An Electromechanical Dendrometer Band

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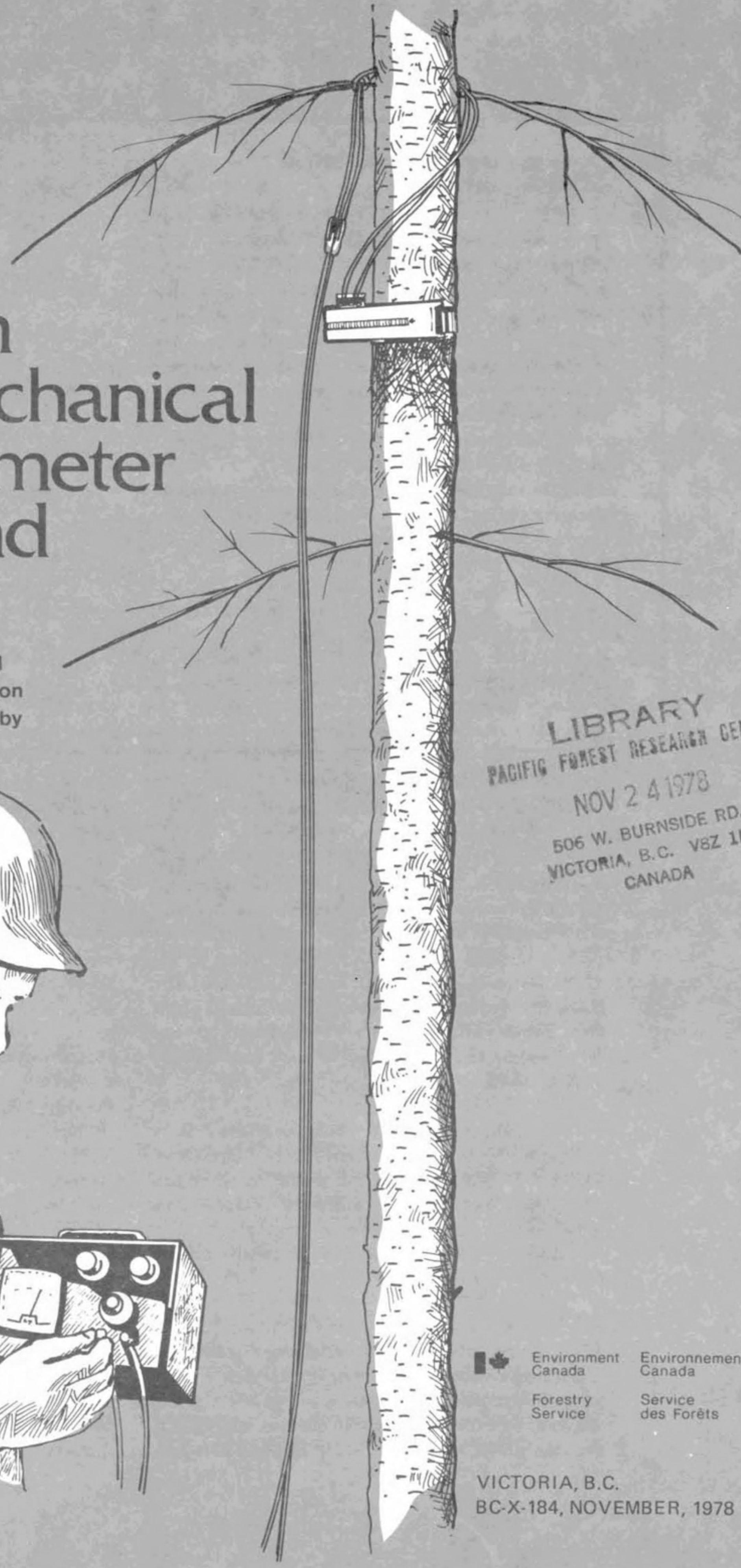

Environment Canada — Environnement Canada
Forestry Service — Service des Forêts

VICTORIA, B.C.
BC-X-184, NOVEMBER, 1978

ABSTRACT

An electromechanical dendrometer band, designed for use in tree physiology studies (Brix, 1978; Crown and Brett et al., 1975), is described and evaluated. The dendrometer meets its design objectives of precision (around 0.2 mm diameter increment), easy installation, ground level reading and low unit cost ($5 - $10). Laboratory tests estimated instrument precision to be ± 0.25 mm (95% confidence interval) and ± 0.16 mm (80% confidence interval). Field tests indicated that band accuracy may be influenced by an initial period of underestimation, owing to initial slack upon installation and by an uneven recording of true increment, because of a tendency of bands to stick.

