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Comparison of different dendrometers and LVDT-sensors in laboratory and field conditions

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Promotor: Prof. dr. ir. Kathy Steppe

Masterproef voorgedragen tot het behalen van de graad van

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De promotor: De auteur:

Prof. dr. ir. Kathy Steppe Aline De Belder

Preface

A master thesis, the word itself has many negative connotations and I was rather scared to start my final year at university. During a course of terrestrial ecology, our professor Kathy Steppe introduced us to several possible thesis topics at the Laboratory of Plant Ecology. I don't exaggerate when I call her one of the most inspirational and enthusiastic people I have ever met with. The topics she suggested were all interesting to me, because they were related to plant ecology. However, exploring all the possibilities, one subject grasped my attention – comparing different dendrometers and LVDT-sensors in the botanical garden in Innsbruck. During my stay in Innsbruck and further research at Ghent University, she was very motivational and the successful ending of my thesis is for a great part due to her. For all these reasons, my first thank you is for her.

A second and very important person I would like to thank, is Philip Deman. He studied all the different sensors that we received and he connected them with a data logger. I would not have been able to keep track of all the wires, so his technical support was of great importance. He also made a concrete block large enough to mount all the sensors, which was a key part of this whole study.

Stefan Mayr and Barbara Beikircher have been very helpful in Innsbruck with the installation of the sensors and to answer all my questions, and they have made me feel extremely welcome. Therefore, they have ensured that my stay at the university of Innsbruck was one of the greatest experiences in my life so far.

It is difficult not to mention my parents and brother in this little speech of gratitude. They did not contribute to this master thesis with their knowledge of dendrometers or LVDT-sensors, but they have supported me the most during this entire study. Therefore, I would like to thank them.

A last thank you goes to you, the reader, because you show an interest in this scientific study!

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Abbreviations

AC	Alternating current
AEC	Agricultural Electronics Corporation
CO_2	Carbon dioxide
COST	European cooperation in science and technology
DC	Direct current
DG	Daily growth
EMS	Environmental Measuring Systems
LERFoB	Laboratoire d’étude des ressources forêt-bois
LVDT	Linear variable displacement transducer
MDS	Maximum daily shrinkage
MRI	Magnetic resonance imaging
RH	Relative humidity
SDV	Stem diameter variation
SF	Sap flow
SRI	Stem radius increment
STACI	Software tool for automatic control of irrigation
STReESS	Studying tree responses to extreme events: a synthesis
THB	Tissue heat balance
UMS	Umweltanalytische Mess-Systeme

English summary

In the past few years many dendrometers and LVDT-sensors (Linear Variable Displacement Transducers) have been developed which deliver daily information on radial stem growth and also allow detection of stress situations like drought. It has been generally accepted that four important components contribute to the measured signal: irreversible radial growth, reversible shrinkage and swelling with changing levels of hydration, contraction and expansion of conducting elements due to the increase and relaxation of internal tensions, and thermal expansion and contraction. However, a wide variety of sensor types exist which may result in different outputs when these sensors respond differently to meteorological conditions. Therefore guidelines are needed for optimal sensor selection and to allow correct interpretation of the sensor signal.

In this research, the performance of 13 different sensors was compared by mounting them on a concrete block and by subjecting them to a temperature regime in a controlled temperature chamber. A temperature correction factor was obtained for the whole sensor system, including the frame and steel rods. Measurements with the same set of sensors were also performed on an intact Norway spruce (*Picea abies*) and a dead trunk of the same species to compare the different outputs. It can be concluded that different amplitudes were obtained, but that long term patterns were similar. Care should therefore be taken when absolute values are considered, but relative patterns are fairly reproducible. This study – part of the COST action STReESS – was conducted both in the botanical garden at the University of Innsbruck in Austria and at Ghent University.

Dutch summary

De laatste jaren zijn veel dendrometers en LVDT-sensoren ontwikkeld die zorgen voor dagelijkse informatie over radiale stamgroei en die detectie toelaten van stress situaties zoals droogte. Het is algemeen aanvaard dat vier belangrijke componenten deel uitmaken van het gemeten signaal: irreversibele radiale groei, reversibele krimp en zwel met veranderende niveaus van hydratatie, inkrimping en uitzetting van geleidende elementen door een toename en relaxatie van interne spanningen, en thermische uitzetting en samentrekking. Er bestaat echter een grote verscheidenheid aan sensor types die mogelijk zorgen voor verschillende *outputs* omdat deze sensoren verschillend zouden kunnen reageren op meteorologische condities. Daarom zijn richtlijnen nodig voor een optimale selectie van sensoren en om ervoor te zorgen dat een correcte interpretatie van het sensor signaal mogelijk is.

In deze studie werden 13 verschillende sensoren met elkaar vergeleken door ze te installeren op een betonblok en door ze te onderwerpen aan temperatuursveranderingen in een temperatuur kamer. Een correctie factor voor temperatuur is bekomen voor het hele sensor systeem, met inbegrip van de frame en de stalen staven. Metingen met dezelfde set sensoren zijn ook uitgevoerd op een intacte fijnspar (*Picea abies*) en een dode stam van dezelfde soort om de verschillende meetsignalen met elkaar te kunnen vergelijken. Er kan worden geconcludeerd dat verschillende amplitudes werden bekomen, maar dat lange termijn patronen vergelijkbaar waren. Voorzichtigheid is daarom aan te raden wanneer absolute waarden worden beschouwd, maar relatieve patronen zijn behoorlijk reproduceerbaar. Deze studie – deel van de COST actie STReESS – werd uitgevoerd in de botanische tuin van de universiteit van Innsbruck in Oostenrijk en op de universiteit van Gent.

Introduction

Scientists may have measured the highest temperature so far in Antarctica on March 24, 2015. The record – 17.5°C – is not yet certified as official by the World Meteorological Organization and it is also difficult to draw a conclusion from a single temperature record (Howard, 2015). However, this extreme measurement might compel even the most sceptic people to reflect deeper on the anthropogenic role in climate change.

Many people have been convinced in the last decades that our climate is changing and that a reduction in CO_2 emissions is needed (Alcaraz-Segura et al., 2010; Allen et al., 2010). However, predicting future climate change remains difficult, because it demands a combination of uncertainties along the cause-effect chain from the actual emissions to a change in temperature (Meinshausen et al., 2009). The carbon cycle, radiative forcing, biological responses and global circulation of winds and currents will all be affected by climate change, but it remains a challenge for scientist to understand to which degree (Friedlingstein et al., 2006; Howard, 2015; Meinshausen et al., 2009). Climate itself, however, will be influenced as well. For instance, forests have a major influence on climate, since they exchange water, energy, carbon dioxide and other chemicals with the atmosphere. This interaction will be affected when both temperature and CO_2 emissions keep increasing.

Land ecosystems and oceans absorb approximately half of the anthropogenic CO_2 emissions. However, the processes responsible are very sensitive to climate (Myneni et al., 2001; Cox et al., 2004). Boreal forests are a large reservoir of terrestrial carbon and it is essential to know if and how the boreal carbon balance is changing. The effect of rising CO_2 concentrations and global temperatures on boreal forests has been discussed in a variety of studies, often getting quite different results when datasets are compared. Climate warming has been associated with both an increase in vegetation greenness (or greening) and a decrease (or browning) in northern regions (Myneni et al., 2001; Tucker et al., 2001; Dong et al., 2003; Slayback et al., 2003). However, studies did not always account for biomass reduction in areas disturbed by fire and the regeneration of biomass that exceeds this reduction. Also the source and processing of different datasets may explain the dissimilar trends in vegetation greenness (Alcaraz-Segura et al., 2010). Conversely, the more southern regions will experience more drought and forest dieback. Since this will result in an enormous amount of extra carbon release in the atmosphere, global warming will be strengthened (Cox et al., 2004; Rammig et al., 2010).

To understand the interactions between tree growth and climate change better, it is first of all important to comprehend tree growth itself. Carbon, as a source of compounds for cambial activity, the tree water status, as a control factor for the metabolism of the entire tree, temperature and the availability of nutrients all influence radial tree growth (Zweifel et al., 2006). To be able to describe the potential of these factors to limit tree growth, simultaneous measurements of the diel stem radius fluctuations and microclimate variables are often used (Deslauriers et al., 2003; Zweifel et al., 2006; King et al., 2013). Dendrometers and LVDT-sensors (Linear Variable Displacement Transducers) are instruments that offer high-resolution temporal data and are therefore essential tools in scientific research.

In the first chapter, the development of different dendrometers and LVDT-sensors is discussed and the information that can be received through the sensor data is summarized. The most important parameters that can be derived from trunk or stem diameter measurements are daily growth and maximum daily shrinkage. Furthermore, the three most essential research areas – irrigation scheduling, forestry and climate studies – where these sensors are used, are discussed. The working principle of both point and band dendrometers, and LVDT-sensors is then explained into more detail. Finally, a brief overview is given to characterize the known temperature sensitivity of the sensors in scientific studies. Chapter 2 includes more information on the sensors used in this research and a description of the experimental settings. The third chapter explains the step-by-step procedure that has been performed to determine temperature sensitivity of all dendrometers and LVDT-sensors, with an overview of the most important results in chapter 4. These results are further discussed in chapter 5 and the most important conclusions are summarized with a suggestion for possible future research.

Chapter 1: Literature review

1.1 Introduction

Climate change and the increase in extreme events will urge the creation of a scientific platform that combines information about plant stress responses caused by these extremities. Dendrochronology – the analysis of tree or growth rings – has an enormous potential to study the impact of climate on tree behaviour because it provides essentially a "*library*" of past information. It meets one of the basic needs: defining changes in biological responses over time (Downes et al., 1999; McLaughlin et al., 2002). This method however is mostly used for retrospective quantification and evaluation of annual radial growth, climate effects and air pollution stress (Daudet et al., 2005; King et al., 2013).

In the past few years many dendrometers and LVDT-sensors (Linear Variable Displacement Transducers) have been developed and introduced into scientific research. Earlier, researchers studied tree stem growth by using handheld measuring tools. Because measurements were not carried out regularly and automatically, small growth fluctuations that occurred during shorter time periods like responses to drought and fertilizer stresses could not be assessed (Breitsprecher and Hughes, 1975; Wang and Sammis, 2008). Also repetition of measurements at the same spot was very difficult with this handheld material (Anemaet and Middleton, 2013). High-resolution dendrometers that could be permanently mounted on the tree became therefore indispensable and were developed since the 19th century. Nevertheless, problems such as unreliability with loss of data and errors from artefacts unrelated to the actual stem growth arose. In the last decades, however, improvements in the equipment have reduced these problems and have made the sensors essential tools in scientific research (Drew and Downes, 2009).

A wide variety of dendrometers and LVDTs exist differing in accuracy, precision, cost, operational simplicity and robustness (Clark et al., 2000). This equipment ensures high-resolution temporal data in comparison to the temporal information that can be derived from growth rings. The accurate measurements of these sensors deliver daily information on radial stem growth and allow detection of stress situations like drought (De Swaef et al., 2009). In early research, measuring the fluctuation in stem size due to the changes in water content was mainly used to assess bias caused in measurements of growth. The importance of water relations in trees was thus neglected in general (Herzog et al., 1995). However, in more recent studies, the importance of water flow has been acknowledged to explain the diurnal tree stem diameter changes and the challenge therefore remains to unambiguously interpret the sensor signal (Sevanto et al., 2003). It has been generally accepted that four important components contribute to this signal: irreversible radial growth, reversible shrinkage and swelling with changing levels of hydration, contraction and expansion of conducting elements due to the increase and relaxation of internal tensions, and thermal expansion (Daudet et al., 2005; Scholz et al., 2008).

Within the COST action (European cooperation in science and technology) STReESS (studying tree responses to extreme events: a synthesis) a group of scientific researchers aim at a wide European study, and collection of both dendrometer and LVDT-data. When different sensors are used also different outputs may be expected because the sensors may respond differently to meteorological conditions like temperature and humidity. Therefore, a comparison between different types of dendrometers and LVDT-sensors is crucial to succeed in the long-term goal of the COST action. This comparison will provide essential information to make sure that further processing of data in the European database will become possible.

This literature review will first cover the information that can be derived from data obtained using dendrometers and LVDT-sensors. Next, the three most important research areas where these sensors are used, are discussed. Finally, the working principles of the equipment is explained, with a distinction between the three major groups of sensors, and an overview of known temperature sensitivities of these sensors is given.

1.2 Why dendrometers and LVDT-sensors?

1.2.1 Information through sensor data

To comprehend the tree's response to short-term changes in environmental conditions such as radiation, temperature, rainfall and soil water content, the continuous measurement of stem radial variation is essential. Both seasonal tree growth and water storage fluctuations over the year can be extracted from dendrometer measurements (Deslauriers et al., 2007). Selecting the ideal dendrometer or LVDT-sensor principally comes down to choosing an instrument with the specified accuracy that is needed at the lowest cost possible (Clark et al., 2000). The accuracy is defined as the maximum error that is expected from the sensor. To be able to interpret the sensor signal, it is important to know what kind of information can be obtained from the sensor data.

With high-resolution dendrometers, diurnal changes in stem size can be detected. The sensor resolution is defined as the shortest distance that the sensor can detect (Wang and Sammis, 2008). To be able to obtain a better measure of radial growth, the diurnal cycle is typically split into different phases. Depending on the authors, either three or five phases are defined. In general, a shrinkage, a recovery and a stem radius increment (SRI) phase are present. Shrinkage is the period from a previous local maximum to a local minimum, recovery is the period from a local minimum until the magnitude of the previous maximum is reached and stem radius increment is growth from the previous maximum to a new maximum (Figure 1a). This three phase approach is a simplification of the five phases used previously which linked diurnal changes in stem diameter with sap flow (SF) measurements. Here, the increment phase is split into two distinct phases: resaturation when there is no sap flow and a period when sap flow increases, but a decrease in radius is delayed. Also shrinkage is separated into a period of fast shrinkage until the maximum sap flow is reached and again a phase of delay when sap flow declines, but the change in radius does not yet increase (Figure 1b). The three-phase approach allows scientists to process the dendrometer signal easier (Herzog et al., 1995; Downes et al., 1999). The reason or advantage to split the diurnal cycle into different phases is that it decomposes the net daily increment into both a rate and a duration which makes examination of relationships with weather conditions more easy (Downes et al., 1999). It has been reported that each phase can indeed be correlated with meteorological variables (Deslauriers et al., 2003; Drew and Downes, 2009; King et al., 2013).

The trunk radius shows a sinusoid waveform over a period of 24 hours with a maximum value before sunrise which is illustrated in Figure 1 at the end of the increment phase. This sinusoid wave is also known as the circadian rhythm of the tree. At this point, the stem will be rehydrated and sap flow will be at its lowest point due to a decrease in transpiration during the night. Subsequently, a decrease in stem radius will follow after sunrise reaching a minimum value approximately two hours before sunset, because transpiration and sequentially sap flow increase during the day. The difference between these two critical points of the wave, representing a daily pattern, is known as the maximum daily shrinkage (MDS) (Herzog et al., 1995; Goldhammer and Fereres, 2001; Daudet et al., 2005; King et al., 2013).

Daily growth of the tree (DG) is defined as the difference between the maximum stem diameter of the next day and the maximum stem diameter of the current day (Fernández and Cuevas, 2010). MDS is used as an indicator for drought stress, whereas DG gives an estimation of tree growth. Stem radius increment is also an indicator of tree growth when radial changes are measured (Robert et al., 2014). A lag period is present between the change in stem size and the rate of transpiration, and can vary daily in each tree section because stored water is not released immediately when transpiration starts. Three major factors affect this response delay: hydraulic flow resistance, storage capacity and transpiration (Zweifel and Häsler, 2001).

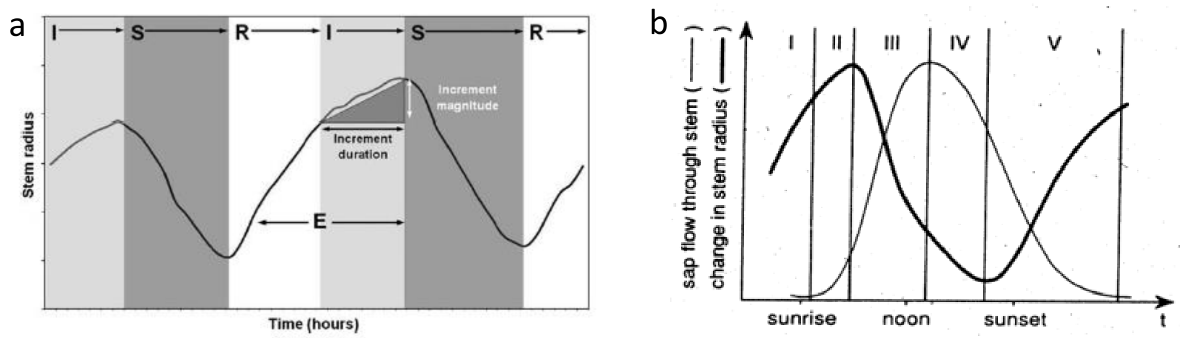

Figure 1: a) Two days of radial stem measurements, showing phases of stem radius increment I, shrinkage S and recovery R. Expansion E is the period of both increment and recovery combined (Drew and Downes, 2009). b) Five phase approach. Phase I: resaturation with no sap flow (SF), Phase II: delay between increase in SF and decrease in radius, Phase III: fast shrinkage until SF reaches its maximum, Phase IV: delay between decrease in SF and increase in radius and Phase V: stem expansion when SF declines (Herzog et al., 1995).

The different parameters that can be derived from trunk or stem diameter measurements with dendrometers are presented in Figure 2, with daily growth and maximum daily shrinkage as the most important ones.

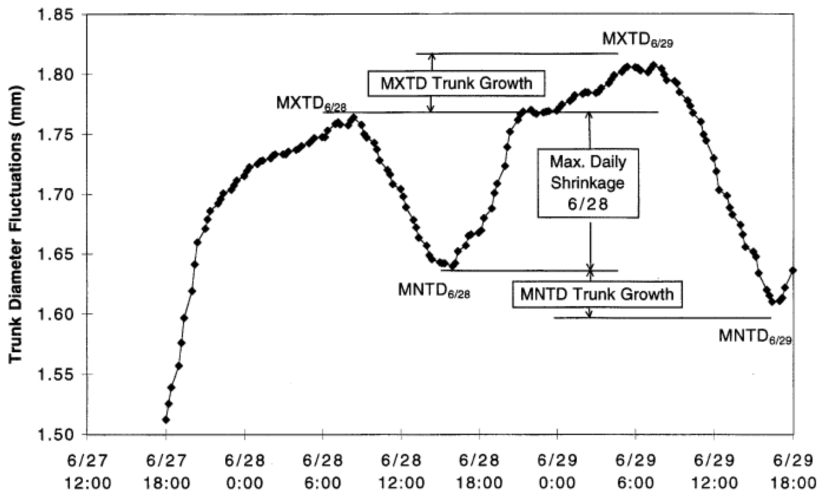

Figure 2: Different parameters that can be derived from trunk diameter measurements with dendrometers. MXTD and MNTD are respectively the maximum and minimum daily trunk diameter. Daily growth is the difference between two subsequent maxima. Maximum daily shrinkage is the difference between the maximum and minimum daily value (Goldhammer and Fereres, 2001).

When radius variation is continuously measured a huge amount of records will be obtained and should be processed. This amount of data will increase even more since studies will increase in duration, replication will intensify and the technology will become less expensive and more readily available (Drew and Downes, 2009; Deslauriers et al., 2011). To make data processing fast and easy, algorithms are often used. There are two distinct methods in data analysis to process high amounts of data. One possibility is to extract one value from the whole time series each day. Another option is to analyse the contraction, expansion and stem radius increment phases separately (Deslauriers et al., 2011).

1.2.2 Applications

There are three important research areas in which dendrometers and LVDT-sensors are successfully used: in irrigation scheduling, in forestry and in climate change studies.

1.2.2.1 Irrigation scheduling

A first application can be found in irrigation scheduling in agriculture. Water scarcity is a rising global problem and therefore precise irrigation is essential. Automated irrigation scheduling would contribute to sustainable agriculture by minimizing the required water input, and also lowering the costs associated with irrigation (Steppe et al., 2008; Fernández and Cuevas, 2010). Avoiding plant drought stress was the initial goal in irrigation scheduling and therefore the soil moisture was monitored with soil capacitance probes or tensiometers. However, irrigation scheduling based on the soil water balance has some uncertainties since trees themselves are highly coupled to changing air humidity whereas grass or soil are primarily dependent on net radiation (Bonet et al., 2010). Since the traditional soil water based approaches are less appropriate because of smaller precision, the plant itself is preferred as an indicator for irrigation requirements (Steppe et al., 2008).

