Radius of curvature measurements and wood diameter: a comparison of different image analysis techniques

Sandrine Paradis-Grenouillet, Alexa Dufraisse, Philippe Allée

Accepted for publication in *British Archaeological Report*
in press

Article of the 4th international meeting of anthracology in Brussels
4-9 September 2008

Radius of curvature measurements and wood diameter: a comparison of different image analysis techniques

S. Paradis*, A. Dufraisse, Ph. Allée*****

Key words: wood charcoal, wood diameter, image analysis software, radius of curvature

*** PhD student, GEOLAB, UMR-CNRS 6042, 39E rue Camille Guérin 87036 Limoges, France.**

** **CR CNRS, Archéozoologie, archéobotanique : sociétés, pratiques et environnements. Muséum national d'Histoire Naturelle, Département EGB, UMS 303-UMR 7209, CP 56, 55 rue Buffon, 75005 Paris, France.**

***** PR, GEOLAB, UMR-CNRS 6042, 39E rue Camille Guérin 87036 Limoges, France.**

Abstract

The study of wood diameter is needed for the understanding of wood supply management. This type of approach, which was launched in the 1990s, has improved considerably as radius of curvature measurement has gained in precision through the introduction of new equipment: stereomicroscope equipped with a camera, and image analysis software. This paper focuses on the first step of the wood diameter study: radius of curvature measurement. This measurement is unusable as it stands, but the data set can be integrated into models to provide better information on wood diameter. In addition to the circle tool technique based on tree-ring curvature, three new techniques are presented here, based on wood rays: Thales' theorem, trigonometry in a right-angled triangle, and trigonometry in an isosceles triangle. This study compares results on perfectly graduated targets and on wood samples for four radii of curvature measurement techniques, to assess their reliability and limits. Three parameters are examined: angle between two wood rays, distance between two wood rays, and radius of curvature.

Introduction:

Charcoal analyses allow firewood management and past environments to be studied by means of wood diameter, tree-ring width, wood physiology, and identification of wood taxa (Vernet, 1992; Thiébault, 2002; Fiorentino & Magri, 2008). However, it is still necessary to improve analytical methods, especially for wood diameter, which is a selection criterion at least as important as species or wood humidity (Chabal *et al.* 1999). This type of approach was launched in the 1970s (Willerding, 1971) and developed and used by other authors (Hillebrecht, 1982; Marguerie, 1992; Marguerie and Hunot, 2007; Ludemann and Nelle, 2002; Dufraisse, 2002, 2006).

The determination of burnt wood diameter is composed of two steps, the first of which being radius of curvature measurement. However, this measurement indicates only the position of the charcoal fragment in a log and not the diameter. The second step is data treatment and interpretation which can be tackled by different models (see the medium wood diameter of Ludemann and Nelle (2002) or the three-dimensional wood model proposed by Dufraisse (2002, 2006), the object of ongoing research).

After a brief review of radius of curvature measurement techniques, mainly based on ring morphology, this paper will focus on new approaches based on wood rays. Measurement techniques using image analysis will be compared, and reliability and limits established, both on perfect targets and on wood samples.

1. Brief history of radius of curvature analysis

Until now, various methods have been developed to evaluate tree-ring curvature, some of which are qualitative and others quantitative.

1.1. A qualitative approach to tree-ring curvature

According to Marguerie (1992) and Marguerie and Hunot (2007), ring curvature estimation depends on standard classification, using constant magnification and a transparent test card. The authors have proposed three groups depending on the degree of the curvature:

- strongly curved rings
- moderately curved rings
- weakly curved rings

Charcoal samples with indeterminate curvature are placed in a fourth group.

The predominance of weakly curved rings in the archaeological sample suggests the use of large diameter wood, e.g. trunks or large branches; the predominance of strongly curved rings indicates the use of small diameter wood, e.g. young trees or small branches.

This approach is not a quantitative measurement of wood diameter but merely a characterisation of ring morphology.

1.2. Quantitative approaches based on tree-ring morphology

In the first quantitative approach, the visual estimate is guided by a graduated target (i.e. different diameters printed on a transparency) (Willerding, 1971; Lundström-Baudais, 1986; Ludemann and Nelle, 2002; Dufraisse, 2002, 2006). The target is placed on top of the charcoal fragment under a stereomicroscope to compare the curvature and angles of both the target and the charcoal fragment. This approach is a visual estimate: observer bias and measurement error are difficult to quantify, i.e. several values may be found by different observers for one charcoal fragment. This method implies the use of very broad diameter classes, so interpretation will also lack precision (Paradis, 2007).

Another approach based on tree-ring morphology uses the "circle tool" found in image analysis software (Chrzavzez, 2006). A few characteristic points are placed along the last visible ring and the software calculates an extrapolation, draws the corresponding circle and gives the diameter of the ring. Even if observer bias is less than for the use of a target printed on a transparency, this method is still influenced by ring morphology variation.

1.3. Quantitative approaches based on wood rays

We have therefore developed another approach based on wood rays, using image analysis software. This method was tested with three geometric formulas (Figure 1):
- Thales' theorem;
- Trigonometry in a right-angled triangle;
- Trigonometry in an isosceles triangle (Paradis, 2007).

