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RESISTOGRAPH and X-Ray Density Charts of Wood Comparative Evaluation of Drill Resistance Profiles and X-ray Density Charts of Different Wood Species

By F. Rinn[1], F.-H. Schweingruber[2] and E. Schär[2]

[1] Consulting Engineers, Heidelberg, Germany

[2] Institute for Forest, Snow and Landscape (WSL), Birmensdorf, Switzerland

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Summary

The RESISTOGRAPH device measures the drill resistance of a fine needle as it penetrates wood. The mean levels of the RESISTOGRAPHIC charts closely correlate with the gross density of dry wood ($r^2 > 0.8$). The charts even reveal density variations within and between tree rings and density variations caused by decay. The density parameters which RESISTOGRAPH charts reveal, e.g. the earlywood and latewood areas in coniferous and deciduous wood correspond to those found in X-ray density charts. But the RESISTOGRAPH resolution is smaller by about one order of magnitude. The average lowest possible limit for tree ring identification from RESISTOGRAPH charts is approximately 0.5 mm. This limit depends on anatomic properties of the wood, on the local geometry of the tree-ring contours, and on the tree-ring density differentiation and is therefore hard to estimate exactly.

Introduction

Density is one of the most significant material characteristics of wood (Kollmann 1951; Panshin and de Zeeuw 1980). Tree-ring density charts and derived time series of tree-ring density parameters give important information about the growth of trees and influencing factors. The time series of tree ring density parameters were commonly determined through X-ray densitometry (Schweingruber 1986). But this high-precision and reliable method is time-consuming and requires expensive measuring procedures. The need for cheaper alternatives is evident.

Drill resistance measurements using conventional drills (diameter appr. 30 mm) have been shown to provide reproducible density characteristics of particle boards (Paulitsch und Mehlhorn 1973). But these methods are little suited for determining density variations of standing trees or structural timber on account of the large bore holes which they leave. RESISTOGRAPH drilling holes have a diameter of 3 mm, which is much less destructive (Rinn 1988; Brandt und Rinn 1989). RESISTOGRAPHIC charts of coniferous and deciduous wood were found to reveal tree-ring variations (Rinn *et al.* 1990). The mean level of the charts closely correlate with the gross density of dry timber (Görlacher und Hättich 1992). A closer look at the informational value of RESISTOGRAPH charts as compared to that of X-ray density charts led to scientific studies to investigate

- the resolution and reproducible representation of intra-annual density variations (early and late wood),
- the resolution limits and the parameters on which they depend, and
- the relation between time series of tree-ring density parameters obtained from RESISTOGRAPH and X-ray density charts (minimum and maximum density, earlywood and latewood width).

This paper shows the result of a first qualitative study based on only a few specimens. The goal of the comparison was to determine whether it would make sense to continue the development of hard- and software for RESISTOGRAPH-systems for tree-ring detection and growth-rate assessment.

The Measuring Method

The RESISTOGRAPH (Fig. 1) drives a fine needle into the wood and measures the drill resistance as it rotates. The needle has a shaft diameter of 1 to 1.5 mm and a maximum length of 1500 mm. The tip of the needle was given a special geometry and grinding (Fig. 2). The drill resistance concentrates at the tip (Rinn 1989a; Rinn *et al.* 1992) because its width is double the width of the shaft (2 to 3 mm). The feed of the needle is constant (variations less than 1 %), and the needle rotates continuously (ca. 1000 rpm). The feed rate varies between the different versions of the RESISTOGRAPH drill and is adapted by the user to the wood density: from 70 mm/min for extremly dense wood like bongossi *(Lophira alata)*

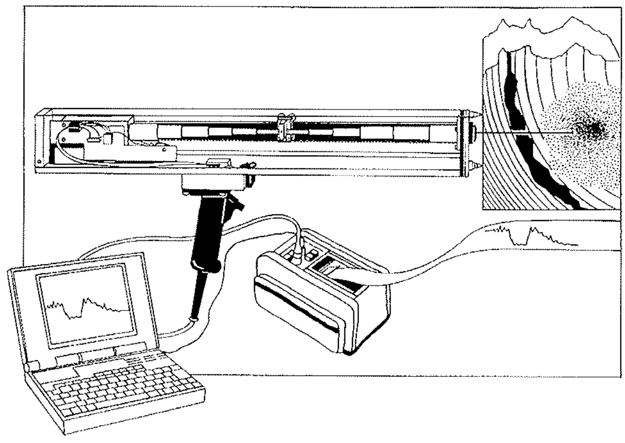

Fig. 1. The RESISTOGRAPH-drill contains two motors, one for the constant feed and one for the rotation of the needle. The needle shaft is stabilized quasi-continuously inside the drilling device by a special telescope. This stabilization is substantial for allowing feed rates of up to 1 meter per minute. The battery pack contains rechargeable batteries, control panels, a thermal printer and an RS232 interface. The profiles can be stored in the battery pack directly.

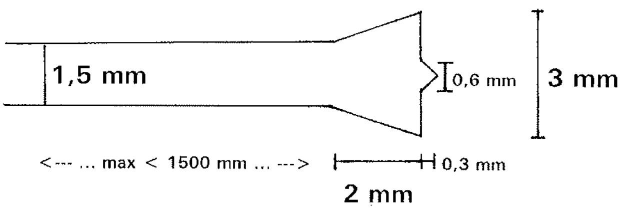

Fig. 2. The geometry of the needle tip determines the resolution in the RESISTOGRAPH drill-resistance charts. The brad point ensures a linear motion of the needle (average deviation below 10 over a length of 100 mm) but influences the measuring results only negligibly (<15%). The maximum length of the shaft is 1500 mm. The corresponding maximum penetration depth is approximately 950 mm. The needle is made from a special steel.

up to 1000 mm/min for very soft wood like Poplar (*Populus* sp.). The drilling depth of the shortest RESISTOGRAPH version is 280 mm, of the standard-version 410 mm and the longest version allows drilling up to 950 mm.