INTRODUCTION

This report describes and evaluates an electromechanical dendrometer band that was developed for use in tree physiology studies (Brix, 1978) which were carried out as part of an ongoing multidisciplinary research project (Crown and Brett et al., 1975), established in 1970 near Shawnigan Lake, B.C. The dendrometer was used to obtain upper stem diameter measurements of more than 300 trees on a weekly basis over three growing seasons from 1973 to 1975.

Dendrometers have been developed in a variety of forms over the last 50 or more years. Existing designs might be categorized according to **what** they measure (circumferential increment or radial increment) and **how** they measure (optically, mechanically or electrically; continuously or discretely in time; remotely or not).

Band dendrometers (Hall, 1944; Liming, 1957; Dobbs, 1969) measure changes in circumference by encircling a stem or branch with a metal band. Bands are held taut by a spring or a clip and are able to expand to register changes in length as the tree grows. Dial gauge dendrometers (Reineke, 1932; Daubenmire, 1945) measure changes in stem or branch radius at a particular point on the circumference. These instruments use screws anchored to the xylem some distance beneath the cambium, to establish a fixed reference point, and record changes in distance between this fixed point and a position on the outer bark which moves as the tree grows.

Several types of transducers have been used to record increments as electrical signals; for instance, a variable differential transformer (Impens and Schalck, 1965) and various types of potentiometers (Phipps and Gilbert, 1960; Dobbs, 1969; Woodman, 1971; Kenerson, 1973). Electrical outputs can always be read remotely. Dendrographs, for continuous recording, have been developed by Fritts and Fritts (1955) and Phipps and Gilbert (1960).

Advantages and disadvantages of existing designs have been discussed by Borman and Kozlowski (1962) and problems of accuracy have been raised by Bower and Blocker (1966) and Auchmoody (1976). Generally speaking, dial gauge dendrometers can provide considerably greater precision than band dendrometers (around 0.02 versus 0.10 mm diameter increment), the greatest sensitivity stated being 0.002 mm by Fritts and Fritts' (1955) dendrograph. Some believe that dial gauge dendrometers may actually measure anomalous meristematic activity, which they induce by their physical damage to cambial tissue when installed. Dendrometer bands, on the other hand, have been found to underestimate increment for as long as an entire growing season or until enough growth has occurred to eliminate the slack in newly installed bands. Whether one wants to measure radial increment in order to be sensitive to differential growth of individual radii or measure circumferential increment in order not to be bothered by this differential growth is purely a matter of experimental objectives.

INSTRUMENT SPECIFICATIONS AND DESIGN

Study objectives defined performance specifications which made unattractive the selection and use of an existing dendrometer design. The plans to study stem form and phenology of total tree growth suggested the need for a band type dendrometer to measure circumferential rather than radial increment. Estimates of growth rates involved suggested a needed precision of around 0.2 mm diameter increment - a precision at or near the limit of existing dendrometer bands. Plans to collect data for more than 300 trees on a weekly basis would necessitate a very low unit cost ($5 to $10 for the budget available). This large number of units would, in addition, require easy installation and ground level reading to achieve a viable field operation. The design would have to accommodate initial stem diameters ranging from about 5 to 25 cm, with seasonal diameter growths of up to 1 cm.

