INVESTIGATION OF LASER AND ULTRASONIC RANGING SENSORS FOR MEASUREMENTS OF CITRUS CANOPY VOLUME

S. D. Tumbo, M. Salyani, J. D. Whitney, T. A. Wheaton, W. M. Miller

ABSTRACT. *This study compared ultrasonic and laser measurements of citrus canopy volume with manual measurement methods. Fifteen trees with different canopy heights and volumes were used. Manual and ultrasonic measurements provided dimensions for computing the canopy volume whereas laser measurements gave information that could be used to compute a 'laser canopy volume index.' Ultrasonic and laser methods agreed with manual methods ($R^2 > 0.85$, RMSE < 2.15 m^3). Laser showed better prediction of canopy volume than the ultrasonic system because of the higher resolution. Ultrasonic or laser sensors can be used for automatic mapping and quantification of the canopy volumes of citrus trees.*

Keywords. *Citrus, Canopy volume, Laser, Ultrasonic, Precision agriculture.*

Cultural practices of Florida citrus are based on groves (large blocks of many hectares), which are treated as uniform production units for yield estimation and fertilizer or chemical application. Precision agriculture facilitates division and management of large blocks into smaller areas or entities. In citrus production, the small area or entity may be an individual tree that can be monitored for yield, canopy volume, and fertilizer and pesticide application. Current efforts in precision agriculture research in citrus have been in yield mapping and variable rate application of fertilizer and pesticide. Little has been done in the measurement and mapping of canopy volumes even though it is known to be an important factor in the application of chemicals and in yield estimation.

Albrigo et al. (1975) used canopy volume for yield estimation of oranges and found a good overall correlation (r = 0.30 to 0.88) between the two factors. Wheaton et al. (1995) also used canopy volume among other parameters to study the effect of tree size, yield, fruit quality, and economic return on citrus scion and rootstock, topping height, and tree density. They found that yield increased with increased tree density during the early years of production. In both studies, canopy volumes were measured manually from geometric linear measurements. Manual measurement of a tree could take about 30 seconds.

Roper (1988) reported on a discrete grove sprayer equipped with foliage sensors positioned to cover an entire spray zone. The foliage sensors actuated spray nozzles in response to foliage sensed within a spray zone. The foliage sensors are ultrasonic generators directing ultrasonic energy into each spray zone and an acoustic sensor for sensing reflected ultrasonic sound from foliage within each zone. Giles et al. (1988) discussed the use of the ultrasonic sensors to measure canopy volume. The measurement system was mounted on an air–blast orchard sprayer and driven up to a maximum of 6 km/h. The system had three ultrasonic ranging units mounted at different heights on each side of the sprayer. Each ranging unit was used to measure distance to the nearest foliage. However, in this study the measurements were not used to compute actual volume, instead the measurements were used to evaluate accuracy and precision of the system and effect of ground speed on measurements. Giles (1989) reported on the electronic orchard tree measuring system for target plant foliage sensing and mapping and related materials application control. The orchard tree measuring system can be used to determine the amount and vertical distribution of sensed centroids in vertical sectors of orchard trees. The detected data can be used to create map of foliar volumes. Rosell et al. (1996) used ultrasonic distance sensors to measure volume of plants and apply chemicals based on unit volume regardless of the size of the trees. They used a single ultrasonic sensor positioned at 145 cm above the ground. However, there was no discussion on how the volumes were measured and used.

Ritchie et al. (1993) used an airborne laser altimeter to measure canopy height. The canopy heights measured with the laser altimeter were significantly correlated with measurements made with ground–based methods (r = 0.87 to 0.99). Nilsson (1996), using an airborne lidar system, estimated tree height and tree volume and found good correlation between ground measurements and airborne measurements (r = 0.77 to 0.85 for height and r = 0.88 for volume). A global positioning system (GPS) receiver was

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The authors are **Siza D. Tumbo, ASAE Member**, Post–Doctoral Research Associate, **Masoud Salyani, ASAE Member Engineer**, Professor of Agricultural and Biological Engineering, **Jodie D. Whitney, ASAE Member Engineer**, Professor of Agricultural and Biological Engineering, **T. Adair Wheaton,** Professor of Horticulture, and **William M. Miller, ASAE Member Engineer**, Professor of Agricultural and Biological Engineering, University of Florida, IFAS, Citrus Research and Education Center, Lake Alfred, Florida. **Corresponding author:** Masoud Salyani, University of Florida, IFAS, Citrus Research and Education Center, 700 Experiment Station Road, Lake Alfred, FL 33850–2299; phone: 863–956–1151; fax: 863–956–4631; e–mail: msi@lal.ufl.edu.

