COMPUTERIZED SCANNING DENSITOMETER FOR AUTOMATIC RECORDING OF TREE-RING WIDTH AND DENSITY DATA FROM X-RAY NEGATIVES[1]

M. L. Parker, J. Schoorlemmer and *L. J. Carver*
Department of the Environment, Canadian Forestry Service
Western Forest Products Laboratory, Vancouver, British Columbia

(Received 24 September 1973)

ABSTRACT

A scanning densitometer has been developed to produce tree-ring width and density data as digital output and graphic plots. The densitometer is part of a data acquisition system that includes an on-line digital computer. X-ray negatives of wood samples are scanned and intra-ring specific gravity is measured at 0.01-mm intervals. Ring boundaries are automatically recorded; and values such as earlywood width, latewood width, minimum ring density, maximum ring density, average latewood density, total ring density and total sample density are produced.

Additional keywords: X-ray densitometry, dendrochronology, wood density, specific gravity, annual growth increments, computer processing.

INTRODUCTION

The development of X-ray densitometry of wood samples within the last decade has greatly improved the scope and potential of tree-ring analysis for dating, climatic studies, and wood quality evaluation. The pioneer work in this field was conducted by Polge and others in France (Polge 1963, 1965a, 1965b, 1966, 1967, 1970a, 1970b, 1971a, 1971b, 1971c; Polge and Garros 1971; Polge and Keller 1969; Polge and Nicholls 1971). Laboratories in Australia, Canada, England, New Zealand, and the United States now are using X-ray densitometry of tree-ring samples for various purposes (Echols 1970, 1971; Ellis 1971; Fletcher and Hughes 1970; Henoch and Parker 1972; Higgs and Rudman 1972; Jones and Parker 1970; McKinnell and Rudman 1973; Megraw and Nearn 1972; Nicholls 1971a, 1971b; Nicholls and Brown 1971; Parker 1970, 1972; Parker and Henoch 1971; Parker and Meleskie 1970; Rudman and McKinnell 1970; Rudman et al. 1969). Research in X-ray densitometry has benefitted from, and contributed to, work conducted in intra-ring density studies by other techniques (Cameron et al. 1959; Marian and Stumbo 1960; Green 1964, 1965; Green and Worrall 1964; Harris 1969; Harris and Polge 1967; Harris and Birt 1972; Kawaguchi 1969).

An X-ray scanning machine and a computerized tree-ring scanning densitometer have been built jointly by the Faculty of Forestry, University of British Columbia, and the Western Forest Products Laboratory, Canadian Forestry Service, both in Vancouver, British Columbia. The basic objective of this research has been to measure accurately ring-width and ring-density values, process these data in large quantities, and compare summarized tree-ring and

[1] The construction of the scanning densitometer and the data-acquisition system was supported by the Faculty of Forestry, University of British Columbia; the Western Forest Products Laboratory, Canadian Forestry Service; Glaciology Subdivision, Inland Waters Branch; and the Geological Survey of Canada. We appreciate the efforts of J.H.G. Smith, with support provided through a National Research Council of Canada Grant (No. A-2077), and R. W. Kennedy, Western Forest Products Laboratory, in providing the facilities required for this project. We also want to thank F. W. Jones for giving us many of the ideas for constructing the system; D. Nyberg and R. Sanders, B.C. Research, for work on the optical and mechanical design of the densitometer; G. Hall and L. A. Jozsa for the illustrations; and R. W. Kennedy, R. W. Meyer, and R. M. Kellogg for making useful comments on the manuscript.

