\text{CLA} = \frac{1}{N} \sum_{1}^{N} \sqrt{(y_i - \bar{y})^2} \quad (1.2\text{-}2)$$

The CLA value is used further as our reference level.

1.2.5 Root Mean Square (of a Distribution)

The Root Mean Square Value is defined as:

$$\text{RMS} = \sum_{1}^{N} \sqrt{(y_i - \text{AVE})^2 \rho_v} \quad (1.2\text{-}3)$$

where ρ_v is the vertical probability density of the data value.

1.2.6 Mean Crest Excursion

The Mean Crest Excursion Value is defined as:

$$\text{MCE} = \sum_{I}^{M} y_i \rho_o \quad (1.2\text{-}4)$$

where ρ_o is the horizontal or excursion probability density of the quantized data level, and I and M are the lower and upper limits of the data levels.

1.2.7 Root Mean Square of Crest Excursion

As Root Mean Square Value of Crest Excursion is defined:

$$RMSCE = \sum_{I}^{M} \sqrt{(y_i - MCE)^2 \rho_o} \qquad (1.2\text{-}5)$$

1.2.8 Average Number of Crossings (10)

As Average Number of Crossings per unit length of the surface is specified the average number of the surface undulations about a preselected level, along the x-axis (see Fig. 1-12). The preselected level in our case is the CLA value.

Let σ^2 be the standard deviation of $Y(y_i)$ i.e.,

$$\sigma^2 = E(Y^2(y_i)),$$

and let σ'^2 be the standard deviation of the slope $Y'(y_i')$,

where $y_i' = \dfrac{y_i - y_{i-1}}{\Delta x}$, i.e.,

$$\sigma'^2 = E(Y'^2(y_i))$$

then

$$ANC = \frac{1}{2\pi\sigma} \sigma' \exp(-y_R^2/2\sigma^2) \qquad (1.2\text{-}6)$$

where y_R is a preselected reference level and in our case is:

$$y_R = k \text{ CLA}$$

where k is a multiplication factor.

However, as it will be seen, (section 3.4.7) a simpler method was used in order to estimate the average number of crossings per unit length.

CHAPTER 2

ROUGHNESS MEASUREMENT

There are various methods and instruments for the testing of paper roughness (1,2,3,4). The best known are air-leak instruments such as the Sheffield, the Bendstep and the like. In these methods a cup-like device containing pressurized gas is applied tightly against the surface of the sheet. The escape of the gas from inside the cup through the gaps along the line of contact with the surface will be a function on the roughness of the surface and will provide a measure of it.

There are also optical methods of measuring surface properties of sheet material, but these are mostly directed to the detection of individual surface blemishes, or to the measurgment of gloss, but some are also directed to the measurement of roughness. A surface roughness meter is disclosed in Canadian Patent 698,194 wherein a two-colour photometer utilizes the difference in the reflectance of two different wave-lengths to devise a measure of the surface roughness. A known method of evaluating surface roughness is to view a sample of the surface through a microscope under suitable magnification and a low angle illumination such that the light will throw the surface into relief and accentuate the shadows cast by the peaks and valleys on the surface; however, the evaluating in this method relies entirely on subjective judgement. The existing methods are generally not adapted to on-line measurements of moving webs, particularly webs travelling at present-day high speeds in the paper machine.

The "Retro-Reflective Unit" (RRU) is an optical device and provides a non-contact method for measuring with high speed the surface roughness of a moving sheet, or web, of paper.

Another device is the "Talysurf 4" (T4) which provides a reliable method for lab testing of small paper samples. The RRU and T4 were used for experimenting (see next chapter) for the purpose of this report, with the T4 as a reference method for comparing the results from the RRU. In fact, it is worth to note here, that the Air Leak instruments by making "Averages" over an area of the order of a few square inches, are doing an unclear statistical analysis of the true geometry of the surface. It seems therefore relevant to correlate the data obtained by those instruments with a statistical analysis of either T4 or RRU.

Further, in this chapter, we will, briefly, describe the Sheffield, T4 and RRU instruments.

2.1 The Sheffield Method (19)

The Sheffield tester gives an instantaneous measurement of paper smoothness. The instrument consists of two main elements, the first is the Precisionaire column instrument for precise indication of air flow and the second is a testing device for application to the paper sample. The test head incorporates two annular rings having a face width

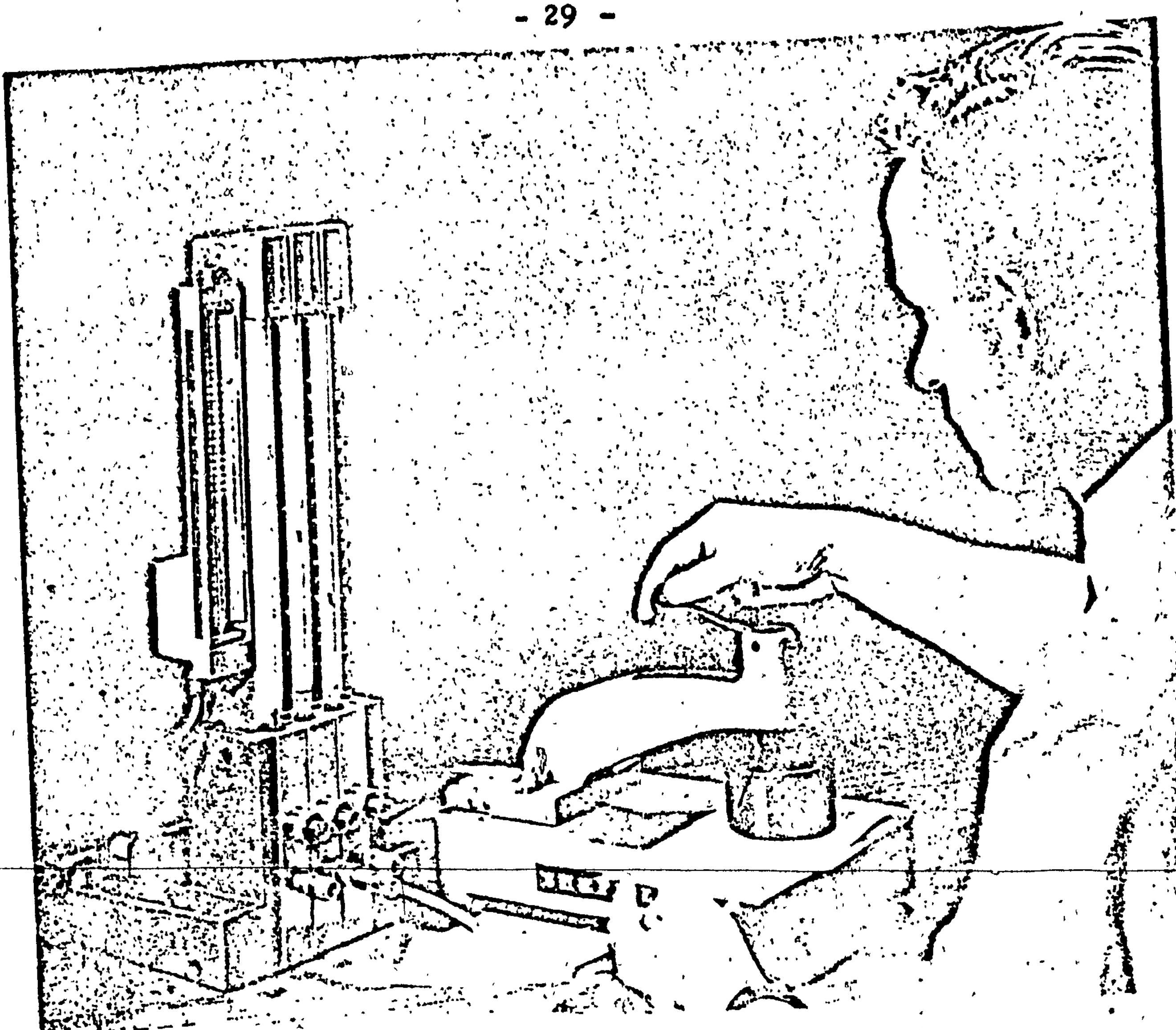


Fig. 2-1 The Sheffield tester.

of 0.015 in. Air from the Precisionaire column instrument is introduced between the two rings while they are in contact with a paper specimen. The rate of air leakage between the smooth surface of the two rings and the top of the paper sample is measured in the Precisionaire instrument and indicates the comparative smoothness of the paper. Because the rate of air flow is indicated, the readings of the instrument are instantaneous regardless of the degree of smoothness. Calibration of the Precisionaire column instrument is made by establishing a known initial rate of air flow in each of the columns of the instrument based on fixed metal orifices. These calibrating orifices are a part of the test fixture, providing a ready reference at any time. The notation system used is numerical, from 0 to 400 units on the Sheffield scale. These units are approximately equivalent to cubic centimeters of air per minute times 10. The 0 represents the "perfect" and the smoothness of the sample decreases as the value of the scale units increase. The Sheffield is sensitive to specks in the paper.

As a rule, testers of the air-flow type are fairly well adapted to the testing of paper smoothness. There are, however, several shortcomings of this type of instrument. The results are more affected by a few large depressions than by an equivalent area of small depressions because the air flow is proportional to the fourth power of the surface channels. This places undue emphasis on accidental defects. The flow of air is affected by the depth of the cavities in the paper surface, which is often not indicative of the suitability of the paper for a certain purpose, for example, in printing, where very deep cavities are no more harmful to printing quality than medium-deep depressions. On the other hand, the flow of air is not greatly influenced by discontinuous irregularities in the paper surface (e.g., wire marks), and these irregularities are often important in the use of the paper. In the case of very smooth papers, such as coated papers, the readings obtained on air flow smoothness testers are principally a measure of transverse porosity, rather than smoothness, and are therefore affected by thickness and density of the sample.

2.2 The "Talysurf 4" Method

The "Talysurf 4" (T4) surface measurement instrument (11) is mainly used for measuring the surface finish of metal parts or components. In this case (4) it was used succesfully as a reference method for measuring the roughness of a paper surface.

The principle is illustrated schematically in Fig. 2-2. The gearbox drives a pick-up slowly across the surface and a sharply-pointed stylus traces the profile of the surface irregularities. The pick-up is an inductive-type transducer, connected in a bridge circuit, in which the vertical movements of the stylus modulate a carrier waveform. This signal is amplified, demodulated and used to operate a recorder. The signal, suitably modified by filters, is also used to operate the CLA meter.

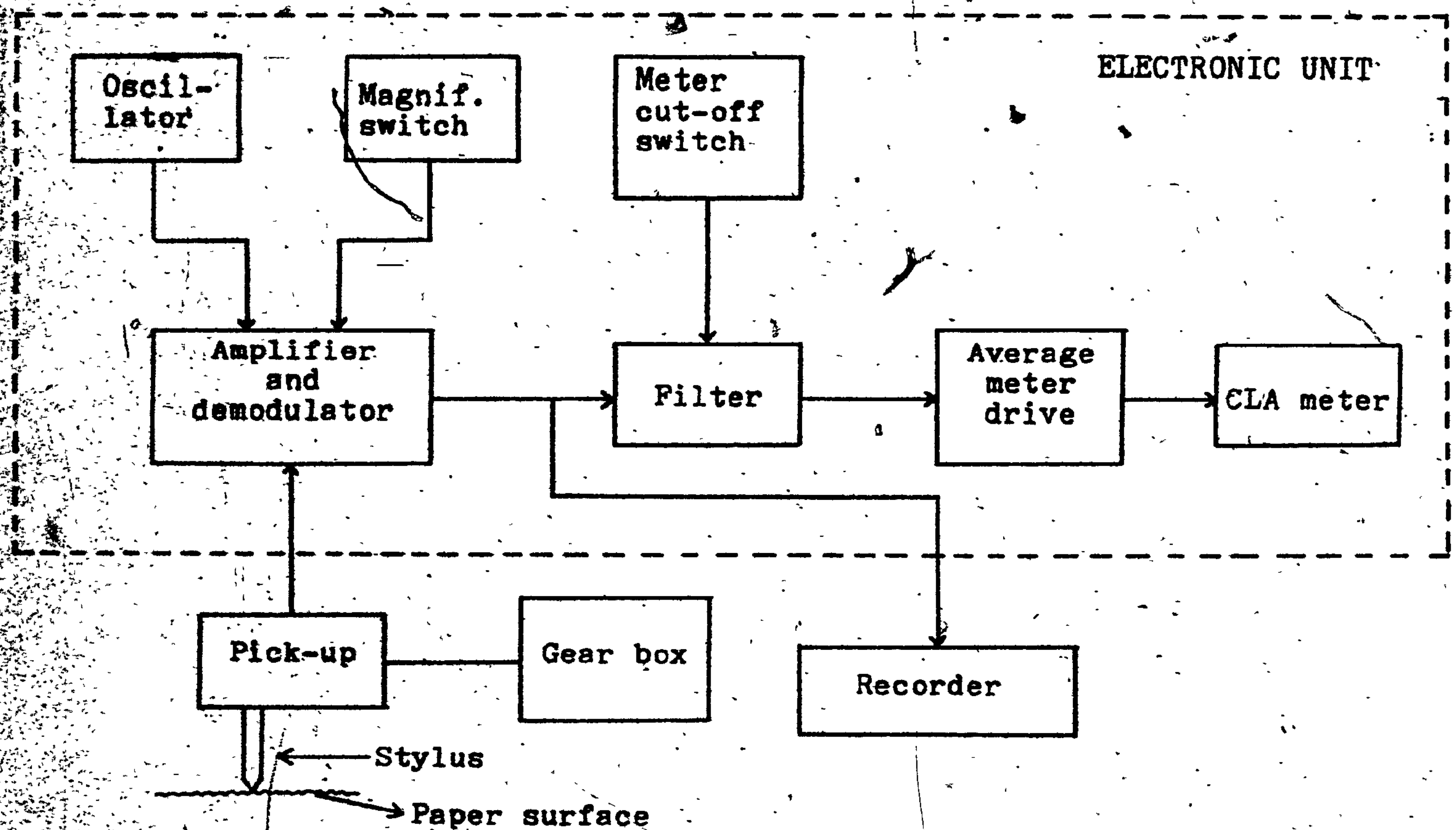


Fig. 2-2 "Talysurf 4" (block diagram)

"The gearbox" includes an electric motor which traverses the pick-up at a selected speed across the work-piece. The drive is in one direction only, the pick-up being traversed manually to the beginning of the stroke. The traversing length is adjustable and the sequence of the measuring cycle is controlled from precision-set contacts inside the gearbox.

"The stand" has a lead screw by which the gearbox can be raised and lowered. The gearbox mounting adapter can be adjusted so that the pick-up traverse is accurately parallel to the base of the stand, thus minimising the time necessary for setting-up a component for measurement.

"The pick-up" projects from the gearbox and is easily removable from it.

"The Electronic Unit" is fully transistorized and contains, on the front panel, the operating controls and CLA meter.

"The Recorder" produces a graph having rectilinear co-ordinates, marking being by electric action on an electro-sensitive chart paper.

The electrical signal from the pick-up represents the relative movement between stylus and pick-up body. For this signal to be truly representative of the surface profile, the pick-up must traverse a path parallel to the general shape of the surface, without vertical movement due to surface irregularities. This is normally achieved by the pick-up riding on a skid (Fig. 2-3) which has a radius large in comparison with the texture spacing. The skid provides a serviceable datum only if the crests are close enough together. If the crests are more widely spaced (Fig. 2-4) the skid tends to follow the profile and thus the vertical movement of the pick-up body contributes to the output signal. In these cases it is preferable to use a flat shoe support for the pick-up (Fig. 2-5) which will span the irregularities.

The texture of a surface may include roughness irregularities of different crest spacings, superimposed on each other, as in the profile shown in Fig. 2-6. To get a true measure of the roughness of this surface it is necessary to choose a sampling length L, long enough to include the various roughness crest spacings exhibited by the surface. In the electrical integrating instrument the meter cut-off values are made equal to the sampling lengths. When the instrument is switched to desired meter cut-off, i.e., to the desired sampling length, the pick-up will traverse the surface to give average results from several consecutive sampling lengths.

On finer surfaces with much closer spaced irregularities, it is possible to use a shorter meter cut-off.

The filters in the Electronic Unit conform to the requirements laid down in the British, U.S. and Canadian Standards and do not give a sharp cut in the response to irregularities of widths greater than the meter cut-off length. Instead there is a gradual attenuation of response as shown in Fig. 2-7. As an example of the use of this chart,

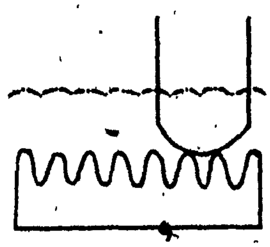


Fig. 2-3 A skid supporting the pick-up gives an almost straight-line movement across the surface.

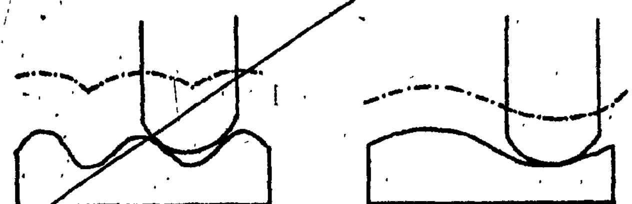


Fig. 2-4 A rounded skid does not provide a service.

