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**Article**

# Method Analysis for Collecting and Processing in-situ Hyperspectral Needle Reflectance Data for Monitoring Norway Spruce

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**Keywords:** in-situ measurements, needle spectra, Norway spruce, portable spectroradiometer, tree vitality

**Summary:** Forest damage induced by bark beetle attacks can cause major economic losses in forestry. Hyperspectral remote sensing data and state of the art very high spatial resolution satellite data offer a great potential for assessing tree vitality. However, a better understanding of the effects of vitality decrease and its impact on the spectral behaviour of needles is needed. Filling this knowledge gap can make a significant contribution to improve the interpretation of remote sensing data. However, it is still unclear which method for needle spectra collection is most suitable. In this work, two methods for spectral reflectance measurements of Norway spruce needles using portable spectroradiometers were tested and analysed: using a classical fore optic and a so-called contact probe. The spectral reflectance data were evaluated with different statistical similarity measure techniques. Besides analysing the measurements themselves, the methods were compared in terms of their practicality. Furthermore, the impact of storage on the reflection behaviour was investigated. The spectral measurements were performed in the field as well as in a laboratory and repeated three times during the 2013 growing season. Based on the obtained results we recommend measuring needle samples with the contact probe of portable spectroradiometers.

**Zusammenfassung:** *Methodenanalyse zur Erfassung und Prozessierung hyperspektraler in-situ Nadelreflexionsdaten zum Monitoring von Fichten.* Durch Borkenkäferbefall hervorgerufene Waldschäden verursachen große ökonomische Schäden in der Forstwirtschaft. In hyperspektralen Fernerkundungsdaten sowie in räumlich sehr hoch aufgelösten Satellitendaten der neuesten Generation wird großes Potential für die Vitalitätsbeurteilung von Bäumen gesehen. Ein besseres Verständnis der Auswirkung von Vitalitätsverlusten auf die spektrale Reflexion von Nadeln könnte einen wesentlichen Beitrag zur Interpretation von Fernerkundungsdaten darstellen. Mit welcher Methode die Nadelspektren gemessen werden sollten, ist aber noch unklar. Die vorliegende Arbeit stellt zwei Methoden für die Messung spektraler Signaturen von Fichtennadeln mittels Feldspektroradiometer vergleichend gegenüber. Neben den Messergebnissen wurden die verwendeten Methoden auch hinsichtlich ihrer Praktikabilität untersucht. Zusätzlich wurden Auswirkungen von Lagerung auf das Reflexionsverhalten analysiert. Die spektralen Messungen fanden sowohl im Feld als auch im Labor statt und wurden in der Vegetationsperiode 2013 dreimal durchgeführt. Die Reflexionsspektren wurden statistisch ausgewertet und mittels Ähnlichkeitsmaßen verglichen. Auf der Basis der erzielten Ergebnisse und der einfacheren Handhabung wird empfohlen, die Samples mittels „contact probe" zu messen.

## 1 Introduction

The characteristic spectral signature of a tree and its foliage provides valuable insights in its vitality and enables tree species identification through remote sensing (Blackburn 2002, Ustin et al. 2004, Asner et al. 2008). Leaf and needle spectral signatures are moreover useful for a detailed assessment of the plant's physiological status. Furthermore, the spectral re-


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flectance at canopy level is important for sensor design studies and various up-scaling tasks.

The acquisition and successful analysis of reflectance spectra from plant tissue of trees is, however, a complex task. Two fundamental problems have to be emphasized. First, it is in general difficult to collect representative leaf/needle samples, given the growth patterns of trees with a huge vertical extent, complicated 3D structures, and shading effects due to self-shading as well as neighbouring trees (Gastellu-Etchegorry et al. 1996, van Leeuwen & Huete 1996, Zarco-Tejada et al. 2004). Secondly, no generally accepted measurement protocol for collecting signatures of leaf/needle samples is available. For example, one may opt for measuring leaf samples directly after harvesting in the field. Alternatively, one may choose to cool the samples for later analysis in the lab. Leaf samples can be measured individually or as a stack of leaves, attached or removed from their twigs, etc. Additionally, a number of alternative measurement devices exist (Koch et al. 1990, Gamon & Surfus 1999, Stone et al. 2003, Malenovský 2006). For example, reflectance spectra can be acquired using lab and field spectroradiometers with or without fore optics, as well as contact probes.

