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Scaling spectroscopic approaches - from leaf albedo to ecosystems mapping

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Abstract

Field based spectroscopy for ecological and environmental monitoring has become an indispensable part of complete observational systems as defined in GEOS (Global Earth Observation System of Systems). Spectral scaling approaches are currently ranging from molecular to ecosystem or even biome scales. We discuss the use of field spectroscopy in relation to supporting large-scale ecosystem and ecotone inventorying, in particular the retrieval of biochemical and structural attributes of vegetation. First, attention will be put on using an object-relational database for the structured compilation of field spectral measurements and corresponding metadata. Spectral libraries have been collected over a wide variety of natural and man-made targets and their sampling scheme is discussed. Second, recent advances in reflectance and radiance terminology for field spectrometers are discussed, propagating the use of spectral albedo. Advanced measurement instrumentation and facilities are presented that complement solar reflective measurements with the angular, thermal and plant fluorescence domains. Further, experiments measuring leaf albedo, transmittance and absorbance are discussed using examples from a wide range of ecosystems and their ecotones. Finally, we discuss scaling approaches from field measurements to airborne and spaceborne mapping methods, demonstrating the wide use of field spectrometers for environmental applications. We conclude on the importance of using field spectrometers over the past one and a half decades at our institutions.

Disciplines

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Scaling Spectroscopic Approaches – from Leaf Albedo to Ecosystems Mapping

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Abstract

Field based spectroscopy for ecological and environmental monitoring has emerged being an indispensable part of complete observational systems as defined in GEOSS (Global Earth Observation System of Systems). Spectral scaling approaches are currently ranging from molecular to ecosystem or even biome scales. We discuss the use of field spectroscopy in relation to supporting large-scale ecosystem and ecotone inventorying, in particular the retrieval of biochemical and structural attributes of vegetation. First, attention will be put on using an object-relational database for the structured compilation of field spectral measurements and corresponding metadata. Spectral libraries have been collected over a wide variety of natural and man-made targets and their sampling scheme is discussed. Second, recent advances in reflectance and radiance terminology for field spectrometers are discussed, propagating the use of spectral albedo. Advanced measurement instrumentation and facilities are presented that complement solar reflective measurements with the angular, thermal and plant fluorescence domains. Further, spectrometric measurements of sun-induced chlorophyll fluorescence are discussed. We focus on radiative transfer based upscaling of leaf optical properties to canopy level and end with an example of soil reflectance spectroscopy. We conclude on the importance of using field spectrometers over the past two decades at our institutions.

Keywords: *field spectroscopy, reflectance factor, Albedo, scaling, imaging spectroscopy.*

1. Introduction

Earth observation based on spectroscopy has been transformed in little more than two decades from a sparsely available research tool into a commodity product available to a broad user community. In the latter half of the 20th century scientists developed first spaceborne instruments that view the Earth in a few spectral bands, capturing a portion of the spectral information in reflected light. However, the few spectral bands of multispectral satellites fail to capture the complete diversity of the compositional information present in the solar reflected spectrum of the Earth. In the 1970s, realization of the limitations of the multispectral approach when faced with the diversity and complexity of spectral signatures found on the surface of the Earth, led to the concept of (imaging) spectrometers (Schaepman, 2009). The use of an imaging spectrometer was also understood to be valid for scientific missions to other planets and objects in our solar system. Only in the late 1970s did the detector array, electronics, computer and optical technology reach significant maturity to allow creation of an imaging spectrometer. With the arrival of these technologies and scientific impetus, first generation instruments

were proposed (Schaeppman et al., 2009). Similarly, non-imaging instruments (‘field spectroradiometers’) emerged and were used as calibration, validation and reference signature collectors on ground (Milton et al., 2009).

The emergence of spectrometers in general and field spectroradiometers for Earth observation purposes in particular fostered the further development of new methods, algorithms and products derived from their measurements. Field spectrometers were used frequently to measure and validate the collective behavior photons, allowing radiative transfer based approaches to emerge more rapidly.

In this paper, we describe approaches and methods that have been developed to measure the interaction of light with vegetation including supporting instrumentation. First, the spectral database SPECCHIO is discussed including a brief summary of reflectance terminology, continued by description of a goniometer allowing multiangular measurements. Following this instrumented approach, recent advances of spectrometric measurements of sun-induced chlorophyll fluorescence are discussed. We then focus on radiative transfer based upscaling of leaf optical properties to canopy level and end with an example of soil reflectance spectroscopy.

2. Spectral Databases and Reflectance Terminology

2.1. SPECCHIO, a spectral database embedded in GEOSS

The collection of spectral ground data under field conditions is crucial for the calibration and validation of airborne and space based remote sensing data and derived products. However, the majority of field campaigns are still very much tied to specific projects and the documentation of sampling conditions and target properties are often treated in a marginal fashion. Consequently, such data are neither well suited for long-term use nor for data sharing with other scientists. This fact seriously restricts the potential of spectral data collections and also hampers the sharing of cost and time incurred by spectral field campaigns among several projects (Pfitzner et al. 2009).

A complete observing system envisions the seamless integration of measurements at various scales, including spectral ground observations (National Research Council 2007). In order to reach this goal, we propose a roadmap as shown in **Figure 1**.

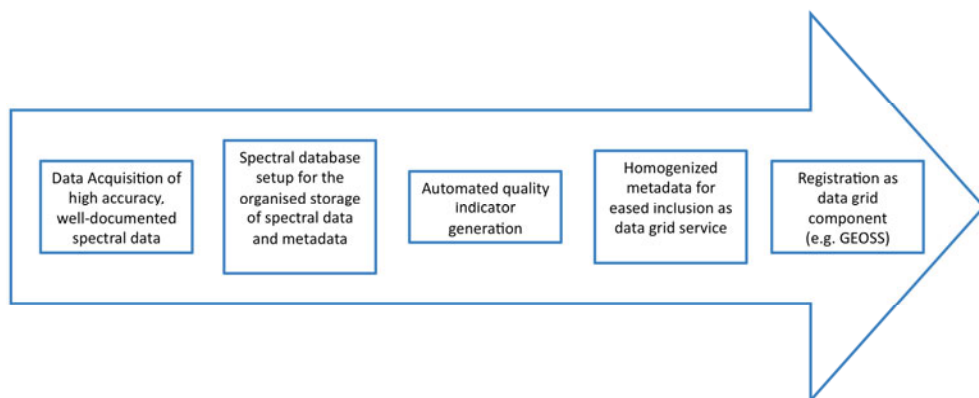


Figure 1: Roadmap for the long-term use and data sharing of spectral ground data within a complete observing system.