The power consumption of the drilling device is measured electronically as a value of the drill resistance. These values are recorded versus the penetration depth (up to 50 measuring points per mm). For dry wood, the drill resistance mainly depends on the density (Görlacher und Hättich 1990; Rinn *et al.* 1989). The charts reveal variations in the density of early- and latewood areas (Figs. 3 and 4), thus indicating decay and decomposition (Fig. 5). Different stages of decomposition can be inferred from the drops of the curves (Fig. 6).

The RESISTOGRAPH method can be considered quasi-non-destructive (maximum bore hole diameter 3 mm) as compared to core sampling (bore hole diameters 10 to 40 mm). The bore chips remain in the bore hole after measurement. RESISTOGRAPH is an easy-to-handle, rapid-measurement tool. The charts produced can be evaluated on the spot and can be catalogued and documented afterwards.

The ordinate of the RESISTOGRAPH charts reveals a relative measure for the power consumption of the drilling device. Since the electronic resolution is 12 bit, the ordinate values in general differ from 0 to 4095. It is possible to calibrate this axis for gross density analysis of dry wood (Görlacher und Hättich 1990) but in most of the applications relative values are sufficient: for detection of tree rings and decay no absolute values are necessary. For wood quality evaluation an additional differentiation between high, middle and low mean level of density is sufficient for most of the desired purposes of the RESISTOGRAPH applications. For calibration of the ordinate for measurements on standing trees, the influence of the moisture content has to be taken into account. This aspect is the subject of several current research projects and will probably open additional practical fields of application for the method.

Materials and Experimental Procedures

A comparison was made of tree-ring density values obtained by radial resistographic boring and by X-ray densitometry of air-seasoned wood. Ten borings were done in six species, i.e. silver fir (*Abies alba*), larch (*Larix decidua*), spruce (*Picea abies*), pine (*Pinus cembra*), lime (*Tilia platyphyllos*) and poplar (*Populus* sp.). The outside-to-inside RESISTOGRAPH borings were aligned perpendicularly to the tree-ring contours as well as possible. The charts were superimposed, and a numerical comparison was made. The 1/100 mm X-ray density values were transformed into 4/100 mm spacings on the abscissa by arithmetic moving average.

Electronic smoothing characterized by a nominal signal resolution of 12 bits and an effective signal resolution of 10 bits (values in the range from 0 to ca. 4,000) was found to occur during

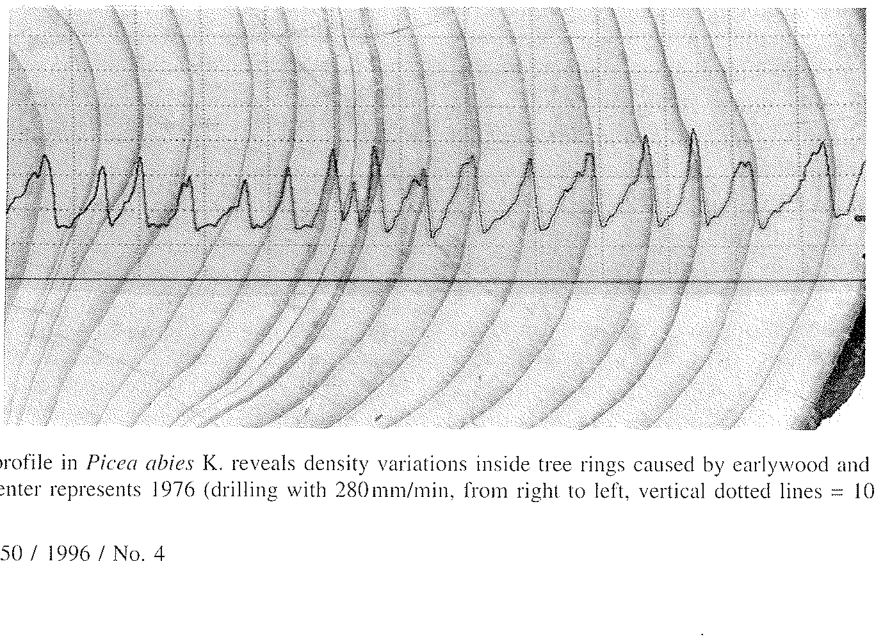

Fig. 3. This drilling profile in *Picea abies* K. reveals density variations inside tree rings caused by earlywood and latewood zones. The narrow rings in the center represents 1976 (drilling with 280 mm/min, from right to left, vertical dotted lines = 10 mm).