This publication discusses two different methods for gathering spectral data with a portable spectroradiometer for monitoring the reflectance of Norway spruce (*Picea abies*, L.). We discuss methods for needle sample storage and preparation. Furthermore we evaluate the spectral data collection *in-situ* and in a laboratory environment and examine the influence of sample freshness. By doing so, we aim to positively contribute to a future harmonization and standardization of measurement protocols, so that outcomes of different studies can be better compared among each other. The findings of this research serve at the same time as a preliminary study to the German/Austrian VitTree project, evaluating different airborne as well as multi- and hyperspectral sensors for an automated assessment of tree vitality, especially for Norway spruce. Norway spruce is particularly important with respect to the early detection of bark beetle attacks using remote sensing data (Wulder et al. 2006, Lausch et al. 2013, Immitzer & Atzberger 2014, Fassnacht et al. 2014).

## 2 Materials and Methods

### 2.1 *Study Site and Needle Collection*

Norway spruce needles were collected during summer-fall 2013 from a 60 year and a 80–100 year old forest stand, located near Altötting (48°13’N, 12°43’E), southeast Germany.

Needle samples were taken from 16 sample trees by tree climbers (Fig. 1). According to other studies (Koch 1988, Schlerf et al. 2010) one to two branches from the sunlit part of the tree crown, between the 12th to 16th whorls, were cut down. From these branches needle samples from the past four growing seasons, ranging from 2010 to 2013, were collected. Directly after cutting down the branches, the needle samples were separated by year, stored in zip lock bags and refrigerated. This sampling method was repeated three times throughout the growing season of 2013 (Tab. 1).

After sample collection, the first spectral measurements were conducted directly in the

**Fig. 1:** Tree climber at work.

field using the contact probe (solely for needle age class 2012). The cut needle samples were then kept in a fridge and measured again the next day. Furthermore, from the same twig a sample was refrigerated overnight, cut the next day and measured with the same spectroradiometer used for the *in-situ* measurements.

The amount of collected samples showed a large variability. The needles from the last two growing seasons (2012 and 2013) were abundant and lush. This indicates excellent growing conditions for the past two years. On the contrary, the needles retrieved from growing year three and four were difficult to identify and collect due to the scarcity and limited size (Fig. 2). This indicates poorer growing conditions in 2010 and 2011.

For security reasons, tree climbers work in teams of two. To evaluate an alternative needle collection method we also tested the shooting of needles, which theoretically requires only one person. Using shotguns, smaller parts of the top branches were shot down. A plastic cover underneath the tree was used to collect the falling branches. Both tested methods, tree climbers and shooting, proved to be adequate in collecting needle samples. Both practices require highly trained staff. We finally preferred tree climbers as they offer increased sampling control and are capable to retrieve larger samples, necessary to collect needles from all four growing years.

## 2.2 *Needle Preparation*

Before running the spectral measurements, the needles were cut off the twigs and placed on a non-reflective plate. This plate was coated with 3M-optical black velvet paint (Fig. 3), to obtain pure needle spectra. The average weight per probe was about 5 g and approximate 5–6 twigs were used per sample. For each tree, the needles of the four last needle age classes were measured separately.

## 2.3 *Measurement Methods*

The day following the needle collection, needle spectra were measured in a laboratory environment. Two passive non-imaging ASD

**Tab. 1:** Needle sample acquisition dates and spectral measurements of different needle ages.

| Measurement | Acquisition date | Contact probe lab | Contact probe field | Contact probe lab next day | Fore optic lab | Fore optic lab twig |
|---|---|---|---|---|---|---|
| 1 | 16.07.2013 | Year 2010–13 | – | – | Year 2010–13 | - |
| 2 | 10.09.2013 | Year 2010–13 | Year 2012 | Year 2012 | Year 2010–13 | Year 2012 |
| 3 | 12.11.2013 | Year 2010–13 | Year 2012 | Year 2012 | Year 2010–13 | Year 2012 |


**Fig. 2:** Needle sample containing the last four growing seasons. Red lines were drawn for separating the different needle ages. The newest needles are found at the right (2013), while the needles at the left immerged in 2010. Note the poor needle growth in 2011 due to unfavourable climatic conditions.

