Review of literature
2. Review of Literature

Forest biometricians are attempting to improve the method and mode of data collection in the most efficient manner possible. Trees are measured to provide data on growth, yield, health, and economic or ecological value. These data are needed to make sound and informed management decisions. Tree diameter measurements are needed for almost all inventory and modeling aspects involving forests. Growth, volume/biomass, health, value assessment, habitat evaluation, etc., are all estimated and modeled using tree diameter measurements. Diameter at breast height (DBH) is commonly collected. Many types of diameter measuring instruments (dendrometers) exist, possessing widely differing properties (e.g., accuracy, precision, cost, operational simplicity, etc.). A dendrometer should be efficient and not disrupt a stem’s normal growth in addition to being ‘simple to use, portable, relatively inexpensive, accurate at all tree heights, and operable independent of distance from point of measurement’ (Avery and Burkhart, 1983).

2.1.1. Variation in reflection capacity of tree bark

Across the visual spectrum, tree trunk reflectance was 2–10 times higher than the surrounding foliage and differed among trees (Yanoviak and Dudley, 2006). The reflectance of irradiation in the stems increased with increasing wavelength and decreased with the age of stems. In the range 400-700 nm it ranged from 18% in 1-year-old stems to 10% in 10-year-old stems, and reflectance in the trunks was equal to 15%. In the range 700-1100 nm, it ranged from 51% in 1-year-old stems to 36% in 10-year-old stems (Pilarski et al., 2008). The decrease of reflectance with the stems age, similarly as in the case of the beech, has been observed in other plant species e.g. in lilac (Syringa vulgaris L.) Pilarski (1989). In species in which the accumulation of cork does not take place because its outer cells peel off, the photosynthetic pigments in cork are present all the time, not only in stems and branches, but also in the trunks and poplar trees belong to these species. They have a characteristic bright grey colour that slightly glitters in the sunshine (Berveiller et al., 2007).
Tree trunks are a conspicuous part of the visual landscape in even the most dense tropical forests, and the light reflected from tree bark is described as having moderate brightness along with moderate to high wavelengths, i.e. they appear as brown (Endler, 1993). (From Yanoviak and Dudley, 2006). Moreover, light reflected from tree trunks tends to be vertically polarized whereas light from leaves generally is polarized in the horizontal plane, and these patterns tend to persist even under heavily shaded conditions (Shashar et al., 1998).

Colour is an important feature providing feedback about fruit ripeness, flower condition as well as location (e.g. von Frisch, 1967; Prokopy et al., 1983; Casper and La Pine, 1984; Kelber et al., 2002). Brightness and colour of a reflective surface are also functions of the characteristics of incident light (Endler, 1993). In case of Apple, number of fruits were detected with an 89 % accuracy rate (Stajnko et al., 2009). The HSI colour space is more appropriate for this purpose in contrast to the RGB colour space as it is easier to segment the images based on their hue values. If we focus on hue plane we can omit the influence of sunny and shaded regions that can affect the results (Stajnko et al., 2009).

The procedures described by Sites and Delwiche (1988) was based on capturing digitalized images while applying additional lighting to the scene. The illumination conditions are selected with care to promote regions of interest and to suppress surrounding light scatter. Some purposed approaches also use night-time conditions, when there is no interference from other light sources. These features determine the degree of contrast between an object and its background, thus influencing signal quality and resource detection (Endler, 1993; Altshuler, 2003).

Soil light reflectance spectra was able to predict soil carbon and clay with 70–88% accuracy (Shepherd and Walsh, 2001). Maximum density and blue reflectance of tree rings were found to be appropriate for assessing changes in accumulated temperature for the growing season (Tene et al., 2011). Several studies have shown that blue reflectance from tree rings is good surrogates for marking past climatic events (McCarroll et al. 2002, Campbell et al. 2007).
2.1.2. Prediction of ground distance/range finding

Rangefinder dendrometers use either a fixed baseline distance or viewing angle and the ability to accurately measure the alternate variable to obtain true and false coincidence angles from which the radius of the stem at that location is calculated. There have been many studies done with varying models of the Barr & Stroud—a short-based, split-image, coincident, magnifying dendrometer. Jeffers (1955) obtained a 95% confidence interval of ±15.2 mm in field tests with an added caveat that standard deviations three times larger may be common where visibility is obscured. Also, with the model FP9, Grosenbaugh (1963) found that volumes of individual trees would be within 4.1% of taped volumes two-thirds of the time. The FP12 performed very satisfactorily in several tests (Sandrasegaran 1969, Bell and Groman 1971, Robbins and Young 1973, Brickell 1976) before modifications (Mesavage 1967) were implemented in the last model—the FP15 (Mesavage 1969a). This unit was found to be more precise (Bower 1971). The Barr and Stroud continues to be a means of comparison to other instruments (Garrett et al. 1997, Williams et al. 1999). The Breithaupt Todis dendrometer (Eller and Keister 1979) and other teletop instruments (Mesavage 1969b, Grosenbaugh 1963, Brickell 1976) differ from the Barr and Stroud in that the convergence angle is fixed and range is measured by varying the baseline distance. What differentiates these instruments from optical callipers, also having two pentaprisms mounted on a scale, is the use of a deflecting prism to define a convergence angle. The advantages of these instruments compared to other similar contemporary instruments are instrument costs and direct measurement readings. Reduced weight is an advantage in Mesavage’s (1969b) modified teletop as opposed to the greater weight of the Breithaupt Todis (Eller and Keister 1979). Mesavage (1969b) reported a coefficient of variation of 0.5% with a percent bias of –0.4% for 12 breast height diameters using a modified teletop instrument. Breithaupt Todis measurements were unbiased within ±7 mm of the actual 95% of the time (Eller and Keister 1979).
2.2.1. Optimization of threshold levels for prediction of crop diameter