Both stem diameter variation (SDV)-derived indices obtained with either dendrometers or LVDT-sensors and the stem water potential (ψ_{stem}) can be used as tools to estimate the water status of crops (Intrigliolo and Castel, 2004; Fernández and Cuevas, 2010). These plant-based water status indicators have proven their usefulness because they incorporate the soil water available to the plant and the climatic conditions (Bonet et al., 2010). However, they do require a reference value measured in plants under non-limiting soil water conditions beyond which irrigation becomes essential (Fereres and Goldhammer, 2003; Steppe et al., 2008; De Swaef et al., 2009). The SDV-derived indices can be recorded continuously and automatically which gives them a strong advantage compared to the stem water potential for which measurement is often destructive and therefore not suited for automatic irrigation scheduling (Offenthaler et al., 2001; Steppe et al., 2008; Bonet et al., 2010). Automatic and continuous recording of the stem water potential has become possible in the last few years with the PSY1 stem psychrometer from ICT international (Patankar et al., 2013; Yang et al., 2013; Vandegehuchte et al., 2014; Wang et al., 2014), but complications with the fragile thermocouples during installation of the psychrometer cups might involve a practical disadvantage (Vergeynst et al., 2014). Yet, the suitability of the SDV-derived indices needs to be evaluated. For instance, the SDV records show high tree-to-tree variability which means that more trees need to be instrumented to minimize this variability. Also day-to-day variability is higher for the SDV-derived indices in comparison to ψ_{stem} which makes the absolute value of these indices unsuitable as sole variable in irrigation scheduling (De Swaef et al., 2009). Furthermore, the equipment to record these indices is very reliable, but robustness is limited. Therefore adequate field management is very important to make data recording and interpretation reliable (Bonet et al., 2010). To overcome these disadvantages many scientists have suggested to combine SDV records with sap flow measurements. However, sap flow depends on the level of hydration of the whole sapwood and is also buffered by storage of water whereas SDV records reflect the extraction of water from the outer part of the stem, the phloem, and the outer xylem (Herzog et al., 1995; Perämäki et al., 2001; Zweifel et al., 2001; Sevanto et al., 2003; Nicolas et al., 2005; Fernández and Cuevas, 2010). Plant-based measurements of sap flow rates and stem diameter variations can also be combined with the water flow and storage model to simulate changes in ψ_{stem} by using the research tool STACI (software tool for automatic control of irrigation). This combination will provide both knowledge on when irrigation is desired and on how much water is needed without measuring the stem water potential (Steppe et al., 2008).

1.2.2.2 Forestry

Also in forest research, dendrometers and LVDT-sensors are frequently used. Maintenance of forests around the globe is very important since they influence climate by exchanging water, carbon dioxide and other chemicals with the atmosphere. The band-type dendrometer is frequently used because this type of sensor measures the circumference of a tree and is easy in its installation. A disadvantage however is the fact that it is less precise in dealing with wood formation along particular radii in the stem (Clark et al., 2000; Drew and Downes, 2009). The profitability of wood supply is determined mainly by the growth rate of trees which can vary significantly over a year and might result in different wood properties (Downes et al., 1999). Knowledge of these properties is important since wood is used to make a variety of products depending on variability in timber stiffness, strength, fibre or vessel dimensions and fibre wall thickness of the raw material (Zobel and van Buitjenen, 1989; Niklas, 1997; Woodcock and Shier, 2002).

Seasonal activity of trees is recorded in the wood structure across the stem radius. When these wood patterns are combined with temporal high-resolution measurements of stem growth, more insight can be gained into the variability of wood properties. Consequently also more information is obtained to know which specific products can be processed (Downes et al., 2009; Drew and Downes, 2009). Prediction of these wood properties will become easier when the relationship between weather and the rate and pattern of stem growth is better understood (Downes et al., 1999). The point-type dendrometer is most appropriate for this kind of research because growth patterns at a specific point can be related to the wood properties of the stem at the same spot (Zweifel and Häsler, 2001; Drew and Downes, 2009). Radial variation in stem or trunk is measured in forestry, which is composed of tree growth and day-to-day rhythms of water storage depletion and replenishment. Shrinkage has been reported mostly for stems of trees, but occurs in other parts as well like roots and reproductive structures (Kozlowski and Winget, 1964; Huck et al., 1970; Faiz and Weatherley, 1982; Herzog et al., 1995; Offenthaler et al., 2001; Deslauriers et al., 2011). Fruits, for example, shrink during the daytime due to transpirational water loss which causes water to be extracted from fruits. During rehydration of the tree at night, fruits will expand (Kozlowski and Winget, 1964). Also roots undergo diurnal variations in radius. However, measuring this contraction and expansion is usually performed with time lapse motion pictures at high magnification or microscopes (Huck et al., 1970; Faiz and Weatherley, 1982). The relationship between stem diameter variations and stem water content has been confirmed by using MRI-measurements (magnetic resonance imaging) to record the water amount and by using dendrometer-measurements for growth recording (De Schepper et al., 2011). Different species are characterized by their pattern of diurnal changes in stem radius with hardwood showing the smallest and succulents the largest amplitudes. With this high-resolution information more insight can be gained into cambial activity and xylem developmental processes (Drew and Downes, 2009).

1.2.2.3 Climate study

A third important research area for dendrometers and LVDT-sensors is the study of climate change. Global climate simulation studies predict increasing droughts and higher summer temperatures in Europe, affecting forest health and productivity in the future (McLaughlin et al., 2003; Thuiller et al., 2005; Hayhoe et al., 2007; Allen et al., 2010). Consequences of broad-scale forest mortality are important to anticipate, since human and environmental systems are tightly coupled. When adult trees die, this will result in more rapid ecosystem changes than tree regeneration and growth can achieve (Allen et al., 2010). Increasing temperature, rising concentration of carbon dioxide and increasing deposition of nitrogen are three major environmental changes to which plants are known to respond (Grace et al., 2002; Thuiller et al., 2005).

Although there are still many uncertainties about the magnitude and direction of climate change, scientists agree that an increase in drought will cause a decline in the net primary production from forests. Turgor pressure in plants will decrease when they experience water deficit and this turgor is an important driver for expansive growth (De Swaef et al., 2009). It is important to note that there is no indication that when precipitation would increase, growth would subsequently increase as well since turgor is maintained through self-regulation of internal water movement (King et al., 2013). Drought is also more likely to affect small plants like seedlings and saplings since they do not yet have a deep rooting system and a great amount of nutrient reserves like mature trees (Hanson and Weltzin, 2000). It is therefore important to note that seedling and sapling trees will respond differently to environmental stress and that their responses are no valid reference for estimations of growth rates and dynamics of mature trees subdued to equal amounts of stress (McLaughlin et al., 2003). McDowell et al. (2008) claimed three mutually non-exclusive mechanisms on how drought could lead to an enormous increase in forest mortality: cavitation increase (Rennenberg et al., 2006; Zweifel and Zeugin, 2008), water stress leading to carbon deficits and metabolic limitations (McDowell et al., 2008; Adams et al., 2009; Breshears et al., 2009) and increased population abundance of biotic agents like insects and fungi (Desprez-Loustau et al., 2006; Raffa et al., 2008; Wermelinger et al., 2008). Physiological knowledge, however, remains inadequate (Allen et al., 2010). Not only the increase in droughts and temperature will cause effects on the environment, since there is increasing evidence that pollutants responsible for climate change will have an impact on biological systems as well. Further increase in exhaust pollutants will thus implicate an effect on how forests will react to climate stress (McLaughlin et al., 2007).

To understand tree responses to these environmental changes it is important to investigate not only water availability and drought, but also potential interactions with other climatic variables that could be affected by human activities like atmospheric CO_2 (carbon dioxide) concentrations. Research is therefore needed to study all factors disturbing both water use and carbon fixation by plants (Hanson and Weltzin, 2000). Dendrometers and LVDT-sensors are very useful here since they measure the fluctuations in stem radius and accordingly monitor the diurnal dynamics of bark water content (Zweifel and Häsler, 2001; Steppe et al., 2015). Measuring the growth of trees itself is also important to understand the effects of changing environmental conditions, because trees play a major role in the coupling of both carbon and hydrological cycles (Deslauriers et al., 2007; Drew and Downes, 2009; King et al., 2013). Massive amounts of water are transported by land plants from their roots to their leaves when they transpire and take up photosynthetic carbon dioxide. This transport involves a complex xylem network, and hydraulic properties of a plant segment only represent a snapshot of the overall plant architecture and physiology (Meinzer et al., 2010). Also stem radius increase, cell production and both wood density and wood properties will be affected by this increase in climatic variability. Wood density is a key parameter for climate studies because of its high sensitivity to climate variations which has been shown in dendroclimatic research (Bouriaud et al., 2005). There is also a link with cavitation (Meinzer et al. 2010). Hacke et al. (2001) showed that higher wood density is associated with more loss of hydraulic conductivity by cavitation. In other studies however, this relationship has not been confirmed (Jacobsen et al., 2008; Meinzer et al., 2008b). Also the inverse relationship between the hydraulic capacitance and wood density, and the contribution of hydraulic capacitance to hydraulic safety can counter the results reported by Hacke et al. (2001) (Pratt et al., 2007; Scholz et al., 2007; Meinzer et al., 2008a; Meinzer et al., 2010). Hydraulic capacitance is defined as the amount of water that can be released from the tissue for a unit decrease in water potential (Vergeynst et al., 2014), whereas hydraulic safety is the resistance to cavitation and estimated vessel implosion resistance (Pratt et al., 2007). Wood density is also correlated with temperature. However, it has been suggested that the length of the growing season may determine wood density rather than temperature, because highest density was obtained at the end of the growing season when temperature declined (Skomarkova et al., 2006). To analyse intra-annual variations in wood density, dendrometers are valued instruments since they offer sufficient precision for investigation of annual patterns (Bouriaud et al., 2005; Rossi et al., 2006; King et al., 2013).

1.3 Different types of sensors

Both dendrometers, or resistance sensors, and LVDTs, or inductance sensors, are highly valued instruments for measuring stem diameter growth. High-resolution dendrometers can be classified into two main categories: point and band types. Often point dendrometers are split up in a radial and a diametric type measuring growth along a single radius or two opposing radii respectively. Band dendrometers are often referred to as the circumferential type which record growth along multiple radii of a plant (Young, 1952; Breitsprecher and Hughes, 1975; Keeland and Sharitz, 1993; Pesonen et al., 2004).

The difference between dendrometers and LVDT-sensors in this literature review is that the working principle of the dendrometers is based on a linear potentiometer and the LVDT-sensors, as the name implies, on a linear variable displacement transducer. The type of equipment that will be discussed here is all in contact with the stem and is therefore denoted as contact dendrometers or LVDTs. Optical forks and calipers, prisms or other devices that do not touch the stem – noncontact or contactless sensors – will not be further mentioned here (Clark et al., 2000; Wang and Sammis, 2008; Drew and Downes, 2009).

1.3.1 Point dendrometers

Point dendrometers can measure stem growth along the radius or diameter of a tree. The working principle of the point type is based on the use of a linear potentiometer which measures a potential difference and will translate the displacement by either contraction or expansion of the stem into an electrical signal (Rossi et al., 2006).

A potentiometer, or resistance sensor, consists of an actuator rod (Figure 3a). An actuator rod is part of the actuator and will make sure that the actuator's mechanical output is physically transferred to the device that it is designed to actuate. In other words, the amount of expansion or contraction of the stem is transferred to a wiper arm by the actuator rod since they are internally attached to each other. This wiper arm has flexible contacts which are coupled to a resistive element (not shown on the figure). This moveable wiper will ensure a change in resistance when it slides along the resistor or conductive strip (Figure 3b). Furthermore, a voltage is applied across the resistive element to provide power to the potentiometer. When the stem expands or contracts the motion axis or actuator rod will make sure that the wiper with the flexible contacts rubs against the resistive element. An output voltage will be obtained which indicates the growth of the stem. The wiper position therefore changes the resistance in the circuit and determines the voltage output (Nyce, 2004).

There is a wide range of designs, sizes and costs of potentiometers. Potentiometers are rather low-cost sensing devices and are usually very simple in usage which gives them an advantage in comparison with the LVDT-sensors (Nyce, 2004). These positive features aside the potentiometers are susceptible to wear due to the fact that the wiper arm rubs against the conductive strip, which makes replacement of the conductive element required over time. They have also a rather low accuracy and low repeatability. The most important disadvantage however is the fact that the output range is limited to the physical size of the potentiometer.

By using the point type, activity of the cambial zone can be measured individually at each specific direction of the stem (Breitsprecher and Hughes, 1975). This recording of stem growth at one place however has also caused the point dendrometers to be called inaccurate in comparison with the band dendrometers since these measure all directions (Wang and Sammis, 2008). When point type dendrometers are used, only one side of the stem is monitored. However studies have indicated that radial increment can vary in different azimuths in certain tree species: *Picea abies*, *Pinus silvestris*, *Olea europaea* and *Podocarpus falcatus* (Mäkinen et al., 2003, 2008; Krepkowski et al., 2012; Cherubini et al., 2013; Robert et al., 2014). Patchiness has also been observed in both radial growth and internal structure of *Avicennia*, a genus of flowering plants containing mangrove trees (Robert et al., 2011; Robert et al., 2014). For that reason it might be needed to install several sensors in different directions to make sure that growth is monitored correctly (Kozlowski and Winget, 1964; Robert et al., 2014).

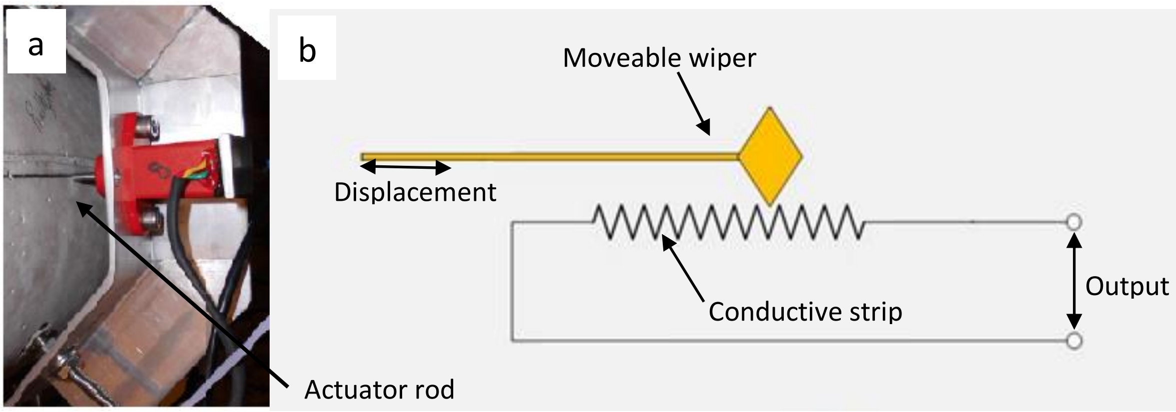

Figure 3: a) "Homemade" point dendrometer Rathgeber, LERFoB, with indication of the actuator rod. b) Schematic overview of the working principle of a potentiometer with indication of the movable wiper and the conductive strip (Nyce, 2004).

Screws are required to mount the point type dendrometer on a tree which causes injuries and may induce abnormal growth around these areas (Breitsprecher and Hughes, 1975). This might affect the sensor signal and make interpretation more difficult.

1.3.2 Band dendrometers

Band or circumferential dendrometers measure growth along the circumference of a tree and, as mentioned, are often used in forestry research (Clark et al., 2000).

Two band-type dendrometers are shown in Figure 4, DC1 and DRL 26 which are manufactured respectively by Ecomatik and EMS Brno (Environmental Measuring Systems). The operating principle of the band dendrometer is also based on the use of a linear potentiometer (Figure 3b).

A major advantage of the band type is their relatively low cost and their easy installation because they do not require a sensor holder and can be directly mounted on a tree without the need of screws (Sheil, 2003; Wang and Sammis, 2008). Damage to the bark and the possible subsequent measuring of abnormal growth will be limited (Breitsprecher and Hughes, 1975). Furthermore, measurements embody an average of all diameters in every direction in comparison to the point types which only monitor one spot or place. Variability caused by direction is thus eliminated (Kozlowski and Winget, 1964; Clark et al., 2000; Wang and Sammis, 2008).

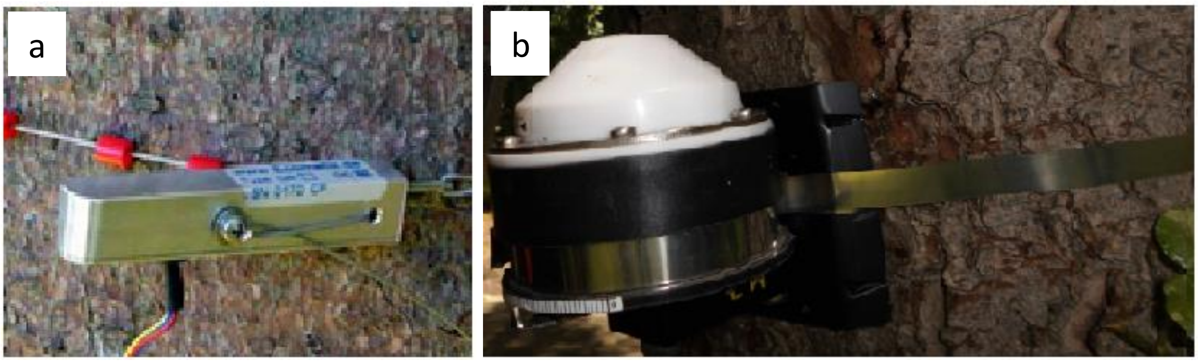

Figure 4: Two band-type dendrometers mounted on a tree, *Picea abies*. a) DC1, Ecomatik b) DRL 26, EMS Brno.

A problem with this type of dendrometer is the underestimation of the trunk growth, especially when recording short-term size fluctuations (Sheil, 2003). This is due to the fact that initially the slacks in the band are taken up by the growth of the tree, which implies that the actual growth during that time is not recorded (Drew and Downes, 2009). Adjustments can be made to amend for the slacks in the band, but care should be taken to avoid overcorrection for slow-growing trees, otherwise negative growth can be obtained (Auchmoody, 1976). Friction between the band and the bark makes measurements of small growth variations unreliable as well, especially during periods of shrinkage. A solution for this problem can be to place rollers, small cylinders or a Teflon-net between the wire and the bark (Breitsprecher and Hughes, 1975).

The band dendrometer manufactured by UMS (Umweltanalytische Mess-Systeme), called the D6 or strain-gage clip-sensor, is different than the potentiometers described earlier (Figure 5a).

This specific clip-sensor consists of four strain gauges which are wired as a Wheatstone full-bridge and are attached to a metal strip. A strain gauge is a device to indicate the strain of a material or structure at the point of its attachment, which, in this case, is the expansion or contraction of the stem (Hannah and Reed, 1992). It will transform the strain or tension in a proportional change of resistance. In a normal Wheatstone bridge (also named resistance bridge) two series of parallel arrangements of four identical resistors are present and form the arms or branches of the bridge. A stabilised direct current (DC) is applied. In a Wheatstone full-bridge circuit, which is used in dendrometer D6, the resistors are replaced by four strain gauges (Figure 5b). The band – an invar steel cable – is placed around the stem and rests upon a Teflon-net to reduce friction and to allow undisturbed movement of the steel cable. This elastic net structure will adapt to the growth of the tree and will not seal the stem. When the stem expands or contracts the sensor will detect these changes in bending and this will result in a resistance change of the strain gauges (Cimbala, 2013; Naleppa, 2013; Storr, 2015).

An advantage of using this Wheatstone full-bridge circuit is that temperature variations are compensated. The strain component caused by changes in temperature will be the same in all four strain-gages of the bridge and, because of their specific connection, will compensate each other. This is only true when the bridge is symmetrical, identical temperature coefficients of all materials are used and temperature effects are the same for all compensating elements. A disadvantage however when using strain-gages is that the working principle to measure stem growth is more complex than with a linear potentiometer (Storr, 2015). However, this has no effect on installation or data acquisition.

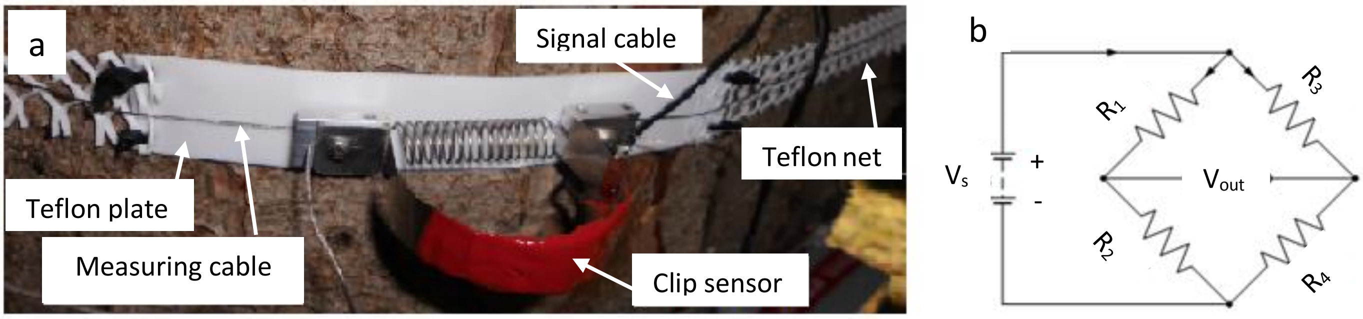

Figure 5: a) Simplified representation of the band dendrometer D6, manufactured by UMS, with indication of the Teflon-net and -plate, the measuring and signal cable and the clip sensor (Naleppa, 2013). b) Schematic representation of a Wheatstone full-bridge circuit where V_s is the source or excitation voltage, V_{out} is the measured signal voltage and R_1, R_2, R_3 and R_4 are strain-gage elements (Storr, 2015).