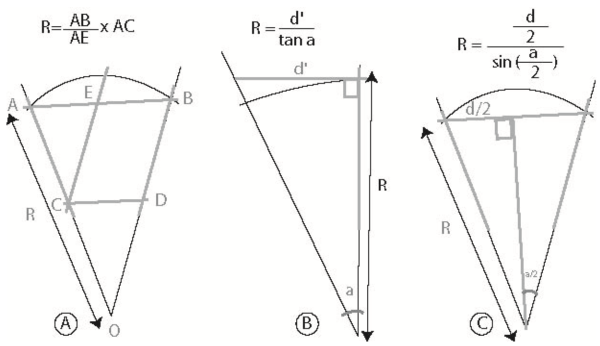

Figure 1: Radius of curvature measurement techniques based on the angle between two notional rays. A: Thales' theorem; B: Trigonometry in a right-angled triangle; C: Trigonometry in an isosceles triangle.

In this work, only the four approaches which use image analysis software (Lucia Nikon) were tested and compared: the circle tool, the Thales' theorem, trigonometry in a right-angled triangle, and trigonometry in an isosceles triangle.

2. Material and methods

These four techniques were compared, first on perfect material (graduated targets printed on paper) in order to exclude the variations of natural material, and then on non-carbonised wood in order to test the reliability of these methods before the effects of carbonisation. Practical applications and assessment on charcoal fragments are underway (Paradis, ongoing PhD).

For each radius of curvature measurement, reliability and limits were tested for three parameters clearly identifiable on wood:

- radius of curvature which corresponds to the distance between the last visible ring and the pith of the wood
- angle between two wood rays
- distance between two wood rays

Wood anatomical vocabulary is used throughout this study, but for perfect target paper printouts, the following terms are used: angle between two notional rays and distance between two notional rays.

2.1. Test on a perfect graduated target

Perfect targets (graduated targets printed on paper) were measured with image analysis software (Lucia, Nikon). They present a large range of values for radius of curvature (0.1cm to 15cm), angle between two notional rays (0.5° to 70°) and distance between two notional rays (0.1cm to 2.5cm) (Figure 2). In total, 236 targets were tested with the four measurement techniques and the measurement was repeated three times (2832 measurements).
For each measurement, the true values of radius of curvature, angle and distance between two notional rays are known, allowing the reliability of each technique to be tested.

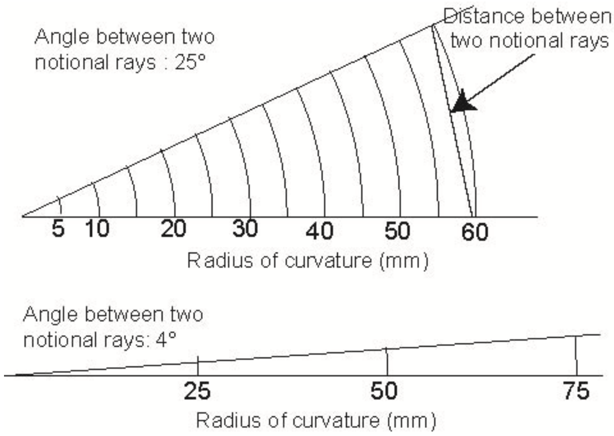

Figure 2: Perfect targets on paper printout used for the comparative study.

2.2. Test on non-carbonised wood

To measure radius of curvature on wood, small and large pieces of oak were used, with radii of curvature up to 20cm.
Freshly cut transverse sections were used to test the four measurement techniques. Nevertheless, only two parameters, radius of curvature and distance between two wood rays, can be controlled (consequently, angles measured depend on both these parameters).
To obtain results in coherence with those from perfect targets, a large range of radii (from 0.3cm to 20cm) and distances between two rays (from 1mm to 23mm) were chosen, allowing a range of angles between 0.5° and 62°.
In total, 100 freshly cut sections of wood were tested, as in the comparative study on perfect targets, i.e. on all three parameters (angle, distance between two rays, and radius of curvature). Each measurement was repeated three times. However, as the true value of the angle is unknown, the six angle values obtained by trigonometry were averaged and used as a reference value.

2.3. Data treatment

For each sample (perfect targets and freshly cut sections of wood), the radius of curvature measurement was repeated three times to calculate an average and then a percentage of error, which is indispensable to compare the error margin (Delta value) for large and small radius of curvature values.

Delta = average of measured radius of curvature – true radius of curvature value
Percentage of error = (delta x 100) / true radius of curvature value

A graphic representation of the percentage of error in a cumulate diagram (Figures 3 and 5) is used to compare the different measurement techniques. This graph allows two thresholds of measurement reliability to be defined. Three reliability classes are determined:

- good reliability;
- medium reliability; (this percentage of error is still acceptable for a radius of curvature measurement)
- poor reliability; (unacceptable for radius of curvature measurement)

These classes allow the reliability and limits of each measurement technique to be evaluated for the three parameters: angle between two wood rays, distance between two wood rays and radius of curvature.