Use of reflected light for crop diameter estimation is a new method of assessment and hence no much studied relate to fixing of threshold level for accurate diameter estimation has been carried out. Juujärvi et.al. (1998) explained a method of tree delineation from the background region. The approach estimates vertical edges for the stem, such that the colors appearing between the edges (the stem region) and out of the edges (the background region) are as distinct as possible. The algorithm searches all reasonable left and right edge combinations within the window. For each edge combinations stem and background intensity histograms are calculated and the left and right edge positions giving the best separation, i.e. when the stem and background histograms overlap as little as possible, for the stem and background segments are finally selected as the correct edge positions. By moving the segmentation window upper on the tree according to estimated previous stem edge positions, it is possible to segment the whole stem out of the image.

2.2.2. Optimization of plot area for prediction of crop diameter

Measuring distance had no impact on measuring accuracy. The trees were located not more than 10 m from the sample plot center point. For the purpose of the project goals, the optimal operational distance was defined as 2 - 15 m (Melkas et al., 2008).

Clark et al. (2000) studied single tree diameter measurements at a constant distance of 12 or 15 meters. A new Laser-camera prototype is based on the reflection of a laser line and point on a tree stem. The laser line reflection breaks at the border lines of the tree stem so that the stem diameter can be measured, based on the length of the reflected laser line. Two photographs were taken from each tree during each measurement occasion. Two diameter measurements were measured per tree (Melkas et al., 2008). It required approximately 7.5 min to measure a sample plot of about 22 trees and 10 sec to measure the diameter of one tree stem.

The error in height and diameter measurement increased with increase in camera distance and measurement height. As the camera distance increased from 25 metres to 50
metres, the error in diameter measurement increased from 0.6 to 1 cm. Photogrammetrically derived volume was 13% less than those which were based on theodolite measurements (Gaffrey et al., 2001).

2.3. Height and Diameter relationship for prediction of height

Forest and Plantation management usually requires updating the growth parameters at regular intervals to refresh the future plans and decisions as affected by market and environmental variables. Investment in forest inventory operations is usually weighed against the tangible benefits gained from the information obtained i.e., the direct economic return from the concerned forest. Any effort to ease and reduce the cost of forest inventories would be highly appreciated. Information of tree height is one of the key items of inventory, required for both forest management and research. The relationship between diameter at breast height (dbh) and total height is a structural characteristic of a tree that describes key elements of stem form, and thus the volume of harvestable stem. Height and Diameter relationship also affects product quality, as it influences wood structure such as lignin and cellulose content, and stiffness, the important properties of the stem (Kroon, et al. 2008). Dbh and total height are the commonly measured variables in forest inventories as they are frequently required for both routine forest management activities and for research purposes. As such, accurate data on these two variables is quite important especially for reliable future management plans. Unlike dbh, total height is less frequently used in creation or application of forest models because measurement of dbh is relatively cost effective, easier and accurate than total height (Moore, 1996 and Shrama, 2009).

An estimation of total height from height-diameter models might be a reliable and cost effective option where such models are available. For height-diameter models, a representative sample of accurately measured total height is used as the response variable and dbh as the predictor variable. To predict height for all the trees in the stand or in each sample plot, statistical models are fitted to establish the relationship between these two attributes. Usually the fitting is carried out at stand or plot level. The heightdbh relationship allows for the assessment of tree volume as well as the description of stand and its
development over time (Curtis, 1967). As a result, the relationship between tree stem height ($h$) and dbh ($d$) is one of the most studied aspects in forestry. There are several literature on height-diameter relationship in forestry tree crops (e.g. Curtis, 1967; Wykoff et al., 1982, Larsen and Hann, 1987; Wang and Hann, 1988; Huang et al., 1992; Moore et al., 1996; Zhang, 1997; Peng, 1999; Fang and Bailey, 1998; Jayaraman and Zakrzewski, 2001; Zhang et al, 2002; Sharma and Portan, 2007; Newton and Amponsah, 2007).