1.3.3 LVDT-sensors

Linear Variable Displacement Transducers or LVDT-sensors are used in research to record linear displacements, but they can also be used to measure other physical quantities like force or pressure (Drumea et al., 2006). In literature also Linear Variable Differential Transformer is often used and abbreviated as LVDT (Drumea et al., 2006; Rossi et al., 2006). In this literature review however the first name will be used consistently.

One LVDT-sensor is presented in Figure 6, the type DG 25 manufactured by Solartron Metrology.

Often both transducer and sensor are used to indicate this measuring device although their definition is not entirely the same. A transducer is a device that transforms a signal to a signal with a different physical form. A sensor is an input device that will guarantee a usable output responding to a certain physical signal input. According to these descriptions a transducer can sometimes be referred to as a sensor and vice versa. More specifically a displacement transducer measures the distance between two positions, for instance the present situation of the stem and the previous position of the stem (Nyce, 2004).

A displacement transducer consists of three magnetic coils or windings, of which one is primary and two are secondary (Figure 7a). Between the primary and the secondary windings a transfer of current takes place and is controlled by a moveable magnetic core, also called an armature. This ferromagnetic core is attached to the object whose position is measured, the stem. Thus when an alternating current (AC) is applied to the primary coil this will induce voltages in the two secondary windings assisted by the armature. The secondary spirals are connected in opposition, so that the voltage in both coils will be equal, but opposite relative to each other. The voltage output is the difference between the two secondary voltages and will change linearly with the movement of the magnetic core (Figure 7b). When the magnetic core is situated in the central linear position the total voltage output will be zero (Nyce, 2004).

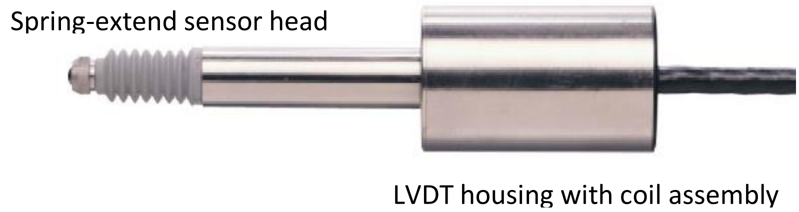

Figure 6: LVDT-sensor DG/2.5 manufactured by Solartron Metrology. Both LVDT housing with the primary and secondary coils inside (not visible) and the spring-extend sensor head are indicated.

A major advantage of these inductance sensors is the fact that there is no contact between the magnetic core or armature and the whole coil construction. This frictionless operation will lead to a longer lifetime and higher robustness than most linear potentiometers. The linearity of the voltage output to displacement is also higher than the linearity of the potentiometer. Furthermore, both accuracy and resolution are good, and sensitivity is high. A sensitive sensor will easily detect small changes in growth which is very important in the specific dendrometer- and LVDT-applications.

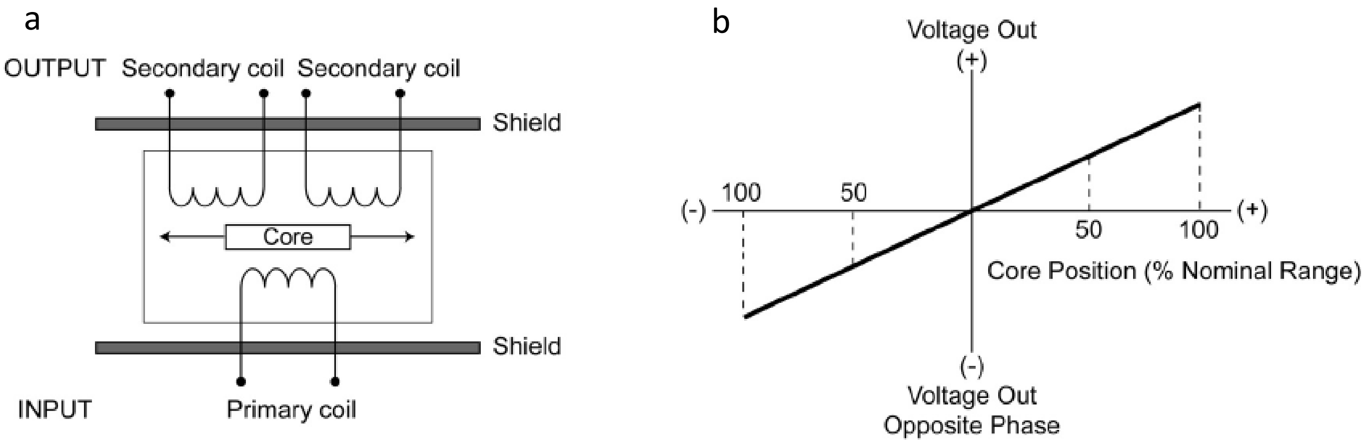

Figure 7: a) Schematic view of an inductance sensor with movable magnetic core and primary and secondary coils. Both input and output side are indicated. b) Graphic representation of the voltage output as function of the core position (Steppe, 2004).

The operating principle of a linear variable displacement transducer is based on magnetic coils, which makes the use of LVDT-sensors in specific research areas – for instance the measurement of water content with MRI – unfavourable and not applicable (De Schepper et al., 2011). They are also generally known to have a higher mechanical and electronic complexity than the linear potentiometers which have been discussed earlier. This complexity makes them more costly (Drakeley, 1988; Nyce, 2004;

Hon et al., 2010). Therefore both lifetime and cost have to be considered when choosing the correct sensor, although information on sensor lifetime is not readily available.

1.4 Temperature sensitivity

The importance of dendrometers and LVDT-sensors lies in the fact that they offer high-resolution temporal data, and that they deliver daily information on radial stem growth. This equipment is therefore used in a variety of research studies. Climatic conditions in which they operate can accordingly be very divergent as well, ranging from cold environments in the boreal forests of Canada (Tardif et al., 2001; Deslauriers et al., 2003; Rossi et al., 2006) or Scandinavia (Strömgren and Linder, 2002; Lagergren and Lindroth, 2004; Mäkinen et al., 2008) to warm and wet environments in tropical regions (Worbes, 1999; Pélissier and Pascal, 2000; da Silva et al., 2001; Vieira et. Al, 2004; Figueira et al., 2008; Biondi and Hartsough, 2010; Grogan and Schulze, 2012).

Knowledge on how sensitive these sensors are to temperature changes is important for correct interpretation of the sensor-data. Small inaccuracies or bias due to thermal expansion of the sensor can make a large difference in the quality of the data (Drew and Downes, 2009). Manufacturers of dendrometers and LVDT-sensors often include a temperature range in which the sensors can be used and also a temperature dependency factor is often given. Dendrometer and LVDT-signals can therefore be corrected for their thermal sensitivity (King et al., 2013). Sensors made by Agricultural Electronics Corporation (AEC) are even painted in white to minimize warming effects (Drew and Downes, 2009). Zweifel and Häsler (2000; 2001) corrected their stem radius measurements with control measurements. These were obtained by mounting the same dendrometer type on both a stone plate and a thin steel plate which were considered non-contracting and non-expanding. It was found that the bias correlated linearly with the air temperature, but no specifications of the steel were given. Assuming that no expansion or contraction of the steel plate took place, might therefore not be realistic. Bucci et al. (2004) and Scholz et al. (2008) made an estimation of the temperature correction factor of the dendrometer types used in their research. Dendrometers were both mounted on an intact tree and on a cut stem, entirely wrapped in aluminium foil to prevent water loss to the atmosphere. Similar temperature and light conditions were insured by placing the cut stem next to the intact tree. The temperature correction factor obtained was similar to the specifications of the manufacturer.

Besides the sensor, the mounting system can show expansion or contraction due to changing temperature. Control runs were therefore carried out by Steppe et al. (2006) who showed that no temperature corrections were needed for the custom-made stainless steel LVDT support system used. Sevanto et al. (2002; 2003) used copper-constantan thermo-elements to measure temperature at the surface of the frames and the expansion of the steel rods of the frame was added to the out-coming signal of the sensor. Wang and Sammis (2008) concluded that thermal correction must be made for both point and band dendrometers when hourly or daily growth measurements are executed. The thermal effect appeared to be negligible for annual growth measurements. They indicated that thermal expansion is related to the perimeter of the trunk or branch for band types, whereas the thermal expansion of the rod in the diameter direction affects the growth measurements for point types. Pesonen et al. (2004) examined the reliability and accuracy of a new band dendrometer and declared that the thermal expansion of the Invar stainless-steel band was negligible. Still, changes caused by temperature were examined by using an iron cylinder of known thermal shrinkage. They concluded that the thermal effect on the steel bar was minor in relation to the actual measurement accuracy of the girth band and changes in stem diameter.

In most scientific research the expansion or contraction of the sensor system including the sensor, frames and rods, is often neglected since it is expected to contribute insignificantly to the total out coming signal. Deslauriers et al. (2003) mentioned the thermal expansion coefficient of the steel rods, but correction of data was not performed. da Silva et al. (2002), Drew et al. (2009), Devine and Harrington (2011) and many other scientific studies did not take changes due to temperature into account.

1.5 Conclusion

This literature review gives an overview of the most important information that can be derived from dendrometer and LVDT-sensor data. Furthermore, research with this equipment in both irrigation scheduling, forestry and climate change studies has been covered. Additionally the working principle of three groups of sensors was explained in more detail and finally a brief summary of known temperature sensitivity of these sensors was given.

This scientific study will go into more detail on how sensitive dendrometers and LVDT-sensors are to temperature changes and will compare different sensors used in present and previous research. In chapter 2 the materials and methods to gather and to process the data are explained. Chapter 3 explains the step-by-step procedure that has been performed to determine temperature sensitivity of all dendrometers and LVDT-sensors used in this study. In chapter 4 the most important results are presented and these are further discussed in chapter 5. Finally, the most important conclusions are summarized and possible future research is suggested.

Chapter 2: Materials and methods

2.1 Experimental setup

This study was executed in two different experimental settings. The first experimental setup was a temperature chamber at the University of Innsbruck and at Ghent University where temperature could be controlled and non-living test material – a concrete block – was used. The second setup was the botanical garden of the University of Innsbruck (47° 16′ N, 11° 23′ E) in Austria. Here the comparison between different types of sensors was performed on an intact Norway spruce, *Picea abies* (L.) Karst., with an average stem diameter of 60 cm and on a dead trunk of the same species with a stem diameter of 28 cm. The study in the botanical garden was done during July and August 2014.

2.2 Data collection

Thirteen different sensors were used in this study (Table 1). In addition, six fine-wire copper constantan thermocouples to measure temperature changes on the sensor frames were used. Both the sensors and thermocouples were attached to a data logger (CR1000, Campbell Scientific) which was expanded with a multiplexer (AM16/32B, Campbell Scientific). Data were logged at five second-intervals and averaged every five minutes. Millivolt signals were converted to millimeter values after calibration of the sensors. Calibration of the point type dendrometers and the LVDT-sensors was accomplished by using a precision micrometer. By changing the spacing and recording the corresponding millivolt signal a linear calibration relation could be established:

$$y(mm) = b_1.x(mV) + b_0 \qquad \text{Eq. 1}$$

where b_0 is the intercept value (in mm) and b_1 is the slope of the relationship between diameter and millivolt signal (in $mm.mV^{-1}$).

To calibrate the band type dendrometer DC1 from Ecomatik, eight metal plates were used of known thickness (0.604 cm) and were placed between the wire of the dendrometer and the concrete block of known circumference (61 cm). The strain-gage clip-sensor made by UMS was also calibrated using this method, but this was only done to check the calibration equation already given by the manufacturer. The band type dendrometer DRL 26 manufactured by EMS is a rotary position sensor and has a built-in data logger. Data were accessed by infrared transmission and were already given in millimeter values which made calibration unnecessary (Kučera, 2012). Circumference values recorded with band type sensors were converted to radius values by dividing the results with pi multiplied by two.

2.3 Temperature sensitivity measurements

In the temperature chamber of the botanical garden, the thirteen different sensors were installed on a concrete block with a height of approximately thirty centimeters and a diameter of twenty centimeters (Figure 8a). Only two sensors could be mounted at the same time. The sensors were subjected to a controlled temperature regime varying temperature from twenty to zero, from zero to thirty and from thirty to twenty degrees Celsius every two hours with steps of ten degrees Celsius. The temperature sensitivity measurements were repeated several times (Table 2) in the temperature chamber at Ghent University where the sensors were simultaneously mounted on a concrete block with a height of approximately one meter and a diameter of nineteen centimeters (Figure 8b). Temperature was controlled and changed from ten to thirty and from thirty to ten degrees Celsius with steps of ten degrees Celsius.

Table 1: Overview of the different sensors, model type and manufacturers. When no specific name was given by the manufacturer, the one used during the study is mentioned between brackets. Both thermal expansion coefficient of the sensors and the temperature range in which they can be used are shown when information was given by the manufacturer. "F.R.": Full range.

Name	Manufacturer	Sensor type	Thermal expansion coefficient	Temperature range
Homemade (Vinicio)	Uni Padova	Potentiometer (point)	-	-
LPS	Natkon	Potentiometer (point)	< 0.28 μm.°C^{-1}	-
DF	Ecomatik	Potentiometer (point)	< 0.1 μm.°C^{-1}	-30°C … 40°C
DR	Ecomatik	Potentiometer (point)	< 0.1 μm.°C^{-1}	-30°C … 40°C
Homemade (Rathgeber)	LERFoB	Potentiometer (point)		-40°C … 130°C
DC1	Ecomatik	Potentiometer (band)	< 0.1 μm.°C^{-1}	-30°C … 40°C
DRL 26	EMS	Potentiometer (band)	-	-30°C … 60°C
D6	UMS	Strain-gage full-bridge (band)	< 4 μm.°C^{-1}	-30°C … 50°C
AEC, series II	Agricultural Electronics	LVDT	-	-
LBB375-PA-100 (LBB375)	Schaevitz Engineering	LVDT	0.009 %F.R.°C^{-1}	5°C … 60°C
MTN/IEUSW05 (MTN)	Monitran	LVDT	-	-30°C … 85°C
DF5	Solartron Metrology	LVDT	< 0.025 %F.R.°C^{-1}	-20°C … 80°C
DG/2.5	Solartron Metrology	LVDT	< 0.02 %F.R.°C^{-1}	-20°C … 80°C

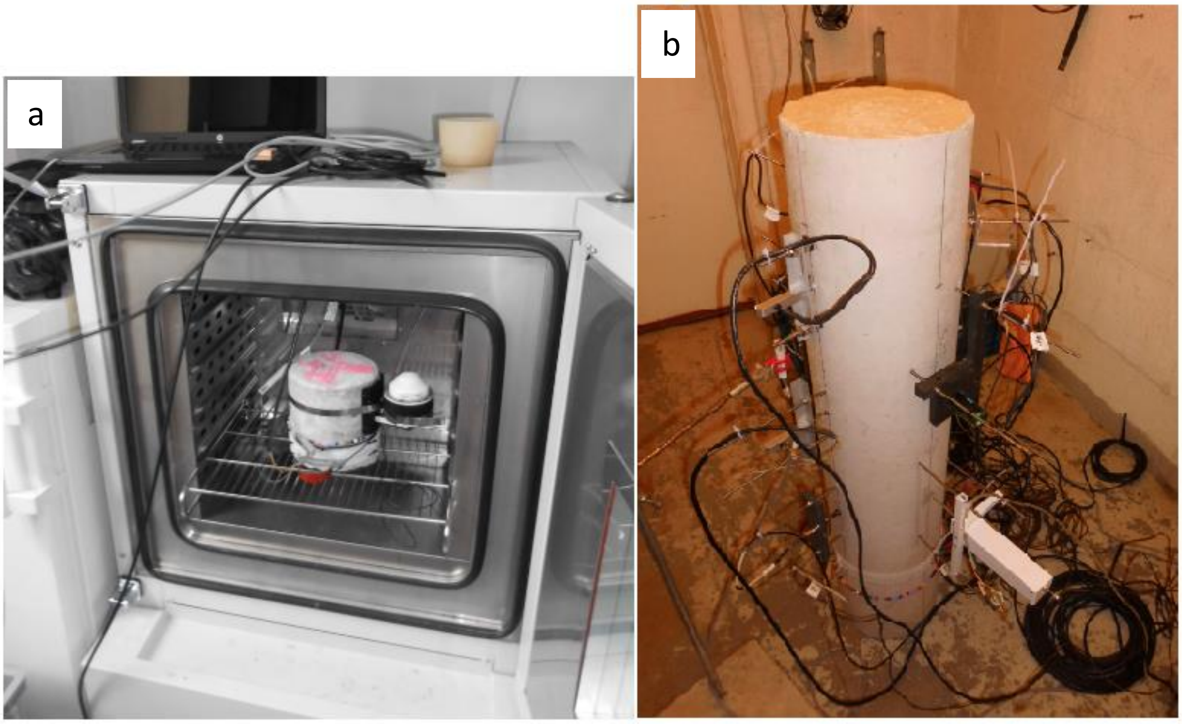

Figure 8: a) Temperature chamber in Innsbruck with the concrete block placed inside. b) Temperature chamber at Ghent University with the concrete block inside.

2.4 Frame position

To test whether the distance between the sensor frame and the concrete block made a difference, two extra experiments were performed. First, the frame was placed as close as possible to the concrete block. Afterwards, the frame was positioned further away (Figure 9a and b). Some sensors however have a frame already attached to the sensor body and therefore placing the frame closer to or further away from the concrete block implies pressing the sensor head more or less (Figure 9c and d).

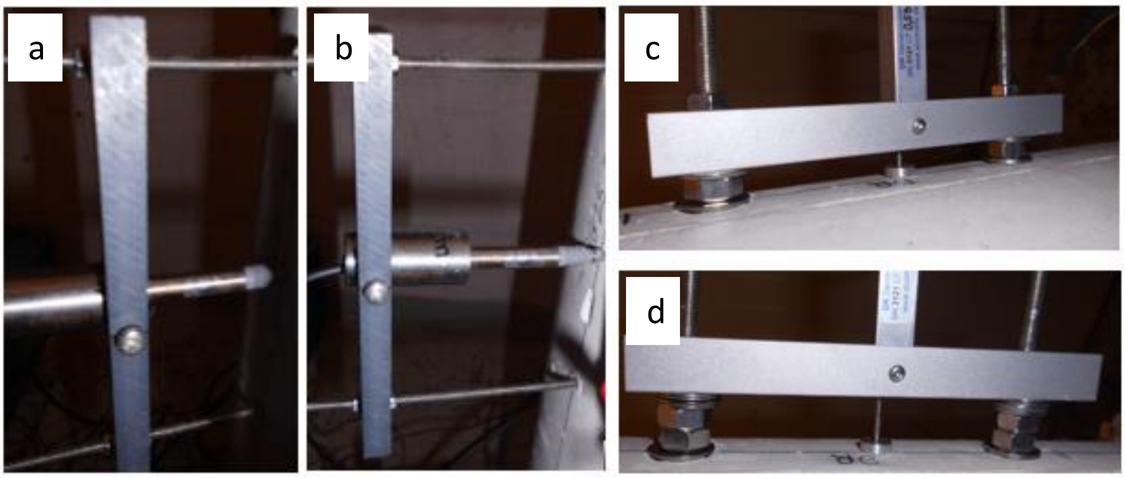

Figure 9: LVDT-sensor DG/2.5, manufactured by Solartron Metrology, when the frame is placed at a distance of a) 4 cm and b) 5.6 cm and dendrometer DR, manufactured by Ecomatik, when the frame is placed at a distance of c) 1 cm and d) 2 cm from the concrete block.

2.5 Botanical garden

2.5.1 Dendrometers and LVDT-sensors

Twelve sensors were installed on the intact Norway spruce at different heights: three band dendrometers, four point dendrometers and five LVDT-sensors (Figure 10).

