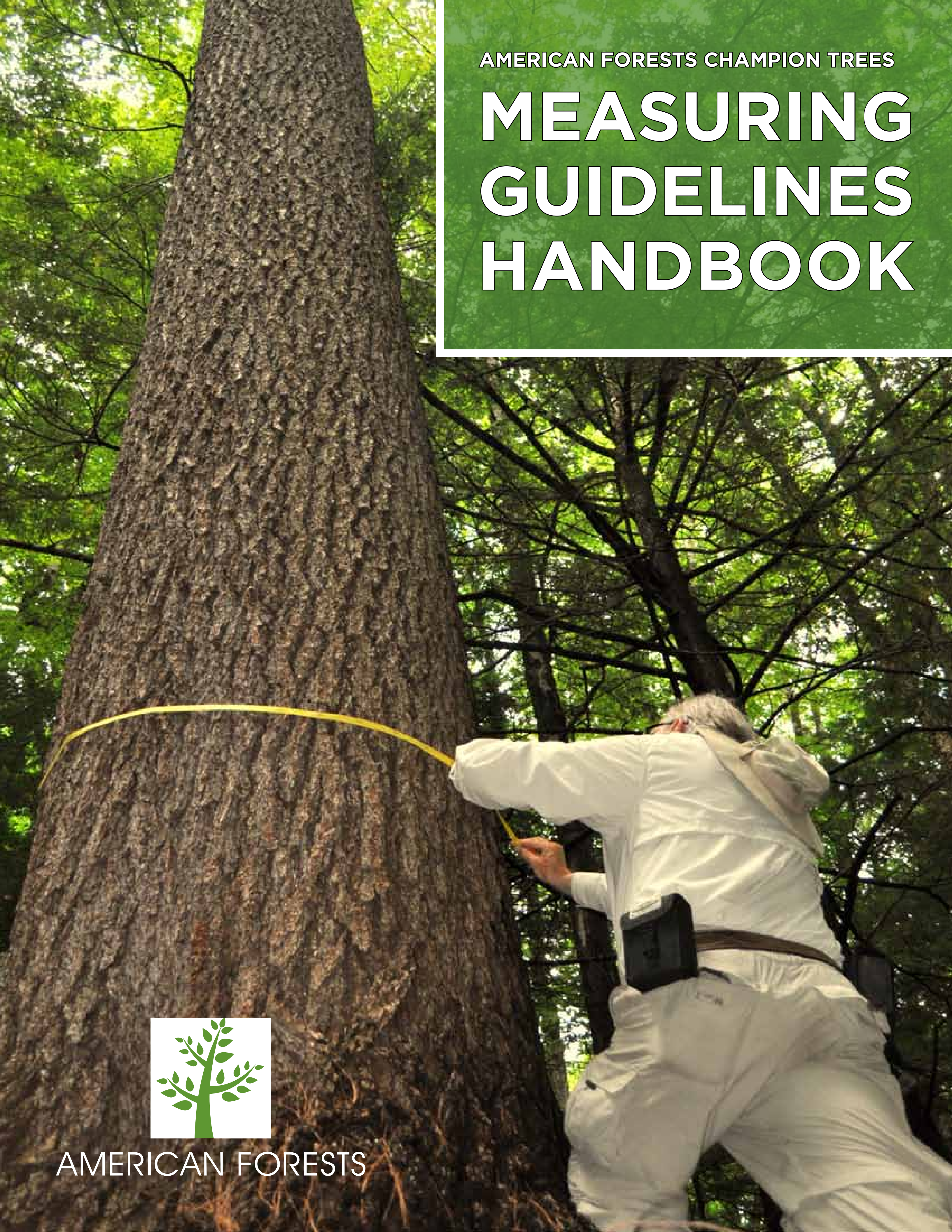
AMERICAN FORESTS CHAMPION TREES

MEASURING GUIDELINES HANDBOOK



AMERICAN FORESTS

ACKNOWLEDGMENTS

The Measuring Guidelines Working Group

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Don Bertolette

American Forests offers deep gratitude and appreciation for the exceptional efforts of two extraordinary tree experts — Bob Leverett and Don Bertolette — who authored and illustrated this handbook for the benefit of Champion Tree measurers everywhere.

Additionally, we thank the other members of Measuring Guidelines Working Group (MGWG): Donna Baldwin, Don Bragg, Phil Radke and Pete Smith.

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Our Partners

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TABLE OF CONTENTS

INTRODUCTION

The call to search for and protect America's biggest trees first came in the September 1940 issue of American Forests magazine, where concerned forester Joseph Sterns published his article "Let's Find and Save the Biggest Trees." Sterns wasn't referring to the famous and historic trees that were already protected, but the giants left standing in virgin forests. The first tree nominated was a chestnut oak in Suffield, Connecticut, in 1940.

American Forests, the nation's oldest national conservation organization, was already 65 years old at this point, having helped create the U.S. Forest Service and the field of arboriculture in the United States. Since that call to locate and measure the largest specimen of many species, American Forests has planted nearly 50 million trees in endangered ecosystems, pioneered the field of urban forestry and maintained the Champion Trees national register, a list of the biggest trees in America. The Big Tree Program is active in all 50 states and the District of Columbia, and is used as a model for several Big Tree programs around the world. With sponsorship since 1990 from The Davey Tree Expert Company, the National Big Tree Program has been able to reach a wider audience and promote the same message for 75 years: regardless of size, all trees are champions of the environment.

Hidden Complexities of Measurement

There has long been a deceptively easy formula for calculating the overall size of a tree when nominating a potential Champion:

Trunk Circumference (inches) + Height (feet) + ¼ Average Crown Spread (feet) = Total Points

However, within each of those measurements resides a vast realm of variations, calculations and potential confusion when dealing with living trees. Our objective with this measurement guide is to harness the highest levels of tree measurement expertise in forestry to create the definitive reference guide for best measurement practices so that anyone from a family out tree hunting for a weekend to a seasoned professional with advanced equipment can properly measure every potential variation, from multi-trunk forms to uneven crown spreads.

A quick scan through this guidebook will reveal many complicated formulas, but do not let that scare you away. We have structured it in a way to be useful for each level of tree measurer: (1) beginning level for non-professionals making initial nominations with basic equipment, (2) intermediate level for State Big Tree Program Coordinators and Certifiers confirming nominations, and (3) advanced level for an elite National Cadre of experts who have advanced measurement equipment, skills, and methods to verify complicated measurements and make a definitive ruling when two trees of the same species have very close point totals.

We hope this guide will be a useful reference for tree enthusiasts and measurement professionals and also lay a foundation of consistent measurement on a national scale so as to be useful for policies and scientific research into understanding, protecting and nurturing not only these incredibly large specimens, but all mature trees.

Equipment Needed

Below is a list of the equipment recommended for use by National Cadre members and certifiers at the State level. Most items will be familiar, but for complete definitions see **Appendix II**. At a minimum, the following items are needed:

- 100-foot tape (200-foot preferable)
- Diameter tape
- Laser rangefinder (measures distance)
- Inclinometer with degrees scale (measures angle in the vertical plane)
- Compass
- Digital camera
- GPS receiver
- Scientific calculator with trigonometry functions
- Plumb bob (to create a vertical line or path)
- Yardstick, meterstick

Additional tools recommended for use by experts (including National Cadre members) include (see definitions in **Appendix II**):

- Densitometer (checks for what is vertically overhead)
- Monocular with reticle (measure width of an object from a distance)
- Forestry calipers (measure diameter of a trunk)
- Advanced hypsometer with capability to do sine-based height measurements
- Smartphone applications (designed to utilize its camera for documentation and measurement)
- Red-beam carpentry/construction laser (measuring devices)

Notes

Titles for **beginning topics are in green** [●], **intermediate topics in blue** [●], and **advanced topics in red** [●]. Sometimes a method applies to both beginning and intermediate measurers because it can be used as a valid certification technique. However, for simplicity, we keep the subsequent highlighting for that method in green.

All these guidelines are works in progress and will undergo revision as new methods and equipment become available.

CIRCUMFERENCE

Introduction to Circumference

Circumference (also called girth) is easy to measure whether done with outstretched arms, a string, or a tape, for single upright trunks on level ground. But good measurements can be surprising difficult to get for trees with complex shapes or in difficult terrain. Measurements are complicated by: (1) tree form, (2) whether a trunk is upright or leaning, (3) single or multiple stems, (4) whether or not the tree is on level or sloping ground, and (5) obstructions that limit access to the trunk.

Basic Circumference ● ●

Wrap a diameter tape around the trunk at 4.5 feet above mid-slope of the tree's base and take the measurement in inches.

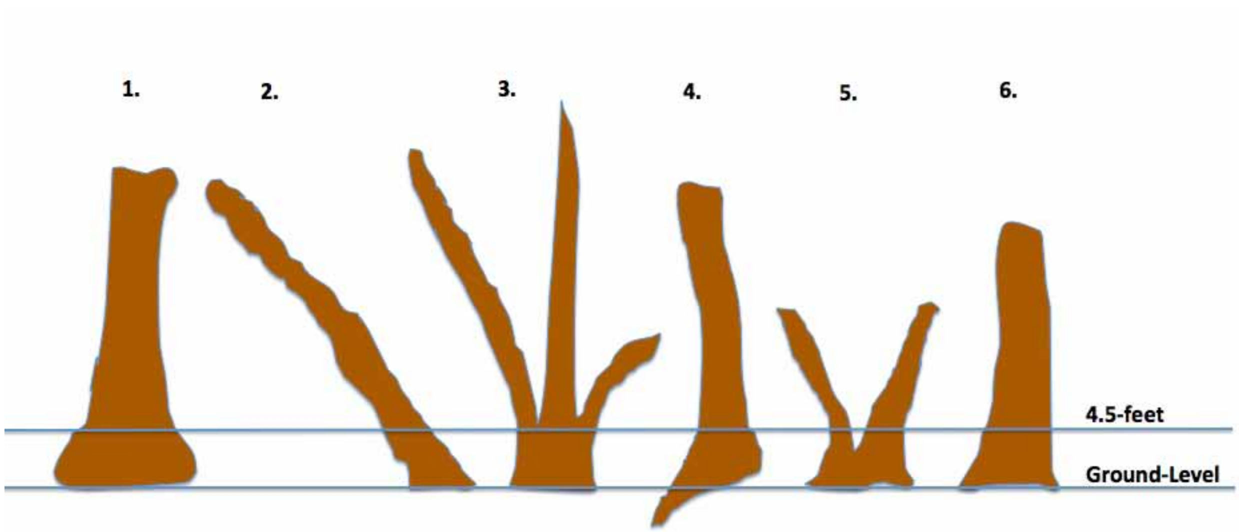
When the trunk is leaning, wrap the tape at 90 degrees to the axis of the lean, instead of parallel to the ground.

The choice of the 4.5-foot height is for convenience. It is approximately chest height, as reflected in the forestry term "diameter at breast height", or DBH.

With trees that exhibit rounded, knotty growths, or burls, limb extensions or any other abnormalities at 4.5 feet above ground level, measure the smallest circumference between 4.5 feet and the ground.

The diagram below gives an idea of the variety of trunk forms we cover.

Diagram of Trunk Forms



Forms 1 and 6 are straightforward.

Forms 2 and 4 require the tape to be wrapped at an angle that is 90 degrees to the axis of the trunk (not shown here), and therefore not parallel to the ground.

For form 4, the tree is also on sloping ground, a situation we discuss in detail on page 8.

Form 3 appears straightforward, but a problem arises if the three trunks appear to represent the fusion of separate trees, i.e. three trunks pressed together. In this situation, we measure the largest trunk.

Form 5 has the potential to also be separate trees, but if considered one, measurement at 4.5 feet would include the open space between the trunks. We must avoid this, and use Rule #2 below.

Measurement Guidelines for Multi-trunk Trees

1. If we conclude that a form actually represents two or more trees that have their trunks pressing together, we measure the largest trunk.
2. If we conclude that the form is a single tree, but splits below 4.5 feet, we measure at the narrowest point between the split and the ground.
3. If we conclude that it is a single tree and the split is above 4.5 feet, we measure the trunk at 4.5 feet.
4. To decide whether a multi-trunk form represents more than one tree, we employ a Pith Test, discussed on page 11.

Standard Circumference Measurement for Trees on Sloping Ground

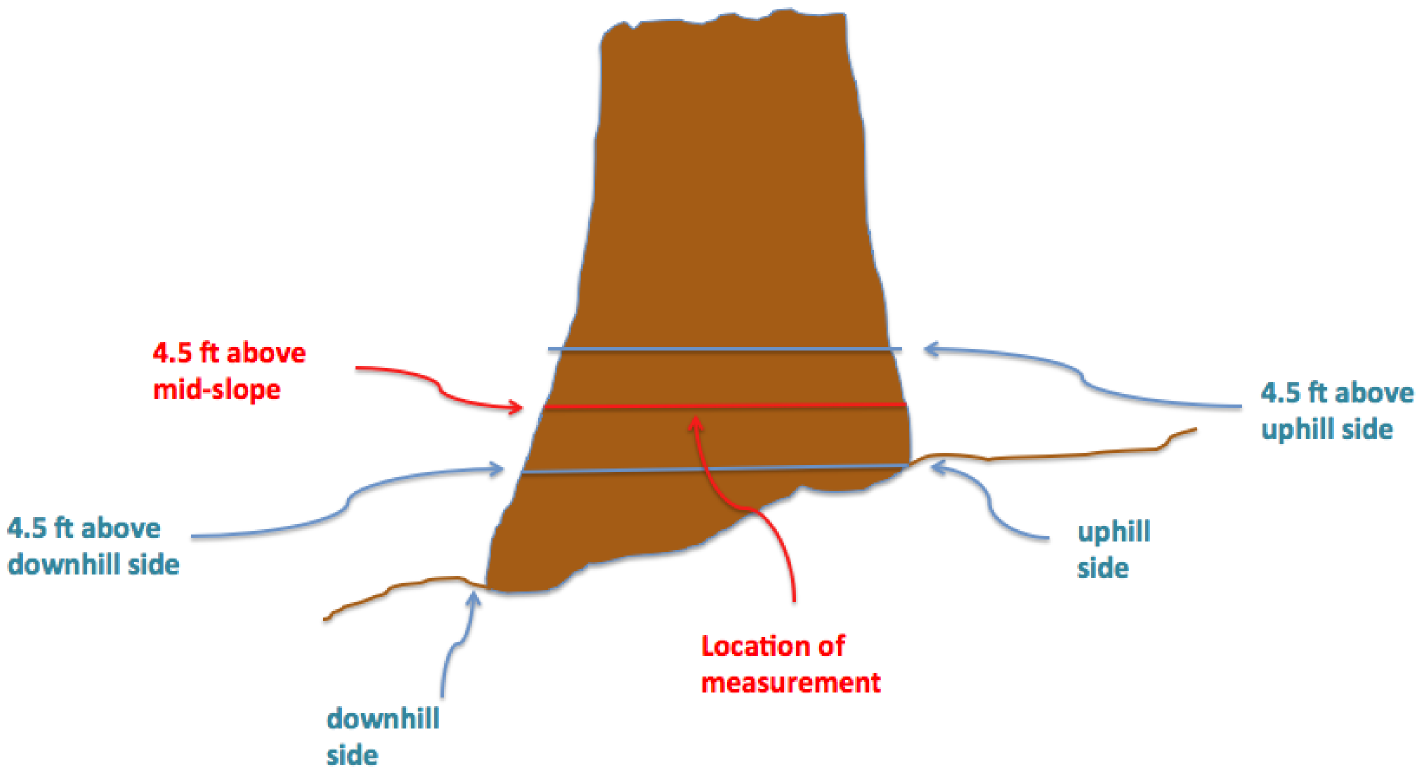
Mid-slope Rule

Locate mid-slope, and go up 4.5 feet to reach measuring height.

Mid-slope is where we judge the seed to have fallen. The mid-slope rule evens the playing field for comparing trees in different terrain by starting where growth began. In contrast, the forestry profession typically goes 4.5 feet above the upslope point.

Measuring circumference on sloping ground takes its simplest form for a single-trunk tree where 4.5 feet above mid-slope is above the location where the trunk touches the ground on the uphill side.

Diagram for Circumference Measurement - Tree on Sloping Ground

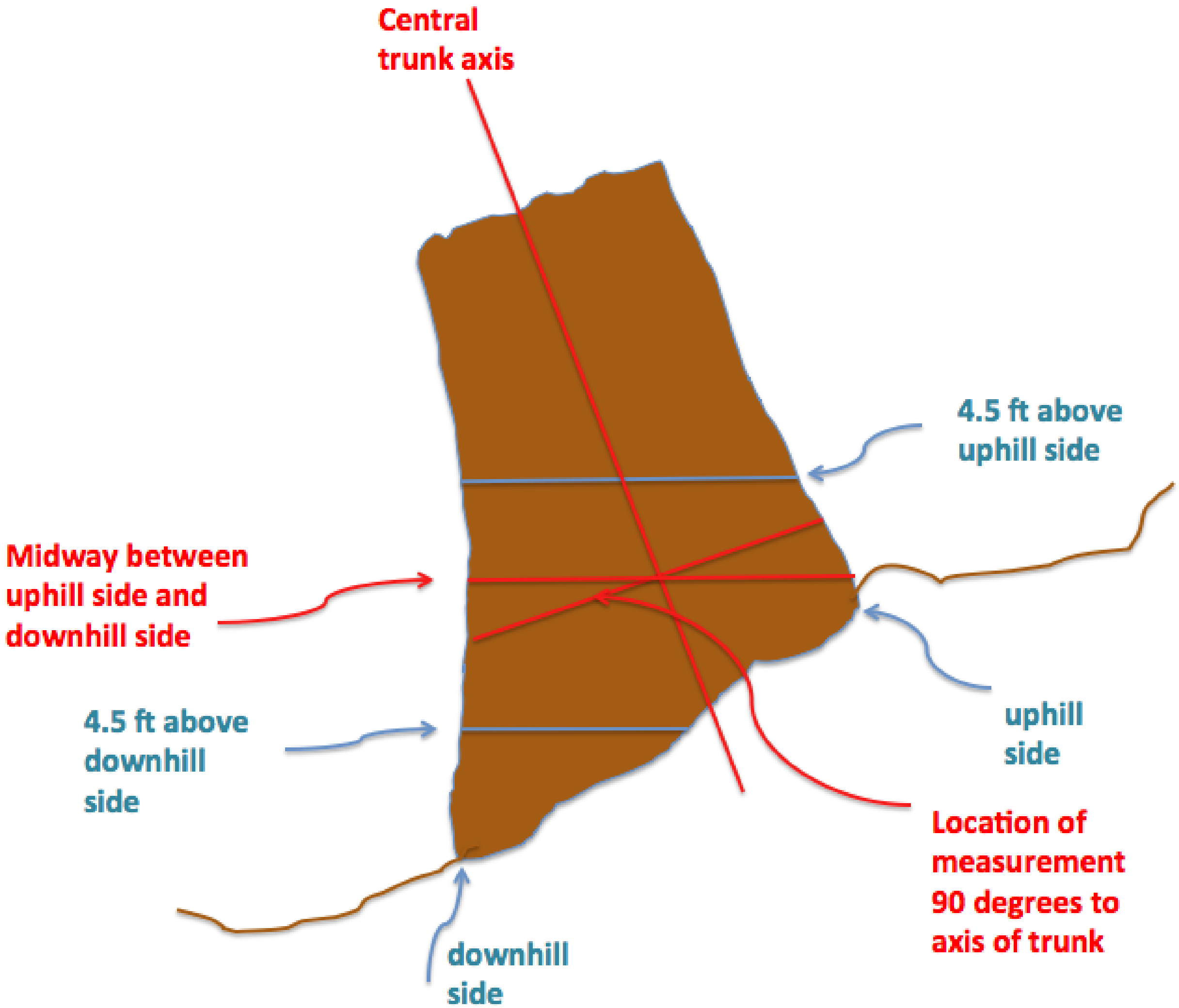


Steps:

1. Locate and mark the point 4.5 feet above where the trunk touches the ground on the uphill side.
2. Locate and mark the point 4.5 feet above where the trunk touches the ground on the downhill side.
3. Go midway between these points and take the girth there. The red line in the above diagram shows where you take the measurement.
4. Be sure that the tape is perpendicular to the axis of the trunk.

Note that these steps do not change if the trunk splits above 4.5 feet from the mid-slope spot as long as we are dealing with one tree. If the tree is also leaning, the following diagram applies.

Diagram for Circumference Measurement
Leaning Tree on Sloping Ground #1



<u>Steps:</u>

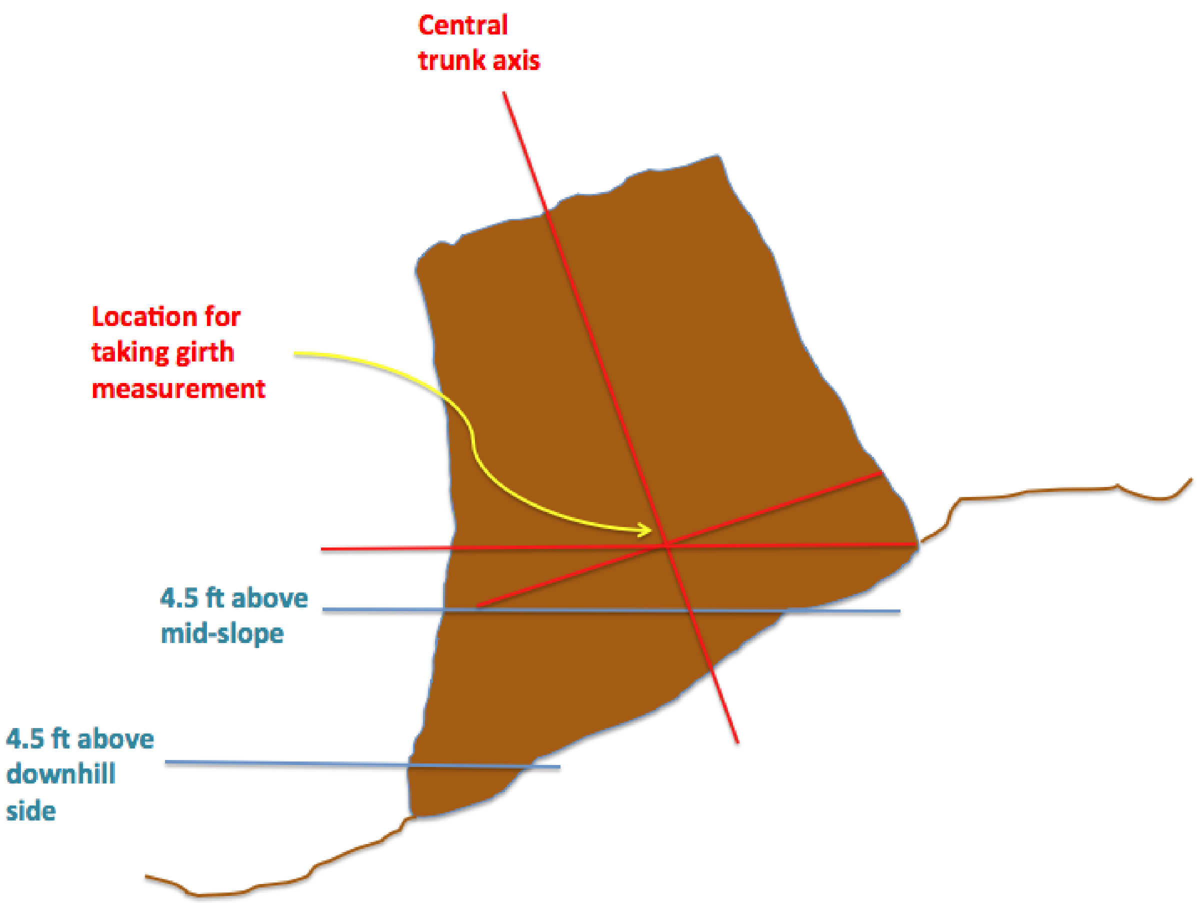
1. Locate the point at mid-slope as shown in the diagram above. Mid-slope is where the pith line intersects the ground.
2. From the mid-slope position, go 4.5 feet up following the center axis of the trunk.
3. Take the circumference measurement at this point at 90 degrees to the axis centerline, the approximate location of the pith line.

The basic idea in all these measurement scenarios is to take the circumference measurement at 4.5 feet above where the seed sprouted, and perpendicular to the central axis of the trunk.

When to Abandon Mid-Slope

The next two diagrams show what can occur for a tree on sloping ground with a trunk that is so large that 4.5 feet above mid-slope is still below the elevation of ground level on the uphill side.

Diagram for Circumference Measurement
Leaning Tree on Sloping Ground #2

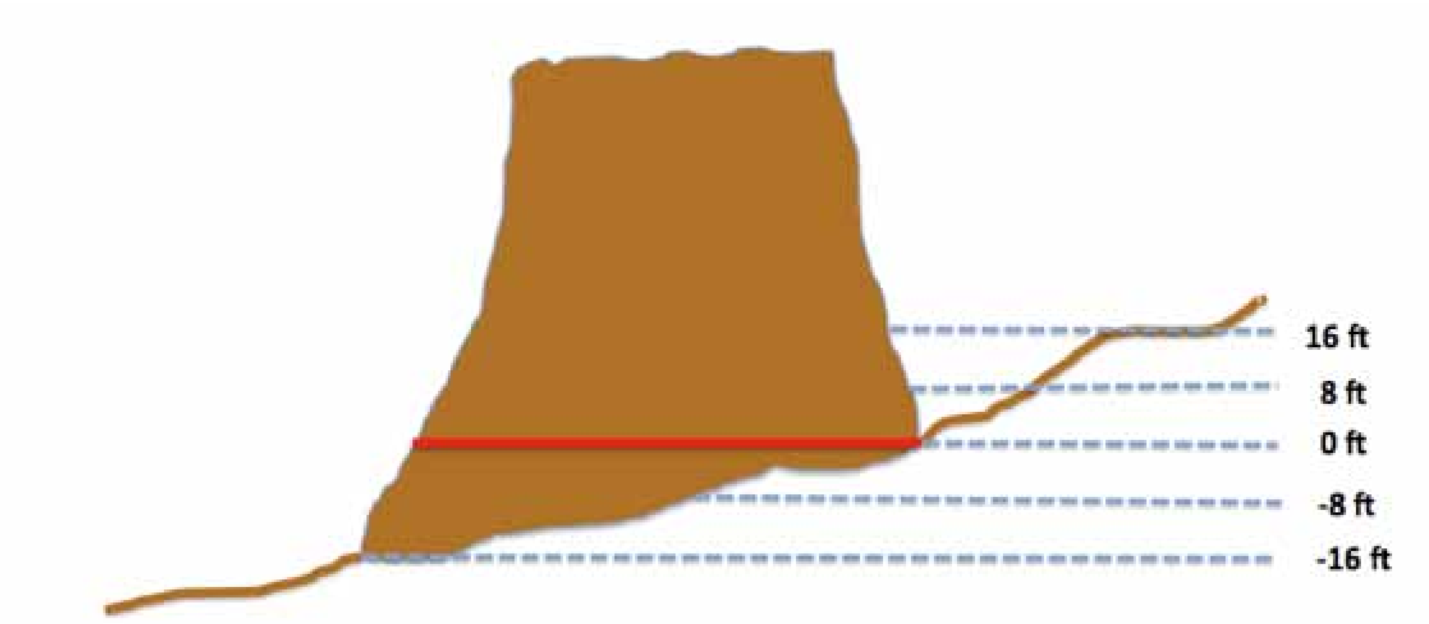


Steps:

1. Go to uphill side at the lowest point above any obvious root swell, and establish this as the point to measure circumference.
2. Stretch the tape at 90 degrees to the central axis of the trunk. Two or more people may be required to complete the measurement.