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also used to record the corresponding locations of laser data. Parker and Matney (1999) used different measurement techniques to predict tree volume and found that the 'Criterion 400 Laser' produced best correlation compared to other methods.

Schwartz Electro–Optics, Inc. (SEO) (Orlando, Fla.) has developed a ground–based laser sensor that acquires range information to produce a two dimensional profile of the tree foliage. However, the laser system does not compute canopy volumes. Walklate et al. (2000) used the SEO laser sensor to study the relationship between orchard tree crop structure and performance characteristics of an axial fan sprayer. They used laser measurements to compute tree area density and height and row volume. They found that tree area density correlated well with spray deposit ($r = 0.79$).

The overall goal of this article was to investigate methods for rapid mapping of canopy volumes in citrus groves. The specific objective was to correlate canopy volume measurements using manual methods, laser, and ultrasonic sensors.

Materials and Methods

Experimental Field and Tree Selection

A citrus grove, with tree spacing of 6.1 × 4.6 m was used for the study. Fifteen trees having different heights and canopy volumes were selected of which one was partially defoliated and one totally defoliated. Tree heights ranged from 1.7 to 3.3 m. In addition, the canopies of the selected trees did not touch adjacent trees. Figure 1 shows one of the orange trees that were used in the measurements.

Manual Tree Volume Measurement and Computation

Two manual methods were used for estimating tree canopy volumes. The first was a formula developed by Whitney (Wheaton et al., 1995), here referred to as Whitney's canopy volume formula, W_{CV} (eq. 1):

$$W_{CV}=\frac{\pi}{4}D_1D_2H_T\left[1-\left(\frac{1-\left(H_I/H_T\right)^2}{3}\right)\right] \quad (1)$$

where
W_{CV} = canopy volume (m^3)
H_T = overall canopy height above the ground (m)
H_I = height to intercept between two adjacent canopies (m)
D_1 = canopy diameter parallel to the row near ground level (m)
D_2 = canopy diameter perpendicular to the row near ground level (m)

The dimension H_I is zero for separate canopies. The second formula used was prolate spheroid canopy volume formula, PS_{CV} (eq. 2) (Albrigo et al., 1975).

$$PS_{CV}=\frac{\pi D_1^2}{4}\left(\frac{2(H_T-H_C)}{3}+(H_C-H_S)\right) \quad (2)$$

where
PS_{CV} = canopy volume (m^3)
H_T = overall canopy height above ground level (m)
D_1 = canopy diameter parallel to the row (m)
H_C = height to the point of maximum canopy diameter (m)
H_S = height from ground to canopy skirt (m)

All dimensions used for manual measurement of canopy volume are shown in figure 2.

Figure 1. One of the 15 citrus trees used in the study.

Ultrasonic Measurements and Volume Computation

An ultrasonic system manufactured by Durand Wayland, Inc. (LaGrange, Ga.) was used to obtain distance from the canopy. The system consisted of 20 ultrasonic transducers and ranging boards (10 per side), a microcomputer, and two serial communication ports set to output ultrasonic readings continuously for diagnostic of the sensors. Since the ports were not made specifically to download raw data to another system for measurement and control, the internal serial communication protocol limited the sampling frequency to 1.6 samples/second. However, at low ground speeds, equivalent horizontal and vertical resolutions could be achieved. The frequency of the pulses from the ultrasonic sensors was 40 kHz and divergence angle was 6 degrees. To avoid signal interference the sensors were fired in groups sequentially such that sensors 1, 5, and 9 were fired first, followed by 3 and 7, then 2, 6, and 10, and finally 4 and 8. Since the sensors were 0.3 m apart, the spacing between sensors fired