Two years of development* led to the design shown in Fig. 1. A nylon frame, which makes contact with the tree via two mounting pads, houses a 50 ohm, ¾ turn, rotary, wire-wound potentiometer whose shaft holds a 4-cm-diameter nylon wheel. A 2.54-cm-wide by 0.2-cm-thick stainless steel band encircles the tree, inserting through the mounting pads and hooked by an S-bend to the rear mounting pad as shown. A leader wire attached to this band and a restraining spring attached to the frame connect to each other at a pin on the edge of the wheel. Spring tension holds the assembly snugly against the tree, holds the band taut and maintains a given potentiometer setting for a given stem dimension. Leads extend from the potentiometer terminals down the stem for reading at ground level. The band, which is free to slide through the mounting pads as stem growth occurs, pulls against the restraining spring and rotates the potentiometer shaft to change the potentiometer resistance by an amount proportional to increment. Changes in potentiometer resistance are measured by differences in scale reading of a locally built null-ohmeter. Bands are installed, by one person climbing the tree with a ladder, before the start of each growing season and with enough band length to accommodate an expected season's growth.

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INSTRUMENT PERFORMANCE

Estimate of Precision

Laboratory tests, as described below, were carried out to estimate dendrometer precision. For these tests, an assembly was built, using a micrometer dial and parts from a discarded tree ring analyser, that could hold the dendrometer frame firmly in place while rotating its potentiometer shaft by means of a linear pull measurable to 0.02 mm. With this assembly, the relation between null-ohmeter readings (in arbitrary units) and linear displacement was investigated. From this investigation, dendrometer precision was considered to be dependent upon three factors: calibration, resolution and reproducibility. Each of these factors is dealt with in turn below.

From the more than 300 dendrometers that had been used, 24 were selected at random for these tests. By using the assembly above, calibration data (change in null-ohmeter reading in arbitrary units/linear displacement in mm) were obtained for each of these 24 potentiometers. Based on linear regression, the potentiometers exhibited a linear response over their full range with a mean calibration constant of 9.81 units/mm, and with a 95% confidence interval on this mean of $\pm$ 0.20 units/mm. For the weekly diameter increments (ranging from 0 to a maximum of 0.7 mm) encountered throughout the study, this uncertainty in calibration contributes negligibly to a measure of instrument precision such as a root-mean-square error. If, however, the dendrometers are to be used to measure much larger increments, for example, seasonal or yearly increments, they should be calibrated individually.