On the next page, we illustrate this situation with numerical values.

Diagram of Very Large Trunk on Sloping Ground



In the above example, 4.5 above the mid-slope position falls 3.5 feet below the point where the trunk meets the ground on the uphill side. Mid-slope is 8 feet below upslope. Were the circumference taken at 4.5 feet above upslope, we would be 12.5 feet above mid-slope. In cases such as this, we modify the 4.5-foot rule, taking the circumference at the red line in the diagram, as in Step 2 listed above.

Is It One Tree or More? — The Pith Test

How can we tell if we are measuring a single tree or multiple trees where two or more trunks are fused? With species such as the eastern cottonwood, silver maple and many others, multiple trunks can be more the rule than the exception. Here is our solution for this problem:

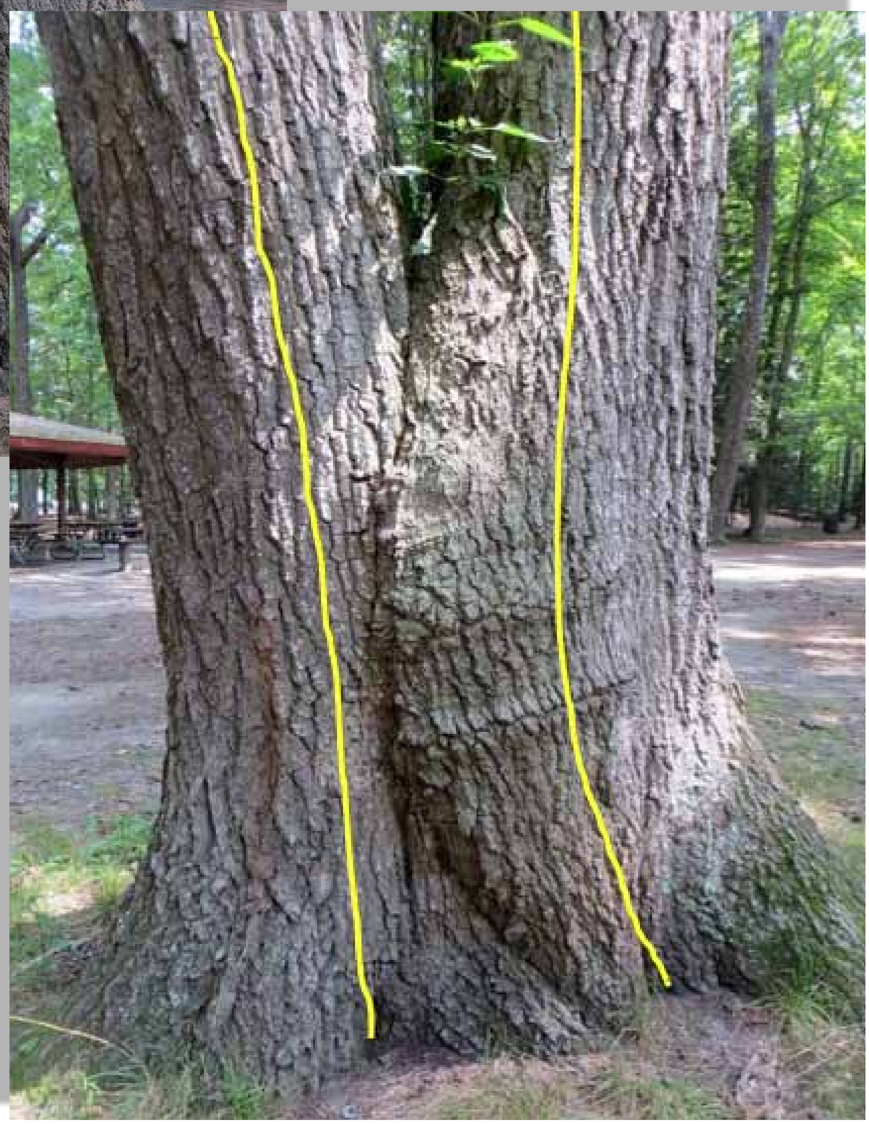
The Pith Test

We follow the central pith lines down the trunk(s):

1. If the pith lines intersect above ground level, we have one tree.
2. If the pith lines at ground level are separated, we have more than one tree.

On the next page are two photographs showing the lower section of a double-trunk oak.

Photograph #1 of Double Trunk Oak Tree



Photograph #2 of Double Trunk Oak Tree

The yellow pith lines are fairly obvious in this example, but other situations may not be so easy.

For those wishing to read more about pith line delineation, please proceed to the **Appendices** section for definitions, delineation exercises, and citations. When in doubt, consult an experienced tree measurement professional.

Circumference Measurements from Diameters

Were tree trunks perfectly circular, the relationship between the distance around the trunk and its thickness would translate to the geometrical relationship expressed in the following formula:

$$C = \pi D$$

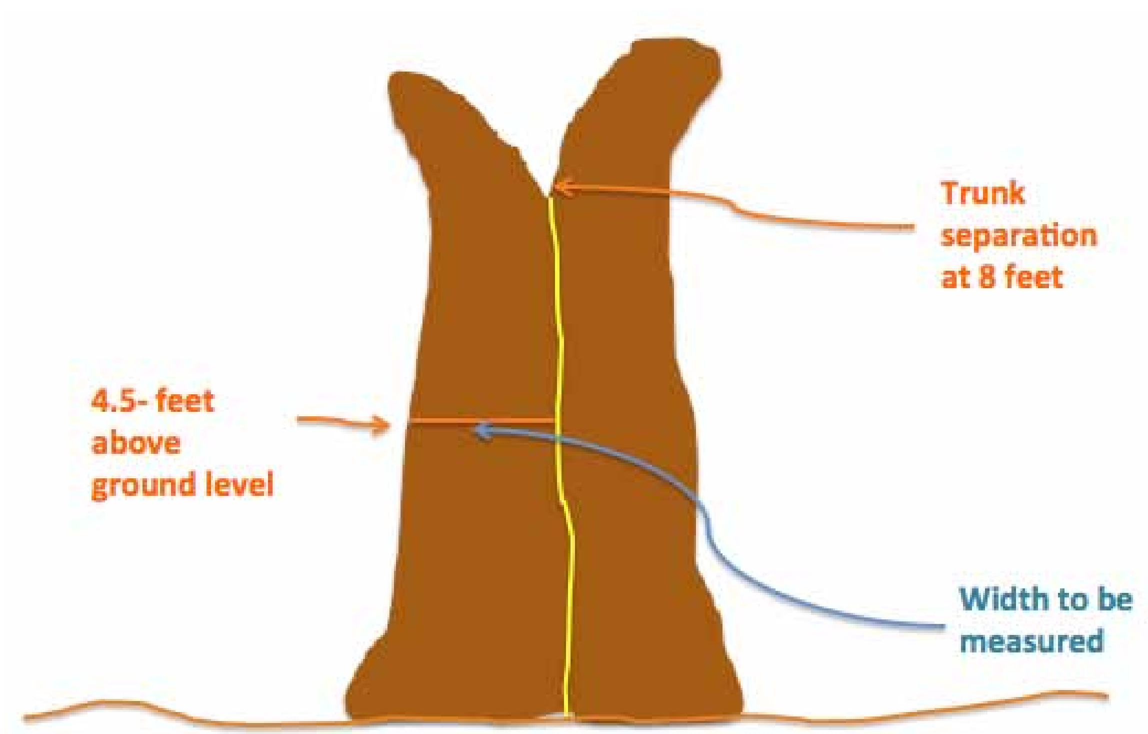
where **C** = circumference, **D** = diameter, and **π** = 3.1416

Caliper Method

Fused trunks are seldom circular, especially near the base. Still, we can approximate a trunk's circumference from its thickness, by using calipers and applying the above formula.

If a trunk is clearly not circular, go 90 degrees to the first measurement, take a second measurement, and average the two.

Diagram of Two-trunk Tree Form Representing Two Separate Trees



Diameter Using Monocular-Reticle Method

Monoculars are designed to measure widths of objects at a distance that are oriented 90 degrees to the line of sight. They use a reticle (a graduated scale across the lens). With these instruments we can accurately measure trunk widths from distances of 200 feet or more. If the trunk is out-of-round, we take a second measurement at 90 degrees to the first measurement and average the two.

Diagram Using Monocular-Reticle

To get the width of the trunk across the reticle, use the following process.

Steps:

1. Measure the distance from the monocular to the edge of the trunk with a laser rangefinder. This distance serves as an estimate for the distance directly to the center of the trunk.

2. Count the stadia marks across the trunk. In the above diagram, the count is approximately 16.5 for the reticle reading.

3. Each reticle monocular has a factor that must be used in a formula to compute width (or length) of the object being measured. The manufacturer supplies the value. Use the factor, the reticle reading, and the distance in the following formula where:

M = reticle reading	**D** = distance in the desired units
F = monocular factor	**W** = width of trunk in same units as distance

$$W = \frac{MD}{F}$$

For example, if the number of marks is 16.5, the distance is 40 feet, and F is 300. The formula gives:

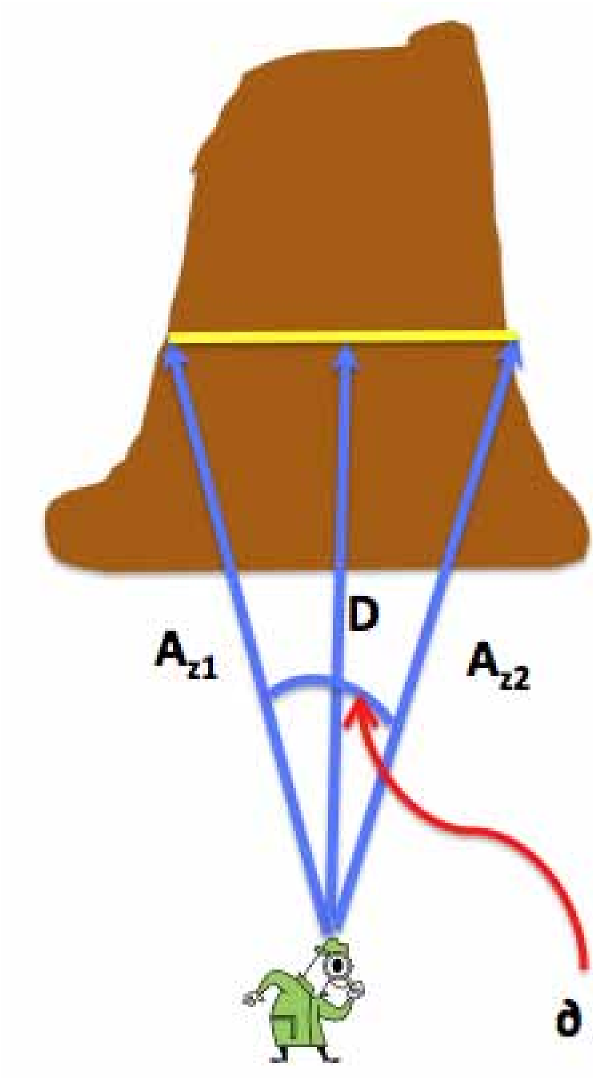
$$W = \frac{(16.5)(40)}{300} = 2.2 \text{ feet}$$

4. Be sure that the reticle is oriented 90 degrees to the axis of the trunk. Some brands of monoculars have two reticle axes for convenience. However, you can always orient a single reticle to be at the correct angle for the object being measured.

Diameter Using Azimuth Method

Level lines from the eye to each side of the trunk create a horizontal angle with the eye at the vertex. We can use this horizontal angle and the distance to the middle of the trunk to compute the third leg of a triangle that would correspond to the diameter of the trunk.

Diagram for Diameter Using Azimuth Method



This method is ideally suited for a laser hypsometer that has a built-in digital compass. The Missing Line Routine can be used to compute the trunk width: you shoot distances to the edges of the trunk, and read the horizontal distance reading of the Missing Line Routine. But getting accurate distances to the trunk edges can be difficult, and errors are exaggerated for small trees. As an alternative, you can use the azimuth feature of an advanced laser rangefinder with a built in compass to compute the horizontal angle using the steps below.

Steps:

1. Measure the distance (**D**) to the middle of the trunk at the desired height using a laser rangefinder.

2. Measure the azimuth of the left and right sides of the trunk at the chosen height using a compass or theodolite.

3. Calculate the horizontal angle ∂ from the two azimuths. In the following formulas, the symbol **| |** denotes absolute value, i.e. the magnitude of a number without an algebraic sign. For example:

both **|3|** and **|-3|** equal 3.

Using absolute values, ∂ is computed as:

$$\text{If } |A_{z2}-A_{z1}|>180 \text{ then } \partial=360-A_{z1}+A_{z2}$$

$$\text{If } |A_{z2}-A_{z1}|<180 \text{ then } \partial=A_{z2}-A_{z1}$$

4. Compute trunk width using:

$$W = 2\left(\frac{D\sin\frac{\partial}{2}}{1-\sin\frac{\partial}{2}}\right)$$

As an example, suppose, the distance to the center of the trunk **D** = 85 feet, $\mathbf{A_{z1}}$ = 359.5 degrees, $\mathbf{A_{z2}}$ = 1.0 degrees. Then **W** = 4.6 feet.

$$\left|A_{z2} - A_{z1}\right| = \left|1.0 - 359.5\right| = 358.5 > 180$$
$$\partial = 360 - 359.5 + 1 = 1.5$$

$$W = 2\left[\frac{85\sin(0.75)}{1-\sin(0.75)}\right] = 4.6$$

The accuracy of this method varies. Sources of error include:

1. Inaccurate distance to trunk
2. Trunk not being round
3. Errors in ∂
4. Not being able to see to the absolute edges of the trunk.

Of the four, ∂ is the weakest link, especially for small trees. For some instruments, compass errors can approach a degree. This method is not sufficiently accurate to use if any of the following conditions exist:

1. The difference in azimuths is small, e.g. under 3 degrees,
2. The trunk is small, e.g. under 3 feet,
3. Trunk distance is over 70 feet,
4. Compass error is likely to be 0.25 degrees or more

In the case of small trunks, the percentage error is high. For large trunks, the absolute error is high.

However, for compass accuracies of 0.2 degrees or better at distances of 30 to 60 feet, the method gives good approximations of average trunk width, provided the measurer takes two measurements at 90 degrees to one another and averages them.

Diameter Using Photographic Method

Digital photographs can be used to measure objects that are at known distances from the camera. This capability can be used when there is an object of known size in the photograph. Measurers can use a spreadsheet program, such as Microsoft Excel, with this method. Consider the following photograph:

Diagram of Two-trunk Tree Form Representing Two Separate Trees

In the photograph, the object of known size, called the reference object, is an 18-inch ruler. It is oriented close to 90 degrees to the line of sight. The diameter of the trunk is also oriented 90 degrees to the line of sight.

With these orientations, we compute trunk width at the yellow line (drawn in Excel as target line) using the following process.

Steps:

1. Record the actual length of the reference object (typically a ruler or yardstick).
2. Set the reference object in a convenient location oriented 90 degrees to the line of sight, and as centered in the photograph as possible.
3. Measure the distance to the center of the reference object from the camera lens using your laser rangefinder.
4. Measure the distance to the target object (object to be measured through the photographic technique) from the camera lens. The target should also be as centered as possible in the photograph.

5. Take a photograph that includes the reference object and target object with the orientations as described above.

6. Import the photograph into a blank Excel worksheet.

7. Using the line shape object of Excel, draw lines on both the reference and target objects (in above image, yellow line across trunk and green line on ruler).

8. Define the following variables:

   R_a = actual length of reference object
   R_x = Excel size of reference object
   T_x = Excel size of target object
   R_d = distance to center of reference object
   T_d = distance to target object
   T_m =measured size of target object

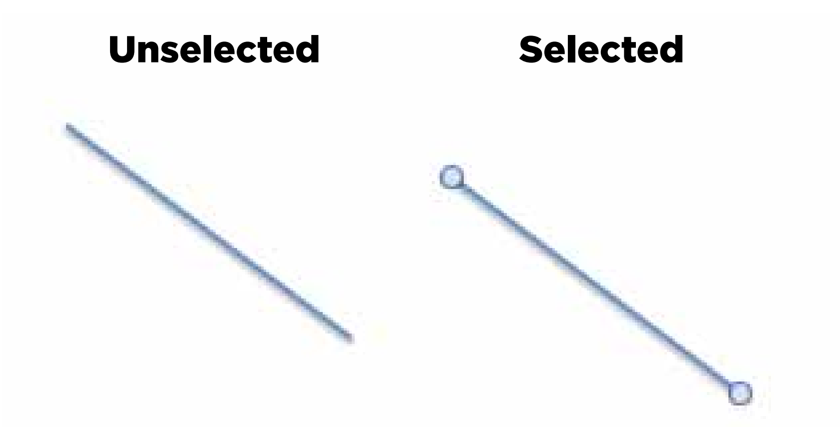
9. Using these definitions, calculate **T_m** with the following formula:

$$T_m = \left(\frac{R_a}{R_x}\right)\left(\frac{T_d}{R_d}\right)T_x$$

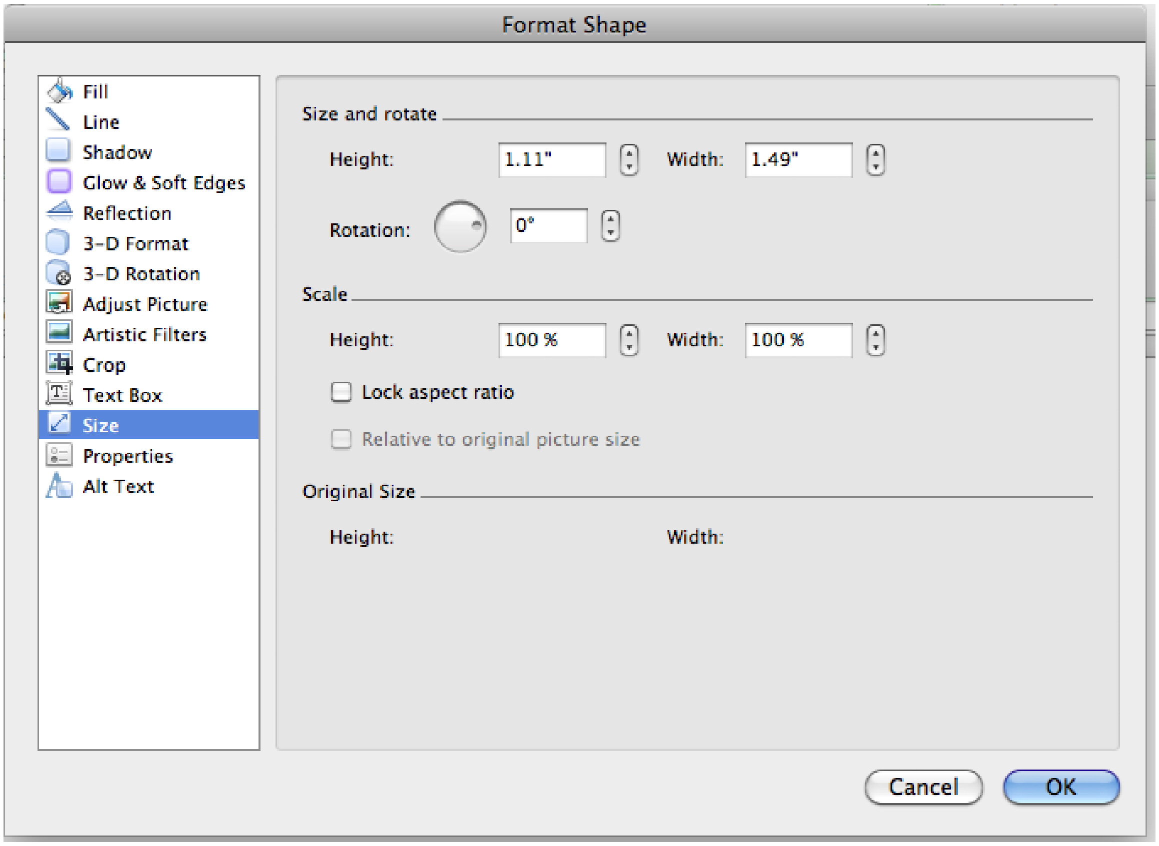
10. To determine the size of an object using Excel (yellow and green lines in photo), use the following procedure:

    a. Select the object by clicking on it. If selected, the ends of the object should show little circles. In the diagram below, the line to the left is not selected and the line on the right is selected.

    b. Diagram of Excel Line Shapes



c. Choose <Insert><Shape><Size> from the Excel menu options. For the above line, you might see something like the following:



d. The size for a line is presented in Excel as the dimensions of a rectangle. The line becomes its diagonal. In the above example, the height of the box is 1.11 units and the width is 1.49. The actual size of the line, meaning its length, is the diagonal of the rectangle with those dimensions.

e. Compute the length of the diagonal using the Pythagorean relationship as follows:

$$ExcelSize = \sqrt{Height^2 + Width^2}$$

Excel's shape object sizes are always computed through these steps. Since the photographic method is fairly involved, American Forests, through its website, provides a template Excel spreadsheet that simplifies the process. As an example, suppose:

$\mathbf{R_a}$ = actual length of reference object = 1.5 feet
$\mathbf{R_x}$ = Excel size of reference object = 0.26
$\mathbf{T_x}$ = Excel size of target object = 0.25
$\mathbf{R_d}$ = distance to center of reference object = 97.5 feet
$\mathbf{T_d}$ = distance to target object = 93.0 feet

The size of the target object, the diameter of a tree = 1.38 feet. Recalling the formula:

$$T_m = \left(\frac{R_a}{R_x}\right)\left(\frac{T_d}{R_d}\right)T_x$$

Substituting the numeric values:

$$T_m = \left(\frac{1.5}{0.26}\right)\left(\frac{93.0}{97.5}\right)0.25 = 1.38$$

The photographic method has added flexibilities. Within the same photograph, the measurer can take distances to multiple targets and compute their widths, so long as the underlying shapes are relatively circular, such as trunks and limbs.

Summary to Circumference

Circumference is usually the simplest dimension to understand and measure. However, extremely larges trees on sloping ground can present challenges that exceed the capability of beginners, and even certifiers. National Cadre members must be able to meet all of these challenges, to include taking circumference measurements from a distance without having to physically contact the tree.

But the ultimate challenge in determining circumference is distinguishing between multi-stem forms representing more than one tree and single trees that simply fork low. The Pith Test, combined with examining bark patterns that form where two trunks meet, can serve to resolve issues in the majority of cases. (Bark pattern analysis is not included here.). Where doubt still exists, a certified member of American Forests' National Cadre will make the determination. If not available, American Forests' Big Tree Coordinator will designate who will make the final determination.

HEIGHT

Introduction to Height

Tree height is a simple concept, but measuring it presents challenges. Errors, often significant, are common for traditional methods. The most foolproof way to achieve accuracy is for experts to climb the tree and carefully drop a tape from its topmost twig, being sure that the path to the ground is vertical. But tape drops are time and energy consuming, and only practicable in limited circumstances. Fortunately, today's ground-based methods can closely approach the accuracy of climbs if done by an experienced measurer with high-performance, accurately calibrated equipment, and an appropriate modern measurement method. Several mainline brands of hypsometers can measure heights to accuracies between 1.5 and 3.0 feet. The most advanced instruments achieve accuracies between 0.1 and 0.2 feet, when the right methods are used.

In this guidebook, we cover three primary approaches to measuring height. However, we will make it clear that we strongly recommend the Sine Method to consistently achieve good results across the widest range of field conditions, and it is a requirement for certification of a national champion except where the certifier can demonstrate that the method being used provides a result that matches the accuracy levels attained with the Sine Method. The Sine Method dates to the mid-1990s, coincident with the introduction of the infrared laser rangefinder. As the most recent method to be developed, it is only now beginning to catch on. Eventually, it should become the method of choice for all height certification, regardless of the level, i.e. national, state, local, but other techniques still have value. In actuality, each measuring technique has an area of applicability: a popular method may work well for certain tree forms, while falling short for others. But regardless of the method employed, there is no substitute for a high level of skill and experience on the part of the measurer.