**Fig. 3:** Cut needles (year 2013) on a black velvet painted plate.

FieldSpec®Pro (Analytical Spectral Devices, Inc., Boulder, CO, USA) spectroradiometer models were used covering a spectral range from 350 nm – 2500 nm.

Both instruments were kept at room temperature for multiple days and were switched on 30 minutes before measuring to increase stability of the measurement. The lamps were turned on at the same time. For the reflectance measurements, two different methods were tested: One used an 8° fore optic lens. The other used a contact probe. The two measurement methods were evaluated to identify possible advantages and disadvantages of the two methods.

**Tab. 2:** Parameter settings of the ASD instruments for the two different measurement methods.

| | Fore optic | Contact probe |
|---|---|---|
| Dark current readings | 80 | 20 |
| White Reflectance readings | 80 | 20 |
| Number of spectra averaged | 40 | 10 |
| Number of saved spectra per run | 2 | 2 |

**Fig. 4:** Measurement setup with 8° fore optic. Two light sources at a distance of 50 cm illuminate the surface at 45°.

## Fore optic lens

When using the 8° field-of-view fore optic lens, the distance between the plate and the fore optic was set to 15 cm. The plate, with the needle sample, was placed directly under the field-of-view of the fore optic. As light source, two Quartz halogen spotlights (with 45° angle) were used to illuminate the surface while minimizing shadows (Fig. 4). At the beginning of the measurements the spectroradiometer was optimized and after approximately every 15 minutes a white reference was taken using a Spectralon panel. Spectrum average was set to 40 (for details see Tab. 2). Per sample 16 spectra (eight double measurements) were taken, to prevent inaccurate measurements due to illumination effects. After each measurement the plate was turned approximately 90° clockwise to minimize possible effects of uneven sample placement and surface roughness.

Alternatively, we measured whole twigs from the samples of year 2012 (Fig. 5 right) instead of cut-off needles (Fig. 5 left).

**Fig. 5:** Different spectra measurement methods: needles with fore optic (left), needles with contact probe (middle) and interlocking twigs (year 2012) with fore optic (right). Note that the light source is an integral part of the contract probe.

### Contact probe

In addition to the laboratory measurements, the samples from year 2012 were measured *in-situ*, directly after the needle collection in the field. For this purpose a so-called contact probe was used (Fig. 5, middle). The contact probe is a mobile device with an integrated 100 W halogen reflectorized lamp. Spectrum average was set to 10, as opposed to 40 used by the fore optic (Tab. 2). Because it is imperative to hold the contact probe steady while pressing it against the needles, a smaller amount of spectrum averages is advantageous. For the calibration a white reference was run every time starting a new sample. Per sample, 16 needle spectra (eight double measurements) were taken. Between the measurements the contact probe was lifted and the needles on the plate rearranged.

Besides the *in-situ* measurements for needle age class 2012, we used the contact probe in a laboratory environment. In the laboratory all four needle age classes were measured with the settings given in Tab. 2. Furthermore the needles, which were measured in the field the day before, were remeasured. For details of all performed measurements see Tab 1.

## 2.4 *Spectral Corrections and Optimizations*

The 16 measurements of each sample were manually checked for outliers and spectra with visually appearing irregularities were removed. This occasionally occurred due to measurement and operator errors. After outlier removal, the measurements were processed with the AS toolbox, a software solution developed at DLR (Dorigo et al. 2006). First a Spectralon correction was applied to every spectrum. This corrects the fact that the Spectralon reference panel is not a truly Lambertian reflector with 100% reflectivity. Then offsets in the spectra were corrected. Such jumps occasionally occurred between the different detectors, VNIR (visible-near infrared), SWIR (shortwave infrared) 1 and SWIR 2. They are caused by a slight temporal change in calibration of the detectors but mainly by target inhomogeneity and fibre optic characteristic (Mac Arthur et al. 2012). For correction, we kept the spectra of the second detector constant and moved the curves of the remaining two units to match the SWIR 1 detector, until the jumps disappeared (additive correction).

