The Future of Imaging Spectroscopy – Prospective Technologies and Applications

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***Abstract*—Spectroscopy has existed for more than three centuries now. Nonetheless, significant scientific advances have been achieved. We discuss the history of spectroscopy in relation to emerging technologies and applications. Advanced focal plane arrays, optical design, and intelligent on-board logic are prime prospective technologies. Scalable approaches in pre-processing of imaging spectrometer data will receive additional focus. Finally, we focus on new applications monitoring transitional ecological zones, where human impact and disturbance have highest impact as well as in monitoring changes in our natural resources and environment. We conclude that imaging spectroscopy enables mapping of biophysical and biochemical variables of the Earth's surface and atmospheric composition with unprecedented accuracy.**

Keywords; imaging spectroscopy, imaging spectrometry, hyperspectral, applications, technology

I. INTRODUCTION

Three centuries ago Sir Isaac Newton published in his 'Treatise of Light' [1] the concept of dispersion of light. The corpuscular theory by Newton was gradually succeeded over time by the wave theory, resulting in Maxwell's equations of electromagnetic waves [2]. But it was only in the early 19th century that quantitative measurement of dispersed light was recognized and standardized by Joseph von Fraunhofer's discovery of the dark lines in the solar spectrum (1817) [3] and their interpretation as absorption lines on the basis of experiments by Bunsen and Kirchhoff [4]. The term spectroscopy was first used in the late 19th century and provides the empirical foundations for atomic and molecular physics [5]. Following this, astronomers began to use spectroscopy for determining radial velocities of stars, clusters, and galaxies and stellar compositions [6]. Advances in technology and increased awareness of the potential of spectroscopy in the 1960s to 1980s lead to the first analytical methods [7, 8], the inclusion of 'additional' bands in multispectral imagers (e.g., the 2.09-2.35 µm band in Landsat for the detection of hydrothermal alteration minerals as proposed by A.F.H. Goetz), as well as first imaging spectrometer concepts and instruments [9-12]. Significant recent progress was achieved when in particular airborne imaging spectrometers became available on a wider basis [13-17] helping to prepare for spaceborne imaging spectrometer activities [18]. However, it lasted until the late 1990s until first imaging spectrometers were launched in space. However, true imaging spectrometers, satisfying the definition given in section II are still sparse nowadays (e.g., CHRIS/PROBA, Hyperion, MERIS).

Today, technological advances in the domain of focal plane development, readout electronics, storage devices and optical designs, are leading to a significantly better sensing of the Earth's surface. Improvements in signal-to-noise, finer bandwidths and spectral sampling combined with the goal of better understanding the modeled interaction of photons with matter will allow for more quantitative, direct and indirect identification of surface materials based on spectral properties from ground, air, and space.

II. IMAGING SPECTROSCOPY

A. *Definition*

In literature, the terms imaging spectroscopy, imaging spectrometry and hyperspectral imaging are often used interchangeably. Even though semantic differences might exist, a common definition is: *simultaneous* acquisition of spatially *coregistered images*, in many, *spectrally contiguous bands*, measured in *calibrated radiance units*, from a remotely operated platform.

Consequently, applying this definition results in quantitative and qualitative characterization of both the surface and the atmosphere, using geometrically coherent spectral measurements. This result can then be used for the unambiguous direct and indirect identification of surface materials, water properties, and atmospheric trace gases, the measurement of their relative concentrations, subsequently the assignment of the proportional contribution of mixed pixel signals (e.g., spectral un-mixing), the derivation of their spatial distribution (e.g., mapping), and finally their evolution over time (multi-temporal analysis).

B. Relevance

Imaging spectroscopy has seen an exponential growth over the past 15 years in terms of referenced publications and associated citations (cf., Fig. 1). This is a good indication of the increasing relevance of this emerging technology. We use searches performed in *altavista.com*, and citations in *scopus.com* using combinations of keywords (e.g., hyperspectral, imaging spectroscopy, and imaging spectrometry) to illustrate the exponential growth.