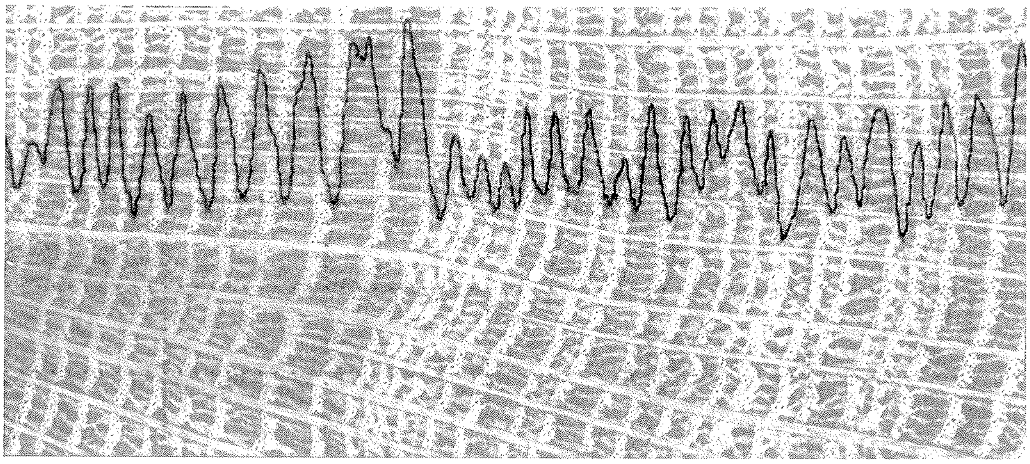

Fig. 4. Density variations in *Quercus robur* as shown in the RESISTOGRAPH profile. Very narrow rings contain only earlywood and, consequently, no significant radical density variations that could be revealed by drill resistance measurements. Therefore, such narrow rings can not be identified in the drill-resistance profile without visual control (drilling with 280 mm/min, right to left, total length 40mm).

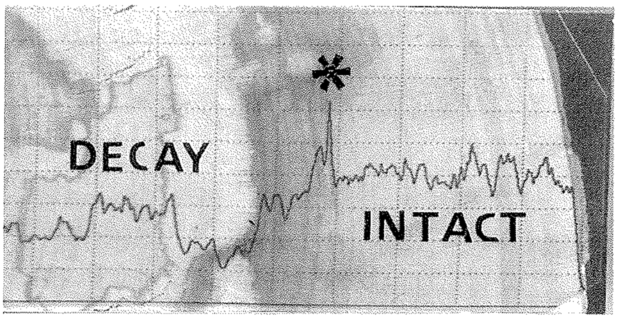

Fig. 5. Drill-resistance profile from *Platanus acerifolia* showing density variations caused by decay (drilling with 280mm/min, right to left, vertical dotted lines = 10mm spacings). After bark and approximately 40mm of intact wood a peak appears indicating a compartimentalization zone with higher density (Eckstein and Saß 1994); afterwards the profile drops down in the decayed part. Peaks caused by compartimentalization zones are not always detected at the dark colored line around the decay zone, but often several mm further outside in the area of intact wood.

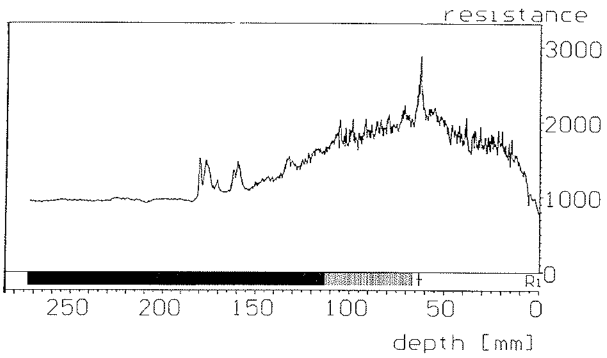

Fig. 6. RESISTOGRAPH profile of *Tilia cordata* with fungal decay. After the bark, the intact wood, and the compartimentalization peak, the profile steadily drops down into the decayed center of the tree. The decayed part is marked by the black beam below the chart. The transition from intact to decay reveals the existance of different stages of decay and is expected to be a measure for the future extension of the decay. The ratio of the thickness of the intact wood compared to the stem radius is a measure for the stability of the tree (Mattheck and Bethge 1993). Thus the further extension of the decay is important to evaluate the future stability of the tree.

RESISTOGRAPH drilling. For graphical comparison the horizontal and vertical offsets were combined until passing through the same point without abscissa or ordinate transformations of the measured values.

The tree-ring borders were set and the tree-ring density parameters were calculated in accordance with the methods known from X-ray density analysis (Schweingruber 1986) applying the DECOM computer program (Rinn 1989b). The boundaries between early- and latewood areas were fixed by automatic DECOM setting at a value of 50% between the minimum and maximum values of the respective tree-ring profiles. If the tree-ring contours are marked in the chart, DECOM calculates 23 tree ring and control parameters, e.g. tree-ring, earlywood and latewood widths (RW, EW, LW), tree-ring, earlywood and latewood integrals (sum of chart values in a segment), different parameter ratios (e.g. specific density = tree ring integral/tree-ring width), and relative percentages of early- and latewood areas. Some control parameters are calculated especially for evaluation of the RESISTOGRAPH charts. The significance of these parameters (e.g. width of the ascending profile at the tree-ring border) becomes evident below. The time series were analyzed by means of the tree-ring time series analysis program TSAP (Rinn 1990). They were correlated numerically and plotted in a graph.