The roadmap involves five stages, shortly described hereafter.

The acquisition of high accuracy spectral data, well documented by according metadata, are fundamental, as they provide a sound basis for all further steps. To attain this level, sound knowledge of the spectrometer with its capabilities and deficiencies, proper instrumentation maintenance, including calibration and quality control, and a rigid sampling and documentation strategy must be in place. The definition of required metadata parameters and their acquisition during the sampling are of utmost importance. According efforts have been made, but further work is needed, and, above all, available standards should be adopted and adhered to by the field spectroscopy community (Hueni et al. 2009; Milton 2004; Milton et al. 2009; Pfitzner et al. 2006, 2009).

Spectral databases are systems for the organized storage of spectral signatures accompanied by associated metadata (Hueni et al. 2009). Currently, all published databases employ relational database technology of diverse provenance as repositories for spectral and metadata and provide interactive user access via graphical interfaces developed in various, mainly web based, technologies. The spectral multiuser database SPECCHIO is today's most prominent system (Bojinski et al., 2003; Hueni et al., 2009), with an online database instance that allows users to obtain individual accounts for testing and data sharing purposes. The SPECCHIO online community includes around 90 users worldwide at the time of writing (see <http://www.specchio.ch> for online version). SPECCHIO has been optimized to reduce the manual user input to a minimum by utilizing automated metadata extraction from spectral input files. In the case of ASD (Analytical Spectral Devices) spectrometers, up to 18 metadata parameters can be gleaned from the binary input files. While data input is one of the most critical points of such a system in terms of user acceptance, adequate attention must also be paid to data output. SPECCHIO supports data retrieval by the definition of metadata space restrictions, which produce sub-projections yielding the compliant spectral data.

The automated generation of data quality indicators (QI) is the third and vital step towards data sharing. Meaningful QIs will allow the selection of existing, suitable spectral data for new applications by people or processes not possessing *a priori* knowledge of the data acquisition procedure. QI generation must use the full metadata context to synthesize meaningful, quantitative QIs.

The homogenization of metadata parameters is a further important step, as it will facilitate the data sharing between research groups using heterogeneous protocols and spectral database systems. Ideally, such a harmonization should be carried out as soon as possible along the road, however, it must be carried out at stage four at latest, as it will enable the integration into a data grid as a service. It must be noted that information derived from the metadata, such as the QIs, will also need homogenizing.

Finally, the integration of spectral database systems into a data grid, such as GEOSS being built up by GEO (GEO 2005), will allow to retrieve spectral ground data via uniform query interfaces by human users and automated processes alike.

2.1. Reflectance Terminology for Field Spectroradiometers

While taking measurements in the field, ambient illumination always includes a diffuse irradiation fraction. Its magnitude and angular distribution depend on the actual atmospheric conditions, surrounding terrain configuration and objects, and wavelength. Thus, outdoor measurements always include hemispherical illumination, which can be described as a composition of a direct and an anisotropic diffuse component. The partitioning into direct and diffuse illumination influences the radiation regime within vegetation canopies. Therefore, field spectroradiometer campaigns should always be complemented with sun photometer measurements to assess the contribution of direct and diffuse irradiance. For field instruments with an IFOV full cone angle of about 4–5 degrees (e.g., PARABOLA (Portable Apparatus for Rapid Acquisition of Bidirectional Observation of the Land and Atmosphere) or ASG (Automated Spectro-Goniometer)), the surface directional reflectance variability across the opening angle needs to be investigated. As long as this variability is unknown - it may not be

neglectable and must be corrected for - the measurements should be reported as HCRF (Hemispherical-Conical Reflectance Factor) (see Figure 2. – Case 8).

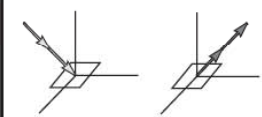
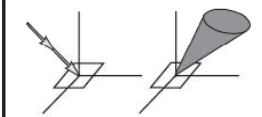
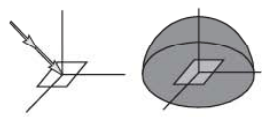

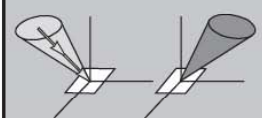
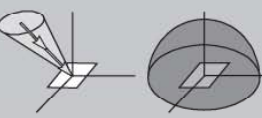
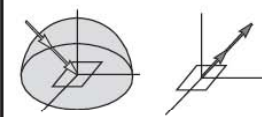
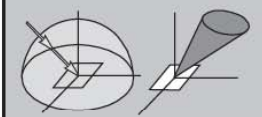
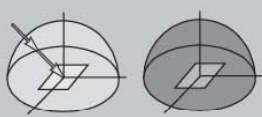
<i>Incoming/Reflected</i>	Directional	Conical	Hemispherical
<i>Directional</i>	Bidirectional Case 1 	Directional-conical Case 2 	Directional-hemispherical Case 3 
<i>Conical</i>	Conical-directional Case 4 	Biconical Case 5 	Conical-hemispherical Case 6 
<i>Hemispherical</i>	Hemispherical-directional Case 7 	Hemispherical-conical Case 8 	Bihemispherical Case 9 

Figure 2: Geometrical-optical concepts for at-surface reflectance terminology (Schaeppman-Strub et al., 2009).

This is true for all sensors with larger FOV, such as the ASD (Analytical Spectral Devices) FieldSpec series (25 deg, while fore-optics allow a restriction to 8 deg or less), and in cases where the sensitivity of the sensor outside of the cone only gradually falls off across several degrees outside of the half power point (Schaeppman-Strub et al., 2009). To complete measurable quantities, the Cases depicted in Figure 2 are used. In a laboratory environment, usually biconical measurements (Case 5) are taken. Case 9 represent albedo meters mounted on measurement towers, and Case 6 measurements are rare (laboratory calibration of an albedo meter).

When measuring in the field, spectrometers in combination with a white reference panel usually report *reflectance factors*. Because sometimes white references are only good approximations to a perfect Lambertian and 100% reflecting surface, these measurements are occasionally called *reflectance*. However, in most cases, neither Spectralon nor BaSO₄ panels are 100% reflecting nor spectrally flat nor Lambertian, these measurements must be reported as *reflectance factors*. When correcting for the non-Lambertian behavior and compensating for not fully reflecting 100%, these panels can be modeled to behave like a Lambertian reference. This would require a spectral calibration as well as a proper measurement of its directional behavior using a goniometer system. If done so, field measurements can be converted to reflectance or various expressions of Albedo (e.g., DHR, BHR, NBAR, etc.) (see Figure 3).