Height-diameter equations can be used to describe the growth relationship at a plot (Curtis, 1967), stand, or a regional level where it is used to predict individual tree heights (Larsen & Hann 1987; Wang & Hann 1988, Huang et al., 1992). A stand is a basic forestry unit of continuous area within which site conditions and management regimes are relatively uniform and it is common practice in some forestry companies that height-diameter equations be estimated at the stand level. For a given species, height-diameter relationship differs from stand to stand due to different stand densities and site qualities. Sometimes even within the same stand variation might be high (Calama and Montero, 2004). Also, height-diameter relationship may change over time (Curtis, 1967).

Height-diameter relationships are used to estimate the heights of trees measured for their diameter at breast height. Such relationship describes the correlation between height and diameter of the trees in a stand on a given date and can be represented by a linear or non-linear mathematical model. In forest inventory designs, diameter at breast height is measured for all trees within sample plots, while height is measured for only some selected trees, normally the dominant ones in terms of their dbh. However, for height-diameter models, more care is needed and a representative sample of accurately measured total-height is used as the response variable and dbh as the predictor variable (Osman, et al. 2013).

Height-diameter equations can either be used for local application or they can have a more generalised use (Soares and Tomé, 2002). Equations dependant on only tree diameters, without considering other stand variables, are only applicable locally to the stand where the height-diameter data were gathered. Generalized height-diameter equations, on the other
hand, are normally functions of tree diameter in addition to other stand variables, and as such can be applied in similar conditions at the regional level (González, et al 2007). A large number of local tree height-diameter equations have been developed and/or validated and reported in literature. Height-diameter models are principally applied in height estimations in forest inventories and as one of the main modules in management-oriented growth models. A major difficulty in modeling the height-diameter relationship is the large number of variables influencing it and thus hindering the construction of generic models based on empirical methods such as linear and nonlinear regression (Guimarães, et al, 2009).

For more comprehensive and accurate height-diameter models, additional variables describing stand density (e.g. basal area or number of stems) and site quality (e.g. site index) should be included into the models (e.g. Sharma and Zhang, 2004; Temesgen and Gadow, 2004; Sharma and Portan, 2007; Newton and Amponsah, 2007).

Statistical modelling has to balance simplicity (i.e., fewer parameters in a model, lower variability in the predicted response, but with more modelling bias) against complexity (i.e., more parameters in a model, higher variability in the predicted response, but with smaller modelling bias). Statistical model selection criteria have to seek a proper balance between over-fitting (i.e., a model with too many parameters, more than actually needed) and under-fitting (i.e., a model with too few parameters, not capturing the right signal) (Yang and Bozdogan, 2011).

However, relationships between the diameter of a tree and its height vary among stands (Calama and Montero, 2004) and depend on the growing environment and stand conditions (Sharma and Zhang, 2004). Height-diameter models are principally applied in height estimations in forest inventories and as one of the main modules in management-oriented growth models. In forest inventories, height is usually measured only for a sub-sample of trees, while diameter is measured for all the sampled trees. The major reasons for measuring only a few trees for height being that it requires a major effort, especially for dense stands and trees that are irregular in shape. The usual solution to these problems is to describe tree height (H) as a function of diameter (D). The resulting equation may then be
used to derive heights for trees for which diameter but not height measurements were taken.

Modelling stand development over time relies on accurate estimates of tree height ($h$) and diameter ($d$). Accurate height measurements are required for describing vertical stand structure and estimating stand development over time (e.g., Dubrasich et al. 1997), stand volume, and site quality (Clutter et al. 1983). However, height is costly to measure and, as a result, trees are frequently sub-sampled for height. Often the sub-sample is concentrated in the trees of greatest diameter; for example, those used to estimate site index. Sub-sampled heights can also be used to localize regional height–diameter ($h$–$d$) functions (e.g., Wykoff et al. 1982; Robinson and Wykoff 2004; Hann 2005).

The relationship between tree height and diameter varies from stand to stand owing to differences in site quality (Larsen and Hann 1987, Wang and Hann 1988), stand density (Larsen and Hann 1987, Zeide and Vanderschaaf 2001, Temesgen and von Gadow 2004), and stand age (Zeide and Vanderschaaf 2001). Even within the same stand, the relationship varies over time (Curtis 1967); by relative position of trees in a stand (Temesgen and von Gadow 2004); and spatial distribution pattern (Aguirre et al. 2003). The relationship between these two dendrometrical attributes varies from one stand to another (Calama and Montero, 2004). There are also other factors determining the relationship. The most obvious among these factors is growing space and stand conditions (Sharma and Zhang, 2004) for a particular height, trees that grow in high density stands tend to have smaller dbh than those growing in less dense stands, because of greater competition among individuals (Calama and Montero, 2004). These facts highlight that stand-level attributes are required for providing generalized height–dbh equations able to predict individual tree height for forest stands on large territories (e.g. at National or Regional levels) maintaining projections within reasonable biological limits (Temesgen and Gadow, 2004). Thus, localization of the regional height–diameter relationship is an important step in obtaining accurate growth and yield estimates.
Several approaches have been exploited in the development of generalized height-DBH models. For instance, Harrison et al. (1986) included stand dominant height in their height-DBH model. Soares and Tomé (2002) used stand dominant height, maximum DBH, and density as predictor variables in addition to DBH. Eerikainen (2003) used stand dominant height, dominant diameter, density, and age information in their models to improve model accuracy. Similarly, Zakrzewski and Bella (1988) exploited quadratic mean DBH and the height of tree with quadratic mean DBH to increase model efficiency.