A bar graph is used to present the reliability of each measurement technique for each parameter (Figures 4 and 6). The interest of the bar graph is that measurement reliability can be assessed for the three parameters. Each parameter was divided into unequal classes depending on the evolution of the percentage of error. For example, for the angle parameter, the percentage of error varies very quickly on small angles and stabilises for angles greater than 8°. The classes for angles between two rays are thus:]0-1°],]1-2°],]2-4°],]4-8°],]8-16°],]16-32°] and above 32°.
For distance between two rays, the classes were established in relation to the most frequent sizes of archaeological charcoal fragments:]0-2mm],]2-4mm],]4-6mm],]6-10mm],]10-15mm] and]15-30mm]. There was a specific focus on small distances between two rays to evaluate the minimal transverse section of charcoal fragment required.
For the radius, the classes are:]0-0.5cm],]0.5-1cm],]1-1.5cm],]1.5-2cm],]2-4cm],]4-6cm],]6-10cm], and]10-15cm], with an additional class for wood sections: above 15cm.
Thus, for each class of each parameter, the percentage of the measurement per reliability class is shown, with good reliability in white, medium in grey and poor in black (Figure 4).

3. Results: reliability and limits of each measurement technique

3.1. On perfect targets

The results of the 236 perfect targets for the four techniques are represented on the cumulate diagram (Figure 3), with the percentage of error on the x axis and the number of measurements on the y axis.

Using this graph, the two thresholds for perfect targets were defined at 10 % and at 30%, corresponding to a 95% confidence level for most of the techniques. The following reliability classes are defined:

- good reliability, lower than 10%;
- medium reliability, between 10 and 30%;
- poor reliability, over 30%.

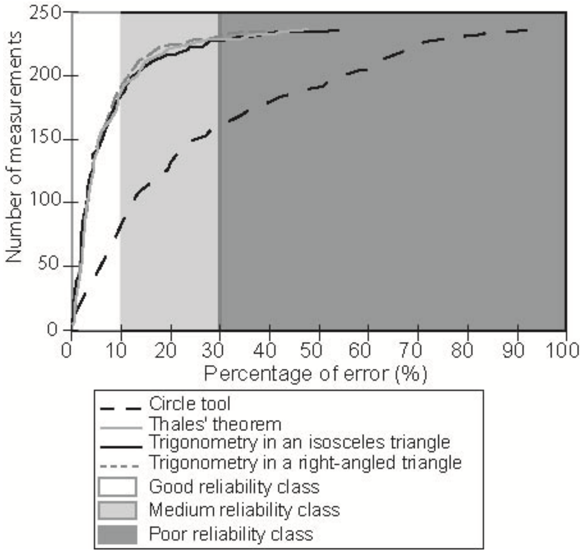

Figure 3 : Graphic representation of the margin of error in a cumulate diagram for the four methods on perfect targets.

3.1.1 The circle tool

The circle tool presents a very high percentage of error, up to 90% (Figure 3). Unlike the other techniques there are very few measurements in the first two reliability classes as can be seen on the graph (the curve corresponding to the circle tool is below those of the other techniques).

The distribution of measurements in the percentage of error diagram indicates that 32% are in the poor reliability class and 33% in the medium class (Figure 4 A). Only 35% are in the good reliability class, which is not sufficient for radius of curvature measurement.

The study of the bar graph for each parameter (angle between two notional rays, distances between two notional rays and radius of curvature) underlines the poor reliability of this tool. In fact, more than half of the measurements with angles lower than 8° have a margin of error of over 30%, which is not suitable for radius of curvature measurement. In addition, it is not relevant to consider only the angles over 8°, due to the correlation between angle and radius of curvature ($r = 0.45$ with $p<0.0001$). In other words, if the angles lower than 8° are removed, many larger radius of curvature measurements are also removed.

For the distances between two notional rays, the measurement is less reliable when the distance is smaller than 1cm. Yet, that is the most frequent size of charcoal fragments in archaeological contexts.

This technique is thus very attractive at first due to the ease and the speed of use, and also it is present in most image analysis software. Nevertheless, this method is unreliable for medium and large radii of curvature.

3.1.2 Thales' theorem

With this technique, only 3% of the measurements are in the poor reliability class and 79% are in the good reliability class (Figure 4 B).
The distribution of reliability for the different parameters gives very good results.
For small angles, all the measurements belong to the medium and poor classes (respectively 83% and 17%). The measurement of angles of less than 1° is technically more difficult. It is harder to draw notional rays for small angles, thus the measurement of the angle could be wrong; there is also the question of observer bias, which leads to a higher percentage of error.
The graph for distance between two notional rays underlines the greater unreliability of distances lower than 2mm (percentage of error of 45%). This inaccuracy means that greater care is required for charcoal fragments with a small transverse section. All radius of curvature classes provide good reliability with only 0% to 10% of measurements in the poor class.

This method is reliable, but it is time-consuming (two notional rays and two series of parallel lines must be drawn and three segments must be measured (AB, AE, AC, cf. Figure 1 A). This technique is consequently not adapted for routine analysis.

3.1.3 Trigonometry in a right-angled triangle

This method is highly reliable because 81% of the measurements are in the good reliability class (lower than 10%) (Figure 4 C). The distribution of reliability for the different parameters gives almost the same result as the Thales Theorem, i.e. with lower reliability on small angles (up to 1°, only 30% of the data are in the good reliability class) and small distances between notional rays (up to 2mm, only 39% of the data belong to the good reliability class). When distances and angles between two notional rays are small (less than 2mm and 1°), it is advisable to obtain a representative average from repeated series of measurements.

This technique is more preferable to the Thales' theorem technique owing to its speed of use. However, automatic drawing of a right-angled triangle is not always available in the software package.