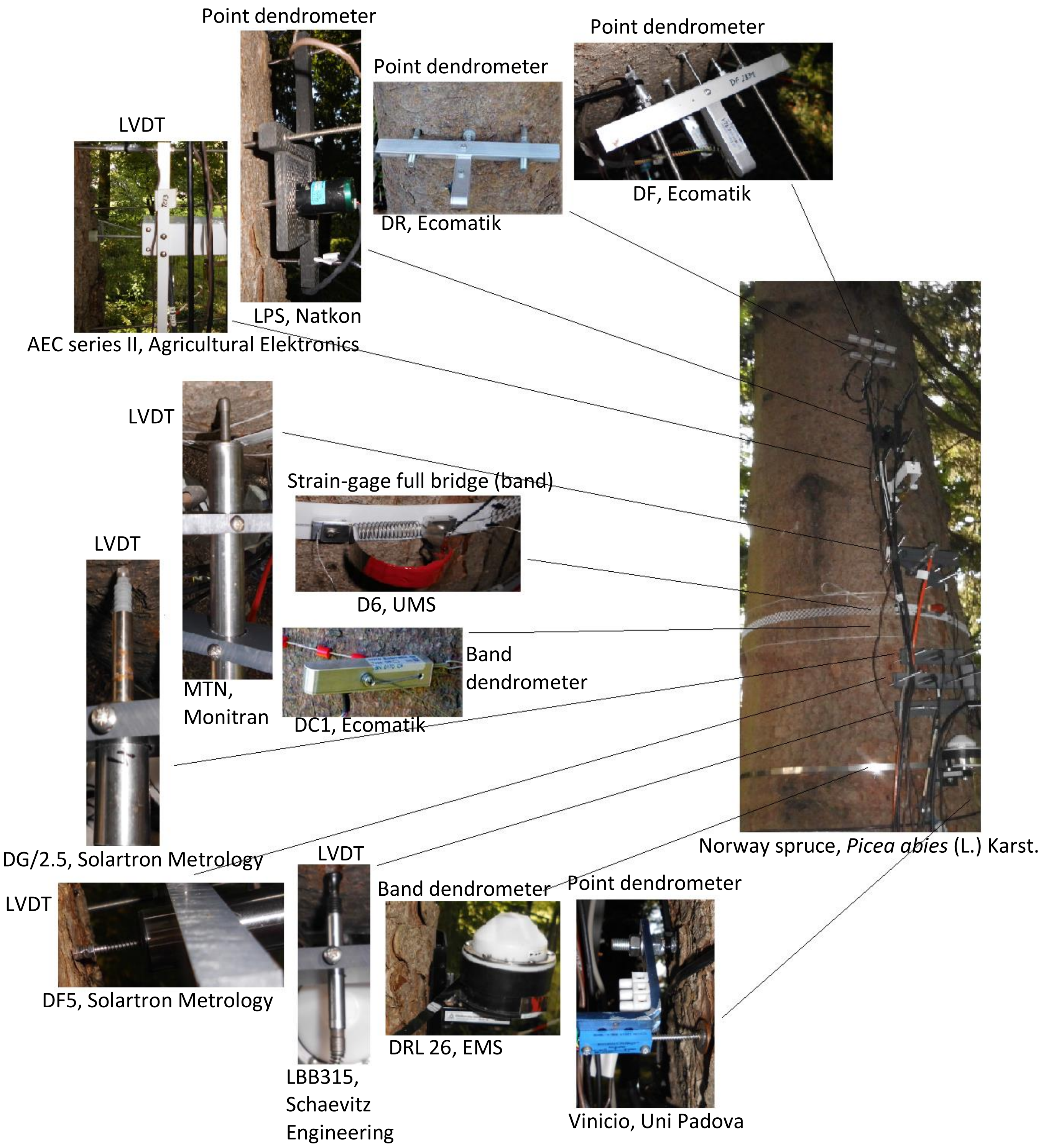

Figure 10: Twelve sensors mounted on a Norway spruce, *Picea abies* (L.) Karst., at different heights.

Four different sensors were available in double and were mounted on a dead trunk as well (DRL 26; AEC, series II; LBB 315-PA-100; DG/2.5). One sensor, the homemade model manufactured by LERFoB (Laboratoire d'étude des ressources forêt-bois) had a small sensor body which made installation on the intact tree impossible. Therefore this specific type could only be fixed on the dead trunk. All sensors were mounted on the north side of the tree. The six available thermocouples were also installed on the sensor frames to measure temperature changes.

2.5.2 Sap flow measurements

In addition to stem diameter variation, sap flow has been measured on the intact tree on both the northern and the southern side with the sap flow system EMS 51 manufactured by EMS Brno (Figure 11c). This model is a watertight unit and measures sap flow using the tissue heat balance method (THB) which integrates sap flow across a radial profile (Čermák et al., 1973). The THB-method requires no calibration since calculation of sap flow is based on an energy balance of a specified volume of woody tissue and the specific heat of water (Herzog et al., 1997; Čermák et al., 2004; Renninger and Schäfer, 2012). The THB-method is often applied as a standard when other methods to measure sap flow are tested (Čermák et al., 2004).

Three stainless steel plate electrodes are used as terminals and they lead an alternating electrical current to the xylem tissues (Figure 11a). Around these electrodes, the xylem tissue is heated and the passing of heat through the conductive phloem is avoided by insulation of the probes (Figure 11b). Temperature difference between the heated and non-heated part of the stem is measured with needle thermistor probes. Of all the heat input power, a small part is lost by heat conduction to the ambient, the rest is carried away by the sap flow (Kučera, 2010). To reduce possible errors due to direct solar radiation, fast temperature changes, wind and rain a weather protection set was installed over the sensor (Figure 11d).

Both sap flow systems were installed at a height of approximately 1.5 m and a circumference of 2 m. Sap flow was measured in $L.h^{-1}$ per cm xylem circumference. In order to obtain sap flow per tree, results need to be multiplied by the xylem circumference at measuring height (Offenthaler et al., 2001).

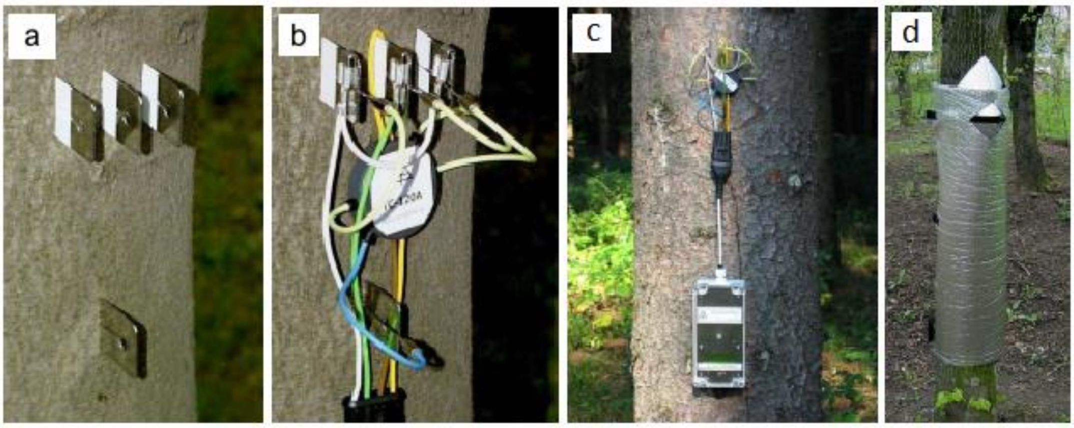

Figure 11: a) Four stainless steel electrodes. b) Power supply. c) EMS 51 sap flow system. d) Weather protection set (Kučera, 2010).

2.5.3 Meteorological measurements

Meteorological conditions in the botanical garden were monitored using a series of sensors. A sensor (EE08 manufactured by E+E Elektronik) with a ventilated radiation shield measured both relative humidity (RH) and air temperature and was installed nearby the experimental tree at a height of approximately 1.5 m and protected from direct solar radiation. Data were logged at five second-intervals and averaged every five minutes with a data logger CR1000, Campbell Scientific . Wind speed (014A manufactured by EMS) and solar radiation (EMS 11 in a AL0171 holder manufactured by EMS) were both measured in the botanical garden with a meteorological station positioned at 100 meters from the experimental location. Values were logged at five second-intervals and averaged every 15 minutes with a data logger ModuLog 3029, EMS.

Chapter 3: Temperature correction factor

3.1 Introduction

Dendrometers and LVDT-sensors are used in a variety of studies and the meteorological conditions in which they are used can span a broad range of temperatures. There is also a large daily variation in temperate forest ecosystems of which the temperature range needs to be defined. Manufacturers sometimes mention the temperature sensitivity of their sensors (Table 1). Also when *"homemade"* sensors are used, scientists need to know how sensitive these are to temperature changes since this may have an influence on the final results and interpretation.

In this chapter the step-by-step procedure that has been performed to determine temperature sensitivity will be explained in detail for one LVDT-sensor (LBB375-TA-040 made by Schaevitz Engineering). In chapter 4 the results of all dendrometers and LVDT-sensors used in this study will be presented.

3.2 Temperature sensitivity

When a point dendrometer or LVDT-sensor is mounted on a tree or on a concrete block, stainless steel rods and a frame are needed to attach the sensor. The frame and rods may also respond to temperature and therefore the temperature sensitivity of the whole sensor system will be studied consisting of frame, rods and sensor. With band dendrometers, the sensor system is defined as the electronic body and the band or wire around the tree or concrete block.

When the entire system is mounted on a concrete block and is exposed to controlled temperature steps between 10 and 30°C it is expected that the effect of temperature on the whole sensor system will be measured. The concrete block itself has also a thermal expansion coefficient, $\alpha_{concrete}$, and will consequently also show a temperature response. The expansion of the concrete block can be calculated using Equation 2 (Sevanto et al., 2003; Steppe, 2004):

$$\Delta r_{concrete} = \alpha_{concrete} . r_{concrete} . \Delta T \qquad \text{Eq. 2}$$

where $\alpha_{concrete}$ is the thermal expansion coefficient of concrete (= 10.10^{-6} °C $^{-1}$; Sellevold et al., 2006), $\Delta r_{concrete}$ is the change in radius of the concrete block by either expansion or contraction with respect to the initial radius (in mm), ΔT is the change in temperature with respect to the initial temperature (in °C) and $r_{concrete}$ is the initial radius of the block (= 95 mm).

Temperature experiments were repeated and thus a mean dataset for both measured signal and temperature response was defined, with their respective standard deviation.

Standard deviation can be calculated:

$$SD_{\Delta r_{concrete}} = \alpha_{concrete} . r_{concrete} . SD_{\Delta T} \qquad \text{Eq. 3}$$

where $SD_{\Delta T}$ is the standard deviation of the mean temperature dataset.

In Figure 12 a graphic representation of the temperature response of the concrete block is shown, and also the temperature pattern.

This concrete response $\Delta r_{concrete}$ needs to be subtracted from the total measured signal to determine the temperature response of the sensor system:

$$\Delta r_{system} = \Delta r_{measured} - \Delta r_{concrete} \qquad \text{Eq. 4}$$

where $\Delta r_{measured}$ is the raw change in signal with respect to the initial signal (in mm), with standard deviation $SD_{\Delta rmeasured}$.

Correlation between Δr_{system}, which reflects the response of the mounted sensor system on the different temperature steps, and the changes in temperature ΔT can now be made as shown in Figure 13.

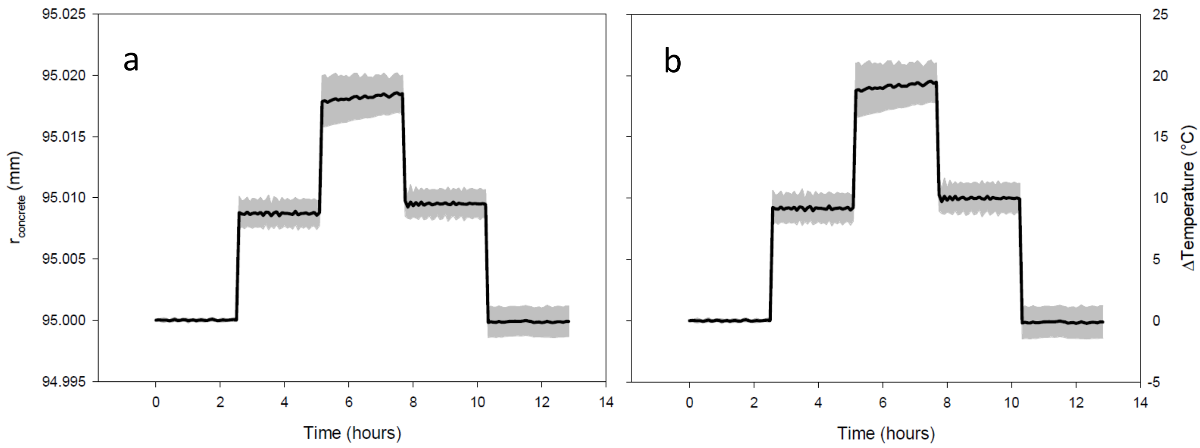

Figure 12: a) Temperature response of the concrete block $r_{concrete}$ with respect to the reference line, which represents the initial radius of the block (r = 95mm). The grey area represents the standard deviation of the concrete expansion. b) Temperature course with respect to the initial temperature (T = 10°C). The grey area represents the standard deviation of the temperature data.

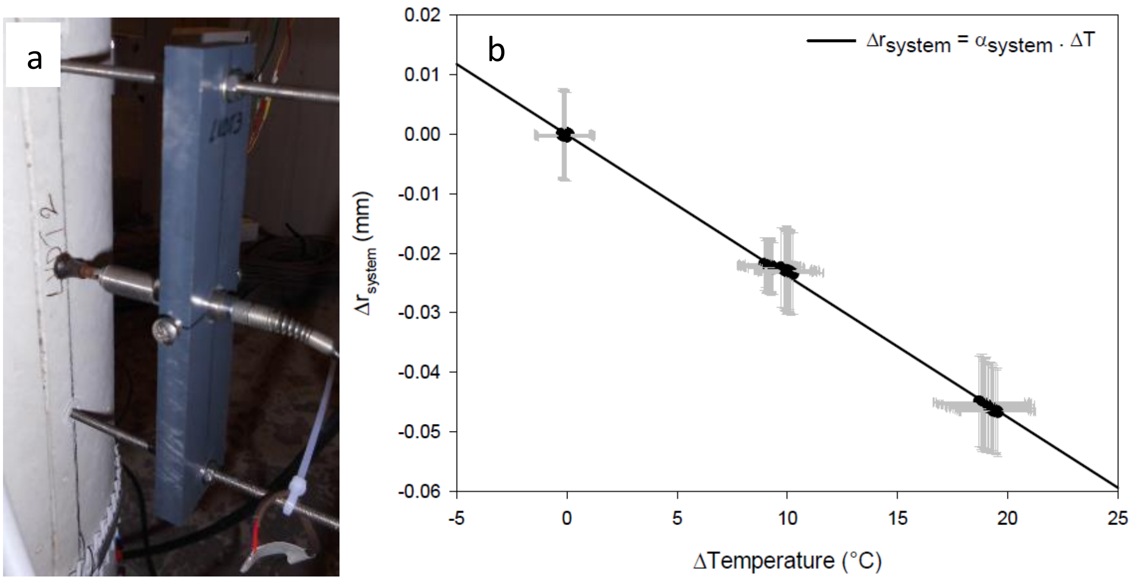

Figure 13: a) LVDT-sensor LBB315 manufactured by Schaevitz Engineering. b) Correlation between Δr_{system} (in mm) and ΔT (in °C) with error bars. Also the linear regression line is fitted to the measuring points and the equation is shown.

Fitting a regression line to the measurement points, resulted in:

$$\Delta r_{system} = \alpha_{system} . \Delta T \qquad \text{Eq. 5}$$

where α_{system} represents the temperature sensitivity of the whole sensor system and is referred to as the temperature correction factor (in mm.°C^{-1}).

Repeating the measurements, resulted in a mean α_{system}, and a mean dataset of temperature records and measured signals, and their respective standard deviation. De error on Δr_{system} can thus be calculated:

$$SD_{\Delta r_{system}} = \sqrt{(\alpha_{system}.SD_{\Delta T})^2 + (\Delta T.SD_{\alpha_{system}})^2} \qquad \text{Eq. 6}$$

3.3 Validation

To evaluate whether α_{system} resulted in a good correction for the temperature response of the whole sensor system, the following procedure was used.

With this correction factor α_{system} and available temperature data, Equation 5 was used to calculate the system's expansion or contraction response to temperature changes. These calculated values Δr_{system} can be subtracted from the total measured signal $\Delta r_{measured}$ by transforming Equation 4:

$$\Delta r_{corrected} = \Delta r_{measured} - \Delta r_{system} \qquad \text{Eq. 7}$$

with standard deviation:

$$SD_{\Delta r_{corrected}} = \sqrt{(SD_{\Delta r_{measured}})^2 + (SD_{\Delta r_{system}})^2} \qquad \text{Eq. 8}$$

Values obtained for $\Delta r_{corrected}$ should show the same trend as those obtained with Equation 3 when the correction is reliable (Figure 14b).

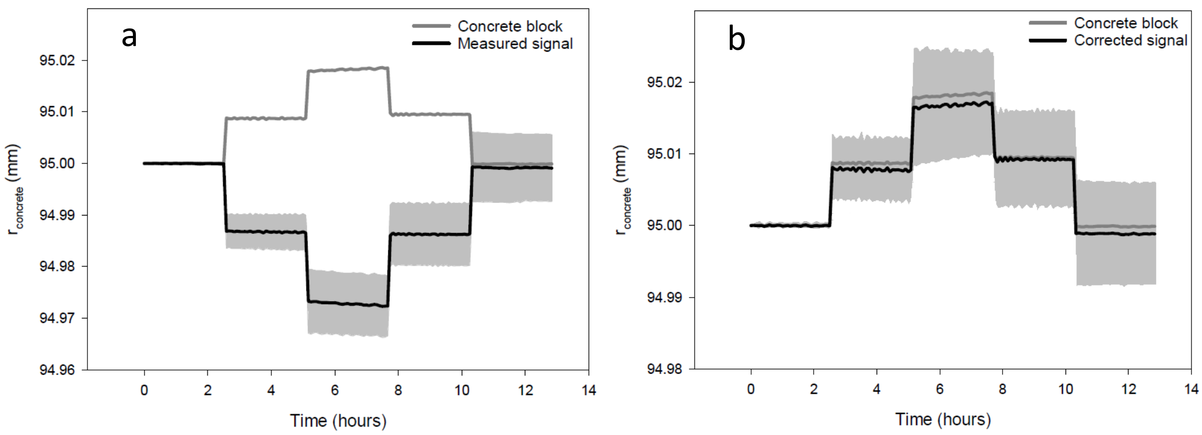

Figure 14: a) The temperature response of the concrete block $r_{concrete}$ with respect to the reference line, which represents the initial radius of the block (r = 95 mm). Also the measured signal $r_{measured}$ is shown with standard deviation (grey area). b) The theoretical temperature response and the corrected measured response of the concrete block are shown. The standard deviation is shown as a grey area.

To validate the correction, a scatter plot is made where the corrected values are plotted in function of the theoretical values of the concrete (Figure 15). A linear regression curve is fitted and both the R^2-value and the slope are calculated. A perfect correction would yield an R^2 =1, a slope of one and an intercept equal to zero.

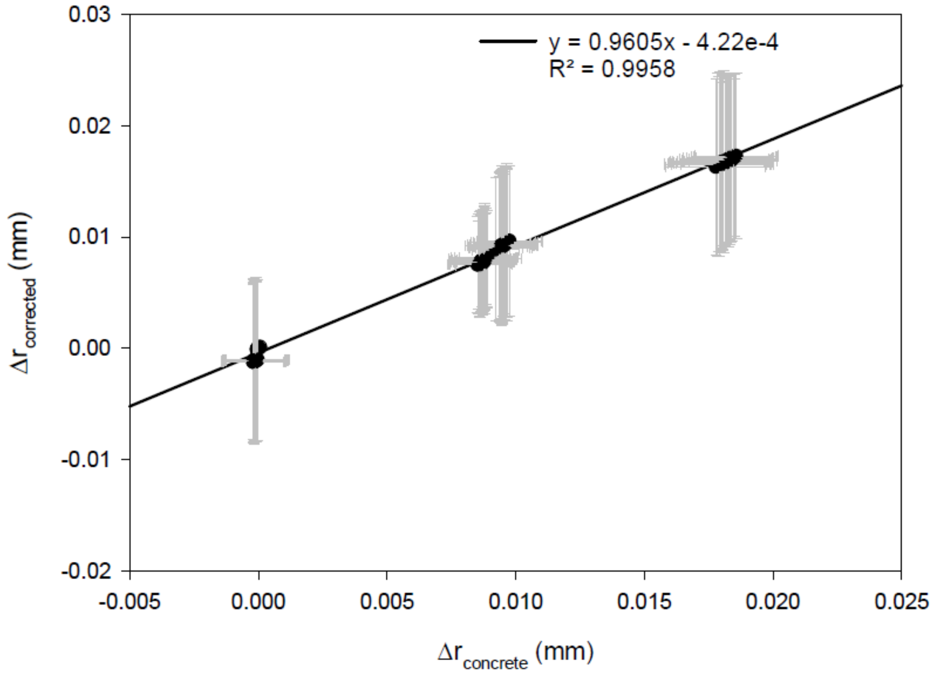

Figure 15: The corrected temperature response of the concrete block $\Delta r_{corrected}$ in function of the theoretical temperature response $\Delta r_{concrete}$. A linear regression curve is fitted and both the equation and the R^2-value are shown.

