

New inexpensive dendrometers for monitoring crop tree growth

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Abstract

A fast-responding dendrometer is needed for measuring tree growth responses (daily or hourly) to drought, fertilization stress and other stresses. This study reports on operational comparisons between new, inexpensive automatic point and band contact dendrometers. Eighteen point and five band dendrometers were installed on pecan tree trunks and branches during the 2005 growing season, and their performance and measurements were compared by analyzing data downloaded weekly. Data indicated that the point dendrometer was accurate. However, band dendrometers may underestimate tree growth (average measured value by a band dendrometer was half that measured by the point dendrometers), and they may not be able to measure the hourly diameter change of small-diameter branches over several days. Point dendrometers were found to be suitable for large-scale tree growth measurements and water and fertilizer stress monitoring due to their fast response (hourly or faster), ease of construction and installation, and low expense (<\$40 each).

Keywords: Automatic, Branch, Dendrometer, Pecan, Point Dendrometer, Trunk, Radial Growth.

Introduction

Dendrometers have been used to measure the change in growth of forest trees (Clark et al., 2000) and fruit trees, notably apples (Link et al., 1998) and peaches (Goldhamer et al., 1999). Dendrometers measure the change in the diameter and growth of a tree. Clark et al. (2000) presented a complete review of the literature on dendrometer types and uses in forestry research and management. There are two categories of dendrometers: contact and noncontact. Contact dendrometers contact the stem physically to measure the diameter of a branch/trunk. A diameter tape (a kind of contact dendrometer) can measure the diameter of a trunk/branch by circling around the trunk/branch surface, assuming the trunk/branch shape is round. Contact dendrometers include calipers, dial gauges, diameter tapes, the Biltmore stick, sector forks, and the Samoan stick (Jackson, 1911; Brown et al., 1947; Tryon and Finn, 1949; Bower and Blocker, 1966; Dixon, 1973; Matérn, 1990; Keeland, 1993; Costella, 1995; Link et al., 1998; Goldhamer et al., 1999; Bitterlich, 1998).

Noncontact dendrometers can obtain measurements remotely. Optical dendrometers are the most commonly used noncontact dendrometers (Clark, 1913; Wheeler, 1962; Eller and Keister, 1979; Robbins and Young, 1968; McClure, 1969; Williams et al., 1999; Parker and Matney, 1999). An optical caliper uses two parallel lines of light to view points on a stem that

represent the diameter. The distance between the two lines, which can be measured by a ruler on the optical dendrometer, is the diameter (Clark et al., 2000).

Noncontact dendrometers can be more efficient than contact dendrometers with a 35 to 40% time savings, and their diameter measurements are comparable in accuracy to measurements by calipers and diameter tapes (Binot et al., 1995). Data measured by non-contact dendrometers can be directly downloaded to a computer (Binot et al., 1995). Automated contact point and band dendrometers are also commercially available. However, instruments cost around \$650, which limits the number that can be installed on a tree to measure branch growth (Agricultural Electronics Corporation, 2003).

Most dendrometers, except the automated ones, are “slow-responding” instruments, because they are typically used to measure tree growth monthly or yearly. To observe growth responses on an hourly or daily cycle (e.g., the responses to water and fertilizer stresses), a fast-responding electronic dendrometer is needed; and at least two sensors/branch must be installed and replicated three to four times (Andales et al., 2006). The minimum cost would be \$20,800 to measure 4 trees, 4 branches per tree, with 2 dendrometers per branch, using commercially available automated fast-responding dendrometers. Consequently, there is a need for low-cost automated contact point or band dendrometers.

Point dendrometers have been criticized for being inaccurate compared to band dendrometers—a point dendrometer can only measure a point diameter growth, while measurements from band dendrometers represent an average of all diameters over all directions (Avery and Burkhart, 1994; Clark et al., 2000). Therefore, multiple point dendrometers are needed for branch/trunk growth measurements. In addition, an automatic point dendrometer is often installed with the LVDT or a linear potentiometer holder (LVDT: linear variable differential transformer) anchored to a measuring branch with two long anchor screws (Andales et al., 2006), so the LVDT or potentiometer will not move as the branch/trunk grows. Band dendrometers do not have this measurement problem; however, an LVDT/potentiometer band dendrometer must be held to the branch with a constant spring tension that allows the band to expand as growth occurs. If the interest is in measuring the expansion and contraction of the trunk diameter throughout the day in response to moisture stress, a band dendrometer may not be sensitive enough because a spring must contract the band, and to accomplish this contraction the spring force must overcome the force of friction as the trunk shrinks.

The objectives of this study were to design inexpensive automatic fast-responding point and band dendrometers and to compare the performance of these two systems to data found in the literature.

Materials and methods

Design

Automatic band dendrometer

The automatic band dendrometer consists of several parts, including a linear potentiometer sensor, stainless steel hose clamps, bolts and nuts, an aluminum channel, and a stainless steel spring (Figure 1). The potentiometer sensor is a Model 9605 BEI made by Duncan Electronics (http://www.beiduncan.com/html/products/linear/mini_sensors.htm). Clamps, bolts, nuts, and aluminum channel can be purchased from a local hardware store. The spring (model: LE 026 C 11s) can be ordered from Lee’s Spring Company (<http://www.leespring.com/>). The hose screw can be used to adjust the dendrometer perimeter to fit different branches and trunks.

The BEI 9605 sensor (Figure 2) gives a linear electrical response that can be converted to linear distance (e.g., diameter growth) when connected to a CR23X or a CR10X datalogger (Campbell Scientific, Inc., Logan, Utah) or to any data logger with the capability of measuring a half bridge circuit.

The 9605 sensor must be wired as shown in Figure 2 or the response curve will be non-linear. The sensor is a linear sliding resistor with terminal 2 connected to the resistor slider (plunger). Terminals 3 and 1 are connected to the resistor's end points. A datalogger measures the voltage (V1) between terminals 2 and 3 and the voltage (Vx) between terminals 1 and 3. The ratio of the resistance between 3 and 2 to the resistance between 1 and 3 is linearly related to the ratio of the length between 2 and 3 to the whole length between 1 and 3. From the ratio of V1 to Vx, the physical position of terminal 2 (plunger position) on the resistor can be determined. Consequently, the change in plunger length can be used to measure change in growth of the tree. The AC half bridge (P5) instruction set for the Campbell CR10X or CR23X is used in the data logger program to record the output from the sensor. Instruction P5 has eight parameters that need to be specified in the program. Appendix 1 shows an example program for a CR10X. Note that if more than one sensor is connected to the data logger, parameter 4 (excitation channel number) must be set to increment by 1 so that the excitation source can be rotated among the three available E (excitation) channels for consecutive sensors.

If two sensors per trunk (or per branch) are installed, a 6-wire cable (e.g., Belden Part No. 9745, 22 AWG, unshielded) can be used to connect the sensor to the data logger. However, a 3-wire cable also can be used to connect the dendrometer to the data logger (e.g., Belden Part No. 8443, 22 AWG, unshielded). Wire lead length should be less than 116 m in order to get accurate measurements of the change in resistance. Longer wire lengths can be used, but calibration should be done with the leads connected to the sensor to account for the connection wire resistance.