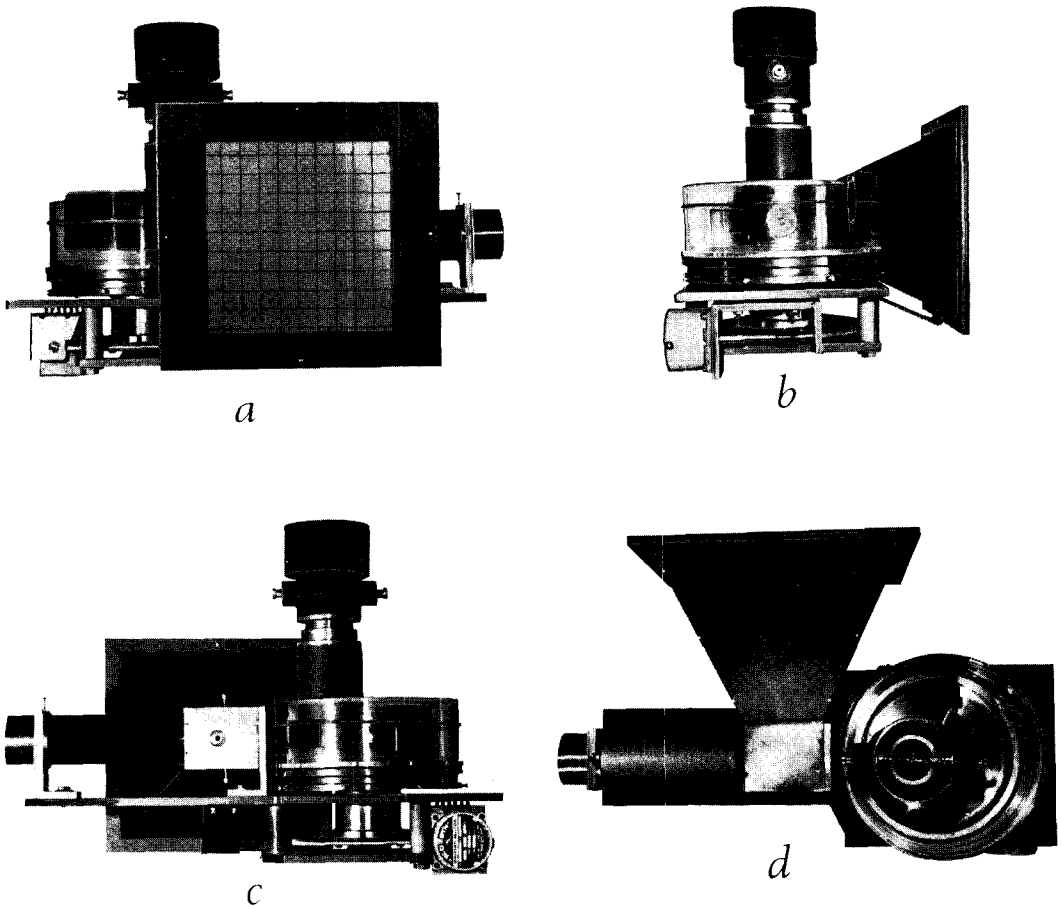

FIG. 1. Tree-ring scanning densitometer. *a*. Front view, *b*. end view, *c*. back view, *d*. top view.

other data in order to determine some of the relationships between tree growth, environmental factors, and wood quality characteristics.

The basic method used in X-ray densitometry is: (1) to produce an image of a tree-ring series on X-ray film by exposing the film with an X-ray beam projected through the transverse cross section of the wood sample, (2) scan the X-ray negative on a densitometer to produce annual ring width and intra-ring density data as a tree-ring density plot or in digital form. These two primary forms of data, ring width and ring density,[2] can be used as the basis for a number of intra-ring statistics, such as earlywood width, latewood width, minimum ring density, maximum ring density, average earlywood density, etc. If the intra-ring width and density characteristics are broken down in this manner, they can be compared with one another, with climatic variables and with other wood quality factors to determine the relationships between these various parameters.

This paper describes a scanning densitometer (Fig. 1) that was built specifically to produce tree-ring width and density data from X-ray negatives. This instrument is based on some of the design principles and component parts of the Geological Survey of Canada tree-ring scanning densitometer and data-acquisition system

[2] The unit of measure is g/cm^3 and the terms "specific gravity" and "density" will be used interchangeably.

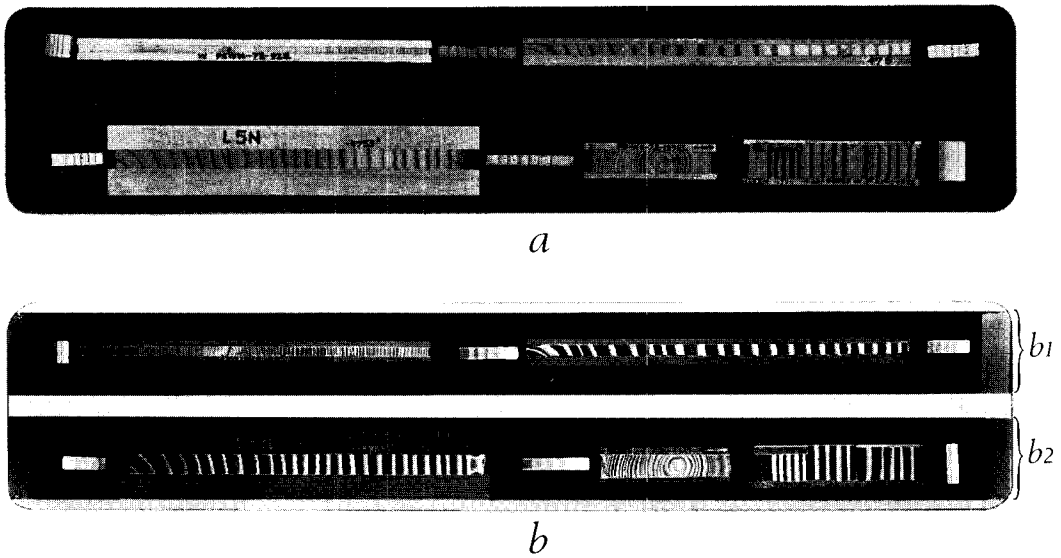

FIG. 2. Production of X-ray negative. *a*. Tree-ring samples and calibration wedges placed on X-ray film; *b*. X-ray negative of items in *a*. Exposure of the radiograph is made in two scans, *b1* and *b2*.