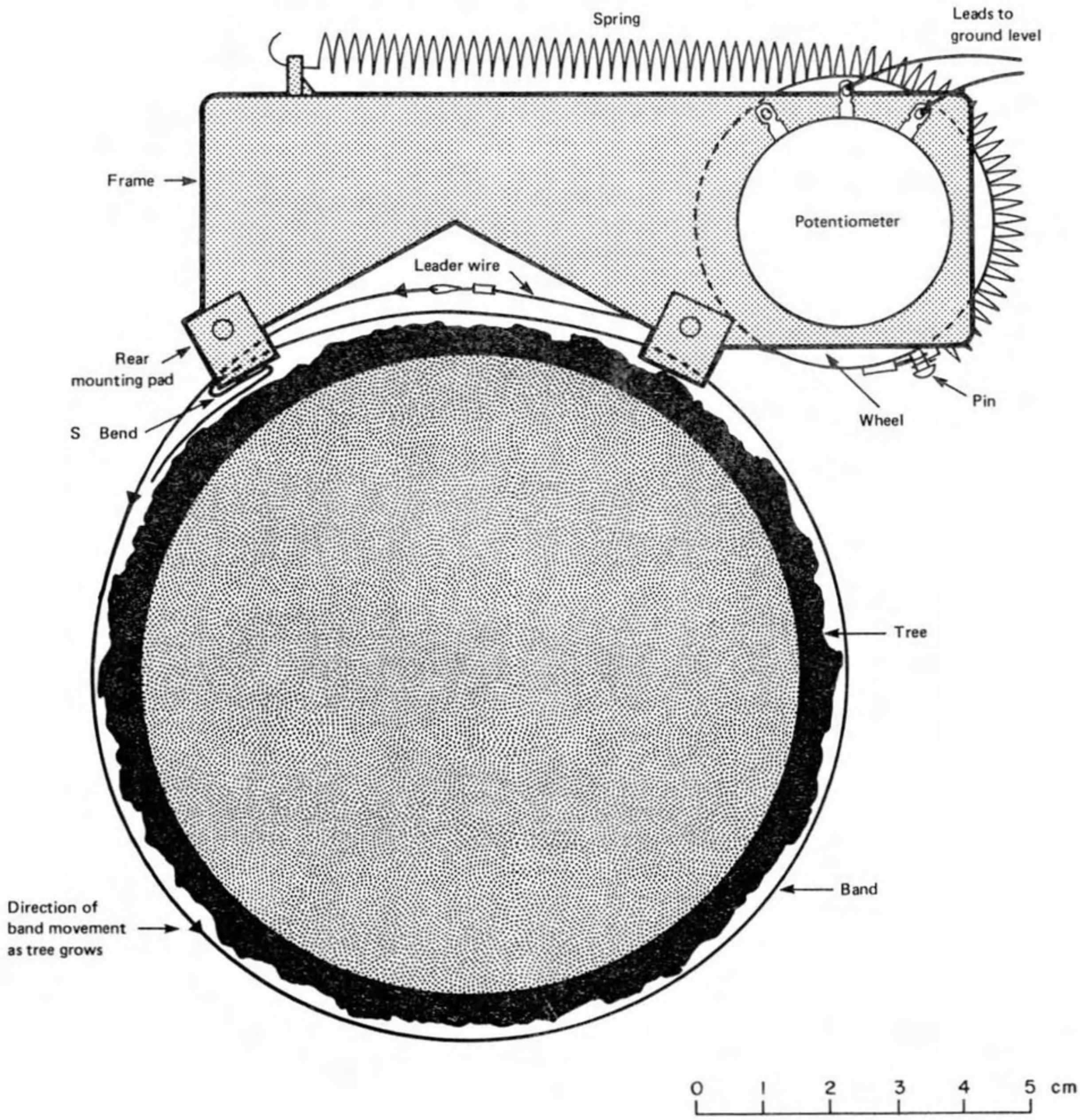

Fig. 1. The Electromechanical Dendrometer Band.

The use of a wire-wound potentiometer introduces an instrument resolution which is governed by the number of potentiometer windings in conjunction with the size of the wheel attached to its shaft. A potentiometer resistance at any instant is determined by **which** winding its sliding terminal is in contact with. Therefore, linear displacements which rotate the shaft so as to move the sliding terminal across a single winding without moving its point of contact from one winding to another will not be resolved. This stepwise behavior is demonstrable by observing discrete jumps in null-ohmeter reading in response to continuous rotation of the potentiometer shaft. The mean size of this step was estimated from the change in null-ohmeter scale units for 50 steps for each of the 24 potentiometers to be 6.3 units with a 95% confidence interval of $\pm$ 0.2 units or, using the calibration above, 0.65 $\pm$ 0.02 mm linear displacement.

This resolution represents the **maximum** difference that can be introduced, by this factor, between an actual linear displacement (however large or small) and the displacement that would be inferred using the instrument calibration above. To see this, consider that a vanishingly small linear displacement could be recorded as a 0.64 mm displacement if the sliding terminal were "just ready" to move its point of contact from one winding to the next or, at the other extreme, any displacement up to 0.64 mm could be recorded as a zero displacement if the sliding terminal had "just shifted" its point of contact. However, since all settings within the initial step are equally likely starting positions, and all settings within the final step are equally likely finishing positions, the recorded change in resistance will have an absolute deviation of one step from the change in resistance of an equivalent stepless potentiometer. This deviation will have a rectangular frequency distribution over the range $\pm$ 1 step. Therefore, the mean absolute deviation will be one half the step size and would contribute an instrument resolution term of 0.32 mm linear displacement to a root-mean-square error.

The precision of the null-ohmeter was investigated by testing it for reproducibility. Being careful to position the potentiometer within a step, this setting was read repeatedly and found to be reproducible to about 1 $\pm$ 1 units, having a mean absolute deviation of 0.81 units (0.08 mm) from the mean reading, and a standard deviation of 1.14 units (0.12 mm). Since two null-ohmeter readings are needed to record linear displacement, this factor would be included twice in a root-mean-square error. Changes in temperature (from 10^{o} to 25^{o}C) and physical handling were not observed to affect reproducibility significantly compared to this.