From the corrected spectra, mean values and standard deviations were calculated. For all subsequent analysis, only these averaged spectra were used.

## 2.5 *Similarity Measures*

For comparing the differences in the reflectance spectra of the two measurement methods, different deterministic and stochastic similarity measures were calculated.

A widely used, simple and deterministic measure is the Euclidian distance (ED). The ED defines the distance between two pixel vectors

$$\mathrm{ED}(s_i, s_j) = \left\| s_i - s_j \right\| \equiv \left[ \sum_{l=1}^{L} (s_{il} - s_{jl})^2 \right]^{1/2} \tag{1}$$

with $s_i$ and $s_j$ being two spectral signatures of two pixel vectors $r_i$ and $r_j$ and $L$ is number of bands (Chang 2003).

Another deterministic measure is the sum of absolute differences (SAD), a way to quantify the difference of spectral signatures

$$\mathrm{SAD} = \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} \left| S_{1(i,j)} - S_{2(i,j)} \right| \tag{2}$$

where the absolute values of $M$ x $N$ pixel windows in the reference spectra $S_{1(i,j)}$ and target spectra $S_{2(i,j)}$ are subtracted (Watman et al. 2004).

Furthermore, the Pearson's correlation coefficient (PCC) was calculated, which measures the linear dependence of two spectral signatures $x$ and $y$ of number of needle samples $n$:

$$\mathrm{PCC} = \frac{\sum xy}{\sqrt{\sum x^2 \sum y^2}} = \frac{\sum_{i=1}^{n} (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \overline{x})^2} \sqrt{\sum_{i=1}^{n} (y_i - \overline{y})^2}} \tag{3}$$

For hyperspectral image analysis another common measure is the spectral angle mapper (SAM), which calculates the angle between two spectra $s_i$ and $s_j$. It is an orthogonal projected-based measure sensitive to changes in spectral shape but insensitive to changes in overall brightness (Kruse et al. 1993, Chang 2003, Cho et al. 2010).

$$\mathrm{SAM}(s_i, s_j) = \cos^{-1} \frac{s_i \times s_j}{\|s_i\| \|s_j\|} \tag{4}$$

As stochastic similarity measure technique, the SID-SAM mixed measure was used. It combines the deterministic SAM with the stochastic spectral information divergence (SID) (Du et al. 2004). The SID gives information over the disparity between two pixel vectors in relation to their probability mass functions (Chang 2003):

$$\mathrm{SID}(r_i, r_j) = D(r_i \| r_j) + D(r_j \| r_i) \tag{5}$$

with $r_i$ and $r_j$ being two pixel vectors and D being the average discrepancy in the self-information of $r$ of band $l$.

The SID and SAM can be combined using the tangent named here as DU, which is calculated as followed:

$$\mathrm{DU} = \mathrm{SID}\,(s_i, s_j) \text{ x } \tan\,(\mathrm{SAM}\,(s_i, s_j)) \tag{6}$$

The advantage of this measure is that it makes two similar spectral signatures more alike and dissimilar signatures easier to distinguish (Du et al. 2004).

## 3 Results and Discussion

### 3.1 *Spectral Differences Between Needle Age Classes*

For every needle year class, spectral signatures were separately analysed, to detect differences between the years and the two measurement methods (fore optics and contact probe). The spectral needle age classes for one sample tree are shown in Fig. 6. Year 2013 had very good growing conditions. This prosper vitality is resulting in higher spectral reflectance in the near infrared. The spectral signatures of year 2010 and 2011 are much lower, due to their age and poorer growing conditions during these years.