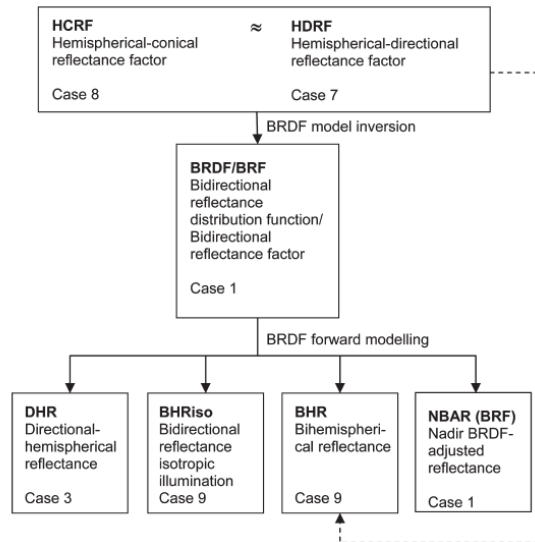


Figure 3: Data processing chain of reflectance quantities (from Schaepman-Strub et al., 2009).

When ignoring the above procedures, uncertainties originating from the conical assumption, imperfect reference panels, and atmospheric composition changes between reference and target measurement are likely to exceed 5-20% of absolute reflectance (Schaepman and Dangel, 2000; Schaepman-Strub et al., 2006; 2009). These uncertainties may further be increased, when including reflectance factors in radiative transfer models, that initially require Albedo (BHR, Case 9) as input spectrum (cf., MODTRAN).

3. Multiangular Measurements using a Dual-view Field Goniometer System

In spectrodirectional remote sensing the Earth's surface reflectance characteristics are studied using directional and spectral dimensions. As a consequence, the reflected radiation from a target is directly measured from various observation directions distributed over the whole hemisphere in order to describe the target specific reflectance characteristic. The underlying concept is called the bidirectional reflectance distribution function (BRDF) (Nicodemus et al. 1977). BRDF knowledge is essential for many applications such as correction of directional effects in RS data and quantitative retrieval of vegetation (Huber et al. 2007; Kneubühler et al. 2008; Strub et al. 2002; Weiss et al. 2000), snow (Painter and Dozier 2004) or soil (Gobron et al. 2000) parameters. Ground-based spectrodirectional measurements are usually performed using goniometer systems. For practical reasons the bidirectional reflectance factor (BRF) is used and defined as the BRDF of the target normalized to the BRDF of an ideal Lambertian surface ($1/\pi$) (Nicodemus et al. 1977). BRF knowledge supports the determination of the surface Albedo, which is a crucial parameter in modeling the Earth's radiation budget.

An accurate retrieval of the bidirectional reflectance factors (BRF) from field goniometer measurements requires knowledge of the angular distribution of the reflected and the incident radiation. Common ground level spectrodirectional measurements can be performed either in the field (Abdou et al. 2000; Sandmeier 2000) or in a laboratory environment (Biliouris et al. 2007; Sandmeier et al. 1998). However, there are obvious technical differences between the two concepts and corresponding measurements are not directly comparable (Dangel et al. 2005).

Field goniometry has the advantage that the target is observed in its natural environment, including the natural illumination by the sun. The major disadvantage is that atmospheric effects and solar zenith angle variations of the illumination have to be taken into account. Furthermore, the total illumination involves all directions within the hemisphere and consists of a diffuse and a direct part. The measured field reflectance quantity is therefore referred to as hemispherical conical reflectance factor (HCRF) based on Martonchik et al. (2000) and Schaepman-Strub et al. (2006). Consequently, the measured HCRF needs to be corrected for the atmospheric influence in order to obtain the target specific BRF. The most exact BRF retrieval from field goniometer measurements can be achieved by following the procedures proposed by Martonchik (1994) and others (Lyapustin and Privette 1999). This implies, however, accurate knowledge of the angular distribution of incoming diffuse radiation at the same time as reflected radiation from the target is collected.

The recently developed Dual-view Field GOniometer System (FIGOS) is able to simultaneously obtain the reflected and the incoming diffuse radiation at high angular resolution (Schopfer et al. 2008), allowing for an improved field BRF retrieval (Figure 4). The goniometer itself consists of three major parts: a zenith arc and an azimuth rail, each of 2 m radius, and a motorized sled, onto which two sensors are mounted. All parts are made of black-coated aluminum in order to minimize scattering effects. Currently, measurements are taken at azimuth steps of 30° and zenith steps of 15° (-75° to 75°). A full dual-view goniometer dataset is completed in about 25 minutes totaling in 66 measurements.

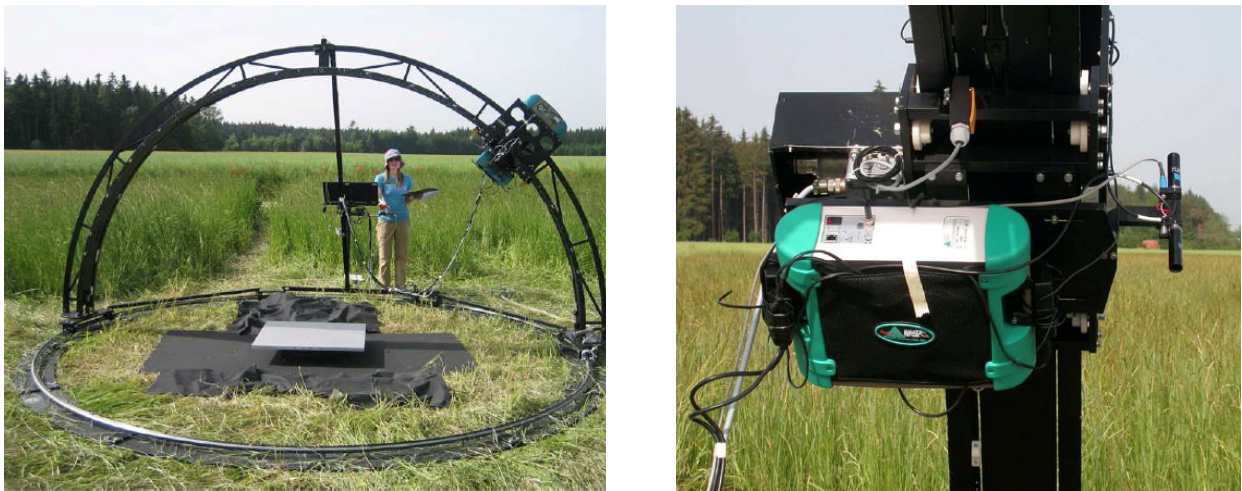


Figure 4: Left: Dual-view Goniometer FIGOS, Right: Close-up of dual-view combination mounted on the zenith arc.