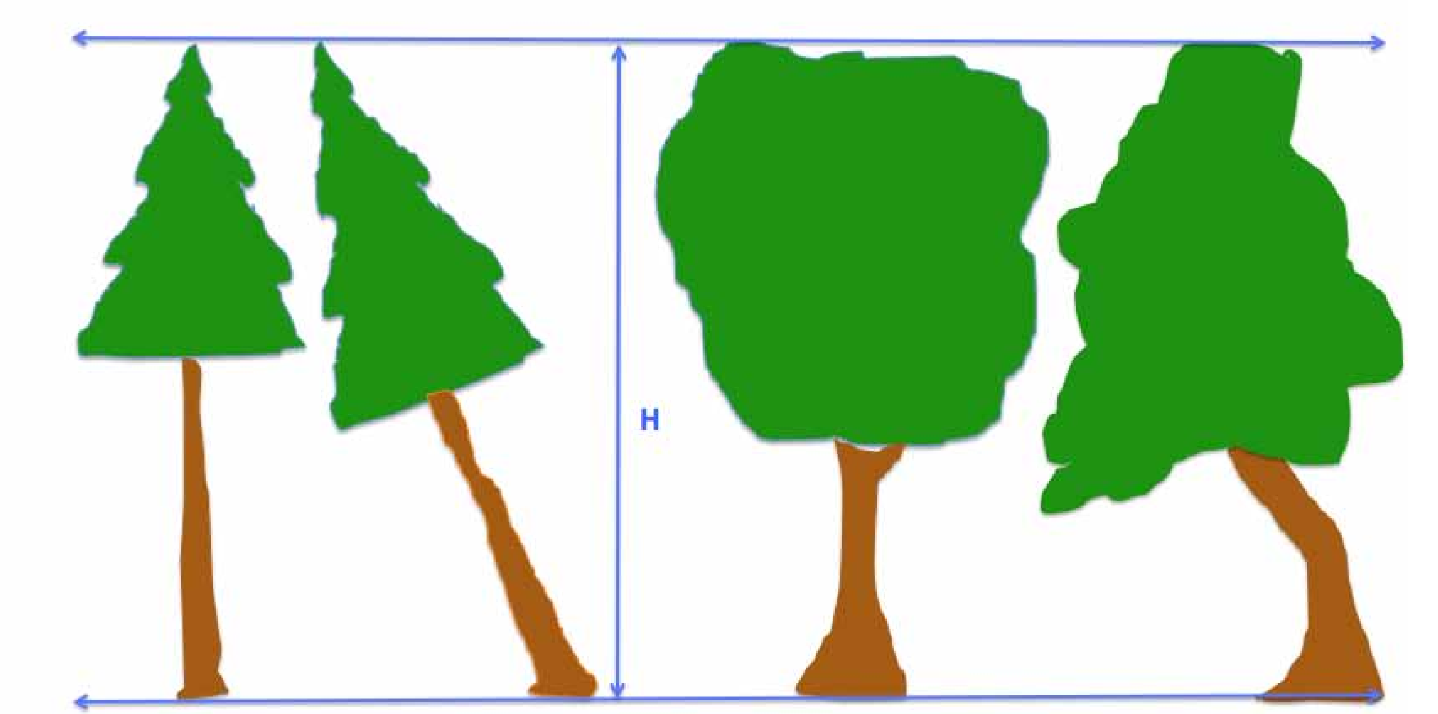
Following the plan for the dimensions of circumference and crown spread, this section on height is organized and color-coded in the same beginning, intermediate, and advanced categories used throughout the guidelines. The beginning level, appropriate for nonprofessionals making initial measurements, features the Stick Method. The intermediate level, intended primarily for Champion Tree certifiers, includes the traditional Tangent Method and its variations. Since it is the most widely used method among forestry professionals, we spend considerable time explaining how to minimize errors. The intermediate level also introduces the Sine Method, the most accurate way of measuring height, because it is simple to learn. The advanced topics are designed principally for the National Cadre whose members are trained to measure the most complex forms in the most difficult terrain.

These guidelines will be periodically updated as new techniques and equipment become available.

Tree Height

Tree height is defined as the vertical distance between two horizontal planes: one plane passing through the highest twig and the other through the base of the tree at mid-slope. **Tree height is not synonymous with trunk length**. All the trees in the diagram below are the same height.

Diagram of Height Profiles



Another way of expressing the idea of tree height is: the vertical separation between the highest twig and mid-slope of the base.

With this definition of height in mind, we turn to the simplest method for measuring it, the Stick Method.

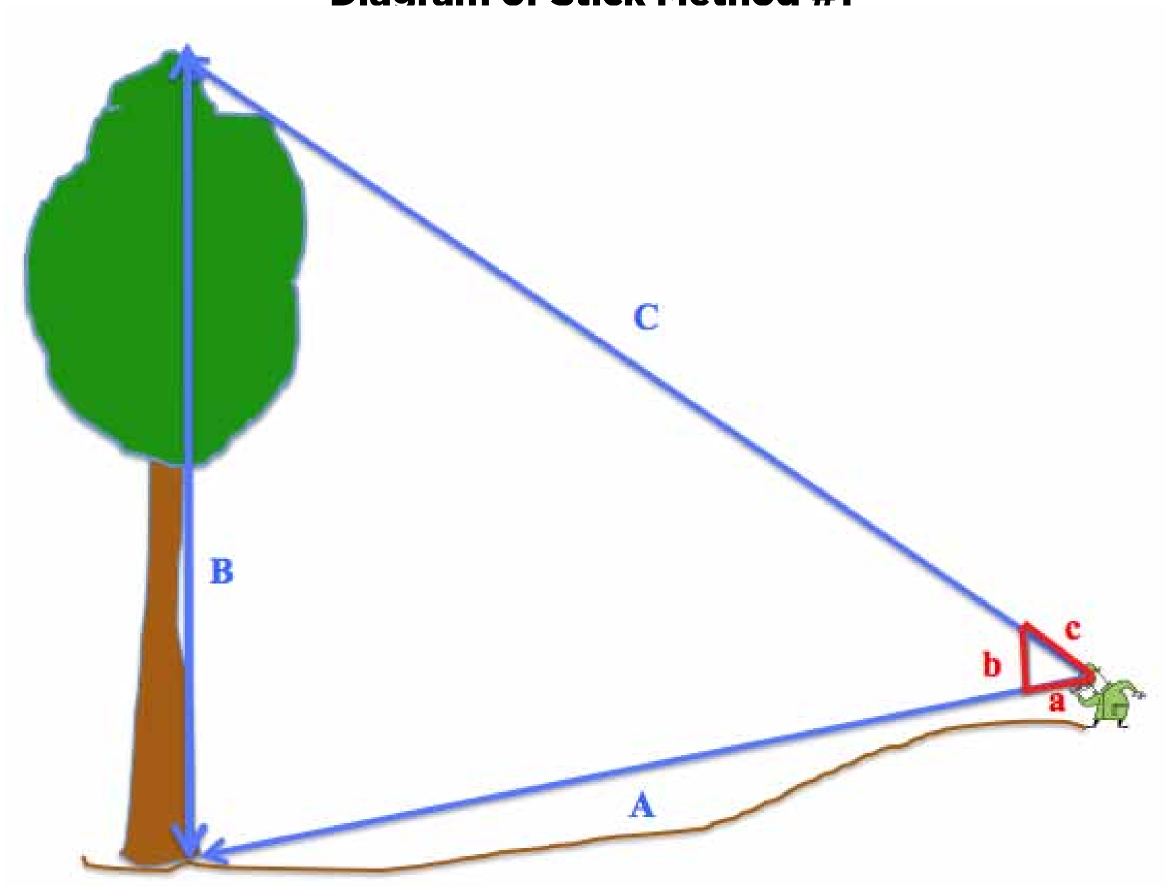
Stick Methods

The Stick Methods use plane geometry to compute the corresponding leg of a large triangle of similar shape to a smaller one. If we have two plane triangles that have the same shape, with one simply being a larger or smaller version of the other, the corresponding angles are equal and the lengths of the corresponding sides are proportional.

Stick Method #1

The small triangle **abc** has the same shape as the larger triangle **ABC**. If we can obtain measurements for **a**, **b**, and **A**, we can compute **B**, the tree's height. But how do we actually create these similar triangles in the field?

Diagram of Stick Method #1



Steps:

1. Hold a ruler or yardstick vertically at arm's length. Move forward or backward from the tree until the part of the stick from the top of your hand to the top of the stick just covers the tree.

2. Measure the length of the stick above your hand to get the side **b** of the small triangle **abc**. A plumb bob attached to the top of the stick can help the measurer insure that it is held vertically.

3. From this position measure the distance from your eye to the top of your hand. This is distance **a**. You can get this distance by extending a string from your eye to your hand and measuring the string length.

4. Next, with a tape, measure the distance from your eye past the top of your hand and on to the base of the tree. This distance is **A**.

5. Use the following formula to compute **B**, the tree's height.

$$B = \frac{A}{a} b$$

For example, if **A** = 120.0 feet, **a** = 2.5 feet, and **b** = 2.7. **B**, the tree's height, is 129.6 feet.

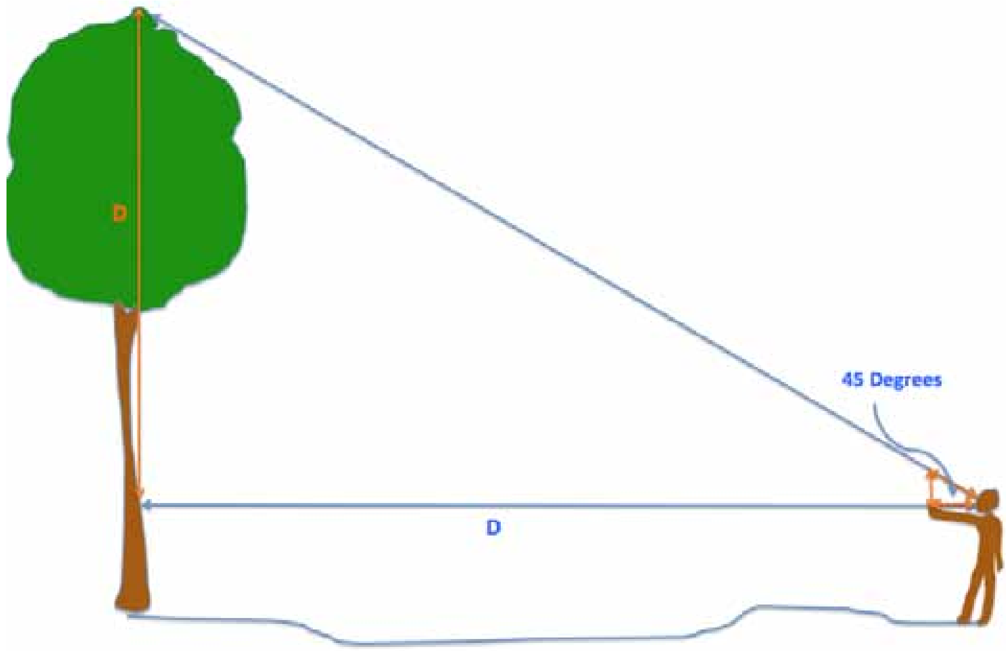
$$B = \frac{120.0}{2.5} 2.7 = 129.6$$

This method is simple and does not require any expensive equipment. A stick of known length can be substituted for the yardstick, but the yardstick has the advantage of facilitating the determination of **b**. We highly recommend it.

Stick Method #2

Measuring **a** and **b** can be tricky, especially **a**. Here is a method that eliminates the need for those measurements.

Diagram of 90-Degree Rotation of Yardstick and the Result



Steps:

1. With your arm extended and holding the stick at a point equal to the length of your outstretched arm, put the beginning end of the stick against your eye (gently), keeping the stick level. Your hand must be at eye level so that the stick is horizontal.

2. Swivel the stick 90 degrees to a vertical position, while keeping your hand in the same place. The distance from eye to hand will then be equal to the length of the stick from hand to end. Since the stick was first held horizontally, and then swiveled to a vertical position, the angle from hand to eye and from eye up to top of stick is 45 degrees. But if in the process, the hand is moved up or down, this angle changes, compromising this method.

3. Move forward or back to a location where the line from your eye across the top of the stick just touches the top of the tree. You may have to go through steps 1 & 2 more than once along with forward or backward movement to get into the final position.

4. The horizontal distance from your eye to the trunk equals the height of the tree above eye level. If the ground is level, you can measure the distance from your feet to the tree. If the ground is not level, you will need the help of an assistant to stretch a tape horizontally from your eye to the tree.

5. Note where the line from your eye across the top of your hand touches the trunk.

6. Measure the vertical distance from this point on the trunk to the ground.

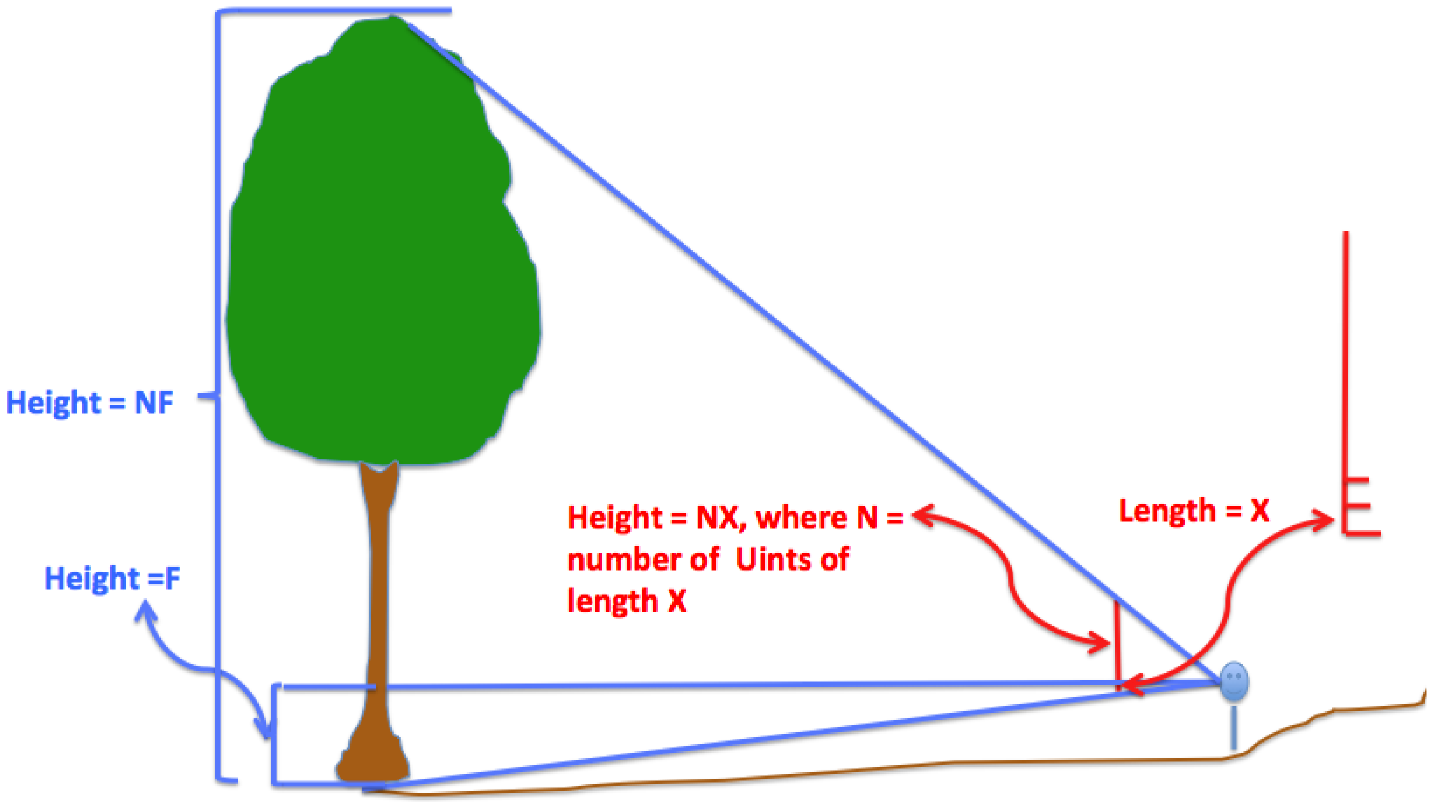
7. Add this number to the distance from eye to trunk obtained in step #4 to get the total height of the tree.

Note that you must get the angles right or this method does not work.

Stick Method #3

The third method requires the least amount of equipment: a yardstick.

Diagram of Stick Method #3



Steps:

1. Put a marker on the trunk at a chosen height above the ground. A four- or five-foot height choice is common. You can use the yardstick to get this distance. Call this height F.

2. Move back until an inch on the yardstick just covers F.

3. Keeping the yardstick in place, sight up the yardstick to the top of the tree. You must be back far enough so the top of the yardstick covers the top of the tree.

4. Read the points on the yardstick corresponding to the top of the tree and the top of your hand. The top of the tree will usually fall within an inch marking. Estimate how much of the inch covers the tip of the tree, expressed as a fraction or decimal, e.g. 1/4th or 0.25.

5. You now have the readings corresponding to the top of the tree and the top of your hand. Subtract the second reading from the first to get the number of inches that matches the whole tree.

6. Multiply this number of inches by the factor F to get the height of the tree.

As an example, suppose 1 inch of the yardstick covers from the ground up to 4 feet on the trunk. If 31.5 inches of the yardstick covers the entire tree, its height is 31.5 x 4 = 126 feet.

Note that Stick Method #3 does not require you to measure the distances from eye to hand and from eye to tree. The drawback is that if F is too small and the measurer is distant from the trunk, it may be difficult to accurately mask the distance F on the trunk. If the distance to the trunk is close, the yardstick may not completely cover the height of the tree. In general, lining up X on the yardstick with F tends to be error-prone because of handshake or poor visibility.

Remember, the inch convention for X is arbitrary, but highly convenient, as is 4 or 5 feet for F. Either factor can be more or less and the method will still work. The smaller F or the larger X is, the shorter the tree that can be covered. Conversely, the larger F or the smaller X is, the taller the tree that can be covered.

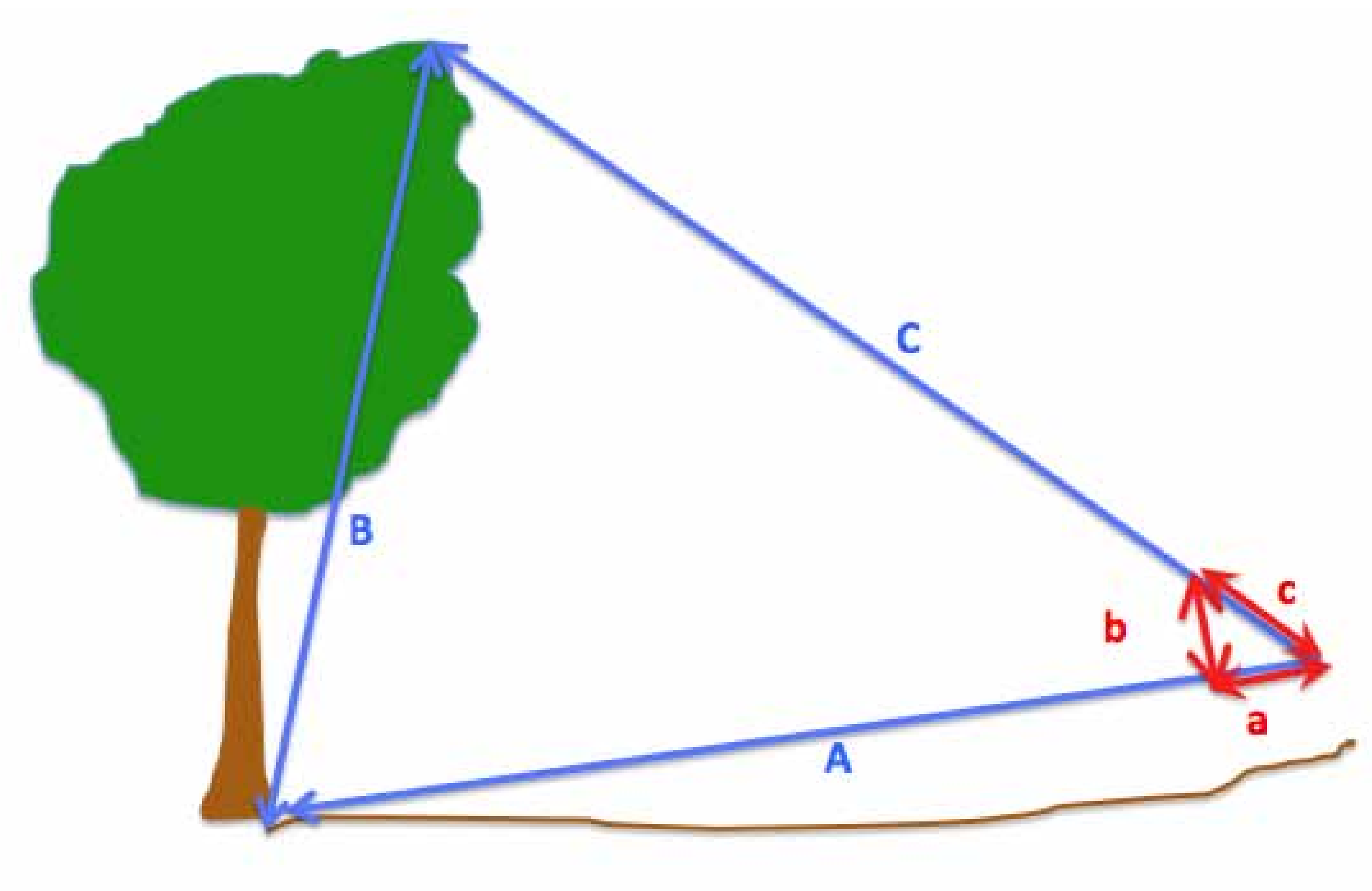
Pitfalls of the Stick Method

For the Stick Method to work, the triangles must be similar, and the top of the tree must be positioned exactly vertical over the base. One or both requirements are often unfulfilled. In addition, holding the yardstick vertically and aligned perfectly with the top and base of the tree requires practice. As previously mentioned, a plumb bob attached to the top of the yardstick can help. A slight tilt in the yardstick introduces a measurement error, since it creates dissimilar triangles.

Furthermore, it is often difficult to accurately measure the distance from the eye to the top of the hand holding the yardstick. A second person may be needed to insure that the yardstick is held vertically to correctly measure length **a**.

In the diagram below, the blue triangle **ABC** and the red triangle **abc** are NOT similar because the top of the tree is not vertically positioned over the base and the stick is not held vertically. This actually creates two sources of error.

Diagram Illustrating Dissimilar Triangles



Various sources describe different ways the Stick Method can be implemented but seldom discuss the pitfalls. Their diagrams show trees with tops vertically over their bases, a situation that is not always realized in the field.

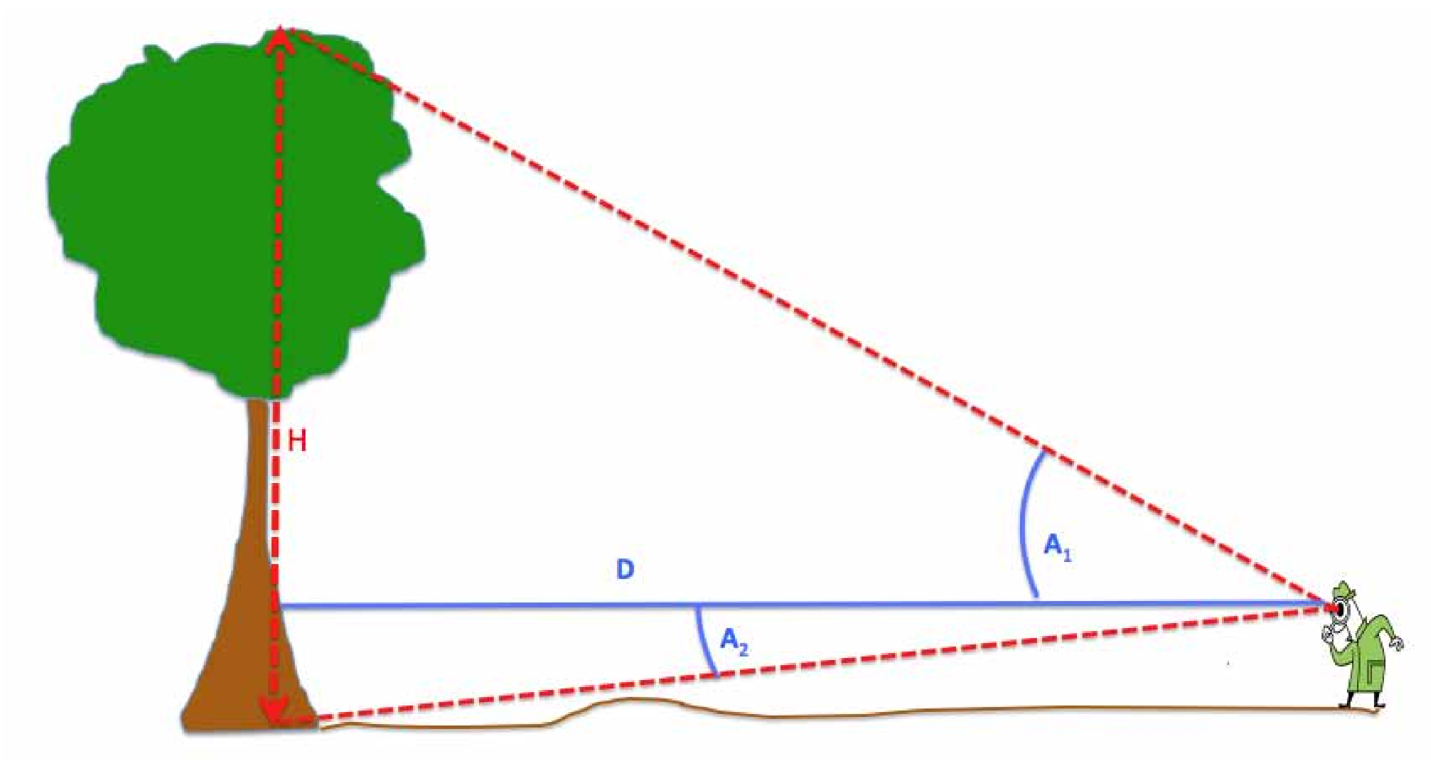
Traditional Tangent Method

This is the most widely used method for measuring tree height, both by professionals and experienced amateurs, and is likely to remain important in the certification process. It is useful where distances cannot be measured directly from the eye to the top or base of a tree. At its simplest, it requires a level distance from the eye to the trunk of the tree, and angles to the top and base. Distances can be obtained with a tape, and angles with a clinometer. Smartphone apps offer clinometers of surprising accuracy and extremely low cost. A scientific calculator with trigonometric functions may be required.

As commonly applied, this method assumes the tree's top and base are in vertical alignment with the end of a level baseline to the trunk. If these assumptions are not met, errors in height will occur.

The underlying mathematical model of the Traditional Tangent Method assumes two right triangles, an upper and a lower, both with vertices at the measurer's eye, and sharing a common baseline. The following diagram illustrates this configuration followed by the computational steps.

Diagram for Traditional Tangent Method



Steps:

1. Measure horizontal distance at eye level to the trunk. Call this distance **D**.
2. Measure the angle from the eye to top. Call this angle $\mathbf{A_1}$.

3. Measure the angle from the eye to base. Call this angle $\mathbf{A_2}$. $\mathbf{A_2}$ will be negative if below eye level.