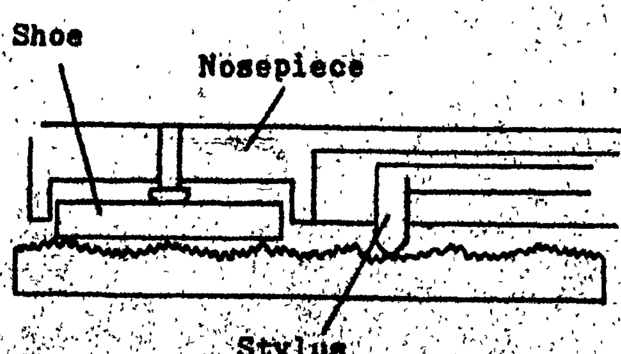


Fig. 2-5 A flat shoe will provide a more satisfactory datum on widely spaced irregularities.

consider a surface having an irregularity spacing of 0.03 in (0,8 mm). With a meter cut-off of 0.1 in (2,5 mm) the chart shows that almost the whole amplitude of the irregularities will contribute only 75% of their amplitude to the meter reading.

The filters are operative only in the meter circuit and do not affect the graph.

The traverse scale (Fig. 2-8) on the gearbox indicates the position of the pick-up in relation to the traverse. The upper scale is divided into four divisions, each 0.1 in (2,5 mm) wide. The lower scale has an index line and J, K, and L traversing length markings; as the pick-up traverses, the scale moves from left to right.

The longest recording traversing length 0.4 in (10,1 mm) is obtainable when the traverse is started with the scales aligned as shown in Fig. 2-8. Note that there is a slight overtravel beyond this position but this overtravel should not be used as it is beyond the normal working limit of the ligament hinge.

The end of any traverse occurs when the index line is just past the right-hand mark, the slight overtravel beyond the right-hand mark is occupied by a switching surge which should be ingored on the recording.

The following limitations should be noted.

a) Maximum crest spacing permissible using shoe nosepiece equal to 0.125 in (3,2 mm).

b) Recommended maximum crest spacing using skid nosepiece

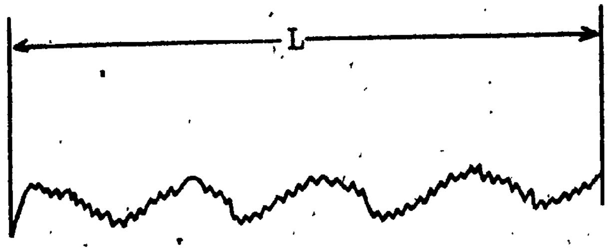


Fig. 2-6 Diagram to illustrate sampling length.

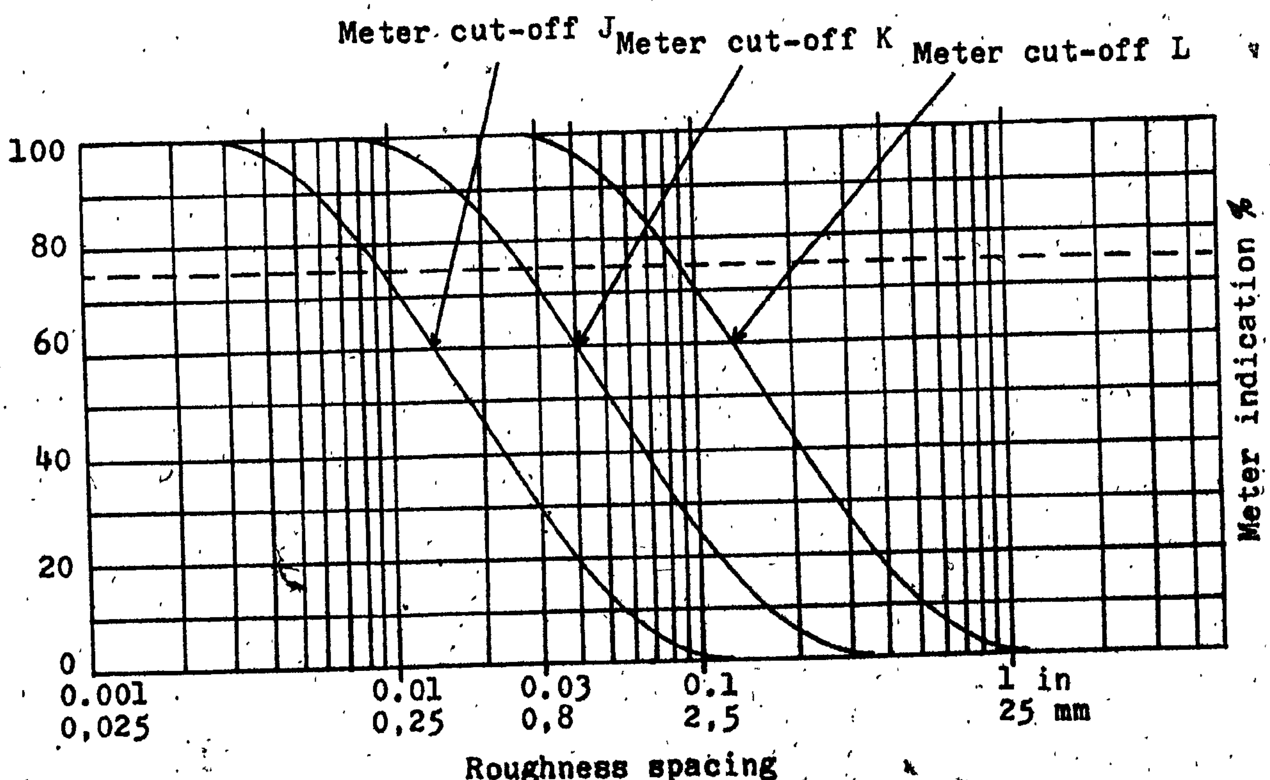


Fig. 2-7 Chart showing effect of cut-off on meter indications.

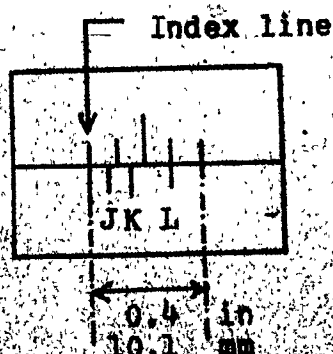


Fig. 2-8 The traverse scale.

equal to 0.03 in (0,8 mm).

c) Crests up to 0.375 in (9,5 mm) spacing can be recorded by the use of an independent datum.

d) The finite dimension of the stylus tip and other factors limit the minimum spacing of roughness which can be accurately recorded. For accuracy at x100 speed and for roughness spacings down to 0.0001 in (0,0025 mm) there is not much reduction in amplitude.

e) The minimum CLA value that can be measured is limited by the inherent noise in the instrument. The noise will not exceed 0.6 μin (0,015 μm) CLA with the Small Bore Pick-up or 0.3 μin (0,0075 μm) with all other pick-ups, in the worst case, i.e., when supported by the Straight Line Datum Attachment. In the conditions under which most measurements are made the noise figure will be less, but of course the above figures do not include noise due to external vibration.

2.3 The "Retro-Reflective Unit" Method

The "Retro-Reflective Unit" (RRU), see Fig. 2-9, offers a way of continuously measuring roughness by a non-contacting method and a new way of examining the structure of the paper surface. As it will be seen in Chapter 4, by comparing, the results from both the T4 and RRU methods appear to be compatible, to the extend that the results of the statistical analysis of the same surface by the two instruments give closely related values.

The paper surface is illuminated with a radiation from

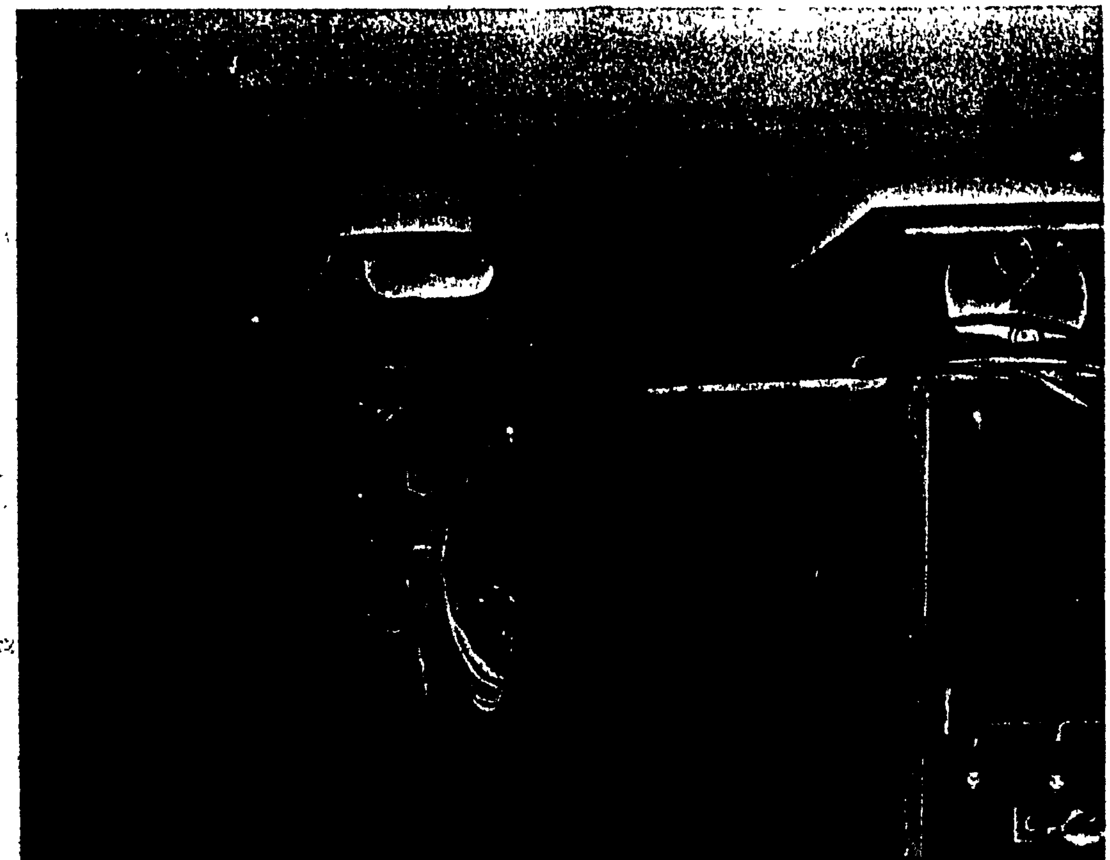


Fig. 2-9 The Retro-Reflective Unit.

First commercial installation of the head of the RRU in a large fine papermachine. In the above picture, the scan is obtained by letting the paper travel above a stationary head. The statistical processing is done by a special purpose hybrid computer not shown here.

an infrared Light Emitting Diode and the intensity of the reflected radiation is measured.

An irregular surface (4) will, in general, scatter a collimated beam of incident radiation diffusely, that is in all directions. At an angle of reflection equal to or slightly greater than the angle of incidence, a specularly reflected beam will also appear. The relative intensities of these two components depend on the roughness of the surface.

This phenomenon has been considered theoretically. When the wavelength of the radiation is less than or slightly greater than the r.m.s. roughness of the surface, scattering is generally considered to be a diffraction effect at the surface. At long wavelengths the problem is thought of in terms of geometrical reflections. A considerable amount of both theoretical and experimental work has been published on this subject (12,13).

For a random surface, with a normal distribution of heights and a specific autocorelation function included in the term m, the reflectance in the specular direction, ρ, is given by an equation of the form:

$$\rho = \rho_0 \exp - \left(\frac{K_1 \sigma \cos \theta}{\lambda}\right)^2 + \rho_0 K_2 m \psi \left(\frac{\sigma}{\lambda}\right)^4 \ldots\ldots$$

where ρ_0 is the reflectance from a smooth surface under identical conditions, σ is the root mean square (r.m.s.) roughness, m includes other roughness factors, θ is the angle of incidence, λ is the wavelength of the radiation, ψ includes instrument factors and K_1, K_2 are constants.

The first part of the equation is due to the specular component and the second to the diffuse.

Since the reflection of the light is not purely specular (i.e., paper does not behave like a mirror), the RRU signal is related to the derivative of the surface (i.e., the rate of change of the roughness), in an unclear manner. Therefore it will be necessary to integrate it, in order to be able to further process it, with the same procedure as in the T4.

Distortion due to oblique illumination causes shadows which mask roughness to some extent. This phenomenon is analogous to the distortion of roughness by the size of the stylus in the T4 method.

The RRU signal is very complicated and there are two ways to study and understand it:

a) To relate it to the true geometry of the surface in a stochastical manner, and

b) To try to reconstruct the surface geometry through real time signal processing (which is under way).

CHAPTER 3

EXPERIMENTS

The basic concept of the experimental work done, was to use one measurement method which in general is giving acceptable results and has been widely accepted (the T4), and to compare these results with the results from the RRU method, presently under development.

In Fig. 3-1 a flow chart of the experimental procedure followed by both the T4 and RRU methods (including data processing) is shown.

3.1 Measurements with the "Talysurf 4"

3.1.1 Brief Description of the Experimental Set-Up

Before taking the final measurements, the instrument was subjected to the following tests in order to secure maximum correctness of the results:

a) Check of the amplifier gain

b) Balance Test

c) Phase Test

d) Sensitivity Test

e) Recorder adjustment

f) Pick-Up Test

The paper sample is attached on a glass cylinder so that the direction of lay to be orthogonal (for cross direction), or parallel (for machine direction) to the cylinder's

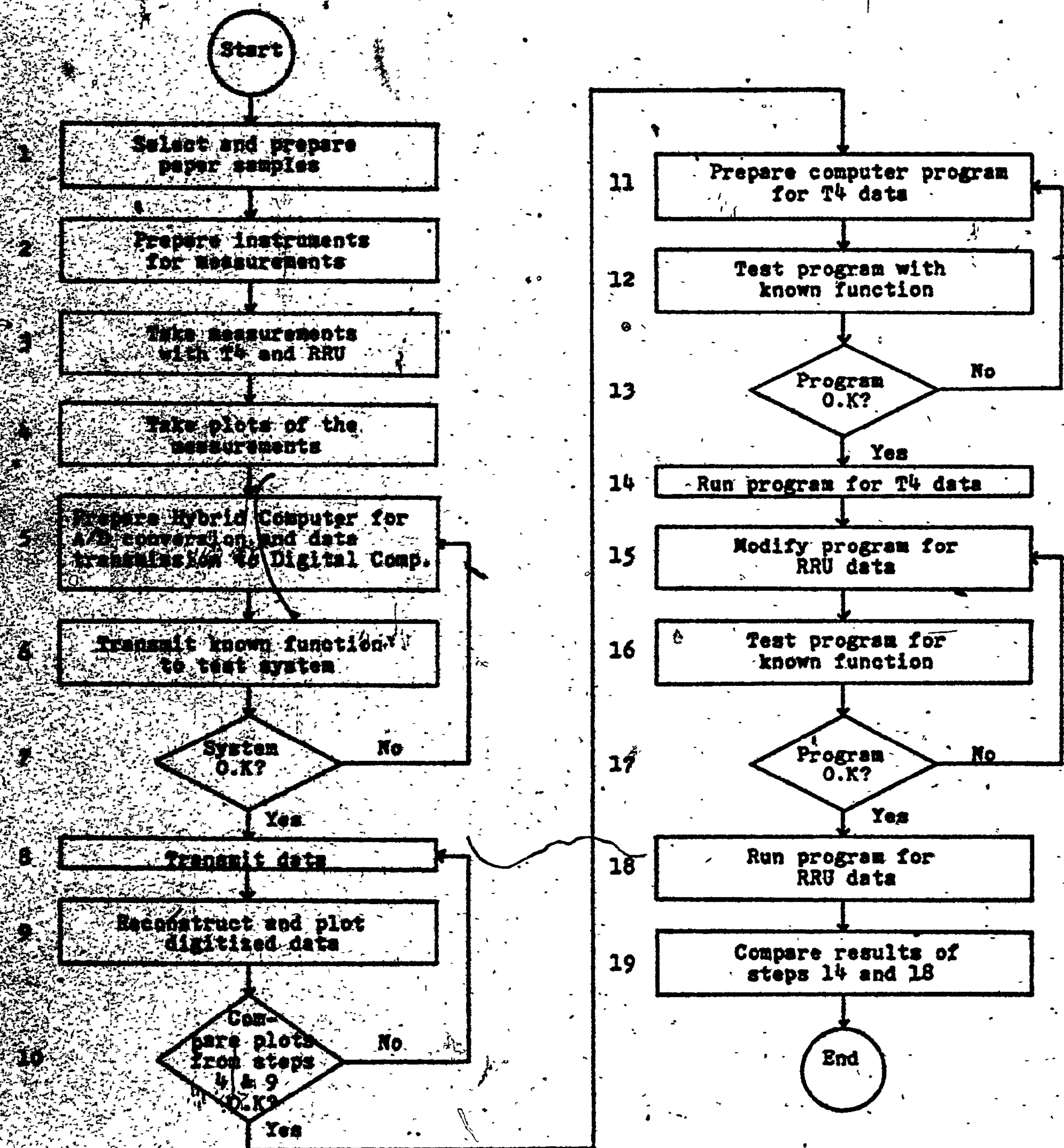


Fig. 3-1 Experimental procedure flow chart.

axis.