The device's dual-view combination, providing the capability to *simultaneously* collect reflected and incoming radiances at high spectral *and* angular resolution, is the main innovative aspect. Two wireless computer-controlled ASD FieldSpec 3 spectroradiometers cover the spectral range from 350 nm to 2500 nm and sample data at intervals of 1.4 nm (350-1050 nm) and 2 nm at 1000-2500 nm with a spectral resolution of 3 nm at 700 nm and 10 nm at 1400/2100 nm, respectively (ASD 2007). By using a dual optic holder both optics are exactly aligned while pointing in opposite directions and the generated shadow at the hotspot direction is minimized to the optic's size, which is about 1 cm in diameter. Consequently, spectrodirectional measurements close to the hotspot are possible and may provide new insights into the reflectance characteristic at this particular observation direction.

4. Spectrometric measurements of sun-induced chlorophyll fluorescence

Plants mediate a significant amount of the gas exchange between the terrestrial bio-geosphere and the atmosphere (Ozanne et al. 2003). Approximately 60 Gt of carbon are annually fixated through the process of plant photosynthesis (Janzen 2004). The measurement and quantification of photosynthetic rates at leaf level is well established, whereas the estimation of photosynthetic rates at canopy or ecosystem scale is still challenging. Canopy photosynthesis is currently quantified by means of an extensive network of eddy covariance (EC) towers. The EC technique provides well understood measurements of canopy gas exchange from a wide range of plant ecosystems at high temporal resolution (Baldocchi et al. 2001). However, the footprint of EC towers is typically in the range of up to ~1 km², depending on the local setup and aerodynamic properties of air masses. Hence, measurements are local and solely representative for the underlying ecosystem (Drolet et al. 2008; Turner et al. 2003).

Remote sensing (RS) offers a unique possibility to investigate the functional state of vegetation canopies in a spatially explicit, multi-scale fashion. Currently existing approaches are a combination of remote measured vegetation “greenness” combined with productivity estimates based on microclimatic and environmental data (e.g. MODIS GPP product). A promising concept for directly measuring photosynthesis using remote sensors is based on a plant protection mechanism carried out within the photosystem II (PS II). The photosynthetic pigments absorb parts of the incoming solar irradiance at a given wavelength and use this energy to drive photosynthetic carbon fixation. Energy that is not used photosynthetically is partly re-emitted as chlorophyll fluorescence at longer wavelengths (Baker 2008; DemmigAdams and Adams 1996). Hence, sun-induced chlorophyll fluorescence (FS) can be considered as direct, scale independent indicator to monitor the functional status of plant photosynthesis (Baker 2008; Govindjee 2004). The weak FS signal which is added to the reflected solar radiation of the canopy is characterized by well defined spectral characteristics with two broad peaks at about 685 and 740 nm (Franck et al. 2002; Lichtenthaler and Rinderle 1988). However, the observation of FS is a challenging task as both fluxes have to be separated and the amount of FS emitted by a sunlit leaf is only about 1-5% of the total reflected light (figure 1-left). We present results from field experiments, which were initialized to evaluate whether spatio-temporal variations of FS can be reliably measured using the actual spectrometer technology.

In the framework of the ESA supported CEFLES2 campaign, carried out in the south of France in 2007 (Rascher et al. 2009), two different set-ups were established for estimating the spatial and temporal variability of FS in 3D-homogeneous agricultural canopies. One stationary set-up exploits an autonomously operating robotic system inclusive an ASD field spectrometer to collect diurnal courses reflected radiation 1m above the canopy. A mobile setup was established to ensure full cover of the FS signal spatial distribution. In both set-ups, a calibrated Spectralon panel (25x25 cm) served as white reference to estimate incident irradiance. The acquired dataset consists of spectral records from four canopy areas (circular area of about 0.5 m diameter each), bracketed by measurements of the reference panel. Four diurnal courses were acquired in a corn field by measuring the reflected radiation each minute. Additionally, eight different crops and a bare soil were spatially characterized. The FS signal was derived from the optical measurements using the modified Fraunhofer Line Depth (FLD) method, proposed by Maier et al. (2003), applied on the O2-A band.

FLD principle (Plascyk 1975) is currently the most frequently used method to derive FS from remote measurements (Alonso et al. 2008; Meroni et al. 2009) and was successfully used in different works (e.g. Carter et al. 1990; Damm et al. 2010; Moya et al. 2004). The FLD method exploits absorption lines existing in radiance measurements (Figure 5-right), to decouple and provide both fluxes in physical units. Solar irradiance at ground level exhibits several absorption bands, which are suitable for the retrieval of FS. The atmospheric molecular oxygen absorption O₂-A band (760 nm) overlaps with the chlorophyll fluorescence emission spectrum and is wide enough to quantify fluorescence from air- and spaceborne platforms.

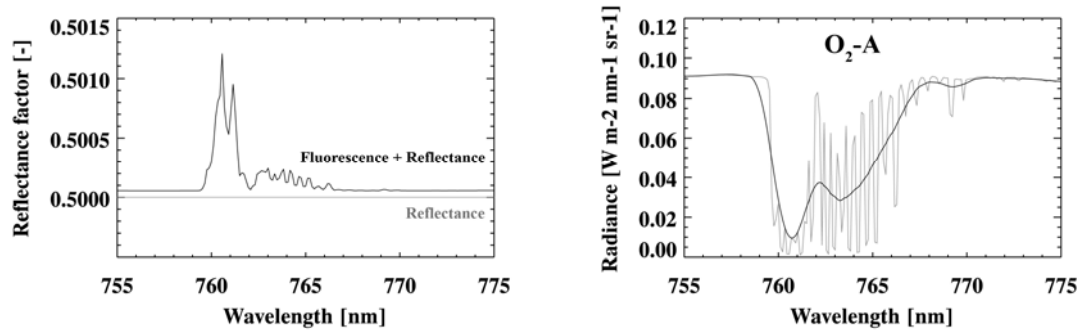


Figure 5: Left: Apparent (fluorescence + reflectance) and real reflectance of a fluorescing vegetation canopy. Right: Radiance signal of the Oxygen-A absorption band with 0.1 nm resolution (grey) and 1.0 nm resolution (black).