4. Define the Height from base to top as **H**.

5. Apply the following formula:

$$H = D\left(\tan A_1 - \tan A_2\right)$$

As an example, suppose the distance **D** to the trunk is 125 feet, the angle $\mathbf{A_1}$ to the top is 37.5 degrees, and to the base -8.7 degrees. The resultant height is 115.0 feet.

$$H = 125.0\left[\tan(37.5) - \tan(-8.7)\right] = 115.0$$

[In the diagram on the previous page, in keeping with convention, angles above eye level are positive and those below are negative. This leads to a height formula that may not be intuitive for those unfamiliar with manipulating algebraically signed numbers. The tangent of a positive angle is positive and the tangent of a negative angle is negative. The product of two positives or two negatives is positive. The product of a positive and a negative is negative. Another way of thinking about it is: heights above eye level are algebraic positives and those below eye level are algebraic negatives. Subtracting a negative height component for the part below eye level from the positive part above eye level is equivalent to adding a positive. Use of algebra and signed angles allows us to use one formula for all situations.]

Tangent Method Through Smartphone Applications

With the introduction of the smartphone, there has been an explosion of applications, or apps, as they are called, that can help with tree measurement. Some make use of the smartphone's built-in camera, gyroscope, accelerometers, compass, and GPS receiver capabilities. As a consequence, we now have clinometer, sextant, and theodolite capabilities packaged in apps that cost a few dollars. Vertical angles can be measured accurately to 0.1 degrees, outperforming mechanical clinometers and many mainline brands of hypsometers, which commonly advertise accuracy of +/- 0.2, +/-0.25, or +/- 0.5 degrees. Consequently, utilizing smartphone apps makes sense. The biggest negative is reading the display through the camera lens in bright light.

If a coordinator or certifier has a smartphone, applications such as Theodolite© and SeeLevel© provide a way to estimate heights that is based on the tangent method. Using Theodolite© for smartphones, we now present the steps needed to calculate the tangent-based height of a tree, and the horizontal distance to an object of known height. Note that the symbols <A>, <B>, and <A-B> represent buttons to tap in the application.

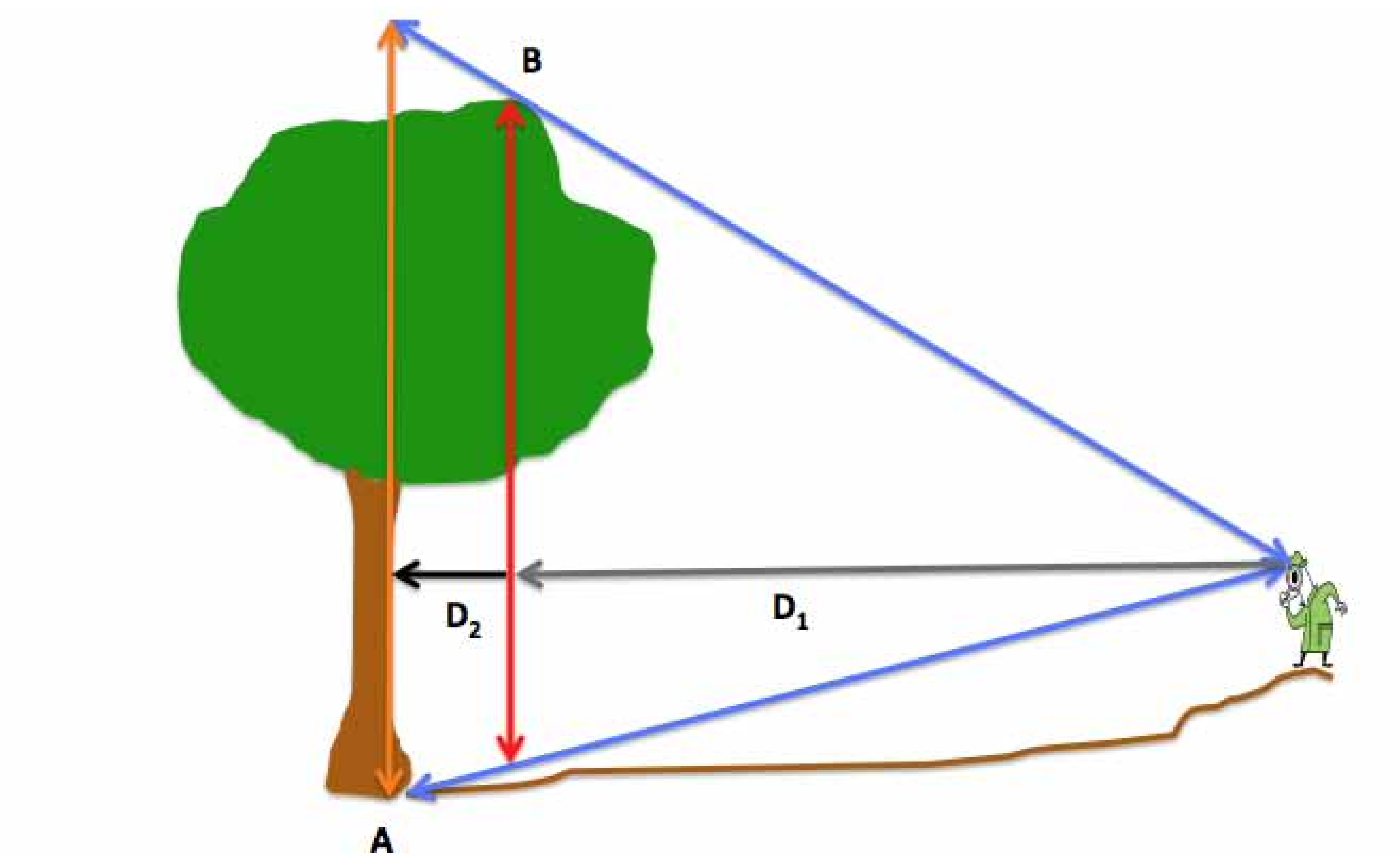
Computing Height with Theodolite©

Steps:

1. Bring up the Theodolite© application.
2. Tap the <A-B> button
3. Tap <Clear> to erase the current A and B selections.
4. Looking through the smartphone camera, aim crosshairs at the base of the object to be measured and tap <A>. The A should flash momentarily.
5. Swivel the smartphone upward using the base or center of the smartphone as the pivot point until the crosshairs appear to touch the top of the object to be measured.
6. Tap <B>. The B should flash momentarily.
7. Enter the horizontal distance to the object, usually interpreted as the trunk.
8. Theodolite© will return the height of the object between points A and B.

The measuring process is subject to the same error possibilities as encountered with a clinometer. The following diagram will help clarify this.

Diagram for Theodolite© Measurements



The measurer's lines of sight are shown in blue. The points A and B are chosen through the camera lens to mark the base and top of the tree. Theodolite© asks for a horizontal distance to use in computing the tree's height. If the measurer gives the distance from eye to trunk (**D_1** + **D_2**), the orange line gives the height computed by Theodolite©. It is obviously too much. If the measurer recognizes that the top is offset from the base and estimates the horizontal eye level distance to the plumb line from the top as **D_1**, then the red line shows the height returned by Theodolite©, which slightly understates the true height, but is good enough.

A typical image of the Theodolite© screen follows. Note that the elevation angle is the vertical angle read through an internal tilt sensor. The horizon angle means the angle of tilt of the base of the smartphone from the horizontal. The azimuth is the compass bearing. Use the 'ZERO' button to compute relative angles and azimuths. This feature allows the user to calculate changes in angles from that reference position. The orientation of the smartphone, at the time the ZERO button is tapped, is the zero reference position.

Diagram for Theodolite© Screen

Computing Horizontal Distance with Theodolite©

Steps:

1. Place an object of known height (a yardstick or a person) beside the middle of the tree trunk at eye level.
2. Choose the A-B option.
3. Tap the <A> button when the horizontal crosshair is aligned with the bottom of the image of the object seen through the camera lens.
4. Tilt the smartphone, using the base of the instrument as the axis of rotation and align the crosshair with the top of the object.
5. Tap the <B> button.
6. Tap the 'Calc' button, followed by the 'Distance from A-B Elevations' option, and enter the known height of the object.
7. Theodolite displays the level distance to the tree, which becomes its baseline.

Computing Height with SeeLevel©

We also present instructions for measuring tree height using the SeeLevel© application. SeeLevel© also uses the traditional Tangent Method, and has the same capacity for error that we emphasize above.

Steps:

1. From the app's menu, select the "Distance C" option.
2. Select the double vertical arrow at the bottom of the screen for the height routine.
3. Enter the horizontal distance to the target in the box in the upper left corner of the screen.
4. Looking at the tree through the camera, align the horizontal crosshair with the bottom of the tree.
5. Press the open lock icon in the lower left corner to lock it. This sets the height reading to zero, which corresponds to the base of the target.
6. Rotate the smartphone around its base, moving the top toward you for objects above eye level. This moves the horizontal crosshair toward the top of the target. Notice that as you move the crosshair upward, the height continuously changes. The app is updating the display using the distance it was given, times the tangent of the angle at the instant. If you move past the top of the target, you simply rotate the smartphone in the reverse direction until the crosshairs are once again aligned with the target.

Tangent Method in ‘Three-point’ Laser Rangefinders/Hypsometers

Some hypsometer manufacturers offer a special tree-height measuring routine called the Tree Height or Three-point Method. The steps are:

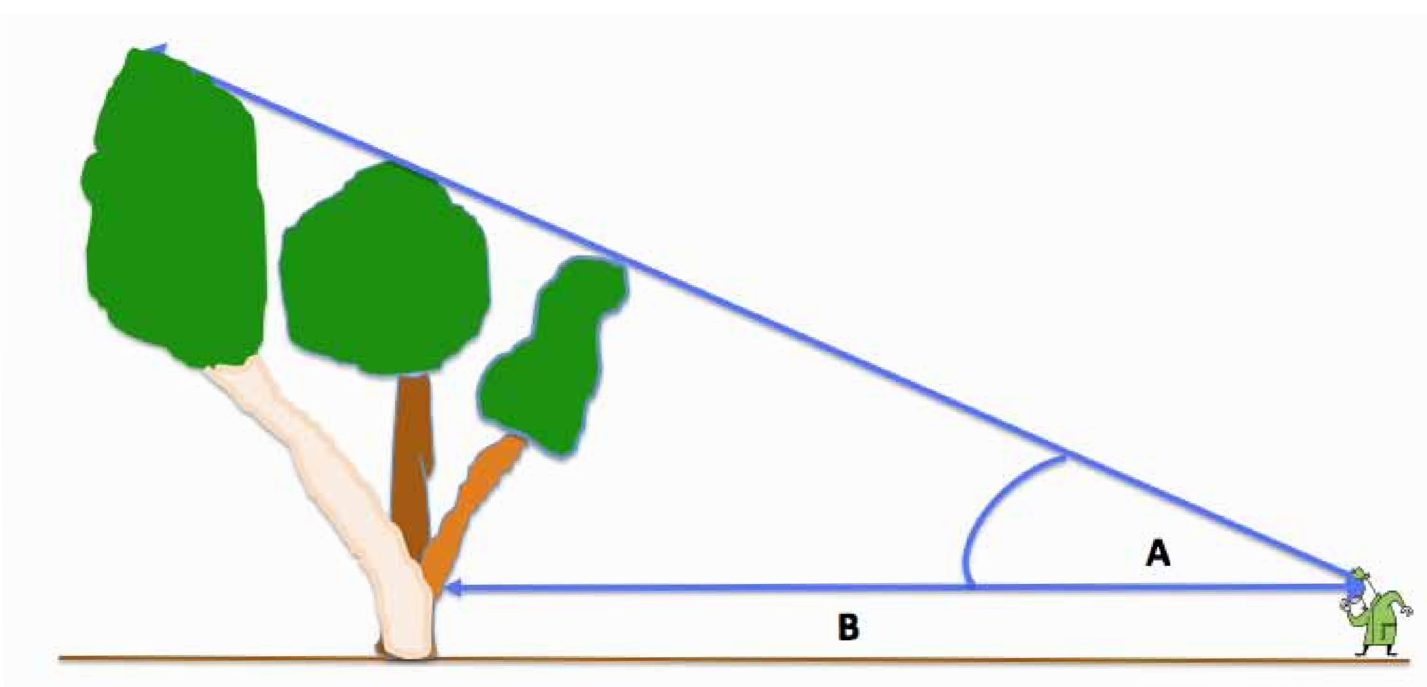
1. Shoot to a convenient point on the trunk to get a baseline distance. The 3-point method automatically computes the horizontal distance to the trunk at eye level.
2. Shoot to the base to get the angle from the eye to the base of the tree.
3. Shoot to the top to get the angle from the eye to the top of the tree.
4. Read the height of the tree on the hypsometer’s display.

The appeal of the 3-point tangent method is that it is easier to shoot angles to points in the crown than distances. With laser-measured distances, the measurer may encounter clutter or hit the wrong target. However, the 3-point procedure automates the traditional Tangent Method that assumes the top of the tree, the point on the trunk at eye level, and the base, lie on the same vertical line. When trees do not conform to this simple vertical alignment, the 3-point method results in height errors exactly like the traditional Tangent Method, manually performed.

Controlling Tangent Errors

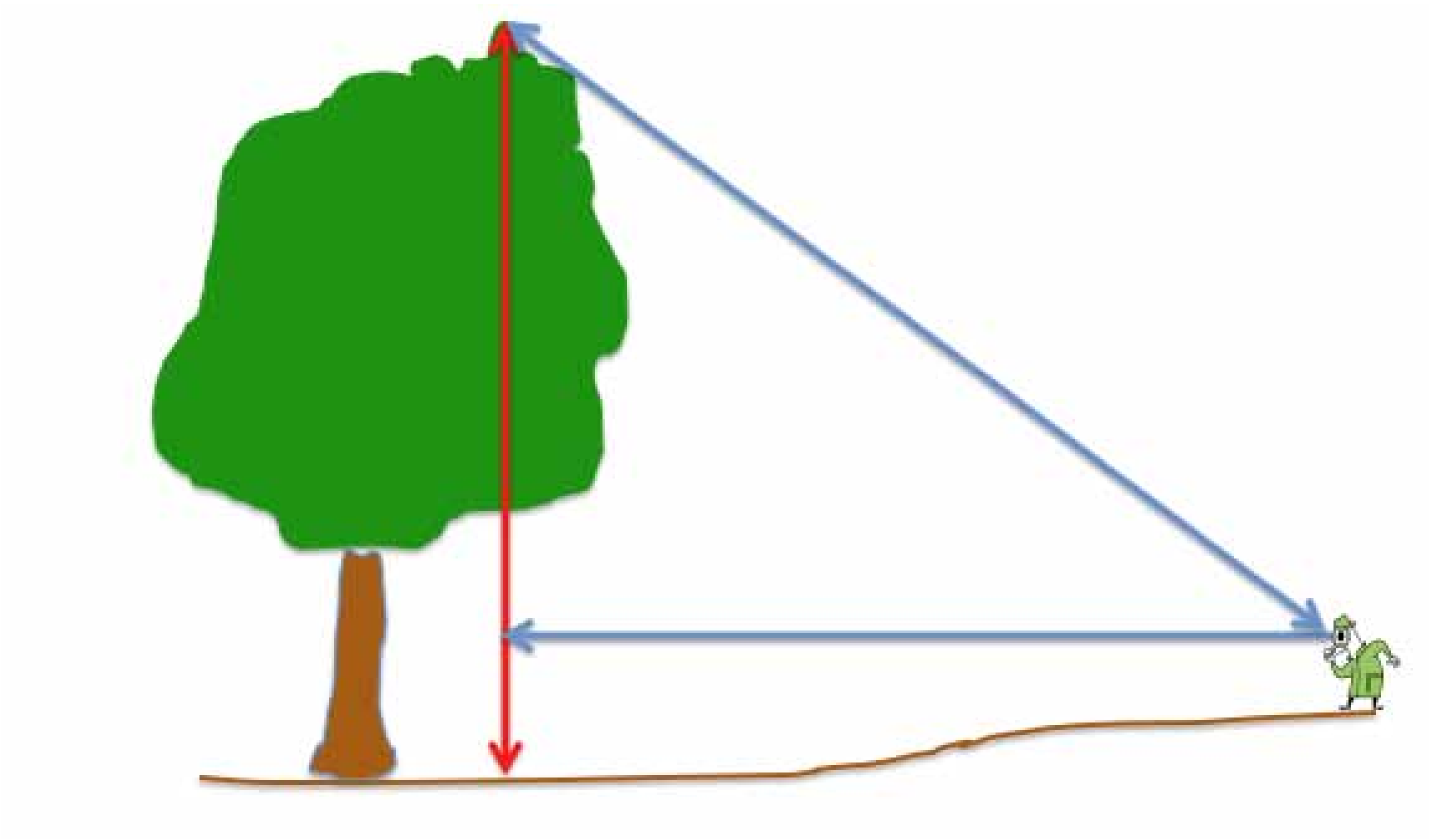
The highest twig of a tree is often not directly over its base. Consider the three trees in the following diagram. They obviously have different heights, but traditional use of the tangent method will yield the same results for all three.

Three Trees: Different Heights, Same Tangent Measurement



The measurer should try to find the spot on the ground directly beneath the top. The horizontal distance from the eye to this spot is the correct baseline for the top. Even approximating this distance is better than generating a large error in height from using an incorrect baseline. The diagram below illustrates this technique.

Diagram of Correct Baseline



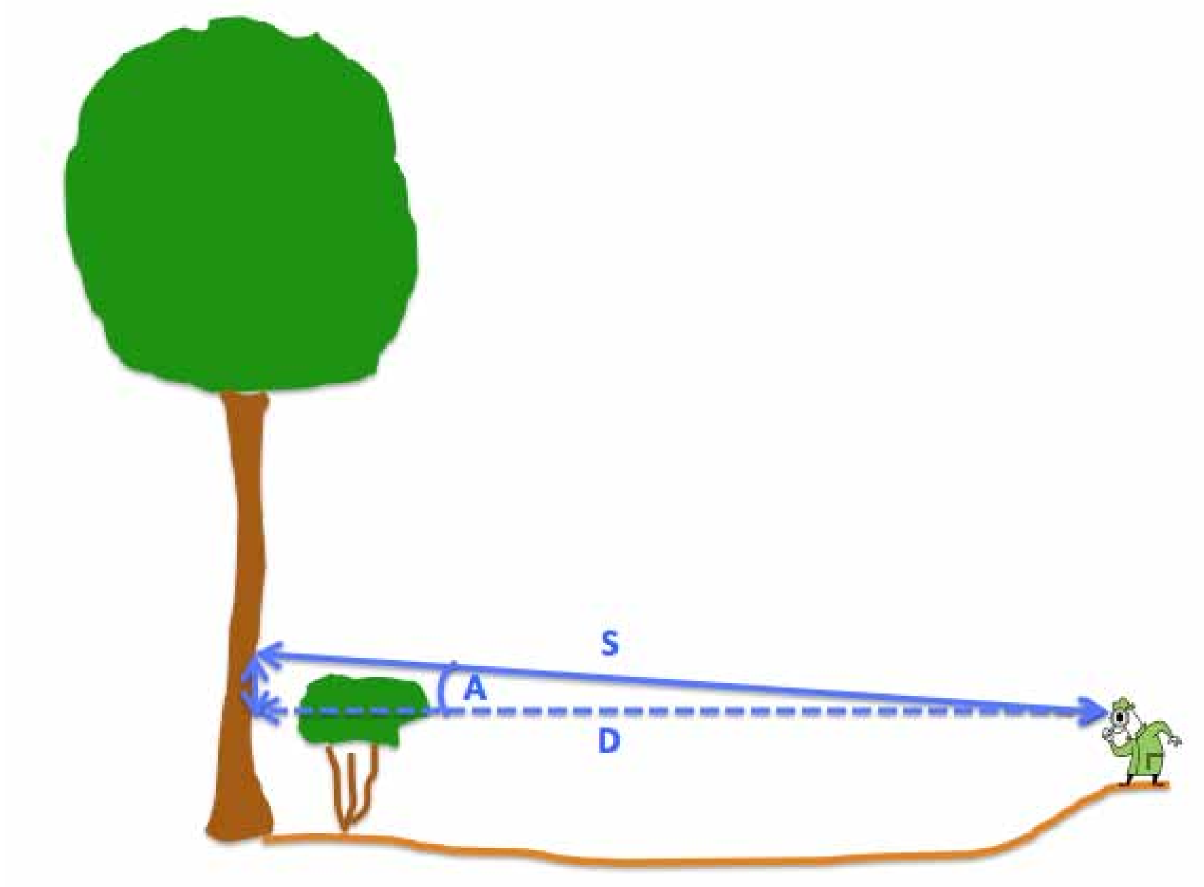
In the diagram, the horizontal blue line is the true baseline. It does not extend all the way to the trunk.

Experienced forestry professionals are often good at figuring out where a plumb line that is dropped from the top would touch the ground. If you can locate this point in order to establish the correct baseline, you can accurately measure the height of the top.

When You Can't See or Reach the Trunk at Eye Level

Sometimes horizontal distance to trunk at eye level can be difficult to measure with a tape because clutter is in the way at eye level, or because the tree is on sloping ground and eye level is out of reach for a tape. But, with a laser rangefinder and clinometer (or hypsometer equivalent), you can obtain horizontal distances to the trunk equivalent to eye level provided you are not shooting too high on the trunk.

Diagram Illustrating Obscured Trunk at Eye Level



Shoot to a convenient point on the trunk with a laser (or possibly measure with a tape), take the vertical angle to that point, and apply the following formula:

$$D = S\cos A$$

where D = horizontal distance to trunk at eye level; S = slope distance to point on trunk; and A = angle to point on trunk.

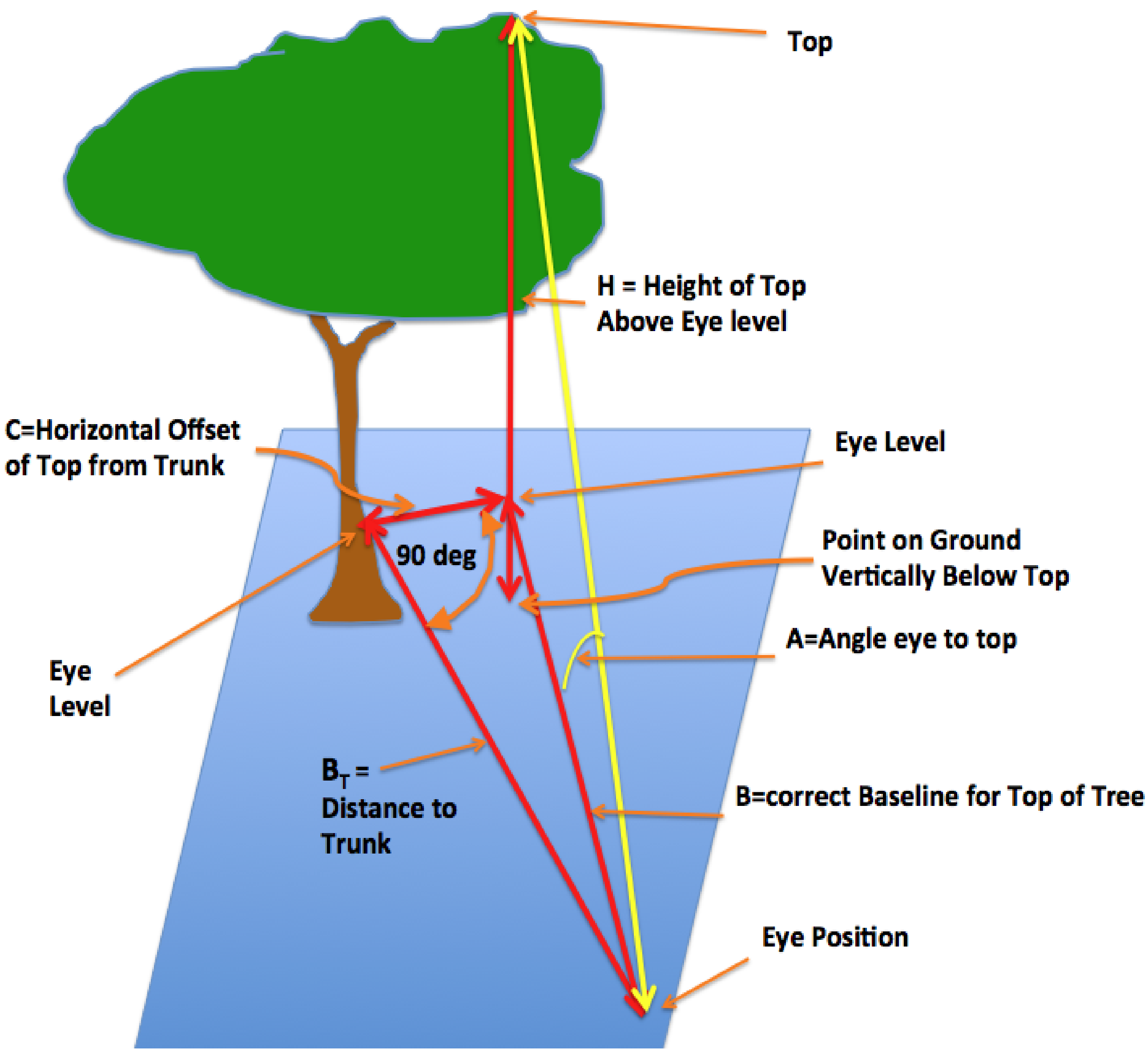
As an example, if S = 135.0 feet and A=6.5 degrees. The resultant level trunk distance D is 134.1 feet.

$$D = 135.0\cos(6.5) = 134.1$$

Tangent Method: 90 Degrees from Top to Line of Sight

A shortcut to the traditional Tangent Method exists for some trees. If you can get positioned so that your line of sight to the trunk is 90 degrees to the vertical plane containing the tiptop and base, then the eye-level distance to the trunk can serve as a surrogate baseline for both the top and base. This technique works especially well for straight-trunk, leaning conifers, but getting into the 90-degree position is seldom easy on broad-crowned hardwoods, or on trees with partially obscured crowns. It is, nonetheless, a tool in the toolkit, and when it can be used, addresses the biggest source of tangent-based height errors. It is also the method most frequently taught in courses in forest mensuration.