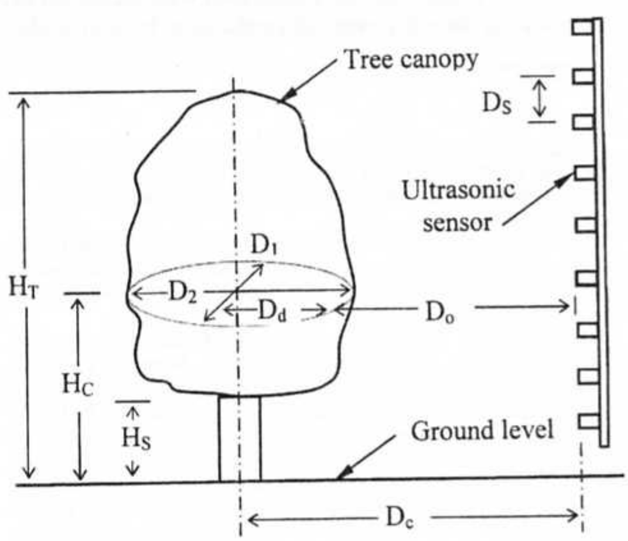

Figure 2. Schematic view of tree, ultrasonic sensors, and dimensions used to compute canopy volumes manually and with ultrasonic measurements.

simultaneously was 1.2 m. This sequential firing of transducers reduced signal interference between ultrasonic transducers.

During calibration of the unit, the maximum distance for each ranging unit was found to be 7.6 m. In the study, only nine ranging units were mounted on a vertical mast such that the transducers were 0.3 m apart with the lowest and the highest located at 0.6 and 3 m above ground, respectively (fig. 2). Each ranging unit was used to measure the distance to the foliage (D_o).

The ultrasonic system was mounted behind a tractor such that the mast holding the ultrasonic units was on the centerline of the tractor. A laptop computer was used to acquire the readings from the RS232 communication port of the ultrasonic system. The speed at which data was sent to the communication port was slow, approximately 1.6 samples per second – where each sample consisted of 10 sensor readings). The sensor range was represented by an 8–bit digital count of 0 to 255 with the digital count of 255 representing maximum distance of 7.6 m. These readings were calibrated to provide distances in meters.

In order to get adequate horizontal and vertical sampling per tree, the tractor was driven at a ground speed of 0.5 km/h between rows and the distance from the sensor to the tree row was about 3 m (10 ft). Each tree was scanned (profiled) three times and data were stored for post–processing. In order to minimize errors in distance measurements, the tractor was maintained at the centerline between the rows by using ranging poles. During data acquisition, the tractor centerline was aligned with the ranging poles. The speed of the tractor was computed experimentally using a stopwatch and a 50–m driving course.

Since the tractor speed, sampling (data acquisition) rate, and sensor spacing were known it was possible to compute approximate canopy volume as follows:

$$U_{CV}=2\sum_{1}^{n}\frac{S\,D_d\,D_S}{S_R} \qquad (3)$$

where

U_{CV} = ultrasonic canopy volume (m^3)
S = tractor speed (m/sec)
D_d = distance from the center of the row to the foliage (m)
D_S = sensor spacing (m)
S_R = sampling rate (samples/sec)
n = number of scans (samples) per tree

The distance $D_d = D_c - D_o$, as shown in figure 2, was the distance from the center of the row to the periphery of the foliage and D_o was the distance from the sensor to the periphery of the foliage. The formula assumed the trees were symmetrical, therefore, the canopy of one side had to be multiplied by 2 to obtain the canopy volume of the whole tree.

Laser Measurements and Laser Canopy Volume Index Computation

Laser measurements were acquired using a SEO (Schwartz Electro–Optics, Orlando, Fla.) laser scanner (Treesense). The scanner contains a laser transmitter and receiver that are co–aligned with a spinning mirror mounted at a 45° angle (Wangler, 1992). As the mirror rotates, range measurements are taken over a 90° vertical scan on both sides

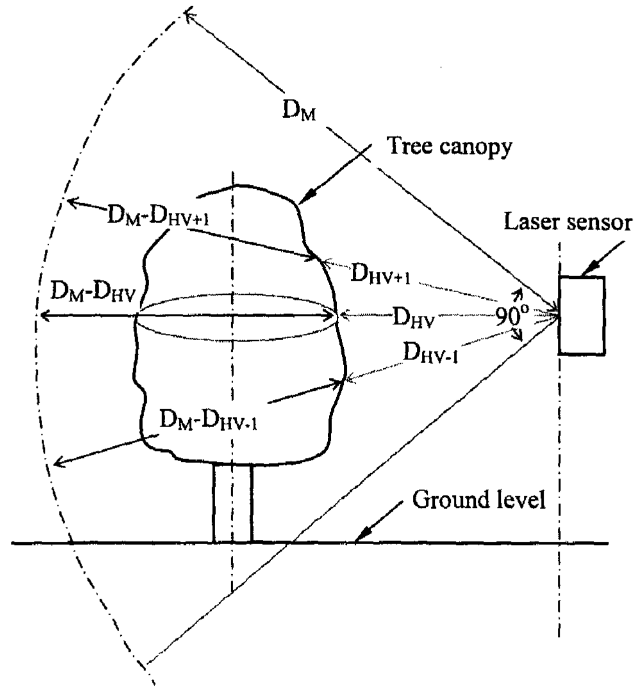

Figure 3. Schematic view of laser setup and parameters that were considered in computing laser canopy volume indices.