The spatial characterization of FS was focused on the investigation of FS signal variability. FS was compared against the well-established Normalized Difference Vegetation Index (NDVI) to evaluate the plausibility of measured FS values. Thereby, low FS values should correspond to low NDVI values and vice versa. Additional variation might be induced by the fact that FS covers complementary information about the canopy specific photosynthetic activity. A first relative evaluation of the results shows an exponential relationship between FS and the NDVI for different crop and surface types. The specific behavior is induced by the well-known saturation effect of the NDVI for dense canopies. Both parameters show a clear difference between the intra- and inner-field variations, which is mirroring the heterogeneity of cultivation, nutrient availability, or species composition. The comparison indicate that the FS values seems plausible: the vital and dense winter wheat fields reach the highest FS values, slightly senescent corn field medium FS values and dry stressed grassland and senescent sunflowers have lowest FS values (see Figure 6 left).

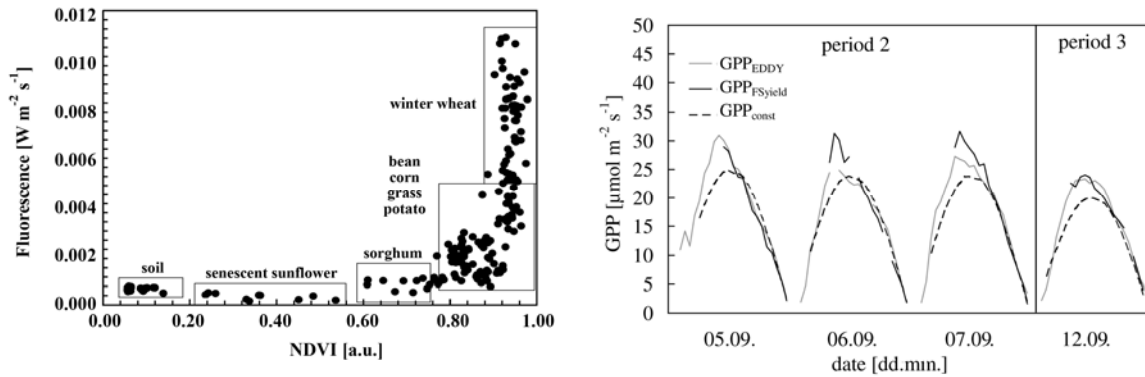


Figure 6: Left: Comparison between the NDVI and sun-induced fluorescence from seven agricultural crops and a bare soil (from Rascher et al. 2010). Right: Diurnal courses of modeled and measured GPP_{EDDY} signal. $GPP_{FSyield}$ based on fluorescence yield. GPP_{const} belongs to GPP modeled with a constant LUE (from Damm et al. 2010).

The temporal analysis aimed at evaluating whether diurnal physiological responses of vegetation canopies may be tracked by FS signals. Diurnal courses of gross primary production (GPP) measured with an eddy covariance tower were used as a proxy for canopy photosynthesis and compared to modeled GPP. The light-use efficiency (LUE) concept (Monteith 1972) was applied to model GPP, whereas the variable LUE term was approximated by remotely measured FS data. The comparison between modeled and measured data shows that the diurnal course including the prominent midday depression can be reproduced with the remote measured fluorescence yield (Figure 2, right) (Damm et al. 2010).

FS is a powerful detectable optical signal that is directly related to actual photosynthetic efficiency. The presented results demonstrate that FS can be reliably measured in field concerning the spatial and temporal terms. Especially the temporal investigation indicates that the FS signal can be used for a better estimate of canopy level carbon fixation. However, the promising results need to be consolidated and dedicated scientific studies are essential to better understand the link between sun-induced FS and variations in photosynthetic carbon fixation. Also the scaling of the fluorescence concept from leaf to canopy to ecosystem scale remains challenging as the impact of several influencing factors, e.g. the impact of structure, atmosphere, directionality, non-photosynthetically active objects, etc. have not been quantified and evaluated in all details.

5. Radiative Transfer based Upscaling

Solving the transfer equations using advanced radiative transfer (RT) models provide a physical foundation for scaling spectro-directional reflectance measurements. Any RT simulation is in principle a bottom-up procedure, where spectral properties of Earth surface objects are characterized by their inherent geometrical distributions and are up-scaled and ‘mixed’ to the spatial pixel size of targeting remote sensing (RS) data of lower spectral/spatial resolution. A structurally highly heterogeneous ecosystem (e.g., a forest stand) is composed of different non-Lambertian scattering elements, mostly leaves of plants, non-photosynthetic vegetation (branches, twigs, etc.), understory vegetation and non-vegetation, etc., occupying the ecosystem space according to present environmental conditions (e.g., terrain configuration – slope, elevation, exposition and consequent light, water, nutrient availability, etc.). Such a complex natural environment can be virtually modelled as a scene assembled out of various

three-dimensional (3D) geometrical primitives. Surface optical and geometrical properties of created 3D objects need to be specified in order to compute multiple-scattering phase functions of the radiative transfer through such a scene. The reflected and/or transmitted optical properties can be measured in the laboratory or field by using portable spectroradiometers coupled with an optical integrating sphere (Figure 7). The surface absorptance a of a given wavelength l can be then easily computed from measured directional-hemispherical reflectance/albedo r and transmittance t following the energy conservation law: $a(l) = 1 - r(l) - t(l)$ (Despan and Jacquemoud 2004).