Chapter 4: Results

4.1 Temperature sensitivity

Temperature sensitivity of all sensor systems was tested and the temperature correction factor has been calculated and validated (Table 2). A variety of responses and even opposite changes have been found with different sensor types (Figure 16 up to Figure 25). The procedure, explained in chapter 3, to obtain these results, is shown for the LVDT-sensor DG/2.5 (Solartron Metrology), the point dendrometer DR (Ecomatik) and the band dendrometer DRL 26 (EMS). Also the measured signal from strain-gage clip-sensor D6 (UMS) is shown, because the R^2-value obtained for this sensor, was very low (Figure 25a and b).

4.1.1 LVDT-sensor DG/2.5

Temperature response of the LVDT-sensor DG/2.5 is opposite to the temperature response of the concrete block (Figure 16a). When the sensor was corrected with its temperature correction factor of -2.4 µm.°C^{-1} (Figure 17b), the corrected signal was equal to the concrete block's response (Figure 16b). The R^2-value for this sensor, 0.9964, was highest in comparison to the other results (Figure 18).

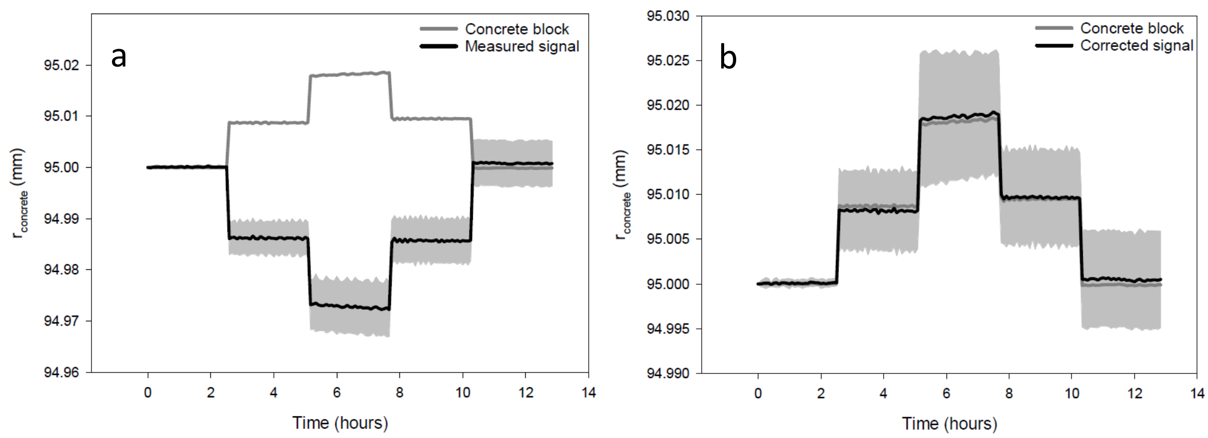

Figure 16: a) The temperature response of the concrete block $r_{concrete}$ with respect to the reference line, which represents the initial radius of the block (r = 95 mm). Also the measured signal $r_{measured}$ is shown for LVDT-sensor DG/2.5 manufactured by Solartron Metrology with standard deviation (grey area). b) The theoretical temperature response and the corrected measured response of the concrete block are shown. The standard deviation is shown as a grey area.

Table 2: Overview of the results of all different sensors. Temperature correction factors and SD are given together with the slope, the intercept and the R^2-values used to validate the correction.

Name	Distance frame-concrete (cm)	Repetitions	Temperature correction factor ($\mu m.°C^{-1}$)	a (-)	b (µm)	R^2
Point dendrometers						
Homemade (Vinicio)	2	4	-0.83 ± 0.05	0.884 ± 0.001	0.38 ± 0.09	0.9839
LPS	3.2	4	-1.1 ± 0.1	1.058 ± 0.009	2.34 ± 0.09	0.9887
DF	2.8	5	-1.06 ± 0.03	0.96 ± 0.01	1.1 ± 0.1	0.9773
DR	1.7	5	-1.25 ± 0.04	1.01 ± 0.02	0.5 ± 0.2	0.9596
Homemade (Rathgeber)	1.1	4	-1.6 ± 0.1	0.96 ± 0.03	2.8 ± 0.3	0.8676
Band dendrometers						
DC1	-	2	-1.1 ± 0.1	1.04 ± 0.02	-6.1 ± 0.2	0.9643
DRL 26	-	2	-0.2 ± 0.1	1.08 ± 0.01	-0.9 ± 0.1	0.9889
Strain-gage clip-sensor						
D6	-	2	-3.7 ± 0.5	1.1 ± 0.2	-35 ± 2	0.0533
LVDTs						
AEC, series II	7.8	5	-4.2 ± 0.3	1.04 ± 0.02	-2.5 ± 0.2	0.9488
LBB375-PA-100 (LBB375)	3.8	7	-2.3 ± 0.1	0.961 ± 0.005	-0.42 ± 0.05	0.9958
MTN/IEUSW05 (MTN)	5.9	7	3.1 ± 0.2	1.02 ± 0.02	-2.3 ± 0.2	0.9168
DF5	3.4	7	-3.2 ± 0.3	1.00 ± 0.02	0.2 ± 0.2	0.9448
DG/2.5	5.6	7	-2.4 ± 0.1	1.003 ± 0.005	0.16 ± 0.05	0.9964

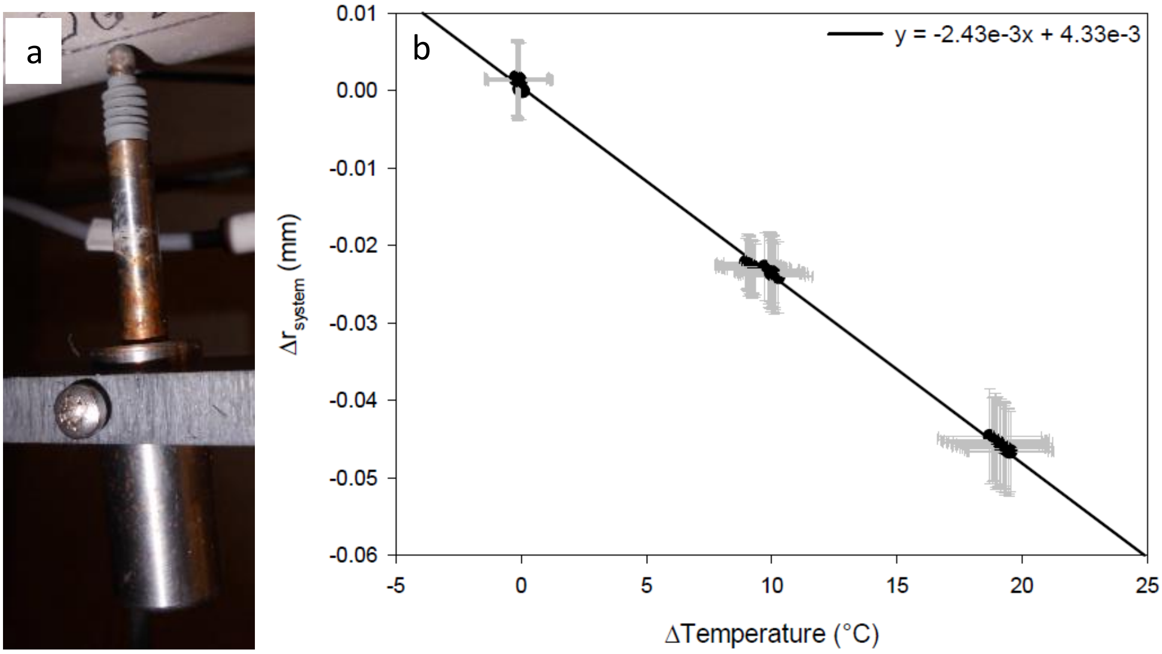

Figure 17: a) LVDT-sensor DG/2.5 manufactured by Solartron Metrology. b) Correlation between Δr_{system} (in mm) and ΔT (in °C) with error bars. Also the linear regression line is fitted to the measuring points and the equation is shown.

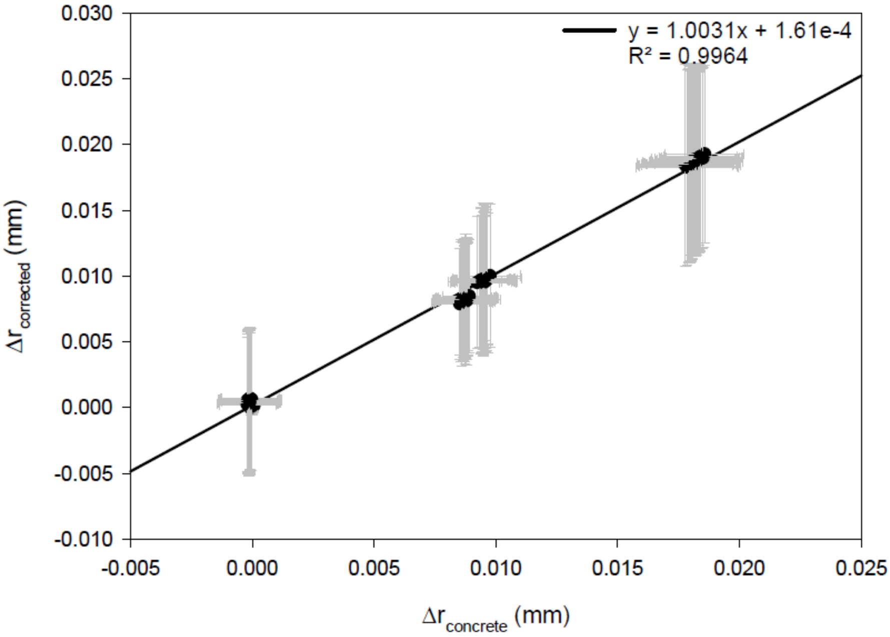

Figure 18: The corrected temperature response of the concrete block $\Delta r_{corrected}$ in function of the theoretical temperature response $\Delta r_{concrete}$. A linear regression curve is fitted and both the equation and the R^2-value are shown.

4.1.2 Point dendrometer DR

Temperature response of the point dendrometer DR was opposite to the temperature response of the concrete block (Figure 19a). When the sensor was corrected with its temperature correction factor of -1.25 µm.°C^{-1} (Figure 20b), the corrected signal showed the same trend as the concrete block (Figure 19b). The R^2-value for this sensor was 0.9596 (Figure 21).

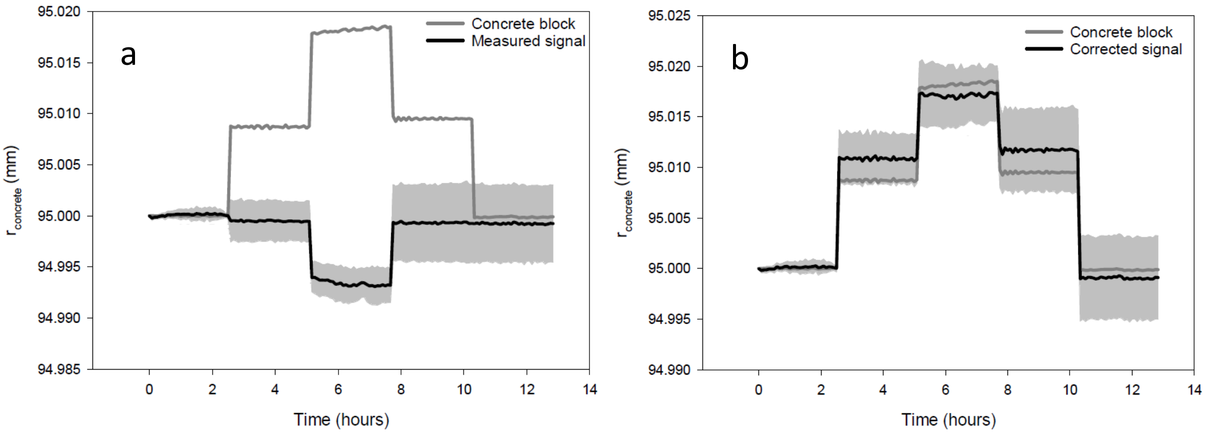

Figure 19: a) The temperature response of the concrete block $r_{concrete}$ with respect to the reference line, which represents the initial radius of the block (r = 95 mm). Also the measured signal $r_{measured}$ is shown for point dendrometer DR manufactured by Ecomatik with standard deviation (grey area). b) The theoretical temperature response and the corrected measured response of the concrete block are shown. The standard deviation is shown as a grey area.

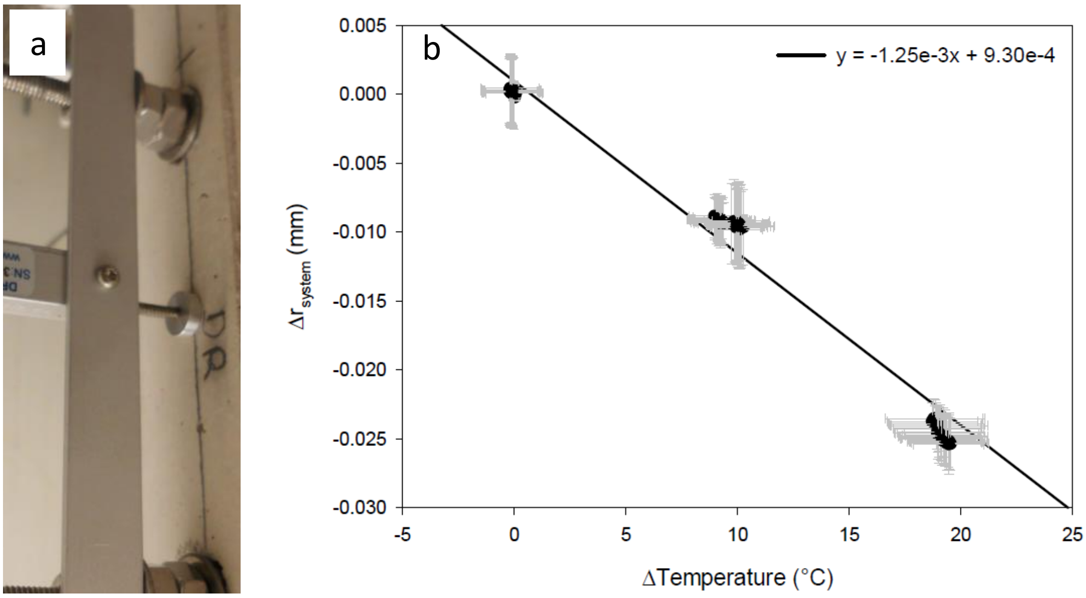

Figure 20: a) Point dendrometer DR manufactured by Ecomatik. b) Correlation between Δr_{system} (in mm) and ΔT (in °C) with error bars. Also the linear regression line is fitted to the measuring points and the equation is shown.

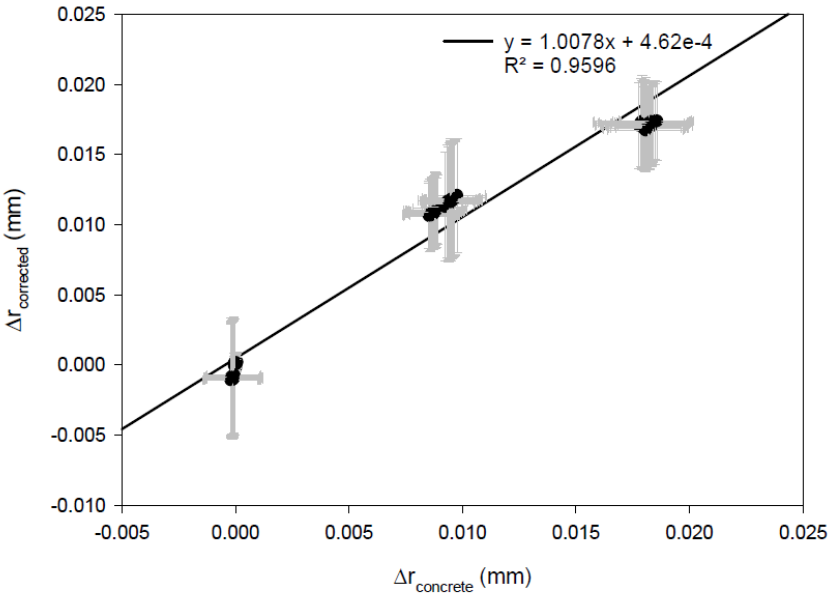

Figure 21: The corrected temperature response of the concrete block $\Delta r_{corrected}$ in function of the theoretical temperature response $\Delta r_{concrete}$. A linear regression curve is fitted and both the equation and the R^2-value are shown.

4.1.3 Band dendrometer DRL 26

The band dendrometer DRL 26 responded less to temperature than the concrete block (Figure 22a). When the sensor was corrected with its temperature correction factor of -0.2 µm.°C^{-1} (Figure 23b), the corrected signal was very similar to the response of the concrete block (Figure 22b). The R^2-value for this sensor was 0.9889 (Figure 24).

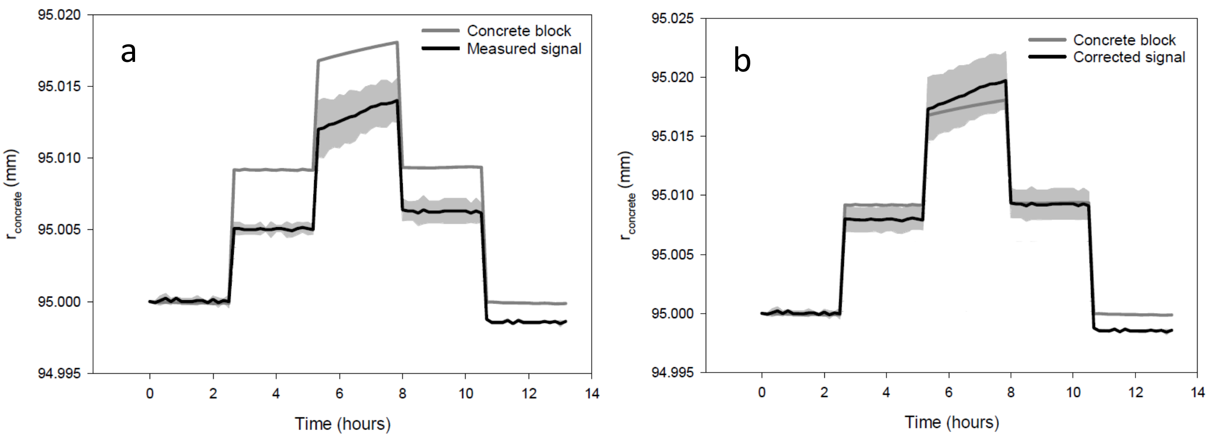

Figure 22: a) The temperature response of the concrete block $r_{concrete}$ with respect to the reference line, which represents the initial radius of the block (r = 95 mm). Also the measured signal $r_{measured}$ is shown for band dendrometer DRL 26 manufactured by EMS with standard deviation (grey area). b) The theoretical temperature response and the corrected measured response of the concrete block are shown. The standard deviation is shown as a grey area.

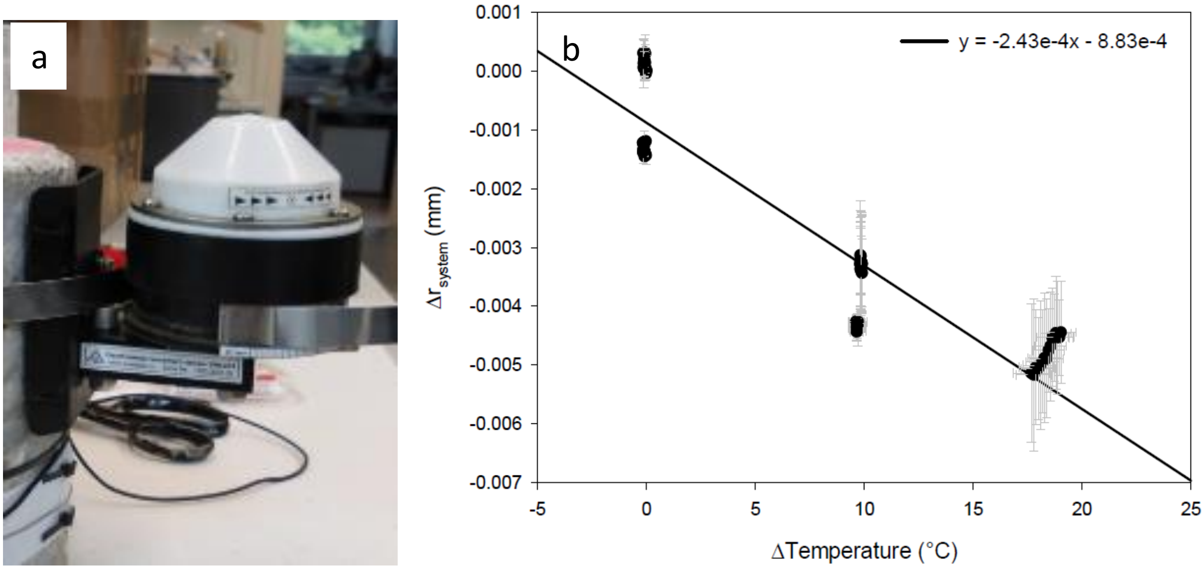

Figure 23: a) Band dendrometer DRL 26 manufactured by EMS. b) Correlation between Δr_{system} (in mm) and ΔT (in °C) with error bars. Also the linear regression line is fitted to the measuring points and the equation is shown.