Construction of a band dendrometer requires two hose clamps (Figure 3, a, b and c). Each clamp perimeter should be longer than the half length of a branch perimeter to be measured. The clamps need to be unscrewed and then connected together (Figure 3, b and c). The screw at the open end is removed so that the other band end can go through the hole (Figure 3, d), and a new screw is inserted and held by a nut (Figure 3, e and f). The screw and nuts should leave some space around the band so that the band can freely move (Figure 3, f). The BEI 9605 is held in an aluminum channel segment which is held on the freely moving band end by two stainless screws (Figure 3, g and h). Appropriate holes on the aluminum channel are drilled and threaded before attaching the BEI 9605 sensor. The thread can be made directly by the screws instead of using threading tools since the aluminum is softer than the steel screw. One side of the spring is connected into the freely moving band end and the other side is connected into an appropriate point of the band (Figure 3, i). The spring choice was based on work by Keeland and Young (2007), who found that a spring length of 76.2 cm (3 inch), outside spring diameter of 6.35 mm (0.25 inch), and wire diameter of 0.66 mm (0.026 inch) work very well for band dendrometers. These springs provide an initial tension of 1.48 N (0.333 lb), a rate of 0.087 N/mm (0.5 lb/inch), and a maximum extension of 190.5 mm (7.5 inch).

Automatic point dendrometer

To build a point dendrometer, the BEI 9605 sensor is mounted in a 25.4 mm C-clamp (available at local hardware stores) that holds the 9605 sensor in place against the trunk or branch of the pecan tree (Figure 4). (We conducted intensive experiments on pecan tree water

use [evapotranspiration] and growth; these dendrometers were initially used to measure pecan tree growth. However, in this paper, we report the dendrometers' design and comparison. These dendrometers can be used for other trees as well). Two holes are drilled at opposite sides of the clamp for the 100 mm hanger bolts. Two nuts on each bolt fix the clamp. Pre-drilling the trunk/branch for the two bolts is required to reduce resistance when driving the bolts into the wood. The BEI 9605 sensor is relatively inexpensive (\$25), so the total cost for an automatic dendrometer (point and band) will be below \$40.

Calibration of the 9605 linear position sensor

The 9605 sensor output V1/Vx ratio, which ranges from 0 to 1.0, is converted into the y-value (length of sensor, mm) using a linear calibration regression equation (Figure 5). The slope of the equation is the change rate of the sensor length to the variation of V1/Vx. When using new sensors, at least three sensors should be tested to verify that the same linear calibration equation can be used for all the sensors. The 9605 sensor attached to a CR10X or CR23X is easily calibrated using a digital caliper and viewing the response (V1/Vx) at various sensor lengths using Loggernet software (Campbell Scientific, Inc., Logan, Utah) or similar data acquisition software. One can also use a battery (e.g., AAA) to provide voltage to Vx and measure the V1 variation with a multimeter. Because of the inner structure of the sensor, the resistance between terminals 1 and 3 may vary when one changes the plunger length; therefore, measuring the resistance variation with plunger length across terminals 2 and 3 and then using the ratio of this resistance to a constant resistance across terminals 1 and 3 to infer V1/Vx may not obtain the true variation and is not recommended. The change of the sensor length over a specified time interval gives the measured linear growth of the radius (point dendrometer) or perimeter (band dendrometer) of the trunk or branch.

Thermal expansion and contraction—sensor resolution

For the point dendrometer, the thermal expansion/contraction variation of the bolt in the diameter direction will affect the diameter measurement. Steel has a thermal expansion rate of $1.2 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$ (Pesonen et al., 2004). The steel expansion rate was used for the point dendrometer thermal expansion correction. The length of the bolt was 100 mm. The bolt expansion/contraction was therefore $1.2 \times 10^{-3} \text{ mm } ^\circ\text{C}^{-1}$. For this study, the measured annual diameter growth ranged from 0.47 mm to 7.1 mm. The annual growth measurement by the point dendrometers used data taken in the afternoon at 14:00. The temperature difference at 14:00 between day 87 (the beginning day of the growth calculation) and day 354 (the end day) was 10°C (temperature data were obtained from weather.nmsu.edu). Therefore, the thermal effect was about 0.012 mm for the annual point growth measurement, which appeared to be negligible compared to annual radial growth (>1 mm per year). However, for hourly growth measurement, thermal effects may be relatively large (e.g., 0.01 mm, because daily temperature change can be 10°C or more) in relation to the daily fluctuation (<0.05 mm per day) in radial growth. Therefore, the thermal correction must be made when using the point dendrometer for hourly measurements.

The thermal correction of the band dendrometer is related to the band effective length (the perimeter of the trunk/branch). The trunk/branch diameters ranged from 85.7 mm to 354.0 mm. The trunk/branch perimeters ranged from 269.1 mm to 1111.6 mm. Therefore, the thermal effect was about 0.13 mm for the annual growth measurement based on the expansion rate of

$1.2 \times 10^{-5} \text{ }^\circ\text{C}^{-1}$ (Pesonen et al., 2004), which is negligible compared to annual radial growth (>1 mm per year). However, for hourly growth measurement, thermal effects may be relatively large (e.g., 0.01 mm, because daily temperature change can be 10°C or more) in relation to the daily fluctuation (<0.05 mm per day) in radial growth. Therefore, the band dendrometers require thermal correction for daily measurements.

The working temperature limit of the BEI 9605 sensor is -40°C to 135°C . The published linear accuracy is 98%, i.e., the error will be 0.02 mm for a 1 mm measurement and 0.001 mm for a 0.05 mm measurement. The major specifications of the sensor are shown in Table 1. More detailed specifications can be found in the user manual (BEI Duncan Electronics, 2004). Sensor resolution (the shortest distance that the sensor can detect) was not provided in the manual. From the data measured in the study, the resolution of the sensor was estimated to be better than 0.01 mm (Figure 6).

Experiments

Dendrometer calibration

The BEI 9605 sensors may have different calibration slopes when new and after they are used for a certain period. Therefore, V1/Vx variation with sensor length was measured for five new sensors (randomly selected) and for five randomly selected sensors having been used for one year. Because the sensors had different lot numbers, V1/Vx variation with sensor length for five sensors from a second lot and three sensors from a third lot (only three sensors from the latter lot were available) were also measured.

Tree growth measurements

Dendrometer measurements

To compare point and band dendrometers, eighteen point dendrometers and five band dendrometers were constructed with BEI 9605 sensors from lot numbers 04-43, 3302, and 3362 and installed on four pecan trees at a 5.1-ha orchard south of Las Cruces, NM ($\text{N}32^\circ 16' 34.37''$, $\text{W} -106^\circ 49' 4.14''$) in March 2005 when the trees were dormant. The orchard was planted in 1970 at 10.0 m by 10.0 m tree spacing. In 2005, the average orchard height was 12 m and trees had a 0.3-m average DBH (diameter at breast height; the average diameter [outside the bark] of a tree 4.5 feet [1.35 m] above mean ground level.) The soil was a Harkey loam (coarse-silty, mixed, calcareous, thermic typic Torrifuvents). The farmer applied 320 kg ha^{-1} of nitrogen through the irrigation system throughout the growing season. The orchard was flood-irrigated from two wells; the water was discharged into the orchard through a high-flow turnout. Sparling Propeller flow meters (Sparling Instruments, Inc., CA) were installed on the pumps to measure irrigation amounts. Daily precipitation and hourly temperature were measured at the Leyendecker Plant Science Center Weather Station ($\text{N}32^\circ 12' 3.89''$, $\text{W} -106^\circ 44' 33.0''$), located 3.1 km from our experimental site, and the data are available from the New Mexico Climate Center Website (<http://weather.nmsu.edu>).