Graphical Comparison of Charts

A numerical comparison of the two methods can only be made with certain reservations. Four main qualifying aspects must be taken into account as significant limitations:

- For methodical reasons the X-ray samples cannot always be taken right from above the drilled holes. This becomes important especially because the local spatial density distribution in the area of the needle tip on its way from bark to pith determines the measured value of drill resistance. Tangential structural deviations therefore disturb a comparison much more than vertical ones.
- While RESISTOGRAPH measurements are taken from air-seasoned wood (ca. 8% moisture), the X-ray analyses are made of slices of conditioned

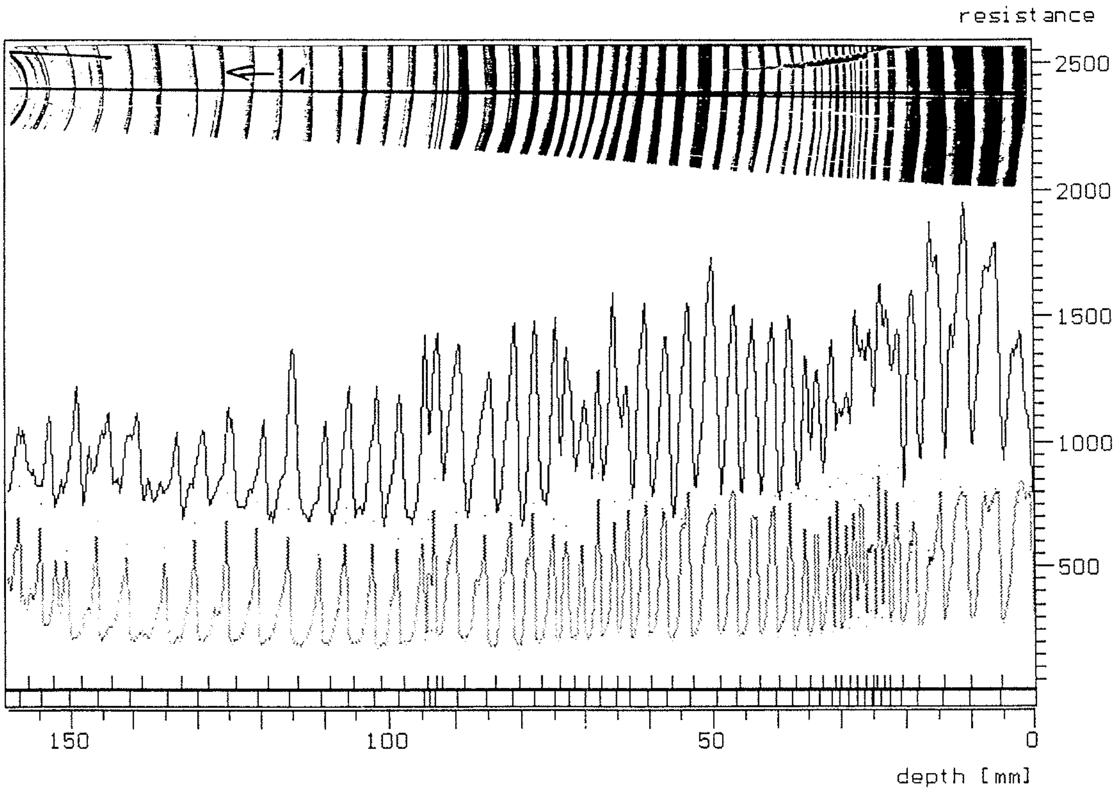

Fig. 7. Surface of *Abies alba* with compression wood, wide and narrow tree rings. The black line indicates the needle's path from right to left. The RESISTOGRAPH curve (–) and the X-ray chart (····) show similarities. The ordinate is relatively scaled referring to the drill-resistance measurement process (feed rate ~60 mm/min). The short vertical ticks below the profiles mark the corresponding tree-ring borders (above for the drill-resistance plot, below for the X-ray plot). The compression wood is visible in both profiles by broad latewood areas. Narrow rings are characterized by a locally higher density level.

wood dried by extraction. The different compositions and degrees of moisture of the specimens are sources of error in chart comparison because they determine the wood density and the drill resistance (Schweingruber *et al.* 1978; Le Naour et Morlier 1991).

- The width of the slotted X-ray aperture (WALESCH 1992) does not correspond to that of the tip of the RESISTOGRAPH needle (3 mm). This increases tangential differences in the measured values, depending on the local curvature of the tree-ring contours.
- The RESISTOGRAPH needle penetrates the wood straight from the bark to the pith while the slotted X-ray aperture is aligned anew with each tree-ring boundary parallel to the contour. Therefore, the abscissa which shows the distance run by the RESISTOGRAPH needle generally does not correspond with the X-ray abscissa (= strings of single tree-ring sections). The deviation of the measured X-ray distance in the tree ring mainly depends on the curvature of the tree-ring contour within the measuring range. Reliable numerical comparisons cannot be made unless one transforms the X-ray chart in accordance with these local curvatures within the respective tree rings.

In spite of these basic methodical restrictions (different measured distances, widths and paths and angles) one finds a surprising similarity between the typical characteristics of the two methods. This similarity allows one to omit abscissa synchronization and width balancing which are time-consuming and improve the results only slightly.

The mean levels of the RESISTOGRAPH charts correspond to the gross density in the wood: Narrow coniferous tree rings give a locally higher density due to a relatively greater proportion of late wood. The levels of the drill resistance characteristics are correspondingly higher (Fig. 7). In the case of the examined coniferous and lime specimens, the dynamic from earlywood minimum to latewood maximum (represented by the standard deviation of the profile) in the RESISTOGRAPH charts is slightly below that in the X-ray charts. The opposite was found for compression wood and for poplar specimen. Current studies investigate whether this is due to extraction of the X-ray samples or whether there are parameters in addition to the wood density influencing the RESISTOGRAPH values.