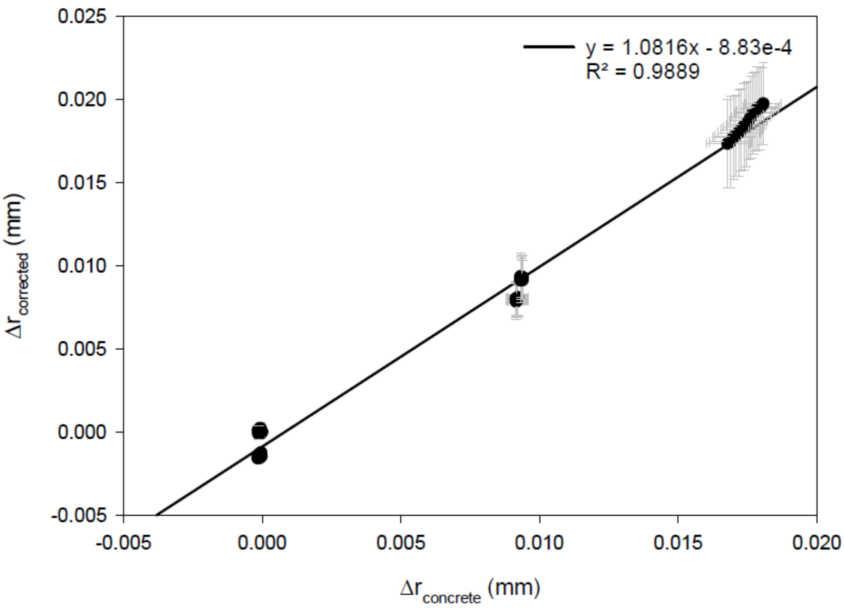

Figure 24: The corrected temperature response of the concrete block $\Delta r_{corrected}$ in function of the theoretical temperature response $\Delta r_{concrete}$. A linear regression curve is fitted and both the equation and the R^2-value are shown.

4.1.4 Strain-gage clip-sensor D6

Strain-gage clip-sensor D6 showed a different temperature response. The measured signal fell back to a minimum value when temperature is increased or decreased (Figure 25b). A reliable temperature correction factor could therefore not be determined (α_{system} was -3.7 µm.°C^{-1} with an R^2-value of 0.0533).

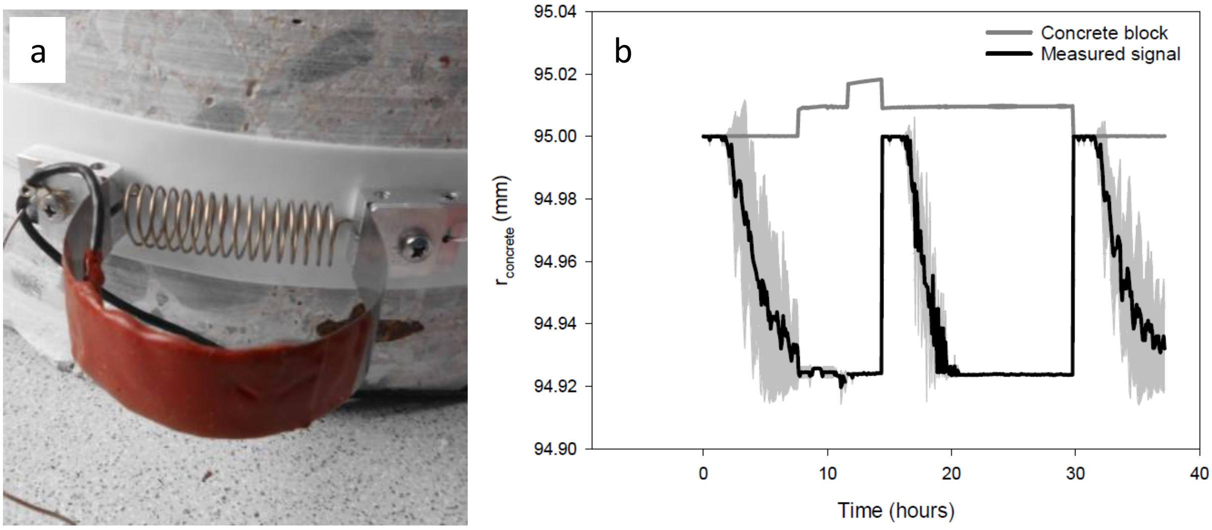

Figure 25: a) Strain-gage clip-sensor D6, made by UMS. b) The temperature response of the concrete block $r_{concrete}$ with respect to the reference line, which represents the initial radius of the block (r = 95 mm). Also the measured signal $r_{measured}$ is shown for D6 manufactured by UMS with standard deviation (grey area).

4.2 Frame position

After repeated measurements to obtain a temperature correction factor for all sensors, the effect of the frame position relative to the concrete block was tested for both LVDT-sensors DG/2.5 and AEC, series II, and point dendrometers DR and DF. Results for point dendrometer DR (Ecomatik) and LVDT-sensor DG/2.5 (Solartron Metrology), are shown in Figure 26 and Figure 27, respectively. In both cases, a different temperature correction factor was found when the frame position was changed.

When the frame of dendrometer DR was placed close to the concrete block, at a distance of 1 cm, the temperature correction factor was -1.40 µm.°C^{-1}. Placement of the frame at a distance of 2 cm, resulted in a correction factor of -1.43 µm.°C^{-1}. These results differed from the -1.25 µm.°C^{-1} value acquired placing the frame at a length of 1.7 cm.

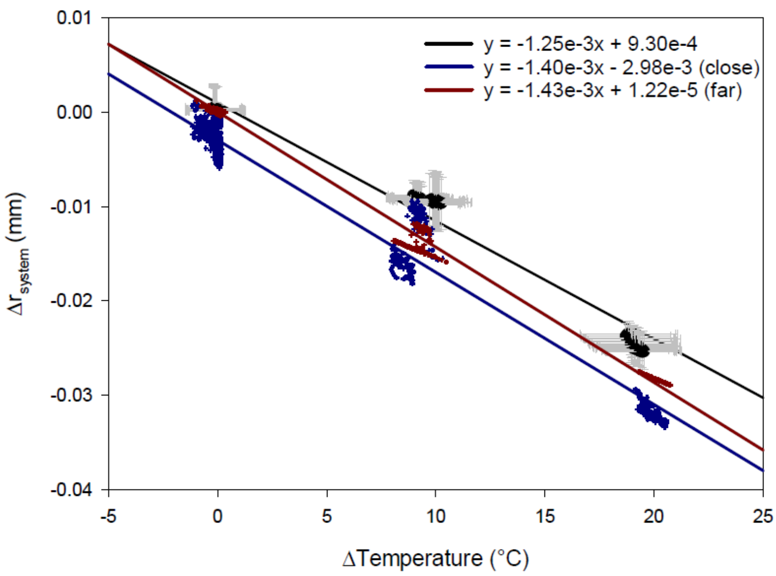

Figure 26: Correlation between Δr_{system} for point dendrometer DR (in mm) and ΔT (in °C) when the frame position was adjusted from 1 cm (dark blue) to 1.7 cm (black) and to 2 cm (dark red). Also the linear regression line is fitted to the measuring points and the equation is shown. Error bars are shown for results at 1.7 cm.

When the frame of LVDT-sensor DG/2.5 was placed close to the concrete block, at a distance of 5 cm, the temperature correction factor was -1.95 µm.°C^{-1}. Placement of the frame at a distance of 8.2 cm, resulted in a correction factor of -2.6 µm.°C^{-1}. These results differed from the -2.4 µm.°C^{-1} value acquired placing the frame at a length of 5.6 cm.

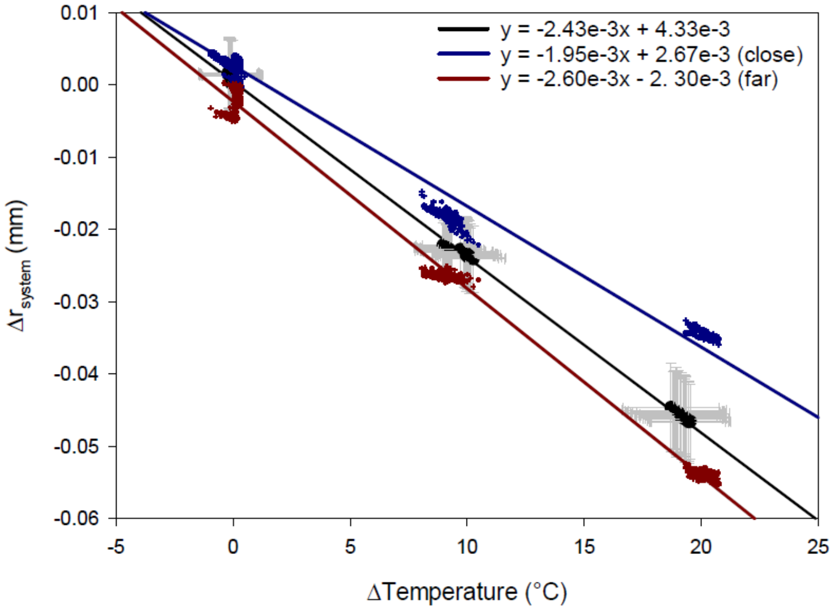

Figure 27: Correlation between Δr$_{system}$ for LVDT-sensor DG/2.5 (in mm) and ΔT (in °C) when the frame position was adjusted from 5 cm (dark blue) to 5.6 cm (black) and to 8.2 cm (dark red). Also the linear regression line is fitted to the measuring points and the equation is shown. Error bars are shown for results at 5.6 cm.

4.3 Botanical garden

4.3.1 Dendrometer and LVDT data

Stem radius measurements of a Norway spruce (*Picea abies* (L.) Karst.) in the botanical garden in Innsbruck during the month of August 2014 show a daily circadian rhythm typical for temperate regions. Both dendrometers and LVDT-sensors were mounted in the same azimuth (north). Data were recorded with a sampling resolution of 5 seconds and averaged every 5 minutes (10 minutes for the band dendrometer DRL 26).

Overall, an increase in stem radius was measured with all eleven sensors (Figure 28a and b). Results for band dendrometer DC1 are not shown, due to installation problems. Stem contraction is observed from mid-morning until late afternoon, while stem expansion starts in the evening and continues until sunrise. The first 2 days of observations showed no increase in daily growth. Upward from August 10, daily growth increased, with a maximum reached on August 14.

All sensors show the same long term pattern, but the daily amplitude varied, especially for strain-gage clip-sensor D6, point dendrometer LPS and LVDT-sensor AEC, series II. Daily amplitude is defined as the difference between the minimum and the maximum stem diameter of one daily cycle of the tree. On August 11, the largest amplitude (approximately 0.6 mm) was measured with the strain-gage clip-sensor D6, made by UMS. The smallest amplitude (almost 0.25 mm) was recorded with the band dendrometer DRL 26, manufactured by EMS (Figure 28a).

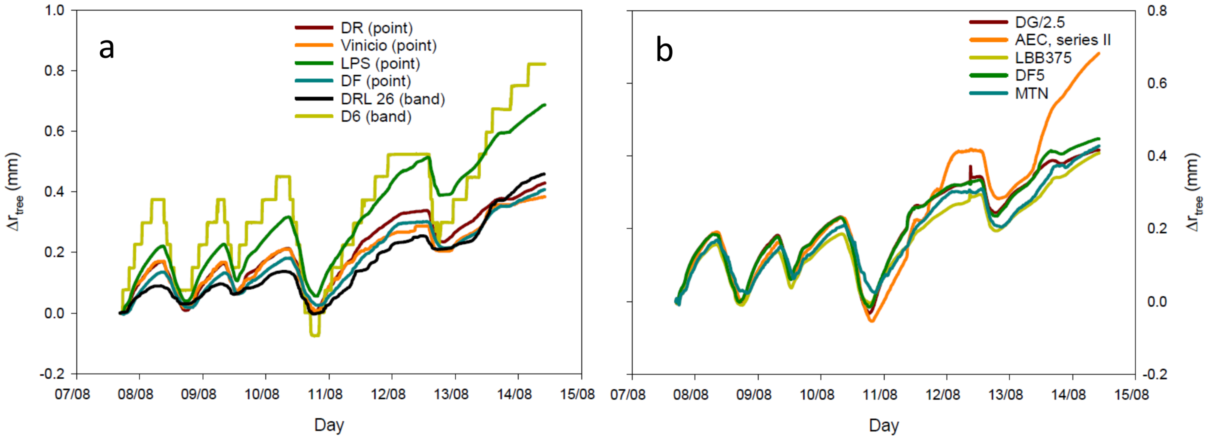

Figure 28: Raw dendrometer (a) and LVDT (b) measurements of the stem radial variation of the Norway spruce. Data were collected during August 2014.

When data are corrected for temperature, only very small differences are detected (Figure 29) in comparison with the raw measurements (Figure 28). Temperature differences are calculated using the initial temperature – 20.85°C – as the reference value. The maximum temperature difference that has been recorded during the whole measurement period amounts -8.91°C between August 11 and 12 (Figure 32b). The temperature correction can be calculated with this maximum temperature difference and with the sensor system with the largest temperature correction factor, -4.2 µm.°C^{-1} for sensor AEC, series II. A maximum temperature correction of 37.4 µm or 0.0374 mm is found for this sensor system. The amplitude for sensor AEC, series II, between August 11 and 12 is almost 0.6 mm. Temperature correction – even when a maximum temperature difference is reached – is visible as a small decrease in stem radius on the morning of August 12 (Figure 29b). For the other sensors however, temperature correction is too small to be clearly noticeable.

Besides the thermal sensitivity of the sensor system, also wood shows expansion due to temperature changes. With an initial radius of 30 cm for the Norway spruce and a thermal expansion coefficient of wood of -3.10^{-6} °C^{-1} (Salmén, 1990; Offenthaler et al., 2001; Sevanto et al., 2003), the thermal expansion of wood can be calculated (Figure 29a and b). For a maximum temperature change of 18°C, thermal expansion of wood would be -0.162 µm.

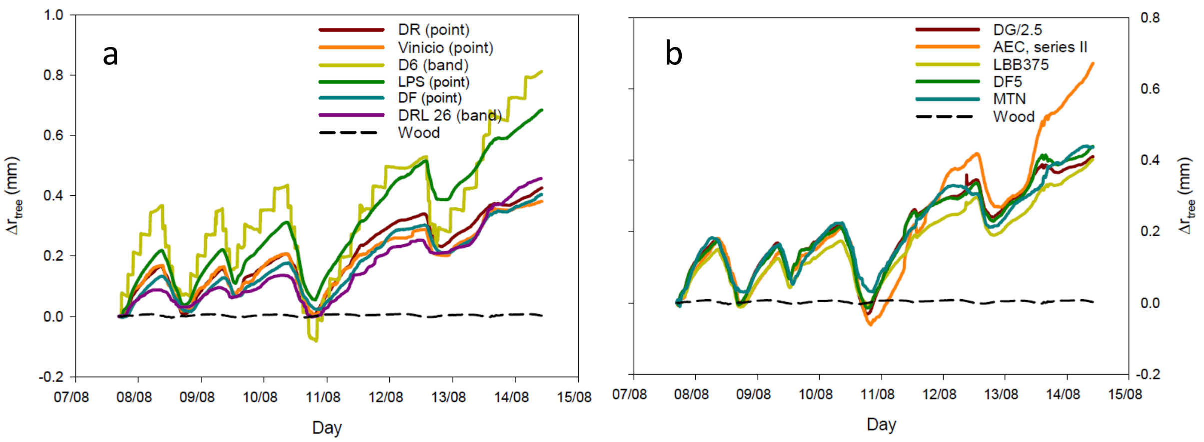

Figure 29: Temperature correction for dendrometer (a) and LVDT (b) measurements of the stem radial variation of the Norway spruce. Thermal expansion of wood is shown with the dashed line. Data were collected during August 2014.

One sensor (DR, Ecomatik) is shown in more detail with and without temperature correction, together with sap flow measurements in the north azimuth of the Norway spruce (Figure 30). Temperature correction does not show a large difference. Sap flow showed a daily rhythm, with an increase at sunrise and a decline at sunset. Dendrometers were also mounted on the north side of the tree.

On August 11, sap flow did not increase due to a rainy period. On the following days, sap flow rates were still relatively low in comparison to the beginning of the observations. During this short timespan (August 11 till 14), the stem expanded progressively and daily growth increased. The daily cycle of stem expansion and contraction was not present between August 11 and 12, only stem expansion occurred at night and during the day. When sap flow was high due to a sunny period (August 7 till 9), daily growth remained almost constant.

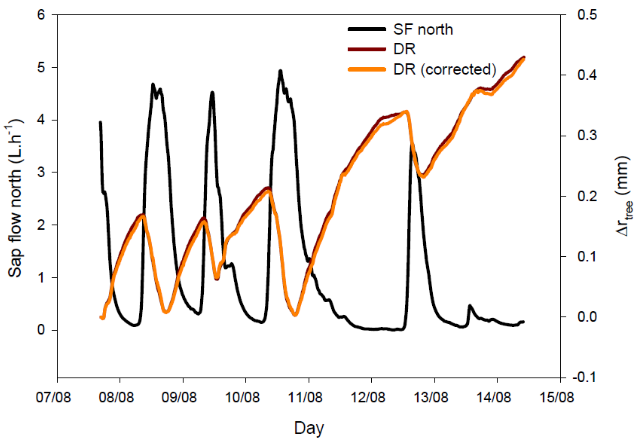

Figure 30: Sap flow rates on the north side of the Norway spruce and dendrometer measurements with DR (Ecomatik) both with and without temperature correction. Data were collected during August 2014 in the botanical garden in Innsbruck.

Stem radius measurements on the dead trunk of the Norway spruce with five sensors, are shown in Figure 31a. All sensor systems show decreasing increment due to the desiccation of the trunk, but the extent of increment change varies. When data are corrected for temperature, daily fluctuations are more clearly visible than on the intact tree, because stem radius changes measured on the dead trunk are smaller (Figure 31b). The band dendrometer DRL 26 from EMS, does not show equal oscillations as the point type and LVDT-sensors. Sap flow was not measured on the dead trunk.

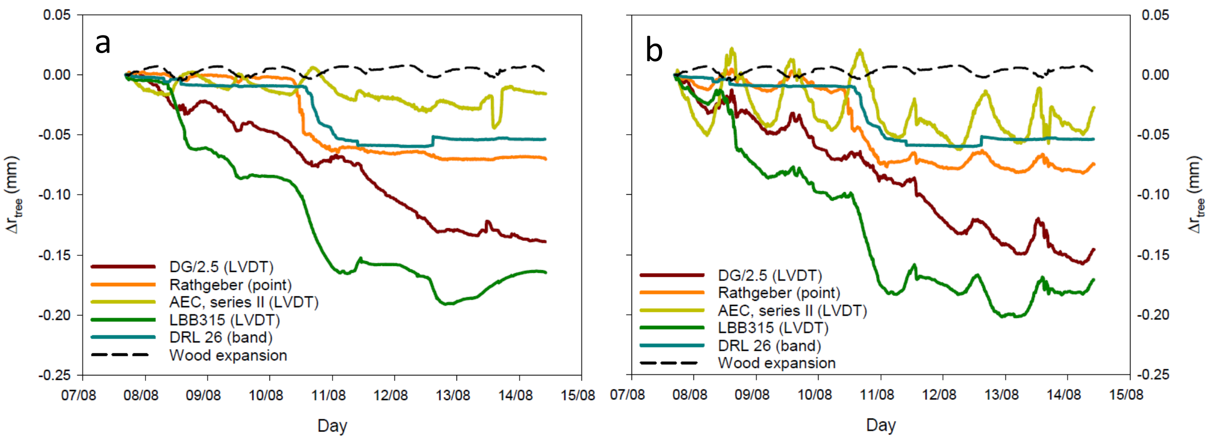

Figure 31: a) Raw LVDT and dendrometer radial stem measurements on the dead trunk of the Norway spruce.
b) Temperature correction for radial stem measurements on the dead trunk. Data were collected during August 2014.