Regarding the similarity measures of the four needle age classes (Fig. 7, columns (contact probe) and columns (fore optic)), year

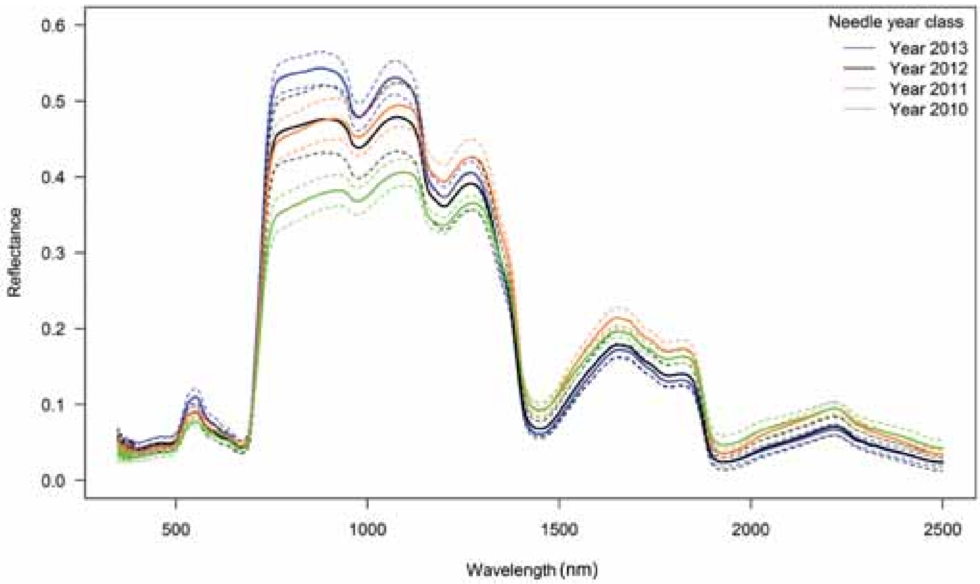


**Fig. 6:** Mean spectra of different needle age classes for one sample measured with contact probe (dotted lines: mean value +/- standard deviation).