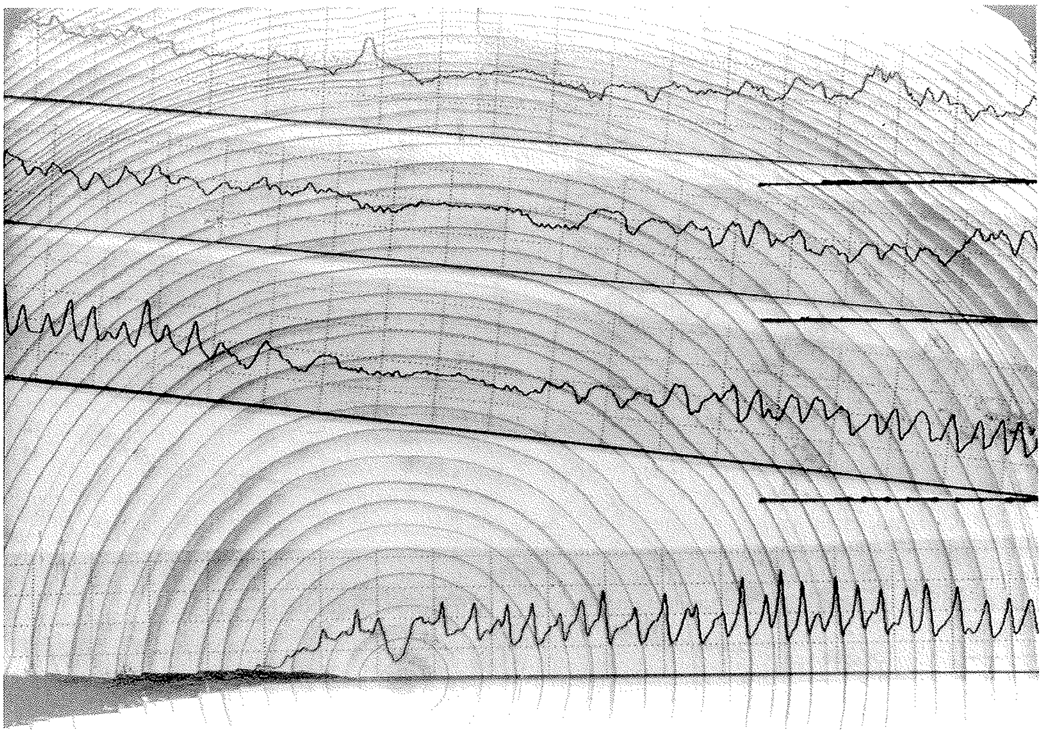

Fig. 8. Profiles of drillings in *Picea abies* (280 mm/min, right to left) visualizing the dependency of the tree-ring resolution from the piercing angle. With a decreasing piercing angle the visibility of tree-ring structures gets worse.

While the X-ray charts show the tree-ring boundaries as abruptly ascending curves, the RESISTOGRAPH charts represent more or less gradual characteristics. This is mainly due to the fact that the brad point takes up about 10% of the drill resistance of the tip of the needle and reaches the latewood before the flat face of the needle penetrates the respective tree ring. In addition, the curvatures of the tree-ring contours, and piercing out of the vertical delay the penetration of the flat face into the latewood. Evidently, the ascending boundary curve depends on the piercing angle and on the curvature. The greater the deviation of the piercing angle from the vertical and the more pronounced the curvature of the tree-ring contours, the longer the stretch of the ascending curve, the larger the latewood areas in the tree rings, and the lower the respective maximum values (Fig. 8). The pronounced curvatures of tree rings near the pith, for example, reduce the levels and increase the lengths of the late wood maxima in the RESISTOGRAPH charts.

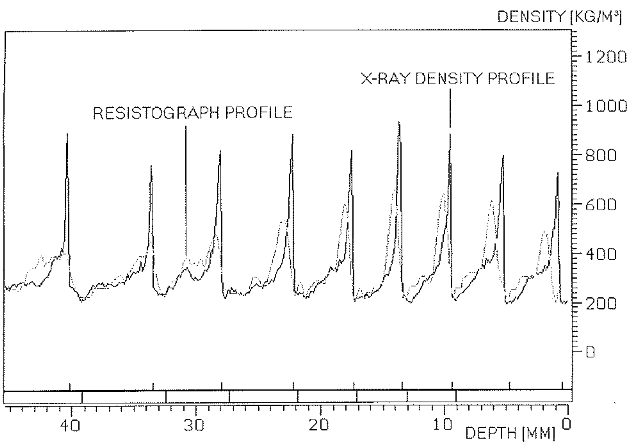

Fig. 9. Two profiles *(Abies alba*, 60 mm/min feed rate) showing tree rings with compression wood, indicated by a broader latewood zone. The typical intra-annual variations correspond to one another.

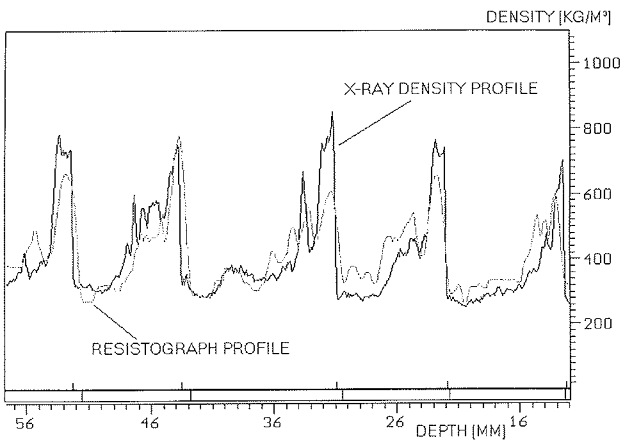

Fig. 10. X-ray density (–) and RESISTOGRAPH chart (····) of *Larix decidua*. The ordinate corresponds exactly to the density (kg/m^3). The typical tree-ring variations in the RESISTOGRAPH chart are very similar to those in the X-ray chart.