3.1.4. Trigonometry in an isosceles triangle

For this measurement technique, 78% of the measurements are in the good reliability class (Figure 4 D).
This technique appears as good as the previous one on perfect targets. Indeed, for the angle between two notional rays, angles of more than 4° indicate very good reliability (between 81 and 92%) and good reliability for angles from 1° to 4° with only 20% of the measurements in the poor class. The reliability for small angles (lower than 1°) is worse, and much greater care is required to obtain satisfactory results. For distance between two notional rays, the results provide very good data from 4mm (between 76% and 100%), but reliability is also good for distances from 2 to 4mm (with only 3% of the measurements in

the poor class). All radius of curvature classes give good reliability, with only 0 to 10% of the measurements in the poor class.

Finally, compared with other techniques, isosceles triangle trigonometry is the fastest method because it requires only two measurements: angle and distance between two rays which reduces the potential for error.

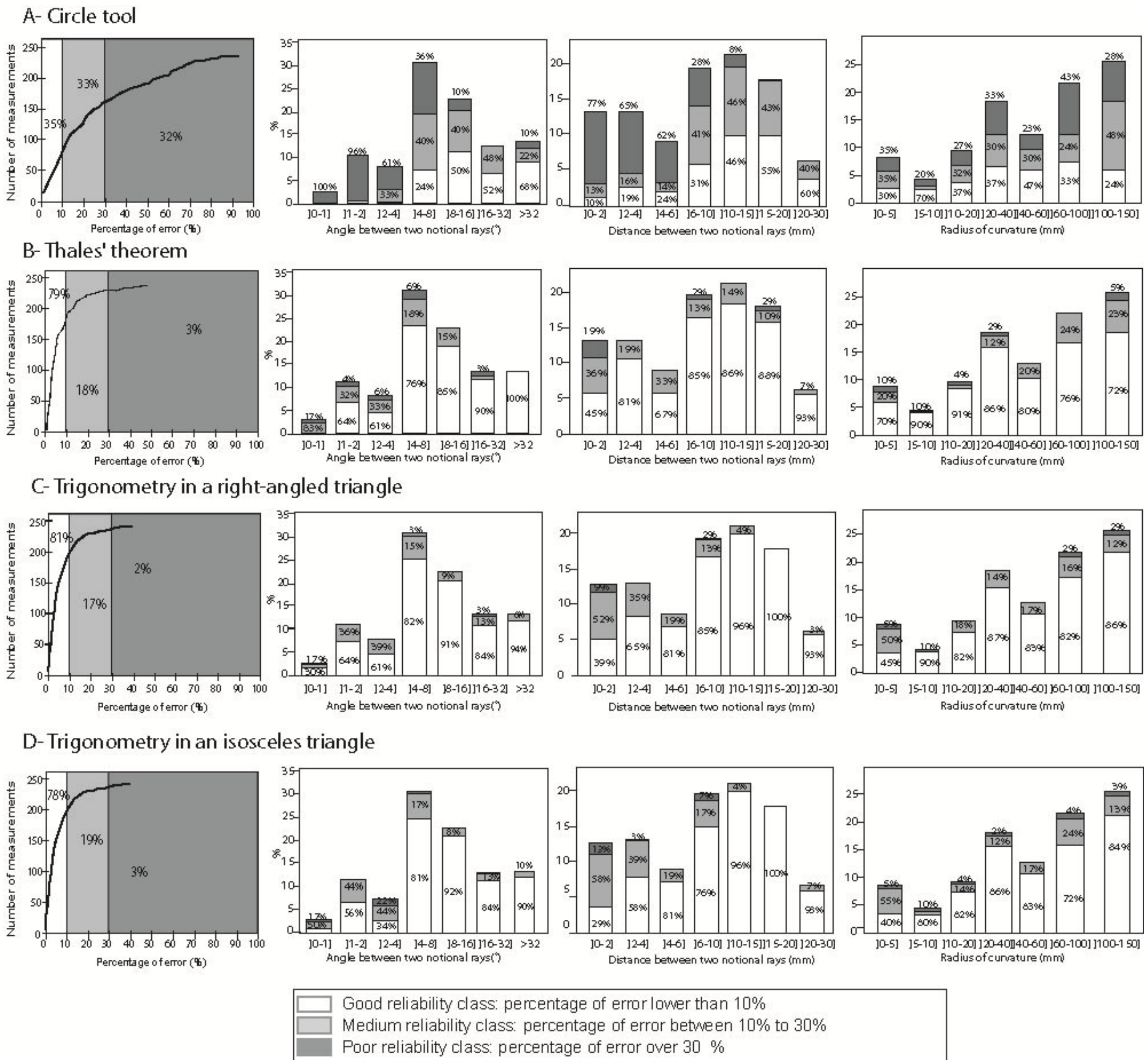

Figure 4 : Reliability of the different measurement techniques on each parameter (angle between two notional rays, distance between two notional rays and radius of curvature) on perfect targets.

3.2. First results on non-carbonised wood

Working only on perfect targets is not representative of the potential of each measurement technique, owing to the variability of natural material. Thus, all four measurement techniques were tested on 100 freshly cut transverse sections. For all techniques, it was very difficult to measure the smallest diameter (less than 1cm) due to the wavy outline of the tree-ring close to the pith.

The stabilisation of the percentage of error is around 70% for a 95% confidence level (Figure 5). However, such a threshold is hardly usable in a study of wood diameter.