The regression of null-ohmeter units on mm linear displacement can be used to place confidence limits on the inverse estimation of mm linear displacement or diameter increment from the observed change in null-ohmeter readings (Natrella, 1969). For a single diameter increment inversely predicted from two null-ohmeter readings, the confidence limits are $\pm$ 0.25 mm (95%) or $\pm$ 0.16 mm (80%).

Estimate of Accuracy

Field tests were carried out to observe dendrometer behavior and assess its accuracy in measuring diameter increments under operational conditions. Because the bands were installed anew each growing season, it was essential to check them for underestimation (Bower and Blocker, 1966; Auchmoody, 1976). Therefore, as one field test, for each of the 300 trees that were measured weekly over each growing season with a dendrometer installation, total increment over the growing season was also measured with a diameter tape. Whatever precision is associated with individual tape readings, collectively, the tape readings should neither overestimate nor underestimate. The comparison of dendrometer null-ohmeter readings with tape readings for 50 of these 300 installations gave a mean dendrometer calibration of 9.69 units/mm linear displacement with a 95% confidence interval of $\pm$ 0.53 units/mm. A t-test of this data set with the data set obtained using the assembly to investigate instrument precision, showed no significant difference (probability $< 1\%$) between the two means. This suggests that the bands have not underestimated increment over an entire growing season and, whatever underestimation they may be subject to for some initial period after their installation, that underestimation is not large enough to significantly lower the total increments that they record for an entire growing season.

A second field test was carried out, to study dendrometer behavior on a weekly basis, immediately after installation and performing near the estimated level of precision. On each of three trees, eight dendrometer bands were installed, four above and four below a vernier band (Brix, 1972) similar to that used by Liming (1957). The vernier in each case had been previously installed by at least one growing season, and is used here as a standard. The dendrometer bands were installed with differing degrees of spring tension - the bands on trees numbered 1,2 and 3 being installed with "low", "medium" and "high" spring tension, respectively. Each set of nine bands spanned a stem length of less than 50 cm centered about the vernier which was situated at breast height. All bands within each set are assumed to measure the same increment (analyses of the data did not show any dependence on relative position). The results of weekly measurements over 4 weeks is shown in Table 1. Total increment over the 4-week period was also measured with a diameter tape.

The data in Table 1 are subject to different interpretations. The following is offered:

1) Looking first at overall vernier and dendrometer performance over the 4-week measurement period by comparing their total readings with the tape readings indicates an underestimation by the dendrometer bands **and** the vernier. One interpretation is to suspect the tape readings in Table 1, since these readings contradict the results of the other field test, which were based on a far greater number of tape readings and, although that test recorded growth only for an entire growing season, it did not suggest the degree of dendrometer underestimation implied by the tape readings in Table 1. However, each tape reading entered in Table 1 is an average of two tape readings, one above and one below the set of nine bands, and each was established by initial and finals readings that were made very carefully, several times and by more than one person. Alternatively, one can suspect the ability of a single band (dendrometer or vernier), however long in place to record accurately a particular increment. Distinct from the question of an initial period of underestimation caused by initial slack at installation is the question of "jerkiness" of response which would be observed if bands were to stick as they attempted to slide through their collars or mounting pads (Liming, 1957). Band underestimation could, therefore, be caused either by slack or sticking, or both. Since sticking should not be synchronized between installations, it should be possible to minimize this effect at least by installing a suitable number of bands to record a particular increment. This latter interpretation does suggest that such a precaution should be taken if the available precision of the bands is to be realized.