(Jones and Parker 1970). The general objective has been to build an instrument that would produce rapidly and accurately tree-ring widths and tree-ring density data in digital form that could be received and processed by an on-line digital computer. Some basic design considerations were that it was desirable to make continuous scans of wood samples from large-diameter trees, measure the density of very small areas at variable speeds, and monitor the area being scanned on a large viewing screen. The scanning densitometer is part of a system that includes a digital computer, plotters, teleprinter, and other components that collectively receive, process, and display intra-ring density data.

FORM OF DATA RECEIVED AND PRODUCED BY THE SYSTEM

Tree-ring width and density data are derived from X-ray negatives of wood samples. These radiographs are produced on an X-ray scanning machine (Parker and Jozsa 1973). X-ray film is exposed by soft X-radiation that passes through oven-dry wood samples of uniform thickness. Calibration wedges, used to calibrate film density, are radiographed simultaneously with the wood samples (Fig. 2).

The radiograph of the tree-ring sample is placed on the densitometer and scanned in a direction from the pith toward the bark. The distance traversed across the sample is measured in 0.01-mm increments and recorded as X-axis data, and specific gravity (oven-dry volume) is recorded on the Y-axis by measuring the intensity of light transmitted through the film. These distance and density data represent intra-ring density values from which a number of tree-ring statistics can be derived (Fig. 3).

The scanning densitometer can be used to produce tree-ring density plots with a nonlinear Y-axis, on a chart recorded without the computer (Fig. 4*b*). It can be used with the computer to produce intra-ring density plots, with a linear Y-axis scale, on an X-Y digital plotter (Fig. 4*c*), as well as printed digital output on the teleprinter (Fig. 5). One of the major functions of the computer is to make the required compensation for the nonlinear relationship between film density and wood density, and produce data in absolute specific gravity terms.