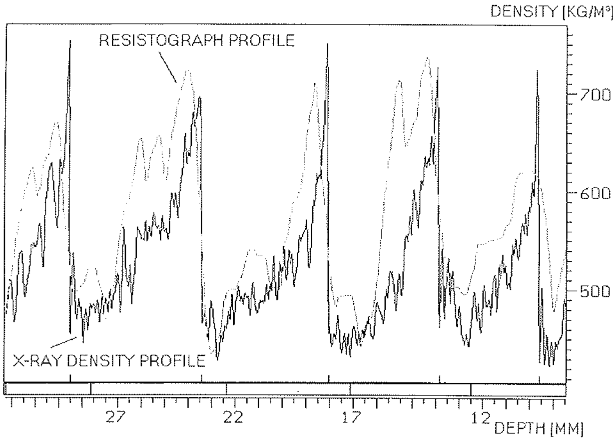

Fig. 11. X-ray density (–) and RESISTOGRAPH chart (····) of *Tilia platyphyllos* (ordinate=density kg/m³). The tree-ring variations in the RESISTOGRAPH chart are very similar to those in the X-ray chart. The RESISTOGRAPH variations are about as sensitive, but the local resolution is less pronounced. The slope of the profile at the tree-ring border indicates that the piercing angle was less than 90°.

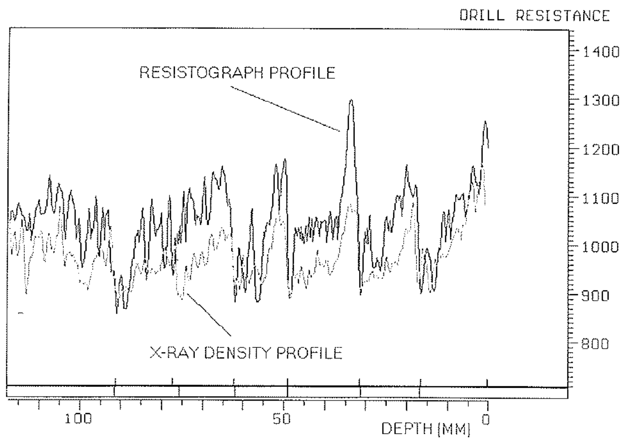

Fig. 12. RESISTOGRAPH (–) and X-ray density chart (····) of *Populus* sp. showing similar tree-ring structures. The intra-annual variations are more pronounced than in coniferous wood. The RESISTOGRAPH chart exhibits a higher sensitivity of these variations than the X-ray chart. The reason for this can not be explained yet. The tree-ring identification is more difficult, because intra-annual variations may be in the same scale as inter-annual variations.

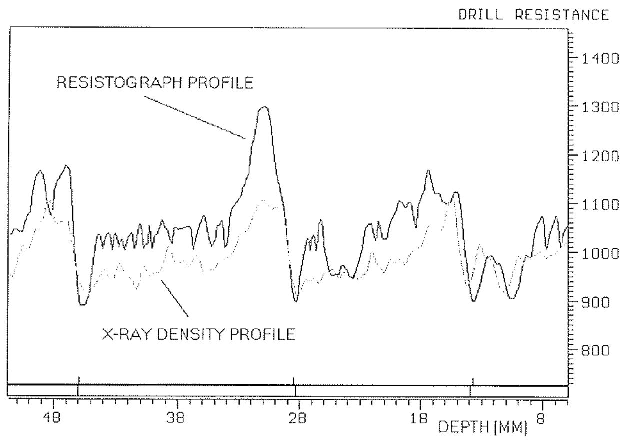

Fig. 13. A zoom from Fig. 12 containing three tree rings of *Populus* sp. which enhance the differences between the RESISTOGRAPH (–) and the X-ray density chart (····).

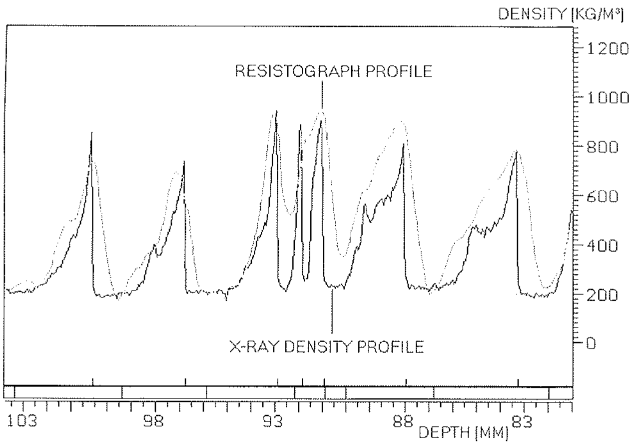

Fig. 14. X-ray density (–) and RESISTOGRAPH-chart (····) of a drilling in *Abies alba*. Two tree rings visible in the center of the X-ray chart appear as one peak in the dotted RESISTOGRAPH chart because of two reasons: 1) The piercing angle was below 90°, indicated by the slope of the curve at the tree-ring border. 2) The outermost of these two narrow rings contains very little earlywood and is dominated by latewood. In such a case the tip of the needle cannot differentiate the earlywood layer from the latewood areas because (if the piercing angle is below 90°) parts of the rotating tip pierce through one of the two late wood zones at any stage of the drilling process. The locally ascending RESISTOGRAPH curve indicates that there are further narrow and "hidden" tree rings in this area, but cannot tell their number and widths. This example shows that it is impossible to give an exact and general tree-ring resolution limit for the RESISTOGRAPH-method.