Many growth and yield models require height and diameter as basic input variables, with all or part of the heights predicted from measured diameters using regional height–diameter functions (Wykoff et al. 1982, Huang et al. 1992, Hann 2005). Regional height diameter functions can also be used to indirectly predict height growth (Larsen and Hann 1987). For example, in the southwestern Oregon version of the ORGANON growth and yield model (Hann 2005), missing heights are directly predicted using the species specific height–diameter equations of Hanus et al. (1999a), and these equations are also used to estimate height growth from diameter growth for minor species. Tree height is also a critical variable in many process and hybrid models, such as Biome-BGC (Running and Coughlan 1988).

2.4 Form Factor for tree volume estimation

Estimating stand volume is a basic requirement in forest management and growth or biomass related studies. This requires the method used to be more accurate and practical under field conditions. Form factor is important for correct tree and stand volume estimation. Form factor is the ratio of tree volume to the volume of a geometrical solid, such as a cylinder, cone or a cone frustum that has the same diameter and height as the tree (Benbrahim and Gavaland, 2003). Determination of volume of trees and their parts on the basis of two basic characteristics, DBH and height, advisable from the practical point of view, is burdened with errors resulting from stem form variation. This variation mainly results from differences in diameter growth rate at different stem heights as well as from differences in tree height increments (Mitscherlich 1970). These differences may be caused by many factors, e.g. species variation, climatic factors, site quality, age, defoliation, and genetic

Basically, the tree volume is derived from $V = ghf$ equation; where "V" is tree volume (in m$^3$), "g" is basal area at breast height (in m$^2$), "h" is tree height (in m), and "f" is the tree form factor. Basal area measurement inside the forest stand can be carried out in a relatively cheap and easy way. However, measuring form factor and height is critically time-consuming and expensive work inside the stand. Although the problems associated with height measurement is somehow solved by applying different diameter and height equations and curves, measuring real form factor is still a crucial problem.

The use of different reference point has resulted in many different types of form factors. Four of the form factors are important due to their popularity namely, absolute form factor (Claughton-Wallin and Mc Vicker, 1920) the breast height form factor (Inoue, 2006) the true form factor (Socha and Kulej, 2005) and the normal form factor (Kajihara, 1969).

Real form factor is explained as the real volume divided by the volume of a cylinder having the basal area equivalent to the tree's basal area at breast height and the height equal to the tree's height (Zobeiri, 2000). Therefore, if such a form factor featuring the defined height and Diameter at Breast Height (DBH) can be achieved, the tree volume assessment will be much easier (Zobeiri and Najjaran, 1984). To calculate the Real form factor, the tree should be cut down and its precise volume should be measured. This is considered as a time-consuming and costly work. As a result, forest researchers have proposed a variety of form factor formulas in order to replace the Real form factor (Girard, 1933). The amount of precision of these form factors varies based on the site, age, and species. For instance, the artificial form factor showed to be extensively different in various even aged Pinus sylvestris stands in Poland and the stand volume error ranged between -2% and -8% (Bruchwald and Grochowski, 1977). Heger (1965) and Assman (1970) have mentioned the advantages of total volume estimation using Natural form factor formula derived from Hohenadl's method. Rahimnejad (2002) studied 150 Loblolly Pine trees in Lakan- Guilan province in order to
replace an appropriate form factor instead of real form factor. However, as Bonyad and Rostami (2005) reported following a form factor investigation of Pinus elliottii stands in 25, 27, and 30 year-ages, no significant difference was observed amongst 0.1 f, 0.5 f, and r f. Thus, they proposed the application of 0.5 f, instead of r f in tree volume assessment (V=g×h×f).

Results of the study showed that there is no significant difference, not only between the Artificial and Real Form factors, but also between Real and Hohenadl’s Form factors at 0.01 and 0.05 probability levels, at the age of 18 years. In other words, Artificial and Hohenadl’s Form factors (0.5 f and h f) are capable enough to replace the Real Form factor (r f) at the age of 18 years over the study area. However, the Real and Natural Form factors proved to be significantly different at 0.01 and 0.05 levels.

As in the previous case studies, no significant difference was observed between the Real and Hohenadl’s Form factor (= 0.05), in the study carried out by Bonyad and Rahimnejad (2004) in Loblolly Pine stands at the age of 26 years. In the other study performed by Mahinpour (2002), in Pinus elliottii stands at the age of 27, none of the calculated Form factors proved the capability to replace the Real Form factor. The amount of accuracy varies based on the site, age, and species. Moreover, the form factor’s capability to replace the Real form factor does not guarantee its preference at the tree’s all growth levels and ages. That is mainly because the tree shape highly varies with age due to its growth. Sometimes, trees belonging to a particular stand even tend to turn into a cone shape from their normal cylinder shape as they grow. Fadaei (2005) studied in Loblolly Pine stands in Pilambara and reported that the Real Form factor in these stands tends to decrease as the stand’s age increases. Hence, any sort of changes in the tree’s shape can highly affect its Form factor. It results in preference of one Form factor over the others at a particular age.