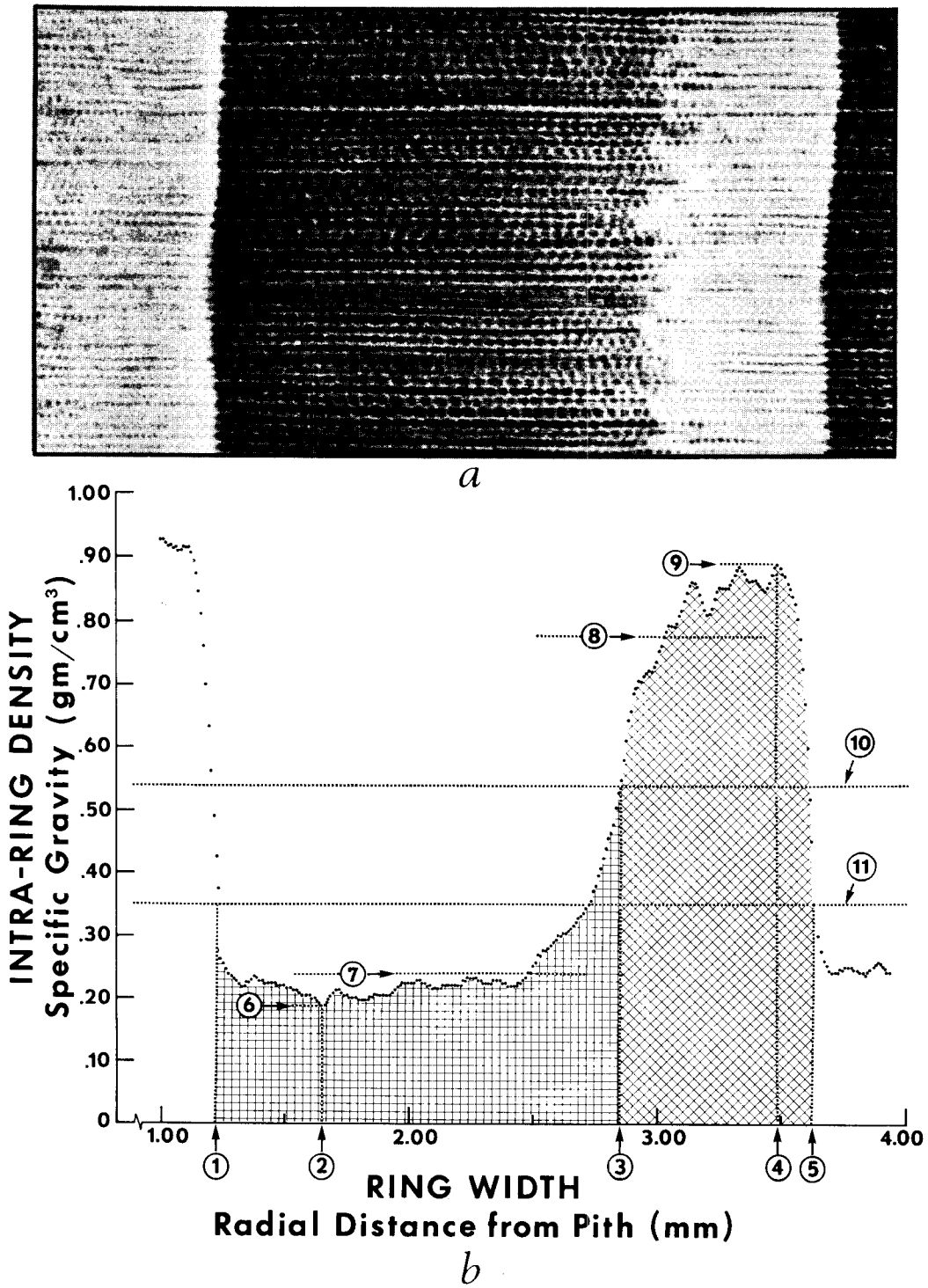

FIG. 3. Intra-ring density levels and width positions. X-ray negative (*a*) and intra-ring density plot (*b*) of annual growth ring.

SCANNING DENSITOMETER DESIGN

The Geological Survey of Canada tree-ring scanning densitometer and data-acquisition system (Jones and Parker 1970) provided useful information on relative intra-ring density and ring-width data; but this older system had several limitations that have been overcome. For example, tree-ring density could not be measured in absolute units of specific gravity because of output drift in the density-measuring photocell and because density data were obtained in analog, rather than digital, signals. In addition, density data were recorded by the time-consuming and somewhat inaccurate method of taking measurements manually from the density plots produced by the X-Y recorder. Some of the basic principles of this first densitometer are incorporated in the design of the present system, such as the stepping motor to measure distance traversed and the transparent plastic cylinder for film transport, but many new features have been added.

The innovations are: (a) a worm-gear system for accurate film transport; (b) a beam-splitting mirror for simultaneous projection of the image of the X-ray film on a viewing screen and the density-measuring photodiodes; (c) a large viewing screen with 10× magnification of the image; (d) a xenon-arc lamp for very bright illumination of the photodiode and viewing screen; (e) a lamp-control system for constant illumination.

Details of the construction of the scanning densitometer are presented in the exploded diagram (Fig. 6). The major components of the illumination system are: the xenon-arc lamp (7); regulated lamp power supply (not shown in diagram), with light-intensity monitoring photodiodes (44, in lamp housing); condenser lenses (8); front-surface mirror (16); collimating lens, located between the front-surface mirror and the film (13); projection lens (35); beam-splitting mirror (47); beam-restricting slit (42); film density measuring photodiodes (44, behind beam-restricting slit); photodiode amplifier (not shown on diagram); and image monitoring screen (50).

The lamp is a high-intensity point source of illumination sufficient to produce a bright image on the viewing screen and photodiodes. The lamp ventilator (3) prevents overheating and the lamp shade (1) reduces extraneous light. The inside surfaces of the components housing the illumination system are blackened to reduce undesirable reflections. The densitometer was at first operated by illuminating the film through the plastic film-transport cylinder (18), but the quality of the image has been improved by cutting a window in the cylinder to reduce the effect of fine scratches, reflections, and refraction. The beam-splitting mirror reflects one-third of the light to the viewing screen and transmits the remainder. The beam of light transmitted through the beam-splitting mirror is restricted by apertures in the mirror housing (46) and the projection tube mount (41).

There is further reduction in width of the light beam by the beam-restricting slit (42). Two slit widths, 100 and 500 μm, have been used. The height of the slit can be reduced by masking, or the slit holder can be removed to expose the entire surface of the photodiode to the image. The diameter of the photosensitive area of the

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X-AXIS DATA

1. Ring Starting Position (RSX)
2. Minimum Ring Density Position (MNDX)
3. Earlywood-Latewood Boundary (ELBX)
4. Maximum Ring Density Position (MXDX)
5. Latewood-Earlywood Boundary (LEBX)

Y-AXIS DATA

6. Minimum Ring Density (MNDY)
7. Mean Earlywood Density (AED)
8. Mean Latewood Density (ALD)
9. Maximum Ring Density (MXDY)