The reason a glass cylinder was used, is the fact that glass has a minimum possible roughness and in the case of thin paper it is desirable that the roughness of the supporting surface does not affect the roughness of the paper sample we want to measure. Further, the sample is placed under the stylus, so that the stylus is traversing the paper surface parallel to the cylinder's axis.

Before taking any final measurements it was desirable to check whether the stylus was "jumping" over the fibers or "slicing" them. This was checked using a stereoscope of sufficient magnification.

It was observed that the stylus was not slicing the fibers, so we could proceed.

The maximum traversing length of the stylus on the paper used, was 10.1 mm.

A schematic of the experimental set-up with all associated instruments is shown in Fig. 3-2.

The external amplifier, microphone and earphones were used in order to be able to record, before each signal recording, the specifications of each paper sample.

Care had to be taken, so that the magnetic tape recorder to be properly calibrated and the amplitude of the signal not to exceed the 20 Volts (the saturation voltage of the amplifiers of the recorder).

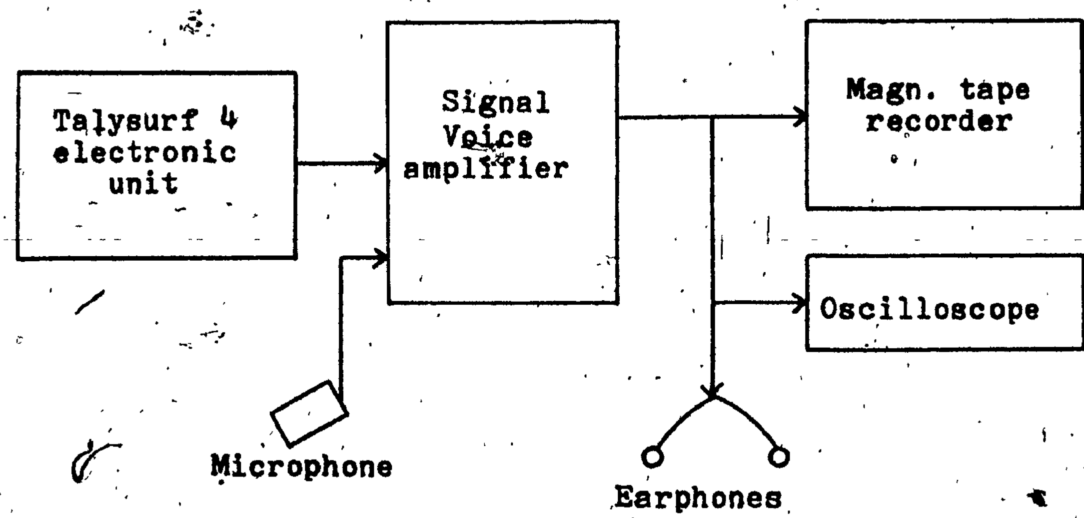


Fig. 3-2 Experimental set-up.

3.1.2 Results of the Measurements

We were given 10 paper samples and for each sample measurements were taken machine direction and cross direction. The signal obtained from each measurement was recorded on the magnetic tape and the CLA values were taken from the CLA meter of the T4.

The results appear in Table 3-1.

In Fig. 3-3 the recordings of 3 different samples are shown, as they were obtained from the T4's pen recorder.

3.1.3 Comments on the Method

The T4 method appears to be working for lab testing. There is consistency in the results (CLA values), but there are several drawbacks.

a) It is an "off line" instrument.

b) Requires direct contact between the stylus and the paper surface.

c) The maximum length of the paper sample that can be tested is approximately 10.1 mm.

d) As it was seen, the stylus has certain limitations regarding the size of the roughness it can measure, but it has also limitations on the bandwidth.

e) The measuring speed is very slow comparing to the production speed for "on line" applications.

Also special care must be taken so that the paper sample is well attached on the glass cylinder, and the stylus does not press very hard on the surface. Careful and lengthy calibration is needed.

TABLE 3-1. CLA values for 10 paper samples.

Paper sample	CLA value: Machine direction	CLA value: Cross direction	Talysurf 4 magnification
340±5	4.30 µm	4.50 µm	1 (500)
300±5	4.10 µm	4.00 µm	1 (500)
210±10	3.20 µm	3.80 µm	1 (500)
180±10	3.10 µm	3.10 µm	1 (500)
160±10	1.50 µm	1.60 µm	2 (1000)
115±5	1.25 µm	1.35 µm	2 (1000)
100±5	1.20 µm	1.25 µm	2 (1000)
90±5	1.10 µm	1.15 µm	2 (1000)
35±2	0.151 µm	0.130 µm	3 (2000)
5±2	0.055 µm	0.062 µm	3 (2000)

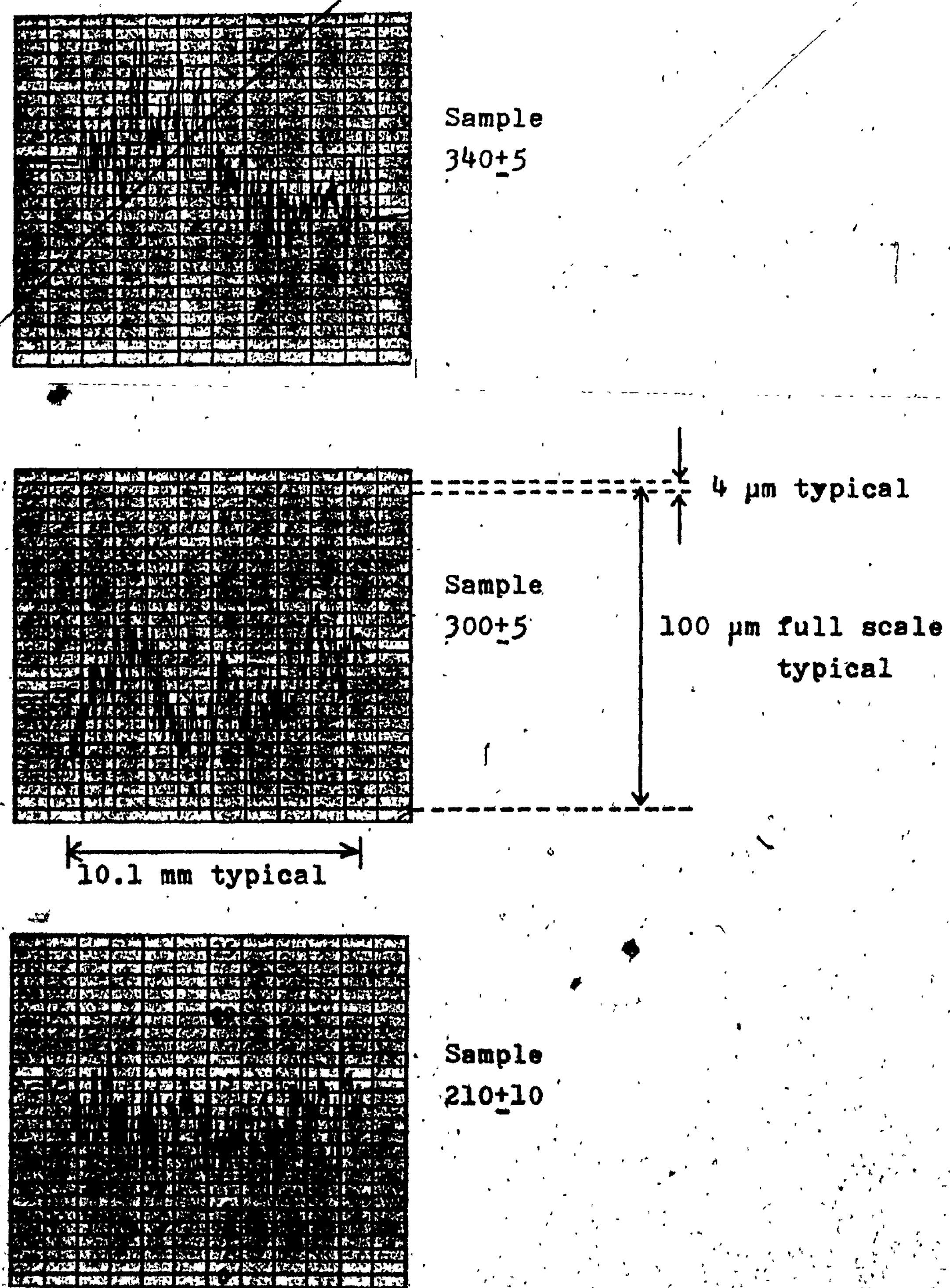


Fig. 3-3 Chart recordings of 3 paper samples. Magnification switch at 1, magnification 500.

On the recorded measurement signal there is a higher frequency noise, which must be rejected before further processing of the signal. This will be achieved, as it will be seen later, by using a Rockland Low Pass Filter, before feeding the signal to the Analog to Digital Converter.

The T4 is giving us a fairly accurate description of the geometry of the paper surface because the stylus size is small when compared with the smallest feature of the surface we are interested in. Hence, the T4 was used as reference for evaluating the RRU.

3.2 Measurements with the "Retro-Reflective Unit"

3.2.1 Brief Description of the Experimental Set-Up

The paper sample (a strip of approximately 0.5 in width and 11 in length) is attached on a metal reel (see Fig. 3-4). The axis of the reel is vertical to the machine direction of the paper.

The reel rotates, driven by a motor of adjustable speed. We worked with the relatively slow speed of approximately 140 RPM ($\approx$ 1540 in/min), because we wanted to have relatively slow signal to record (see Chapter 3.3 A/D Conversion and Data Transmission). Since The RRU has a field of view of 0.1 mm, we have as bandwidth of the signal:

$$\frac{1540}{60} \times 25 \approx 642 \text{ Hz}.$$

3.2.2 Results - Comments

We used the same 10 paper samples that were used to

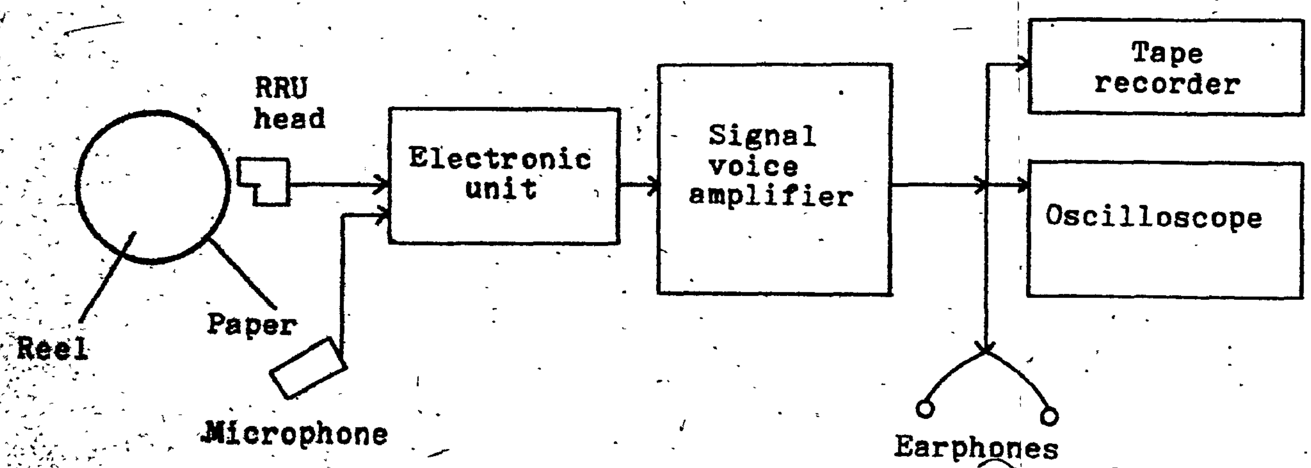


Fig. 3-4 Experimental set-up.

take measurements with the T4, but only Machine Direction measurements were taken, because the final on-line instrument is taking Machine Direction measurements.

In Fig. 3-5 a photograph of the signal is shown as it is seen on the oscilloscope.

The signal from each measurement was recorded on magnetic tape. Before each signal the specifications of each paper sample were also recorded.

The method appears to give useful results. It offers the advantage of continously measuring the roughness without contact with the surface and, relatively, with high speed.

In our case we were restricted on 11 in length of paper sample (for on-line applications the measuring can be done on a contiuous basis) although for further processing only fraction of this length will be used, without affecting the accuracy of the results. This can be seen as follows: Suppose our samples have a Gaussian Distribution. The CLA value is given by:

$$CLA = \frac{1}{N} \sum_{1}^{N} \sqrt{(y_i - \bar{y})^2}$$

and the variance (14) of a sample is given by:

$$s^2 = \frac{1}{N} \sum_{1}^{N} (y_i - \bar{y})^2$$

Combining the above two equations we find:

$$s^2 = N\ CLA^2$$

Let us apply a variance confidence test (15) in our first paper sample which has CLA = 4.30 (as given by the T4).

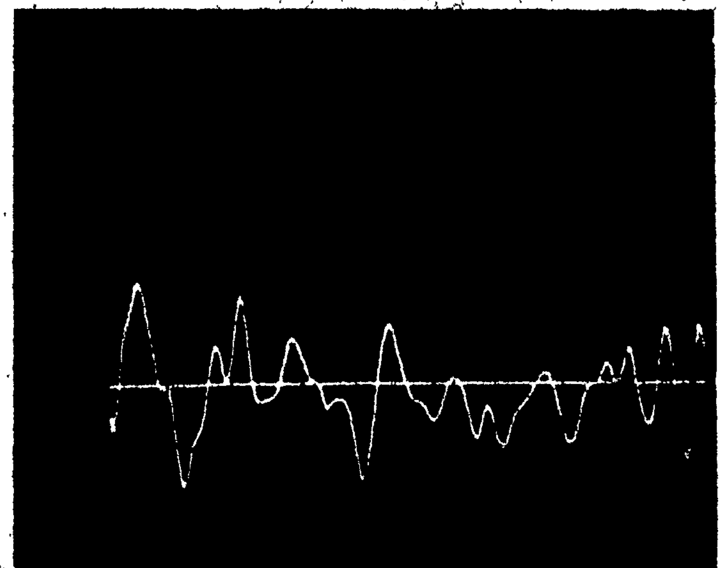


Fig. 3-5 Signal from the RRU.
(0.1 msec/cm, 5 V/cm).

We will ask the confidence interval for the measured variance of the sample s^2, for 4000 data points and with a probability of 95%.

Applying the procedure for "Determining of a Confidence Interval for the Variance of a Normal Distribution" (15) we find that:

$$72015 \leq \sigma^2 \leq 76523 \text{ and } 4.25 \leq CLA \leq 4.37$$

where σ^2 s^2 is the variance of the normal distribution. So, by using 4000 points we can say with probability 95% that the real value of the CLA of our distribution is between 4.25 and 4.37.

Further, taking in mind that we will be working with 4000 data points taken within approximately 10 mm of paper, we are having one data point every $\frac{0.010}{4000} \approx 2.5$ μm, which is sufficient if we compare it to the duration of the crest excursion which, as it will be seen, is of the order of 60 to 100 μm.

As it was mentioned, the signal obtained from the RRU is related to the derivative of the roughness in an unclear manner and it will be integrated before further processing. This integration was thought to be done after the A/D conversion, solely for the purpose of this report.

3.3 Analog to Digital Conversion and Data Transmission

Since the data (as they were recorded on the magnetic tape) are in continuous form and we want to process them further with Digital Computer, it was necessary to convert them to Digital form and this form to be compatible with the Digital Computer to be used.

3.3.1 <u>The Data Link and the ADCAT System</u> (16,17)

The Data Link (Hybrid Computer Hardware Package) and the ADCAT system is an Analog to Digital Conversion package, designed for the EAI 690 Hybrid Computer and the CDC 6400 Digital Computer.

It processes signals from 2 to 8000 Hz at a sampling rate of twice the specified frequency (and that is why it was important to have low speed (slow signal) of the reel, when taking measurements with the RRU).

In Chapter 3.2.1 we have seen that the bandwidth of the signal was approximately 642 Hz. For 2 x 8000 sampling rate we get $\frac{2 \times 8000}{642} \approx 25$ samples.

The maximum number of data points of a sample that can be transmitted is 7500.

Communication with the CDC 6400 is established through the telephone TWX system, in conjunction with the interactive subsystems of the CDC 6400.

The ADCAT system is specially designed so that it can handle signals from the "Talysurf 4" as well as from other sources (the RRU). Firstly, it requires a set of "Acquisition Parameters" to be specified. These parameters are:

a) Number of Data Points and

b) Sampling Frequency.

Secondly, it requires the "Transmission Parameters" to be specified. These parameters are:

a) Data File Name

b) Magnification (the magnification that was used on the T4, or 1 and 10 if other signal source was used, as the RRU) and

c) Error Abort Option (what to do in case of transmission error).

In Appendix I appears a print-out of the messages required to establish communication between the EAI 690 and the CDC 6400.

3.3.2 The Transmission Set-Up

In Fig. 3-6 a schematic of the transmission set-up is shown.

In Appendix I a print-out sample is shown from the TWX for the transmission.

The number of points that was transmitted per sample was 4000. (The computer program was also written to process 4000 points.) The sampling frequency was 1000 Hz for the signals from the T4 and 8000 Hz for the signals from the RRU.

The sampling frequencies were selected as follows: The continuous signals from both the T4 and RRU were analyzed with a spectrum analyzer and were found to include frequencies well below the specified sampling frequencies (except the superimposed higher noise frequencies).