(fig. 3). The range information was used to produce a two–dimensional profile of the foliage. Other laser scanner specifications were: 2100–rpm mirror scan rate, laser wavelength of 904 nm, 6–ns pulse width, 512 scans per revolution, and maximum range of 10 m. However, for this study the maximum range was set at 4.8 m. The spatial resolution of the laser was 50 mm and angular resolution of the rotating mirror was 0.7 degrees.

The laser sensor was mounted at the front/center of a tractor at 1.8 m above the ground. The tractor ground speed was 0.5 km/h. Each tree was scanned three times using the TreeLab program developed by SEO. The scanned false color images were screen captured and converted into bitmap images. Figure 4 shows a grayscale image of the orange tree (fig. 1) converted from a false color laser image. Each bitmap pixel represented a distance from the sensor to the foliage. The false color pixels were converted into distances in meters (D_{HV}) (fig. 3). The subscripts 'H' and 'V' represent horizontal and vertical pixels, respectively. The distance (D_{HV}) was used to compute distance, $D_M - D_{HV}$, which was the distance from laser maximum distance (D_M) to the periphery of the canopy (fig. 3). For each canopy, the distances ($D_M - D_{HV}$) were summed up to obtain laser canopy volume index (LCVI) as shown in equation 4:

$$LCVI=\sum_{V=0}^{V=i}\sum_{H=0}^{H=j}(D_M - D_{HV}) \qquad (4)$$

where

LCVI = laser canopy volume index (m)
D_M = maximum distance of the laser (m)
D_{HV} = distance from the laser unit to the canopy (m)
i = number of distances in vertical direction
j = number of distances in horizontal direction

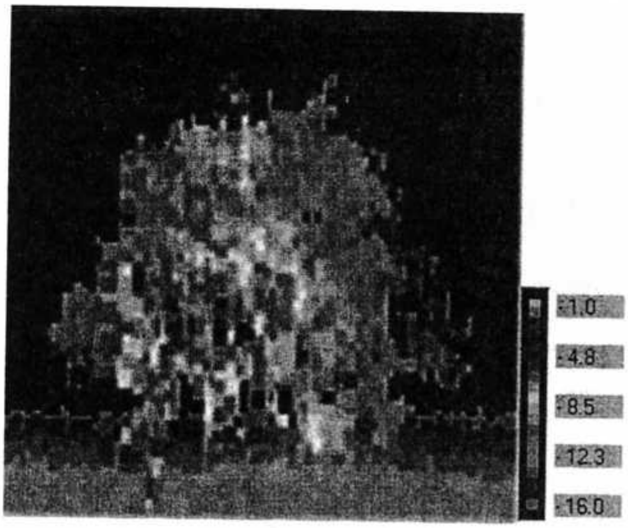

Figure 4. Grayscale tree image converted from a false color laser scanned image and the color legend showing distance in feet.

Comparison of Laser, Ultrasonic, and Manual Measurements

After computation of Whitney's, prolate spheroid, ultrasonic canopy volume, and laser canopy volume index for each tree, each method was compared to another using linear regression methods. For each case, coefficients of multiple correlation, R^2, and root mean square errors (RMSE) were computed using SPSS statistical software. RMSE is a measure of the amount of error in the prediction of dependent set of values for a given independent set of values. In addition, each method was plotted against another to identify outlier points.

Results and Discussions

Manual Measurement of Canopy Volume

Table 1 shows manual measurements of the 15 trees and their corresponding canopy volumes, which were computed using Whitney's and prolate spheroid canopy volume formulae. The canopy volumes based on the prolate spheroid formula were linearly correlated with canopy volumes based on Whitney's formula. The regression results and correlation coefficients are shown in figure 5.