PREDETERMINED DENSITY LEVELS

10. Earlywood-Latewood Density Level (ELDY)
11. Latewood-Earlywood Density Level (LEDY)

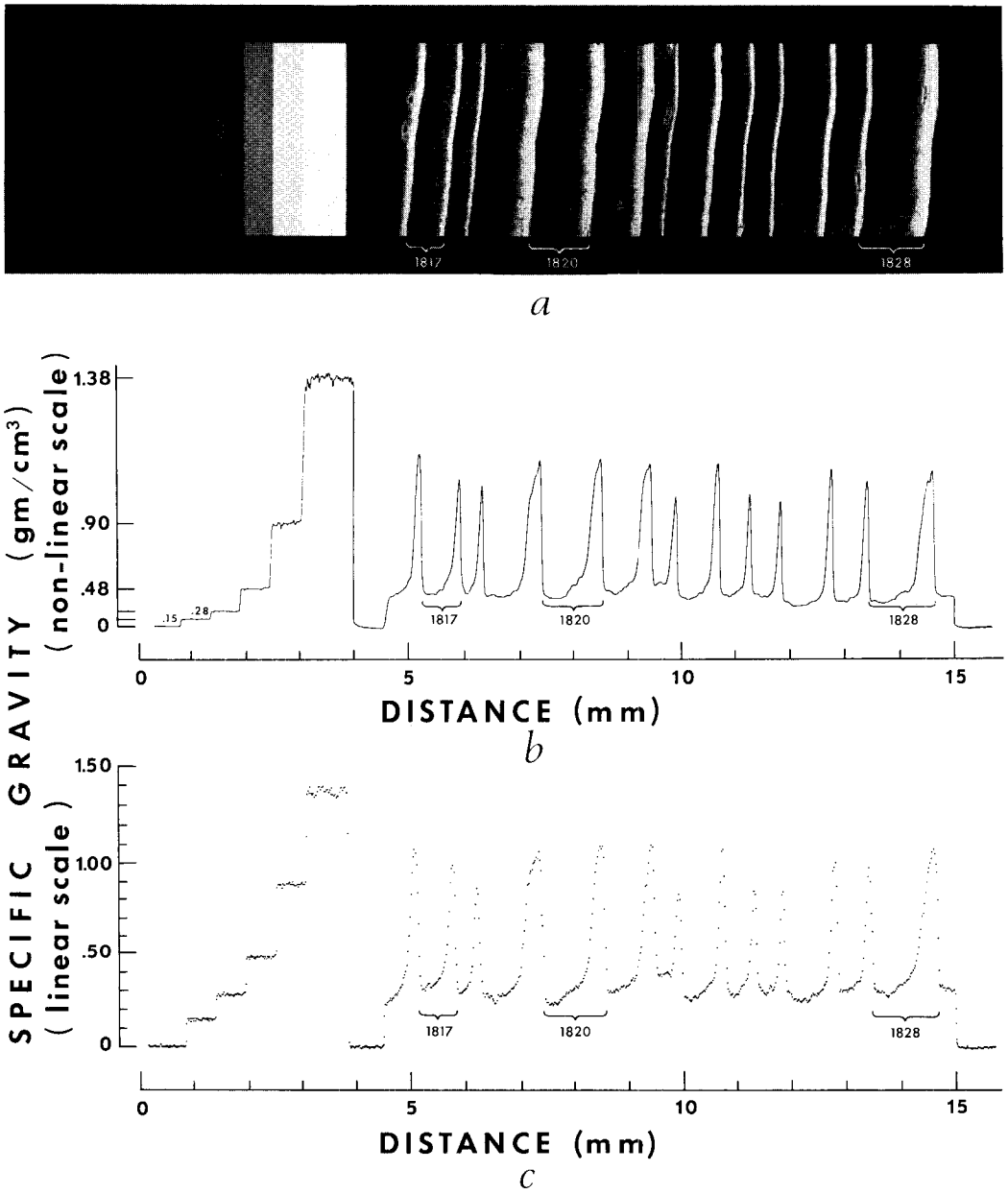

FIG. 4. Form of plotted output from system. *a*. X-ray negative of density wedge and tree-ring sample; *b*. Intra-ring density plot produced on the chart recorder; *c*. Intra-ring density plot produced on the digital X–Y plotter with the computerized system.

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FIG. 5. Printed output for ring-years 1818 and 1819 shown in Fig. 4. *a*. Width-density data acquisition program; *b*. Width-density calculation program; *c*. Intra-ring density data acquisition program.

a TREE-RING WIDTH-DENSITY DATA ACQUISITION PROGRAM
SAMPLE: PS-69-579

RSX= 586 ELDY= .540 LEDY= .350 BFRZ= .520

YEAR	FORM RSX	ELBX LEBX	MNDY MXDY	MNDX MXDX	AED ALD	LE2	EL2	LE3	EL3
1818	1	615	.30	591	.35				
	586	630	.87	620	.68	0	0	0	0
1819	1	703	.25	652	.31				
	630	737	1.09	728	.86	0	0	0	0

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b TREE-RING WIDTH-DENSITY CALCULATING PROGRAM
SAMPLE: PS-69-579

INFORMATION FOR EACH ANNUAL RING
EW=EARLYWOOD LW=LATEWOOD T=TOTAL

A=RING WIDTH (.01 MM)
B=MINIMUM AND MAXIMUM DENSITY AND DENSITY RANGE (GM/CC)
C=MEAN DENSITY (GM/CC)
D=RING VOLUME FOR 1 CM THICK DISK (CC)
E=RING WEIGHT FOR 1 CM THICK DISK (GM)
F=PERCENT WIDTH
G=PERCENT VOLUME
H=PERCENT WEIGHT
I=MINIMUM-MAXIMUM DENSITY RATIO
J=LATEWOOD-EARLYWOOD VOLUME RATIO
K=LATEWOOD-EARLYWOOD WEIGHT RATIO
L=ESTIMATED DISTANCE FROM PITH TO BEGINNING OF RING (.01 MM)
M=NUMBER OF THIS RING IN SERIES
N=ESTIMATED NO OF RINGS FROM PITH