Less pronounced curvatures and perpendicular piercing result in steep boundary gradients in RESISTOGRAPH charts. The intra-annual characteristics then are in good accordance with the X-ray density values (see, e.g. Figs. 9 to 14). Since the width of the ascending tree-ring gradient is a measure of the tree-ring correspondence and resolution in RESISTOGRAPH charts, it was entered in the list of tree-ring parameters as a resolution quality control variable.

It is hard to give an exact limit for tree-ring resolution in RESISTOGRAPH charts. For the geometric shape of the needle tip, the average lowest limit for tree-ring identification from RESISTOGRAPH charts was found to be approximately 0.5 mm. This limit mainly depends on the following three aspects:

- anatomic properties of the wood (see Fig. 4)
- local geometry of the tree-ring contours and piercing direction (see Figs. 9 and 15)
- the differentiation of the tree-ring density.

If several of these limitations come together, it may occur that it is impossible to detect a tree ring with a width of more than 1 mm.

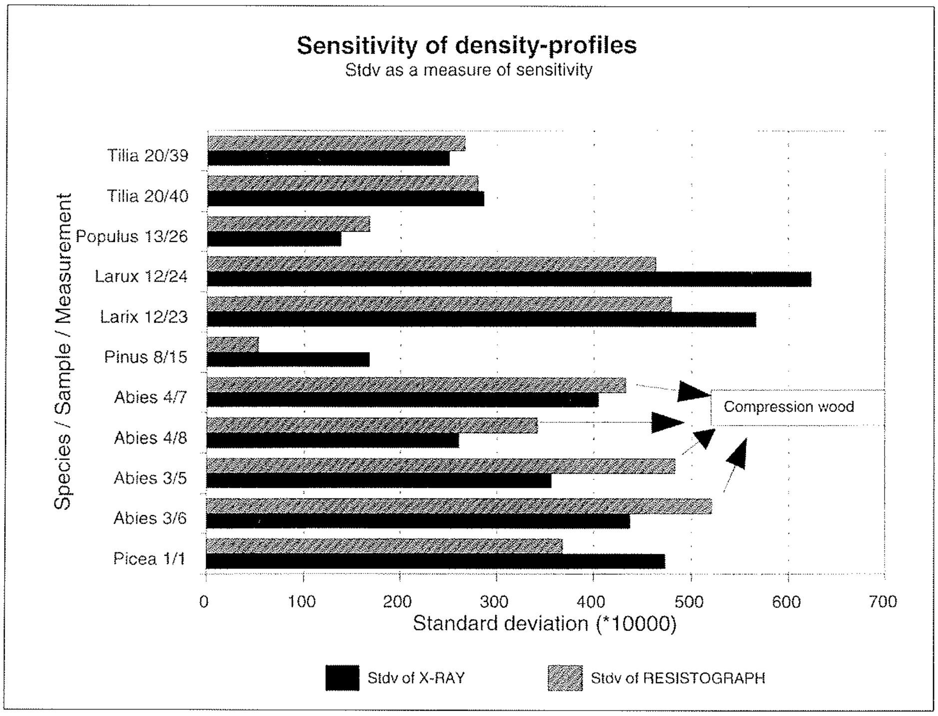

Fig. 15. The standard deviation is a measure of the sensitivity of the charts to differences between the density of earlywood and latewood areas. In the case of *Populus* sp. and in compression wood zones of conifers the RESISTOGRAPH sensitivity was found to be slightly above that of the X-ray charts, but slightly below in most other cases. Similar values are obtained for lime.

Numerical Comparison of Charts

Averages, variances and standard deviations were calculated by means of DECOM (Fig. 15 and Table 1) to obtain values for the numerical comparison of charts. The standard deviation is a measure of the sensitivity or dynamics of the charts and can be considered a criterion for differentiation between the densities of early- and latewood areas.

The tree-ring density parameters were correlated as time series in a special computer program TSAP (Rinn 1990). Cross-correlations, synchronisms and T-values were calculated to compare the charts numerically (Table 1).

The parameters tree-ring, earlywood and latewood widths and tree-ring integral show a high correlative correspondence and synchronism. In view of the visual comparison of charts, this accordance proves the basic findings: in the ideal case of perpendicular piercing and little pronounced tree-ring curving, the tree-ring parameters of both methods are in qualitative and quantitative agreement. This provides additional proof for the high correlation between drill resistance and wood density. Disturbances such as compression wood, narrow tree rings, piercing out of the vertical, and curved and/or meandering contours can impede tree-ring identification in the RESISTOGRAPH charts and require additional core sample or

Table 1. Correlation values for different tree-ring parameter series derived from X-ray-density and RESISTOGRAPH profiles (points, cross correlation C and "Gleichläufigkeit" G in % for all samples)

Sample	*Picea* 1		*Abies* 5		*Abies* 6		*Abies* 7		*Abies* 4/8		*Larix* 23		*Larix* 24		*Populus*		*Tilia* 39		*Tilia* 40	
Points (= rings)	61		51		45		34		34		9		7		6		13		15	
Parameter	C	G	C	G	C	G	C	G	C	G	C	G	C	G	C	G	C	G	C	G
Ring width	100	88	98	89	98	88	100	89	100	98	97	100	99	100	96	100	87	100	92	88
Ring integral	95	65	91	62	91	74	99	84	99	95	52	86	93	100	90	100	89	95	85	85
Minimum value	58	60	55	53	75	59	42	77	69	52	–51	57	– 5	60	30	100	36	55	33	62
Maximum value	20	52	19	49	47	58	27	56	–10	41	94	86	3	80	68	100	22	64	9	77
Earlywood width	97	82	91	72	92	78	99	86	92	86	– 4	71	69	100	77	100	85	55	70	69
Latewood width	21	61	68	57	58	69	69	64	70	75	19	79	–25	40	56	100	77	64	28	69
Border jump width	5	48	3	49	13	67	51	64	– 6	52	88	86	–33	60	51	100	6	73	–2	46
Min-Max distance	95	77	81	65	84	80	92	69	96	81	69	86	83	100	74	100	25	55	59	81

wood slice comparisons – if all tree rings are to be detected. As is evident, RESISTOGRAPH is not an independent dendrochronological tool for measurements on trees but a suitable tool for measurement and analysis of the densities of slices of wood and of core samples.