The dendrometer measurements were collected with a CR23X data logger. The sampling frequency was 1 hour. Measurements continued from March 28, 2005 (Julian day 87) through January 14, 2006 (Julian day 14). The trees broke dormancy in early April, 2005.

The dendrometers were installed on trunks, primary branches and secondary branches (the installation position and branch and trunk diameters are provided in Table 2). The band dendrometers were installed near (~ 1 cm) the corresponding point dendrometers.

Manual measurements

To check the dendrometer accuracy, the core samples of annual rings were taken at the corresponding dendrometer measurement locations using a borer tool (5-mm inside diameter, Suunto, Finland) in April 2008. For each trunk/branch, 4 core samples were taken, of which 1 or 2 samples corresponded to the point dendrometer measurement points (Table 2). Then the width (annual radial growth) of the 2005 annual ring on each core sample was measured using an electronic caliper (Model No. CD-6" CS, Mitutoyo Corp, Japan).

Data analysis

Calibration slopes

A calibration slope was obtained for each sensor from the V1/Vx and sensor length change data using a linear regression method (Figure 5). The slope and constant in a regression equation were evaluated using T tests to see if they were statistically significant. One-way ANOVA (analysis of variance) was used to test if the calibration slopes were different for new sensors, old sensors, and sensors from different lots.

Tree growth measured by dendrometers

Dendrometer measurements were converted to length using the average of all the calibration slopes, which were statistically similar (Table 3). The point and band dendrometer measurements were corrected for thermal effects (see the section *Thermal expansion and contraction and sensor resolution*). The temperature at the beginning of the growth season was used as the base temperature. Each length measurement then had subtracted from it the product of $1.2 \times 10^{-2} \text{ mm } ^\circ\text{C}^{-1}$ and the temperature variation ($^\circ\text{C}$) (the difference between the current and the base temperature). The length change (Lband for band dendrometers, Lpoint for point dendrometers, mm) during the growing season (from 14:00 day 87 to 14:00 day 354) was calculated. The Lband value measured by band dendrometers was divided by Pi (3.14) to obtain the diameter growth, and the resultant value was divided by 2 for comparison with the point dendrometer L point value, which was the radius growth.

Dendrometer accuracy

The annual radius growth measured by dendrometers was compared with the manual measurement. The point dendrometer measurements were divided into three groups: trunk, primary branch and secondary branch (Table 2). In each group, the radius growth data were used in one-way ANOVA analyses to test if the difference between measurements from point and manual measurement was significant. The Minitab (2000) statistical software package was used for all the statistical analyses.

For the accuracy analysis of band dendrometer measurements, the mean of each 4 manual measurements of radial growth on the corresponding branch/trunk was calculated. (The manually measured data were not available for the secondary branch on tree 2 [diameter = 10.1 cm, Table 2] because the branch was removed by the farmer before 2008.) Then, all the measurements of annual radial growth (branch/trunk diameter ranged from 198.1 mm to 330 mm) by band dendrometers were compared to the manually measured means by one-way ANOVA.

In addition, the time series (daily and yearly durations) of band and point measurements were plotted against each other.

Results and Discussion

Calibration slopes

Good fits were obtained in the regression calibrations (see the sample calibration in Figure 5) ($R^2 > 0.99$, $T > 260$, $P < 0.0001$). The calibration slopes were statistically similar ($F = 0.63$, $P = 0.605$, and Table 3) for the three different categories of BEI 9605 sensors: new, old, and different lots. The average slope was 12.643 mm. The 95% confidence interval was 12.576 mm to 12.709 mm. Therefore, if the average slope (12.643 mm) is used, the possible error obtainable from the slope calibration would be within ± 0.066 mm for the full scale ($V_1/V_x = 1$) and the relative error would be ± 0.066 mm / 12.643 mm (the full scale) = $\pm 0.5\%$. To use these sensors to measure tree growth, several sensors (e.g., five in this study) would be enough to represent calibration for all sensors.

Daily measurements

Figure 6 shows the hourly measurements of point and band dendrometers in nine days (days 217 to 226). Branch or trunk growth usually occurred from sunset through morning, with peak growth occurring during the morning from around 7 a.m. to 12 p.m. From afternoon to sunset, the diameter of the tree shrank due to increased evapotranspiration drawing some water from the stems (Génard et al., 2001; Pesonen et al., 2004).

Band dendrometers were more sensitive to the hourly changes of trunks (dendrometer 9 in Figure 6) and larger branches (dendrometer 13 in Figure 6) than to changes in smaller branches (dendrometer 8 in Figure 6), because trunks and larger branches may undergo larger changes than do smaller branches over that period (Table 3).

Point dendrometers had different responses on different points of the trunk or branch (dendrometers 11 and 12 in Figure 6) because the radial change of each point was different. Point dendrometers can be sensitive to the radial changes of smaller branches (dendrometers 11 and 12 in Figure 6). Multiple (at least two) point dendrometers are required to measure growth of a branch/trunk accurately, which is feasible with a low-cost dendrometer.

Seasonal measurements

Figure 7 shows the seasonal radius growth measured by point and band dendrometers. The tree branch and trunk grew from day 87 to around day 260 (September 17). After day 260, the trunk and branches did not show significant growth. During wintertime (day 354, 2005 to day 14, 2006), the diameters of trunk and branches shrank because the trees had not been irrigated since day 276.

There are large oscillations shown in the graphs from days 149 to 272. This is the tree response to an irrigation cycle (compared with irrigation, precipitation provided a small amount of water). When irrigation occurred, branches and trunks started to grow and kept growing for about 7 days; then the diameters shrank as the trees experienced water stress.

Point dendrometer measurements may have large magnitude variations (point dendrometers 11, 12, and 20 in Figure 7), and point dendrometers on different points of a trunk or branch may give different measurements. However, band dendrometers always measure relatively smooth curves because the measurement represents an average of all diameters over all directions, eliminating variability caused by direction (Clark et al., 2000).

Dendrometer accuracy

Point dendrometer measurements were statically the same as the manually measured data (Table 4; all the one-way ANOVA P values were larger than 0.05). The annual radial growth measured manually and by point dendrometers was reasonable compared with data in Nelson et al. (1965), who found the average 10-year radius growth of unmanaged pecan (DBH = 150.2 mm

to 304.8 mm) in the northeast Louisiana Delta to be 24.13 mm, i.e., an average annual radius growth of about 2.413 mm. The DBH of our measured trunk ranged from 295.4 mm to 354.0 mm and the average radius growth in 2005 was 2.50 mm (manual measurements, n=16) and 2.79 mm (n=5, measured by dendrometer) (Tables 3 and 4). The diameters of primary branches ranged from 198.1 mm to 273.4 mm and the average radius growth was 2.28 mm (manual) and 2.36 mm (dendrometer). The diameter of secondary branches ranged from 101.1 mm to 152.8 mm and the average radius growth was 1.70 mm (manual) and 1.64 mm (dendrometer).