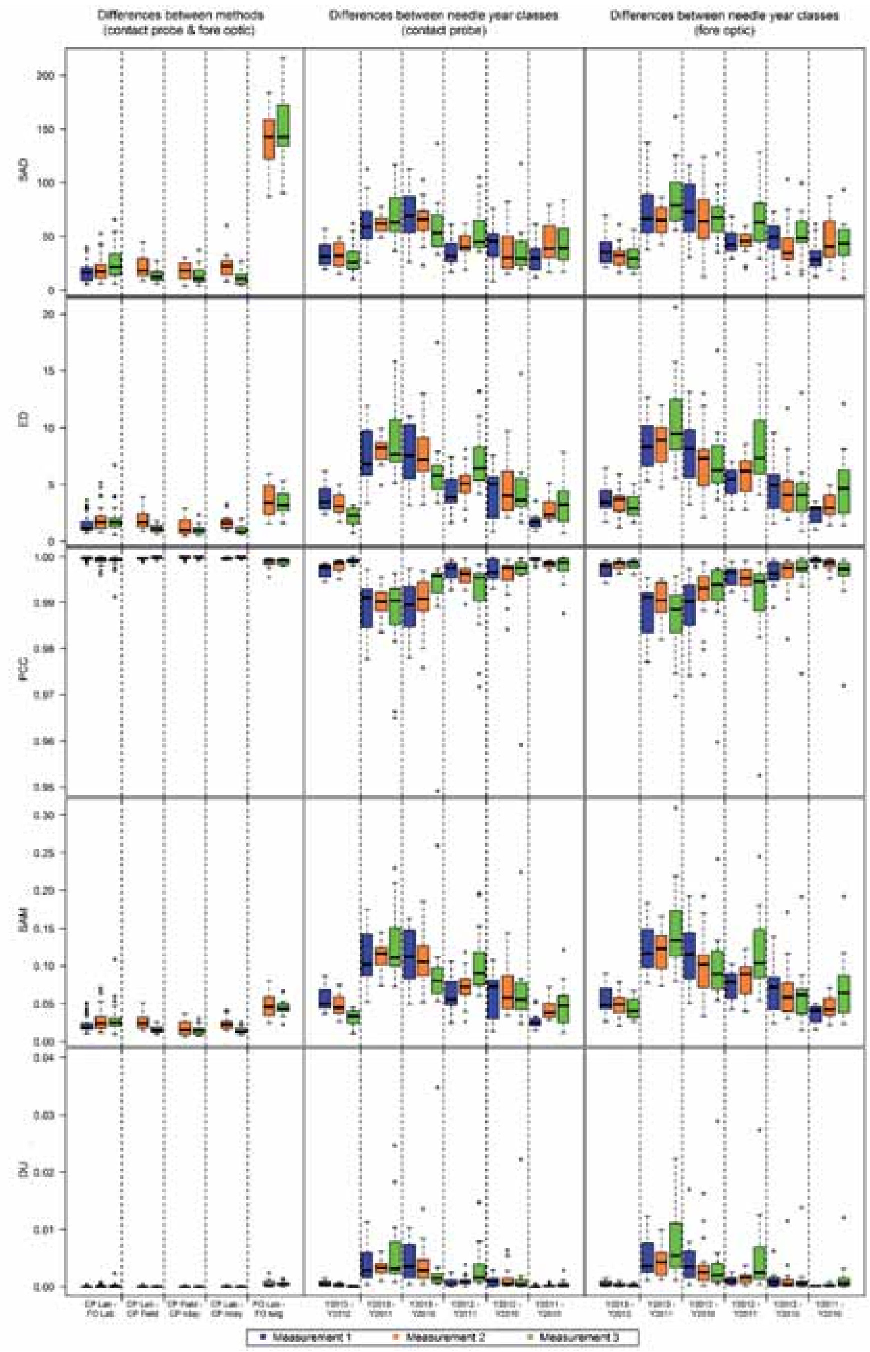


**Fig. 7:** Statistical analysis and applied similarity measures (SAD: sum of absolute differences, ED: Euclidean distance, PCC: Pearson's correlation coefficient, SAM: spectral angle mapper, and DU: mixed measure after Du et al. 2004) for different methods (CP: contact probe, FO: fore optic) and needle year classes (Y).

2012 and year 2013 have high agreement values as well as year 2010 and 2011, which is especially visible in the DU measure. When comparing the applied measurement methods both techniques yield similar levels (Fig. 7, middle and right columns as before), however, with lower variations for the contact probe measurements. Due to the differences in spectra between needle year classes, for time series analyses it is important to repeat measuring the same needle year classes.

## 3.2 *Spectral Differences Between in-situ and Cooled Samples*

When comparing the spectra of the fresh samples to the one day old samples, no major differences are noted in the spectral signal (Fig. 8). Likewise, no significant differences are visible between the fresh *in-situ* samples and the laboratory samples, which were cut and measured the next day.

## 3.3 *Differences Between Contact Probe and Fore Optic Measurements*

### Spectral differences between contact probe and fore optic

All similarity measures indicate little differences between the two methods (Fig. 7, column (contact probe & fore optic)). Hence, from a statistical point of view, both methods produce comparable results with only marginal differences. ED and SAM reveal analogous results. Overall illumination is not a highly influencing factor. The low DU values indicate similar results with both methods. Together this demonstrates that the contact probe and the fore optic are both suitable for measuring needle reflectance.