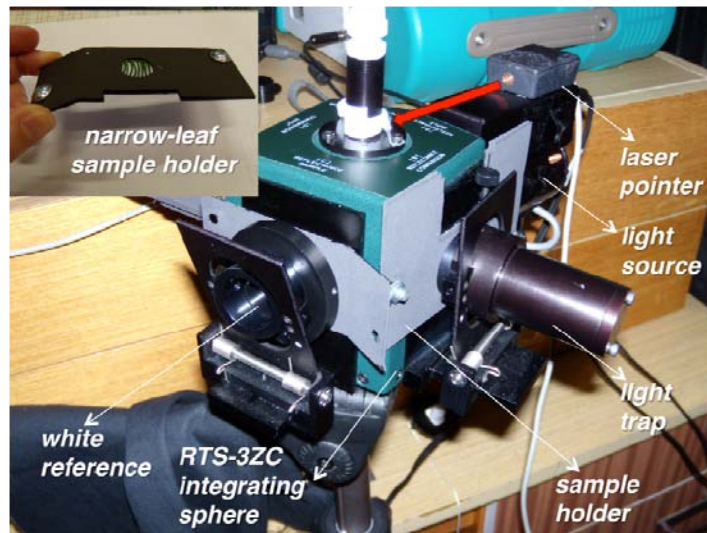


Figure 7: Measurement of the leaf optical properties of Norway spruce (*Picea abies* /L./ Karst.) needles with the RTS-3ZC optical integrating sphere and ASD FieldSpec-3 spectroradiometer with a sample holder customized for narrow laves (left upper corner).

Coupled RT models from two distinct spatial scales, leaf and canopy, are linked describing vegetation ecosystems and their ecotones. Leaf models are simulating interactions of photons with the leaf biochemical compounds (e.g., foliar pigments, proteins, water molecules, etc.) and an internal cellular tissue structure (i.e., epidermis layers, palisade parenchyma and spongy mesophyll), while the canopy models are supplying interactions with the other surrounding canopy photosynthetically active and inactive structures and introducing the geometrical-directional component into the simulated system. Coupling and inversion of both RT model types represents an efficient way to retrieve information on the vegetation structure and/or biochemical constituents from remotely sensed air-/spaceborne spectro-directional image data (Jacquemoud et al. 2009; Schaepman et al. 2005; Ustin et al. 2009, Kokaly et al. 2009). One of the most frequently used leaf level RT models in quantitative RS approaches is PROSPECT (Ferret et al. 2008; Jacquemoud and Baret 1990). PROSPECT's base lies in the generalized 'plate model' of Allen et al. (1969), assuming that leaf can be represented by a pile of N homogeneous plates separated by $N-1$ air spaces. The model was originally calibrated to simulate the optical properties of dicotyledonous leaves, therefore, a recalibration effort was needed to make it applicable also for the monocotyledon narrow-leaf plants. We have created a narrow-leaf sample holder (Malenovsky et al. 2006a) and adopted the original Daughtry's method (Daughtry et al. 1989) to measure optical properties of the Norway spruce (*Picea abies* /L./ Karst.) needle leaves in the LabSphere optical integrating sphere RTS-3ZC coupled with the ASD FieldSpec-3 spectroradiometer (see Figure 7). Optical properties of 110 needle samples of last three generations were used to recalibrate the PROSPECT specific absorption coefficients of dry matter content and chlorophyll a+b

content, resulting in better match between measured and simulated reflectance, transmittance and absorbance (integrated root mean square error of all three properties < 1%). PROSPECT inversion of 46 testing needle samples revealed an improved model performance in estimation of the original inputs (mesophyll structural number N , chlorophyll – C_{ab} , dry matter – C_m , and water content – C_w) – see Figure 8.

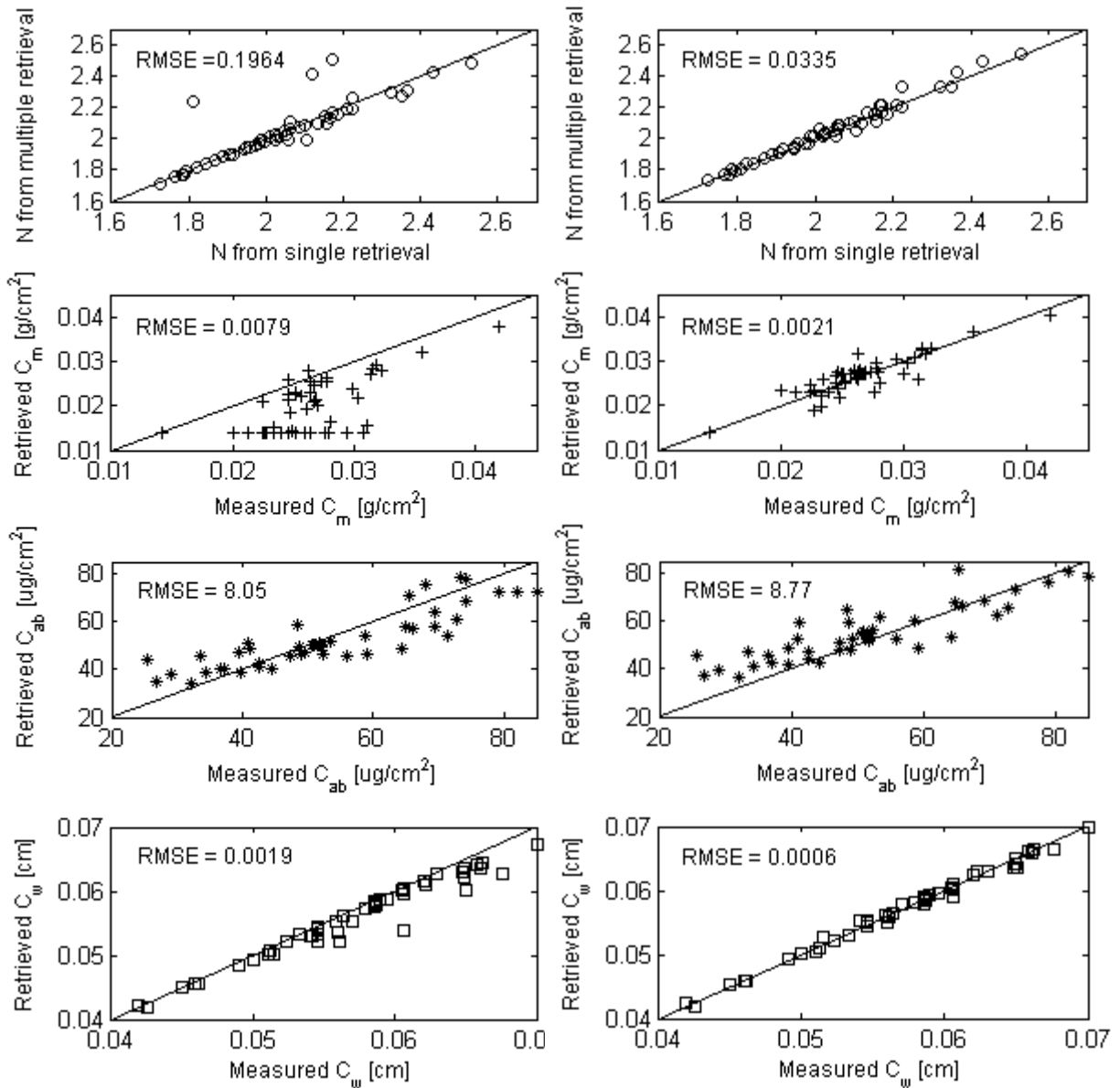


Figure 8: Results of the constrained inversion of the original (graphs in left column) and recalibrated (graphs in right column) PROSPECT retrieving concurrently all the model inputs (C_{ab} , C_m , C_w , and N) using 48 samples of the testing dataset. The merit function was not based only on the spectral information, but it was constrained by measured prior knowledge on targeting values and variability limits of the retrieved parameters (Malenovsky et al. 2006a); (RMSE = root mean square error between measured and simulated values; solid line represents a one-to-one relationship function