However, the band dendrometer's measurement was significantly different than manual measurements (Table 4, $F=10.6$, $P<0.05$). The measurements from band dendrometers (Table 4, mean=1.40 mm) were 42% lower than the manual measurements (mean=2.42 mm).

The underestimate of band dendrometer measurements may be caused by the slack between the band and the branch/trunk surface. Although the spring on the band forces the band tightly against the trunk/branch surface, the band may not touch the surface seamlessly, and this may cause some slack. If this is true, it is important to consider that measurements in the literature taken by automated band dendrometers may underestimate tree growth.

Further observations

The BEI 9605 sensor should not be held tightly by the screws and clamps; otherwise the plunger will not be able to move freely. The plunger should be evaluated after installation to ensure that it can move freely.

Thermal correction needs to be done for the point and band dendrometer measurements, especially for hourly measurements. The temperature data at a local weather station can be used for the correction, but onsite temperature data would be preferable.

Dendrometers can be installed in remote areas, but sometimes that makes it difficult to travel frequently to the site. It is possible to set up remote access using a local telephone line or a wireless phone line to connect to the datalogger (www.campbellsci.com). Even so, because the sensors may be affected by small animals and other environmental factors, routine physical checks would be required.

Conclusions

The high accuracy, fast response, ease of fabrication and installation, and low cost of automated point contact dendrometers make them suitable for tree growth measurements and for water and fertilizer stress monitoring. Multiple point dendrometers should be installed when making branch/trunk diameter growth measurements because the radial change at each point will be different. Band dendrometers underestimate tree growth, and they may not be able to measure the hourly diameter change of small-diameter branches (e.g., 10.1 cm in this study for pecan trees) over several days. Our data indicates that researchers should be careful when using growth data in the literature if measurements were obtained using automated band dendrometers.

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Appendix 1: A sample program (Instruction 5 setting) for a Campbell CR10X data logger to read the 9605 sensor.

Parameter	Setting	Note
01	4	Reps (i.e., 4 sensors connected to the logger)
02	15	2500 mV Fast Range (The voltage and scanning code for the readings)
03	1	First SE channel (i.e., 1 st sensor is connected to single-ended channel 1, 2 nd sensor connected to SE 2, 3 rd sensor connected to SE 3, 4 th sensor connected to SE 4)
04	11	Excitation begins at E1 and is incremented by 1 (i.e., E1 excites sensor 1, E2 excites sensor 2, E3 excites sensor 3, E1 excites sensor 4)
05	2500	mV Excitation voltage
06	1	Input (memory) location number for first measurement
07	1	Multiplier (This may be set to the slope of the calibration line)
08	0	Offset (This may be set to the y-intercept of the calibration line)

Table 1. Specification of 9605 sensor.

Total Electrical Travel (A) mm (inches)	12.7 (0.50)
Active Electrical Travel mm (inches)	10.0 (0.40)
Linearity Over Active Electrical Travel	± 2%
Mechanical Life	2,000,000 Full Cycles
Actuation Force Newtons (oz.)	4.0 (14.4) Maximum, supplied with internal spring to return actuator to extended position.
Temperature Limits °C	-40 to 135

Table 2. Dendrometer placement on pecan trees in the pecan orchard, and other trunk/branch parameters.

Tree No.	Trunk/branch information and dendrometer type	Sensor number and placement					
		Trunk		Primary Branch		Secondary Branch	
		SE*	NW	SE	NW	SE	NW
1	Trunk or branch diameter (mm)	327.6		218.4		85.7	
	Point dendrometer No.	#1	#2	#3	#4	#6	
	Measured annual radius growth by the sensor† (mm)	3.57	2.85	2.87	0.57	1.3	
	Band dendrometer No.				#5		
	Annual radius growth measured by the sensor† (mm)				0.88		
	Annual radius growth measured manually‡ (mm)	3.77	2.75	2.70	1.57	1.76	1.79
2	Trunk or branch diameter (mm)	354.0		198.1		101.1	
	Point dendrometer No.	#7		#10		#11	#12
	Measured annual radius growth by the sensor (mm)	1.54		0.91		0.24	0.23
	Band dendrometer No.	#9			#8		
	Annual radius growth measured by the sensor (mm)	1.39			0.33		
	Annual radius growth measured manually (mm)	1.72	1.93	2.2	1.31	N/A§	N/A
3	Trunk or branch diameter (mm)	295.4		273.4		152.8	
	Point dendrometer No.	#14		#15	#16	#17	#18
	Measured annual radius growth by the sensor (mm)	2.85		4.29	N/A	1.17	2.21
	Band dendrometer No.				#13		
	Annual radius growth measured by the sensor (mm)				1.8		
	Annual radius growth measured manually (mm)	2.26	2.75	3.48	2.08	1.47	2.01
4	Trunk or branch diameter (mm)	330.0		254.8		141.6	
	Point dendrometer No.	#19	#20	#22		#23	
	Measured annual radius growth by the sensor (mm)	3.28	N/A	3.16		1.88	
	Band dendrometer No.	#21					
	Annual radius growth measured by the sensor (mm)	1.56					
	Annual radius growth measured manually (mm)	3.13	2.78	3.21	3.33	1.83	1.39

*: SE = southeast side; NW = northwest side.

†: the growth during day 87 (March 28) to day 354 (December 20) in 2005.

‡: annual ring width in 2005

§: N/A: not available. Datalogger channel for dendrometer 16 had problems and did not record the data. Dendrometer 20 had outliers after day 188 and the annual radius growth could not be calculated.

Table 3. Mean and standard deviation (Std.) of annual radius growth (during day 87 [March 28] to day 354 [December 20] in 2005) for pecan tree trunk and branches measured by point and band dendrometers and measured manually.

	Automatic point dendrometer	Automatic band dendrometer	Measured manually
Trunk or branch diameter range	Mean/Std.	Mean/Std.	Mean/Std.
mm	mm	mm	mm
Trunk 295.4-330.0	2.818 / 0.776, n=5 ^(a)	1.475 / 0.120, n=2	2.50 / 0.71, n=16
Primary branch 198.1-273.4	2.36 / 1.576, n=5	1.340 / 0.257, n=2	2.28 / 0.69, n=16
Secondary branch 85.7-152.8	1.172 / 0.8187, n=6	0.330 / N/A ^(b) , n=1	1.70 / 0.20, n=12

^a: n: sample number;

^b: N/A: not available.

Table 4. One-way ANOVA test results for radius growth measured by point and band dendrometers vs. the corresponding manual measurements.