In order to reject the noise a Rockland filter was used (Low Pass Filter) before feeding the signals to the

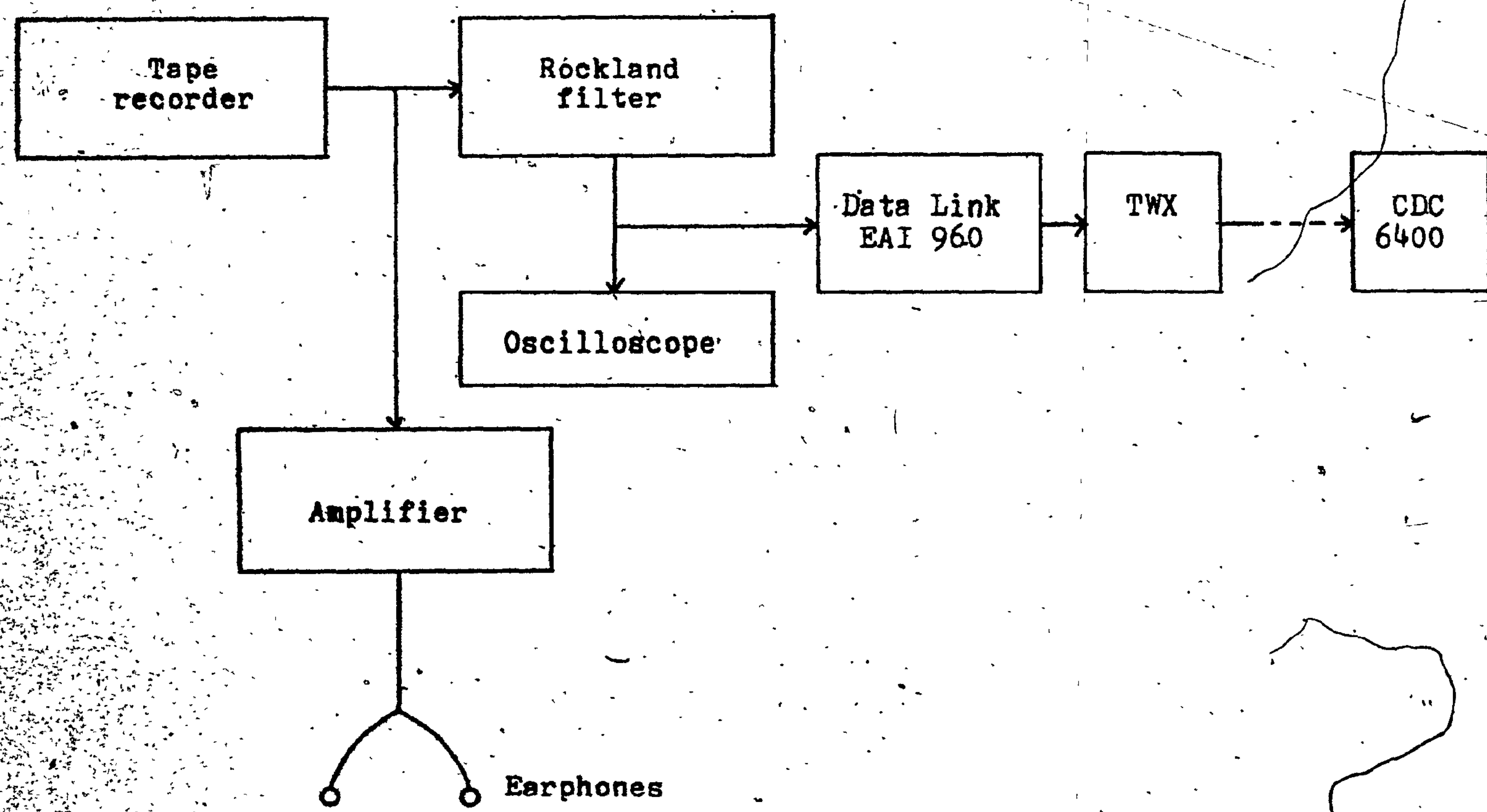


Fig. 3-6 The transmission set-up.

A/D converter of the Hybrid computer. The filter was set at the following cut-off frequencies:

100 Hz for the signals from the T4

25000 Hz for the signals from the RRU.

When transmitting signals from the RRU, the tape recorder was set at lower speed (3.75 in/sec) than the recording speed (60 in/sec), but of course different amplifiers were used and the recorder had to be recalibrated. The lower recorder speed was used again, in order to have slower signal.

Because of the relatively small number of data points (4000) and the low speed, only fraction of the duration of the signals (length of paper sample) was used, but this did not affect the results (see section 3.2.2).

3.3.3 Results

The transmission time was usually between 15 to 25 min. per file, depending on the work load of the CDC 6400. In Appendices II and III are shown 2 print-outs of the first data points of the same paper sample for measurements with the T4 and the RRU.

As further precaution against transmission errors the data points were reconstructed with a plotter linked to the CDC 6400 and the results were compared to plots of the continuous signals.

In Figs. 3-7 and 3-8 the same signal is shown before and after the transmission (reconstructed).

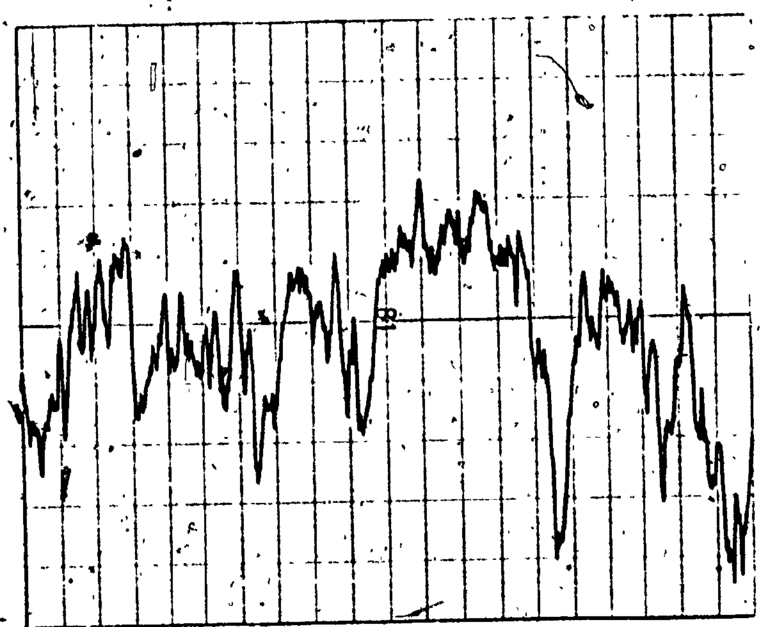


Fig. 3-7 Chart recording from the RRU. (20 mV/line sensitivity, 5 mm/sec speed).

RRU sample 300±5, continuous signal as recorded in the magn. tape. This portion of the signal after A/D conversion is given reconstructed in Fig. 3-8.

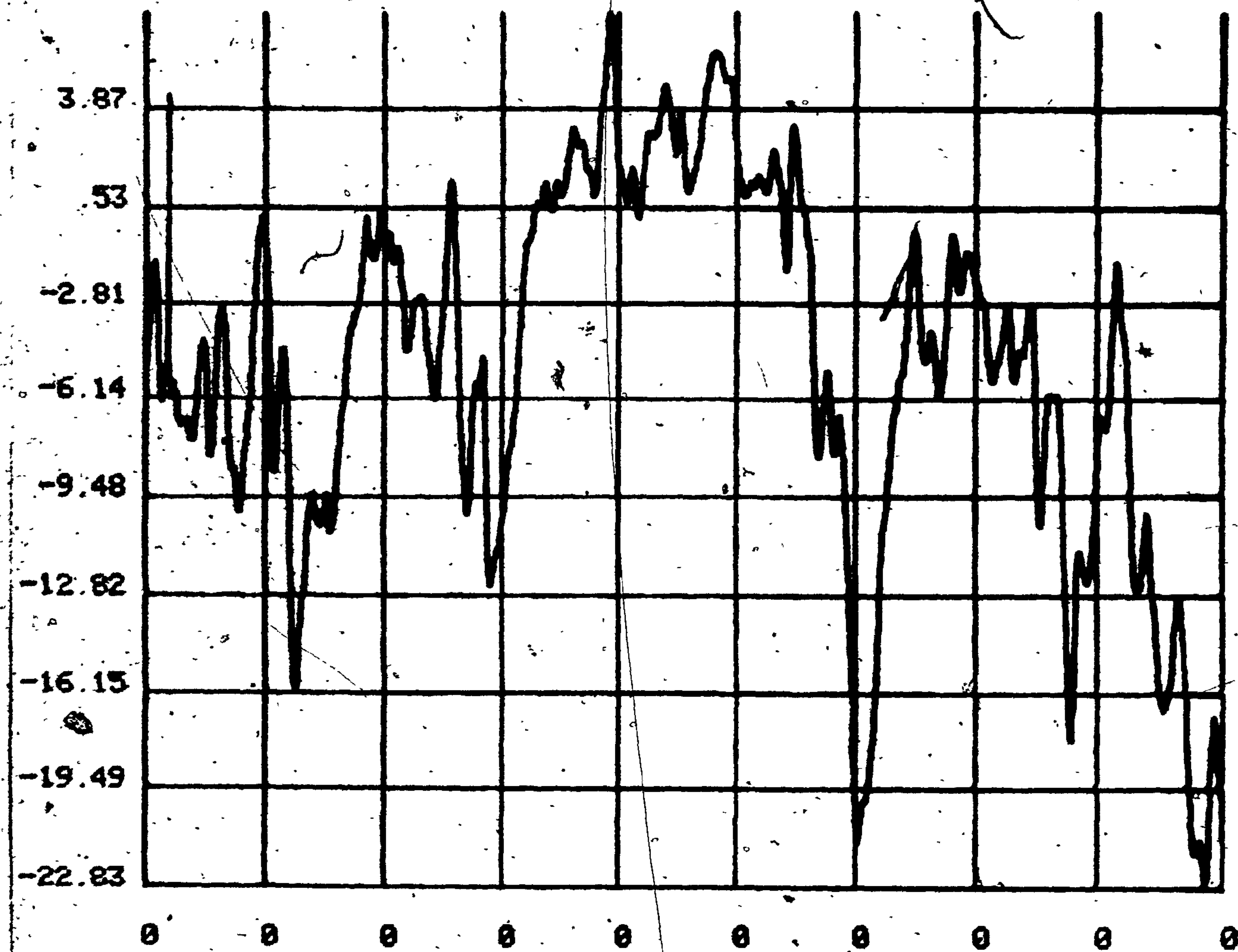


Fig. 3-8 RRU sample 300±5 reconstructed first 2000 data points.

3.4 The Computer Program

This program (see Appendix IV) was written in order to calculate the following seven parameters:

a) YB (Mean Value of the Data)

b) CLA (Center Line Average of the Data)

c) AVE (Average Value of the Data)

d) RMS (Root Mean Square of the Data)

e) ANC (Average Number of Crossings)

f) MCE (Mean Crest Excursion)

g) RMSCE (Root Mean Square of Crest Excursion)

The program is divided in different sections, the Main Program and seven Subroutines. This program is using simple and repetitive calculations and it will be, futher, analysed section by section.

3.4.1 The Main Program

In Fig. 3-9 a flow chart of the procedure followed in the program is shown.

The step numbers in the explanations below, refer to the number of steps in the flow chart.

STEP 1: The data are read from the mass storage,as they were transmitted, to the computer memory, and an array (Y) is formed containing 4000 data points.

STEP 2: A main DO LOOP starts here. On each repetition (pass) the Data Filter is changed (see subroutine Filter).

STEP 3: An other DO LOOP (nested) starts here, by calling the subroutine Limits.The subroutine Limits changes

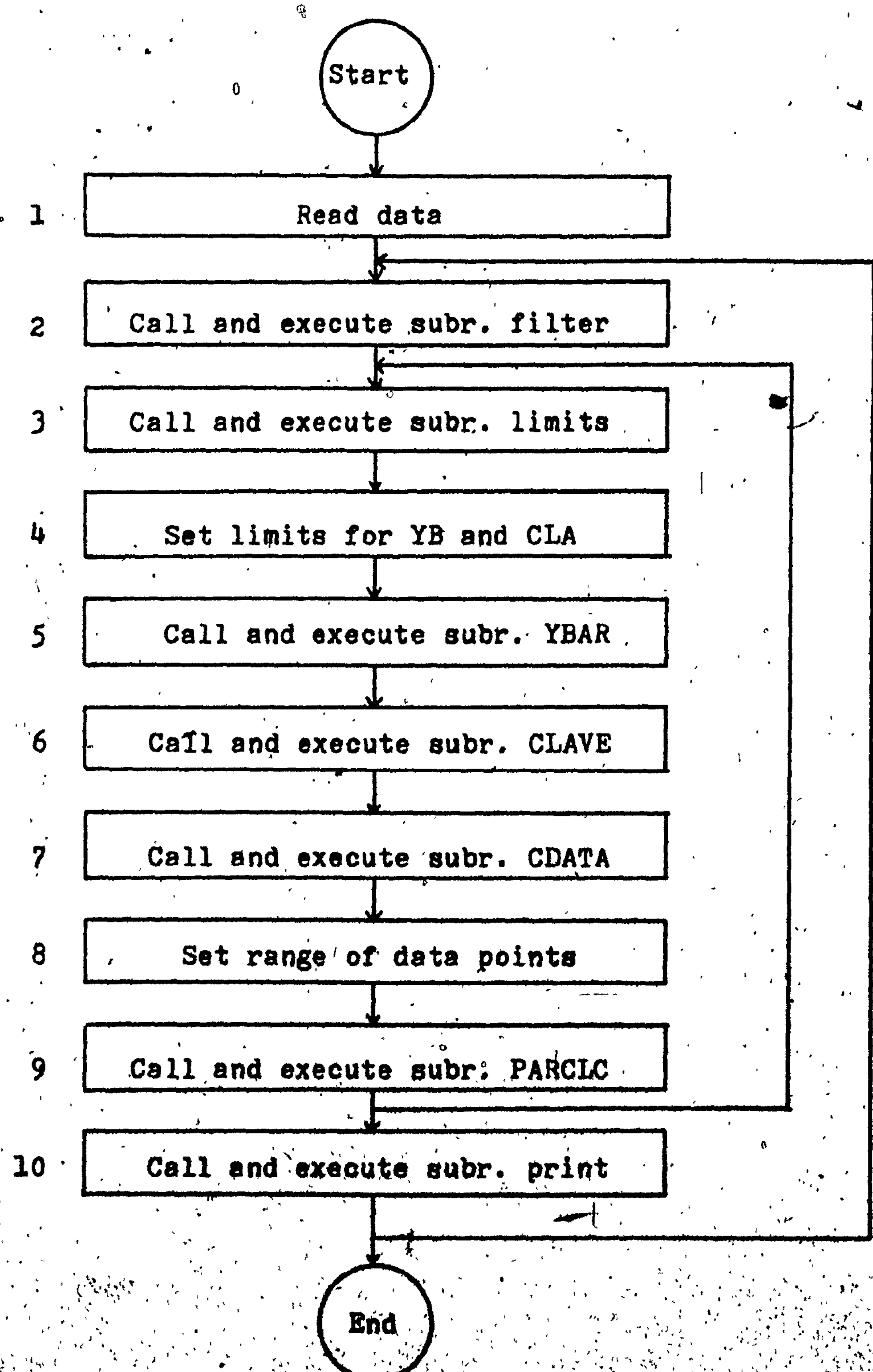


Fig. 3-9 The computer program flow chart.

the data limits on each pass through the filter loop, in order to achieve filtering effect on undesirable high values of the data.

STEP 4: The limits are implemented here for calculating the YB (Mean Value) and CLA (Center Line Average).

STEP 5: The YB is estimated here.

STEP 6: The CLA is estimated here.

STEP 7: The limits and control data required for calculations made in the next subroutine (PARCLC) are set here.

STEP 8: The range of data points is set here, for calculations made in the next subroutine (PARCLC).

STEP 9: This subroutine PARCLC, calculates the parameters ANC, AVE, RMS, MCE,and RMSCE for the specified range of data points and limits.

STEP 10: In this subroutine the parameters (final results) are printed.

3.4.2 Subroutine Filter

This subroutine serves to implement the filter change by calculating the required parameters on only part of the data array. So, a filtering action is achieved.

Then calculations of the same parameters are repeated in the next section etc., and finally the results are averaged to achieve the filtering effect.

Each filter section contains different number of data points: For ICUT = 1 contains 4000 points (no filter)

For ICUT = 4 contains 1000 points per section etc.

The parameter KNP is the number of data points in each filter section.

The parameter KUL indicates the number of passes (repetitions) through the filter loop (nested DO LOOP) for each of the filter values: For ICUT = 1 it is KUL = 1
For ICUT = 4 it is KUL = 300 etc.

3.4.3 Subroutine Limits

This subroutine changes the data limits on each pass through the filter loop, in order to achieve the filtering effect.

The parameter KLW sets the lower limit of the range of the data points to be treated during the pass through the filter loop. On each pass the lower limit is shifted by 10 data points.

The parameter KUP sets the upper limit of the range of the data points. On each pass it is shifted by 10 data points higher.

Therefore, in each pass only 20 data points are changed.

3.4.4 Subroutine YBAR

In this subroutine the mean value of the data is calculated within the previously specified limits.

The results for each filter pass are processed further in order to obtain the final (averaged) value.