### Usability

A main difference between the two methods is the performance flexibility. The fore optic method requires a laboratory environment and an elaborate set up. The set up includes consistent illumination at a favourable angle and a

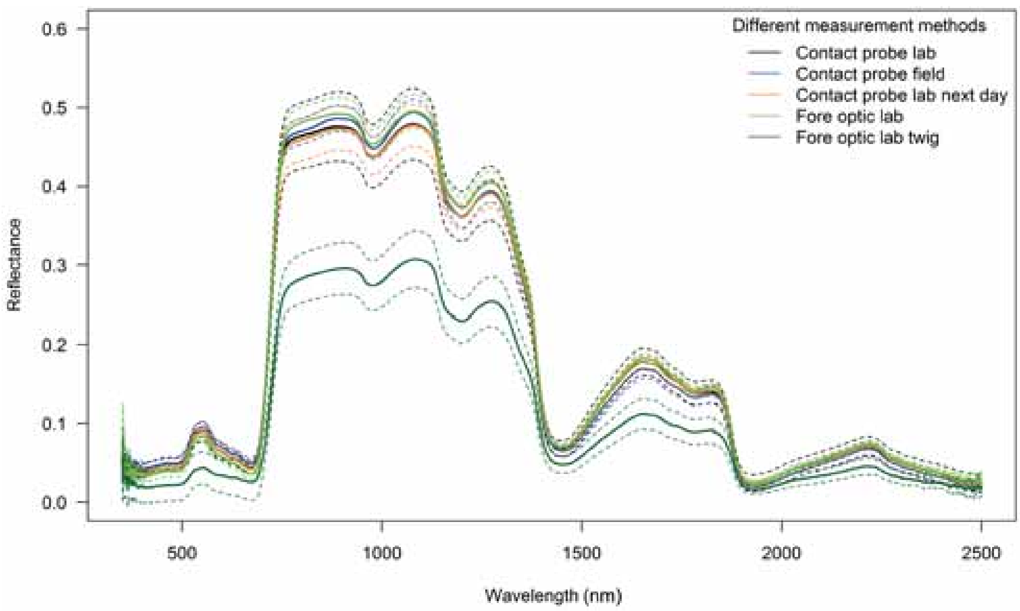


**Fig. 8:** Mean spectra of different measurement methods for one sample of needle age class 2012 (dotted lines: mean value +/- standard deviation).

construction covered with low reflective plastic foil to cancel out any spectral interference. In contrast to this, the contact probe measurements are straightforward and require fewer set up. Using the contact probe, no significant differences were noticed between the *in-situ* measurements and the laboratory measurements. We conclude that the contact probe offers increased mobility and flexibility, which allows sampling under different circumstances and with different states of needle freshness.

### Measurement time

The two measurement methods differ markedly regarding the measurement time. As the number of spectrum averages collected for a given sample was set higher for the fore optic, the sampling with the contact probe was faster. In principle, it would be possible to reduce the amount of spectrum averages when using the fore optic. However, the contract probe measurements would still be less time consuming due to the speed of each consecutive measurement and the contact probe being more precise in handling. In our setting, the performance of the contact probe was faster, despite the white reference calibration was repeated after every sample. With the fore optic it was run only every 15 minutes.

### Measurements in case of small sample size

In case of measuring a small sample size due to a poor growing season (2011 in Fig. 2), the contract probe proved to be more accurate compared to the fore optic as it requires fewer needles per sample. Collecting spectra from a small sample with the fore optic lens, proved to be challenging. When applying the fore optic on a thin layer of needles the measurements were considerably inconsistent due to the lack of an optically infinite thick layer. Whilst processing these signatures, quite many divergent measurements had to be removed, resulting in an average containing fewer samples with higher intra-sample variability.

## 3.4 *Spectral Differences Between Twigs and Cut Needles*

As expected, the spectra of cut needles revealed vast differences compared to the spectra of the twigs. The differences mainly arose from stronger shading effects when measuring the twigs, readily seen in the lower reflectance level across the visible-SWIR spectral region (Fig. 8). The spectral signature of the twig is also lower compared to the needle spectra, since the branch is also measured. At the same time, the within-sample standard deviation is considerably increased when measuring twigs instead of needles (Fig. 8).

Except SAD, all applied similarity measure techniques show a very high agreement between the spectral signatures of the needles compared with the twig spectra (Fig. 7). This indicates that the overall shape of the spectra is preserved. Due to the lower reflectance of twigs in contrast to needle spectra (Fig. 8), the SAD indicates a lower agreement. It must be noted that for measuring twigs a larger sample size is needed. For years with less needles, measuring whole twigs results in a much lower agreement. Layering the branches would for example be impractical for needle years 2011 and 2010, due to the lack of samples and inability to fully cover the field of view of the fore optic. Based on these findings we recommend the needle cutting method because of the increased spectral signal purity and more importantly the reduced sample size.