The recalibrated PROSPECT model was coupled with a Discrete Anisotropic Radiative Transfer (DART) canopy level model (Gastellu-Etchegorry et al. 2004) to simulate a top of canopy bidirectional reflectance factor (BRF) of a mountainous spruce stand in order to develop and test sensitivity of a robust chlorophyll estimating optical index named *Area under curve Normalized to Maximal Band depth* between 650-725nm (ANMB₆₅₀₋₇₂₅) (Malenovský et al. 2006b). Both RT models were parameterized using the data acquired within the field survey of the Norway spruce forest stands situated near the village Modrava (48°59'N, 13°28'E), at the Šumava Mts. National Park (Czech Republic). Heterogeneous representative 3D scenes of three canopy closures with variable leaf area index (LAI) and leaf chlorophyll a+b tent (C_{ab}) were generated out of averages and standard deviations of the tree field measurements. In total, 162 DART simulations were performed to reproduce the very high spatial resolution spectral images as potentially captured by the AISA Eagle airborne sensor (Specim Ltd., Finland) (Figure 9). In the final step only spectral signatures of sunlit crown pixels of spectral bands from 648-726 nm were extracted to build the virtual canopy BRF database that was used to design the robust forest leaf chlorophyll estimating optical index ANMB₆₅₀₋₇₂₅. A similar PROSPECT/DART up-scaling RT mechanism was applied in a study investigating the influence of woody elements (branches and trunks) of a Norway spruce forest stand on nadir canopy reflectance (Malenovský et al. 2008). Introduction of woody material into the DART model noticeably reduced nadir TOC reflectance at near infrared wavelengths. Both of the studies demonstrated capabilities of the physical radiative transfer modeling approach in bridging the gap between the leaf spectro-directional information and reflectance of the structurally complex coniferous canopy.

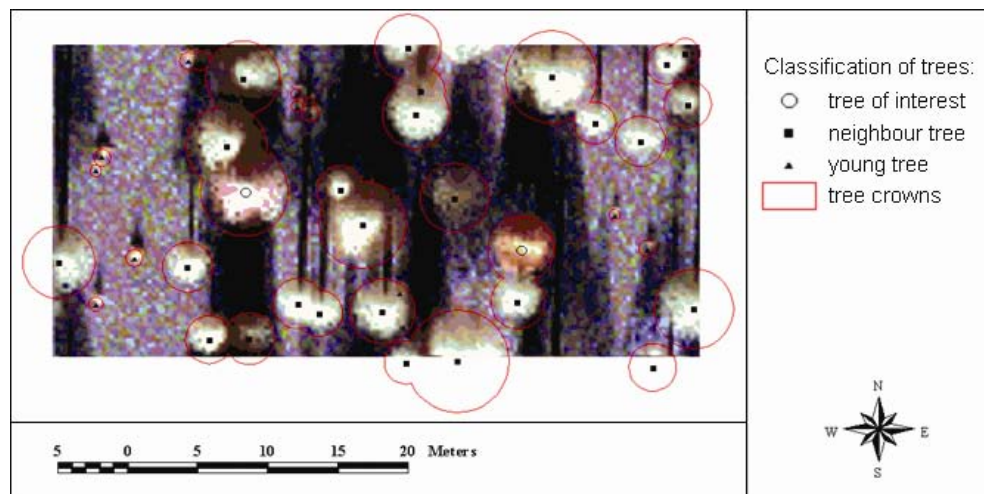


Figure 9: False colour RGB composite of DART simulated nadir AISA Eagle bands (R = 800, G = 552 and B = 681 nm) for a Norway spruce research plot at the Šumava Mts. National Park (Czech Republic) (from Malenovský et al. 2006b).

6. Applications of Soil Reflectance Spectroscopy

Reflectance spectroscopy has proven to be a powerful method to determine soil properties in the laboratory (Ben-Dor et al. 1997; Reeves III et al. 2000; Sudduth and Hummel 1993), under field conditions (Barnes et al. 2003; Stevens et al. 2008) and from imaging spectrometers (Ben-Dor et al. 2002; Gomez et al. 2008). Many soil properties can be determined from the reflectance information, but most research efforts have been put in the estimation of soil organic carbon (SOC). Reflectance

spectroscopy can be used to get fast estimates of several soil properties, thus can be used to achieve an intensive spatial and temporal sampling, without the vast increase in costs regular soil sampling would face.

The setting in which spectroscopy is operated (field, laboratory, airborne) influences the accuracy that can be achieved. Stevens et al. (2008) showed that under controlled conditions, accuracies compared to chemical soil analysis can be achieved. However, these accuracies are obtained for studies where local calibrations are used and where the soil property of interest is the main variable in the area. The accuracy drops as soon as multiple soil types occur, or soil properties have to be estimated for soil types that were not included in the model-calibration (Bartholomeus et al. 2008). This is shown in Figure 10, where the double square root of the SOC content is plotted against the inverse of the summed reflectance in the visible wavelengths. The trend in this relation for the cambisol and luvisol samples deviates from the general trend. Using a model, based on these other soil types for the estimation of SOC in cambisol or luvisol samples would give a low accuracy for these soil types. Including all soil types in one general model will give overall low prediction accuracy. In general, models perform worse when they are calibrated for multiple soil types. Furthermore, when the range of the soil property in question is not fully covered by the calibration set inaccurate models are the results. The need for local calibration limits practical implementation of reflectance spectroscopy on a large scale.