The strong correlation (R^2 = 0.98; RMSE = 1.2 m^3) between Whitney's canopy volume and prolate–spheroid canopy volume formulae (fig. 5) indicates that the two methods were in a good agreement. In figure 5, trees 2 and 11 seem to fall below the 1:1 regression line. More specifically, either Whitney's formula under–predicted or prolate spheroid formula over–predicted the two canopy volumes. That may be explained by the difference in the two formulae. Whitney's formula uses two diameters (parallel and perpendicular to the tree row) in computing canopy volumes, whereas prolate spheroid uses only one diameter (diameter parallel to the row). On the other hand, prolate spheroid formula uses skirt height and height to the point of maximum diameter whereas Whitney's formula does not.

Table 1 shows that skirt height for most trees was about 0.5 m; however, skirt height for tree 2 was 0.3 m. The difference in the two diameters also might have contributed

Table 1. Tree dimensions and canopy volumes calculated using Whitney's and prolate spheroid canopy volume formulae.

Tree ID[a]	Tree Height (H_T) (m)	Height to Max. Diameter (H_C) (m)	Skirt Height (H_S) (m)	Parallel Diameter (D_1) (m)	Perpendicular Diameter (D_2) (m)	Whitney Formula (m^3)	Prolate Spheroid (m^3)
1	3.2	1.3	0.5	3.4	3.6	19.8	17.9
2	2.9	1.3	0.3	3.1	2.7	13.1	15.7
3	2.5	1.1	0.5	3.7	3.3	15.8	16.2
4	2.6	1.0	0.4	3.0	3.1	12.8	12.1
5	2.4	1.1	0.5	2.6	2.5	8.1	8.1
6	1.7	0.8	0.6	1.2	1.4	1.5	0.9
7	3.2	1.2	0.6	2.5	2.2	9.2	9.6
8	2.0	0.9	0.6	2.2	1.9	4.3	3.9
9	2.8	1.1	0.5	2.9	3.1	13.2	11.7
10	3.3	1.0	0.5	3.0	3.0	15.7	14.6
11	1.9	1.0	0.5	2.4	1.5	3.7	5.1
12	2.2	1.0	0.6	2.3	2.1	5.6	4.9
13	2.0	0.8	0.6	2.2	2.3	5.2	3.7
14	1.8	0.8	0.5	2.0	2.0	3.8	3.0
15	1.9	0.9	0.4	2.3	2.3	5.3	4.8
Min	1.7	0.8	0.3	1.2	1.4	1.5	0.9
Max	3.3	1.3	0.6	3.7	3.6	19.8	17.9
Mean	2.4	1.0	0.5	2.6	2.5	9.1	8.8
S.D.	0.5	0.2	0.1	0.6	0.7	5.6	5.5

[a] Min = minimum, Max = maximum, Mean = average, S.D = standard deviation.

to the difference between Whitney's and prolate spheroid based–volumes for tree 2. Table 1 also suggests that the difference in volumes for tree 11 might be due to the difference in the two diameters (D_1 = 2.4 m and D_2 = 1.5 m). That difference was because the rest of the trees had almost the same parallel (D_1) and perpendicular diameters (D_2). Possibly the average of the two formulae provide the best canopy volume estimate because almost all tree dimensions are considered. Trees 7 and 6 (table 1, fig. 5), were partially and totally defoliated trees, respectively, and were included

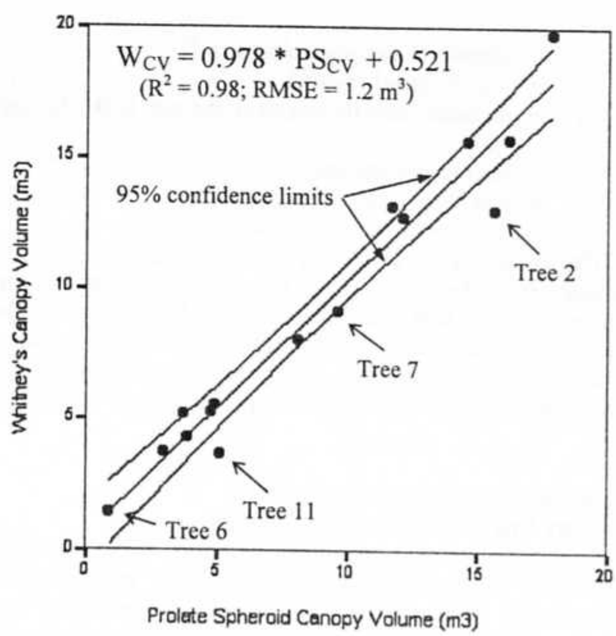

Figure 5. Relationship between prolate spheroid and Whitney's canopy volume formulae.

to investigate the effect of defoliated trees on instrumental measurement of canopy volumes.