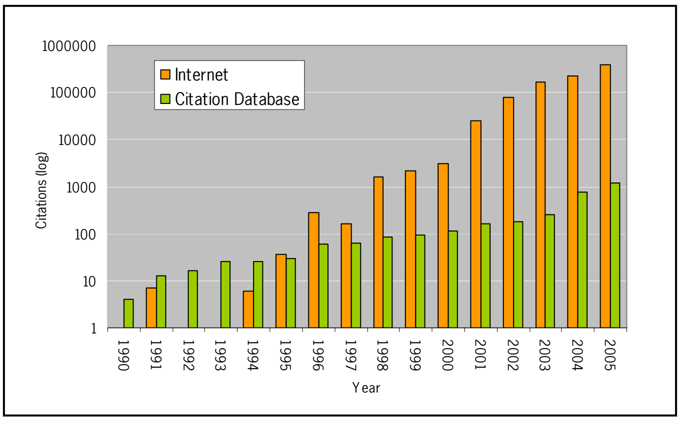

Figure 1. Internet based and citation database search for ‘imaging spectroscopy’ (1990-2005).

A thematic separation of the search terms used in the above overview will be increasingly difficult in the future, since methods based on imaging spectroscopy are not exclusively applied in Earth observation, but also in space research [19], exobiology [20], neurosciences [21], chemometrics [22], amongst others [23, 24].

III. Instruments

Earth observation based on imaging spectroscopy has been transformed in less than 30 years from a sparsely available research tool into a commodity product available to a broad user community. Currently, imaging spectrometer data are widespread and they prove for example, that distributed models of biosphere processes can assimilate these observations to improve estimates of Net Primary Production, and that in combination with data assimilation methods, access complex variables such as soil respiration, at various spatial scales [25]. However, a lack of data continuity of airborne and spaceborne imaging spectrometer missions remain a continuing challenge to the user community. There is an emerging need to converge exploratory mission concepts (e.g., former ESA’s Earth Explorer Core Mission proposal SPECTRA [26]) and technology demonstrators (e.g., NASA’s Hyperion on EO-1 [27]), and operational precursor missions (e.g., ESA’s CHRIS on PROBA [28]), towards systematic measurement and operational missions (e.g., ESA’s MERIS on ENVISAT [29], NASA’s MODIS [30] on Terra/Aqua). Despite the naming of MODIS, this instrument is not unanimously accepted being a true imaging spectrometer applying a rigorous definition of spectral band contiguity.

Several initiatives proposing space operated Earth Observation instruments in these categories have been submitted for evaluation and approval (e.g., HERO (Hyperspectral Environment and Resource Observer, Natural Resources Canada, Canadian Space Agency), EnMAP (Environmental Mapping and Analysis Program (GFZ (Germany)), Flora (NASA GSFC proposal), FLEX (ESA Earth Explorer proposal), SpectraSat (Full Spectral Landsat proposal), ZASat (South African proposal (University of Stellenbosch)), HIS (Chinese Space Agency), etc.). However for the time being, airborne imaging spectrometer initiatives (e.g., [31, 32]) will continue to provide the majority of new instruments, before continuation missions for Landsat, MERIS, MODIS and others are realized.

IV. Technology

Imaging spectrometer instrument technology will profit from true spectroscopy focal plane arrays, with improved quantum efficiency, several readout ports, a rectangular design and consistent readout in the spectral domain [33, 34], eventually also being expanded to the emissive part of the spectrum. To achieve high spectral-spatial uniformity and high precision measurements advanced optical designs are required combined with enabling components (curved, high-efficiency dispersive elements [35, 36] and ultra-straight slits). Opto-mechanical designs must focus on spectral and radiometric stability [37]. With stability, spectral, radiometric and spatial calibration [38, 39] can be readily established from the spectral features of the atmosphere as well as uniform/measured calibration targets on the Earth [40, 41]. Reprogrammable on-board logic and implementation of (lossless) data compression [42, 43] will help to overcome the downlink capacity problems. Additional reduction in downlink volume can be realized by combining onboard processing capability with non–traditional data reduction techniques such as cloud screening, band aggregation (when appropriate), and employing lossy compression over “stable” targets (e.g. Sahara Desert, Makhtesh Ramon) some of the time. With focus on these technology areas, spaceborne imaging spectrometers may be developed with the required instrument performance. Multiple-sensor approaches as well as operating imaging spectrometers in the multiangular and thermal domain will further broaden the field of applications.