The mean value is estimated through the formula:

$$YB = \frac{1}{LHI-LLO} \sum_{LLO}^{LHI} Y(I)$$ where

YB is the mean value

LHI is the high data limit for this filter section

LLO is the low data limit for this filter section

Y(I) is the data value

The final mean value is estimated by summing the mean values of all filter passes and dividing by the number of the filter passes.

3.4.5 Subroutine CLAVE

In this subroutine the the Center Line Average of the data is estimated within the specified limits for each filter pass. The calculation is made through the formula:

$$CLA = \frac{1}{LHI-LLO} \sum_{LLO}^{LHI} \left| Y(I) - YB \right|$$

The estimates from each filter pass are summed and averaged (divided by the number of passes) in order to obtain the final result.

3.4.6 Subroutine CDATA

In this subroutine the limits and control data that will be used in the next subroutine are specified.

DY is the vertical resolution required for calculating the Average and RMS values.

YREF is the most negative value of the data accepted by the program.

L is the number of levels above YREF, used to quantize the data. Each level is more positive than YREF and differs from the previous level by DY.

YMAX is the maximum positive value of data accepted by the program.

DS is the horizontal resolution (distance between data points).

ATIME is the time offset used in calculating the Mean Crest Excursion and the RMS of the Crest Excursion.

YLEVEL is the vertical level above which horizontal excursions are to be detected for calculation of the MCE and RMSCE.

LA is the maximum number of data points in an horizontal excursion, above YLEVEL, acceptable to the program.

3.4.7 Subroutine PARCLC

In this subroutine the following five parameters are calculated for the specified range and limits of data points.

AVE (Average Value)

ANC (Average Number of Crossings)

RMS (Root Mean Square)

MCE (Mean Crest Excursion)

RMSCE (Root Mean Square of Crest Excursion)

In Fig. 3-10 is shown a detailed flow chart of this subroutine.

PDEN is the vertical probability density, initially set at zero.

TEXC is the horizontal probability density, initially set at zero.

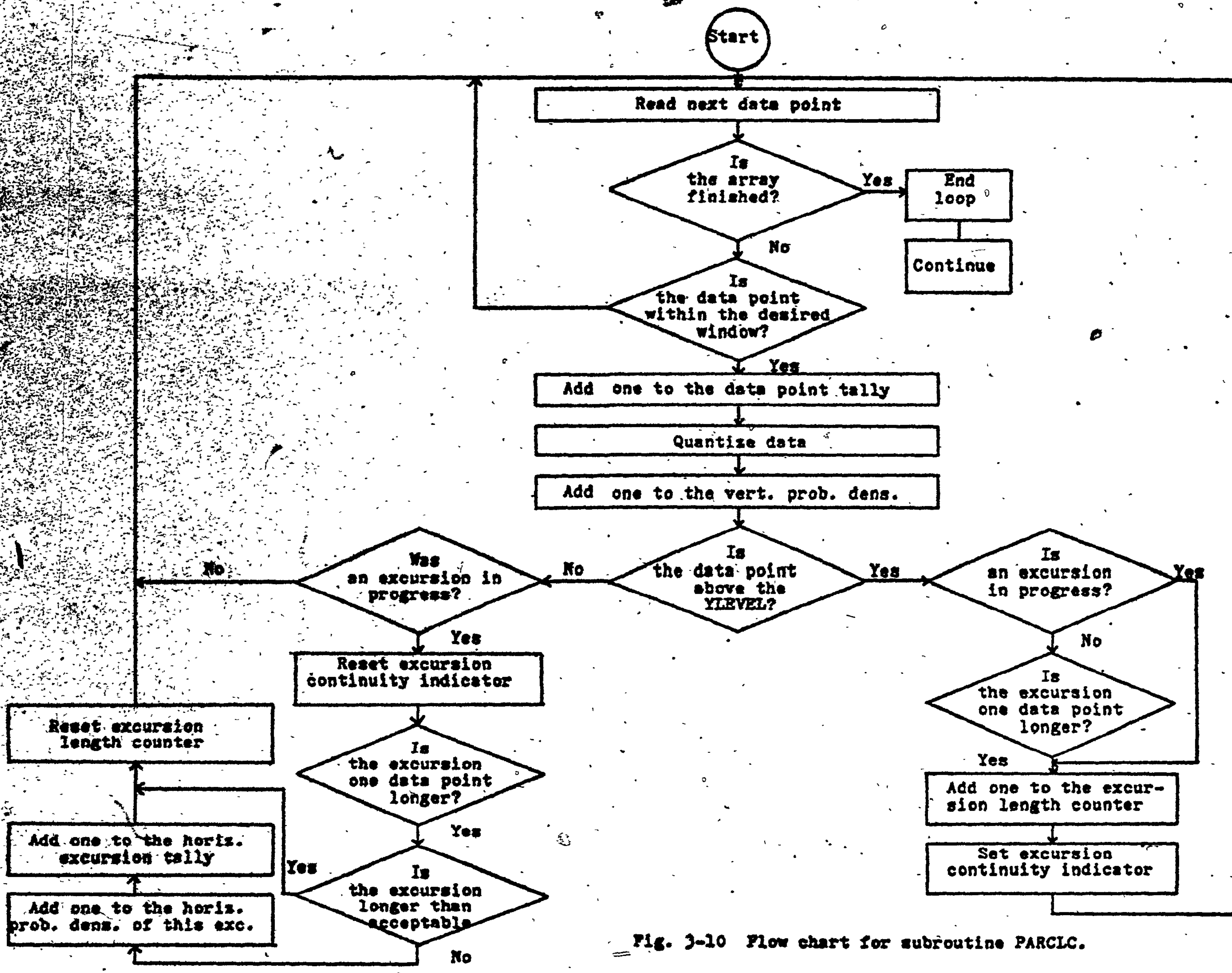


Fig. 3-10 Flow chart for subroutine PARCLC.

66

ATIME is the minimum acceptable horizontal excursion (the time offset initially set at zero).

K is the excursion continuity indicator. When K = 1, an excursion is in progress. When K = -1, an excursion is not in progress.

LDA is the excursion length counter, initially set at zero.

SUM1 is the data point counter, initially set at zero.

SUM2 is the excursion counter, initially set at zero.

J is the parameter which converts the data Y(I) into the level number above YREF corresponding to Y(I).

The ANC (Average Number of Crossings per unit length) is calculated through the formula

$$ANC = SUM2 \times \frac{4000}{l \times KNP} \quad \text{where}$$

SUM2 is the number of excursions,

KNP is the number of data points in each filter section,

4000 is the total number of data points, and

l is the length of the paper sample.

For the T4 it was l = 0.4 in (≈ 10155.55 μm) equal to the maximum traversing length of the stylus.

For the RRU it was used the same length, as follows: the reel of the RRU, on which there was attached a paper sample of approx. 11 in. was rotating with 140 rpm.

The RRU was scanning 140 x 11 = 1540 in/min, or

$$\frac{1540}{60} = 25.66 \text{ in/sec of paper.}$$

When transmitting the data, for 4000 points were needed 0.25 secs, and 25.66 x 0.25 = 6.42

When recording, the speed was 60 in/sec, but when transmitting the speed of the recorder was 3.75 in/sec, so the length of the paper was

$$\frac{6.42 \times 3.75}{60} = 0.4 \text{ in.}$$

The AVE (Average Value of the input data) is calculated through the formula:

$$AVE = \sum_{K=1}^{L} PNT(K) \times PDEN(K)$$ where

AVE (RIVE) is the average value,

PNT is the quantized data value,

PDEN is the vertical probability density, and

L is the number of quantized data values.

The RMS value of the vertical excursions is calculated through the formula:

$$RMS = \sum_{K=1}^{L} \sqrt{(PNT(K) - AVE)^2 \times PDEN(K)}$$

The MCE (Mean Crest Excursion of the horizontal excursions) is estimated through the formula:

$$MCE = \sum_{I=ITIME}^{LA} PNT(I) \times TEXC(I)$$ where

ITIME is the lower acceptable excursion length, LA is the upper acceptable excursion length,

PNT is the quantized data level, and

TEXC is the probability density (horizontal) of the quantized data level.

The RMSCE (RMS of Crest Excursion) is estimated through the formula:

$$RMSCE = \sum_{I=ITIME}^{LA} \sqrt{(PNT(I) - MCE)^2 \times TEXC(I)}$$ where

the parameters are specified as for estimating the MCE.

3.4.8 Subroutine PRINT

This subroutine gives a print-out of the averaged (over the filter sections) parameters.

3.4.9 The Modified Main Program (Appendix V)

As it was mentioned, the signal that was recorded from the RRU was the derivative of the signal we needed, therefore the Main Program was modified for processing the data from the RRU by numerically integrating them.

Further, we will briefly describe the procedure.

It was used a difference equation for step by step integration (18).

Consider the differential equation

$y' = Ay$ (3.4-1) with

$y(t_0) = y_0$ and A = constant.

Using the Euler-Couchy formula

$y_{k+1} = y_k + hy'_k$ (3.4-2) , $k = 0, 1, \dots, n-1$

and substituting eq.(3.4-2) into eq.(3.4-1) we get:

$$y_{k+1} - (1 + Ah)y_k = 0 \qquad (3.4\text{-}3)$$

which is our difference equation.

The solution of eq.(3.4-3) is:

$$y_n = y_o(1 + Ah)^n = y_o(1 + Ah)^{(t_n - t_o)/h} \qquad (3.4\text{-}4)$$

For step by step application the solution takes the form:

$$y_{k+1} = y_k(1 + Ah)^{(t_{k+1} - t_k)/h} \qquad (3.4\text{-}5)$$

In eq.(3.4-5), y_k is known (stored in the computer), and we used:

$h = \frac{1}{4000} = 0.000025$ (we have 4000 points total),

$A = 1$ (arbitrary),

$t_{k+1} - t_k = 0.25$ (arbitrary).

Before the main (filter) DO LOOP in the Main Program and between STEP 1 and STEP 2, it was inserted an other DO LOOP (with 4000 passes) in order to execute the numerical integration according to the eq.(3.4-5).

CHAPTER 4

RESULTS - COMMENTS

In this chapter the experimental results will be presented with comments, and comparison will be done of the results of the methods discussed in chapter 2.

During all measurements, transmissions and data processing precautions were taken, so that to avoid (or at least to minimize) any systematic or random errors. However, the results for some of the parameters do not coinside completely, when comparing the two methods that we used (T4 and RRU), and the reasons for this will be discussed.

4.1 Comparison of Sheffield and RRU Roughness

Although no experiments were done with the Sheffield instrument, in Fig. 4-1 are shown, for reference purpose, the results of different measurements with the Sheffield and RRU instruments, for different types of paper.

In Fig. 4-2, also, are shown two roughness profiles for the same paper. One profile is giving the average Sheffield roughness and the other the average RRU roughness.

These results suggest that the correlation between the Sheffield and the RRU is reasonably good, hence it will be enough to compare the RRU and T4.

4.2 Experimental Results - Comparison

The Tables 4-1, 4-2 and 4-3 show the results for 3 different samples. We will, further, consider the results for each parameter and comment on them.

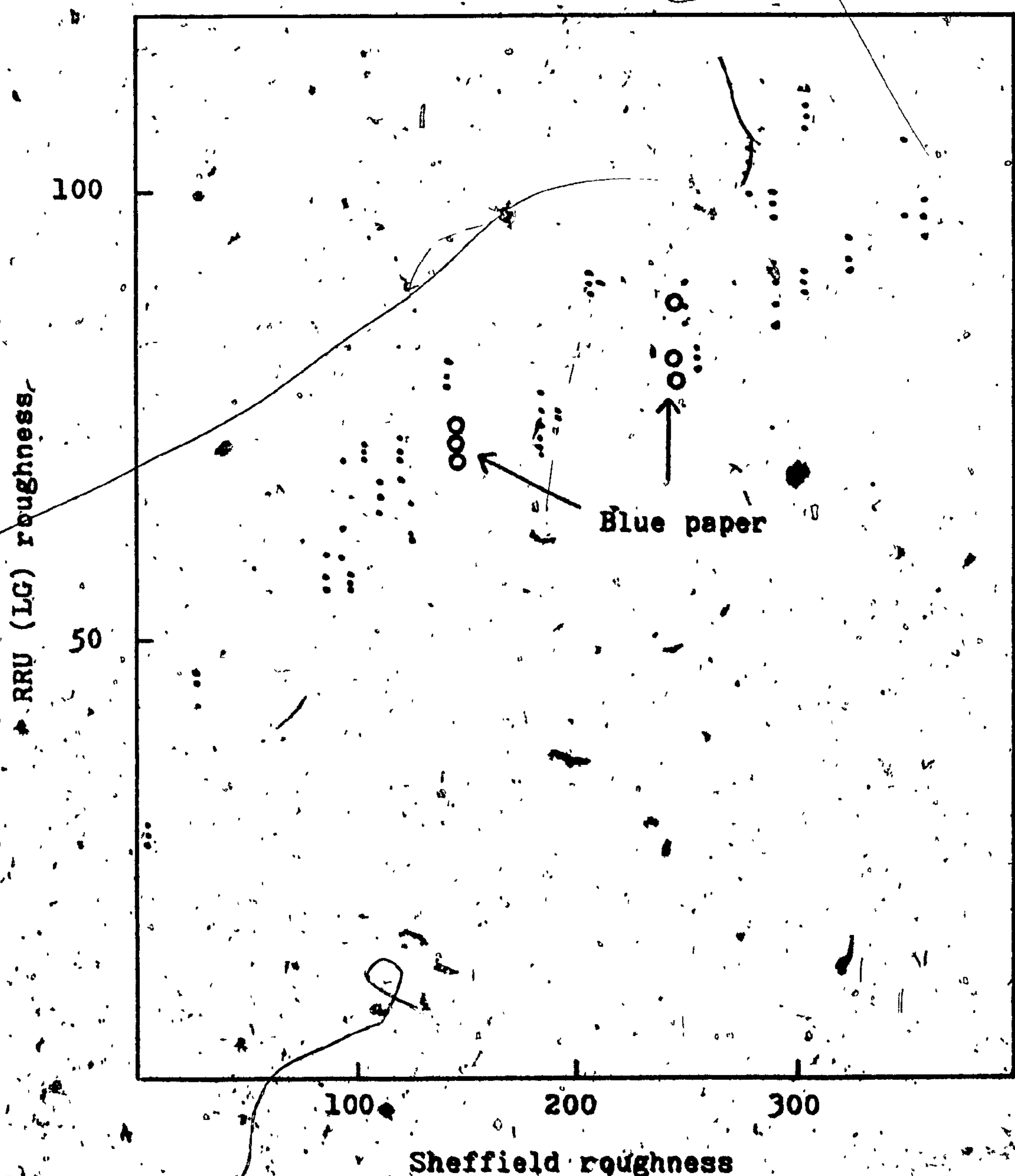


Fig. 4-1 Comparison of RRU (LG) and Sheffield roughness measurements (2600 FPM).

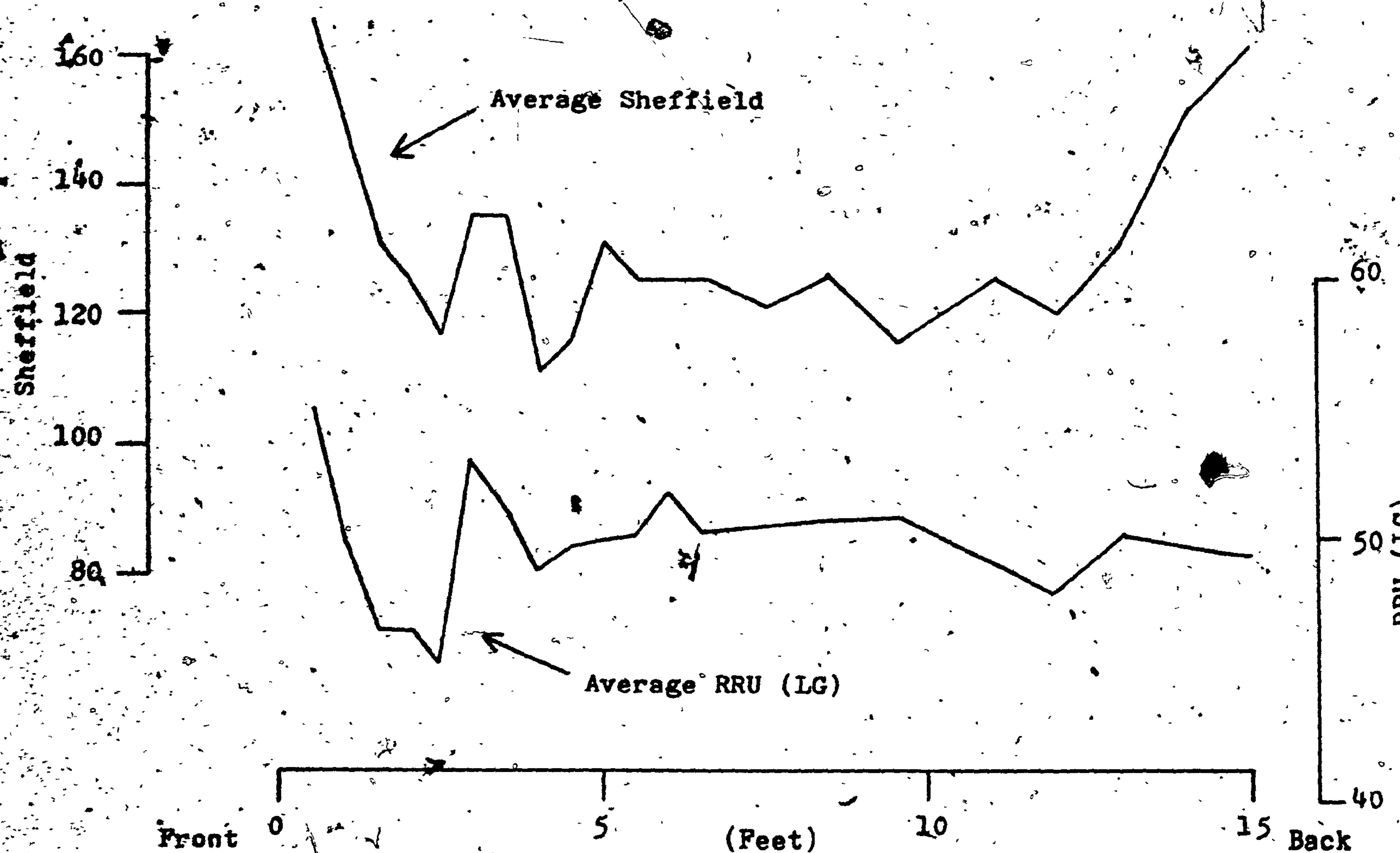


Fig. 4-2 Comparison of Sheffield and RRU (LG) roughness profiles.