YEAR		A	B	C	D	E	F	G	H	I	J	K
1818	EW	29	.30	.35	.18	.06	66	65	49 /	.34	.53	1.03
	LW	15	.87	.68	.10	.07	34	35	51 /		L	M N
	T	44	.57	.46	.28	.13			/		586	1 20
1819	EW	73	.25	.31	.50	.15	68	67	42 /	.23	.49	1.36
	LW	34	1.09	.86	.24	.21	32	33	58 /			
	T	107	.84	.48	.74	.36			/		630	2 21

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c INTRA-RING DENSITY CONFIGURATION DATA ACQUISITION PROGRAM
SAMPLE: PS-69-579

WIDTH= 44 1818
44 22
.32 .30 .30 .30 .31 .31 .32 .32 .33 .34
.35 .36 .41 .45 .55 .72 .80 .87 .85 .72
.58 .46

WIDTH= 107 1819
107 54
.36 .30 .28 .30 .29 .28 .28 .39 .28 .27
.26 .25 .25 .26 .29 .28 .28 .28 .29 .29
.29 .29 .29 .30 .31 .31 .32 .32 .33 .34
.35 .35 .37 .39 .40 .44 .54 .60 .71 .80
.90 .91 .97 .99 1.02 1.04 1.06 1.05 1.08 1.04
.99 .74 .68 .50

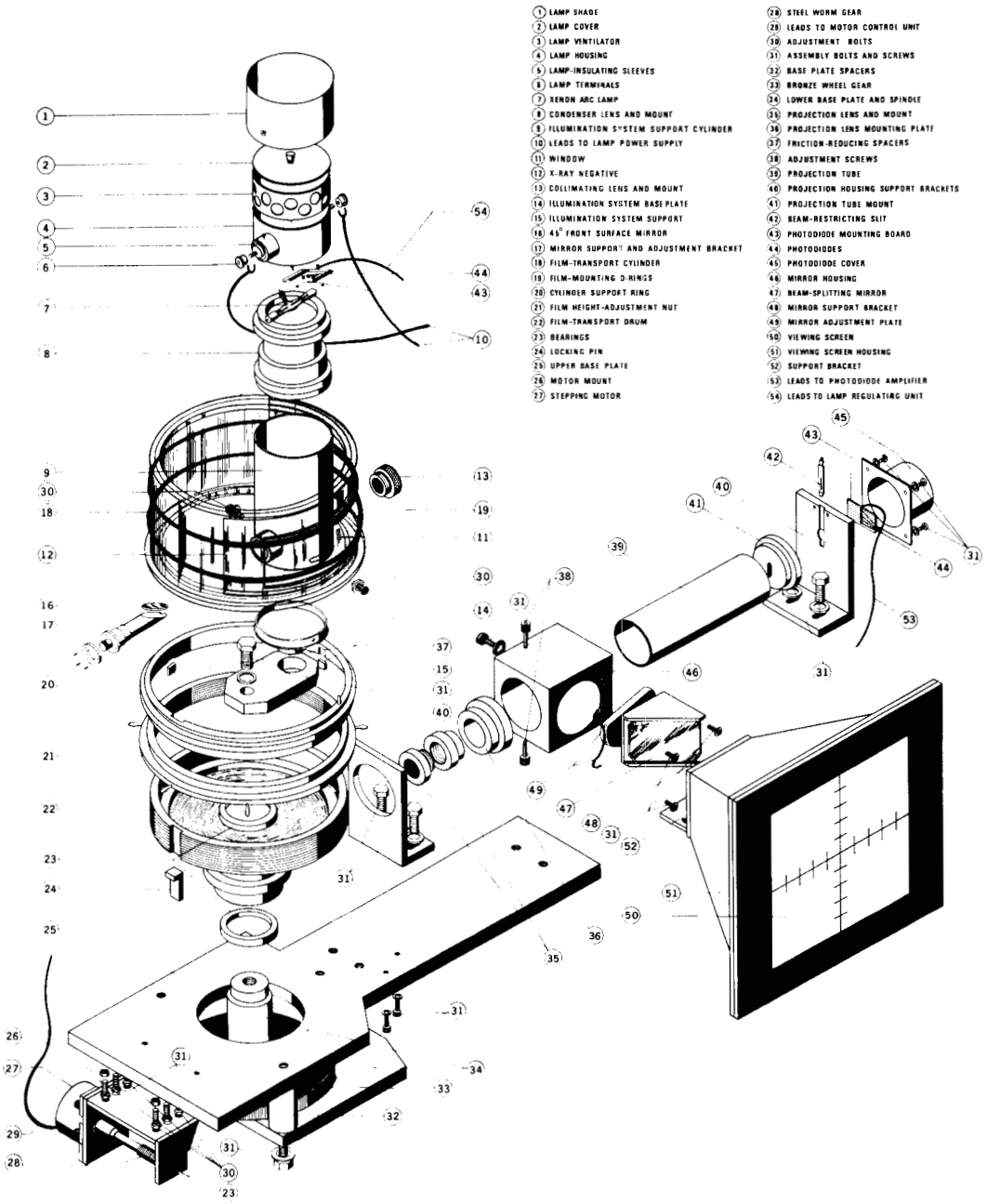

FIG. 6. Exploded diagram of tree-ring scanning densitometer.