Diagram Illustrating Obscured Trunk at Eye Level



Steps:

1. Move around the tree to a point where the line of sight to the trunk is 90 degrees to the vertical plane that includes the top of the tree and the trunk at eye level. It is much easier to visualize the vertical plane with a straight-trunk leaning tree.
2. Measure the distance $\mathbf{B_T}$ from eye to the trunk at eye level with a tape or laser rangefinder and the angle A from eye to the top with a clinometer. Notice that the direction of the surrogate baseline differs from the direction of the top.
3. Use the following formula to approximate **H**, the height of the tree above eye level.

$$H \approx B_T \tan A$$

The correct baseline, **B**, is not known. However, if **C**, the horizontal distance of the top from the base, is less than 20% of $\mathbf{B_T}$, then the error in the real baseline **B** will be under 2% of $\mathbf{B_T}$. The resulting height error will be small. As an example, suppose $\mathbf{B_T}$ = 125.0 feet, **C** = 15 feet, and **A** = 47.7 degrees. **B** is computed as:

$$B = \sqrt{125^2 + 15^2} = 125.9$$

The computed height will be:

$$H \approx 125.0 \tan(47.7) = 137.4$$

The actual height is:

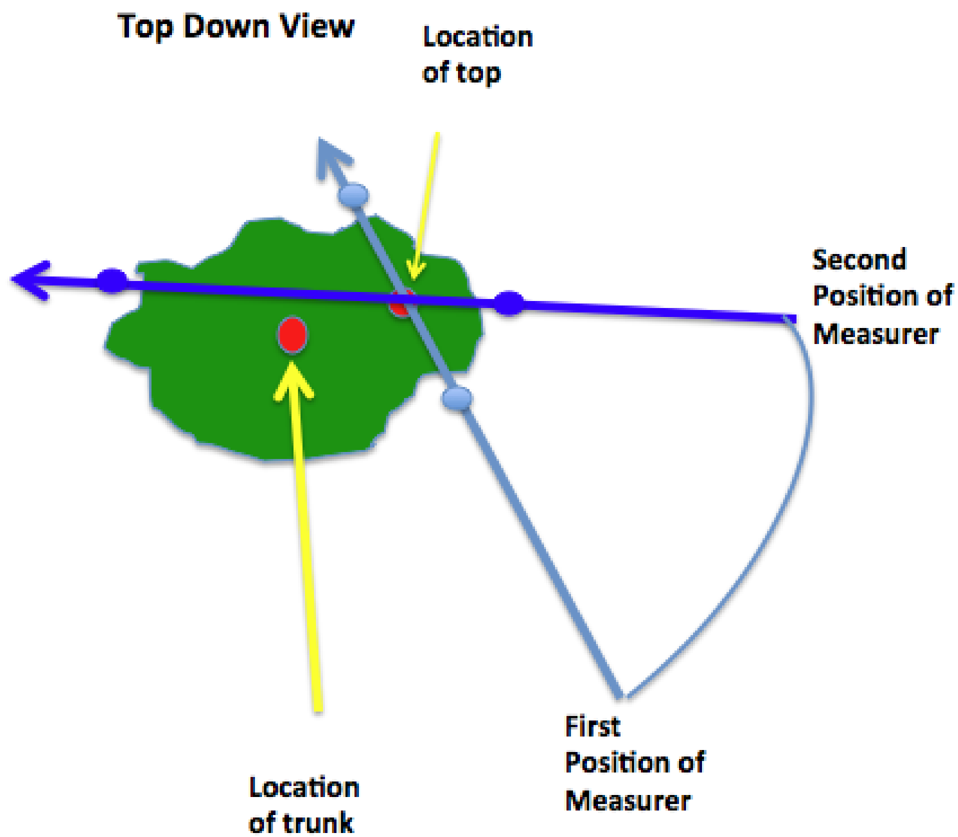
$$H = 125.9 \tan(47.7) = 138.4$$

The height error is 138.4 – 137.4 = 1.0 feet due to the baseline error. One foot is an acceptable error.

Measuring the Top of the Tree Using Cross-Triangulation

This two-person method is the Cadillac of the Tangent-based procedures when it can be applied. It allows you to locate the point on the ground directly beneath the top of a tree.

Diagram Illustrating Obscured Trunk at Eye Level



<u>Steps:</u>

1. Sight the top with a plumb bob and direct an assistant to walk toward the top carrying a tape. Insure that the assistant passes beneath the top, laying the tape on the ground after passing beyond the top.
2. Move to a second position between 30 and 60 degrees from the first. It can be more, but shouldn't be less than 30.
3. Sight the top again using the plumb bob and direct the assistant to walk toward the top carrying a second tape. Insure that the assistant passes beneath the top, laying the tape on the ground and across the first tape.
4. From either of the sighting locations, measure the horizontal distance to the point of intersection of the tapes. This is a valid baseline for the top of the tree from the chosen sighting position at eye level.
5. Using a clinometer, measure the angle from eye to top and use the previously given formula for computing height by the Tangent Method.

Cross-triangulation is labor intensive and cannot be effectively performed without two people. Its biggest drawback is identifying the same point in the crown from the two locations. As you move around the tree, different points in the crown come into or exit the measurer's view. If there is a lot of surrounding vegetation, you may not be able to locate two spots that are sufficiently separated to lay out the crossing paths.

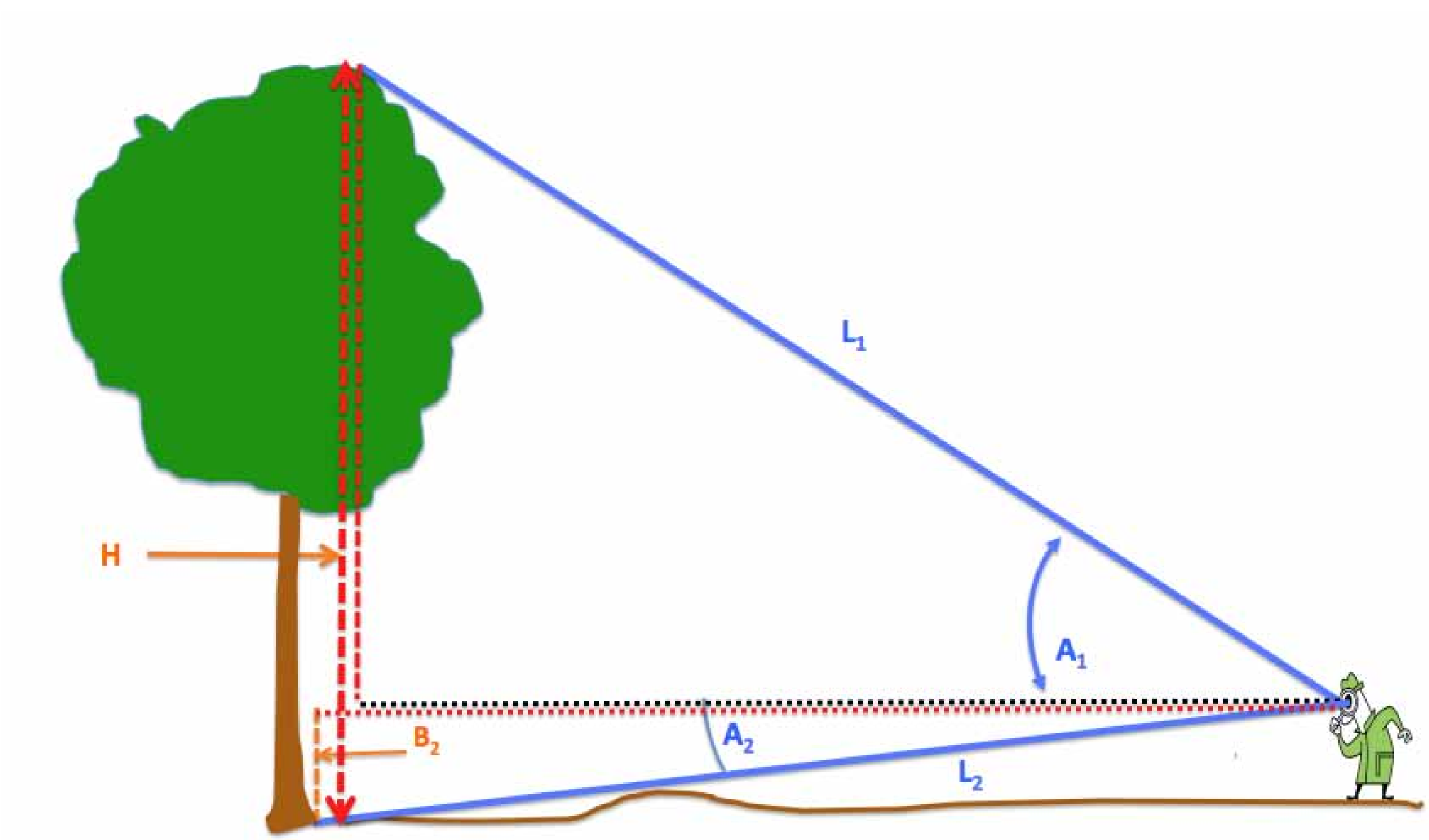
Sine Method – the Preferred Method

American Forests requests State Big Tree Coordinators and Certifiers use this method when at all possible. It is the official method for National Cadre members. It became practical with the introduction of infrared laser rangefinders. The Sine Method is the simplest and most direct way to measure tree height from the ground when the top and base can be seen by the infrared laser.

It may take you a little time to locate the tiptop of a complex crown, but that time is usually measured in minutes. Once you locate the top from a spot where the base is also visible, the laser and clinometer measurements, the calculations, and recording the results should take about two minutes.

As your skills develop using high performance, accurately calibrated equipment, you should be able to obtain results accurate to +/- 2 feet or better, regardless of where the top of a tree is in relation to the base.

Diagram for Sine Method



Steps:

1. Measure distance from eye to top with a laser rangefinder. Call this distance $\mathbf{L_1}$.
2. Measure distance from eye to base with a laser rangefinder. Call this distance $\mathbf{L_2}$.
3. Measure angle from eye to top with a clinometer. Call this angle $\mathbf{A_1}$.
4. Measure angle from eye to base with a clinometer. Call this angle $\mathbf{A_2}$.
5. Define the Height from base to top as **H**.
6. Apply the following formula:

$$H = L_1 \sin A_1 - L_2 \sin A_2$$

Angles above eye level are positive and angles below eye level are negative.

As an example, suppose the $\mathbf{L_1}$ = 175.5 feet, $\mathbf{L_2}$ = 115.0 feet, $\mathbf{A_1}$ = 38.9 degrees, and $\mathbf{A_2}$ = -7.7 degrees. The height is 125.6 feet.

$$H = 175.5\sin(38.9) - 115.0\sin(-7.7) = 125.6$$

Note that in the diagram, the trunk does not figure into the Sine Method. If this seems counter-intuitive, remember, a tree's height is the vertical distance between two horizontal planes: the upper plane contacts the tree's tiptop, and the lower plane passes through the mid-slope of the base. If these two contact points are visible, accurate heights can be easily obtained with little or no view of the rest of the tree. Forget the trunk when measuring height with Sine.

As with all techniques, the Sine Method has its challenges. Visibility to the top or base of the tree can be a problem. Laser shots aimed toward the target through leaves and twigs may hit an intervening obstacle. However, with experience, you will learn how to "thread the needle," and to recognize what would be a reasonable value for the target as it appears.

Sine Method Using Advanced Hypsometers

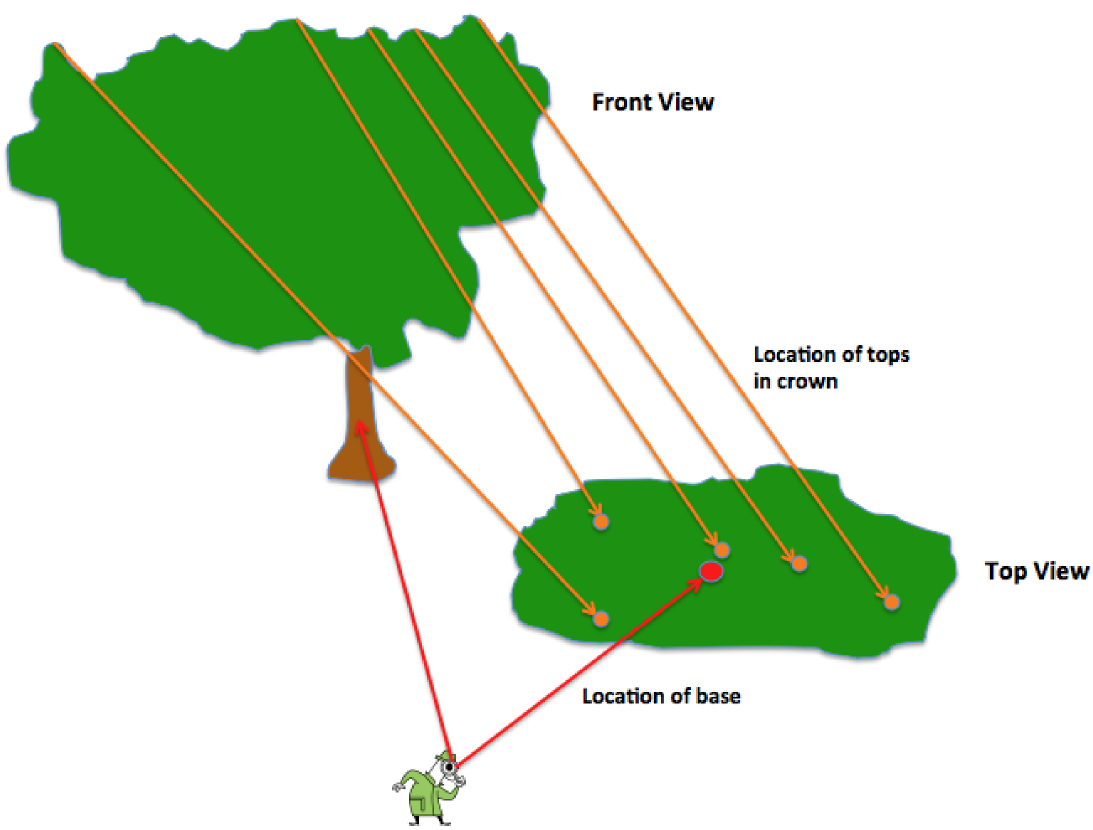
Advanced hypsometers employ the Sine Method under one name or another. It is a 2-point routine, often called the Missing Line Routine.

The advantage of the 2-point routine is that the instrument does all the work. The top height above eye level and below are automatically added together for you. However, once the initial shot is taken, you can usually back up and shoot again to insure that the intended target has been hit. The same capability should exist for the second shot, i.e. you should be able to back up and repeat it as many times as desired, before completing the routine. It may take several tries at both the top and bottom before you feel confident of the result.

Sine Method Used to Locate Highest Point Among Competing Tops

Across most of the Eastern United States (much less so in the Western U.S.), deciduous trees predominate. Champion Trees often exhibit broad crowns and some are in locations where there is dense canopy cover. It can be a challenge to locate the highest twig of the tree. From a distance, it is difficult to visually discern the relative distances between the various twigs, even with the optics of hypsometers. The Sine Method allows us to find which of several twigs is the highest before doing the measurement to the base.

Diagram for Locating the Top



Steps:

1. Starting from one side of the crown, choose a convenient top. Shoot the distance with a laser rangefinder and take the angle with a clinometer.

2. Compute the height of that top using the sine formula.

3. Choose another candidate and shoot the distance. If the top appears to be at about the same angle, but the distance is closer, stop and go to another candidate in the direction of left to right (or vice versa, if you started on the right side of the crown). If the distance is farther away, shoot the angle and compute the height. If the height is greater, that becomes the number to beat.

4. Tops that are farther away, but at a slightly lower angle, can be higher. Look for distant tops buried in the crown.

5. The farther away from the center of the crown, the less likely a top will be the highest for younger trees. But the crowns of older trees become increasingly asymmetrical, leading to high points that are increasingly horizontally separated from the trunk.

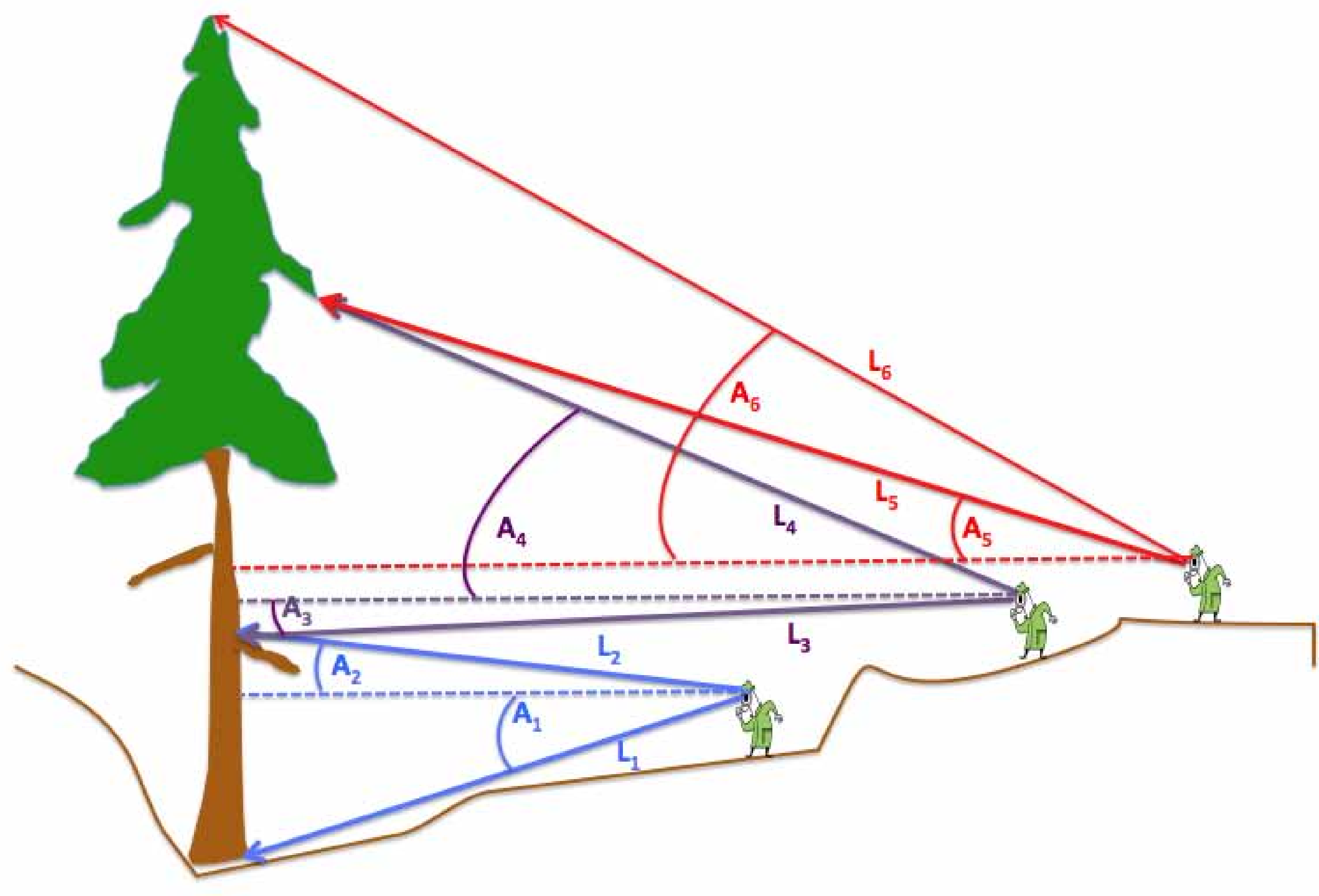
6. Keep your eye in the same horizontal plane during the search.

7. After the highest top has been found, complete the process by applying the Sine Method to the base and combining the results.

Sine Method Using Sections

As mentioned above, in dense forest you may not be able to see the top and/or base of a tree from a single location. In these cases, try to divide the tree into sections, with each section treated as a separate tree and visible from a different location. See the diagram below. Red arrows define one section of the tree, purple a second, and blue a third.

Diagram of Sine Method Using Sections



Steps:

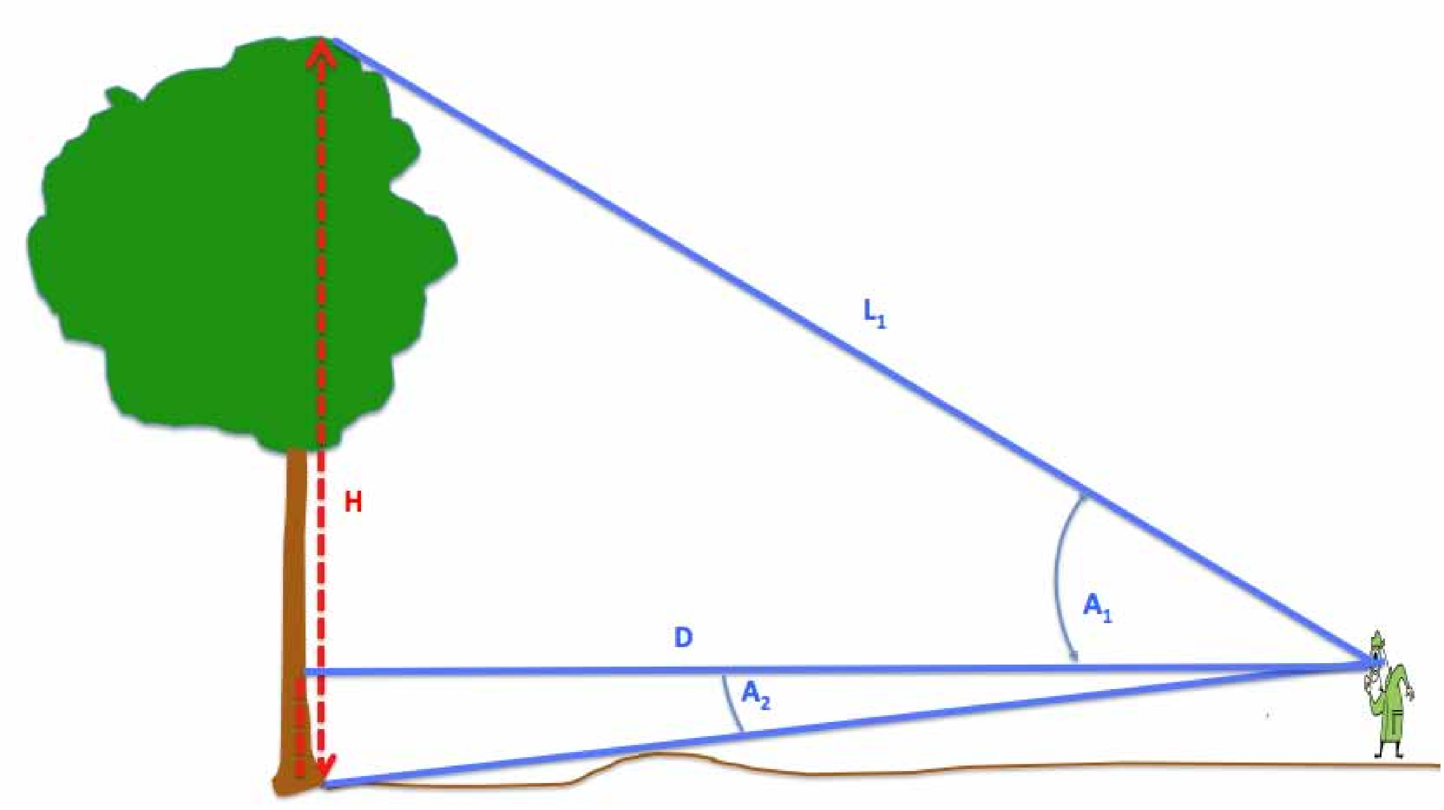
1. Find a location where the base up to a distinctive feature can be seen and measure the intervening height.
2. From the distinctive feature find another location where it can be seen up to another point. Measure the interval.
3. Repeat this sectioning process as many times as necessary.

The assumption we make is that these sections can only be seen from different locations. You are “seeing” the tree in sections, measuring them individually, and adding the sections together.

Sine-Tangent Method

If the top of a tree can be 'seen' by a laser rangefinder or hypsometer, but the base can't because of intervening vegetation, it may still be possible to see the base with the eye. If so, a clinometer can be used to measure the base angle and a combination of Sine and Tangent Methods used for the tree: Sine to the top and Tangent to the base.

Diagram for Sine-Tangent Method



Steps:

1. Measure distance from eye to top with a laser rangefinder. Call this distance $\mathbf{L_1}$.
2. Measure level distance from eye to the trunk with a laser rangefinder. Call this distance **D**.
3. Measure angle from eye to top with a clinometer. Call this angle $\mathbf{A_1}$.
4. Measure angle from eye to base with a clinometer. Call this angle $\mathbf{A_2}$.
5. Define the Height from base to top as **H**.
6. Apply the following formula

$$H = L_1 \sin A_1 - D \tan A_2$$

7. If the distance to the trunk is not level, define that distance as **B**.

8. Take the Angle $\mathbf{A_3}$ to the point on the trunk and apply the following formula to get the level distance **D**.

$$D = B\cos(A_3)$$

Angles above eye level are positive and angles below eye level are negative.

As an example, suppose $\mathbf{B_1}$ = 95.5 feet, $\mathbf{A_3}$ = -2.8 degrees, $\mathbf{L_1}$ = 160.5 feet, $\mathbf{A_1}$ = 41.3 degrees, and $\mathbf{A_2}$ = -10.3 degrees. The tree's height is 123.3 feet.

$$B = 95.5\cos(-2.8) = 95.4$$

$$H = 160.5\sin(41.3) - 95.4\tan(-10.3) = 123.3$$

The Sine-Tangent Method is an extremely valuable tool that is often overlooked because measurers are reluctant to mix methods. The point on the trunk being measured will be horizontally offset from the base if the trunk leans or is curved, but if the point of measurement isn't too high, trunk lean/curve can usually be ignored. The corresponding situation between the crown and trunk is a different matter.

Sine Method Using Red-Beam Construction Lasers ●

Although infrared lasers are the preferred tools for measuring distance to the tops and bases of trees, red-beam lasers have a role. Construction or carpentry instruments provide measurers with tools that can be used to check the accuracy of the infrared laser measurers, as well as measure shorter distances to exceptional levels of accuracy. For clear, flat targets, accuracies of +/-1.5 millimeters are attainable. The problem for longer distances is clarity of the target itself and the challenge of seeing the red beam. Special red goggles help slightly, but in bright light, the red beam cannot be seen. On cloudy days and in later afternoon, the beam is visible for greater distances.

For explanation purposes here, we assume the instrument has a built-in tilt sensor to allow the measurer to shoot the hypotenuse distance to a target and then display the vertical distance between the target and the instrument. This is simply the Sine Method applied to the target relative to the instrument (there is no eye piece to look through). This feature allows the instrument to serve as a conventional laser-clinometer combination. The weak links are its tilt sensor accuracy, narrow beam on wind-disturbed targets (twigs), and the visibility of the beam.