TABLE 4-1. Comparative results. Sample 340±5.

Parameter	T4	T4 data computer	RRU data computer
Mean Value	-	-1.06388	-0.33568
CLA	4.30	4.35274	0.04334
ANC	-	8.66521	9.45295
RMS	-	4.30656	0.06117
MCE	-	74.43561	68.23264
RMSCE	-	47.30285	40.47858

TABLE 4-2. Comparative results. Sample 300±5.

Parameter	T4	T4 data computer	RRU data computer
Mean Value	-	5.73179	-0.28876
CLA	4.10	5.33900	0.05025
ANC	-	5.90810	0.39168
RMS	-	5.87945	0.06783
MCE	-	60.25630	66.16046
RMSCE	-	63.89711	54.14564

TABLE 4-3. Comparative results. Sample 210±10.

Parameter	T4	T4 data computer	RRU data computer
Mean Value	-	3.59631	-0.21054
CLA	3.20	4.70997	0.04689
ANC	-	5.51422	6.14826
RMS	-	4.80687	0.05746
MCE	-	100.83016	94.81740
RMSCE	-	79.64431	71.92135

4.2.1 The Mean Value

The mean values for all samples, from the T4 and RRU, differ. This difference is due to the variable (and different for each instrument) zero level (see example in 4.2.2).

The mean values obtained by processing signals from the RRU show consistency.

The mean values obtained by processing signals from the T4 are positive for samples # 2 and # 3, and negative for sample # 1. This is due, also, to the zero adjustment of the T4 while taking measurements, which is difficult since it depends upon the position of the stylus.

The mean value as such, does not carry information for the T4, whereas it does for the RRU, since it is related to the color of the paper. For this reason the mean value is not a factor for the comparison of the two methods.

4.2.2 The CLA Value

In general, we can say that there is consistency between the results from the T4 and RRU (note that the results from the RRU have to be multiplied by 100 because of magnification and scaling factors).

The zero level adjustment does not affect the CLA value. This can be seen from the following example:

Consider the 4 data points as shown in Fig. 4-3. Their mean value is:

$$\bar{y}_1 = \frac{1}{4} \sum_{1}^{4} y_i = \frac{1}{4}$$

Their CLA value is:

$$CLA_1 = \frac{1}{4} \sum_{1}^{4} \left| y_i - \bar{y}_1 \right| = \frac{11}{4}$$

Now, suppose we shift the zero level lower by 1 unit, while the absolute distances between the data points remain the same. The new arrangement is shown in Fig. 4-4, and the new mean value is:

$$\bar{y}_2 = \frac{1}{4} \sum_{1}^{4} y_i = -\frac{3}{4} \qquad \text{and}$$

the new CLA value is:

$$CLA_2 = \frac{1}{4} \sum_{1}^{4} \left| y_i - \bar{y}_2 \right| = \frac{11}{4}$$

i.e. although the mean value changed, the CLA value remained the same.

As it can be seen, the results from the CLA meter of the T4 are systematically lower than the other results. This was probably due to over-damping of the CLA meter.

4.2.3 The Average Number of Crossings

There is consistency between the results, with exception the result from the RRU for sample # 2, where, as we believe, the speed of the reel, on which the paper sample is attached, was not properly adjusted.

4.2.4 The Root Mean Square Value

In general, there is consistency between the values from the T4 and the RRU (note that the values from the RRU

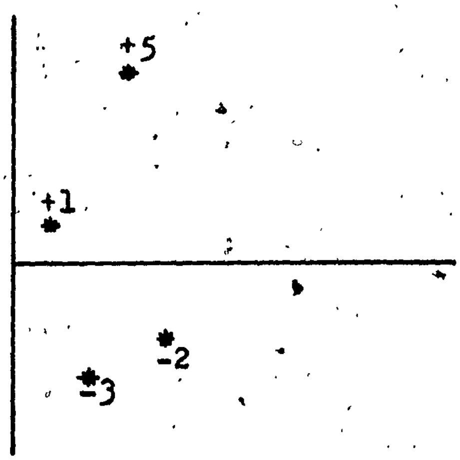


Fig. 4-3 Relative position of data points.

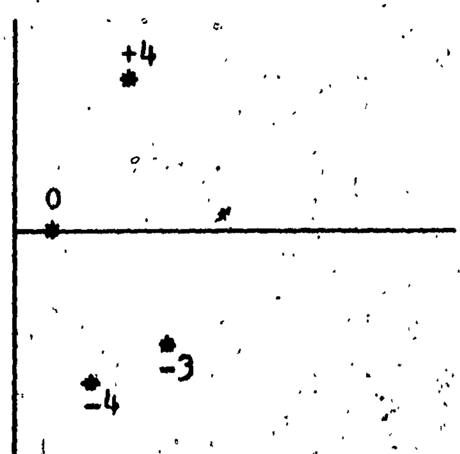


Fig. 4-4 Shifted data points.

have to be multiplied by 100, because of magnification and scaling factors.

In the Table 4-4 we are testing the ratio RMS/CLA, for confirmation of a rule of thumb (4) according to which it must be: $RMS/CLA \approx 1.2 \pm 0.1$

4.2.5 The Mean Crest Excursion

There is consistency between the results from the T4 and the RRU, although there is a small difference between the results for the same sample. This difference is less than 10%.

4.2.6 The Root Mean Square of Crest Excursion

Here, again, there is consistency between the results for the different samples.

The results for the same sample differ, with the results from the RRU been consistently lower than the results from the T4.

4.3 Conclusion

4.3.1 Comments

The RRU method offers the following advantages:

a) It is a non-contact method,

b) It can be a continuous method, and

c) It is a fast method when proper hardware implementation is made (see Fig. 4-5 for RRU roughness versus production speed).

The above advantages are valuable for "on line" industrial applications, while the T4 is useful only for

TABLE 4-4. RMS/CLA ratio for 3 samples.

	T4	RRU
sample 340±5	0.99	1.42
sample 300±5	1.10	1.34
sample 210±10	1.02	1.23

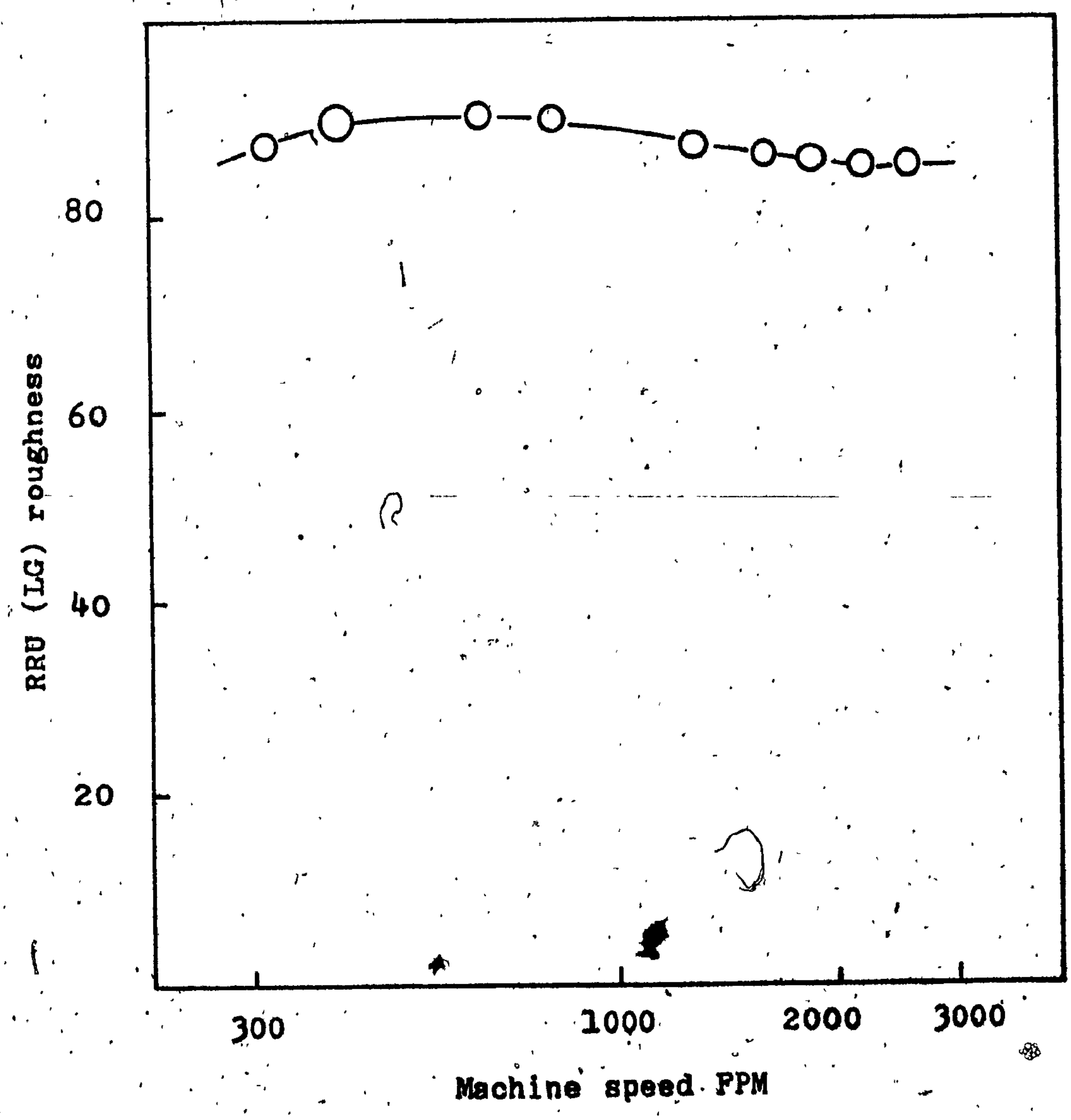


Fig. 4-5 Graph of machine speed versus RRU (LG) roughness.

laboratory testing.

It is believed that the results are valid, the discrepancies being due mainly to experimental oversight and not procedural (or method) deficiency.

The small number of samples considered does not permit yet definitive and clear answers.

The techniques used for the experimental set up and the analysis were cumbersome, long, difficult at best. Systematic surface analysis requires more sophisticated tools. The Graphic Laboratory of Concordia University is intended to be such a tool. A striking comparison could be made by the fact that weeks of frustrating work will be limited to a few minutes of on line processing.

It is too early to speculate upon the results that the new approach will permit. This technical report indicates that the direction of research seems proper and therefore warrants work further.

Whether further analysis will permit finer surface feature distinction (which is of great use to the papermaker) remains to be proven. Active work is under way, and results will be the subject of future thesis patents or reports.

4.3.2 Summary

Two experimental methods for obtaining information on the roughness of a paper surface were used in this report.

Given the paper samples, measurements were taken with the reference method, "Talysurf 4" and the "Retro-Reflective Unit".

The continuous electrical signals were converted to digital and transmitted (utilizing an Hybrid Computer) to a Digital Computer. The data, in discrete form now, were further processed in order to estimate certain statistical surface parameters, which can describe the paper roughness.

The values of these parameters (for each instrument) were estimated with the same program and the results, for the same paper sample, were compared in order to obtain an idea of the efficiency of each method, specially of the novel "Retro-Reflective Unit" method.

From an economic point of view, the cost of both T4 and RRU are similar, therefore the decision to use one or the other instrument is left with the specific technical applications to be done.

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APPENDIX I

ADCAT Communications Print-Out

In the print-out are shown the required aquisition and transmission parameters, data file name, magnification, number of processed data points and whether any transmission errors have occured.

This transmission was for the paper sample 300±5, with signal obtained from the RRU.

DIAL.

74/04/25. 10.22.06.
KRONOS TIME SHARING SYSTEM - VER. 2.1-04.
USER NUMBER: DAEFH75
PASSWORD
[redacted]
TERMINAL: 16,TTY
RECOVER /SYSTEM:ADCAD

ADCAT 2.0 640/6400 10.22.59. 74/04/25. LEVEL 012

AQUISITION PARAMETERS:

N=4000

F=8000

T=0.25SEC.

TRANSMITION PARAMETERS:

DATA FILE NAME IS:
? GLSAMP2

MAGNIFICATION IS:
? 9.

UNRECOVERED ERROR ABORT OPTION IS:
? Y

COMMAND.
? /END

10.45.07.

TOTAL NUMBER OF POINTS PROCESSED : 4000

TOTAL RECOVERED TRANSMITION ERRORS: 0

TOTAL UNRECOVERED TRANSMITION ERRORS: 0
END.

CP 0.775 SECS.

RUN COMPLETE.

BYE

DAEFH75 LOG OFF. 10.45.48.
DAEFH75 CP 0.775 SEC.

APPENDIX II

T4 Data Points Print-Out

The first 329 data points are shown as they were transmitted and stored in the CDC 6400.

These data points are for the paper sample 300±5, with signal from the T4.

74/03/13. 15.18.

14

KRONOS TIME SHARING SYSTEM - VER. 2.1-03.
USER NUMBER: DAEFH75
PASSWORD
[redacted]
TERMINAL: 6, TTY
RECOVER /SYSTEM:BAT
$RFL,20000.
/ATTACH,SAMPLE2
/COPY,SAMPLE2