Dendrometer type	Point	Band	Band	Band
Branch diameter range (mm)	295.4-330	198.1-273.4	85.7-152.8	198.1-330
Sample number (n)	5	5	4	4
ANOVA F/P values	0.02/0.89	0.02/0.89	0.24/0.64	10.6/0.02
Mean radius growth (dendrometer vs. manual) (mm)	2.79/2.85	2.36/2.48	1.64/1.77	1.40/2.42

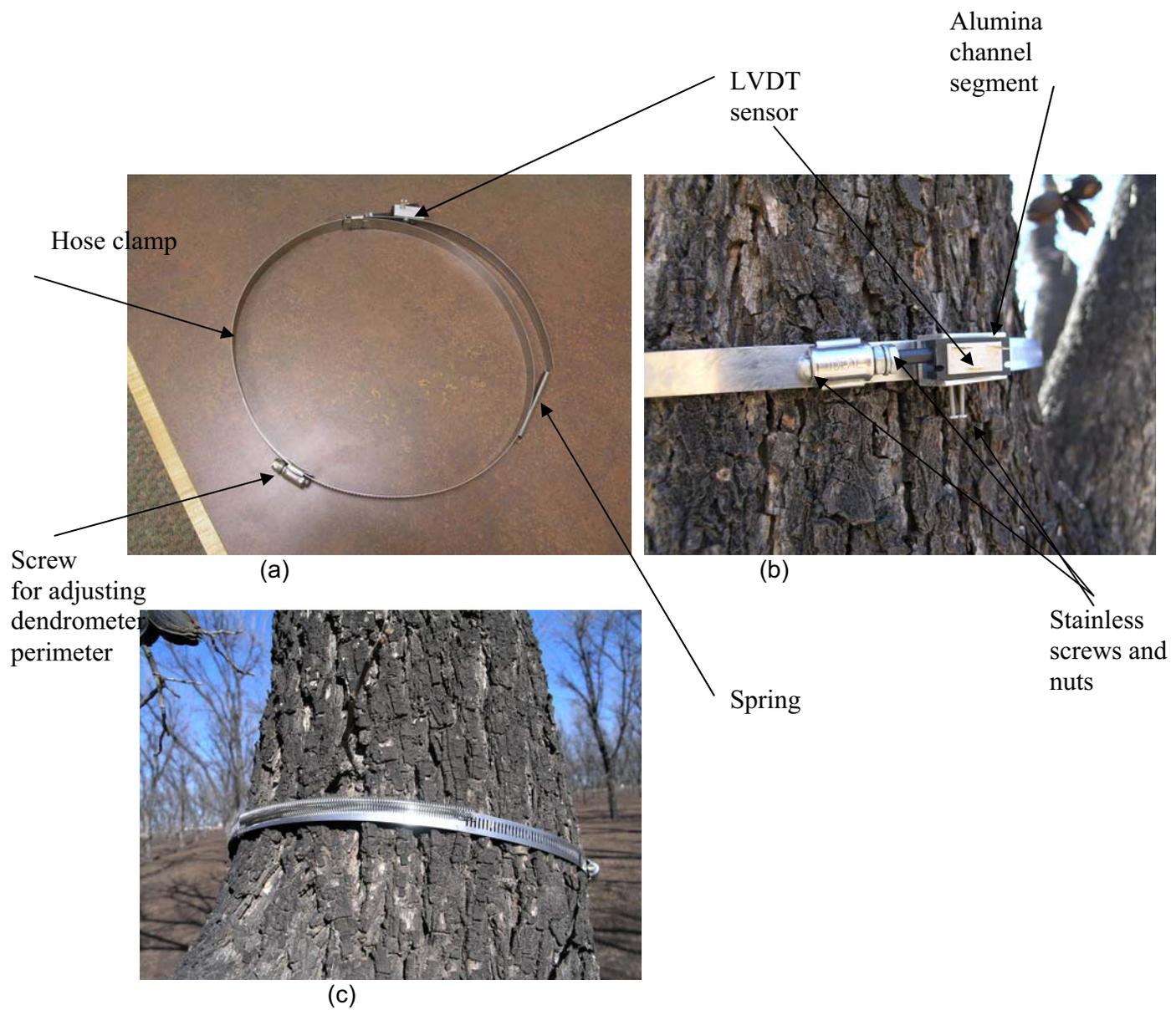


Figure1. A sample automatic band dendrometer. (a) a band dendrometer before installation; (b) the LVDT sensor side view after installation; (c) the spring side view after installation.

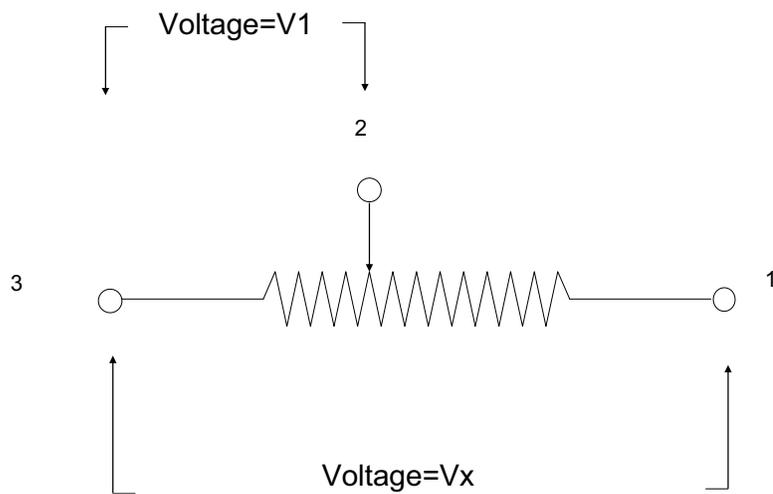
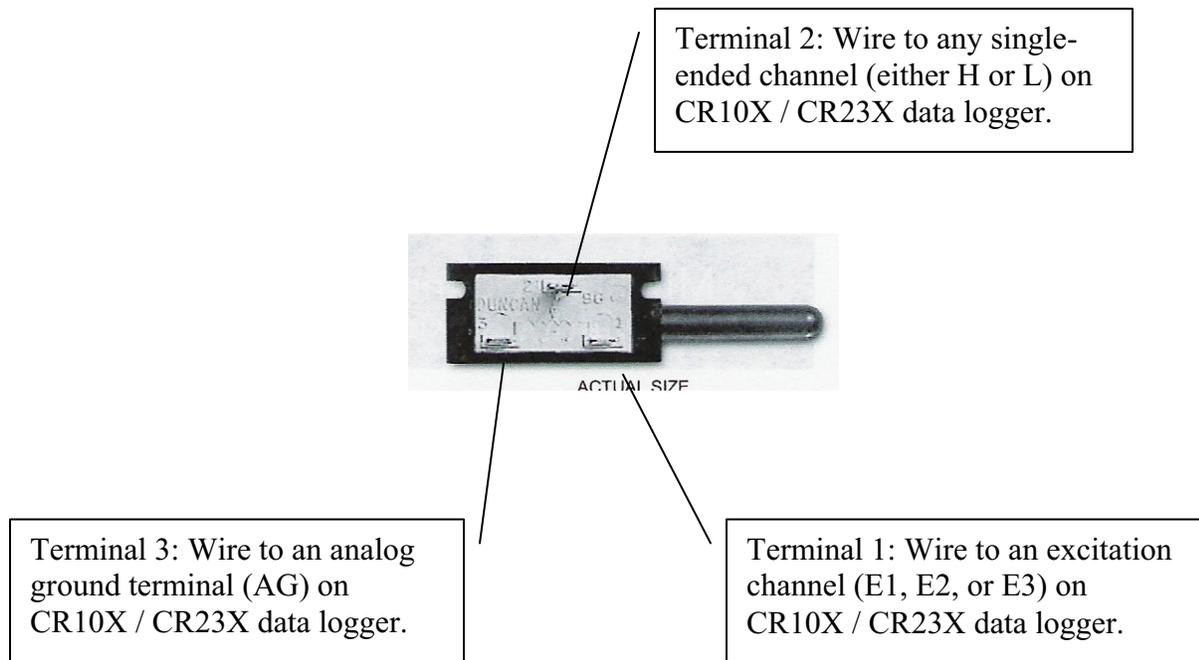


Figure 2. Wiring Diagram of a BEI 9605 linear motion position sensor to a CR10X or CR23X datalogger. Above: the sensor; bottom: the circuit diagram.