We assume the instrument has the following modes useful to tree-measurers.

1. Straight-line distance from instrument to target.

2. Vertical distance from target above or below instrument.

3. Horizontal distance of target from instrument.

4. Straight-line distance between two horizontally displaced targets. This mode corresponds to the Missing Line Routine that is built into advanced laser measuring devices.

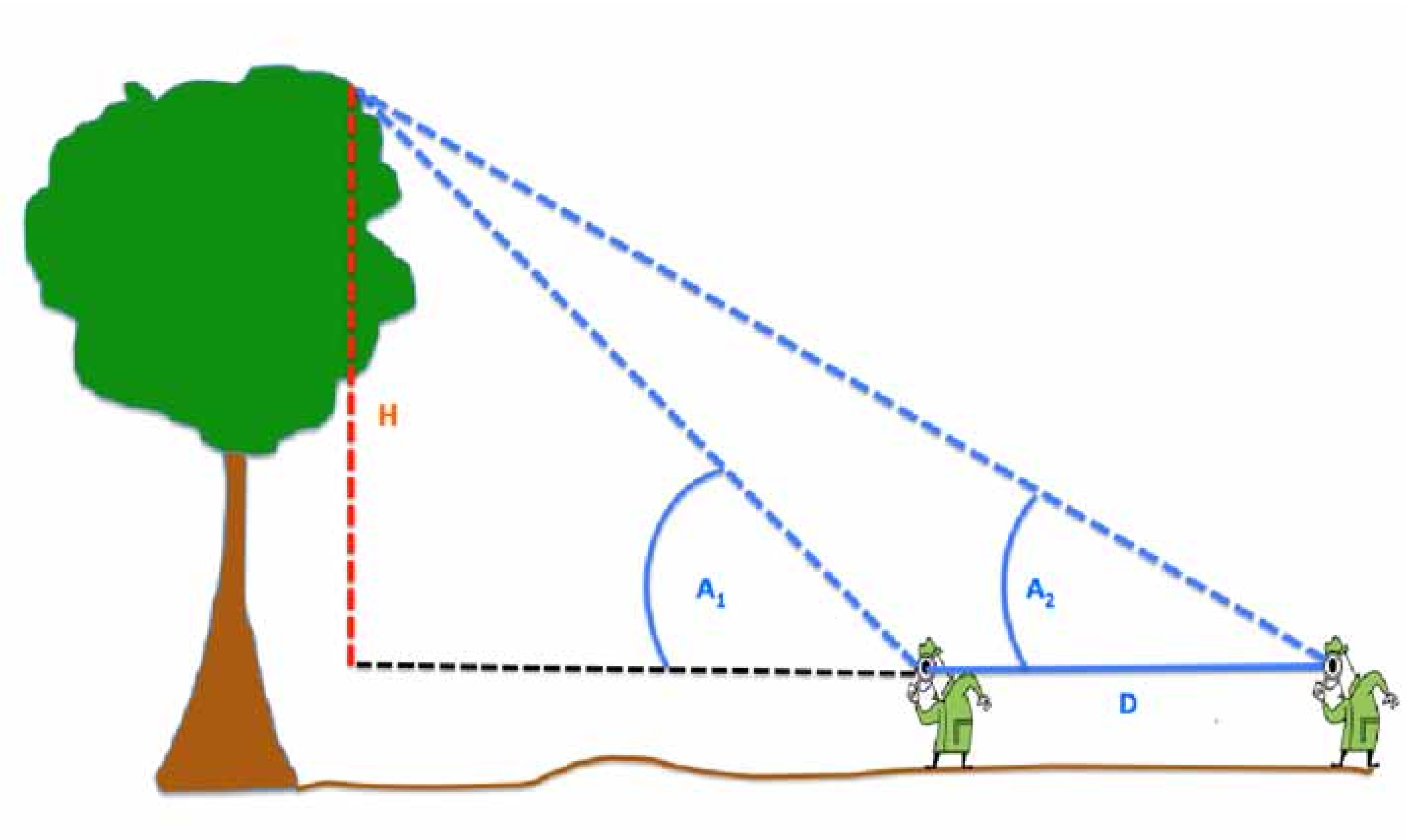
The availability of the above modes allows you to calculate the horizontal crown-to-trunk offset. You can calculate the horizontal separation between top and base by using first the horizontal distance mode to the top of a tree, then the horizontal distance mode to the base of the tree, and subtracting the two results.

External Baseline Methods for Level and Sloping Terrain

There are times when a measurer cannot successfully shoot through leaves and branches with a laser rangefinder, but can see the target visually. Also, the measurer may not have a laser, easy access to the trunk or points vertically beneath the top via a tape. The External Baseline Method provides a possible solution. For tape and clinometer users, the External Baseline Method eliminates the crown-to-base horizontal offset error, which has long been the most significant tree height measurement problem.

If we can measure the angles to the top of the tree from the ends of a horizontal baseline that points in the direction of the top, we can compute the height of the top above the eye at either end of the baseline. For sloping baselines, the calculation is more involved. The baseline does not extend to either the spot on the ground directly beneath the top of the tree or to the trunk. The baseline is external.

Diagram for External Baseline - Level



Steps:

1. Establish a level baseline **D** that points in the direction of the top of the tree. A baseline 25 to 50 feet is generally satisfactory. The baseline and the top should all lie in the same vertical plane.

2. From the forward end of the baseline, measure the angle $\mathbf{A_1}$ from the eye to the top.

3. From the rear end of the baseline, measure the angle $\mathbf{A_2}$ also from the eye to the top.
4. Calculate the height of the top above eye level using the following formula.

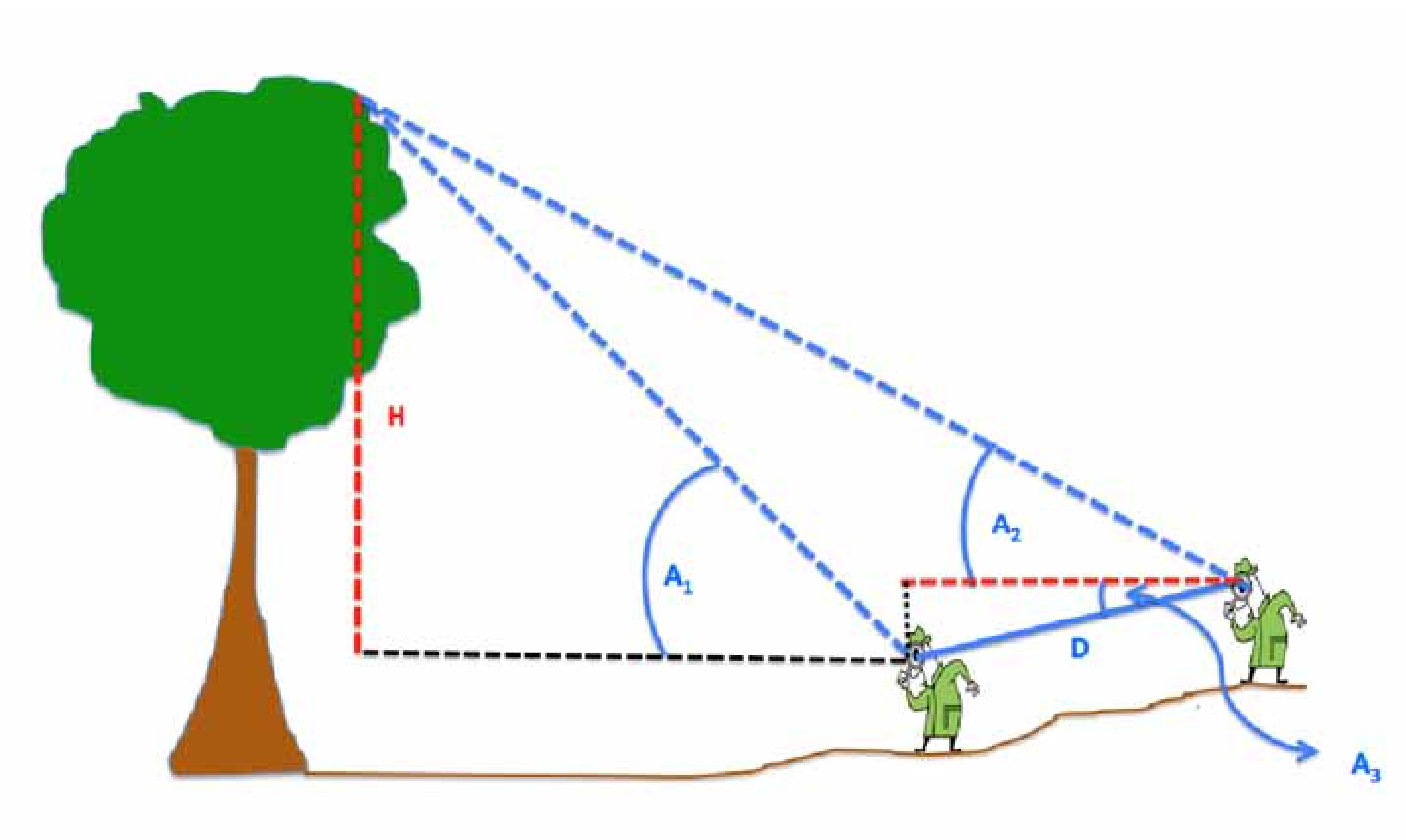
$$H = \frac{D\tan(A_1)\tan(A_2)}{\tan(A_1) - \tan(A_2)}$$

As an example, suppose **D** = 35 feet, $\mathbf{A_1}$ = 35.5 degrees, and $\mathbf{A_2}$ = 31.3 degrees. Then the tree's height **H** above eye level is 144.2 feet.

$$H = \frac{35.0\tan(35.5)\tan(31.3)}{\tan(35.5) - \tan(31.3)} = 144.2$$

A similar process can be used to get the height below eye level. Measuring the baseline distance and the two angles to a high level of accuracy is especially important to the external baseline method. Baseline errors should not exceed a tenth of a foot and angle errors should not exceed 0.2 degrees.

Diagram for External Baseline - Sloping



Steps:

5. Establish a baseline **D** that points in the direction of the top of the tree. A baseline 25 to 50 feet is generally satisfactory. The baseline and the top must all lie in the same vertical plane. For best results, the baseline should be sloping down from the distant to the forward points of measurement.

6. From the forward end of the baseline (closest to the tree), measure the angle $\mathbf{A_1}$ from the eye to the top.

7. From the rear end of the baseline, measure the angle $\mathbf{A_2}$ also from the eye to the top.

8. From the rear end of the baseline, measure the angle $\mathbf{A_3}$ from eye position to eye position to the front end of the baseline. This may require the use of a tripod or an assistant.

9. Calculate the height of the top above eye level at the nearer position using the following formula:

$$H = \frac{D\cos(A_3)\tan(A_1)\left[\tan(A_2) - \tan(A_3)\right]}{\tan(A_1) - \tan(A_2)}$$

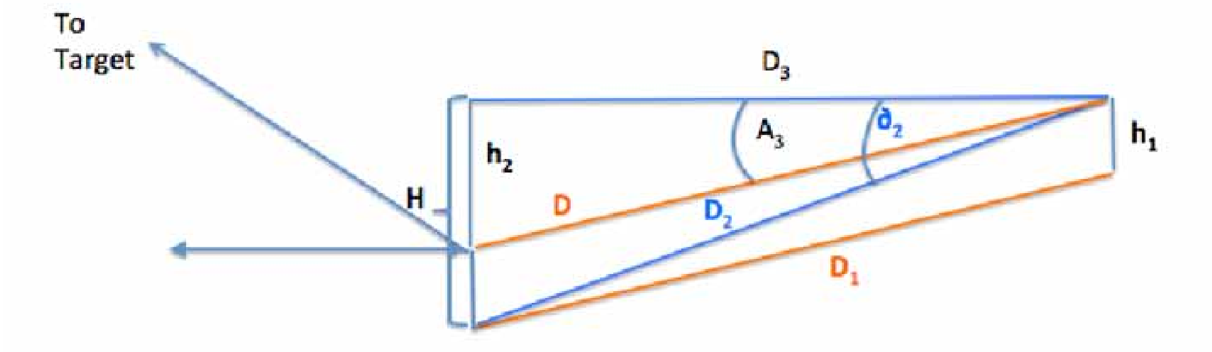
As an example, suppose **D** = 30.0 feet, $\mathbf{A_3}$ = -7.0 degrees, $\mathbf{A_1}$ = 38.5 degrees, and $\mathbf{A_2}$ = 35.1 degrees. The tree's height above eye level is 89.5 feet.

$$H = \frac{30.0\cos(-7.0)\tan(38.5)\left[\tan(31.1) - \tan(-7.0)\right]}{\tan(38.5) - \tan(31.1)} = 89.5$$

A similar process can be used to get the height below eye level. Measuring the baseline distance and the three angles accurately is even more important for the sloping external baseline situation than the level one because the extra variable $\mathbf{A_3}$ has been added.

If the measurer does not have a tripod, but does have accurate instruments, the length of the baseline and angle of the baseline from the more distant eye position to closer eye position relative to the target can be computed. The following diagram shows the variables and formulas.

Diagram for External Baseline - Sloping



$$D_3 = D_2 \cos(\partial_2)$$

$$H = D_2 \sin(\partial_2)$$

$$h_2 = H - h_1$$

$$A_3 = \tan^{-1}\left(\frac{h_2}{D_3}\right)$$

$$D = \frac{D_3}{\cos(A_3)}$$

D and $\mathbf{A_3}$ correspond to the same variables in the formula

$$H = \frac{D\cos(A_3)\tan(A_1)\left[\tan(A_2) - \tan(A_3)\right]}{\tan(A_1) - \tan(A_2)}$$

As an example, suppose $\mathbf{D_2}$= 37.5 feet, ∂ =-10.5 degrees, and $\mathbf{h_1}$ = -5.5. The negative values are below eye level. We want to compute D and $\mathbf{A_3}$.

The computations are:

$$D_3 = 37.5\cos(-10.5) = 36.872$$

$$H = 37.5\sin(-10.5) = -6.834$$

$$h_2 = -6.834 - (-5.5) = -1.334$$

$$A_3 = \tan^{-1}\left(\frac{-1.334}{36.872}\right) = -2.072$$

$$D = \frac{36.872}{\cos(-2.072)} = 36.896$$

This method is computationally intensive. In such cases, an Excel spreadsheet can be created to do the calculations. American Forests will have a series of such spreadsheets available for use by Cadre members. There are also smartphone apps available for download that can assist with calculations in the field.

However, if the measurer has a pole about eye level in height or with graduated marks, placing the pole in the ground at the forward location can work. A red beam construction laser comes in very handy in this method to measure distances very accurately. The weakness of the method is that it is more sensitive to angle and distance errors than the prior methods.

Summary to Height

It has long been assumed that traditional height measuring methods for timber management are sufficient for trees in big tree competitions. This has not proven to be the case, especially for trees that are huge or exhibit complex shapes. In the course of dealing with giants, such as the General Sherman Tree in Sequoia National Park which is the largest tree by volume in the world, measurers must use sophisticated techniques. Smaller trees can also exhibit highly complex shapes and also require advanced methods such as those described above.

CROWN SPREAD

Introduction to Crown Spread

The crown of a tree is arguably its most visible feature, especially when viewed from a distance. It often dwarfs the trunk and accounts for a significant part of the height. Of the three dimensions used in the champion tree formula, crown spread is the most difficult to accurately measure.

Following the layout for the other two dimensions, this section is organized into beginning, intermediate, and advanced topics. We highlight the beginning in green, the intermediate in blue, and the advanced in red.

Crown Spread

Below is a photograph of an American elm with a very balanced crown.

Crown spread is the horizontal separation of two points on opposite sides of the crown. The horizontal line joining the two points may or may not run through the trunk.

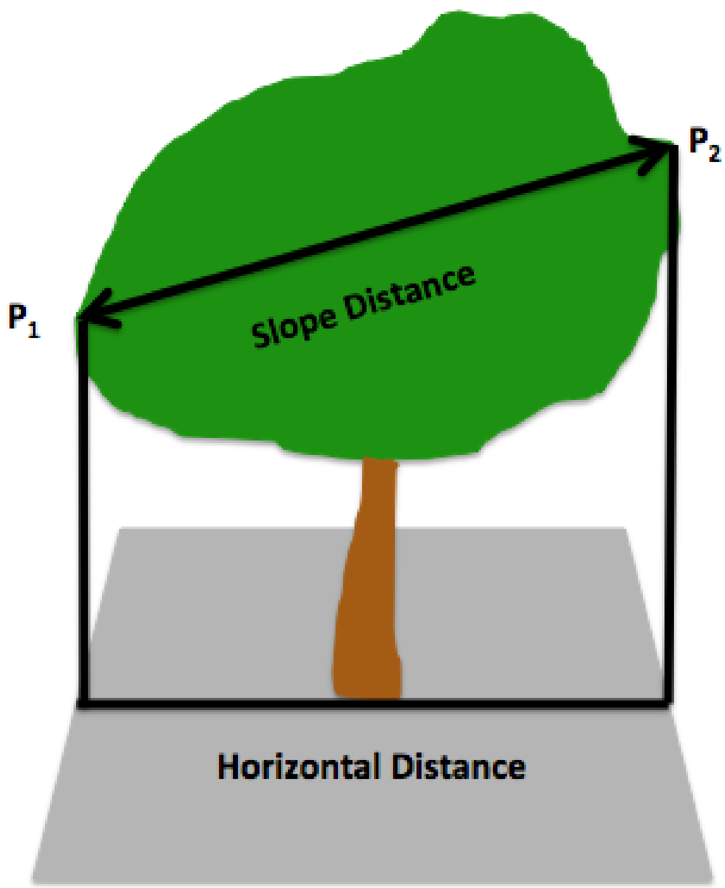
With this definition in mind, we offer three approaches to measuring crown spread: the 2-Axis Method, the Spoke Method, and Measuring from a Distance. The first two methods project the outline of the crown vertically onto the ground, or more precisely, onto a horizontal plane. The third projects the outline of the crown onto a vertical plane as seen from the side.

To work with the first two approaches, we use the drip-line. Picture water rolling off an umbrella, creating a visible line on the ground that follows the perimeter of the umbrella. We can follow a similar process to outline the crown of a tree.

But unlike the umbrella, the points that form the irregular path of the crown's outermost extensions come from different elevations. We want the horizontal distance between points on opposite sides of the crown to measure spread.

The diagram below illustrates this concept. **P_1** and **P_2** are the points representing an extension of the crown. The distance between these points is projected onto a horizontal plane.

Diagram of Horizontal Projection



When you cannot position yourself under the crown, you must use our third approach, which measures crown spread from a distance. This method makes use of the vertical plane as seen from the side, a camera's eye view, shown below.

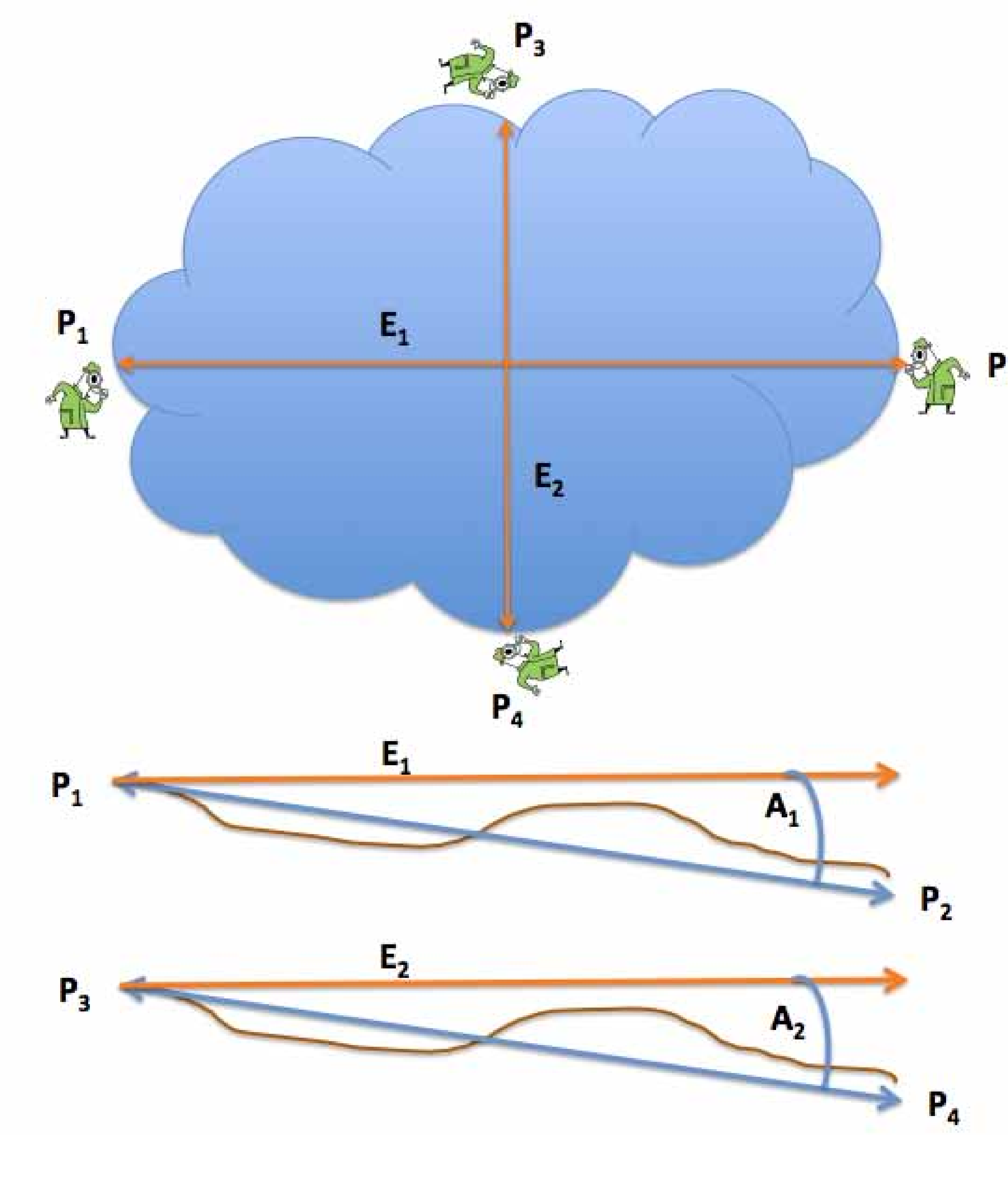
An American Sycamore

Axis Method

The simplest and quickest method of computing average crown spread is to take two measurements of the widest spreads at 90 degrees to one another as illustrated in the diagram on the next page. $\mathbf{P_1}$, $\mathbf{P_2}$, $\mathbf{P_3}$, and $\mathbf{P_4}$ represent the points at the extensions of the crown. $\mathbf{E_1}$ and $\mathbf{E_2}$ represent the horizontal distances between $\mathbf{P_1}$ and $\mathbf{P_2}$ and $\mathbf{P_3}$ and $\mathbf{P_4}$, respectively.

Note that the widest spread does not have to go through the trunk. Although that is a method that has been used traditionally, it is not the one that American Forests currently recommends.

Diagram of Horizontal Projection



The lower part of this diagram illustrates that the paths from **P_1** to **P_2** and **P_3** to **P_4** are slope distances. The orange lines are the horizontal distances we seek.

Steps:

1. Locate the longest crown spread by following the drip-line around the crown marking the spots on the ground directly beneath the ends of the longest extension. In the diagram these points are labeled $\mathbf{P_1}$ and $\mathbf{P_2}$.

2. Circle around 90 degrees to the path of $\mathbf{P_1}$ to $\mathbf{P_2}$ and find the longest crown extension. Mark the ends of this second extension. In the diagram, they are $\mathbf{P_3}$ and $\mathbf{P_4}$.

3. If the ground is level, measure the distance on the ground between $\mathbf{P_1}$ and $\mathbf{P_2}$, and similarly for $\mathbf{P_3}$ and $\mathbf{P_4}$.

4. 4. If the ground is not level, calculate the horizontal distance $\mathbf{E_1}$ equivalent to the distance $\mathbf{X} = \mathbf{P_1 P_2}$ and $\mathbf{E_2}$ equivalent to $\mathbf{Y} = \mathbf{P_3 P_4}$ using the formulas below. (See lower part of the diagram.)

$$E_1 = X \cos A_1$$

$$E_2 = Y \cos A_2$$

5. Calculate the average of $\mathbf{E_1}$ and $\mathbf{E_2}$. If $\mathbf{S}$ = the average spread, then

$$S = \frac{E_1 + E_2}{2}$$

6. In the lower part of the diagram, the ground is shown as sloping downward from left to right. However, the formulas work regardless of the direction of slope.