Nevertheless, the Artificial Form factor showed a great practical ease over the Hohenadl’s Form factor. This is because of the fact that just one diameter is required to be measured inside the stand, at higher than the breast height, for calculating Artificial Form factor. Hence, it can be considered as an effective tool in terms of reducing measurement
costs and time. In addition, the results showed that the volumes yielded from f0.5 and fh were not significantly different from the real volume, and were much less erroneous compared to the volume derived from f0.1. (Fadaei, et al 2008)

Stem form variation is affected by the provenance in grand fir. Provenances of mother stands that grew at higher altitudes were characterized by greater stem volume in comparison with provenances of lower altitudes, at equal DBH and height (Socha and Kulej 2005). Dudzinska (2003) found differences between mountain and lowland trees in respect of the stem form in European Beech. Similar conclusions were drawn for the Norway spruce stem form (Socha 2002). In Abies grandis stem form variation was influenced by the provenance (genotype). Knowledge of factors affecting the stem form of forest trees is the basis of correct determination of tree volume, not burdened with systemic errors. Stem tapering, affecting the quality of timber to a certain extent, may be one of the criteria of provenance selection.

Socha and Kulej (2007) estimated the provenance variation of the tree form factor and taper of European larch and concluded that differences in the values of the stem form and taper, observed on the basis of a direct comparison, resulted from differences in the growth rate of the analyzed larch provenances causing a significant diversification of diameter and height of trees but the differences between provenances were not statistically significant. In the case of true stem form factor (f0.05) significant differences in absolute values of this trait were found between provenances from Myślóbórz Pólnoc and Konstancjewo-Tomkowo. However, these differences resulted from the relationship between the true form factor and diameter and height of trees. The elimination of the effect of diameter and height made these differences statistically insignificant (α = 0.05). More detailed information on the stem form of larch was obtained on the basis of analysis of relative diameters at different heights of the stem. In this case, irrespective of assumed diameter in respect of which relative diameters at individual stem heights were computed, and in spite of a certain diversification of mean stem profiles of individual partial populations, no significant effect of the genotype (provenance) on their variation was found. The variation
of the stem form was not significantly affected by the provenance region, either. The observed differences in mean diameters from individual stem heights were statistically insignificant.

The diameter increment along the stem changes depending on stand density, as the diameter in the bottom part of the stem increases and in the top part decreases, with decrease of stand density. In consequence, the lowering of stand density causes decreasing of slenderness of trees thus making them more stable. It also increases their tapering. Although the influence of stand density on stem slenderness and tapering is obvious, there is no definite information whether it significantly affects the form factor and fullness of the stem.

The differences in the stem form due to different stand density are relatively small. The diameter increment in the bottom stem part increases and the increment in the top part decreases as the stand density decreases. Therefore, diameters in the bottom stem part increase faster than those in the top part. However, the diameter increase expressed in relative values does not necessarily accompany a faster increase of actual diameters. Also, the diameter, in reference to which individual relative diameters are computed, is changing, and this causes that value of the relative diameter remains the same in spite of a considerable increase of stem tapering and slenderness (Socha, 2007).

Stand density determines the stem form of trees to a certain degree. However, the differences in the stem form were relatively small and concerned the top part of the stem. Because the form of the top part relatively affects little the total stem volume, the application of the stand density index in equations determining volume does not cause any significant increase of the proportion of the explained variance, and this seems to eliminate the usefulness of this characteristic as the independent variable in empirical equations for volume determination.
2.5 Comparison of different dendrometers for estimation of volume of standing crop

Dendrometers can be divided into two categories; those that contact the stem physically and those that obtain measurements remotely. Conventional callipers and diameter tapes are the primary “contact” dendrometers used by foresters. The simplicity of their manufacture, design, and operation has left them unassailable since their inception with the only significant technical advances coming in the form of digital recording devices. Callipers measure the distance between parallel tangents of a closed convex region, while diameter tapes measure the perimeter or girth of this region. Diameter tapes can be said to be more “consistent” (Avery and Burkhart 1994) than callipers as the measurement represents an average of all diameters over all directions, thus eliminating variability caused by direction. However, it is now recognized that departures from the assumptions of convexity and circularity hinder the simple attainment of the elusive “diameter.” If used properly, both tools provide comparable results with the majority of bias caused by mathematical models that do not accurately represent stem cross sections (Brickell 1970, Biging and Wensel 1988). More on cross-sectional geometry and related concepts can be found in Matérn (1990).

