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-component; 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 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.

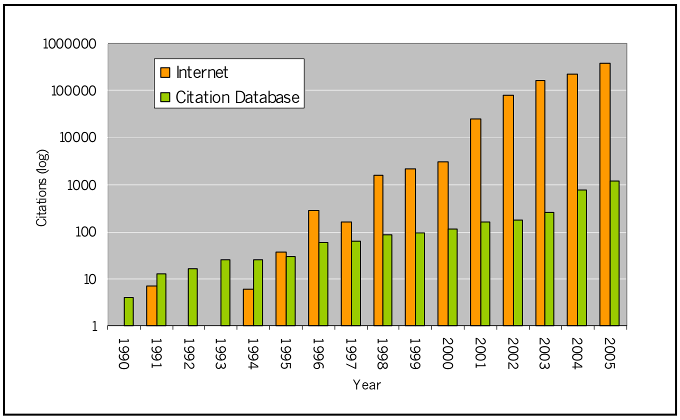

Figure 1. Internet based and citation database search for 'imaging spectroscopy' (1990-2005).

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. Further morphological approaches for joint exploitation of the spatial and spectral information available in the input data will be explored [50-52]. There is a trend towards establishing integrated systems solutions supporting data assimilation [53]. 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 [54]. 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 [55].

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 [56-58].

In both managed and unmanaged ecosystems the spectroscopy focus is on detection and identification of plant succession, phenology, plant functional types [59], and on monitoring invasive species [60, 61]. 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 [62], plant and canopy scales [63, 64]: 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 [65, 66]. 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 [67, 68]. In contrast to the soil, the characterization of snow optically equivalent grain size is currently only possible with the required accuracy using spectroscopy [69, 70].

Limnological, coastal, and open ocean applications will also profit from increased spectral resolution [71, 72], allowing for more accurate estimations of water quality.

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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References

[1] I. Newton, *Opticks: Or, a Treatise of the Reflexions, Refractions, Inflexions and Colours of Light*. London: Sam Smith and Benj. Walford, 1704.

[2] J. C. Maxwell, *A Treatise on Electricity and Magnetism*. Oxford: Clarendon Press, 1873.

[3] J. Fraunhofer, "Bestimmung des Brechungs- und Farbenzerstreuungs-Vermoegens verschiedener Glasarten, in Bezug auf die Vervollkommnung achromatischer Fernroehre," vol. 56: Gilberts Annalen der Physik, 1817, pp. 264-313.

[4] R. Bunsen and G. Kirchhoff, "Untersuchungen ueber das Sonnenspektrum und die Spektren der Chemischen Elemente," *Abh. kgl. Akad. Wiss.*, pp. 1861, 1863.

[5] M. Born and E. Wolf, *Principles of Optics*, 7 ed. Cambridge: Cambridge University Press, 1999.