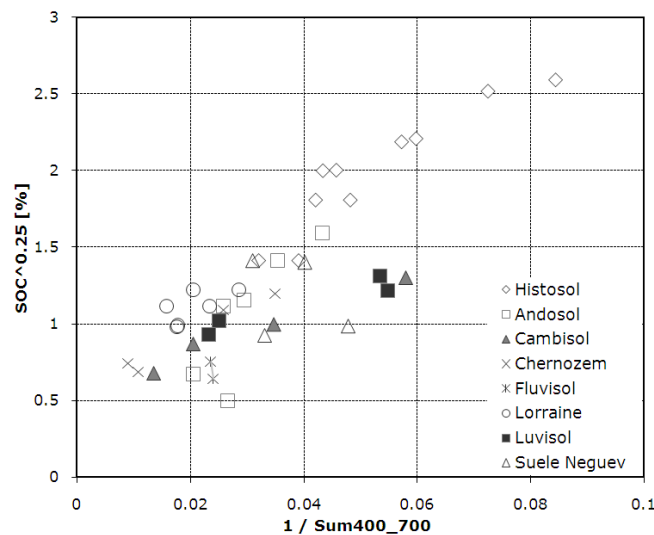


Figure 10: Double square root of SOC for different soil types plotted against the inversed sum of the reflectance in the visible wavelengths.

The limitation of local calibrations can only be overcome with a large spectral database, which covers: a) as many soil types as possible, b) the full range that can occur for the soil properties that have to be estimated, and c) is measured under a fixed standardized protocol. From this database a dedicated set of spectra or samples can be selected, that match the local conditions. Whether the selection criteria are based on environmental properties (e.g. soil type, topography, region, texture class) or spectral similarity is an important topic of research. Although large soil collections exist (e.g. at ISRIC), they have not been collected with the construction of spectral soil property models in mind. Existing soil spectral libraries are often limited to a specific geographic region and exist of a limited number of samples. A combined effort to construct a global spectral library has been initiated by the Soil Spectroscopy Group (Viscarra Rossel, 2009). Since many soil studies are based on multivariate statistical techniques (e.g. Partial Least Square Regression), the models rely on very accurate and stable

spectral measurements. Small differences in spectral sampling interval can result in errors in estimated soil properties. Therefore, stable and reliable instrumentation in combination with a fixed measurement protocol is required.

Studies based on reflectance measurements under field conditions (including airborne campaigns) have to deal with a number of disturbing factors, like spatial and temporal variation in moisture content, surface roughness and influence of vegetation. For bare soil patches especially variation in moisture content has a large influence on the applicability of soil property models. Soil moisture shows no linear relation with the sampled wavelength, therefore soil spectral libraries collected under well-controlled laboratory conditions cannot be applied to the situation in the field. Furthermore, models developed for the one year cannot be applied to another year without a significant loss in accuracy (Stevens et al. 2008). When existing spectral libraries are used, lower prediction accuracy has to be accepted or some pre-treatments have to be applied to collected samples, which makes a true field. At least samples should be dried, which can be done in a rather basic setting (e.g. air drying). Recent research for soils in the Siberian tundra (Table 1), shows that good calibrations can be found for Total C and K and moderate calibrations for pH and total N, when air dried soil samples are used, where the moisture content of the undried samples ranged between 15% and 89%. Spectral measurements of the soil surface are only possible if vegetation is absent. In this case, the conditions at the surface should be representing the subsurface soil conditions to be able to use the estimated soil properties for environmental modeling. In general, this is only true for agricultural areas. For natural eco-systems subsurface sampling or subsurface spectral measurements have to be done, e.g. following the method of Ben-Dor et al. (2008).

Table 1: PLSR results for air-dried samples of tundra soil:

	PH	Total P	Total K	Total N	Total C
R²	0.683	0.301	0.856	0.747	0.841
RMSE	0.4	36.897	171.646	0.257	4.694
RPD	1.79	1.17	2.65	1.97	2.51

RMSE = Root Mean Square Error, RPD =Ratio of Performance to Deviation

A precondition for reliable outcomes is that reflectance measurements in the field are harmonized by using controlled illumination settings. For soil samples, this can easiest be achieved by using a contact probe. When larger areas have to be sampled (e.g. to bridge the scaling gap to airborne imaging spectrometer data) sampling protocols within a plot can be used. Typically, a number of spectral measurements are done on fixed locations within a plot, and spectra are averaged to come to a general spectral signature.

Conclusions

We report on recent advances of using spectroradiometric instrumentation at various spatial, spectral and temporal scales. Reflectance terminology has recently received much attention. Improved measurement instrumentation has contributed to a significant shift in uncertainties from measurement noise towards structural and systematic measurement setup.

Structural support to spectral measurements has been given by the implementation of spectral databases. The systematic collection and administration of metadata is facilitated with the use of such databases. Similar to the emergence of data standards and other standardization efforts, spectroradiometric measurements, its data and metadata will also develop into more standardized and

structured approaches. A next generation database will also include content and thematic searches over spectral data (e.g., find all spectra with chlorophyll *a* content of 0.5 – 2 mg/m²).

Even though still sparsely available, various goniometers have been developed, supporting the measurement of the directional behavior of non-Lambertian targets. Again, due to improved measurement quality, uncertainties while ignoring directional effects in measurements will emerge to the most significant source of uncertainty in spectrodirectional measurements.

A multitude of applications using spectroradiometers demonstrate that areas such as scaling, inventorying and productivity assessment are currently possible with unprecedented accuracy. These measurements and applications however demonstrate the urgent need of simultaneous biochemical, structural, and biophysical parameter measurements using instrumentation other than spectrometers. Destructive leaf sampling for Chl and N analysis has become the main time constraining factor in spectral data collection. Unfortunately, similar progress in manufacturing such measurement instrumentation cannot be observed compared to the progress of spectral instrumentation.

Spectroscopy in Earth related remote sensing has gradually moved from measuring vegetation-light interactions in the 1980s, to photon-vegetation interaction in the late 1990s to nowadays. We expect further advances in instrumented approaches and technology to be soon able to measure photon-matter interactions. A significant contribution of doing so would not only be technological advances, but also

a) variable and programmable spectral sampling intervals and resolution of field based instrumentation,

b) simultaneous spectral measurements of downwelling (hemispherical and/or conical irradiance and reflected radiance, and

c) very high spectral resolution instruments for particular applications such as sun induced fluorescence measurements for vegetation productivity assessment.

We are convinced that such instrumentation will be available from commercial providers to the scientific community in short time.

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