An exact limit for the linear dimension of tree-ring structures which cannot be resolved in RESISTOGRAPH profiles was not found because of the decisive influence of the local geometrical conditions (tree-ring contour curvature) and of the variations in the local densities. The 0.3 mm brad point penetration depth of the present version defines a resolution or clear identification of the tree rings whose earlywood widths are below 1/3 mm if there is no curvature. The existence of tree-ring contour curvature and non-perpendicular penetration increases this limit.

The differences in the sensitivity of the two methods have yet not been explained. Depending on the wood species, the RESISTOGRAPH profiles seem to be more or less influenced by latewood zones. In conifers compression wood raises the drill resistance more than the X-ray-density. This probably indicates that the drill resistance is not only a function of density but in addition is slightly influenced by other wood properties.

Efforts have been made to improve the information through intra-annual transformation of the RESISTOGRAPH tree-ring parameters. The transformation reference parameter is the angle of the ascending gradient at the tree-ring boundary, i.e. the DECOM-derived tree-ring control parameter. A very flat ascending gradient indicates that the tree ring was pierced out of the vertical or that the tree-ring contour is extremely curved. One obtains a correspondingly distorted chart which can be approximated to the radial geometry by conversion ("unfolding").

Prospects

The RESISTOGRAPH method is based on a simple measuring principle. Nevertheless, we found a good qualitative and quantitative correspondence between the RESISTOGRAPH and the high-resolution X-ray density charts under certain conditions.

Limits of the RESISTOGRAPH method

It is difficult or impossible to identify narrow tree rings of undefined density in the drill-resistance charts. One assumes an average lower identifiable tree-ring width limit of ca. 0.5 mm. Perpendicularly pierced tree rings narrower than this limit can be identified in some cases. Piercing out of the perpendicular, however, can even impede a clear resolution of tree rings wider than 0.5 mm. Since these restrictions are mainly due to the specific anatomy of wood,

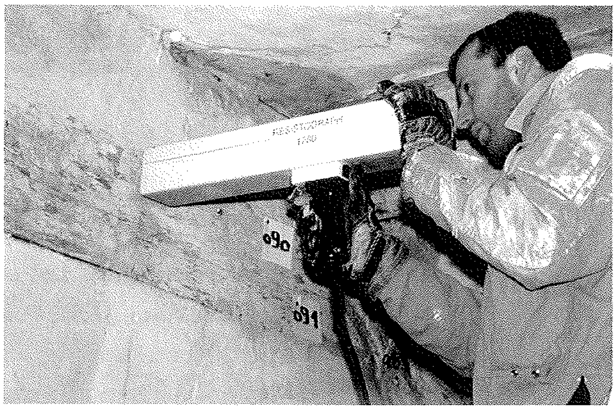

Fig. 16. The RESISTOGRAPH-device in use in an historic building to assess information on the status of the timber.

fundamental improvements cannot be expected from further technical modifications. A reliable detection and analysis of the narrower tree rings requires a visual inspection of core samples in addition to the assessment of radial density trends and the determination of the tree-ring density parameters of tree rings whose resolution is high enough.

The drillings for the comparison described have been carried out with a feed rate of 60 mm/min. Current observations show that the sensitivity of the drill-resistance profiles depends on the feed rate. By means of a special electronic regulation, higher feed rates induce higher sensitivity of the obtained profiles. Since the new version of the RESISTOGRAPH allow feed rates which are higher by one order of magnitude, the resolution especially for tree-ring density variations has been much improved. These developments mainly provide better handling, but the limitations caused by wood-anatomical properties may not be influenced.

So far, RESISTOGRAPH analyses have been limited to the detection and evaluation of relative changes in the drill resistance. These variations provide sufficient information for the determination of tree-ring parameters (and for evaluating wood quality and decay). The influence of the moisture content of wood and of the pre-stresses in green wood on the absolute drill resistance values is currently being investigated.

Fields of application and future uses

The RESISTOGRAPH device has been shown to be a suitable tool for estimating the growth trends in trees in the open. Application of the RESISTOGRAPH method suggests itself especially for fast-growing conifers. The close correlation of the charts with the gross densities, and the identifiability of cracks, decay and of areas of compression wood make RESISTOGRAPH devices a tree and timber inspection tool which can be recommended for research, forestry and the wood working industry, e.g. for testing structural timber (Ehlbeck and Görlacher 1990) and tree inspection (Mattheck and Bethge 1993).

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Frank Rinn
Consulting Engineers/
Ingenieurbüro
Bierhelder Weg 20
D-69126 Heidelberg
Germany

Fritz-Hans Schweingruber
Ernst Schär
Institut für Wald,
Schnee und Landschaft(WSL)
Zürcher Straße 111
CH-8903 Birmensdorf
Switzerland