2) Comparing individual dendrometer readings with vernier readings, and considering the vernier as standard, shows dendrometer performance with respect to initial slack. From the analysis of dendrometer precision, differences between vernier and individual dendrometer readings up to about 0.3 mm can be accounted for by instrument behavior - dendrometer step size of $0.64/\pi = 0.2$ mm plus vernier precision of about 0.1 mm (Liming, 1957). Differences greater than 0.3 mm probably indicate initial slack. Inspection of Table 1 shows that:

   - in the first week, more "low" tension bands (tree 1) had initial slack than either "medium" or "high" tension bands (namely, 4 obvious and 2 marginal cases versus 1 marginal case versus 1 obvious and 4 marginal cases, respectively), and

   - after the first week, all dendrometer readings were within 0.3 mm of the vernier reading, indicating that no slack remained after the first week.

   This comparison suggests that bands should be installed with greater spring tensions than were these low tension bands and that bands can be installed snugly enough such that, for the bark conditions encountered here, only a nominal amount of growth is needed to take up initial slack and end the period of underestimation.

3) Inspecting Table 1 for variability among dendrometer readings shows that:

   - variability (expressed as the standard deviation of eight band readings per week per tree) is greater in the first week than in any of the following 3 weeks, and

   - for the last 3 weeks, when supposedly underestimation is not occurring and variability should be due to instrument precision alone, dendrometer variability observed under operational conditions is consistent with the earlier analysis of instrument precision.

CONCLUSIONS

The electromechanical dendrometer band discussed in this report was designed to meet the constraints of precision (0.2 mm diameter increment), easy installation, ground level reading and low unit cost ($5 to $10). The analyses in this report and the successful use of the dendrometer in obtaining the

Table 1. Data from second field test to study dendrometer behavior on a weekly basis

				Diameter Increment (mm)									
				Dendrometer									
Tree	Week	Tape	Vernier	1	2	3	4	5	6	7	8		
1	1		0.5	–0.21	0.07	0.14	–0.21	0.22	0.23	0.36	0.52	0.14	0.26
	2		0.2	0.11	0.35	0.15	0.11	0.29	0.12	0.03	0.36	0.19	0.12
	3		0.1	–0.01	–0.04	0.21	0.02	0.13	0.08	0.05	0.20	0.08	0.09
	4		0.1	0.27	0.08	0.06	0.16	0.20	0.18	0.10	0.02	0.13	0.08
	TOTAL	1.9	0.9	0.16	0.46	0.56	0.08	0.84	0.61	0.54	1.10	0.54	
2	1		0.3	0.31	0.12	0.15	0.18	0.37	0.45	0.31	0.00	0.24	0.15
	2		0.1	0.28	0.16	0.24	0.15	0.13	0.26	0.16	0.30	0.21	0.07
	3		0.1	0.12	0.07	0.22	0.17	0.23	0.06	0.23	0.11	0.15	0.07
	4		–0.1	0.06	0.06	0.18	0.20	0.10	0.25	0.14	0.15	0.14	0.07
	TOTAL	1.2	0.4	0.77	0.41	0.79	0.70	0.83	1.02	0.84	0.56	0.74	
3	1		0.8	0.64	0.68	0.55	0.64	–0.06	0.53	0.51	0.49	0.50	0.24
	2		0.5	0.37	0.28	0.30	0.32	0.47	0.31	0.35	0.39	0.35	0.06
	3		0.4	0.34	0.64	0.30	0.29	0.44	0.60	0.68	0.28	0.45	0.17
	4		0.1	0.33	0.12	0.40	0.38	0.86	0.20	0.32	0.39	0.38	0.22
	TOTAL	2.2	1.8	1.68	1.72	1.55	1.63	1.71	1.64	1.86	1.55	1.67	

needed data indicate that the dendrometer has indeed met its design objectives and fulfilled its purpose.

The precision of the dendrometer could have been improved by using a more finely would potentiometer and/or a larger diameter wheel in order to decrease its step size, step size being the major factor determining instrument precision. However, the existing design has successfully met its objectives and such modification which might have increased unit cost, would still have left the same problems of accuracy associated with slack and sticking. This behavior, which seems to be characteristic of band type dendrometers, suggests that these bands should

- be preinstalled (in terms of time or amount of tree growth) to avoid their underestimating increment because of initial slack, and

- be used in sufficient number to enable reporting of increment as an average of band readings to guard against inaccuracies owing to sticking of individual bands.

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BC-X-184

November, 1978