Consequently, a compromise has been found with a threshold of 45% which corresponds to an 80% confidence level for most of the techniques.
The three reliability classes have been adapted to correspond well with the evolution of the percentage of error. Classes defined are the following (Figure 5):

- good is lower than 20%;
- medium is between 20% and 45%;
- poor is above 45%.

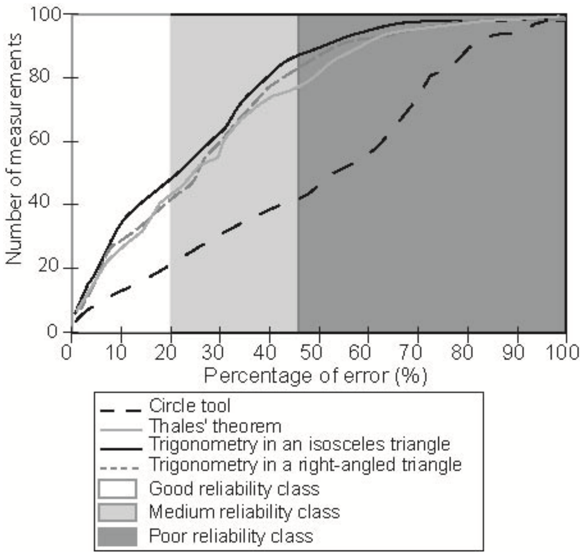

Figure 5 : Graphic representation of the margin of error in a cumulate diagram for the four methods on freshly cut transverse sections.

3.2.1. The circle tool

On the cumulate diagram of the percentage of error, only 18% of the measurements are in the good reliability class and 60% are in the poor reliability class defined above (Figure 6 A).
For angle between two wood rays, the reliability for small angles is very poor: 100% of the measurements with angles below 2° are in the poor reliability class and more than 60% for angles from 2° to 8°; the results are better for angles over 8°. But as there is a correlation between angle and radius of curvature (cf. §3.1.1.), it is not acceptable to work only on large angles. For distance between two wood rays, the results are also very poor for all distances under 2cm (up to 100% of the measurements are wrong) instead of 1cm on perfect targets. An increase in the proportions of wrong measurements is undeniable from 4cm (i.e. 8cm of diameter) (from 58% to 100% of the measurements are in the poor reliability class).

All these observations underline the limits of the circle tool proposed in the software. In other words, with this measurement technique it is possible to measure only small radii of curvature with large angles (> 8°) on large transverse sections (>2cm); which are not common in archaeological charcoal samples.

3.2.2. Thales' theorem

The technique of the Thales' theorem is characterised by 76% of reliable measurements (42% in the good reliability class and 34% in the medium class) which is better for a study of radius of curvature (Figure 6 B). The distribution of reliability for the three parameters reinforces the results obtained on perfect targets: there from 34% to 67% of wrong measurements for angles below 2°, and 43% for small distances between two wood rays (less than 2mm). It is thus necessary to be careful with such values, as previously mentioned for perfect targets.

3.2.3. Trigonometry in a right-angled triangle

For this method, only 18% of the measurements are in the poor reliability class (Figure 6 C). In detail, from 17 to 24% of the measurements are in the poor reliability class for angles over 2°, 44% belong to the poor reliability class for angles below 2°. For distances between two wood rays of less than 1cm, from 12 to 28% of the measurements are in the poor reliability class. Surprisingly, the smallest distances present the best results (14% and 12% of wrong measurements respectively for]0-2 mm] and]2-4 mm] classes) which may be due to the variability of wood samples. For radius of curvature, the poor reliability class appears from 2cm with a percentage of 8% to 33%, which is acceptable for radius of curvature measurements.
Finally, the distribution of reliability on the three parameters shows better results than for the Thales' theorem. Thus, the technique of trigonometry in a right-angled triangle is well adapted to radius of curvature measurements, taking into account the natural variability of wood.

3.2.4. Trigonometry in an isosceles triangle

In the trigonometry in an isosceles triangle technique, only 15% of the measurements are in the poor reliability class and 48% are in the good reliability class (Figure 6 D).
Furthermore, the results of the distribution of reliability on the bar graph also show the good reliability of each parameter, whatever the angles (angle <2°, 33% of wrong measurements), distances between two wood rays (distance <6mm, from 22 to 28% of wrong measurements) and radius of curvature (length >4cm, 17% to 22% of wrong measurements).

This technique provides the best results on wood sections. In addition, it is a quick and easy technique to apply, which is compatible with a routine analysis.