V. (Pre-)Processing

The data processing chain will improve with advanced last-generation computing environments, such as parallel and grid computing, as well as distributed computing approaches that profit from local (user) resources [44, 45]. These advances will increase efficiency in processing data and meet timeliness needs. Preprocessing imaging spectrometer data is adopting multi-instrumented approaches, including improved estimation of the composition of the atmosphere which allows retrieval of surface reflectance and ultimately the derivation of highly accurate Albedo products (blue/white-sky Albedo (BHR); black-sky Albedo (DHR)) [46]. Classification approaches are also changing from hard classifiers towards approaches of soft classifiers based on expert systems [47], Support Vector Machines [48], Markov Random Fields (MRF) for sub-pixel mapping [49], and image change detection and fusion to full expert system spectral analysis [50]. Further morphological approaches for joint exploitation of the spatial and spectral information available in the input data will be explored [51-53]. There is a trend towards establishing integrated systems solutions supporting data assimilation [54]. These solutions will provide scalable approaches, allowing the integration of multiple data sources. Data assimilation will further advance solid coupling of physical models, which link soil-vegetation-atmosphere-transfer (SVAT) models to state space estimation algorithms [55]. Spectroscopy will be increasingly integrated into a multidisciplinary research environment, complemented by *in situ* sensing. Networks of *in situ* sensors exist already (e.g., FLUXNET), and with telecommunication technologies its increasingly feasible for these networks to achieve (near) real time integration of heterogeneous sensor webs into the information infrastructure [56].

VI. Applications

Emerging applications in imaging spectroscopy will not only focus on regional, national or global scales but are also needed to monitor transitional zones, in particular ecotones, (e.g., ecosystem-, communities-, or habitat boundaries) like tundra – boreal forest and forest – heathland, etc., where much of the pressure for change in terms of climate-related disturbance and human impacts are identified. In managed ecosystems the improved precision is a key economical factor, contributing to better yield estimates as well as use of high resolution spectroscopy for species identification and mapping [57-59].

In both managed and unmanaged ecosystems the spectroscopy focus is on detection and identification of plant succession, phenology, plant functional types [60], and on monitoring invasive species [61, 62]. Biochemical applications concentrate on the retrieval of moisture content, C, N, and potentially P cycles, and connecting soil, leaf, and plant functioning with atmospheric fluxes using quantitative approaches. The pigment and photosynthetic system of vegetation is of increasing interest, that will finally allow coupling models from molecules to leaf [63], plant and canopy scales [64, 65]: Imaging spectroscopy for molecular ecology is an emerging research topic.

The sound retrieval of combined atmospheric and vegetation properties will further allow refining 3D radiative transfer approaches in particular in partly cloudy atmospheres [66, 67]. Quantitative physically-based soil models are still to be developed taking into account the full spectral coverage (e.g., reflective and emissive) currently available, although many of the basic spectral interactions have long been a focus of interest [68, 69]. In contrast to the soil, the characterization of snow optically equivalent grain size is currently only possible with the required accuracy using spectroscopy [70, 71].

Studies over the last decade have shown that imaging spectrometry is the ideal tool to separate the complex optical properties of inland waters and the coastal ocean [72, 73]. Particularly when the bottom is imaged the scene is very complex and algorithms that use the full spectral information in the imaging spectrometer data are needed to solve the three variable problem and provide information on bathymetry, bottom type and water column optical properties [74-76].

VII. Conclusions

Earth Observation related imaging spectroscopy has significantly gained in importance over the past 30 years. Advances in sensor technology, electronics, and (pre-) processing have led to the development of a suite of new applications.

Imaging spectroscopy enables biophysical and biochemical variables of the Earth's surface and atmospheric composition to be mapped with unprecedented accuracy. In addition to this, our quantitative understanding of photon-matter interactions has been significantly enriched by the opportunity to look at simultaneous acquisition of many, contiguous spectral bands.

Practically, to achieve new success requires improved data quality and wider availability of consistent remote sensing observations to the user community. Secondly, broader availability of high-performance computing resources is needed to run quantitative, physically based models.

We have demonstrated in this paper the development of significant new fields of technology and applications and we identify potential near-term advancements. However, the imaging spectroscopy community has to increase its efforts to convince relevant stakeholders of the urgency to acquire for the Earth, continuous highest quality imaging spectrometer data for extended periods of time. The observed trends indicate that this need is becoming better understood and seen as essential for the sustainable development of our resources and the protection of our environment.

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