The electronic tree measuring fork (ETMF) (Binot et al. 1995) is another true contact instrument. The ETMF has two arms, 60° apart, that contact the tree. Diameter is computed by measuring the speed of ultrasonic waves from a transmitter to a receiver. In the study by Binot et al. (1995), diameter results were comparable to callipers and diameter tapes with a 35 to 40% time savings. Concerns were noted regarding bias caused by signal interference induced by bark characteristics of some species. A plethora of other devices viz the Biltmore stick (Jackson 1911), sector fork (Bitterlich 1998), Samoan stick (Dixon 1973), etc. are hybrid instruments which contact the stem and the results are interpreted visually. Matérn (1990) found all these instruments to have a positive bias, increasing proportional to diameter, compared to conventional caliper measurements. Although these tools are very handy and
probably the most common instruments among practitioners, their reliability and subjectivity generally prohibit their use in scientific or large-scale inventory work.

Optical dendrometers do not require the stem to be approached and is a non contact dendrometer. Several styles of optical dendrometers have been designed based on the fork, caliper, and rangefinder principles (Grosenbaugh 1963). To measure a diameter optically, two lines of sight must exist between the observation location and two tangents on the stem lying in the plane representing the desired diameter. Perspective geometry utilizing various angle and distance measurements is then used to calculate the diameter of the stem in this plane.

Optical callipers use two parallel lines of sight to view points on a stem that represent the diameter making measurement precision. Direct readings of parallel tangents require only aspect to be controlled when making measurement comparisons with conventional callipers. Some of the early optical callipers were non coincident (Clark 1913) and experienced difficulties maintaining parallelism, but instruments using pentaprism (Wheeler 1962, Eller and Keister 1979) or parallel mirrors (McClure 1969) have succeeded in producing excellent results. Diameters are limited to the instrument’s length (usually 91 cm), though longer, less portable, versions can easily be constructed (Grosenbaugh 1963).

A number of empirical studies have been performed with pentaprism since their resurgence in the early 1960s. Wheeler (1962) measured ten trees at two heights (1.4 and 5.3 m) using a Wheeler’s pentaprism caliper. Measurements were within ±13 mm of wooden caliper measurements using a 95% chi-square test. Robbins and Young (1968) compared three dendrometers namely the Wheeler pentaprism, an early version of the McClure pentaprism (that only permitted direct readings to the nearest 13 mm), and a diameter tape to conventional callipers. Twenty stems were measured, containing marked diameters at 6 heights (from 1.5 to 10 m). The ranges of errors relative to conventional callipers were –18, 33, –18, 20, and –20, 25 mm for diameter tape, McClure, and Wheeler pentaprism respectively. All instruments studied had a slight positive bias between 3 and 5 mm. However, Robbins and Young (1973) found the McClure pentaprism produced greater
average differences than the Wheeler pentaprism and the Barr & Stroud dendrometer in a study on ten trees at eight heights (1.5 to 10 m). The Wheeler pentaprism demonstrated time savings over the other two instruments and has finer graduations and greater magnification than the McClure instrument. A range of differences between −16 and 37% was presented by Garrett et al. (1997) for breast height and undefined upper stem diameters on 25 stems. Parker and Matney (1999) experienced a standard error of 0.56%, about a mean percentage difference of −4.16% for diameters at 5 m heights using a Wheeler pentaprism. Efficiency and ease of use are the consistently noted advantages of optical caliper instruments.

Optical forks use the principle of similar triangles to determine the angle between two intersecting tangents of the stem at the desired diameter location. Distance from the line of sight intersection to the point of measurement (range, \(d_2\)) needs to be obtained as well as the distance (\(d_1\)) to a baseline (\(b\)) measurement. Some of these dendrometers work with a fixed fork angle where \(d_1\) and \(b\) are defined by the “apparatus”—whether it be a wedge prism alone (Rennie and Leake 1997), a wedge prism mounted to one lens of an ordinary pair of binoculars (Bitterlich 1984), or any other object of set dimension (thumb, coin, etc.) placed at a set distance (e.g., arm length) from the eye. Number of devices have been used with distance measuring methodologies ranging from contact (Stoehr 1960, Qazi 1975), to pacing alone, to taped measurements using an inclinometer for horizontal distance and height calculation (Vaux 1952, Rennie and Leake 1997). The observer must adjust the range (\(d_2\)) to the stem until the limiting distance of the apparatus is achieved. Although the components of these “instruments” are inexpensive, implementation is challenging. Other optical forks vary or measure the line of sight angle.

Military binoculars having a mil-scale (Forbes 1955), a transit fitted with a reticle (Robinson 1962), and other handmade instruments (Qazi 1974) have been used to accomplish this purpose. The Spiegel Relascope (Rennie and Leake 1997) and the Tele-relaskop (Parker 1997) are two commercially available units that use pendulous relative unit scales from which heights and diameters are determined given one known height, diameter,
or distance. The multipurpose Relascope has not fared well when used to measure upper stem diameters (Garrett et al. 1997, Ashley and Roger 1969, Rennie and Leake 1997). Relascope errors are sometimes attributed to a lack of magnification, which is improved with the 8× magnification of the Tele-relaskop. The latter instrument has been shown quite capable for diameter measurements (Garrett et al. 1997, Parker 1997), but not very useful for height determination (Williams et al. 1994).