Comparison between Ultrasonic and Manual Methods

Average values of canopy volumes based on Whitney's and prolate spheroid methods were computed and used as canopy volumes based on manual methods. These values were taken as "ground truth" for comparison to automated (instrumental) methods. A strong correlation existed between ultrasonic canopy volumes versus canopy volumes based on manual methods ($R^2 = 0.90$ and RMSE = 1.66 m^3) (fig. 6).

As was the case in figure 5, some volumes were over–predicted or under–predicted such as trees 4, 7, and 14. It was assumed that the ultrasonic technique over–predicted the volumes for trees 4 and 14 because of the presence of tall grass under the two trees. On the other hand, ultrasonic measurement was lower for the partially defoliated tree 7. Since tree 6 was very small and defoliated, the two methods agreed very well. Tree 7 was a bigger tree compared to tree 6 (table 1) and had some foliage. This caused the ultrasonic sensors to detect the presence of the little foliage on the tree. However, the ultrasonic sensor predicted much less volume for tree 7 compared to the manual methods, which means that the ultrasonic method was much better than manual measurements, which ignore canopy density.

Comparison between Laser, Ultrasonic, and Manual Methods

Figure 7 shows a good correlation between laser canopy volume indices and Whitney's/prolate spheroid–based average volume ($R^2 = 0.85$ and RMSE = 2.15 m^3). The relatively high RMSE values were due to trees 3, 4, 7, and 14 (fig. 7). For example, tree 7 was partially defoliated and its "volume" was reduced but the manual measurements considered it a healthy tree. When tree 7 was removed from the regression, the correlation increased to $R^2 = 0.95$ and RMSE = 1.87 m^3.

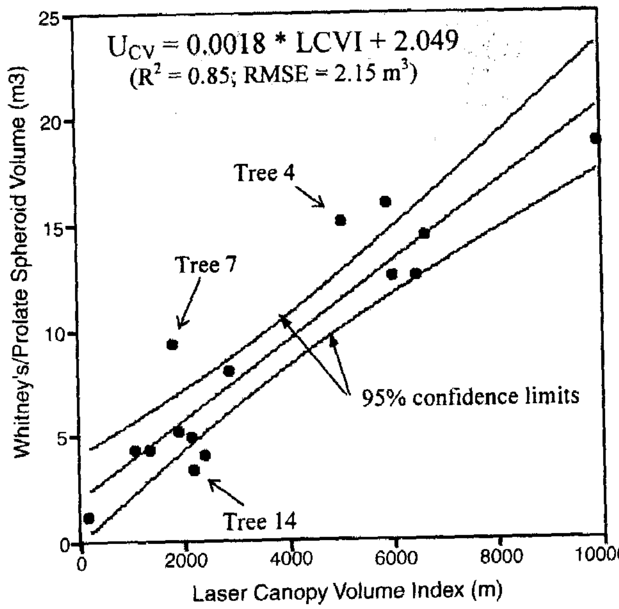

Figure 7. Relationship between laser canopy volume index and the average of Whitney's/prolate spheroid canopy volumes.

Tree 14 was over–predicted by the laser because of the tall grass at the bottom of the tree, as was the case with the ultrasonic system. However, the volume for tree 4 was over–predicted by the ultrasonic (fig. 6) but under–predicted by the laser (fig. 7). Although there was some grass at the bottom of tree 4 and the foliage was less dense, the laser system was able to detect the porous grassy areas because of its very high resolution (50 mm) compared to ultrasonic sensors (300 mm) at 3–m from the sensor(s).