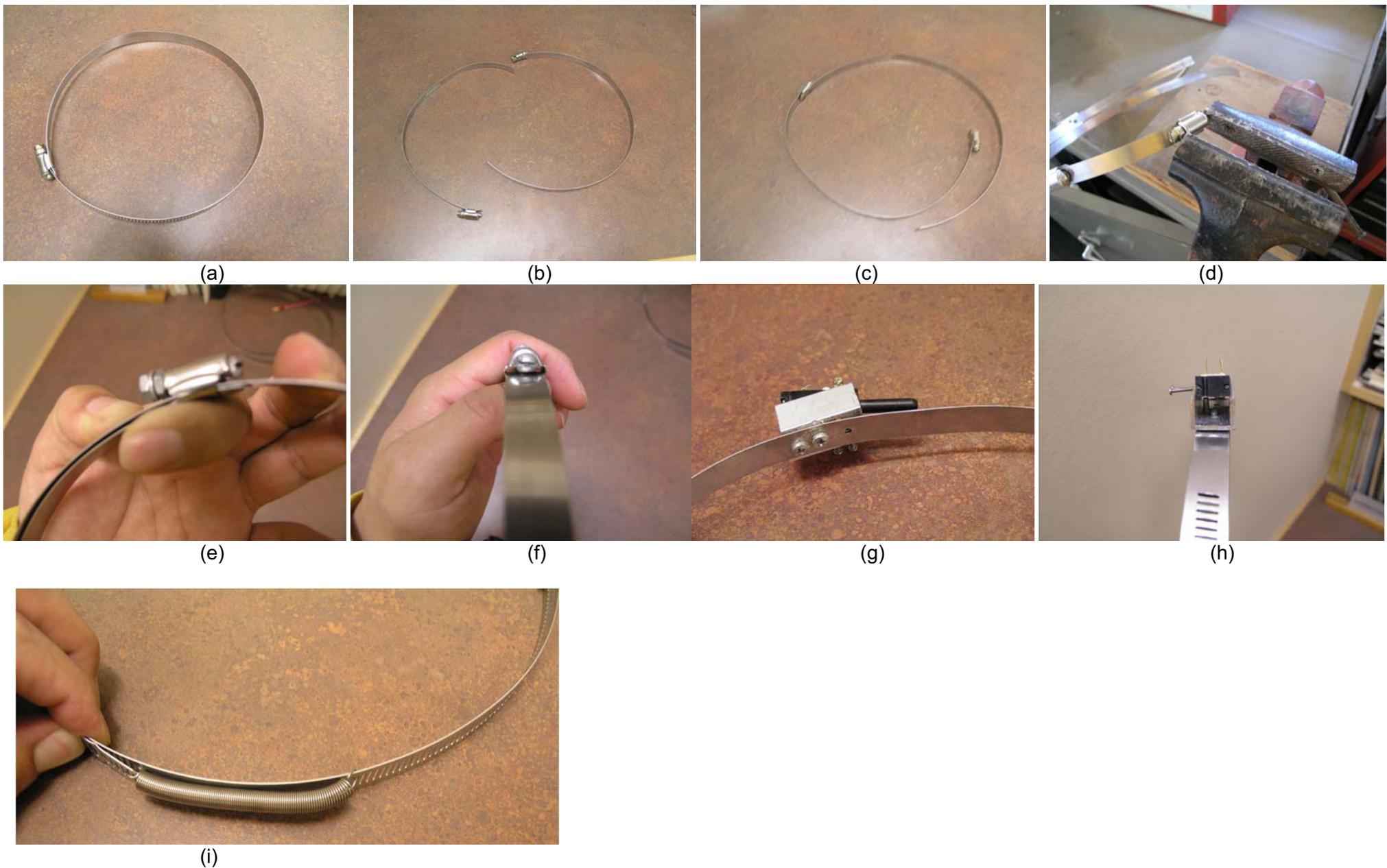


Figure 3. Automatic band dendrometer construction. (a) original hose clamp; (b) two unscrewed clamps; (c) two clamps are connected together; (d), (e), (f) replace the original screw (at the open end of the two connected clamps) with a smaller screw and insert the other clamp band end into the hole; (g), (h) hold the sensor in an aluminum channel segment which is held on the freely moving inserted clamp end; (g) the bottom view; (h) one side view; (i) plug one side of the spring into the freely moving band end and the other side into an appropriate position of the band.