[6] J. B. Hearnshaw, *The Analysis of Starlight. One hundred and fifty years of astronomical spectroscopy*: Cambridge Univ. Press, 1986.
[7] E. S. Arcybashev and S. V. Belov, "The Reflectance of Tree Species [orig. russ.]," in *Russian Data on Spectral Reflectance of Vegetation, Soil, and Rock Types*, D. Steiner and T. Guterman, Eds. Zurich: Juris Druck + Verlag, 1958, pp. 232.
[8] R. J. P. Lyon, "Evaluation of infrared spectroscopy for compositional analysis of lunar and planetary oils," Stanford. Res. Inst. Final Rep. Contract NASA, 49(04) 1962.
[9] A. F. H. Goetz, L. C. Rowan, and M. J. Kingston, "Mineral Identification From Orbit - Initial Results From The Shuttle Multispectral Infrared Radiometer," *Science*, vol. 218, pp. 1020-1024, 1982.
[10] W. Collins, S. H. Chang, and G. L. Raines, "Mineralogical Mapping of Sites Near Death Valley, California and Crossman Peak, Arizona, using Airborne Near–Infrared Spectral Measurements," presented at Proc. Intl. Symp. on Remote Sens. of Environ., 2nd Thematic Conference on Remote Sensing for Exploration Geology, Fort Worth, TX, 1982.
[11] G. Vane, "Introduction Airborne Imaging Spectrometer (AIS-1, AIS-2)," presented at Proc. Second Airborne Imaging Spectrometer Data Analysis Workshop, Pasadena, CA, 1986.
[12] G. Vane, A. F. H. Goetz, and J. B. Wellman, "Airborne Imaging Spectrometer - A New Tool For Remote-Sensing," *Ieee Transactions On Geoscience And Remote Sensing*, vol. 22, pp. 546-549, 1984.
[13] A. F. H. Goetz, G. Vane, J. E. Solomon, and B. N. Rock, "Imaging spectrometry for earth remote sensing," *Science*, vol. 228, pp. 1147, 1985.
[14] J. F. R. Gower, G. A. Borstad, and H. R. Edel, "Fluoresence Line Imager: First Results from PAssive Imaging of Chlorophyll Fluoresence," presented at International Geoscience and Remote Sensing Symposium (IGARSS), Michigan, 1987.
[15] F. A. Kruse, K. S. Kierein-Young, and J. W. Boardman, "Mineral mapping at Cuprite, Nevada with a 63-channel imaging spectrometer," *Photogrammetric Engineering & Remote Sensing*, vol. 56, pp. 83, 1990.
[16] N. Rowlands, R. A. Neville, and I. P. Powell, "Short-wave infrared (SWIR) imaging spectrometer for remote sensing," *Proceedings of SPIE - The International Society for Optical Engineering*, vol. 2269, pp. 237, 1994.
[17] R. O. Green, M. L. Eastwood, C. M. Sarture, T. G. Chrien, M. Aronsson, B. J. Chippendale, J. A. Faust, B. E. Pavri, C. J. Chovit, M. Solis, M. R. Olah, and O. Williams, "Imaging spectroscopy and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)," *Remote Sensing of Environment*, vol. 65, pp. 227, 1998.
[18] A. F. H. Goetz and M. Herring, "The High-Resolution Imaging Spectrometer (Hiris) For Eos," *Ieee Transactions On Geoscience And Remote Sensing*, vol. 27, pp. 136-144, 1989.
[19] R. N. Clark, T. M. Hoefen, J. M. Curchin, R. H. Brown, J. Lunine, R. Jaumann, K. D. Matz, D. P. Cruikshank, R. M. Nelson, B. J. Buratti, K. H. Baines, D. L. Matson, T. B. McCord, G. Bellucci, F. Capaccioni, P. Cerroni, A. Coradini, V. Formisano, V. Mennella, J. P. Bibring, Y. Langevin, P. D. Nicholson, B. Sicardy, C. Sotin, K. Hibbits, and G. Hansen, "Compositional maps of Saturn's moon Phoebe from imaging spectroscopy," *Nature*, vol. 435, pp. 66, 2005.
[20] L. Arnold, S. Gillet, O. Lardire, P. Riaud, and J. Schneider, "A test for the search for life on extrasolar planets. Looking for the terrestrial vegetation signature in the Earthshine spectrum," *Astronomy and Astrophysics*, vol. 392, pp. 231, 2002.
[21] I. M. Devonshire, J. Berwick, M. Jones, J. Martindale, D. Johnston, P. G. Overton, and J. E. W. Mayhew, "Haemodynamic responses to sensory stimulation are enhanced following acute cocaine administration," *NeuroImage*, vol. 22, pp. 1744, 2004.
[22] J. A. Fernández Pierna, V. Baeten, A. M. Renier, P. Dardenne, and R. P. Cogdill, "Combination of support vector machines (SVM) and near-infrared (NIR) imaging spectroscopy for the detection of meat and bone meal (MBM) in compound feeds," *Journal of Chemometrics*, vol. 18, pp. 341, 2004.
