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Continuous and long-term measurements of reflectance and sun-induced chlorophyll fluorescence by using novel automated field spectroscopy systems

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ABSTRACT

In this paper we present novel automated field spectroscopy systems for collecting unattended, continuous and long-term measurements of plant canopies and, more in general, of Earth's ecosystems. These systems simultaneously collect *high* and *ultra-high* resolution spectra in the visible to near-infrared (VNIR) domain employing two spectrometers: i) the first covers the spectral range 400–1000 nm with a 1.0 nm spectral resolution; ii) the second provides a sub-nanometer spectral resolution within the 700–800 nm spectral range. The data collected by the first spectrometer allow retrieval of VNIR reflectance, while the higher spectral resolution data from the second device permit estimation of vegetation Sun-Induced Fluorescence (SIF) in the O_2–A band. The instruments are constructed by assembling commercial and on-the-shelf optoelectronic devices to facilitate reproduction of the instrument for promoting measurements over different ecosystems. The instrument's optical design, data collection and processing, laboratory and in-field calibration methods are reported and discussed. The high spectral resolution and the rigorous calibration methods enable accurate estimation of SIF in physical units by exploiting almost the same retrieval concept as that of the European Space Agency FLuorescence EXplorer mission. The instruments have been operated in several field campaigns with the aim to show: i) the possibility of continuous and seasonal monitoring of plant growth and activity of an agricultural crop; and ii) the diverse and specific daily course patterns of different types of canopy. The datasets of canopy reflectance, vegetation indices and SIF collected are shown and discussed.

1. Introduction

Hyperspectral remote sensing is becoming a powerful and reliable approach for Earth observations, as it allows a detailed observation of important bio- and geo-physical parameters related to Earth's dynamic processes. The use of hyperspectral sensors has various advantages (Goetz, 2009) including: i) detection of narrow spectral features related to particular parameters; ii) exploitation of over-determined mathematical equations to increase the retrieval accuracy; and iii) simultaneous estimation of a certain number of parameters. The benefits of hyperspectral data have been demonstrated for many environmental applications covering studies on the biosphere, atmosphere, cryosphere, lithosphere and hydrosphere (Schaepman et al., 2009).

Currently, the Hyperion sensor launched by NASA in November 2000 aboard the Earth Observing-1 (Middleton et al., 2013; Ungar, Pearlman, Mendenhall, & Reuter, 2003) is still the only hyperspectral satellite mission devoted to land surface studies. In the last decade, several studies have laid the basis for upcoming space missions for supplying operational hyperspectral observations of Earth-surface reflected radiance. The Hyperspectral Infrared Imager (HyspIRI) (Green, Asner, Ungar, & Knox, 2008) under development by NASA, the Environmental Mapping and Analysis Program (EnMAP) (Kaufmann et al., 2008) by the German Aerospace Center (DLR) and the Hyperspectral Precursor of the Application Mission (PRISMA) (Galeazzi et al., 2009) by the Italian Space Agency (ASI), are some of the programs that will be launched in the next few years.

Beyond these, the FLuorescence EXplorer (FLEX) mission currently candidate to the European Space Agency (ESA) 8^{th} Earth Explorer (EE8) (Drusch et al., 2008) aims to detect the faint red glow of the Sun-Induced Fluorescence signal (SIF) emitted by plants. The FLEX satellite carries the FLuORescence Imaging Spectrometer (FLORIS) (Kraft, 2012; Kraft et al., 2013) to measure fluorescence at the oxygen absorption bands, the reflectance in the red-edge and the Photochemical Reflectance Index (PRI). It will fly in tandem with the Sentinel-3 satellite to take

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advantage of complementary measurements from the Ocean and Land Color Instrument (OLCI) and the Sea and Land Surface Temperature Radiometer (SLSTR).

The exploitation of the SIF signal is a novel approach to inferring plants' photosynthetic activity improving vegetation gross primary production models of natural and managed ecosystems (Baker, 2008; Flexas et al., 2002; Papageorgiou & Govindjee, 2004). In fact, plants respond continuously to the varying environmental conditions that modulate the photosynthetic rate. The SIF signal is promising as a probe of this process because it arises directly from the core of the photosynthetic machinery, thus providing instantaneous information on plant functioning (Damm, Kneubuhler, Schaepman, & Rascher, 2012; Zarco-Tejada et al., 2009; Zarco-Tejada, Catalina, González, & Martín, 2013).

In support of future satellite missions, airborne and field spectroscopy measurements have a fundamental role, offering valuable data to consolidate instrument's features, algorithm prototyping and to better understand the link between optical signals and parameters/processes at different observational scales. Recently, in support of FLEX preparatory studies, the novel high-performance airborne imaging spectrometer *HyPlant* and ground-based high-resolution spectroscopy systems have been developed and operated during extensive field campaigns to study the spatial and temporal behaviors of SIF. The *HyPlant* is a narrow-band imaging spectrometer developed by the Forschungszentrum Jülich (Jülich Research Center, Germany) in cooperation with SPECIM Imaging Ltd. (Finland). The imagery provided by *HyPlant* (Rossini et al., 2015) was fundamental in retrieving the first airborne maps of SIF at high spatial resolution (1–3 m) and investigating the contributions of the different landscape elements to the upwelling signal. In parallel, ground-based instruments provide ground-truth measurements for remote sensing data, and furthermore they are powerful tools in investigating the temporal (i.e. diurnal to seasonal) behavior of SIF in relation to plant photosynthesis. In the last decade, automatic field spectroradiometers for unattended measurements of vegetation by using different instruments and configurations (Corp et al., 2010; Daumard et al., 2010; Drolet et al., 2014; Gamon, Cheng, Claudio, MacKinney, & Sims, 2006; Gamon, Rahman, Dungan, Schildhauer, & Huemmrich, 2006b; Hilker, Nesic, Coops, & Lessard, 2010; Huber, Tagesson, & Fensholt, 2014; Leuning, Hughes, Daniel, Coops, & Newnham, 2006; Meroni et al., 2011) have been proposed. A review of some of the instruments employed for continuous vegetation optical sampling in flux towers sites is available from Balzarolo et al. (2011). Most of these instruments offer spectral measurements in the visible to near-infrared (VNIR), but the only ones featuring high-resolution spectrometers for SIF detection are those proposed in Meroni et al. (2011) and Daumard et al. (2010). In this framework, the international initiatives SpecNet (Gamon et al., 2006), the ESSEM COST action EUROSPEC (ES0903) and the recently founded ESSEM COST action OPTIMISE (ES1309) aim at the definition of common ground-based instruments, measurement protocols and data processing as the basis for a further global network. The distributed and systematic/standardized ground-based measurements within the network will potentially offer several advantages to the remote sensing community for improving atmospheric corrections, calibration/validation of airborne and satellite products and understanding optical signals in both space and time domains.