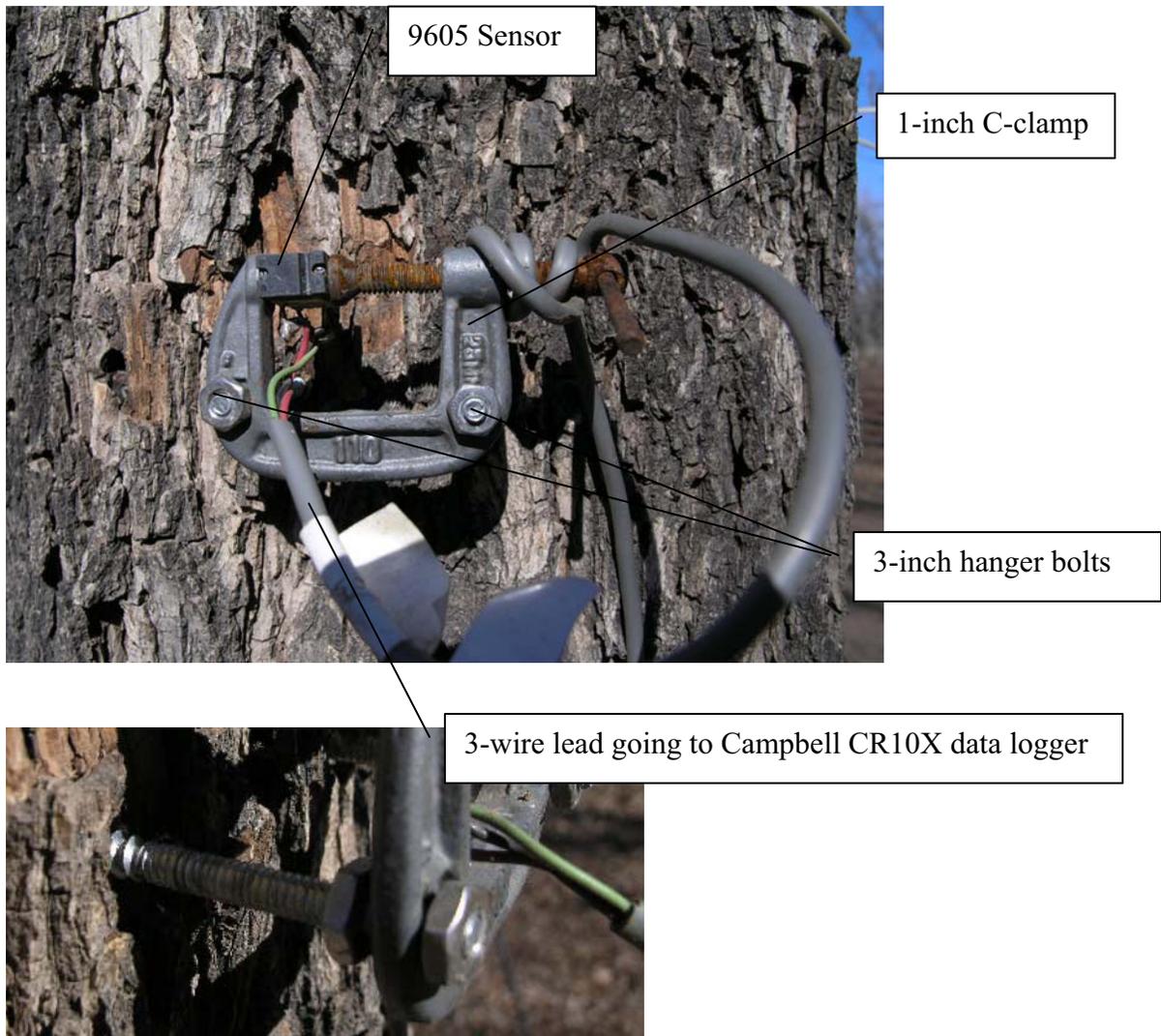


Figure 4. Mounting a 9605 sensor to a pecan branch. Top figure: the general mounting; bottom figure: the mounting bolt.

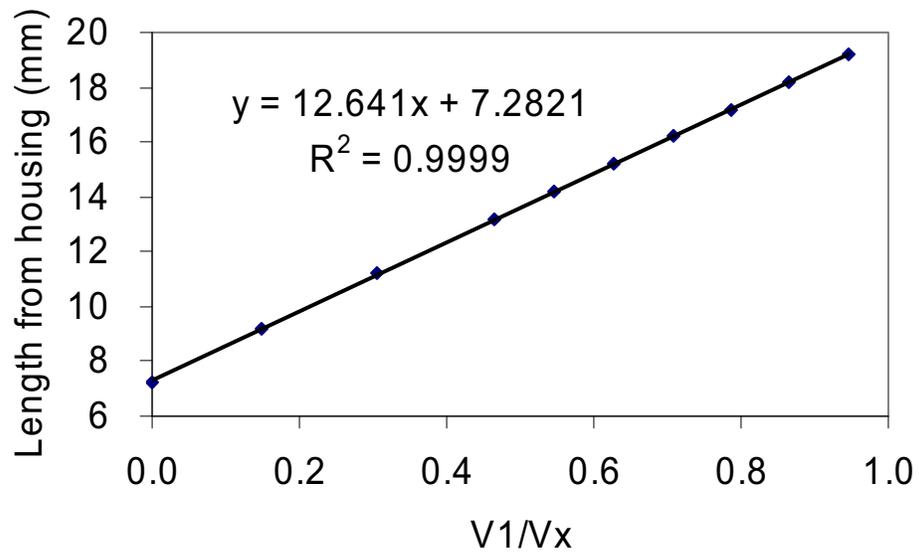


Figure 5. The linear response of a BEI 9605 sensor to change in length of the sensor. $V1/Vx$ is the ratio of the voltage across terminals 2 and 3 to that across terminals 1 and 3 of the 9605 sensors (see Figure 2 for the terminals). 'Length from housing' refers to the sensor plunger length outside of the sensor box.

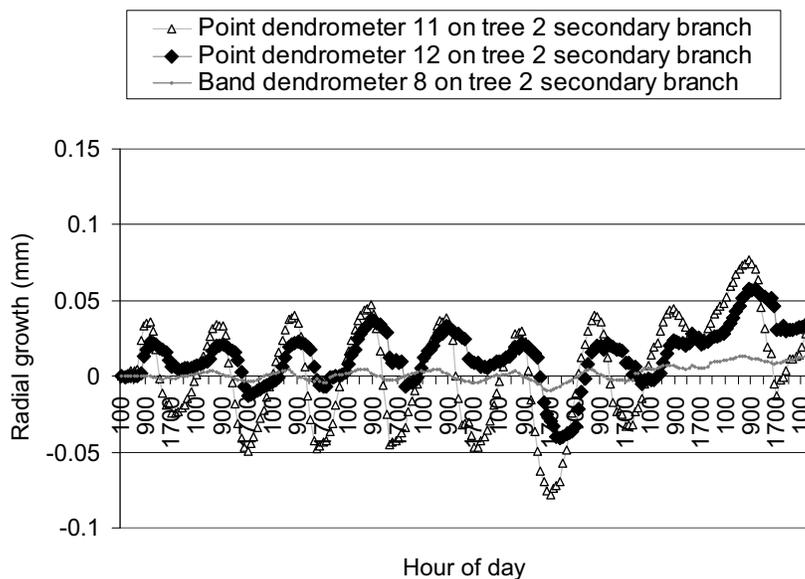
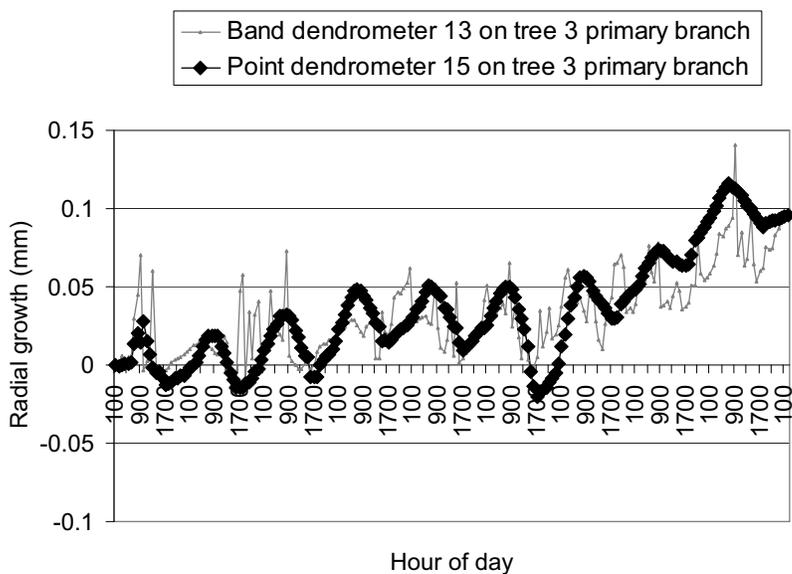
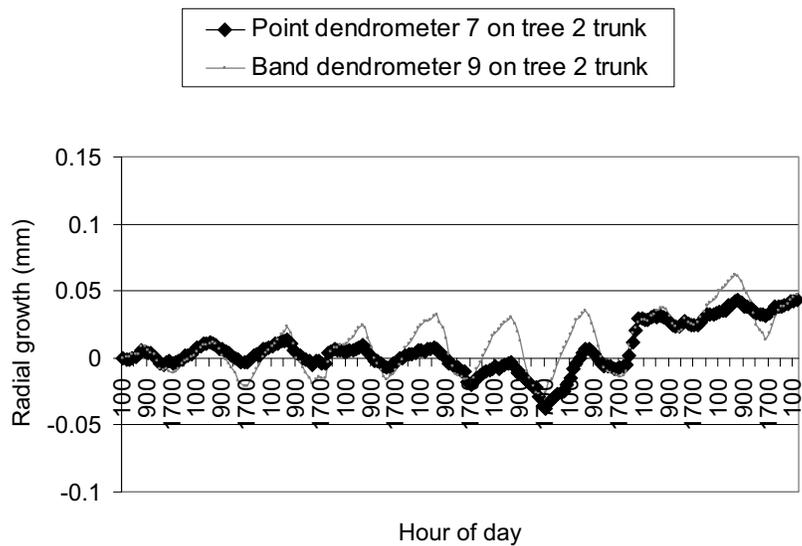