[23] O. Geßner, A. M. D. Lee, J. P. Shaffer, H. Reisler, S. V. Levchenko, A. I. Krylov, J. G. Underwood, H. Shi, A. L. L. East, D. M. Wardlaw, E. T. H. Chrysostom, C. C. Hayden, and A. Stolow, "Femtosecond multidimensional imaging of a molecular dissociation," *Science*, vol. 311, pp. 219, 2006.
[24] G. M. Miskelly and J. H. Wagner, "Using spectral information in forensic imaging," *Forensic Science International*, vol. 155, pp. 112, 2005.
[25] M. Menenti, M. Rast, H. Bach, F. Baret, B. van de Hurk, L. Jia, Z. L. Li, W. Knorr, M. Probeck, W. Mauser, J. Miller, J. Moreno, M. Schaepman, W. Verhoef, and M. Verstraete, "Understanding vegetation response to climate variability from space with hyper-spectral, multi-angular observations," presented at 9th International Symposium on Physical Measurements and Signatures in Remote Sensing (ISPMSRS), Beijing (Cn), 2005.
[26] M. Rast, F. Baret, B. van de Hurk, W. Knorr, W. Mauser, M. Menenti, J. Miller, J. Moreno, M. E. Schaepman, and M. Verstraete, *SPECTRA - Surface Processes and Ecosystem Changes Through Response Analysis*. Noordwijk: ESA Publications Division, 2004.
[27] S. G. Ungar, D. Reuter, J. S. Pearlman, and J. A. Mendenhall, "Overview of the Earth Observing One (EO-1) mission," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 41, pp. 1149, 2003.
[28] M. A. Cutter, L. S. Johns, D. R. Lobb, T. L. Williams, and J. J. Settle, "Flight Experience of the Compact High Resolution Imaging Spectrometer (CHRIS)," presented at Proceedings of SPIE - The International Society for Optical Engineering, 2004.
[29] J.-L. Bezy, G. Gourmelon, R. Bessudo, G. Baudin, H. Sontag, and S. Weiss, "ENVISAT Medium Resolution Imaging Spectrometer (MERIS)," presented at International Geoscience and Remote Sensing Symposium (IGARSS), 1999.
[30] V. V. Salomonson, W. L. Barnes, P. W. Maymon, H. E. Montgomery, and H. Ostrow, "MODIS: advanced facility instrument for studies of the earth as a system," *IEEE Transactions on Geoscience and Remote Sensing*, vol. v, pp. 145, 1989.
[31] R. Richter, A. Mueller, M. Habermeyer, S. Dech, K. Segl, and H. Kaufmann, "Spectral and radiometric requirements for the airborne thermal imaging spectrometer ARES," *International Journal of Remote Sensing*, vol. 26, pp. 3149, 2005.
[32] M. E. Schaepman, K. I. Itten, D. Schlaepfer, J. W. Kaiser, J. Brazile, W. Debruyn, A. Neukom, H. Feusi, P. Adolph, R. Moser, T. Schilliger, L. De Vos, G. Brandt, P. Kohler, M. Meng, J. Piesbergen, P. Strobl, J. Gavira, G. Ulbrich, and R. Meynart, "APEX: Current Status of the Airborne Dispersive Pushbroom Imaging Spectrometer," presented at Proceedings of SPIE - The International Society for Optical Engineering, 2004.
[33] P. Chorier, M. Vuillermet, and P. Tribolet, "Space activity at Sofradir and new results for hyperspectral detectors," presented at Proceedings of SPIE - The International Society for Optical Engineering, 2004.
[34] T. Chuh, "Recent developments in infrared and visible imaging for astronomy, defense and homeland security," presented at Proceedings of SPIE - The International Society for Optical Engineering, 2004.
[35] D. R. Lobb, "Theory of concentric designs for grating spectrometers," *Applied Optics*, vol. 33, pp. 2648, 1994.
[36] P. Mouroulis, "Low-distortion imaging spectrometer designs utilizing convex gratings," *Proc. SPIE*, vol. 3842, pp. 594, 1998.
[37] X. Xiong, N. Che, and W. Barnes, "Terra MODIS on-orbit spatial characterization and performance," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 43, pp. 355, 2005.
[38] R. O. Green, B. E. Pavri, and T. G. Chrien, "On-orbit radiometric and spectral calibration characteristics of EO-1 hyperion derived with an underflight of AVIRIS and In situ measurements at Salar de Arizaro, Argentina," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 41, pp. 1194, 2003.