.561523438E+01	.537109375E+01	.537109375E+01	.537109375E+01	.537109375E+01	.524902344E+01	1
.524902344E+01	.524902344E+01	.524902344E+01	.512695313E+01	.512695313E+01	.512695313E+01	1
.512695313E+01	.512695313E+01	.500488281E+01	.500488281E+01	.488281250E+01	.463867188E+01	1
.451660156E+01	.439453125E+01	.415039063E+01	.402832031E+01	.378417969E+01	.366210938E+01	2
.354003906E+01	.329589844E+01	.329589844E+01	.317382813E+01	.317382813E+01	.317382813E+01	2
.317382813E+01	.317382813E+01	.329589844E+01	.329589844E+01	.341796875E+01	.354003906E+01	2
.354003906E+01	.366210938E+01	.390625000E+01	.402832031E+01	.427246094E+01	.451660156E+01	3
.433349609E+01	.500488281E+01	.512695313E+01	.524902344E+01	.537109375E+01	.537109375E+01	3
.537109375E+01	.537109375E+01	.537109375E+01	.537109375E+01	.537109375E+01	.537109375E+01	3
.549316406E+01	.561523438E+01	.573730469E+01	.573730469E+01	.610351563E+01	.622558594E+01	4
.634765625E+01	.646972656E+01	.646972656E+01	.646972656E+01	.634765625E+01	.634765625E+01	4
.622558594E+01	.610351563E+01	.610351563E+01	.598144531E+01	.573730469E+01	.573730469E+01	4
.598144531E+01	.610351563E+01	.610351563E+01	.622558594E+01	.634765625E+01	.646972656E+01	5
.646972656E+01	.659179688E+01	.646972656E+01	.634765625E+01	.622558594E+01	.598144531E+01	5
.573730469E+01	.561523438E+01	.549316406E+01	.549316406E+01	.549316406E+01	.549316406E+01	5
.549316406E+01	.561523438E+01	.561523438E+01	.573730469E+01	.573730469E+01	.610351563E+01	6
.622558594E+01	.634765625E+01	.659179688E+01	.683593750E+01	.695800781E+01	.708007813E+01	6
.732421875E+01	.756835938E+01	.781250000E+01	.805664063E+01	.842285156E+01	.866699219E+01	6
.891113281E+01	.915527344E+01	.927734375E+01	.939941406E+01	.952148438E+01	.952148438E+01	7
.952148438E+01	.964355469E+01	.964355469E+01	.952148438E+01	.952148438E+01	.939941406E+01	7
.915527344E+01	.903320313E+01	.878906250E+01	.830078125E+01	.793457031E+01	.744628906E+01	7
.695800781E+01	.646972656E+01	.610351563E+01	.561523438E+01	.524902344E+01	.500488281E+01	8
.488281250E+01	.463867188E+01	.451660156E+01	.439453125E+01	.439453125E+01	.427246094E+01	8
.427246094E+01	.427246094E+01	.427246094E+01	.427246094E+01	.427246094E+01	.427246094E+01	8
.451660156E+01	.451660156E+01	.463867188E+01	.488281250E+01	.500488281E+01	.524902344E+01	9
.549316406E+01	.573730469E+01	.598144531E+01	.634765625E+01	.659179688E+01	.683593750E+01	9
.708007813E+01	.720214844E+01	.744628906E+01	.756835938E+01	.769042969E+01	.781250000E+01	9
.793457031E+01	.805664063E+01	.817871094E+01	.842285156E+01	.854492188E+01	.878906250E+01	10
.891113281E+01	.915527344E+01	.939941406E+01	.964355469E+01	.101318359E+02	.103759766E+02	10
.108642578E+02	.111083984E+02	.115966797E+02	.119628906E+02	.123291016E+02	.126953125E+02	10
.129394531E+02	.133056641E+02	.135498047E+02	.135498047E+02	.139160156E+02	.140380859E+02	11
.141601562E+02	.141601562E+02	.141601562E+02	.141601562E+02	.140380859E+02	.140380859E+02	11
.140380859E+02	.140380859E+02	.140380859E+02	.140380859E+02	.140380859E+02	.141601562E+02	11
.141601562E+02	.141601562E+02	.142822266E+02	.142822266E+02	.142822266E+02	.142822266E+02	12
.142822266E+02	.142822266E+02	.141601562E+02	.140380859E+02	.139160156E+02	.135498047E+02	12
.134277344E+02	.131835937E+02	.129394531E+02	.126953125E+02	.123291016E+02	.120849609E+02	12
.118408203E+02	.117187500E+02	.117187500E+02	.115966797E+02	.115966797E+02	.117187500E+02	13
.117187500E+02	.118408203E+02	.118408203E+02	.119628906E+02	.119628906E+02	.120849609E+02	13
.120849609E+02	.120849609E+02	.119628906E+02	.119628906E+02	.119628906E+02	.119628906E+02	13
.120849609E+02	.120849609E+02	.122070312E+02	.123291016E+02	.123291016E+02	.124511719E+02	14
.125732422E+02	.125732422E+02	.126953125E+02	.126953125E+02	.126953125E+02	.126953125E+02	14
.128173828E+02	.126953125E+02	.128173828E+02	.128173828E+02	.129394531E+02	.129394531E+02	14
.129394531E+02	.130615234E+02	.130615234E+02	.130615234E+02	.130615234E+02	.129394531E+02	15
.129394531E+02	.126953125E+02	.125732422E+02	.123291016E+02	.120849609E+02	.119628906E+02	15
.117187500E+02	.114746094E+02	.113525391E+02	.111083984E+02	.109863281E+02	.107421875E+02	15
.106201172E+02	.104980469E+02	.103759766E+02	.101318359E+02	.100097656E+02	.964355469E+01	16
.964355469E+01	.952148438E+01	.939941406E+01	.927734375E+01	.927734375E+01	.927734375E+01	16
.939941406E+01	.952148438E+01	.964355469E+01	.964355469E+01	.101318359E+02	.103759766E+02	16
.107421875E+02	.108642578E+02	.111083984E+02	.111083984E+02	.113525391E+02	.113525391E+02	17
.113525391E+02	.113525391E+02	.113525391E+02	.113525391E+02	.112304687E+02	.112304687E+02	17
.111083984E+02	.111083984E+02	.111083984E+02	.112304687E+02	.112304687E+02	.112304687E+02	17
.112304687E+02	.111083984E+02	.109863281E+02	.107421875E+02	.103759766E+02	.100097656E+02	18
.964355469E+01	.915527344E+01	.854492188E+01	.793457031E+01	.720214844E+01	.646972656E+01	18
.573730469E+01	.512695313E+01	.451660156E+01	.390625000E+01	.329589844E+01	.292968750E+01	18
.256347656E+01	.231933594E+01	.219726563E+01	.207519531E+01	.219726563E+01		

TERMINATED

APPENDIX III

RRU Data Points Print-Out

The first 364 data points are shown as they were transmitted and stored in the CDC 6400.

These data points are for the paper sample 300±5, with signal from the RRU.

```
74/04/25. 10.52.41.
KRONOS TIME SHARING SYSTEM - VER. 2.1-04.
USER NUMBER: [illegible]
PASSWORD
[redacted]
TERMINAL:      0,TTY
RECOVER /SYSTEM:bat
$RFL,20000.
/attach,glsamp2
/copy,glsamp2
-.188720703E+00 -.182861328E+00 -.176513672E+00 -.169189453E+00 -.163330078E+00 -.156738281E+00   1
-.155395508E+00 -.149658203E+00 -.145263672E+00 -.143066406E+00 -.139892578E+00 -.136230469E+00   1
-.134033203E+00 -.134887695E+00 -.130371094E+00 -.130859375E+00 -.132568359E+00 -.132812500E+00   1
-.136962891E+00 -.138427734E+00 -.140747070E+00 -.140625000E+00 -.140136719E+00 -.139892578E+00   2
-.141113281E+00 -.142578125E+00 -.144775391E+00 -.148681641E+00 -.152343750E+00 -.154296875E+00   2
-.158203125E+00 -.163085938E+00 -.166992188E+00 -.169189453E+00 -.175903320E+00 -.179687500E+00   2
-.183105469E+00 -.187500000E+00 -.193359375E+00 -.196777344E+00 -.197265625E+00 -.200439453E+00   3
 .868099219E-02 -.200927734E+00 -.202636719E+00 -.205566406E+00 -.206787109E+00 -.206542969E+00   3
-.208251953E+00 -.213012695E+00 -.210205078E+00 -.212646484E+00 -.216796875E+00 -.220947266E+00   3
-.222412109E+00 -.223144531E+00 -.228637695E+00 -.225562500E+00 -.229248047E+00 -.232421875E+00   4
-.238769531E+00 -.239746094E+00 -.241699219E+00 -.246215820E+00 -.250000000E+00 -.254150391E+00   4
-.255859375E+00 -.260253906E+00 -.264404297E+00 -.269775391E+00 -.273559570E+00 -.275390625E+00   4
-.277832031E+00 -.282226563E+00 -.282470703E+00 -.281005859E+00 -.282958984E+00 -.285400391E+00   5
-.289062500E+00 -.284423828E+00 -.283203125E+00 -.282958984E+00 -.283203125E+00 -.278808594E+00   5
-.275512695E+00 -.273437500E+00 -.271728516E+00 -.267333984E+00 -.262207031E+00 -.255126953E+00   5
-.251220703E+00 -.244262695E+00 -.241333008E+00 -.233642578E+00 -.228271484E+00 -.221923828E+00   6
-.215087891E+00 -.210205078E+00 -.205322266E+00 -.203247070E+00 -.196533203E+00 -.191650391E+00   6
-.184814453E+00 -.177001953E+00 -.173095703E+00 -.168212891E+00 -.168090820E+00 -.163574219E+00   6
-.159667969E+00 -.156372070E+00 -.150578906E+00 -.146972656E+00 -.143798828E+00 -.144653320E+00   7
-.144531250E+00 -.144042969E+00 -.146240234E+00 -.148193359E+00 -.150390625E+00 -.152099609E+00   7
-.156494141E+00 -.160156250E+00 -.163330078E+00 -.169921875E+00 -.175537109E+00 -.183105469E+00   7
-.189453125E+00 -.198486328E+00 -.203125000E+00 -.206298828E+00 -.210937500E+00 -.215820313E+00   8
-.219238281E+00 -.226562500E+00 -.227783203E+00 -.234008789E+00 -.232421875E+00 -.235107422E+00   8
-.238525391E+00 -.242187500E+00 -.242675781E+00 -.244873047E+00 -.249633789E+00 -.251708984E+00   8
-.252929688E+00 -.255859375E+00 -.259765625E+00 -.264404297E+00 -.263671875E+00 -.265747070E+00   9
-.266601563E+00 -.271484375E+00 -.273925781E+00 -.274902344E+00 -.276123047E+00 -.278076172E+00   9
-.281372070E+00 -.275390625E+00 -.274169922E+00 -.273193359E+00 -.275390625E+00 -.272705078E+00   9
-.271728516E+00 -.273559570E+00 -.275390625E+00 -.275390625E+00 -.274658203E+00 -.276855469E+00  10
-.278076172E+00 -.280517578E+00 -.281372070E+00 -.280883789E+00 -.281494141E+00 -.285644531E+00  10
-.288330078E+00 -.286621094E+00 -.290527344E+00 -.294189453E+00 -.303833008E+00 -.303466797E+00  10
-.303710938E+00 -.309570313E+00 -.313720703E+00 -.320312500E+00 -.322509766E+00 -.324340820E+00  11
-.326171875E+00 -.331542969E+00 -.335937500E+00 -.340087891E+00 -.336669922E+00 -.336181641E+00  11
-.343872070E+00 -.344726563E+00 -.346923828E+00 -.343994141E+00 -.336181641E+00 -.337158203E+00  11
-.337402344E+00 -.339965820E+00 -.336914063E+00 -.326416016E+00 -.321533203E+00 -.317138672E+00  12
-.315673828E+00 -.309692383E+00 -.304809570E+00 -.298828125E+00 -.293701172E+00 -.290151133E+00  12
-.281494141E+00 -.275146484E+00 -.270019531E+00 -.269653320E+00 -.265625000E+00 -.260009766E+00  12
-.256347656E+00 -.254150391E+00 -.249511719E+00 -.246337891E+00 -.246215820E+00 -.248168945E+00  13
-.240478516E+00 -.235839844E+00 -.231689453E+00 -.227783203E+00 -.222778320E+00 -.218872070E+00  13
-.216918945E+00 -.207275391E+00 -.202392578E+00 -.195486328E+00 -.196533203E+00 -.193115234E+00  13
-.190917969E+00 -.192504883E+00 -.188476563E+00 -.185791016E+00 -.184326172E+00 -.184082031E+00  14
-.184814453E+00 -.187011719E+00 -.192504883E+00 -.193359375E+00 -.192626953E+00 -.192626953E+00  14
-.193359375E+00 -.194091797E+00 -.197021484E+00 -.203369141E+00 -.207031250E+00 -.208984375E+00  14
-.210937500E+00 -.218087891E+00 -.216796875E+00 -.220703125E+00 -.226806641E+00 -.234375000E+00  15
-.236816406E+00 -.240234375E+00 -.245117188E+00 -.250000000E+00 -.253173828E+00 -.256103516E+00  15
-.262817383E+00 -.265625000E+00 -.270263672E+00 -.273437500E+00 -.278564453E+00 -.283203125E+00  15
-.285888672E+00 -.285278320E+00 -.281494141E+00 -.278076172E+00 -.275634766E+00 -.267089844E+00  16
-.259033203E+00 -.250244141E+00 -.246215820E+00 -.236816406E+00 -.226684570E+00 -.218872070E+00  16
-.205322266E+00 -.195434570E+00 -.184814453E+00 -.179809570E+00 -.172851563E+00 -.164306641E+00  16
-.157470703E+00 -.148681641E+00 -.139892578E+00 -.131103516E+00 -.125122070E+00 -.119140625E+00  17
-.111083984E+00 -.106689453E+00 -.102783203E+00 -.993652344E-01 -.939941406E-01 -.938720703E-01  17
-.898437500E-01 -.832519531E-01 -.805664063E-01 -.788574219E-01 -.783691406E-01 -.778808594E-01  17
-.803222656E-01 -.859375000E-01 -.878906250E-01 -.937500000E-01 -.101074219E+00 -.109375000E+00  18
-.117187500E+00 -.129394531E+00 -.142700195E+00 -.149902344E+00 -.158203125E+00 -.166015625E+00  18
-.171386719E+00 -.174560547E+00 -.179687500E+00 -.184692383E+00 -.185058594E+00 -.186767578E+00  18
-.188232422E+00 -.188964844E+00 -.186720703E+00 -.191650391E+00 -.195434570E+00 -.197265625E+00  19
-.200927734E+00 -.206054688E+00 -.206496094E+00 -.209716797E+00 -.212646484E+00 -.218872070E+00  19
-.218750000E+00 -.221435547E+00 -.224609375E+00 -.227294922E+00 -.227050781E+00 -.228515625E+00  19
-.231689453E+00 -.237915039E+00 -.236572266E+00 -.237548828E+00 -.239746094E+00 -.238525391E+00  20
-.236816406E+00 -.235595703E+00 -.241333008E+00 -.238525391E+00 -.237548828E+00 -.238525391E+00  20
-.241455078E+00 -.243408203E+00 -.244384766E+00 -.248168945E+00 -.248535156E+00 -.249267578E+00  20
-.250000000E+00 -.252685547E+00 -.257324219E+00 -.259033203E
```

APPENDIX IV

The Computer Program Print-Out

The entire program is shown (including subroutines and results) for the paper sample 300±5, with signal from the RRU.

The results are shown in page 103.

```
PROGRAM    PAPERL        CDC 6600 FTN V3.0-P296 OPT=1  74/03/25. 16.48.12.    PAGE    1

      PROGRAM PAPERL (TAPE12,INPUT,OUTPUT)
      DIMENSION Y(4800)
      READ(12,2) Y
    2 FORMAT(4(E15.9,1X))
C
      DO 1 JJ=1,6
      CALL FILTER (XVR,XCLA,XANC,XRIVE,XRMSVE,XXMCE,
     +XRMSCE,YRSUM,KNP,KUL,JJ)
C
      DO 99 II=1,KUL
      CALL LIMITS (KN2,KLW,KNDL,KNDU,KUP,II)
C
      LLO=KLW
      LHI=KUP
    3 CALL YBAR (Y,LLO,LHI,YR,VYR,II,YRSUM)
      CALL CLAVE (Y,LLO,LHI,YR,CLA,XCLA,KUL)
C
      CALL CDATA (DY,YREF,L,YMAX,LA,DS,ATIME,YLEVEL,CLA,YR)
C
      LLO=KLW
      LHI=KUP
      CALL PARCLC (Y,LLO,LHI,YREF,YMAX,YLEVEL,LA,L,
     +ATIME,DS,XANC,XRIVE,XRMSVE,XXMCE,XRMSCE,DY,KUL,II,KNP)
   99 CONTINUE
C
      CALL PRINT (KNP,XVR,XCLA,XANC,XRIVE,XRMSVE,XXMCE,XRMSCE)
C
    1 CONTINUE
      END
```

```
PROGRAM    PAPFR1                              CDC 6600 FTN V3.0-P296 OPT=1  74/03/25. 16.48.12.     PAGE   2

SYMBOLIC REFERENCE MAP

ENTRY POINTS
 6073  PAPFR1

VARIABLES     SN  TYPE          RELOCATION
 6303  ATIME      REAL                          6274  CLA       REAL
 6302  AS         REAL                          6275  DY        REAL
 6264  II         INTEGER                       6251  JJ        INTEGER
 6265  KLW        INTEGER                       6266  KMDL      INTEGER
 6267  KMOKI      INTEGER                       6262  KNP       INTEGER
 6263  KUL        INTEGER                       6270  KUP       INTEGER
 6277  L          INTEGER                       6301  LA        INTEGER
 6272  LMT        INTEGER                       6271  LLO       INTEGER
 6254  XANC       REAL                          6253  XCLA      REAL
 6255  XRIVF      REAL                          6260  XRNSCE    REAL
 6256  XRNSVF     REAL                          6257  XXNCE     REAL
 6252  XYR        REAL                          6305  Y         REAL      ARRAY
 6273  YR         REAL                          6261  YRSUM     REAL
 6304  YLEVEL     REAL                          6300  YMAX      REAL
 6276  YREF       REAL

FILE NAMES       MODE
 2022  INPUT              4044  OUTPUT              0  TAPE10     FMT

EXTERNALS        TYPE   ARGS
    CDATA                10                 CLAVE
    FILTER               11                 LIMITS
    PARCLC               10                 PRINT           8
    YBAR                  7

STATEMENT LABELS
    0  1                      6244  2     FMT                    0  3          INACTIVE
    0  99

STATISTICS
  PROGRAM LENGTH   10057B     4143
   BUFFER LENGTH    6066B     3126
```

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```
      SUBROUTINE FILTER (XYR,XCLA,XANC,XRIVE,XRMSVE,XXMCE,
     +XRMSCE,YRSUM,KNP,KUL,JJ)
      DIMENSION ICUT(4)
      DATA (ICUT(I),I=1,4)/1,4,12,40/
      XYR=XCLA=XANC=XRIVE=XRMSVE=XXMCE=XRMSCE=0.0
      YRSUM=0.0
      KNP=4000/ICUT(JJ)
      KUL=(4000-(4000/ICUT(JJ)))/10
      IF(KUL.LE.0) KUL=1
   10 RETURN
      END
```


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SYMBOLIC REFERENCE MAP

ENTRY POINTS
2 FILTER

VARIABLES SN		TYPE	RELOCATION		SN		TYPE	
30	ICUT	INTEGER	ARRAY		0	JJ	INTEGER	F.P.
0	KNP	INTEGER		F.P.	0	KUL	INTEGER	F.P.
0	XANC	REAL		F.P.	0	XCLA	REAL	F.P.
0	XRIVE	REAL		F.P.	0	XRMSCE	REAL	F.P.
0	XRMSVE	REAL		F.P.	0	XXMCE	REAL	F.P.
0	XYR	REAL		F.P.	0	YRSUM	REAL	F.P.

STATISTICS
PROGRAM LENGTH 34B 28

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```
      SUBROUTINE LIMITS (KNP,KLW,KMDL,KMDU,KUP,II)
      KLW=1+1*(II-1)
      KUP=KLW+KNP-1
      RETURN
      END
```


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SYMBOLIC REFERENCE MAP

ENTRY POINTS
 2 LIMITS

VARIABLES	SN	TYPE		RELOCATION					
0 II		INTEGER		F.P.	0 KLW	INTEGER		F.P.
0 KMDL		INTEGER	*UNUSED	F.P.	0 KMDU	INTEGER	*UNUSED	F.P.
0 KNP		INTEGER		F.P.	0 KUP	INTEGER		F.P.