For example, suppose the distance $\mathbf{X}$ = 97.0 feet, $\mathbf{A_1}$ = 5.5 degrees, $\mathbf{Y}$ = 78.5 feet, and $\mathbf{A_2}$ = 4.5 degrees. Then $\mathbf{E_1}$ = 96.6 feet, $\mathbf{E_2}$ = 78.3 feet, and $\mathbf{S}$ = 87.5 feet.

$$E_1 = 97.0 \cos\left(5.5\right) = 96.6$$

$$E_2 = 78.5 \cos(4.5) = 78.3$$

$$S = \frac{96.6 + 78.3}{2} = 87.5$$

(American Forests Crown Spread Tree Points
0.25 x 87.5 = 21.9, rounded down to 21)

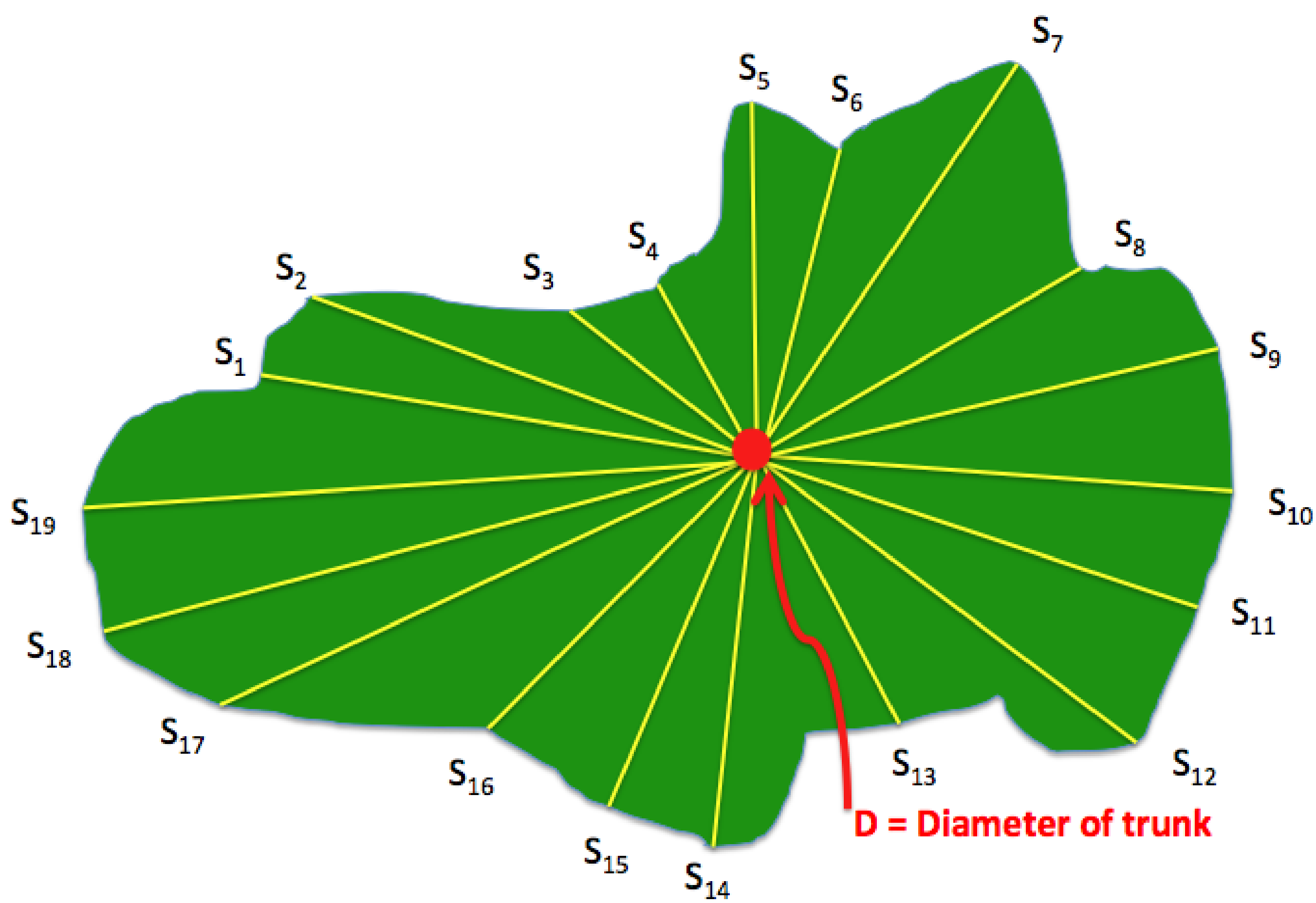
Spoke Method

Trying to establish a drip-line path by looking up into outstretched branches is not easy, and banking on two measurements to capture the average spread leaves a lot of room for error. Also, if a crown is highly irregular in shape, the 2-Axis Method may not be sufficiently accurate. The Spoke Method provides more insurance.

Imagine the perimeter of a bicycle wheel bent out of shape in several places. The wheel represents the drip-line of the crown of a tree. On the wheel, the spokes measure the distance to the hub. Let the trunk play the role of the hub. If we were to calculate the average spoke length, double it, and add the diameter of the hub, we would have an average distance across the wheel. In the diagram, the variable sequence $\mathbf{S_1}$, $\mathbf{S_2}$, $\mathbf{S_3}$, ..., identifies the spokes. We take the corresponding vertical angles of the spokes to a common height on the trunk, since the ground may not be level. Ideally a ribbon is wrapped level around the trunk at a convenient height to present a clear target.

Each ($\mathbf{S_i}$, $\mathbf{A_i}$) pair of values (slope distance and angle) allows us to compute the equivalent horizontal distance, which we will call $\mathbf{R_i}$.

Diagram of Horizontal Projection



$$A_s = 2\left[\frac{S_1 + S_2 + S_3 + \ldots + S_n}{n}\right] + D$$

Steps:

1. Locate the drip-line and follow it around the crown.

2. From a sample number of **n** locations, measure the distance from the eye to the trunk at a pre-determined height. Define these distances as $\mathbf{S_1}$, $\mathbf{S_2}$, $\mathbf{S_3}$, ..., $\mathbf{S_n}$. Measure the corresponding vertical angles with a clinometer as values of $\mathbf{A_1}$, $\mathbf{A_2}$, $\mathbf{A_3}$, ..., $\mathbf{A_n}$. Remember, the $\mathbf{S_i}$ values (where the subscript stands for any integer from 1 to n) are slope distances from eye to trunk. To get the corresponding horizontal distances use the formula:

$$R_i = S_i \cos A_i$$

3. Compute the average of the horizontal distances $\mathbf{R_i}$, double the average and add the diameter of the trunk. If **d** = diameter and **W** defines the average crown width, compute **W** using the compact formula below.

$$W = 2\left(\frac{R_1 + R_2 + R_3 + ... + R_n}{n}\right) + d$$

4. Use a densitometer or clinometer to locate the edge of the crown as the tree is circled. These instruments allow you to identify the position that is vertically overhead.

5. There is no maximum number of radii or spokes required. However, four is the logical minimum. Eight is a good compromise, but the best approach is to measure each conspicuous limb extension.

As an example, suppose we have the following measurements:

$\mathbf{S_i}$ (Distance in Feet)	$\mathbf{A_i}$ (Angle in Degrees)
35.5	-3.5
41.7	-2.8
38.2	-5.6
46.4	4.3
34.7	2.9
39.1	1.8

$$R_1 = 35.5\cos(-3.5) = 35.4$$

$$R_2 = 41.7\cos(-2.8) = 41.7$$

$$R_3 = 38.2\cos(-5.6) = 38.0$$

$$R_4 = 46.4\cos(4.3) = 46.3$$

$$R_5 = 34.7\cos(2.9) = 34.7$$

$$R_6 = 39.1\cos(1.8) = 39.1$$

$$W = 2\left[\frac{35.4 + 41.7 + 38.0 + 46.3 + 34.7 + 39.1}{6}\right] = 78.4$$

The average crown spread from the 6 measurements is 78.4 feet.

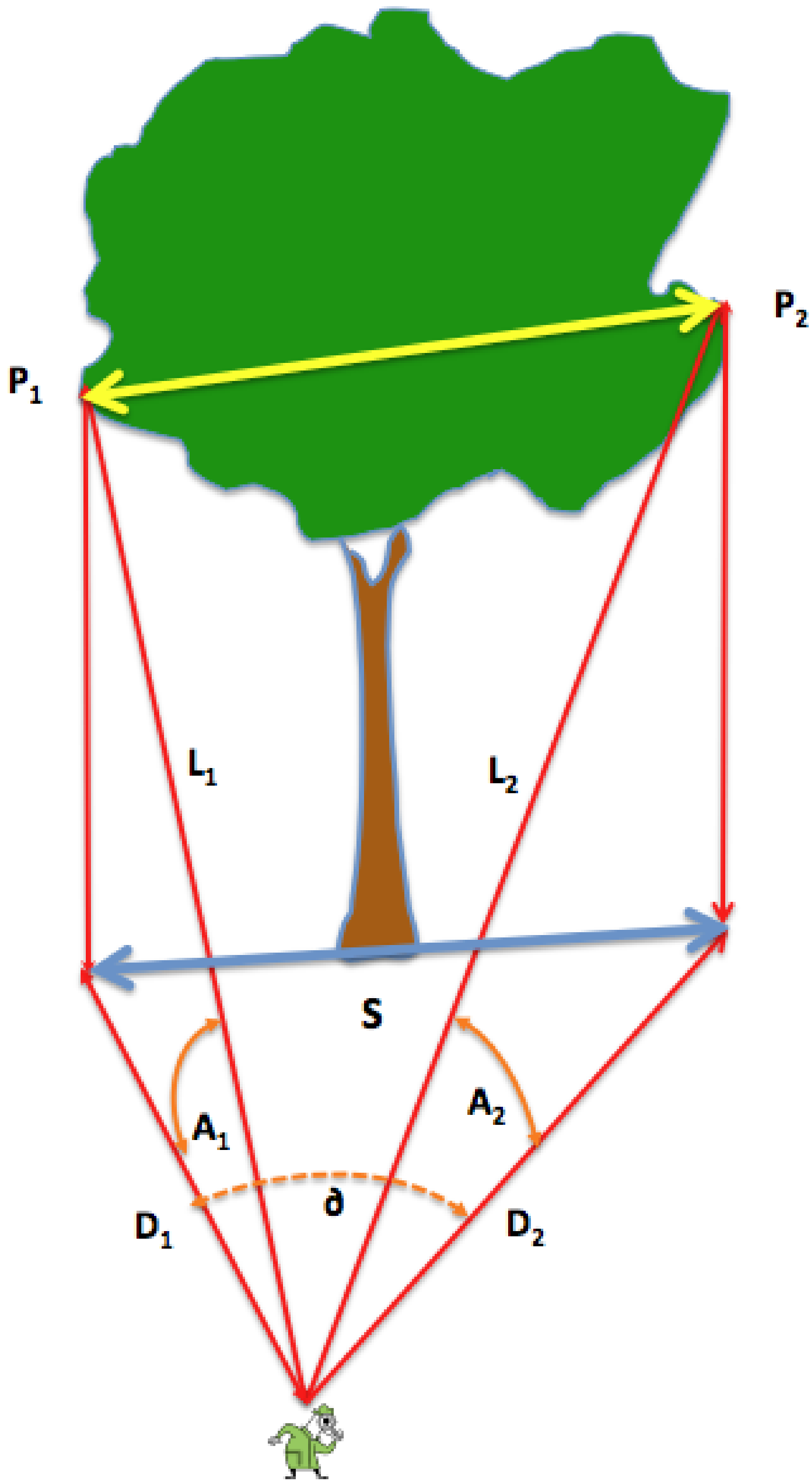
(American Forests Crown Spread Tree Points
0.25 x 78.4 = 19.6, rounded down to 19)

Measuring from a Distance — Method #1: Azimuth Difference Crown-Spread Method ●

What if the measurer does not have direct access to the drip-line? This occurs to one degree or another for many crown-spreads. The next method employs the law of cosines to measure spread as seen from a distance. You need a laser rangefinder, clinometer, and a device such as a compass or theodolite to measure angles in the horizontal plane. You calculate horizontal angles as the difference in azimuths. For example, if the first azimuth is 135.5 degrees and the second is 141.6 degrees, the horizontal angle is 141.6 – 135.5 = 6.1 degrees. If the first azimuth is 350 degrees and the second is 10 degrees, then the horizontal angle is (360-350) + 10 = 20 degrees.

This method computes the third side of a plane triangle from two sides and the included angle. The actual triangle is formed by projecting three points onto a horizontal plane. One point represents the measurer's eye, the second point corresponds to the tip of the foliage on the left side of the crown projected down to eye level, and the third point corresponds to the tip of the foliage on the right side projected down to eye level. The horizontal distance between these projected points is a measure of crown width.

Diagram of Azimuth Difference Crown-Spread Method



Steps:

1. Measure the distance $\mathbf{L_1}$ and vertical angle $\mathbf{A_1}$ to the crown point $\mathbf{P_1}$ using a laser rangefinder and clinometer.

2. Measure the distance $\mathbf{L_2}$ and vertical angle $\mathbf{A_2}$ to the crown point $\mathbf{P_2}$.

3. With a compass or a theodolite, measure the azimuths of $\mathbf{P_1}$ and $\mathbf{P_2}$.

4. Compute the difference between azimuths for $\mathbf{P_2}$ and $\mathbf{P_1}$. This will give you the horizontal angle ∂, which is the same as the horizontal angle between $\mathbf{D_1}$ and $\mathbf{D_2}$ in the diagram above. If $\mathbf{A_{z1}}$ corresponds to $\mathbf{P_1}$ and $\mathbf{A_{z2}}$ corresponds to $\mathbf{P_2}$, then compute ∂ by the following method:

   The symbols **| |** represent magnitude of the included value, i.e. absolute value. For example, **| -3 | = 3**. The algebraic sign is dropped.

   If $|A_{z2} - A_{z1}| > 180$ then $\partial = 360 - A_{z1} + A_{z2}$
   If $|A_{z2} - A_{z1}| < 180$ then $\partial = A_{z2} - A_{z1}$

5. Compute the horizontal distance **S** between $\mathbf{P_1}$ and $\mathbf{P_2}$:

$$D_1 = L_1 \cos A_1$$

$$D_2 = L_2 \cos A_2$$

$$S = \sqrt{D_1^2 + D_2^2 - 2D_1D_2\cos\partial}$$

6. No assumption is made about the orientation of **S** relative to the line of sight other than it is in a horizontal plane. Nor is there any assumption about where the trunk is relative to **S**. The method measures horizontal distance between two points, as viewed from a distance, regardless of where they lie relative to the trunk or other features of the tree.

7. This method can be repeated from different locations circling the tree and an average taken of the **S** values.

   As an example, suppose $\mathbf{A_{z1}}$ = 325.2 degrees, $\mathbf{A_{z2}}$ = 2.1 degrees, $\mathbf{L_1}$ = 130.5 feet, $\mathbf{L_2}$ = 118.2 feet, $\mathbf{A_1}$ = 22.2 degrees, and $\mathbf{A_2}$ = 31.6 degrees. Then we have:

$$\partial = |325.2 - 2.1| = 323.1 > 180$$

$$\partial = 360 - 323.1 + 2.1 = 39.0$$

$$D_1 = 130.5\cos(22.2) = 120.8$$
$$D_2 = 118.2\cos(31.6) = 100.7$$

$$S = \sqrt{120.8^2 + 100.7^2 - 2(120.8)(100.7)\cos(39)} = 76.3$$

Because this is an unorthodox method, we offer additional comments. The Azimuth Difference Crown Spread method captures the horizontal separation of two points in the crown. It isn't the width of the equivalent silhouette since it takes crown depth into consideration. Silhouette width is strictly two-dimensional.

Azimuth Difference Crown Spread is simple to do using an instrument with a compass and missing line routine. With these instruments set to missing line and on the horizontal distance return, you shoot to $\mathbf{P_1}$ followed by $\mathbf{P_2}$ and read the answer on the display. The challenge lies in hitting the targets when there is clutter in the line of sight or multiple targets around the twig being shot. What often appears to be a distinct spot from a distance may be several clusters of leaves or needles positioned at different distances.

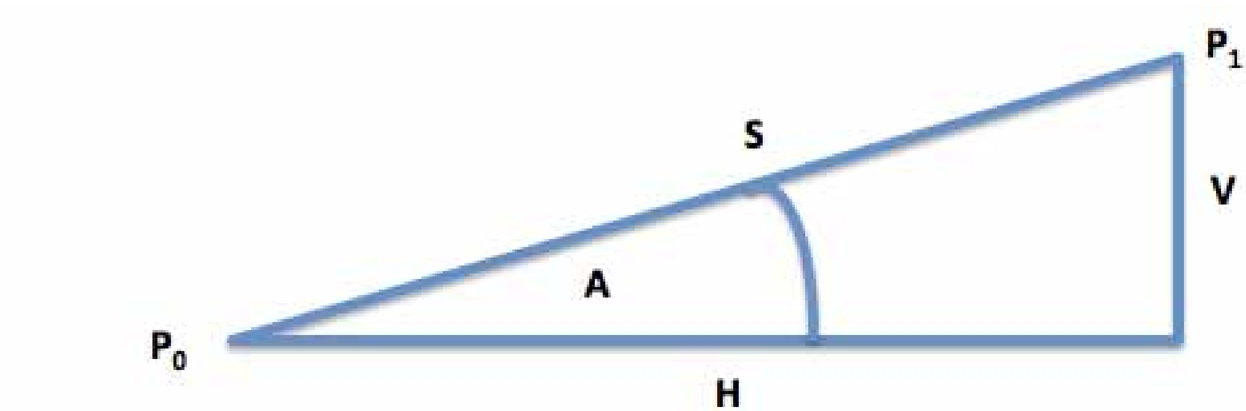
Measuring from a Distance — Method #2: External Baseline Crown Spread Method ●

The last method we will present follows the concept of the Azimuth Difference technique, i.e. crown width is being measured from a distance. While the method is computationally complicated, it does not require a horizontal angle-measuring device, which is often the weak link in the process. Five horizontal distances are used to compute a sixth: the horizontal distance between two points, one on the left side of the crown (from the viewer's perspective) and one on the right.

This means that the measurer will need to take 9 or 10 measurements (if using a laser and clinometer), or 5 measurements (if using a hypsometer with a horizontal distance mode), and enter them into a program to automatically calculate D. With the use of a spreadsheet available from American Forests, the process is very easy.

We begin by reviewing the components of distance between two points.

Diagram of Distance Components Between Two Points



In the above diagram, three distances can be associated with the line $\mathbf{P_0P_1}$. The linear path **S** is often called the slope distance. The vertical separation between $\mathbf{P_0}$ and $\mathbf{P_1}$ is defined as **V** and the horizontal separation is defined as **H**. The vertical angle of $\mathbf{P_1}$ relative to $\mathbf{P_0}$ is defined as **A**. The triangle **SVH** is a right triangle by virtue of the fact that **H** and **V** are at a right angle to one another.

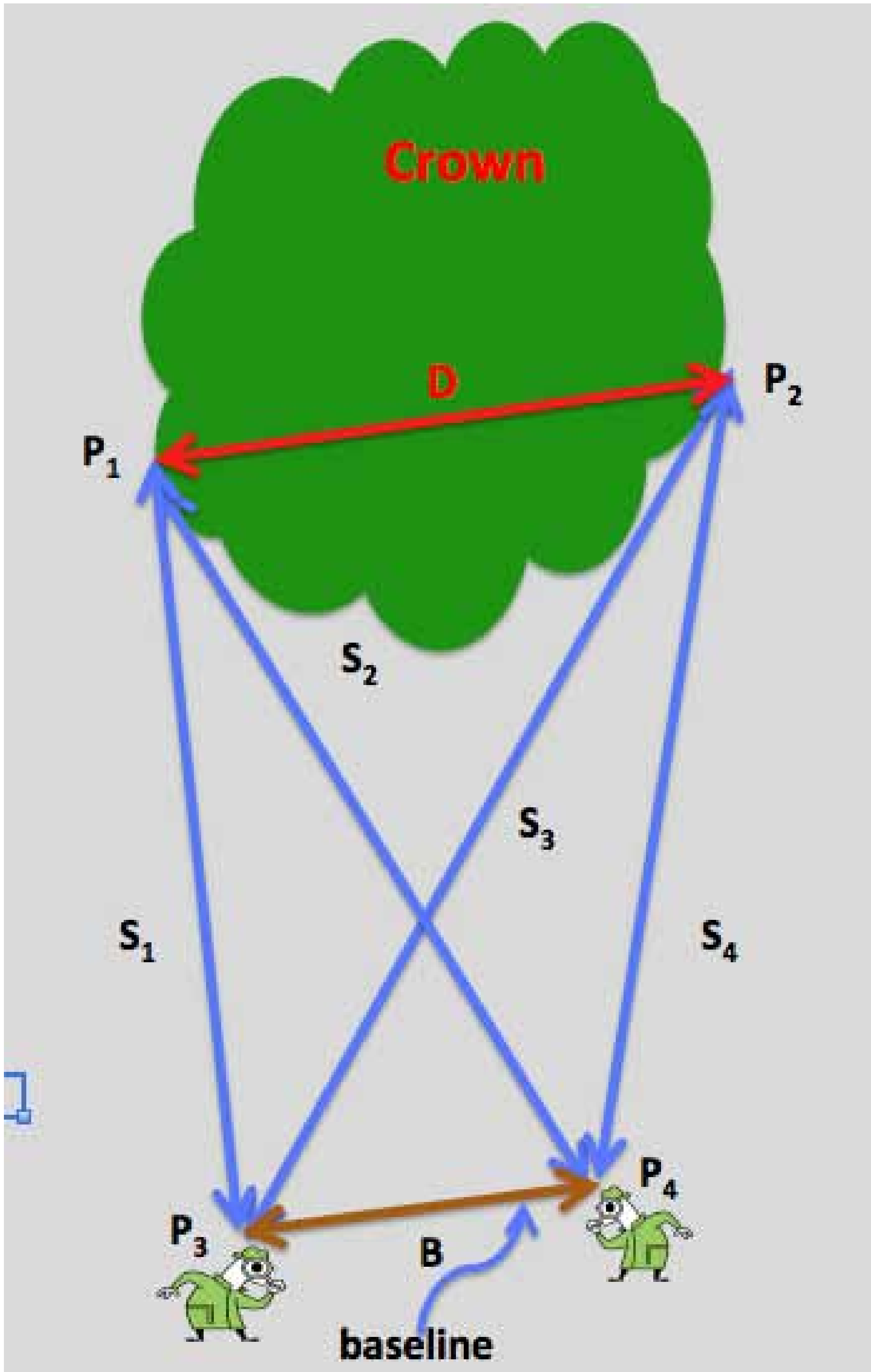
If we know **S** and **A** (laser rangefinder and clinometer), we can use the following relationships to compute **V** and **H**:

$$V = S\sin A \quad \text{and} \quad H = \cos A$$

We measure vertical distances for tree height, but horizontal distances for crown-spread.

Note that in the following diagram, the distances denoted by $\mathbf{S_i}$ are horizontal, not slope. The view is top down.

Diagram for External Baseline Crown Spread Method



Steps:

1. Establish two points $\mathbf{P_3}$ and $\mathbf{P_4}$ external to the tree roughly parallel to the vertical plane of the crown's silhouette. The length **B** of $\mathbf{P_3P_4}$ is employed as an external baseline.

2. P_1 and $\mathbf{P_2}$ are points representing the maximum crown extension from the left to the right edges of the crown as seen from the baseline **B**.

3. S_1 is the horizontal distance from $\mathbf{P_3}$ to $\mathbf{P_1}$. $\mathbf{S_2}$ is the horizontal distance from $\mathbf{P_4}$ to $\mathbf{P_1}$. Similarly $\mathbf{S_3}$ measures $\mathbf{P_3}$ to $\mathbf{P_2}$, and $\mathbf{S_4}$ measurers $\mathbf{P_4}$ to $\mathbf{P_2}$.

4. The diagram shows the horizontal angles between the sides of the triangles formed by the S_i and **B** values. For example, A_1 + A_2 is the angle between S_1 and **B**, and A_3 + A_4 is the angle between S_4 and **B**.

5. We repeatedly apply the law of cosines to get **D**, the horizontal distance between P_1 and P_2.

$$A_1 + A_2 = \cos^{-1}\left(\frac{S_1^2 + B^2 - S_2^2}{2S_1B}\right)$$

$$A_2 = \cos^{-1}\left(\frac{S_3^2 + B^2 - S_4^2}{2S_3B}\right)$$

$$A_1 = (A_1 + A_2) - A_2$$

$$D = \sqrt{S_1^2 + S_3^2 - 2S_1S_3\cos A_1}$$

As an example, suppose the baseline and crown distance measurements are as follows: S_1 = 105.5 feet, S_2 = 115.7 feet, S_3 = 118.2 feet, S_4 = 101.3 feet, and **B** = 28.5 feet.

$$A_1 + A_2 = \cos^{-1}\left(\frac{105.5^2 + 28.5^2 - 115.7^2}{2(105.5)(28.5)}\right) = 103.9$$

$$A_2 = \cos^{-1}\left(\frac{118.2^2 + 28.5^2 - 101.3^2}{2(118.2)(28.5)}\right) = 47.8$$

$$A_1 = (103.9) - 47.8 = 56.1$$

$$D = \sqrt{101.5^2 + 118.2^2 - 2(101.5)(118.2)\cos(56.1)} = 104.4$$

The **cos⁻¹** symbol stands for the inverse or arccosine function. Excel names this function **ACOS**. It is the angle that corresponds to the ratio of the adjacent side of the triangle to hypotenuse supplied inside parenthesis after the **cos⁻¹** symbol.

Remember that $\mathbf{S_1}$, $\mathbf{S_2}$, $\mathbf{S_3}$, $\mathbf{S_4}$, and **B** are all horizontal distances. A simple way to compute **B** is to stand at one end of the baseline and shoot the distance and angle from the eye to the other end and apply the cosine formula.

Densiometers and Densitometers

Densiometers (a hemispherical mirror, divided into quadrants for estimations of percent cover, as in crown spread), and densitometers (for example, the GRS densitometer, which uses vertically and horizontally aligned levels to fix a point directly overhead) can be used to more accurately fix the crown perimeter.

Future Directions

Aerial photogrammetry has been employed with some success in measuring crown spread, but much more must be known about the relationship of the camera optics and the forest surface.

Less subject to lens aberration in aerial photogrammetry, satellite imagery has the advantage of providing a synoptic view, with surprisingly high resolution. It is remarkably distortion free, if properly registered. Sub-meter resolution is common, and better resolution is available in urban areas. While many sources are now available, Google has made imagery available nearly worldwide for little more than the cost of the software (a free version is available, but with less measurement capability).

Summary to Crown Spread

Crown spread is the most difficult of the three measurements to take. Average crown spread has a weight of $^1/_4$ in the champion tree formula, which greatly reduces its impact. It is often simply estimated by eye because of limited access to the drip-line and/or obstacles to identifying the outermost crown extensions. However, National Cadre members and other experts have additional tools that are not likely to be employed at the state level because of their computational complexity.

APPENDIX I

Tree Definition, Implications for the National Big Tree Progam, and Pith Analysis

Introduction

What defines a tree? When we see a tree with more than one trunk, are we seeing just that — a tree with multiple trunks — or could we be seeing more than one tree? How do we treat complex forms for the purpose of the National Big Tree Program? How do we measure them?

Formation of a Tree

SPROUTING

In a survey of several plant physiology texts and peer-reviewed articles (see Literature Cited section), and supported by information gathered in university-level ecological tree physiology texts, we have assembled a series of general views or assumptions about how trees grow in temperate climates: gymnosperms (coniferous) and angiosperms (deciduous)

First, turning to physiological tree ecology, we consider how most angiosperms and some gymnosperms sprout. Here, quoting Ng 1999, "A tree can be defined as a plant that, when undisturbed, develops a single, erect wood trunk. Brown 1967 and Zimmermann and Brown 1974 explain that the form in a tree "...is controlled by growth regulators that emanate from the distal tip of a shoot, through the loosely defined mechanisms of apical dominance and apical control. Which is to say, the tree's primary response is to grow vertically, barring external forces. Sakai et al 1995 note that although a few species of trees will naturally produce secondary trunks, the vast majority of species will do so only when apical control is destroyed, or blocked by some extrinsic factor.