4.3.2 Meteorological and sap flow measurements

Relative humidity (RH), temperature and radiation was measured in the botanical garden in Innsbruck during August 2014 (Figure 32a and b). Vapour pressure deficit (VPD) – the drying power of the air – was then calculated using both temperature and relative humidity data (Equation 9 up to 11).

$$e°\,(T_a) = 0.6108\,\exp\left(\frac{17.27\,T_a}{T_a + 237.3}\right) \qquad \text{Eq. 9}$$

$$RH = \frac{e}{e°}100 \qquad \text{Eq. 10}$$

$$VPD = e° - e \qquad \text{Eq. 11}$$

where e° is the saturated vapour pressure (in kPa), e the actual vapour pressure (in kPa) and T_a the air temperature (in °C).

A lag period is present between radiation and VPD (Figure 32a) and maximum values were measured at August 10, 2014.

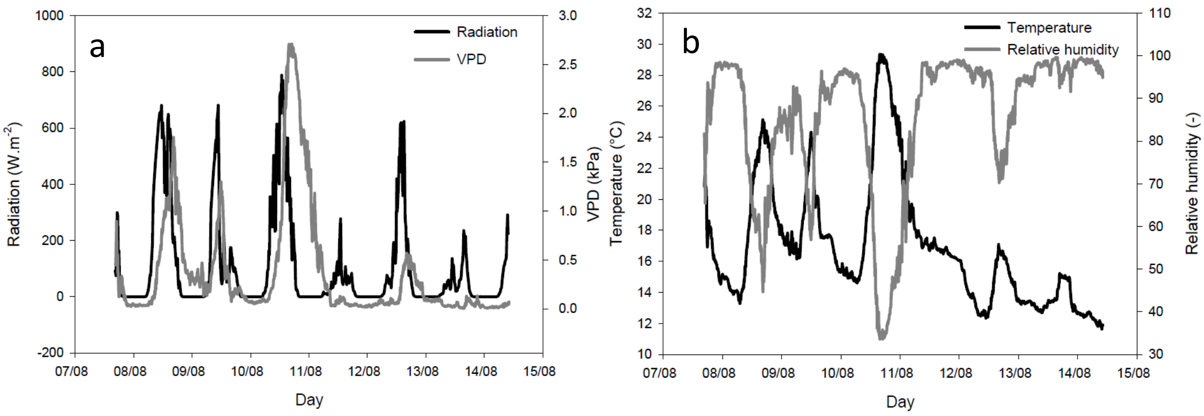

Figure 32: a) Radiation measurements and vapour pressure deficit (VPD) calculations. b) Temperature and relative humidity measurements. Data were collected in the botanical garden in Innsbruck during August 2014.

Sap flow rates on both the north and south azimuth of the Norway spruce in the botanical garden in Innsbruck show a clear daily pattern during the month of August in 2014 (Figure 33). On the south side of the tree, sap flow rate is lower than on the north side.

At night, resaturation of the stem takes place and sap flow is absent. In the morning, when the sun rises, sap flow increases rapidly and reaches a maximum value at noon (approximately 5 $L.h^{-1}$ north and 3 $L.h^{-1}$ south on August 10). From this moment on, sap flow decreases again until the baseline is reached. On August 8 and August 10 an oscillation in sap flow rate is observed at its maximum point.

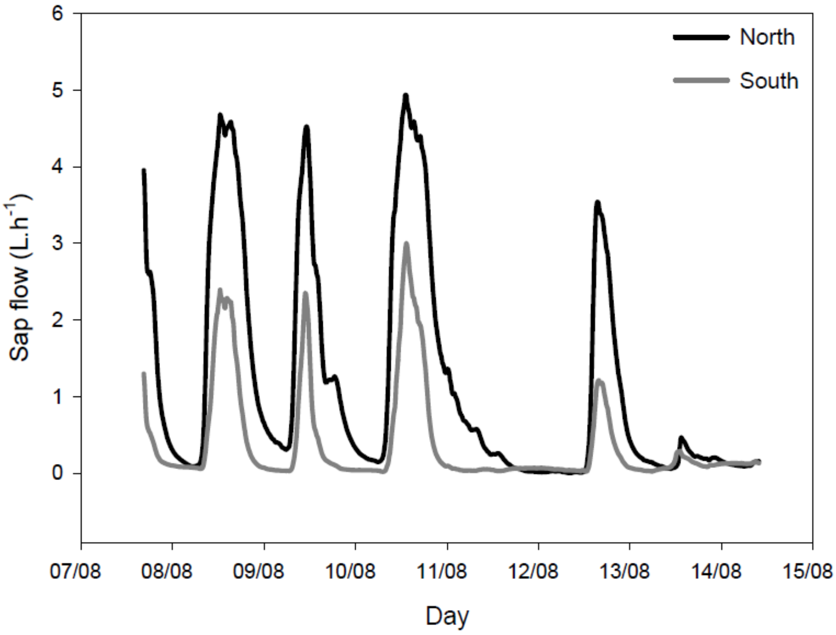

Figure 33: Time-course of sap flow rates on the north and south side of the Norway spruce. Data were collected during August 2014.

Chapter 5: Discussion

5.1 Temperature sensitivity

Temperature sensitivity of dendrometers and LVDT-sensors is not always known beforehand. Sometimes specifications are given by the manufacturer (Kučera, 2012; Naleppa, 2013), but this is not always the case (Table 1). Possible expansion or contraction due to the sensor is therefore often neglected in scientific literature (da Silva et al., 2002; Drew et al., 2009; Devine and Harrington, 2011).

In this study, temperature sensitivity was tested and a temperature correction factor was obtained for the whole sensor system by mounting all the different sensor types on a concrete block and subjecting them to a temperature regime. Temperature sensitivities indicated by manufacturers for the sensor itself (Table 1) did not correspond with results obtained in this study for the whole sensor system (Table 2). For instance, dendrometers DF, DR and DC1 from Ecomatik showed a ten times higher sensitivity to temperature (-1 $\mu m.°C^{-1}$) than was indicated by the company (0.1 $\mu m.°C^{-1}$). Results for the sensor LPS from Natkon gave a correction factor (-1.1 $\mu m.°C^{-1}$) approximately 5 times as high as the company value (0.28 $\mu m.°C^{-1}$). Results for the strain-gage clip-sensor D6, made by UMS, were similar (± 4 $\mu m.°C^{-1}$), but the R^2-value (0.0533) obtained in this study was extremely low, which indicates that the temperature correction factor is not reliable. A reason for this might be that this sensor works on a different principle than the other dendrometers and LVDT-sensors that were tested. In this specific type, four strain gauges are wired as a Wheatstone full-bridge. Temperature variations are therefore compensated, because the strain component caused by temperature changes will be the same in all four strain-gages and will offset each other (Hannah and Reed, 1992; Cimbala, 2013; Naleppa, 2013; Storr, 2015). Temperature response of D6 is presented in Figure 25b, which shows that the sensor signal indeed falls back to a minimum value when a temperature regime is applied. Because the sensor expands or contracts via a spring, there is a time-lag between temperature changes and response of the sensor.

Results show that using the temperature correction factors given by manufacturers may underestimate the real temperature sensitivity of the whole sensor system. Although temperature sensitivity of the whole sensor system was observed and not only of the sensor itself, it is important to know expansion or contraction caused by temperature response of sensor, frame and rods. Therefore, when using correction factors from the manufacturer, it is important to take temperature response of the frame and the steel rods into account as well, especially when small radius or diameter variations need to be observed.

Another important remark is that temperature correction factors obtained in this study are almost always negative (except LVDT-sensor MTN, Monitran), whereas temperature sensitivities given by the manufacturer are always positive. However, only nominal values are given by the companies, which are not the same as the actual value. It is therefore not recommended to use these temperature sensitivity values, since no indication is given whether the correction for temperature needs to be subtracted or added to the raw signal. On annual – or even daily – scale, however, temperature correction is not equally important (5.3 Botanical garden).

5.2 Frame position

In scientific studies, dendrometers and LVDT-sensors are valued instruments. It is impossible to mount a sensor exactly the same way in every study and therefore it is important to know whether the sensor’s response changes whenever the frame is placed closer to or further away from the sensor body.

When the distance between the concrete block and the frame was adjusted, temperature correction factors differed with nearly 0.2 µm.°C^{-1} for dendrometer DR (Figure 26) from the original results. This could be explained by the fact that the frame of this type of dendrometer is attached to the sensor body (Figure 9c and d). By placing the frame closer to or further away from the concrete block, the sensor head is pushed in more or less. This means that data might be recorded at the measuring limits of the sensor, which may have caused a deviation in the temperature correction factor. Others sensors with attached frame are dendrometers DF from Ecomatik, the homemade models Vinicio and Rathgeber from Uni Padova and LERFoB, and LVDT-sensor AEC, series II from Agricultural Electronics. When the frame was not attached to the sensor body, as for LVDT-sensor DG/2.5, results did also not agree with the temperature correction factor found earlier (Figure 27). A possible explanation for this deviation could be that the frame was not placed in the middle of the sensor body during these measurements, but on both ends of the sensor (Figure 9a and b). Therefore, stability was not secured, and, again, results differed. During the tests however, the sensor was pushed in similar to dendrometer DR, which may also have caused a deviation. Other sensors with a separate frame are dendrometer LPS from Natkon and LVDTs LBB315-PA-100 and LBB375-TA-040 from Schaevitz Engineering, and both DF5 from Solartron Metrology and MTN from Monitran.

For both LVDT and dendrometer, results differed most when the sensor was placed close to the concrete block. Data were, on closer examination, recorded at the measuring limits of the sensors when the frame was placed close to the concrete block. This was both times not the case when the frame was placed further away. Data were then situated in the ‘error bar’ area of results when the frame was placed between the two extreme situations. This indicates that care should be taken to ensure that data are not recorded at the measuring limits of the sensor. However, more tests are needed to understand the effect of the frame distance relative to the concrete block or tree.

5.3 Botanical garden

Measurements of both stem radius (Figure 28) and sap flow (Figure 33) were performed on a Norway spruce (*Picea abies* (L.) Karst.) in the botanical garden in Innsbruck during the growing season in August. An overall stem radius increase was observed during the measuring period. It has been reported previously that temperate northern hemisphere forests show a clear seasonal variation in daily stem increment, with the daily water balance and prevailing weather conditions like temperature being important factors affecting this variation (Zweifel and Häsler, 2001; Mäkinen et al., 2003; Deslauriers et al., 2003; 2007; McLaughlin et al., 2007; Drew et al., 2009).

Simultaneously measuring the radius of the stem and the sap flow rate, reveals a close relationship (Herzog et al., 1995). The daily cycle consists of stem contraction during the day and stem expansion at night (Wronski et al. 1985; Herzog et al., 1995; Pallardy, 2008; Devine and Harrington, 2011; King et al., 2013). When canopy water demand exceeded water absorption via the roots, the stem contracted. Sap flow increased during this period. A delay between sap flow increase and stem contraction is affected by hydraulic flow resistance, storage capacity and transpiration (Zweifel and Häsler, 2001). Expansion of the stem was observed during the night when water uptake was greater than water loss to the atmosphere. During stem expansion, sap flow rates were at a minimum value (Figure 30). Sap flow rates were significantly higher on the north side of the Norway spruce than in the south orientation (Figure 33). Studies have verified that sap flow can change considerably among different branches in specific locations of the stem (Steinberg et al., 1990; Alarcan et al., 2003; Nicolas et al., 2005; Burgess and Dawson, 2008). Variability in flow needs to be taken into account over the radial profile and over the circumference of trees at the same height (Nadezhdina et al., 2002; Čermák et al., 2004). In this study however, both sap flow sensors were installed at the same height in the stem, only the azimuth differed. A change in sap flow measurements in different orientations, but at the same height have been reported for *Picea abies* (Offenthaler et al., 2001). Often a mean value for SF is calculated for the sample trees (Čermák et al., 1995). High radiation and vapour pressure deficit had a negative effect on stem expansion (Figure 32a). When radiation is high, also the water demand of the atmosphere – and thus VPD – is high and relative humidity is low (Figure 32b). The primarily effect of high VPD is to inhibit cell enlargement and growth, because it has an indirect effect on cell turgor pressure. This effect of VPD also indicates the importance of the water component (Major and Johnsen, 2001; Deslauriers et al., 2003).

All sensor systems installed on the Norway spruce showed the same long term pattern, but daily amplitudes varied. This indicates that LVDTs, point and band dendrometers cannot be compared with each other directly. It seems that relative patterns are fairly reproducible, but care should be taken with absolute values. However, when annual growth patterns are studied, all sensor systems give similar information. When the measurements were corrected for temperature, no clear difference was observed (Figure 29). When a calculation was made for the sensor with the largest temperature correction factor (LVDT AEC, series II) and with the largest possible temperature difference (-8.91°C between August 11 and 12), the theoretical temperature correction was 37.4 µm or 0.0374 mm in comparison with an amplitude of 0.6 mm. During this maximum temperature difference, a small drop is visible when measurements with and without temperature correction are compared for this LVDT-sensor on August 12 (Figure 28b and 29b). All other sensors however, showed a smaller temperature sensitivity and therefore, temperature correction is almost not visible.

This study has indicated that temperature correction is most essential when small variations need to be studied and less on annual scale. It is equally important to take wood expansion and contraction due to temperature changes into account when this has a significant contribution. However, when wood expansion is compared with the sensor data (Figure 29), it shows that the thermal effects of wood are negligible. A contribution of 0.162 µm at a maximum temperature change of 18°C is insignificant relative to the maximum daily growth.

Sensors installed on a dead trunk of the Norway spruce, did not show equal extent of increment. All systems showed a decreasing increment, which is due to desiccation of the trunk. Small fluctuations can be seen, but daily fluctuations are not clearly visible (Figure 31a). When all measurements were corrected for temperature, daily trends emerged (Figure 31b). This shows that temperature correction becomes essential when small variations need to be studied. However, flat curves or slight positive temperature responses based on temperature reactions of the trunk are not obtained, although this was expected. Different outputs can be related to the position of the sensors on the stem, since all sensors were mounted in the same azimuth, but at different heights. It is plausible that desiccation of the trunk is not homogenous along its entire height. LVDT-sensor AEC, series II, showed the smallest increment change and was positioned closest to were the stem was cut. LVDT-sensor LBB315 was mounted lowest and showed the largest increment changes.

Conclusions

Dendrometer or LVDT-data is used in important research areas like irrigation scheduling, forestry and climate change studies. Therefore, it is important to consider that part of the measured signal is due to the thermal expansion or contraction of the sensor itself, and both the frame and the steel rods in case point types are used. To be able to interpret the sensor signal correctly, a better understanding is needed of this thermal response. This master thesis has consequently led to a better idea or notion of the temperature sensitivity of dendrometers and LVDT-sensors.

Results have shown that temperature needs to be taken into account when small variations are observed. However, when annual cycles are studied, temperature sensitivity of the sensor systems is negligible. Care should be taken with correction factors specified by the manufacturers, because most often only a correction is given for the sensor itself and not for the whole system, including the frame and steel rods to mount the sensor on a tree. Furthermore, no indication is given whether the temperature response of the sensor over- or underestimates daily growth of the tree, which makes an exact correction difficult.

Thermal expansion or contraction of the wood itself has been considered as well. When expansion coefficients from scientific literature are used, it can be determined that wood expansion can be neglected, since its contribution is insignificant.

Within the COST action STReESS, a group of scientific researchers aim at a wide European study, and collection of dendrometer and LVDT-data. However, since a wide variety of sensors has been developed and introduced into scientific research, it is important to know whether the outputs of different studies are comparable. In this master thesis, different types of sensors were compared to each other and it can be stated that different amplitudes were obtained. Nevertheless, long term patterns are similar. Relative patterns are therefore fairly reproducible for all sensors, but care should be taken when absolute values for maximum daily shrinkage or daily growth are considered. When it is also taken into account that temperature sensitivity is not significant on annual scale, it can be concluded that the choice of sensor will mostly depend upon robustness and cost.

Future research

This master thesis has given a better understanding of the temperature sensitivity of dendrometers and LVDT-sensors. However, the development of new sensors and custom made frames will be carries on in the future. Temperature sensitivity tests will therefore continue to be indispensable.

The effect of the frame position relative to the concrete block – or tree – has been studied as well. However, more tests are be needed in the future to have a better understanding of this effect, since no repetitions have been carried out in this study.

References

Adams HD, Guardiola-Claramonte M, Barron-Gafford GA, Villegas JC, Breshears DD, Zou CB, Troch PA, Huxman TE. 2009. Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. PNAS 106 (17), 7063-7066.

Alarcón JJ, Domingo R, Green SR, Nicolás E, Torrecillas A. 2003. Estimation of hydraulic conductance within field-grown apricot using sap flow measurements. Plant and soil 251, 125-135.

Alcaraz-Segura D, Chuvieco E, Epstein HE, Kasischke ES, Trishchenko A. 2010. Debating the greening vs. browing of the North American boreal forest: differences between satellite datasets. Global Change Biology 16, 760-770.

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EH (T), Gonzalez P, Fensham R, Zhang Z, Castro J, Demidova N, Lim JH, Allard G, Running SW, Semerci A, Cobb N. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management 259, 660-684.

Anemaet ER and Middleton BA. 2013. Dendrometer bands made easy: using modified cable ties to measure incremental growth of trees. Applications in Plant Sciences 1 (9), 1300044.

Auchmoody LR. 1976. Accuracy of band dendrometers. U.S.D.A. Forest Service Research Note NE-221. Forest Service, US Department of Agriculture, Upper Darby, Pennsylvania, USA.

Biondi F, Hartsough P. 2010. Using automated point dendrometers to analyse tropical treeline stem growth at Nevado de Colima, Mexico. Sensors 10 (6), 5827-5844.

Bonet L, Ferrer P, Castel JR, Intrigliolo DR. 2010. Soil capacitance sensors and stem dendrometers. Useful tools for irrigation scheduling of commercial orchards? Spanish Journal of Agricultural Research 8 (S2), S52-S65.

Bouriaud O, Leban JM, Bert D, Deleuze C. 2005. Intra-annual variations in climate influence growth and wood density of Norway spruce. Tree Physiology 25, 651-660.

Breitsprecher A and Hughes W. 1975. A recording dendrometer for humid environments. Biotropica 7 (2), 90-99.

Breshears DD, Myers OB, Meyer CW, Barnes FJ, Zou CB, Allen CD, McDowell NG, Pockman WT. 2009. Tree die-off in response to global-change-type drought: mortality insights from a decade of plant water potential measurements. Frontiers in Ecology and the Environment 7, 185-189.

Bucci SJ, Scholz FG, Goldstein G, Meinzer FC, Hinojosa JA, Hoffmann WA, Franco AC. 2004. Processes preventing nocturnal equilibration between leaf and soil water potential in tropical savanna woody species. Tree Physiology 24, 1119-1127.

Burgess SSO and Dawson TE. 2008. Using branch and basal trunk sap flow measurements to estimate whole-plant water capacitance: a caution. Plant soil 305, 5-13.

Čermák J, Deml M, Penka M. 1973. A new method of sap flow rate determination in trees. Biologia Plantarum 15 (3), 171-178.

Čermák J, Cienciala E, Kučera J, Lindroth A, Bednářová E. 1995. Individual variation of sap-flow rate in large pine and spruce trees and stand transpiration: a pilot study at the central NOPEX site. Journal of Hydrology 168, 17-27.

Čermák J, Kučera J, Nadezhdina N. 2004. Sap flow measurements with some thermodynamic methods, flow integration within trees and scaling up from sample trees to entire forest stands. Trees 18, 529-546.

Cherubini P, Humbel T, Beeckman H, Gärtner H, Mannes D, Pearson C, Schoch W, Tognetti R, Lev-Yadun S. 2013. Olive tree-ring problematic dating: a comparative analysis on Santorini (Greece). PLoS ONE 8 (1), e54730.

Cimbala JM. 2013. Stress, strain and strain gages. Available at: https://www.mne.psu.edu/me345/Lectures/Strain_gages.pdf (Accessed: 17 February 2015).

Clark NA, Wynne RH, Schmoldt DL. 2000. A review of past research on dendrometers. Forest Science 46 (4), 570-576.

Cox PM, Betts RA, Collins M, Harris PP, Huntingford C, Jones CD. 2004. Amazonian forest dieback under climate-carbon cycle projections for the 21st century. Theoretical and Applied Climatology 78, 137-156.

da Silva RP, dos Santos J, Tribuzy ES, Chambers JQ, Nakamura S, Higuchi N. 2002. Diameter and increment growth patterns for individual tree growing in Central Amazon, Brazil. Forest Ecology and Management 166, 295-301.

Daudet FA, Ameglio T, Cochard H, Archilla O, Lacointe A. 2005. Experimental analysis of the role of water and carbon in tree stem diameter variations. Journal of Experimental Botany 56, 135-144.

De Schepper V, van Dusschoten D, Copini P, Jahnke S, Steppe K. 2011. MRI links stem water content to stem diameter variations in transpiring trees. Journal of Experimental Botany 63 (7), 2645-2653.