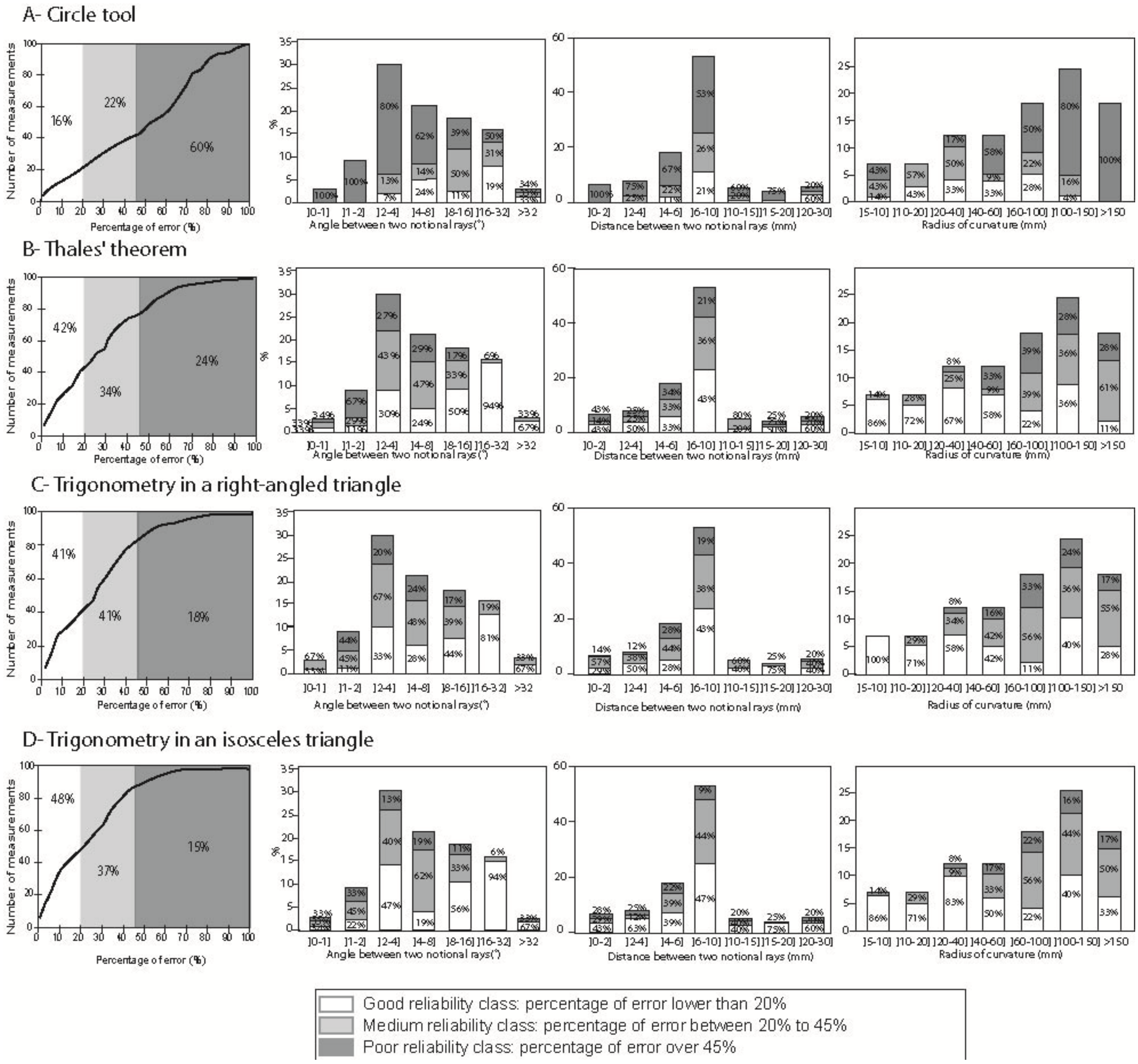

Figure 6: Reliability of the different measurement techniques on each parameter (angle between two notional rays, distance between two notional rays and radius of curvature) on freshly cut transverse sections.

4. Discussion

Overall, the results of the percentage of error for wood are worse than for perfect targets, which is not surprising considering the natural variability of wood.
In order to establish the limits of each measurement technique on notional targets and on wood transverse sections, each parameter was divided into three classes based on characteristic values (8° for angles and 4mm for distances between two wood rays (notional rays for perfect targets) (Figure 7):
- for angles:]0-8°],]8-30°] and]30-70°];
- for distance between two wood rays:]0-0.4cm],]0.4-1cm] and]1-3cm];
- and for radius of curvature:]0-2.5cm],]2.5-7.5cm] and]7.5-20cm].

Next, a notation was attributed to each parameter as follows to allow discussion of the general reliability of each measurement technique (Figure 7):
- “- -” for more than 60% of wrong measurements;
- “-” for 45 to 60% of wrong measurements;

- “+” for 20 to 45% of wrong measurements;
- “+ +” less than 20% of wrong measurements.

A: targets	Angle between rays			Distance between rays (cm)			Radius of curvature (cm)		
	]0-8°]	]8-30°]	]30-70°]	]0-0,4]	]0,4-1]	]1-3]	]0-2]	]2-6]	]6-20]
Circle tool	-	++	++	-	-	+	-	+	+
Thales’ theorem	++	++	++	+	++	++	+	++	++
Trigonometry in a right-angled triangle	++	++	++	++	++	++	++	++	++
Trigonometry in an isosceles triangle	++	++	++	+	++	++	+	++	++

B: wood sections	Angle between rays			Distance between rays (cm)			Radius of curvature (cm)		
	]0-8°]	]8-30°]	]30-70°]	]0-0,4]	]0,4-1]	]1-3]	]0-2]	]2-6]	]6-20]
Circle tool	--	-	-	--	--	--	-	-	--
Thales’ theorem	-	+	++	-	-	+	++	+	-
Trigonometry in a right-angled triangle	-	+	++	+	+	+	+	+	+
Trigonometry in an isosceles triangle	+	++	++	+	+	++	+	++	+

Figure 7: Synthesis table. A : on perfect targets ; B : on freshly cut transverse sections. In grey, the best techniques for routine analyse.