Quoting Halle 1999, Putz and Sharitz 1991 state, "A shrub, on the other hand, is a woody plant that, when undisturbed, branches spontaneously at or below ground level to produce multiple stems." This would seem to answer the question, but it is more complicated than that.

As explained by Del Tredici 2001, "In general, a tree will develop secondary trunks in response to injury to its primary trunk or root system, to displacement of its primary stem out of the normal vertical orientation, or to a dramatic change in surrounding environmental conditions. As such, a secondary trunk formation in trees — e.g., basal sprouting — is generally considered to be an induced response to exogenous environment factors."

Morphologically, Del Tredici 2001 found "…trees sprout, in the case of the vast majority of trees, the greatest potential for the production of secondary trunks is localized at the collar." The collar as defined by Sutton and Tinus 1983, is "…the point on the seedling axis where the root and the shoot systems come together. Less easily described is the precise morphological description. Del Tredici 2001, found "…given that the collar is a secondary structure that does not develop until a tree is several years old,…in mature trees the collar develops at or just below ground level and is readily identifiable by the presence of numerous suppressed buds that protrude out from the trunk." Del Tredici 2001 thinks that it is these suppressed buds that allow "…a species to persist in the face of pathogen infestations".

Another scenario that initiates sprouting is the mechanical falling of trees. Known for centuries as coppicing, land managers interested in a "…sustainable supply of relatively small diameter stems on short rotation…" need only to fall trees for the initial yield, then wait for sprouting stumps to grow for a decade or two before repeating the operation. This can be reiterated indefinitely if care is taken to minimize impact with each re-entry. However, this is for a market of small diameter timber, a population different than what we consider in big tree competition.

The conclusion is that normal development for most tree species is that of a single trunk growing vertically upward and that injury around the root collar may release latent buds to form new trunks. Some species, like silver maple, may do this prolifically while others, like white pine, very seldom do it.

TRUNK DEVELOPMENT

In the absence of external forces, a tree will annually add a layer of new wood. Looking at a cross-section of a trunk, this strategy is revealed as concentric annual rings that approach the geometric shape of a circle. In a perfect tree world, a trunk's cross-section would be nearly circular. The diagram below shows the cross-section of a trunk that is nearly circular.

In the real world, a tree must contend with external forces… gravity, ground slope, adjacent objects (other trees, rocks, etc.), solar incidence, forest openings, and prevailing weather patterns. Some forces remain constant through the life of a tree (topographic features, solar incidence patterns) while others change slowly over that time (tree gaps or forest openings resulting from natural or human-caused disturbances). Still other forces can bring about sudden change (earthquake, floods, soil creep, a fallen tree).

Trees respond to these external forces. The response to gravity and solar incidence is to re-orient in order to attain a vertical position. How much and how fast the tree responds determines the degree to which the cross-section will display deviation from circular by creating what we call reaction wood patterns.

The following figure from Fritts 1979, displays the differing angiosperm and gymnosperm responses to growing on a steep slope.

Angiosperms express eccentricity in reaction wood...as noted by Fritts 1976, by putting "...**tension** on the uphill side of a tree, to pull the tree back up straight..."

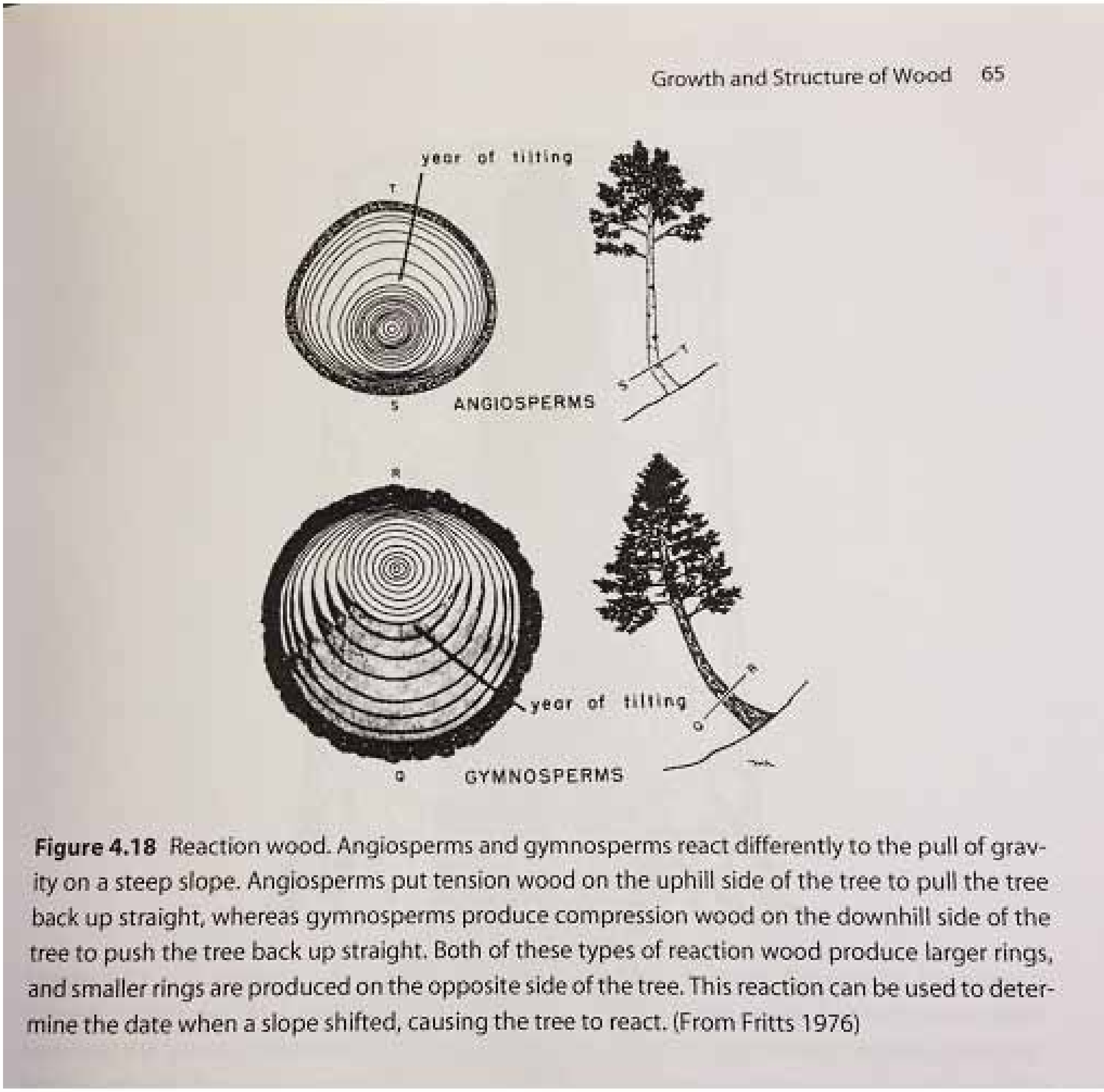

Growth and Structure of Wood 65

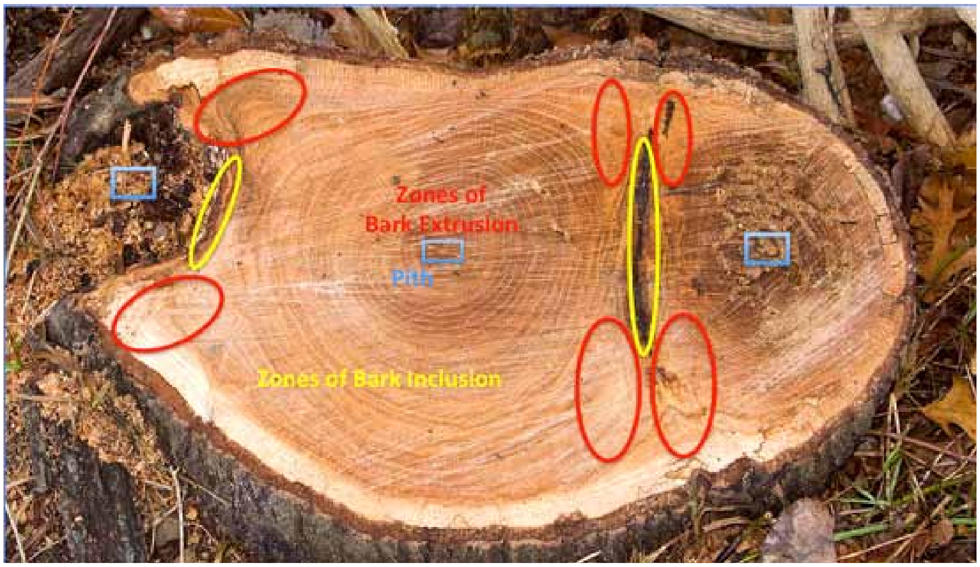
Figure 4.18 Reaction wood. Angiosperms and gymnosperms react differently to the pull of gravity on a steep slope. Angiosperms put tension wood on the uphill side of the tree to pull the tree back up straight, whereas gymnosperms produce compression wood on the downhill side of the tree to push the tree back up straight. Both of these types of reaction wood produce larger rings, and smaller rings are produced on the opposite side of the tree. This reaction can be used to determine the date when a slope shifted, causing the tree to react. (From Fritts 1976)

Gymnosperms express eccentricity in reaction wood...here, in a deodar cedar, by growing **compression** wood on the underside to buttress or 'push the branch up', as captured by Mario Vaden in a 2011 photograph on the next page, right side.

Below, adjacent stems go from rounded oblong, to elliptical, to circular (as they go from bark extrusion phase to base inclusion phase).

Here the force of opposing objects (adjacent stems of same species in this case) causes

Zones of bark extrusion and inclusion



Compression wood

the trees to push (extrude) growing concentric annual rings out of round, and to the sides (note eccentricity occurring after a dozen or so years, as each tree's stems begin pushing against the others). When of the same species, such tree's stems will begin to 'grow around' the extrusion (not unlike a tree 'growing over' a fire scar), and eventually surround, or include the tree's base. Over time, the exterior appearance approaches circularity, as each successive annual ring 'averages' the oblong to an elliptical cross-section. After several hundred years of bark inclusion, it can be difficult to discern the dynamics of annual ring growth response, and the tree(s)' origin.

Implications for Champion Tree Nominations

When a nominator nominates what he/she thinks is a large tree with multiple trunks, how should we treat the multiple trunks in order to be fair to single-trunk competitors? Should we include all the trunks in determining points for championship status? In the past, the thinking was mixed among the state programs on this issue. Some states attempted to enforce the one-trunk rule, while others allowed circumference measurements to include multiple trunks. The use of the standard 4.5 feet above base rule is convenient but arbitrary, leading to situations where clearly two or more trunks pressed together were being measured for circumference as though it were one trunk. In other cases, at 4.5 feet, where multiple trunks were separated, the rules varied on what to measure. Some programs measured the largest trunk at 4.5 feet. Other programs measured lower toward the ground at the point of least circumference. At that point either of two situations existed: (1) the individual trunks were pressed together forming what might appear as a single trunk, or (2) the individual trunks (or limbs) had converged above and one trunk (with a single pith line) was being measured.

The topic of what is fair has been debated from both sides of the aisle. Nobody argues for measuring two or more separate trees and submitting them as one, but there has been a fair amount of disagreement around coppices.

American Forests' objective in this matter is to develop clear rules for comparing trees for the purpose of selecting the champion of a species. The new rule is: **for the purpose of crowning champions, the largest single trunk (whether you are dealing with two or more trees or a coppice form) will be measured at the narrowest point between 4.5 feet and ground level**. In the American Forests' webinar on measuring tree circumference (available at americanforests.org), here is the refined definition of a tree:

> ***A tree is a woody plant having one pith line at ground level, with a single set of concentric annual rings, that surround that pith line, with each annual growth increment…forming an erect perennial stem (trunk) at least three inches in diameter, at a point 4.5' above the ground, with a definitely formed crown of foliage, and a mature height of at least 13 feet.***

For the vast majority of younger trees, the point of circumference measurement occurs at 4.5 feet above ground level. Champion trees are usually older and more complex in form, so the rule of measuring the smallest circumference between 4.5 feet and the ground must be invoked more frequently, and this becomes complicated if multiple trunks are pressed together. The objective is still to measure the circumference of the largest trunk, part of which cannot be directly accessed. Such measurement requires the advanced methods explained in the guidelines.

When viewing relatively large (and often old) trees, as we do for champion tree nominations, making a decision as to whether we are looking at one or multiple trunks should be the first step, whether we are looking at it in the field in person, or viewing a digital image of it in the office. Once that decision has been made, it is then that American Forests' circumference measuring guidelines should be followed.

The location of the pith line(s) relative to ground level and breast height (4.5') determines whether the nominee is:

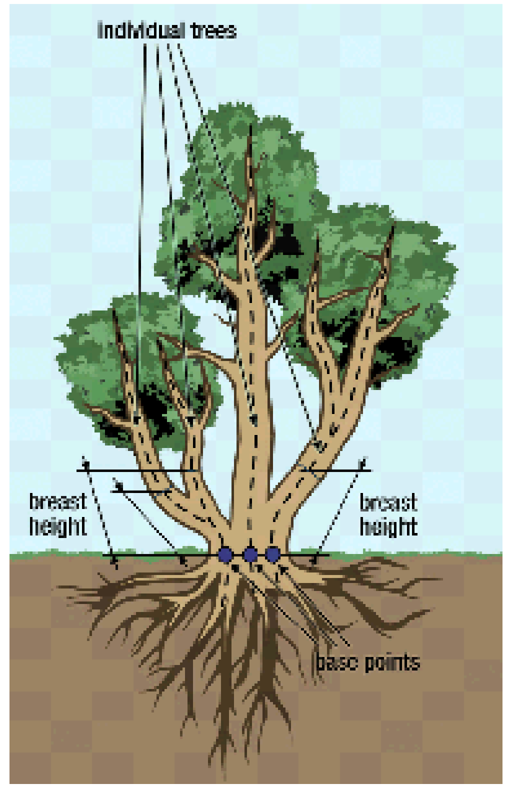
- **A single tree, exhibiting a single trunk at ground level (simplest situation),**
- **A single tree that consists of multiple trunks very near ground level (a coppice, that requires that only the largest trunk be measured), or**
- **Multiple trees at ground level (the single largest is selected for measurement).**

This is a very different approach from locating where branching begins on the tree's exterior surface. The pith line approach is a clear break with past tradition.

The certifier of a nomination should view the tree in person and even if the nominator is present at certification, full documentation by the certifier is required. Nomination and certification are two separate activities. In either case, the tree should be viewed from all sides, to get a sense of where the pith line (or assumed central axis) would be, particularly at the ground level. Circling the tree at least once in the field, or viewing at least four digital images (taken in all four quadrants) will help.

Briefly, the nomination should, at a minimum, include:

1. Four digital images/photographs capturing four quadrants (not necessarily based on cardinal direction.
2. At least one 'big picture' all-encompassing tree view.
3. All pictures should include reference objects (person along side, dbh/cbh tape wrapped around base at height measured, ruler).



How to Delineate Pith Lines

For the purpose of this exercise, select an image with a simple single trunk, drag and drop a digital image from any of the champion trees from American Forests' Champion Tree national registry into any line/annotating software, such as a PowerPoint presentation software.

<u>PowerPoint Directions:</u>

1. Once you have the image placed, click on "Insert".
2. Click on the "Shapes" icon, sliding cursor over to the downward triangle, and dragging it down to the top row choice "Lines and Connectors".
3. Select the third icon on the third line of "Lines" (when you hover the cursor over the icon it reads "Freeform"). Clicking on that icon changes your cursor symbol to a cross, which becomes the beginning of a line when you click on it.
4. Click on a point some ten feet in the image or so above the base, just to get used to the delineation part of the exercise, and try running the cursor down the middle of the trunk, clicking as you need to, to turn left or right to stay with the assumed pith line.
5. When you get to the bottom of the trunk, double click at the base, which ends the line, and leaves it in a box. If you are happy with the result, you can go on to the next one.

If you like to try your hand at a more complex base, where you're initially unclear as to whether it is a single- or multi-stem, the process is similar.

Unless external forces can be determined to have an altering influence on the tree's natural tendency towards a circular cross-section, generally running pith lines down the center of the tree's presented 'front' is going to be relatively close. Having four images from each quadrant of the tree helps to more accurately inform the delineation. Should there be noticeable external forces in play, adjust the delineated pith line appropriately (recalling an angiosperm's tension wood reaction, or a gymnosperm's compression wood response).

Generally the more severe the bend, the closer the pith line(s) would be to the inside edge. These are relative considerations generalized across many species, and across a wide array of diameters. An exaggerated example would be where two adjacent trees (measured at ground level), each on a growth path to reaching a 20" diameter, had grown against one another, so that the interference resulted in a combined width of 38" from side to side. We could reasonably assume that they grew independently of each other until each had grown to 19" in diameter at the base, and then began conjoining (fusing, inosculating, etc.). In this case we can assume central axes would not require much, if any, adjusting.

However, assume that two adjacent trees, each on a growth path to achieve a 20" diameter at the base, interfere with one another so that the observed outside width of the compressed pair is 24" (side to side). Locating the pith lines requires significant adjustment from where each would be placed centrally within its trunk. The axes could be as close as two inches apart, at ground level.

Somewhere between the above two scenarios, careful observers can usually judge if there is one stem or more than one at ground level for nomination purposes. In those cases where the certifier is convinced that there is a single pith line at ground level, but that the point of divergence into multiple trunks (or limbs) cannot be confidently made, we provide an alternative circumference determination method below. If at 4.5 feet, the individual trunks can be measured, an equivalent single trunk can be constructed, and its circumference computed.

To assist in making this more complex calculation, an Excel-based solution can be used and is available through American Forests.

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APPENDIX II

Glossary of Terms

- ***Apical Meristem*** — Located at the initial shoot tip, and tips of branches and roots, it is the origin for elongation, height growth of branches, roots in a tree. Meristematic activity is generally annual and the meristem after that year becomes the tree's pith (see definition on page 82) and is the bundle of cells produced by the upward growth of the apical meristem, allowing trees to reach to greater heights and creating the cambium initials that start secondary thickening of trees. A secondary meristem is produced in most gymnosperms and dicots and enables a tree to grow in circumference laterally through time and produce (generally annually incremented) concentric tree rings. [The pith cells at the center of the stem are left in the path traveled by the apical meristem. Hoadley 1980]

- ***Bark*** — Outermost layer of stems and roots of woody plants (refers to all the tissues outside of the vascular cambium.

- ***Bark extrusion*** — As two adjacent stems enlarge into each other, they will eventually extrude out the bark and develop cambium/phloem layers into areas of more space and less pressure.

- ***Bark inclusion*** — The zone between adjacent stems where bark is 'captured' by being grown over, until the two stems finally grow apart (similar to manner in which a tree's bark repair wounds such as caused by fire, and other injury vectors).

- ***Base line*** — The level line from the measurer's eye to the tree, as used in Tangent and Sine Methods of height measurement…may be actual (in the case of the Tangent Method), or assumed (in the case of the Sine Method). In the case where the level line from the measurer's eye to the tree is not possible, an external baseline may be employed with trigonometric formulas.
- ***Bole*** — the main, primary stem or trunk of a tree. With its origins in Old Norse and Middle High German words meaning "plank", the word bole typically refers to the part of a tree trunk that can be used for making lumber or other wood products.
- ***Branch*** — a division of a primary or secondary stem connected to the central trunk of a tree. Large branches are known as limbs or boughs and small branches are called twigs.
- ***Breast Height*** — A convenient place for measuring or examining large trees, 4.5 feet (1.37 m) above ground line by convention in the United States. In Europe and elsewhere, breast-height is 1.5 m (4.5 feet) above ground-line.
- ***Burl*** — A large rounded outgrowth on the trunk or branch of a tree.
- ***Canker*** — An imperfection on the trunk, limb or twig of a tree caused by an organism that kills a part of the tree's tissue.
- ***Circumference*** — The measurement of circumference tape wrapped tightly around the trunk of a tree perpendicular to the axis of the trunk. Used interchangeably with girth.
- ***Circumference at Breast Height (CBH)*** — The measurement of a diameter tape wrapped tightly around the trunk of a tree at breast-height (4.5 feet above the mid-point of the slope at ground-line in the United States). The term circumference comes from a widely-adopted simplifying assumption that tree stems, in cross-section, are approximately circular.
- ***Compression Wood*** — See ***Reaction Wood***.
- ***Crown*** — The upper part of a tree, apart from the main stem, consisting of the branches, foliage (needles or leaves), and reproductive parts (nuts, fruit, cones, catkins, etc.).
- ***Crown spread*** — The averaged width of a tree crown. This can be simply the average of the widest span and the width of the crown at 90 degrees off of the widest span, or more accurately measured as the average of an array of width maximums (for example figuratively as though spokes in a wheel).
- ***Crown width*** — The span of a tree crown.
- ***Diameter at Breast Height (DBH)*** — The straight-line distance, measured outside of the bark, from one side of a tree trunk to the opposite side, measured at breast-height (4.5 ft above ground-line in the United States). Direct measurement of dbh can be accomplished using special tree calipers. Often, DBH is determined indirectly by first measuring the circumference at breast-height (see ***CBH***), then dividing CBH by the constant pi = 3.1459.

- ***Epicormic sprout*** — An adventitious growth that emerges from dormant buds along the trunk and branches of a tree, usually in response to injury or some manner of a defense mechanism to a pathogen. The practice of coppice reproduction relies on a tree species' ability to epicormically sprout after tree has been harvested.

- ***Foliage*** — The collection of leaves or needles forming a tree's crown.

- ***Fork*** — Bifurcation, the point where a tree's trunk, branch, or twig splits into two or more trunks, branches, or twigs, respectively. In this definition no distinction is made between a limb (large branch) and a branch.

- ***Girth*** — Another term for the circumference of a tree. Circumference and girth are used interchangeably.

- ***Girth at Breast Height (GBH)*** — Same as ***CBH***. The measurement of a tape drawn snugly around the trunk of a tree at breast-height (4.5 ft above ground-line in the United States). See also, ***CBH***.

- ***Height*** — See ***Total Height***.

- ***Leaf*** — In angiosperms, a usually green, flattened lateral structure attached to a stem and makes food through the process of photosynthesis. Conifer trees often have needle shaped leaves or clusters of needle shaped leaves.

- ***Pith*** — Central axis of growth of the trunk of a tree. (See ***Apical Meristem***). In the absence of external forces such as adjacent stems, gravity (leaning tree), slope change, snow loading, uneven translocation of nutrients, the pith will generally form the central axis of the trunk.

- ***Reaction Wood*** — Trees growing on a slope or those that are tilted produce reaction wood to maintain or regain their vertical orientation. Gymnosperms produce compression wood on the downhill side of the tree…Angiosperms produce tension wood on the uphill side of the tree …to pull the tree up straight. The differing responses cause the pith to be displaced upslope from center in a conifer and downslope from center in a hardwood tree.

- ***Stem*** — One of the tree's structural axes that supports leaves. Trunk, limb, bough, branch, and twig are all names used to describe tree stems.

- ***Stem Inclusion*** — Over time, the bark extrusion zone may be included (inosculated, or conjoined) and covered by the combined base growth, much as when a tree encloses a wound. May in time enclose multiple stems over time and appear to be forked single stem tree in appearance.

- ***Shrub*** — A woody plant of relatively low height that has several stems arising from the base and lacks a single trunk.

- ***Tension Wood*** — See ***Reaction Wood***.

- ***Total Height*** — The vertical distance between a horizontal plane running through the top most point of a tree and a horizontal plane running through the mid-slope point of the base at ground level.
- ***Tree*** — A woody plant having one pith line at ground level, with a single set of concentric annual rings, that surround that pith line, with each annual growth increments…forming an erect perennial stem (trunk) at least three inches in diameter, at a point 4.5' above the ground, with a definitely formed crown of foliage, and a mature height of at least 13 feet.
- ***Trunk*** — The main stem of a tree, including wood and bark, starting at the root collar at or near ground line and going up to a more-or-less indeterminate point, often as low the first large branch, or as high as can be traced before the stem branches into divisions that can no longer be identified as belonging to a central main stem.

Description of tools

Required at National Cadre Level

- 100' Tape (200' preferable) — Either fiberglass or steel
- Diameter Tape — Measuring tape reading circumference directly in feet and hundredths of feet on one side, and diameter as a function of Pi on the other side
- Laser Rangefinder — A device which uses laser energy for determining the distance from the device to a place or object
- Compass — A handheld instrument measuring angles from true magnetic north
- Clinometer — An instrument for measuring angles of slope or inclination.
- Digital Camera — A camera that stores images digitally rather than recording them on film. Once a picture has been taken, it can be downloaded to a computer system, and then manipulated with a graphics program.
- Global Positioning System (GPS) Receiver — A handheld electronic device that can determine the latitude and longitude of a point on earth by computing the time difference from different satellite signals
- Scientific Calculator (with Trigonometric Functions) — A handheld electronic calculator capable of calculating mathematic and trigonometric functions
- Plumb bob — A weight, usually with a pointed tip on the bottom, that is suspended from a string and used as a vertical reference line, or plumb-line
- Yardstick (or meterstick) — A wooden or metal stick with graduations in inches and feet, or meters, used as a reference object for scaling digital imagery

Desired Tools at Expert Level

- Densitometer — A handheld device used to determine canopy edge and coverage, either by a series of spirit levels, or from a scored hemispherical mirror (referred to as a spherical densiometer).

- Monocular with reticle — A hand held monocular with graduations across its field of vision (reticle) allowing measurement of object widths, where calculations are possible when distance and the reticle function are known.
- Forestry calipers — A handheld device used to capture tree diameters, as measured by the separation of parallel caliper arms, when positioned at opposite edges of a tree's trunk.
- Laser Hypsometer — A handheld electronic device used to measure distances (slope and horizontal), vertical angles, and horizontal azimuth; and provide digital readout, or electronic transmission of same. For National Cadre purposes, selected laser hypsometers should base their height calculations on sine relationships.
- Red-beam Laser Measuring Devices — A handheld electronic distance measuring device relying on the timed reflection of the visible red-beam (portion of spectrum) laser signal to accurately measure distance.
- Smartphone applications designed to use its camera for documentation and measurement — Providing overlays on camera image, detailing angles (horizontal, vertical), distance estimates, location (GPS, Military grid); storage of collected data, and transmission through smartphone cell coverage of data to remote electronic addresses.