photodiode is 0.625 mm. A 10× enlargement of the sample image is cast on both the viewing screen and the photodiode. The area on the film that is measured by each reading, therefore, is 10 μm in the radial direction and 625 μm in the tangential direction when the 100-μm slit is used and 50 × 625 μm when the 500-μm slit is used. These dimensions can be reduced by further masking of the slit.

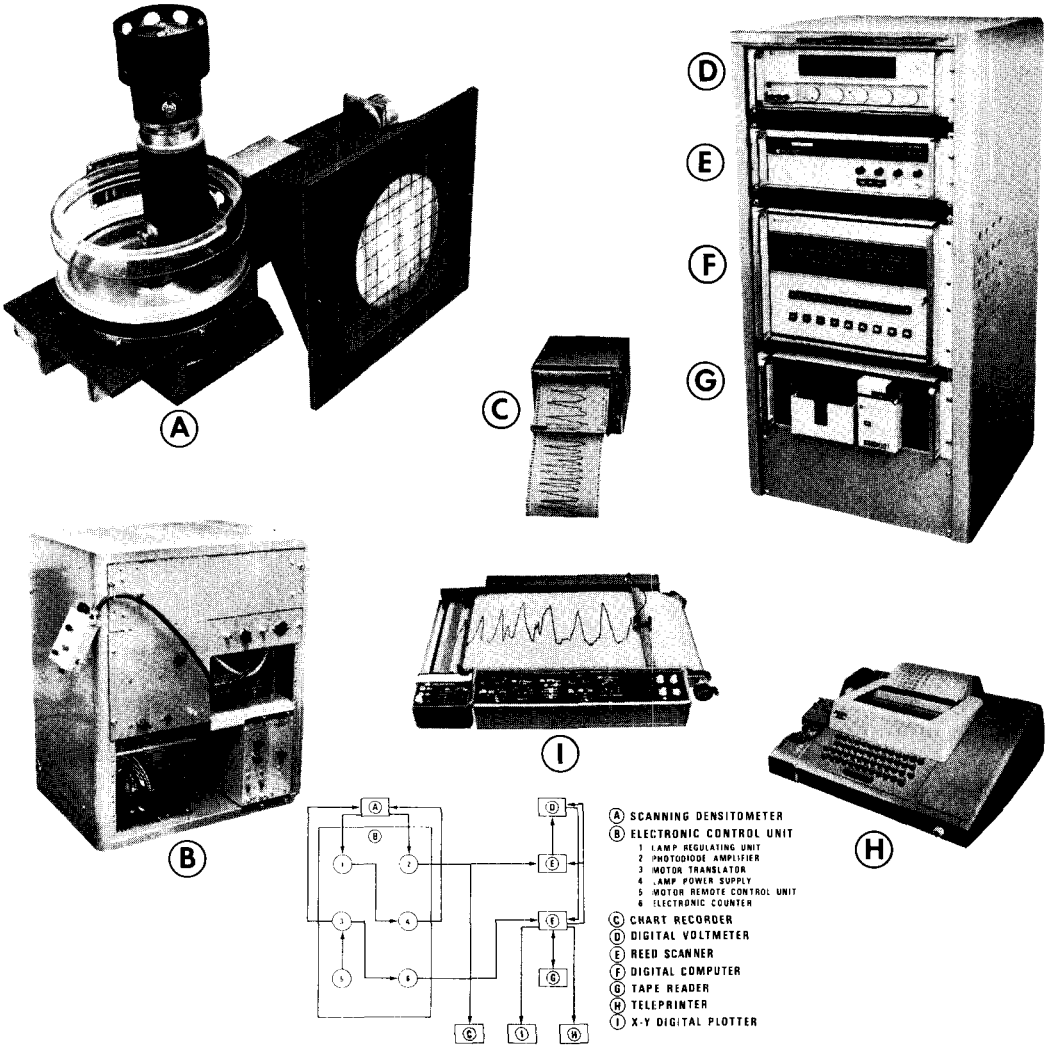

FIG. 7. The computerized tree-ring width-density data-acquisition system.

The major components of the film-transport system are: the stepping motor (27) and motor translator with hand-held, remote control unit; the steel worm gear (28) and bronze wheel gear (33); the film-transport drum (22) with film-height adjustment nut (21); and the transparent plastic film-transport cylinder (18) with a window (11) and rubber O-rings (19) to hold the film (12) in place. The outside circumference of the film-transport cylinder, upon which the film rests, is 90 cm. Each electronic pulse to the stepping motor rotates the motor shaft 1/200 revolution, corresponding to a film movement of 0.01 mm.