Figure 8 shows strong correlation between laser and ultrasonic measurements ($R^2 = 0.96$ and RMSE = 0.98 m^3). However, the volumes of some of the trees, such as tree 7, were slightly over–predicted by the ultrasonic system. The higher resolution of the laser unit compared to that of the

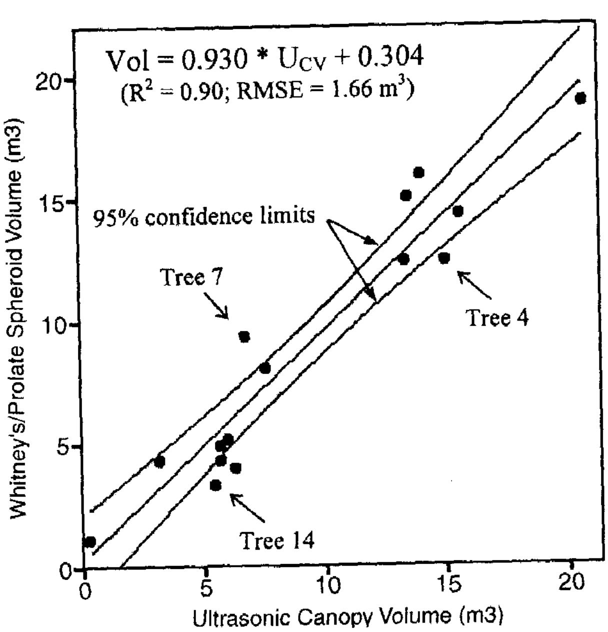

Figure 6. Relationship between ultrasonic canopy volume and the average of Whitney's/prolate spheroid canopy volumes.

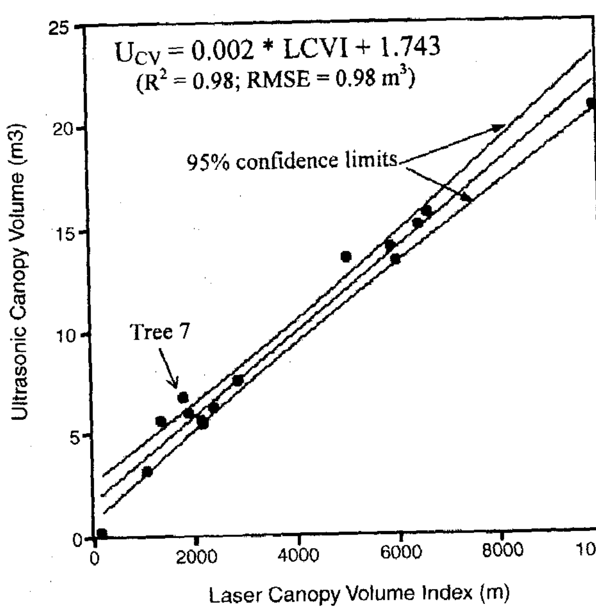

Figure 8. Relationship between laser canopy volume index and ultrasoni canopy volumes.

ultrasonic sensors was assumed as the reason for the ultrasonic system to over–predict the partially defoliated tree. The stronger correlation between laser and ultrasonic compared to laser and manual measurements was because the resolution of ultrasonic measurements was intermediate between laser and manual measurements.

It appears that if trees were symmetrical with a full canopy, the three canopy volume methods (manual, ultrasonic, and laser measurements) would predict equivalent canopy volumes. In a grove where there are combinations of full canopy and partially defoliated trees, the laser unit would predict canopy volume more accurately.

Summary and Conclusion

This article compared three methods (manual, ultrasonic, and laser) for estimating canopy volumes in citrus. In the manual measurements, two formulae (Whitney's and prolate spheroid) for computing canopy volumes were compared. The two formulae showed strong correlation ($R^2 = 0.98$; RMSE = 1.20 m^3); therefore, it was assumed that the average of the two measurements might be a good representation of canopy volume based on manual methods.

The estimated canopy volumes based on manual measurements showed good correlation to ultrasonic ($R^2 = 0.90$; RMSE = 1.66 m^3) and laser measurements ($R^2 = 0.85$; RMSE = 2.15 m^3). However, ultrasonic measurements showed stronger correlation with laser measurements ($R^2 = 0.98$; RMSE = 0.98 m^3) compared to manual measurements. This observation could be explained by the fact that resolution of the ultrasonic system was higher than that of manual measurements but less than that of the laser. In addition, the laser was better in estimating canopy volumes of partially or fully defoliated trees compared to the ultrasonic sensor.

It can be concluded that laser measurements can provide good estimation of canopy volumes especially in a grove where there are significant numbers of partially defoliated trees or small replants. The other advantage of the laser over ultrasonic system may be the high speed of data acquisition with the former. Despite the sensitivity of ultrasonic sensors to temperature, the system provided good canopy volume estimates. Therefore, the two systems are valuable tools for automatic mapping of canopy volumes in citrus groves.

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