[39] R. O. Green, "Spectral calibration requirement for Earth-looking imaging spectrometers in the solar-reflected spectrum," *Applied Optics*, vol. 37, pp. 683, 1998.

[40] M. Kneubuehler, M. E. Schaepman, K. J. Thome, and D. Schlaepfer, "MERIS / ENVISAT Vicarious Calibration Over Land," presented at Proceedings of SPIE - The International Society for Optical Engineering, 2004.

[41] N. Fox, J. Aiken, J. J. Barnett, X. Briottet, R. Carvell, C. Frohlich, S. B. Groom, O. Hagolle, J. D. Haigh, H. H. Kieffer, J. Lean, D. B. Pollock, T. Quinn, M. C. W. Sandford, M. Schaepman, K. P. Shine, W. K. Schmutz, P. M. Teillet, K. J. Thome, M. M. Verstraete, and e. Zalewski, "Traceable Radiometry Underpinning Terrestrial - and Helio- Studies (TRUTHS)," *Advances in Space Research*, vol. 32, pp. 2253, 2003.

[42] J. Mielikainen, "Lossless compression of hyperspectral images using lookup tables," *IEEE Signal Processing Letters*, vol. 13, pp. 157, 2006.

[43] B. Penna, T. Tillo, E. Magli, and G. Olmo, "Progressive 3-D coding of hyperspectral images based on JPEG 2000," *IEEE Geoscience and Remote Sensing Letters*, vol. 3, pp. 125, 2006.

[44] J. Brazile, M. E. Schaepman, D. Schlaepfer, J. W. Kaiser, J. Nieke, and K. I. Itten, "Cluster versus grid for large-volume hyperspectral image preprocessing," presented at Proceedings of SPIE Vol. 5548, Atmospheric and Environmental Remote Sensing Data Processing and Utilization: an End-to-End System Perspective, 2004.

[45] A. Plaza, D. Valencia, J. Plaza, and P. Martinez, "Commodity cluster-based parallel processing of hyperspectral imagery," *Journal of Parallel and Distributed Computing*, vol. 66, pp. 345, 2006.

[46] G. Schaepman-Strub, M. Schaepman, S. Dangel, J. Martonchik, and T. Painter, "Reflectance quantities in optical remote sensing – definitions and case studies," *Remote Sensing of Environment*, 2006 (in print).

[47] D. G. Goodenough, A. S. Bhogal, D. Charlebois, A. Dyk, and R. J. Aspinall, "An Intelligent System For Monitoring Forests," in *Spatial Information for Land Use Management*, R. J. Aspinall, Ed.: Gordon and Breach, 2000, pp. 129-141.

[48] G. Camps-Valls and L. Bruzzone, "Kernel-based methods for hyperspectral image classification," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 43, pp. 1351, 2005.

[49] T. Kasetkasem, M. K. Arora, and P. K. Varshney, "Super-resolution land cover mapping using a Markov random field based approach," *Remote Sensing of Environment*, vol. 96, pp. 302, 2005.

[50] A. Plaza, P. Martinez, J. Plaza, and R. Perez, "Dimensionality reduction and classification of hyperspectral image data using sequences of extended morphological transformations," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 43, pp. 466, 2005.

[51] F. Dell'Acqua, P. Gamba, A. Ferrari, J. A. Palmason, J. A. Benediktsson, and K. Arnason, "Exploiting spectral and spatial information in hyperspectral urban data with high resolution," *IEEE Geoscience and Remote Sensing Letters*, vol. 1, pp. 322, 2004.

[52] J. A. Benediktsson, J. A. Palmason, and J. R. Sveinsson, "Classification of hyperspectral data from urban areas based on extended morphological profiles," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 43, pp. 480, 2005.

[53] A. Olioso, Y. Inoue, S. Ortega-Farias, J. Demarty, J. P. Wigneron, I. Braud, F. Jacob, P. Lecharpentier, C. Ottle, J. C. Calvet, and N. Brisson, "Future directions for advanced evapotranspiration modeling: Assimilation of remote sensing data into crop simulation models and SVAT models," *Irrigation and Drainage Systems*, vol. 19, pp. 377, 2005.

[54] K. M. Andreadis and D. P. Lettenmaier, "Assimilating remotely sensed snow observations into a macroscale hydrology model," *Advances in Water Resources*, vol. 29, 2006.

[55] S. Chien, B. Cichy, A. Davies, D. Tran, G. Rabideau, R. Castaño, R. Sherwood, D. Mandl, S. Frye, S. Shulman, J. Jones, and S. Grosvenor, "An autonomous earth-observing sensorweb," *IEEE Intelligent Systems*, vol. 20, pp. 16, 2005.