As shown in figures 7 and 8, the circle tool is not recommended. In fact, its reliability is poor for almost all parameters and the value dispersion does not follow the trend of true radius of curvature values (Figure 8). Thus, it becomes impossible to measure radius of curvature above 4cm. In addition, the absence of correlation between measured value and real values makes it almost impossible to establish a potential corrective factor.

The three other techniques based on wood rays (and not on tree-ring morphology) provide relevant results with good correlation between the measured value and true radius of curvature values.

The reliability of freshly cut transverse sections of wood is good, with more than 80% of the measurements included in the first two reliability classes. If dispersion increases clearly for large radii of curvature, all values follow the trend of the true values, unlike results for the circle tool. Thus, with these observations, measurement techniques based on wood rays are good for radius of curvature measurement. However, the Thales’ theorem is not adapted for routine analysis, as it is too time-consuming. Trigonometry in a right-angled triangle requires software with an automatic right-angle feature and it is difficult to use with very large angles, which required a wide camera field to draw the straight lines for the right angle.

The most efficient technique for routine analysis is trigonometry in an isosceles triangle, which is the fastest technique and the most reliable on wood transverse sections. In addition, taking into account the care required with small angles and distances between two wood rays, this technique is compatible with the necessity of increasing the number of measurements in order to limit observer bias.

We must also recall that for measurements on wood sections, the chosen threshold was established at 45% which provides an 80% confidence level (instead of 95% for the perfect target). Even if this percentage of error can be balanced by the measurement of numerous fragments, this choice also allows relevant diameter classes to be established for the interpretation of archaeological samples (which was not possible with a threshold of 70%: diameter classes would be too broad to be used for interpretation). As a first application, the minimal diameter classes which can be used for wood diameter study are:
]0-1cm],]1-2cm],]2-4cm],]4-8cm],]8-16];]16-28] and >28cm.
As regards the large dispersion of the measured values on large radii of curvature (Figure 8), the creation for broad classes such as]16-28cm] and >28cm is indispensable to improve interpretation.

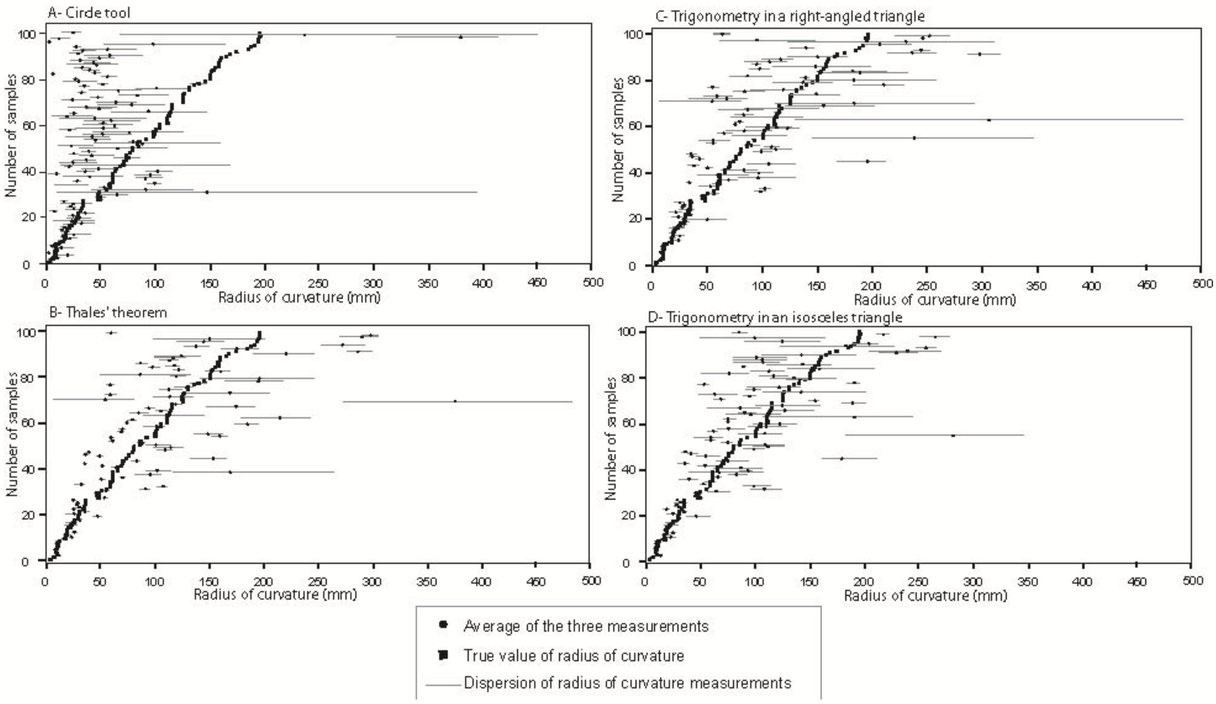

Figure 8 : Dispersion of measurements around the radius of curvature on freshly cut transverse section.

In addition, this study allows a minimal size of charcoal fragment to be estimated. Analyses show that results are acceptable for distances of about 4mm using trigonometry in an isosceles triangle (but 6mm for the two other techniques based on the wood rays). It is however possible to measure the radius of curvature on a small section, but it still fiddly for the manipulator.

These analyses used only oak sections, for reasons of wood ray size and tree-ring homogeneity. However, the question of other wood species is still pending. First observations on beech indicate that the technique can be used with large rays; nevertheless, for wood with small rays (like chestnut), it will be more difficult. Thus, to estimate the potential of the radius of curvature measurement on each type of wood (for large and small wood rays), further analyses are necessary.