Earlier reports on diameter measurement using camera methods showed varied error values in measurement. Marsh (1952), first used cameras to measure tree diameters and obtained diameters within ±20.3 mm error. Bradshaw (1972) used camera in conjunction with a clinometer and tape for calculation of slope distance, where diameter at different heights were measured with an accuracy of ±9.9 mm. Crosby et al. (1983) similarly used 35 mm camera and a telescoping rod to measure height and a scale attached to the rod to determine the photo scale in Eastern White Pine (Pinus strobus). A prototype Minolta camera using the autofocus capability as a rangefinder was tested by Takahashi et al. (1997). An experiment conducted in Hinoki (Chamaecyparis obtusa) showed a mean error of +1.6 mm and S.D. of 4.6 mm after corrections for bark and systematic errors. Diameter determined in Scots pine by photographing single pine stems with a simple digital camera resulted in a -0.6mm to -2.8 mm bias and 7.0 to -9.4 mm RMSE (Varjo et al., 2006). The accuracy of camera methods were comparable to steel calliper’s accuracy, which varies between 2.7 and 6.9 mm (Hypponen and Roiko-Jokela, 1978; Paivinen et al., 1992).

Cameras also fit into the optical fork category. Rather than measuring the angle at a point between the intersection of the lines of sight and the diameter being measured, a measurement is taken from an image. Marsh (1952) provided some of the first results of using terrestrial photogrammetry to measure tree diameters but the reported results were not very good: ±63.5 mm for oblique photos and ±20.3 mm for horizontal photos. Ashley and Roger (1969) designed a device and procedure that placed the camera in a set orientation to the stem. They did not present any field test results for this device, but reported an accuracy of ±7.6 mm for laboratory measurements of fixed targets (every 5 ft up to 100 ft on a flat
surface). Bradshaw (1972) used a camera with a 135 mm lens and a basic scaling formula to obtain 26 diameters from a single stem with an accuracy of ±9.9 mm. Another study using a 200 mm lens and a scale of known length was conducted by Crosby et al. (1983). Average errors reported by this study were 0.063% and 0.089% for black and white photos and slides, respectively, with standard deviations of 1.91 and 2.40% on diameters less than 50 cm. In a study by Takahashi et al. (1997), a prototype range-finding camera with a 500 mm lens produced results with mean error of +0.15 mm and standard deviation of 4.9 mm, after corrections for false diameter and distance. In another experiment, 29 diameter measurements of hinoki (Chamaecyparis obtusa) stems produced a mean error of +1.6 mm and standard deviation of 4.6 mm, after corrections for bark and systematic errors. Clark et al. (2000a) used a nonmetric digital camera to measure diameters within 40 mm at any heights to 20 m and within 25 mm at heights below 5 m. The most recent advancement for dendrometers is the use of laser instruments (Carr 1992) to measure distance finally eliminating concerns about tree lean (Grosenbaugh 1980, 1981, 1991). This is accomplished by measuring the time lag between emission and reception of precisely directed energy pulses from the unit. Diameter accuracies as reported in some empirical studies range from 8 mm (Fairweather 1994) to 14.3 mm (Williams et al., 1999). Some criticisms of current instruments include: understorey obstructions interfering with distance measurement, parallax effects, and difficulty viewing through the reticle (used to measure the angle between the lines of sight).

Measurement conditions like low light conditions, terrain, species, morphology, understorey and wind may affect the performance of some instruments more than others. Experimental procedures like marked observation points, control for aspect, range of diameters, heights, distances, etc., and statistical analysis (e.g., paired observations vs. mean error, standard deviation vs. 95% chi-square, percent vs. absolute units) can influence results or prohibit side-by-side comparison between studies (Clark et al., 1998).

Most of the literature about forestry applications of terrestrial photography has focused on obtaining upper stem diameters and tree height. Since taking multiple
photographs was expensive, the method could not be followed. Recent advances in the field of microelectronics expand the opportunity for terrestrial photography of trees. The invention and development of Charged-Coupled Devices (CCDs) allow the capture of light rays at resolutions almost comparable to film emulsion methods. The output of the CCDs is an image in digital format. The advantages are quick and cost effective developing and printing of images, easy storage and organization of images and provision for digital image manipulation. All these allow operations which could never be accomplished with standard film technology.

Clark et al. (2000) attempted to estimate diameter and height using commercially available digital camera in 20 red oak (Quercus spp.) stems and estimated the volume. The error was found to be within 8% of the volume calculated using tape measurements of individual stems (Clark et al., 2000a).

The height, diameter and volume on 20 hardwood and 20 softwood stems using traditional optical Dendrometers, an experimental camera instrument, and mechanical callipers were studied and compared. There were no significant differences among the methods for volume or height except stem diameters. In camera method, the discrepancies in diameter were observed in larger stems. (Clark et al., 2001).