[56] K. L. Castro-Esau, G. A. Sanchez-Azofeifa, B. Rivard, S. J. Wright, and M. Quesada, "Variability in leaf optical properties of mesoamerican trees and the potential for species classification," *American Journal of Botany*, vol. 93, pp. 517, 2006.

[57] D. G. Goodenough, A. Dyk, K. O. Niemann, J. S. Pearlman, H. Chen, T. Han, M. Murdoch, and C. West, "Processing Hyperion and ALI for forest classification," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 41, pp. 1321, 2003.

[58] D. G. Goodenough, H. Chen, A. Dyk, T. Han, S. McDonald, M. Murdoch, K. Olaf Niemann, J. Pearlman, and C. West, "EVEOSD Forest Information Products from AVIRIS and Hyperion," presented at International Geoscience and Remote Sensing Symposium (IGARSS), 2003.

[59] S. Schmidtlein and J. Sassin, "Mapping of continuous floristic gradients in grasslands using hyperspectral imagery," *Remote Sensing of Environment*, vol. 92, pp. 126, 2004.

[60] G. P. Asner and P. M. Vitousek, "Imaging spectroscopy studies of hawaiian ecosystems, carbon properties, and disturbance," presented at Proceedings of SPIE - The International Society for Optical Engineering, 2005.

[61] E. Underwood, S. Ustin, and D. DiPietro, "Mapping nonnative plants using hyperspectral imagery," *Remote Sensing of Environment*, vol. 86, pp. 150, 2003.

[62] L. Bousquet, S. Lacherade, S. Jacquemoud, and I. Moya, "Leaf BRDF measurements and model for specular and diffuse components differentiation," *Remote Sensing of Environment*, vol. 98, pp. 201, 2005.

[63] J. R. Miller, M. Berger, L. Alonso, Z. Cerovic, Y. Goulas, S. Jacquemoud, J. Louis, G. Mohammed, I. Moya, R. Pedros, J. F. Moreno, W. Verhoef, and P. J. Zarco-Tejada, "Progress on the Development of an Integrated Canopy Fluorescence Model," presented at International Geoscience and Remote Sensing Symposium (IGARSS), 2003.

[64] C. Bacour, S. Jacquemoud, Y. Tourbier, M. Dechambre, and J. P. Frangi, "Design and analysis of numerical experiments to compare four canopy reflectance models," *Remote Sensing of Environment*, vol. 79, pp. 72, 2002.

[65] G. Wen, A. Marshak, and R. F. Cahalan, "Impact of 3-D clouds on clear-sky reflectance and aerosol retrieval in a biomass burning region of Brazil," *IEEE Geoscience and Remote Sensing Letters*, vol. 3, pp. 169, 2006.

[66] A. Lyapustin and Y. Wang, "Parameterized code SHARM-3D for radiative transfer over inhomogeneous surfaces," *Applied Optics*, vol. 44, pp. 7602, 2005.

[67] E. R. Stoner and M. F. Baumgardner, "Characteristic variations in reflectance of surface soils," *Soil Science Society of America Journal*, vol. 45, pp. 1161, 1981.

[68] J. R. Irons, G. S. Campbell, J. M. Norman, D. W. Graham, and W. M. Kovalick, "Prediction and measurement of soil bidirectional reflectance," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 30, pp. 249, 1992.

[69] T. H. Painter and J. Dozier, "Measurements of the hemispherical-directional reflectance of snow at fine spectral and angular resolution," *Journal of Geophysical Research D: Atmospheres*, vol. 109, 2004.

[70] J. Dozier and T. H. Painter, "Multispectral and hyperspectral remote sensing of alpine snow properties," *Annual Review of Earth and Planetary Sciences*, vol. 32, pp. 465, 2004.

[71] J. R. Schott, "The Evolution of Spectral Remote Sensing from Color Images to Imaging Spectroscopy," presented at Society for Imaging Science and Technology: Image Processing, Image Quality, Image Capture, Systems Conference, 2003.

[72] T. Kutser, L. Metsamaa, N. Strombeck, and E. Vahtmae, "Monitoring cyanobacterial blooms by satellite remote sensing," *Estuarine, Coastal and Shelf Science*, vol. 67, pp. 303, 2006.