Conclusion

This work is the first which compares different measurement techniques, and is the first step towards mapping the limits and reliability of each measurement technique for a better interpretation of the data and their use models to determine wood diameter. This study shows that radius of curvature measurement based on tree-ring morphology alone must be avoided. The trigonometry in an isosceles triangle technique is the best method, with good reliability and ease of use.
This comparative study has shown the advantages and drawbacks of the techniques using image analysis software. Now it is indispensable to test these methods on charcoal fragments (Paradis, ongoing PhD). The first results show that measurement on charcoal is easier due to the better visibility of wood rays and the ease with which a fresh transverse section can be obtain by a simple split. But these analyses are still in progress.

Thanks to Farid Boumediene and Guillaume Grenouillet for their help on the statistical aspects and to Carmela Chateau, Emanuelle Grimaud and Amy Wells for English corrections. Thanks also to Romain Rouaud for discussion which was very helpful in the construction of new measurement techniques.

References

Chabal, L., Fabre, L., Terral, J.-F., and Théry-Parisot, I., 1999. L'anthracologie. In J.E. Brochier C. Bourquin-Mignot, L. Chabal, S. Crozat, L. Fabre, F. Guibal, P. Marinval, H. Richard, J.F. Terral, I. Théry (éds.), *La Botanique*, 43-104. Paris, Errance (Collection "Archéologiques").

Chrzavzez, J., 2006. *Apport méthodologique et étude de cas: la grotte de Fumane dans les Pré-Alpes italiennes*. Master II Environnement et Archéologie, Paris I.

Dufraisse, A., 2002. *Les habitats littoraux néolithiques des lacs de Chalain et Clairvaux (Jura, France) : collecte du bois de feu, gestion de l'espace forestier et impact sur le couvert arboréen entre 3700 et 2500 av. J.-C. Analyses anthracologiques.* PhD Thesis, Université de Franche-Comté, Besançon.

Dufraisse, A., 2006. Charcoal anatomy potential, wood diameter and radial growth. In A. Dufraisse (ed.), *Charcoal analysis: new analytical tools and methods for archaeology. Papers from the Table-Ronde held in Basel 2004*, 47-59.Oxford, Archaeopress (British Archaeological Reports International Series 1483).

Fiorentino, G., and Magri, D.(eds), 2008. *Charcoals from the past: cultural and palaeoenvironmental implications. Proceedings of the third international meeting of anthracology (Lecce, Italy, June 28th - July 1st 2004)*. Oxford, Archaeopress (British Archaeological Reports International Series S1807).

Hillebrecht, M.L, 1982. *Die Relikte der Holzkohlewirtschaft als Indikatoren für Waldnutzung und Waldentwicklung*. *Untersuchungen an Beispielen aus Südniedersachsen*. Göttinger Geographische Abhandlungen 79

Ludemann, T., and Nelle, O., 2002. *Die Wälder am Schauinsland und ihre Nutzung durch Bergbau und Köhlerei*. Freiburg, Forstwissenschatliche Fakultät der Universität Freiburg und Forstlische Versuchs- und Forschungsanstalt Baden-Württemberg.

Lundström-Baudais, K., 1986. Etude paléoethnobotanique de la station III de Clairvaux. In Pierre Pétrequin (éd.), *Les sites littoraux néolithiques de Clairvaux-les-Lacs (Jura). I, Problématique générale, l'exemple de la station III*, 311-391. Paris, Maison des Sciences de l'Homme.

Marguerie, D. (ed.), 1992. *Evolution de la végétation sous l'impact anthropique en Armorique du Mésolithique au Moyen Age : études palynologiques et anthracologiques des sites archéologiques et des tourbières associées*. Rennes, U.P.R. n° 403 du C.N.R.S.

Marguerie, D., and Hunot, J.-Y., 2007. Charcoal analysis and dendrology: data from archaeological sites in North-western France. *Journal of Archaeological Science* 34, 1417-1433.

Nelle O, 2002. *Charcoal burning remains and forest stand structure – Examples from the Black Forest (suth-west Germany) and the Bavarian Forest (south-east Germany).* BAR international Series, 1063. Oxford: Archaeopress. 201-207

Paradis, S., 2007. *Etude dendro-anthracologique : une approche méthodologique pour l'étude des calibres de bois. Application sur des charbonnières médiévales du Mont-Lozère (France, 48)*. Master Pro Archéosciences, Université de Dijon.

Thiébault, S. (ed.), 2002. *Charcoal analysis. Methodological approaches, palaeoecological results and wood uses. Proceedings of the Second International Meeting of Anthracology, Paris, september 2000*. Oxford, Archeopress (British Archaeological Reports International Series 1063).

Vernet, J.-L. (ed.), 1992. *Les Charbons de bois, les anciens écosystèmes et le rôle de l'homme*. Colloque organisé à Montpellier en décembre 1991, Paris, Bulletin de la Société Botanique Française, Actualités Botaniques, 2/3/4.

Willerding, U., 1971, *Methodische Probleme bei der Untersuchung und Auswertung von Pflanzenfunden.* Vor- und frühgeschichtlichen Siedlungen. - Nachr. aus Niedersachsens Urgesch. 40: 180-198.