With the advent of new concepts and ideas, it is possible to estimate the biomass of a tree without destroying the tree itself. This concept is referred to as Montes method in which a tree is measured in a photograph using grids along the axis of the main stem and branch independently. It is not possible to weigh a tree in a photograph, but the volume of different components can be estimated from it using approximations of geometric solids and corresponding diameter measurements. If the density of each tree component is known or measured, it becomes possible to estimate biomass from estimated volume without felling the tree. This method involves separation of main stem and branches for estimation of biomass (Montes, et al., 2000). Adhikari (2005) proposed a much simpler method known as model stem method in which the grids were formed in the axis of the main stem and total biomass including branches was estimated at once.
Measurement errors from digital image can occur in several ways. Delineation between the trees and background is most important factor. The delineation becomes subjective when tree boundaries are not clear and the visibility is hampered by foliage and other stems. Time, season, weather conditions, orientation, and camera settings affects spectral sensitivity. Too little or too much light can reduce spectral contrast between the stem from the background (Clark et al., 2000a). Using digital images in yield measurements provide good or better accuracies than any optical dendrometers available, require much less time to collect vast data since each image contains a large number of diameter and height measurements, provide image viewing after capture to assess image quality and make necessary adjustments, acquire images at one point in time, but measurements can be made many times for multiple purposes, assure quality and provide opportunity for re-measurement from a single image.

By combining equipment and procedural modifications with improved data flow from imagery to information, terrestrial digital imagery may revolutionize stem or even plot level data collection. The use of digital imagery and image processing software as a multi-measurement dendrometer offers many advantages over existing optical instruments, while providing accuracy that is equivalent to, or better than, traditional methods (Clark et al., 2001).

Laser technology has been used for tree measurements. The accuracy in measuring DBH varied from 8 mm to 16 mm with laser relascope (Kallinvirta et al., 2005) and from 8.8 mm to 14.3 mm with laser-dendrometers (Parker and Matney, 1999). With camera-based systems the accuracies obtained have varied from 7.0 mm to 9.9 mm (Ashley and Roger 1969; Bradshaw 1972; Varjo et al., 2006). The accuracy achieved by Vastaranta et al. (2009) were also similar: 8.3 mm (4.5%) with Terrestrial laser scanner (TLS), 8.5 mm (4.9%) with the laser camera and 14.3 mm (8.3%) with the laser-relascope. Melkas et al. (2008) reported that it required approximately 7.5 min to measure a sample plot of about 22 trees and 10 sec to measure the diameter of one tree stem using Laser-camera.
Howe and Adams, (1988) reported that Clinometer was observed to underestimate the height consistently by 3.9%. Height measured through five different instruments viz., Suunto Clinometers, Speigel Relaskop, Enbeeco Clinometers, Speigel tele-relaskop, Laser height finder showed an average error values ranging from 2 to 5 ft (Williams et al., 1994). Comparatively Tele-relaskop produced more error than other instruments especially when the height of the trees was higher than 90 feet.

Gaffrey et al. (2001) reported that the error in height and diameter measurement increased with increase in camera distance and measurement height. As the camera distance increased from 25 metres to 50 meters, the error in diameter measurement increased from 0.6 to 1 cm. Photogrammetrically derived volume was 13% less than those which were based on theodolite measurements.

There have been many attempts for predicting height-diameter relationships for different species and in different forest regions. The approaches used for developing height-diameter models have varied from linear to nonlinear models. Most of the models were developed keeping DBH as predictor variable for estimating total tree height (e.g. Arabatzis and Burkhart, 1992; Huang et al., 1992; Moore et al., 1996; Huang, 1999). The height-diameter relationship varied from stand to stand, and even within the same stand it changed with age (Flawelling and de Jong, 1994; Lappi, 1997; Eerikäinen, 2003), stand densities and site qualities (Sharma and Zhang, 2004; Tremesgen and Gadow, 2004; Mehtätalo, 2005, Sharma and Portan, 2007; Newton and Amponsah, 2007).

Omule (1980) reported that bias in DBH and subsequent basal area per hectare measurements were as negligible. The coefficient of variation (CV) among crew was 8.16 and 4.09% for DBH and basal area. Heights were significantly underestimated and the among-crew CV was 21.86%. In general, measurement errors are not negligible. Their magnitude should be estimated per inventory and included in the total error of the inventory estimate (Omule, 1980).

Fastie (2010) studied basal area in an Alaskan birch forest using a traditional Bitterlich prism in comparison to complete tree measurement and GigaPan imager. He observed that
the prism measurement was 13% underestimated and Image analyser method was 9% underestimated in the basal area of the forest. Adam Dick has developed a protocol for estimating basal area from digital panoramas and has also pioneered a technique for mapping trees using digital panoramas (Dick et al. 2010).

Vanclay (1995) stated that when inventories use large BAFs and sample small trees, this may lead to considerable bias. Inventories in the tropics commonly use $BAF = 10 \text{ m}^2 \text{ ha}^{-1}$, and may sample trees as small as 3 cm dbh, and this may lead to overestimates of 200% in the smallest size class. However Mannel et al. (2006) and Salek and Zahradnik (2008) compared the wedge prism along with actual measurement of trees and reported that wedge prism as an accurate tool for measurement of basal area.