## 3.5 *Similarity Measures*

When comparing the similarity measure techniques, all methods show similar results, with only minimal variations. The ED and SAM reach nearly the same values, this occurs when the angle between the spectra is small and overall brightness differences are small (Du et al. 2004). The SAD is the only measure where smaller variations can be seen, mainly differences between the needle and twig measurement. This is caused by the off-set of the needle and twig spectra (Fig. 8).

## 4 Conclusion and Outlook

Our analysis indicates a number of advantages of measuring needle spectra with the contact probe. The contact probe can be easily applied both in the field as well as in the laboratory. Other advantages of conducting the measurement with the contact probe are its faster performance and its ability to collect spectra from also smaller sample sizes (Tab. 3). Furthermore, the contact probe measurements can be carried out *in-situ* independently of weather conditions, such as sun illumination and cloudiness, and without a fixed measurement setup, e.g. halogen lamps. In rainy conditions the needles can even be sampled in a car trunk. This flexible and user-friendly approach can be adapted to a wide range of projects.

The study confirmed former studies, which state that spectra of different needle age classes are significantly different. From a monitoring point of view – if based on needle spectra – it is thus very important to repeat measuring the same needle year classes. Otherwise there is a potential for misinterpreting the results. From a remote sensing perspective the strong influence of needle age is problematic, as needle measurements cannot simply be up-scaled to aircraft or satellite levels. For example, it is not clear which mixture of which needle age classes best corresponds to the integrated measurement of remote devices. One has also to consider that needles are usually only collected from the upper part of the crown (as in this study), whereas a remote sensor measures the integral part of the canopy. Additionally, for using these pure needle spectra as ground truth data or for up-scaling, one would also need to measure and take into account the tree's wooden parts (Malenovský 2006). Shadowing effects due to crown structure etc. are as well ignored when working at leaf scale (Schlerf et al. 2010).

Based on our analysis, we cannot recommend measuring entire twigs instead of cut needles. When measuring spectra of twigs a bigger sample size is needed, which might not be sufficient for years with poor growing conditions. In addition, twig spectra show a higher variance compared to the single needle spectra due to illuminations effects and shadows, which occur when rotating the plate between each of the eight double measurements.

Two alternative needle collection methods were evaluated: tree climbers and the use of shotguns. Tree climbers were finally preferred as they offer increased sampling control and are capable to retrieve larger samples. Enough samples are necessary in particular for older needle ages and needles grown during unfavourable growing conditions. Shooting down small branches sometimes fails to deliver samples for several growing seasons. With this method mistakes can arise when the needles fail to fall on the plastic canvas. However, concerning the sample retrieval speed shooting is considerably faster. Cutting down one or two larger branches with three repetitions throughout the growing season, has also the potential to alter the vitality of the tree and influence its spectral signature. By removing only small parts of the foliage the adverse effects on the tree are negligible.

A more detailed analysis of the needle spectra is planned. This will include the interpretation of chemical analyses and the differences between stressed and unstressed needles. During the summer of 2013, half of the measured trees were artificially damaged by removing a strip of bark along the circumference of the trunk (roughly at breast height, see Fig. 1). This damage disrupts the nutrient flow and influences the vitality of the tree. The differences in spectra of the stressed and unstressed trees will be described in an upcoming publication. Therefore, needle sampling will be continued in the vegetation period 2014. Additionally, we have planned chemical analyses

**Tab. 3:** Comparison of the two measurement methods.

| | Spectral measurements | |
|---|---|---|
| | fore optic | contact probe |
| Accuracy | + | + |
| Speed | - | + |
| Flexibility | - | + |
| Handling small samples | - | + |

in 2014 to create a better understanding of the differences in spectra and its chemical components.

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