In this paper, we present two automated field spectroscopy systems, the Multiplexer Radiometer Irradiometer (MRI) and its compacted version SFLUOR box, which are capable of collecting unattended, continuous, long-term hyperspectral measurements. The instruments' technical design, the rigorous calibration methods, the data collection, and processing chain are explained through the paper. The reliability of radiance, reflectance, and derived spectral indices collected in different remote sensing campaigns are presented and discussed. In particular, the possibility of continuous and long-term monitoring of plant growth and activity is evaluated during the entire growing season of an agricultural crop. Thereafter, extensive ground-based measurements collected for the calibration and validation of the *HyPlant* sensor, allowed observing the diverse and specific daily course patterns of different types of canopy. Although the use of these instruments is mainly intended for vegetation studies, spectral measurements collected may be helpful in studying the temporal dynamics over any terrestrial ecosystem (e.g. inland water, snow, glaciers, and soils), and they can support calibration and validation of airborne and satellite remote sensing data.

2. Instruments description

The automated field spectroscopy systems were developed by assembling commercial-grade optoelectronic devices. The design concept is based on the use of an optical switch to sequentially select between several input fiber optics fixed to the up-looking (i.e. toward zenith) and the down-looking entrance foreoptics. The optical switch is a fiber optic multiplexer MPM-2000-2x8-VIS (Ocean Optics Inc., USA) with optical throughput > 40% in the VNIR (350–1000 nm) able to connect up to 8 different input channels to output ports connected to two different spectrometers. The switch between adjacent input channels is performed in 150 ms with a positioning accuracy above 99% using a direct current motor with encoder. The actual configuration connects each spectrometer to 3 input ports: i) the up-looking CC-3 cosine-corrected irradiance probes (Ocean Optics Inc., USA) to collect the down-welling irradiance (E_g); ii) the down-looking bare fiber optics with a Field-Of-View (FOV) of 25° to measure the up-welling radiance from the target surface (L_s) and; iii) a "blind" port used to record the instrument dark-current (DC). The conceptual layout of the instruments is shown in Fig. 1A. The entrance foreoptics are connected to the multiplexer input ports using 5 m long optical fibers (one for each spectrometer) with a bundle core of 1000 μm diameter. The connection between the multiplexer output ports and the spectrometers is obtained with 0.3 m long optical fibers. This set-up enables sequential measurements of DC, E_g and L_s spectra simultaneously with two spectrometers.

The two spectrometers embedded in these systems are the High Resolution HR4000 holographic grating spectrometers (Ocean Optics Inc., USA) covering the VNIR with different spectral resolutions. The first spectrometer (hereafter $SPEC_{Full}$) covers the 400–1000 nm spectral range with a *Full Width at Half Maximum* (FWHM) ≃ 1.0 nm. The second spectrometer (hereafter $SPEC_{Fluo}$) is instead optimized to provide higher spectral resolution (FWHM ≃ 0.1 nm) in the 700–800 nm range around the atmospheric oxygen absorption band at 760 nm (O_2–A). The spectrometer optical bench consists of a 5 μm wide entrance slit, diffraction grating with a groove density of 600 (1800) mm^{-1} for $SPEC_{Full}$ ($SPEC_{Fluo}$) respectively and the 3648-element linear CCD-array detector (Toshiba TCD1304AP, Japan) with a 14-bit A/D resolution. Currently, commercial linear CCD detectors offer a relatively limited number of pixels over the spectrum at the different wavelengths. Therefore, the integration of two spectrometers into the MRI system was required to provide both the high spectral resolution for fluorescence retrieval and the continuous VNIR spectral coverage at the same time. The main technical characteristics of the HR4000 spectrometers are summarized in Table 1.

The devices embedded in the field spectroscopy systems are connected to a PC that controls the multiplexer via RS232 and the spectrometers through a USB 2.0 connection. The multiplexer, spectrometers and electronic devices are hosted in a waterproof box customized to permit connection to the optics and electrical interfaces. A cooling system limits variations of the box air temperature thus reducing instrument-related effects such as spectral drifts and detector noise.

The MRI and SFLUOR box have the same optical design concept and operative procedures. However, the SFLUOR box was built recently; therefore, minor technical solutions were improved based on the previous experience. The SFLUOR box differs for an overall compact design (box dimensions 0.31 m × 0.55 m × 0.48 m), and for the integration of the cooling system within the instrument box. These technical solutions facilitate the field installation of the instrument, especially when it must be operated on scaffolding towers to perform measurements