Figure 6. Hourly measurements of automatic point and band dendrometers during day 217 to day 226. Top figure: for tree 2 trunk (diameter=35.4 cm); middle figure: for tree 3 primary branch (diameter=27.3 cm); bottom figure: for tree 2 secondary branch (diameter=10.1 cm).

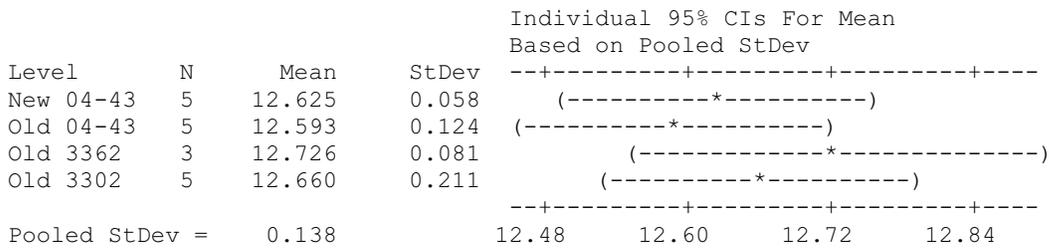


Figure 7. The mean, standard deviations (StDev), and confidence intervals (CIs) of calibration slopes (mm) for new and old BEI 9605 sensors (used for one year). The lot numbers are: 04-43, 3362, and 3302.

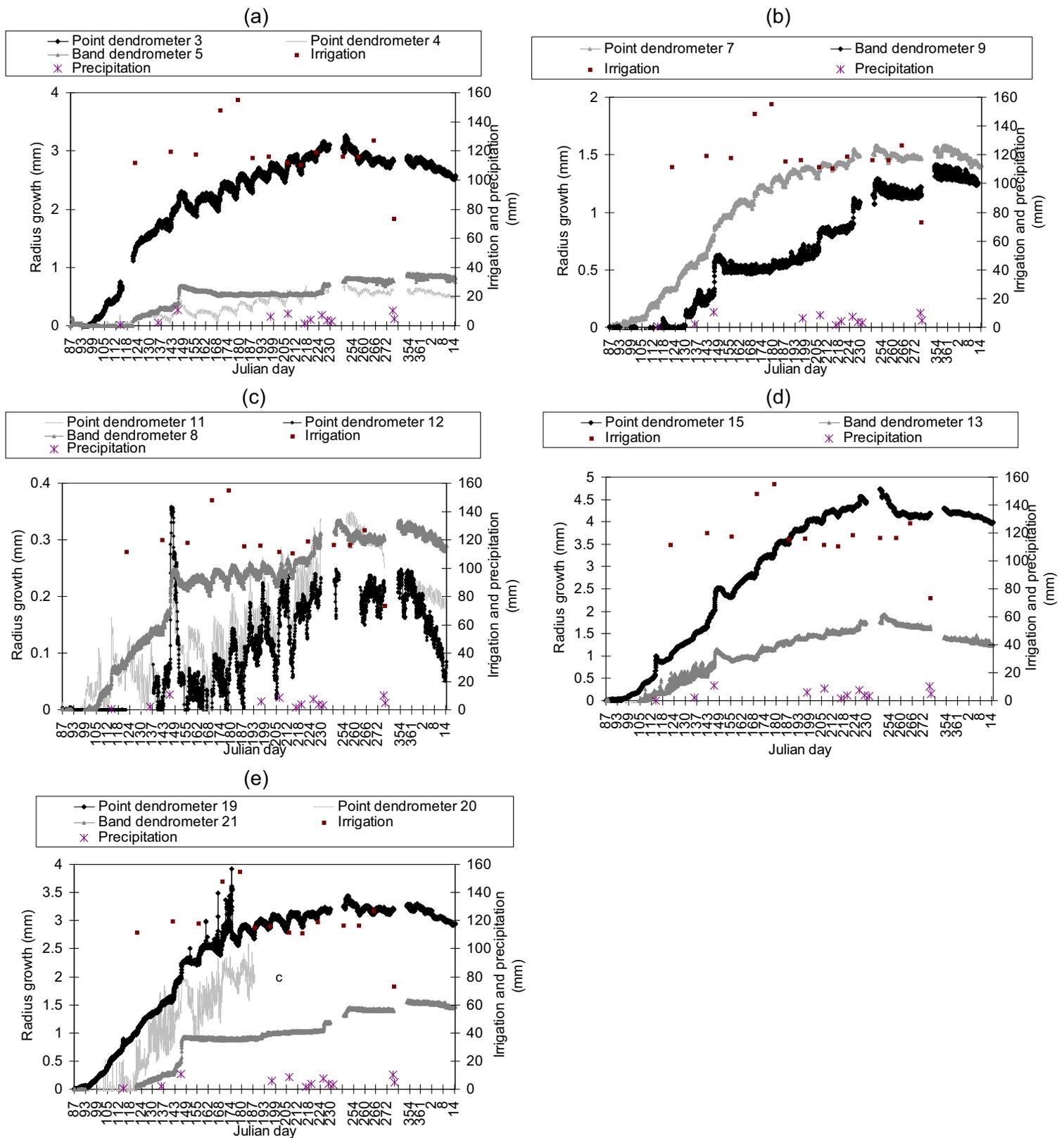


Figure 8. Measurements of selected point and band dendrometers of : (a) tree 1 primary branch (diameter=21.8 cm); (b) tree 2 trunk (diameter=35.4 cm); (c) tree 2 secondary branch (diameter=10.1 cm); (d) tree 3 secondary branch (diameter=27.3 cm); (e) tree 4 trunk (diameter=33.0 cm). Irrigation and daily precipitation were shown on the figure (daily precipitation amount smaller than 1 mm was not shown). The period was from day 87 of 2005 to day 14 of 2006. There were missed dendrometer data from day 231 to day 249 and from day 276 to day 353 because of datalogger power failures. Point dendrometer 20 had outliers (had negative 2-mm growth after day 188 because the transducer was tilted upward; the outliers are not shown on the figure).