STATISTICS
 PROGRAM LENGTH 13B 11

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```
      SUBROUTINE CDATA (DY,YREF,L,YMAX,LA,DS,ATIME,YLEVEL,CLA,YR)
      DY=0.1
      YREF=-5.5
      L=256
      YMAX=(L*DY)+YREF
      DS=10155.555555/4000
      ATIME=0.0
      YLEVEL=CLA+YR
      LA=192
      RETURN
      END
```

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SYMBOLIC REFERENCE MAP

ENTRY POINTS
 2 CDATA

VARIABLES	SN	TYPE	RELOCATION				
0	ATIME	REAL	F.P.	0	CLA	REAL	F.P.
0	DS	REAL	F.P.	0	DY	REAL	F.P.
0	L	INTEGER	F.P.	0	LA	INTEGER	F.P.
0	YR	REAL	F.P.	0	YLEVEL	REAL	F.P.
0	YMAX	REAL	F.P.	0	YREF	REAL	F.P.

STATISTICS
 PROGRAM LENGTH 31B 25

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```
      SUBROUTINE  YBAR                    CDC 6600 FTN V3.0-P296 OPT=1  74/03/25. 16.48.12.      PAGE    1

            SUBROUTINE YBAR (Y,LLO,LHI,YB,XYB,II,YBSUM)
            DIMENSION Y(1)
            YB=0.
            DO 5 I=LLO,LHI
  5         YB=YB+Y(I)
          5 CONTINUE
            YB=YB/(LHI-LLO)
            YBSUM=YBSUM+YB
            XYB=YBSUM/II
  10        RETURN
            END
```

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```
      SUBROUTINE  YBAR                    CDC 6600 FTN V3.0-P296 OPT=1  74/03/25. 16.48.12.      PAGE    2

      SYMBOLIC REFERENCE MAP

 ENTRY POINTS
   2  YBAR

 VARIABLES    SN  TYPE       RELOCATION
   35  I          INTEGER                      0  II      INTEGER         F.P.
    0  LHI        INTEGER        F.P.          0  LLO     INTEGER         F.P.
    0  XYB        REAL           F.P.          0  Y       REAL    ARRAY   F.P.
    0  YB         REAL           F.P.          0  YBSUM   REAL            F.P.

 STATEMENT LABELS
    0  5

 STATISTICS
   PROGRAM LENGTH     55B    45
```

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```
SUBROUTINE  CLAVE                              CDC 6600 FTN V3.0-P296 OPT=1  74/03/25. 16.48.12.        PAGE     1

                SUBROUTINE CLAVE (Y,LLO,LHT,YR,CLA,XCLA,KUL)
                DIMENSION Y(1)
                CLA=0.
                DO 15 I=LLO,LHT
                CLA=CLA+ABS(Y(I)-YR)
             15 CONTINUE
                CLA=CLA/(LHT-LLO)
                XCLA=XCLA+CLA/KUL
                RETURN
                END
```


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```
SUBROUTINE  CLAVE                              CDC 6600 FTN V3.0-P296 OPT=1  74/03/25. 16.48.12.        PAGE     2

     SYMBOLIC REFERENCE MAP

ENTRY POINTS
    2  CLAVE

VARIABLES      SN  TYPE              RELOCATION
    0  CLA         REAL                 F.P.          36  I       INTEGER
    0  KUL         INTEGER              F.P.           0  LHT     INTEGER          F.P.
    0  LLO         INTEGER              F.P.           0  XCLA    REAL             F.P.
    0  Y           REAL        ARRAY    F.P.           0  YR      REAL             F.P.

INLINE FUNCTIONS   TYPE    ARGS
    ABS            REAL       1  INTRIN

STATEMENT LABELS
    0  15

STATISTICS
  PROGRAM LENGTH      56B       46
```

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```
      SUBROUTINE PARCLC (Y,LLO,LHI,YREF,YMAX,YLEVEL,LA,L,
     +ATIME,DS,XANC,XPIVE,XRMSVF,XXMCE,XRMSCE,DY,KIN,KNP)
      DIMENSION Y(1)
      DIMENSION PDEN(1000),TEXC(200)
      ITIME=ATIME+1.
      K=-1
      LDA=0
      DO 500 I=1,LA
  500 TEXC(I)=0.
      DO 600 I=1,L
  600 PDEN(I)=0.
C
      SUM1=0.
      SUM2=0.
      DO 20 I=LLO,LHI
      IF(Y(I).LT.YREF.OR.Y(I).GT.YMAX) GO TO 20
      SUM1=SUM1+1.0
      J=(Y(I)-YREF)/DY+0.5
      PDEN(J)=PDEN(J)+1.0
      IF(Y(I)-YLEVEL.LT.0.0) GO TO 70
      IF(K.GT.0) GO TO 174
      IF(ABS(Y(I)-YLEVEL).GE.ABS((Y(I-1))-YLEVEL)) LDA=1
  174 CONTINUE
      LDA=LDA+1
      K=1
      GO TO 20
   70 IF(K.LT.0) GO TO 20
      K=-1
      IA=LDA+1
      IF(ABS(Y(I)-YLEVEL).GE.ABS(Y(I-1)-YLEVEL)) IA=LDA
      IF(LDA.GT.LA) PRINT 360,LDA
  360 FORMAT(//20X,*OVERRANGE LDA = *,I4)
      IF(LDA.GT.LA) GO TO 61
      TEXC(IA)=TEXC(IA)+1
      SUM2=SUM2+1.0
   61 LDA=0
   20 CONTINUE
C
      ANF=SUM2*6000.0/(10155.55555*KNP)
C
      RIVE=0.
      IF(SUM1.LE.0.0) GO TO 65
      DO 22 K=1,L
      PNT=YREF+(K-0.5)*DY
      RIVE=RIVE+PNT*PDEN(K)
   22 CONTINUE
      RIVE=RIVE/SUM1
C
      RMSVE=0.
      C1=0.
      DO 50 K=1,L
      PNT=YREF+(K-0.5)*DY-RIVE
      C1=C1+PNT**2*PDEN(K)
   50 CONTINUE
      C1=C1/SUM1
```


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```
      RMSVE=SQRT(CI)
      XMCE=0.
      IF(SUM2.LE.0.0) GO TO 64
      DO 62 I=ITIME,LA
      PNT=(ATIME+I)*DS
      XMCE=XMCE+PNT*TEXC(I)
   62 CONTINUE
      XMCE=XMCE/SUM2
   64 CONTINUE
C
      RMSCE=0.0
      CI=0.
      DO 63 I=ITIME,LA
      PNT=(ATIME+I)*DS
      CI=CI+(PNT-XMCE)**2*TEXC(I)
   63 CONTINUE
      CI=CI/SUM2
      CI=ABS(CI)
      RMSCE=SQRT(CI)
      XANC=XANC+ANC/KUL
      XRIVE=XRIVE+RIVE/KUL
      XRMSVE=XRMSVE+RMSVE/KUL
      XXMCE=XXMCE+XMCE/KUL
      XRMSCE=XRMSCE+RMSCE/KUL
   65 CONTINUE
      RETURN
      END
```


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SYMBOLIC REFERENCE MAP

ENTRY POINTS
2 PARCLC

VARIABLES

SN	NAME	TYPE		RELOCATION	SN	NAME	TYPE		RELOCATION
277	ANC	REAL			0	ATIME	REAL		F.P.
303	CI	REAL			0	DS	REAL		F.P.
0	DY	REAL		F.P.	272	I	INTEGER		
276	IA	INTEGER			267	ITIME	INTEGER		
275	J	INTEGER			270	K	INTEGER		
0	KNP	INTEGER		F.P.	0	KUL	INTEGER		F.P.
0	L	INTEGER		F.P.	0	LA	INTEGER		F.P.
271	LDA	INTEGER			0	LHI	INTEGER		F.P.
0	LLO	INTEGER		F.P.	306	ROEN	REAL	ARRAY	
301	PNT	REAL			300	RIVE	REAL		
305	RMSCE	REAL			302	RMSVE	REAL		
273	SUM1	REAL			274	SUM2	REAL		
2256	TEXC	REAL	ARRAY		0	XANC	REAL		F.P.
304	XMCE	REAL			0	XRIVE	REAL		F.P.
0	XRMSCE	REAL		F.P.	0	XRMSVE	REAL		F.P.
0	XXMCE	REAL		F.P.	0	Y	REAL	ARRAY	F.P.
0	YLEVEL	REAL		F.P.	0	YMAX	REAL		F.P.
0	YREF	REAL		F.P.					

FILE NAMES MODE
OUTPUT FMT

EXTERNALS TYPE ARGS

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```
INLINE FUNCTIONS   TYPE    ARGS
      ABS          REAL      1   INTRIN

STATEMENT LABELS
  121  20                      0  22                      0  50
  120  61                      0  62                      0  63
  211  64                    252  65                     66  70
   63  176                   256  340      FMT            0  500
    0  600

STATISTICS
  PROGRAM LENGTH    2650B     1448
```


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```
SUBROUTINE  PRINT                         CDC 6600 FTN V3.0-P296 OPT=1  74/03/25. 16.48.12.     PAGE    1

          SUBROUTINE PRINT (KMP,XYB,XCLA,XANC,XRIVE,XOMSVE,XXMCE,XRMSCE)
          PRINT 330
      330 FORMAT(1H1)
          PRINT 320,KMP
      320 FORMAT(////20X,*CUTOFF LENGTH = *,I5,2X,*DATA POINTS*)
          PRINT 200,XYB
      200 FORMAT(//20X,7HYBAR = ,F9.5)
          PRINT 230,XCLA
      230 FORMAT(//20X,6HCLA = ,F9.5,//)
          PRINT 890,XANC
      890 FORMAT(//20X,*ANC = *,F9.7,//)
          PRINT 260,XRIVE
      260 FORMAT(//20X,*AVE = *,F9.5)
          PRINT 270,XOMSVE
      270 FORMAT(//20X,*OMS = *,F9.5)
          PRINT 300,XXMCE
      300 FORMAT(//20X,6HMCE = ,F9.5)
          PRINT 310,XRMSCE
      310 FORMAT(//20X,8HRMSCE = ,F9.5)
          RETURN
          END
```

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```
      SUBROUTINE  PRINT                              CDC 6600 FTN V3.0-P296 OPT=1  74/03/25. 16.48.12.      PAGE     2

      SYMBOLIC REFERENCE MAP

 ENTRY POINTS
    2  PRINT

 VARIABLES      SN  TYPE            RELOCATION
     0  KNP         INTEGER             F.P.          0  XANC       REAL                F.P.
     0  XCLA        REAL                F.P.          0  XPIVE      REAL                F.P.
     0  XRMSGE      REAL                F.P.          0  XRMSVE     REAL                F.P.
     0  XXNCE       REAL                F.P.          0  YYR        REAL                F.P.

 FILE NAMES          MODE
     OUTPUT           FMT

 STATEMENT LABELS
    71  250     FMT                 74  230     FMT                  104  260     FMT
   107  270     FMT                112  300     FMT                  115  310     FMT
    63  320     FMT                 61  330     FMT                  100  800     FMT

 STATISTICS
   PROGRAM LENGTH      121B      81

          OVERRANGE LOA =  486
```

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```
          CUTOFF LENGTH =  4000  DATA POINTS

          YBAR =   5.73179

          CLA =    5.33970

          ANC = 5.0083963

          AVE =    6.41156

          RMS =    5.87965

          MCE =  60.25630
```

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```
EXCHANGE PACKAGE.

P        0  A0   6311  B0      0     (A0)  0000 0000 0000 0000 6405
RA   52400  A1   6334  B1  10355     (A1)  0000 0000 0000 0000 0000
FL   27400  A2  27600  B2     22     (A2)  0000 0000 0000 0000 0000
EM       7  A3  21351  B3  21352     (A3)  0000 0000 0000 0002 7600
RAX      0  A4   6370  B4      1     (A4)  0000 0000 0000 0000 1750
FLX      0  A5   6365  B5     52     (A5)  0000 0000 0000 0000 0001
MA     400  A6  16754  B6     74     (A6)  0000 0000 0000 0000 6364
            A7   6371  B7   6362     (A7)  0000 0000 0000 0000 0001

X0  7777 7777 7777 7700 0000
X1  [illegible] 0000 0000 0000 0000
X2  [illegible] 0000 0000 0000 0000
X3  [illegible] 0000 0000 0002 7600
X4  6227 0000 0000 0000 0000
X5  [illegible] 0000 0000 0025 4137
X6  [illegible] 0000 0000 0000 6344
X7  [illegible] 0000 0000 0006 0001

(RA)    [illegible] 0165 1200 0000 0000
(RA+1)  [illegible] 0000 0000 0000 0000

DUMP FROM  16452 TO 16552

16450   50400 00004 37035 53244   50500 00006 27600 53350   24006 50500 00005 44720   27003 53350 51200 16423
16454   24600 53020 66076 51740   30630 24706 53750 46000   04000 16424 46000 46000   00000 00000 00000 06363
16460   00000 00000 00000 00000   20557 77777 77760 16441   20367 77777 77760 16442   00000 00000 00000 00000
16464   20000 00000 00000 16457   00000 00000 00000 00000   [illegible]               [illegible]
      DUPLICATED LINES.
16500   20017 20316 03550 16502   00000 00000 00000 27600   04000 04223 00000 00000   74600 54010 51600 16502
16504   01400 00001 51300 21765   63052 61600 00074 46000   54334 63710 54114 53230   26423 64320 20452 67562
16510   56334 22227 73567 11472   53230 15650 36446 22654   56630 03130 16507 46000   03110 16506 02000 16514
16514   50500 00010 51400 16762   53350 50500 00006 43773   30034 53450 43600 24500   26015 62740 20755 46000
16520   61200 00001 51700 16771   51600 16771 22710 46000   61100 20756 51700 16767   63700 56710 66121 46000
16524   06710 16521 50500 00007   61200 00001 53450 46000   61100 17006 62740 170[illegible]   43700 56710 66121 46000
16530   06710 16527 50500 00001   43700 53450 10646 46000   51700 16773 51600 16772   51700 16774 46000 46000
16534   51500 16772 51400 06376   51300 06400 52250 06404   31024 24700 31032 24600   12074 03300 16621 43000
16540   51500 16772 51400 06376   52350 06404 51500 06375   31234 51400 16763 24102   44215 51500 16773 30174
16544   51400 16762 51200 06404   24101 30554 26111 31332   22711 52270 17005 30126   24605 51700 16775 24503
16550   56650 31450 24004 24601   56620 03300 16565 43000   51500 16770 37605 36560   03350 16563 51500 16772
```

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APPENDIX V

The Modified Main Program Print-Out

The main program is shown as it was modified to integrate the RRU data.

The rest of the program (including the suroutines) is not shown, because it remained the same.

The results shown are for the paper sample 300±5, with signal from the RRU.

PROGRAM SLPAR2 CDC 6600 FTN V3.0-P296 OPT=1 74/10/08. 13.09.05. PAGE 1

```
      PROGRAM SLPAR2 (TAPE1=,INPUT,OUTPUT)
      DIMENSION Z(4000),Y(4000)
      READ(1,2)(Z(I),I=1,4000)
    2 FORMAT(6(E15.9,1X))
      Y(1)=Z(1)
      DO 4 I=1,4000
      Y(I+1)=Z(I)+(I)*0.00025)**1000)
    4 CONTINUE
      DO 1 JJ=1,4
      CALL FILTER (XYR,XCLA,XANC,XRIVE,XRMSVE,XXMSE,
     *XRMSCE,YASUM,KMP,KUL,JJ)
C
      DO 99 II=1,KUL
      CALL LIMITS (KMP,KL,KMDL,KMDU,KUP,II)
C
      LL=KL
      LH=KUP
    3 CALL YBAR (Y,LL,LH,YB,YV,II,YMEAN)
      CALL CLAVE (Y,LL,LH,YB,CLA,XCLA,KUL)
C
      CALL CRATA (DY,YREF,L,YMAX,LA,DS,ATIME,YLENL,CLA,YB)
C
      LL=KL
      LH=KUP
      CALL PARCLC (Y,LL,LH,YREF,YMAX,YLENL,L,ANC,
     *ATIVE,RS,XANC,XRIVE,XRMSVE,XXMSE,XRMSCE,DY,LL,II,KMP)
   99 CONTINUE
C
      CALL PRINT (KMP,XYR,XCLA,XANC,XRIVE,XRMSVE,XXMSE,XRMSCE)
C
```


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```
CUTOFF LENGTH = 4000 DATA POINTS

YBAR = -.28876

CLA = .05025

ANC = -.3916869

AVE = -.33720

RMS = .05783

MCE = 66.15046

RMSCE = 54.14564
```

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