Deslauriers A, Morin H, Urbinati C, Carrer M. 2003. Daily weather response of balsam fir (*Abies balsamea* (L.) Mill.) stem radius increment from dendrometer analysis in the boreal forests of Québec (Canada). Trees 17, 477-484.

Deslauriers A, Rossi S, Anfodillo T. 2007. Dendrometer and intra-annual tree growth: What kind of information can be inferred? Dendrochronologia 25, 113-124.

Deslauriers A, Rossi S, Turcotte A, Morin H, Krause C. 2011. A three step procedure in SAS to analyse the time series from automatic dendrometers. Dendrochronologia 29, 151-161.

Desprez-Loustau ML, Marçais B, Nageleisen LM, Piou D, Vannini A. 2006. Interactive effects of drought and pathogens in forest trees. Annals of Forest Science 63, 597-612.

De Swaef T, Steppe K, Lemeur R. 2009. Determining reference values for stem water potential and maximum daily trunk shrinkage in young apple trees based on plant responses to water deficit. Agricultural Water Management 96, 541-550.

Devine WD and Harrington CA. 2011. Factors affecting diurnal stem contraction in young Douglas-fir. Agricultural and Forest Meteorology 151, 414-419.

Dong J, Kaufmann RK, Myneni RB, Tucker CJ, Kauppi PE, Liski J, Buermann W, Alexeyev V, Hughes MK. 2003. Remote sensing estimates of boreal and temperature forest woody biomass: carbon pools, sources and sinks. Remote Sensing of Environment 84, 393-410.

Downes G, Beadle C, Worledge D. 1999. Daily stem growth patterns in irrigated *Eucalyptus globulus* and *E. nitens* in relation to climate. Trees 14, 102-111.

Downes G, Drew D, Battaglia M, Schulze D. 2009. Measuring and modelling stem growth and wood formation: An overview. Dendrochronologia 27, 147-157.

Drakeley GM. 1988. Digital motor feedback for a position actuator. U.S. Patent 4,756,229, issued July 12, 1988.

Drew DM and Downes GM. 2009. The use of precision dendrometers in research on daily stem size and wood propriety variation: a review. Dendrochronologia 27, 159-172.

Drew DM, Downes GM, Grzeskowiak V, Naidoo T. 2009. Differences in daily stem size variation and growth in two hybrid eucalypt clones. Trees 23, 585-595.

Drumea A, Vasile A, Comes M, Blejan M. 2006. System on chip signal conditioner for LVDT sensors. Electronics Systemintegration Technology Conference 1 (1), 629-634.

Faiz SMA and Weatherley PE. 1982. Root contraction in transpiring plants. New Phytologist 92, 333-343.

Fereres E and Goldhammer DA. 2003. Suitability of stem diameter variations and water potential as indicators for irrigation scheduling of almond trees. Journal of Horticultural Science and Biotechnology 78, 139-144.

Fernández JE and Cuevas MV. 2010. Irrigation scheduling from stem diameter variations: A review. Agricultural and Forest Meteorology 150, 135-151.

Figueira AM and S, Miller SD, de Sousa CAD, Menton MC, Maia AR, da Rocha HR, Goulden ML. 2008. Effects of selective logging on tropical forest tree growth. Journal of Geophysical Research 113, G00B05, doi:10.1029/2007JG000577.

Friedlingstein P, Cox P, Betts R, Bopp L, von Bloh W, Brovkin V, Cadule P, Doney S, Eby M, Fung I, Bala G, John J, Jones C, Joos F, Kato T, Kawamiya M, Knorr W, Lindsay K, Matthews HD, Raddatz T, Rayner P, Reick C, Roeckner E, Schnitzler KG, Schnur R, Strassmann K, Weaver AJ, Yoshikawa C, Zeng N. 2006. Climate-carbon cycle feedback analysis: Results from the C^4MIP model intercomparison. Journal of Climate 19, 3337-3353.

Goldhammer DA and Fereres E. 2001. Irrigation scheduling protocols using continuously recorded trunk diameter measurements. Irrigation Science 20 (3), 115-125.

Grace J, Berninger F, Nagy L. 2002. Impacts of climate change on the tree line. Annals of Botany 90, 537-544.

Grogan J and Schulze M. 2012. The impact of annual and seasonal rainfall patterns on growth and phenology of emergent tree species in Southeastern Amazonia, Brazil. Biotropica 44, 331-340.

Hacke UG, Sperry JS, Pockman WT, Davis SD, McCulloh KA. 2001. Trends in wood density and structure are linked to prevention of xylem implosion by negative pressure. Oecologia 126, 457-461.

Hannah RL and Reed SE. 1992. Strain gage user's handbook. Chapman and Hall, London.

Hanson PJ and Weltzin JF. 2000. Drought disturbance from climate change: response of United States forests. The Science of the Total Environment 262, 205-220.

Hayhoe K, Wake CP, Huntington TG, Luo L, Schwartz MD, Sheffield J, Wood E, Anderson B, Bradbury J, DeGaetano A, Troy TJ, Wolfe D. 2002. Past and future changes in climate and hydrological indicators in the US Northeast. Climate Dynamics 28, 381-407.

Herzog KM, Häsler R, Thum R. 1995. Diurnal changes in the radius of a subalpine Norway spruce stem: their relation to the sap flow and their use to estimate transpiration. Trees 10, 94-101.

Herzog KM, Thum R, Zweifel R, Häsler R. 1997. Heat balance measurements – to quantify sap flow in thin stems only? Agricultural and Forest Meteorology 83, 75-94.

Hon RC, Pollack TH, Kieffer MH, Kirkconnell CS. 2010. Noncontinuous resonant position feedback system. U.S. Patent 7,684, 955, issued March 23, 2010.

Howard BC. 2015. Antarctica may have hit highest temperature on record. National Geographic, published March 31, 2015.

Huck MG, Klepper B, Taylor HM. 1970. Diurnal variations in root diameter. Plant Physiology 45, 529-530.

Intrigliolo DS and Castel JR. 2004. Continuous measurement of plant and soil water status for irrigation scheduling in plum. Irrigation Science 23, 93-102.

Jacobsen AL, Pratt RB, Davis SD, Ewers FW. 2008. Comparative community physiology: nonconvergence in water relations among three semi-arid shrub communities. New Phytologist 180, 100-113.

Keeland BD and Sharitz RR. 1993. Accuracy of tree growth measurements using dendrometer bands. Canadian Journal of Forest Research 23 (11), 2454-2457.

King G, Fonti P, Nievergelt D, Büntgen U, Frank D. 2013. Climatic drivers of hourly to yearly tree radius variations along a 6 °C natural warming gradient. Agricultural and Forest Meteorology 168, 36-46.

Kozlowski and Winget. 1964. Diurnal and seasonal variation in radii of tree stems. Ecology 45 (1), 149-155.

Krepkowski J, Bräuning A, Gebrekirstos A. 2012. Growth dynamics and potential for cross-dating and multi-century climate reconstruction of *Podocarpus falcatus* in Ethiopia. Dendrochronologia 30, 257-265.

Kučera J. 2010. User manual EMS 51 sap flow system for large tree trunks. EMS Brno, Brno, Czech Republic.

Kučera J. 2012. User manual Dendrometer increment sensor DRL 26A. EMS Brno, Brno, Czech Republic.

Lagergren F and Lindroth A. 2004. Variation in sapflow and stem growth in relation to tree size, competition and thinning in a mixed forest of pine and spruce in Sweden. Forest Ecology and Management 188, 51-63.

Major JE, Johnsen KH. 2001. Shoot water relations of mature black spruce families displaying a genotype x environment interaction in growth rate. III. Diurnal patterns as influenced by vapor pressure deficit and internal water status. Tree Physiology 21, 579-587.

Mäkinen H, Nöjd P, Saranpää P. 2003. Seasonal changes in stem radius and production of new tracheids in Norway spruce. Tree Physiology 23, 959-968.

Mäkinen H, Seo JW, Nöjd P, Schmitt U, Jalkanen R. 2008. Seasonal dynamics of wood formation: a comparison between pinning, microcoring and dendrometer measurements. European Journal of Forest Research 127 (3), 235-245.

McDowell N, Pockman WT, Allen CD, Breshears DD, Cobb N, Kolb T, Plaut J, Sperry J, West A, Williams DG, Yepez EA. 2008. Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? New Phytologist 178, 719-739.

McLaughlin SB, Nosal M, Wullschleger SD, Sun G. 2007. Interactive effects of ozone and climate on tree growth and water use in a southern Appalachian forest in the USA. New Phytologist 174, 109-124.

McLaughlin SB, Shortle WC, Smith KT. 2002. Dendroecological applications in air pollution and environmental chemistry: research needs. Dendrochronologia 20 (1-2), 133-157.

McLaughlin SB, Wullschleger SD, Nosal M. 2003. Diurnal and seasonal changes in stem increment and water use by yellow poplar trees in response to environmental stress. Tree Physiology 23, 1125-1136.

Meinshausen M, Meinshausen N, Hare W, Raper SCB, Frieler K, Knutti R, Frame DJ, Allen MR. 2009. Greenhouse-gas emission targets for limiting global warming to 2 °C. Nature 458, 1158-1163.

Meinzer FC, Campanello PI, Domec JC, Gatti MG, Goldstein G, Villalobos-Vega R, Woodruff DR. 2008a. Constraints on physiological function associated with branch architecture and wood density in tropical forest trees. Tree Physiology 28, 1609-1617.

Meinzer FC, McCulloh KA, Lachenbruch B, Woodruff DR, Johnson DM. 2010. The blind men and the elephant: the impact of context and scale in evaluating conflicts between plant hydraulic safety and efficiency. Oecologia 164, 287-296.

Meinzer FC, Woodruff DR, Domec JC, Goldstein G, Campanello PI, Gatti MG, Villalobos-Vega R. 2008b. Coordination of leaf and stem water transport properties in tropical forest trees. Oecologia 156, 31-41.

Myneni RB, Dong J, Tucker CJ, Kaufmann RK, Kauppi PE, Liski J, Zhou L, Alexeyev V, Hughes MK. 2001. A large carbon sink in the woody biomass of northern forests. PNAS 98 (26), 14784-14789.

Nadezhdina N, Čermák J, Ceulemans R. 2002. Radial patterns of sap flow in woody stems of dominant and understory species: scaling errors associated with positioning of sensors. Tree Physiology 22, 907-918.

Naleppa M. 2013. User manual dendrometer D6. UMS GmbH, München, Germany.

Nicolas E, Torrecillas A, Ortuño MF, Domingo R, Allarcón JJ. 2005. Evaluation of transpiration in adult apricot trees from sap flow measurements. Agricultural Water Management 72, 131-145.

Niklas KJ. 1997. Mechanical properties of Black Locust (*Robinia pseudoacacia* L.) wood. Size- and age-dependent variations in sap- and heartwood. Annals of Botany 79, 265-272.

Nyce DS. 2004. Linear position sensors: theory and application. John Wiley & sons, Wiley Interscience electronic collection.

Offenthaler I, Hietz P, Richter H. 2001. Wood diameter indicates diurnal and long-term patterns of xylem water potential in Norway spruce. Trees 15, 215-222.

Pallardy SG. 2008. Physiology of woody plants. Academic Press, San Diego.

Patankar R, Quinton WL, Baltzer JL. 2013. Permafrost-driven differences in habitat quality determine plant response to gall-inducing mite herbivory. Journal of Ecology 101, 1042-1052.

Pélissier R and Pascal JP. 2000. Two-year tree growth patterns investigated from monthly girth records using dendrometer bands in a wet evergreen forest in India. Journal of Tropical Ecology 16, 429-446.

Perämäki M, Nikinmaa E, Sevanto S, Ilvesniemi H, Siivola E, Hari P, Vesala T. 2001. Tree stem diameter variations and transpiration in Scots pine: an analysis using a dynamic sap flow model. Tree Physiology 21, 889-897.

Pesonen E, Mielikäinen M, Mäkinen H. 2004. A new girth band for measuring stem diameter changes. Forestry 77 (5), 431-439.

Pratt RB, Jacobsen AL, Ewers FW, Davis SD. 2007. Relationships among xylem transport, biomechanics and storage in stems and roots of nine Rhamnaceae species of the California chaparral. New Phytologist 174, 787-798.

Raffa KF, Aukema BH, Bentz BJ, Carroll AL, Hicke JA, Turner MG, Romme WH. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. BioScience 58, 501-517.

Rammig A, Jupp T, Thonicke K, Tietjen B, Heinke J, Ostberg S, Lucht W, Cramer W, Cox P. 2010. Estimating the risk of Amazonian forest dieback. New Phytologist 187, 694-706.

Rennenberg H, Loreto F, Polle A, Brilli F, Fares S, Beniwal RS, Gessler A. 2006. Physiological responses of forest trees to heat and drought. Plant Biology 8 (5), 556-571.

Renninger HJ, Schäfer KVR. 2012. Comparison of tissue heat balance- and thermal dissipation-derived sap flow measurements in ring-porous oaks and a pine. Frontiers in Plant Science 3, 103. Published online 2012 May 21, http://dx.doi.org/10.3389/fpls.2012.00103.

Robert EMR, Jambia AH, Schmitz N, De Ryck DJR, De Mey J, Kairo JG, Dahdouh-Guebas F, Beeckman H, Koedam N. 2014. How to catch the patch? A dendrometer study of the radial increment through successive cambia in the mangrove *Avicennia*. Annals of Botany 113, 741-752.

Robert EMR, Schmitz N, Okello JA, Boeren I, Beeckman H, Koedam N. 2011. Mangrove growth rings: fact or fiction? Trees 25, 49-58.

Rossi S, Deslauriers A, Anfodillo T, Morin H, Saracino A, Motta R, Borghetti M. 2006. Conifers in cold environments synchronize maximum growth rate of tree-ring formation with day length. New Phytologist 170, 301-310.

Salmén L. 1990. Thermal expansion of water-saturated wood. Holzforschung 44, 17-19.

Scholz FG, Bucci SJ, Goldstein G, Meinzer FC, Franco AC, Miralles-Wilhelm F. 2007. Biophysical properties and functional significance of stem water storage tissues in Neotropical savanna trees. Plant, Cell and Environment 30, 236-248.

Scholz FG, Bucci SJ, Goldstein G, Meinzer FC, Franco AC, Miralles-Wilhelm F. 2008. Temporal dynamics of stem expansion and contraction in savanna trees: withdrawal and recharge of stored water. Tree Physiology 28, 469-480.

Sellevold EJ, Bjøntegaard Ø (2006) Coefficient of thermal expansion of cement past and concrete: mechanisms of moisture interaction. Materials and Structures 39 (6), 809-815.

Sevanto S, Vesala T, Perämäki M, Nikinmaa E. 2002. Time lags for xylem and stem diameter variations in a Scots pine tree. Plant, Cell and Environment 25, 1071-1077.

Sevanto S, Vesala T, Perämäki M, Nikinmaa E. 2003. Sugar transport with environmental conditions controls time lags between xylem and stem diameter changes. Plant, Cell and Environment 26, 1257-1265.

Sheil D. 2003. Growth assessment in tropical trees: large daily diameter fluctuations and their concealment by dendrometer bands. Canadian Journal of Forest Research 33 (10), 2027-2035.

Skomarkova MV, Vaganov EA, Mund M, Knohl A, Linke P, Boerner A, Schulze E-D. 2006. Inter-annual and seasonal variability of radial growth, wood density and carbon isotope ratios in tree rings of beech (*Fagus sylvatica*) growing in Germany and Italy. Trees 20, 571-586.

Slayback DA, Pinzon JE, Los SO, Tucker CJ. 2003. Northern hemisphere photosynthetic trends 1982-99. Global Change Biology 9, 1-15.

Steinberg SL, McFarland MJ, Worthington JW. 1990. Comparison of trunk and branch sap flow with canopy transpiration in pecan. Journal of Experimental Botany 41, 653-659.

Steppe K. 2004. Diurnal dynamics of water flow through trees: design and validation of a mathematical flow and storage model. Ph.D. Thesis. Ghent University, Ghent, Belgium.

Steppe K, De Pauw DJW, Lemeur R. 2008. A step towards new irrigation scheduling strategies using plant-based measurements and mathematical modelling. Irrigation Science 26, 505-517.

Steppe K, Sterck F, Deslauriers A. 2015. Diel growth dynamics in tree stems: linking anatomy and ecophysiology. Trends in Plant Science xx, 1-9. http://dx.doi.org/10.1016/j.tplants.2015.03.015.

Storr W. 2015. Wheatstone bridge. Available at: http://www.electronics-tutorials.ws/blog/wheatstone-bridge.html (Accessed: 10 March 2015).

Strömgren M and Linder S. 2002. Effects of nutrition and soil warming on stemwood production in a boreal Norway spruce stand. Global Change Biology 8 (12), 1194-1204.

Tardif J, Flannigan M, Bergeron Y. 2001. An analysis of the daily radial activity of 7 boreal tree species, northwestern Québec. Environmental Monitoring and Assessment 67, 141-160.

Thuiller W, Lavorel S, Araújo MB, Sykes MT, Prentice IC. 2005. Climate change threats to plant diversity in Europe. PNAS 102 (23), 8245-8250.

Tucker CJ, Slayback DA, Pinzon JE, Los SO, Myneni RB, Taylor MG. 2001. Higher northern latitude normalized difference vegetation index and growing season trends from 1982-1999. International Journal of Biometeorology 45, 184-190.

Vandegehuchte MW, Guyot A, Hubeau M, De Swaef T, Lockington DA, Steppe K. 2014. Modelling reveals endogenous osmotic adaptation of storage tissue water potential as an important driver determining different stem diameter variation patterns in the mangrove species *Avicennia marina* and *Rhizophora stylosa*. Annals of Botany 114, 667-676.

Vergeynst LL, Dierick M, Bogaerts JAN, Cnudde V, Steppe K. 2014. Cavitation: a blessing in disguise? New method to establish vulnerability curves and assess hydraulic capacitance of woody tissues. Tree Physiology xx, 1-10. doi:10.1093/treephys/tpu056.

Vieira S, de Camargo PB, Selhorst D, da Silva R, Hutyra L, Chambers JQ, Brown IF, Higuchi N, dos Santos J, Wofsy SC, Trumbore SE, Martinelli LA. 2004. Forest structure and carbon dynamics in Amazonian tropical rain forests. Oecologia 140 (3), 468-479.

Wang H, Guan H, Deng Z, Simmons CT. 2014. Optimization of canopy conductance models from concurrent measurements of sap flow and stem water potential on Drooping Sheoak in South Australia. Water Resources Research 50, 6154-6167. doi:10.1002/2013WR014818.

Wang J and Sammis TW. 2008. New automatic band and point dendrometers for measuring stem diameter growth. Applied Engineering in Agriculture 24 (6), 731-742.

Wermelinger B, Rigling A, Schneider Mathis D, Dobbertin M. 2008. Assessing the role of bark- and wood-boring insects in the decline of Scots pine (*Pinus sylvestris*) in the Swiss Rhone Valley. Ecological Entomology 33 (2), 239-249.

Williams CDH. No date. Introduction to sensors. Available at: http://newton.ex.ac.uk/teaching/CDHW/Sensors/ (Accessed: 17 February 2015).

Woodcock DW and Shier AD. 2002. Wood specific gravity and its radial variations: the many ways to make a tree. Trees 16, 437-443.

Worbes M. 1999. Annual growth rings, rainfall-dependent growth and long-term growth patterns of tropical trees from the Caparo Forest Reserve in Venezuela. Journal of Ecology 87, 391-403.

Wronski EB, Holmes JW, Turner NC. 1985. Phase and amplitude relations between transpiration, water potential and stem shrinkage. Plant, Cell and Environment 8, 613-622.

Yang Y, Guan H, Hutson JL, Wang H, Ewenz C, Shang S, Simmons CT. 2013. Examination and parameterization of the root water uptake model from stem water potential and sap flow measurements. Hydrological Processes 27, 2857-2863.

Young HE. 1952. Practical limitations of the dial gauge dendrometer. Ecology 33 (4), 568-570.

Zobel BJ and van Buitjenen JP. 1989. Wood variation: its causes and control. Springer, Berlin Heidelberg New York.

Zweifel R and Häsler R. 2000. Frost-induced reversible shrinkage of bark of mature subalpine conifers. Agricultural and Forest Meteorology 102, 213-222.

Zweifel R and Häsler R. 2001. Dynamics of water storage in mature subalpine *Picea abies*: temporal and spatial patterns of change in stem radius. Tree Physiology 21, 561-569.

Zweifel R and Zeugin F. 2008. Ultrasonic acoustic emissions in drought-stressed trees – more than signals from cavitation? New Phytologist 179, 1070-1079.

Zweifel R, Zimmermann L, Zeugin F, Newbery DM. 2006. Intra-annual radial growth and water relations of trees: implications towards a growth mechanism. Journal of Experimental Botany 57 (6), 1445-1459.