FEATURES OF THE ELECTRONIC COMPONENTS

The electronic components of the system consist of: the xenon lamp and lamp-control unit; the stepping motor and related control units; the photodiode and amplifier assembly; and the computer and its peripheral devices.

The xenon short-arc lamp is a high-pressure gas discharge lamp designed for use

in optical devices. Its outstanding features are a very high radiant intensity and luminance resulting from a high concentration of power and a spectral distribution ranging from medium-wave ultra-violet to short-wave infrared. This continuous spectrum results in illumination closely resembling natural daylight. In addition, the spectral energy distribution remains constant throughout the lamp life and is independent of fluctuations in voltage and lamp current.

Continuous power is supplied to the lamp from a 14-volt, 5-amp DC power supply. To provide good stability, photodiodes are mounted in the lamp housing to monitor light intensity. If the photodiodes sense a change in light intensity, the regulating unit alters the power supplied to the lamp to provide constant illumination.

The stepping motor, used to rotate the X-ray negative and plastic film-transport cylinder past the density measuring photodiode, converts electrical digital signals into mechanical movement. This type of motor is particularly desirable for this application, because one electrical pulse always moves the film-transport unit a fixed distance. The motor starts and stops immediately and is locked into position as soon as the run switch is released. It can be operated one step at a time or it can be run at variable speeds from about 4 to 300 steps per second in both forward and reverse directions; therefore, as well as being a positioner, the motor has the capability of variable speed, enabling the operator to move the film rapidly to an area of interest and then to scan slowly to insure that maximum detail is recorded.

The motor translator or control unit converts an electrical analog signal into a series of electrical pulses used to drive the motor. These pulses also are transferred to a digital counter and the accumulated count is used to determine position relative to an initial starting position. A remote hand-held control unit is incorporated into the system. This consists of a set of switches that provide the capability of selecting direction and speed of motor rotation.

The density-monitoring device is a silicon planar photodiode. It has a very fast speed of response, low dark current enabling detection of very low light levels, and a quantum detection efficiency constant over six decades of light intensity, thereby providing an excellent dynamic range. The photodiode is positioned behind the X-ray film, where it is illuminated by light from the xenon lamp, so that the intensity of light reaching the photodiode is proportional to density variations of the film. The photodiode converts this incident light into an electrical signal that is amplified by a high-grain, low-drift, low-noise amplifer. This signal can be transferred directly to a chart recorder or to the data-acquisition system.

The data-acquisition system (Fig. 7) includes a mini-computer with various peripheral devices. These are a reed scanner, a digital voltmeter, a high-speed paper-tape reader, a point plotter, and a teletype unit. The signal from the photodiode and amplifier assembly is transferred to the reed scanner. This unit consists basically of a set of switches or channels that are activated individually when a command signal arrives from the computer. The computer continually monitors the counter and initiates the measurement, conversion and transfer of photodiode voltage via the digital voltmeter and reed scanner each time the counter advances. The density signal is passed through the scanner and into the digital voltmeter where it is converted from an analog to a digital signal. This in turn is transferred to the computer for processing. Positional information from the counter is transferred directly into the computer.

The inclusion of an on-line computer in the system makes it very versatile. The computer can be programmed in a number of ways to receive distance and density signals from the densitometer, make the required calculations, and produce the desired results during operation. For example, the electronic pulses that activate the stepping motor and the electronic counter, and the voltage signals from the photodiodes, are converted directly to distance-

from-pith readings and specific gravity values. These can be printed, plotted, and punched on tape as soon as the tree ring is scanned. Width, density, weight, and volume values for earlywood, latewood, total ring, selected number of rings, or total sample can be quickly and accurately calculated, displayed, and stored for future use. Density variation between annual rings is used to automatically trigger the system at the ring boundaries, so that ring-width measurements are made objectively and rapidly without stopping the scanning procedure. The operator can use the switch registers on the computer, the teleprinter keyboard, and the remote-control unit to countermand the automatic signals in order to produce correct output for aberrations, such as cracks in the wood, resin pockets, false annual rings, absent rings, etc.

DISCUSSION

The scanning densitometer has been in operation since 1971, and although used primarily for measuring ring width and density, it also has been used to analyze distance and density data on film in fields other than dendrochronology. For example, densitometric plots of airborne infrared imagery produced by this densitometer were used to study temperature profiles of the Mackenzie River (Mackay 1972).

The major use of the system will be to produce intra-ring density data of tree-ring series. The potential for obtaining tree-ring dates is improved in many cases if ring density as well as ring width data are used (Parker and Henoch 1971). The use of intra-ring density measurements also adds a new dimension to studies in dendroclimatology (Polge 1970b; Parker and Henoch 1971; Fritts 1972). Perhaps most important to the forest products industry, X-ray densitometry of wood samples provides a useful tool for evaluating certain production problems and strength properties of wood, and the effectiveness of silvicultural practices such as fertilization and thinning.

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