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Special issue on the Hyperspectral Infrared Imager (HyspIRI): Emerging science in terrestrial and aquatic ecology, radiation balance and hazards

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A B S T R A C T

The Hyperspectral Infrared Imager (HyspIRI) mission is proposed to be the first satellite system with the capability to provide global, repeat coverage across the visible and shortwave infrared spectrum, as well as eight channels in the midwave and thermal infrared. HyspIRI has stated objectives to address a host of pressing earth science questions, from radiation budgets to ecosystem functions. A sizable science community has grown to support the mission, and their ongoing research demonstrates HyspIRI's potential to greatly expand our knowledge of the earth system. This special issue features a collection of papers, some reviews and others novel science, that cover the wide array of topics relevant to HyspIRI's mission and reaffirm the necessity for HyspIRI.

1. Introduction

Satellite remote sensing has dramatically altered our perspective of the earth and vastly expanded our understanding of the earth's land, ocean, and atmosphere. Beginning in the 1970s with Landsat-1, the Coastal Zone Color Scanner (CZCS), and the Advanced Very High resolution Radiometer-1 (AVHRR), space-based observations of earth ecosystems and environments have proven enormously successful and useful, to the point where, for all practical purposes, satellite data have become a requirement for evaluating global change. The early proof-of-concept missions have evolved into today's Landsat-8, Moderate-Resolution Imaging Spectrometer (MODIS), and Visible Infrared Imaging Radiometer Suite (VIIRS), among others. Each routinely provides operational products that enable scientists and resource managers to study the earth system across local, regional, and global scales.

From the outset, and continuing through to today, virtually all spaceborne sensors have been multispectral systems, with a few to several wavebands selected for their specific observational capabilities. However, it has been well understood that much more information about water, land, and atmospheres is contained in a full spectrum than in a few wavebands, no matter how well chosen. Technological advances in the 1980s made possible the development of airborne imaging spectrometers, with the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) possibly being the most important (ISI Web of Science reports 1,826 peer-reviewed publications related to "AVIRIS" or "Airborne Visible/Infrared Imaging Spectrometer" between 1989 and mid-May 2015). These sensors rapidly realized their potential, and the 1990s saw a burgeoning of use, from case studies to regional-scale applications. However, it was not until the 2000s that hyperspectral systems were placed on space-based platforms (Hyperion, HICO). These were proof-of-concept missions, and they exceeded their objectives, but they lacked the capacity for long-term, global-scale mapping.

In the thermal infrared, multiple bands allow calculation of both kinetic temperature and emissivity spectra. There is a long history of remote sensing in this region of the spectrum, beginning with the six-band airborne Thermal-Infrared Multispectral Scanner (TIMS) in the early 1980s. In the present day, both MODIS and VIIRS have multiple midwave and thermal infrared bands providing twice-daily global coverage at coarse spatial resolutions (1 km), and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) delivers five thermal infrared bands at 90 m spatial resolution with a 16-day repeat cycle, but a narrow field of view that does not permit global coverage. There is no current thermal infrared sensor that combines multiple bands needed for temperature-emissivity separation, a sub-100 m spatial resolution, and a frequent

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repeat interval with global coverage, which are necessary to answer a wide range of Earth science studies related to surface composition, hydrology, and volcanology.

In response to the need for global measurements across the visible to thermal infrared, the concept for the Hyperspectral Infrared Imager (HyspIRI) was developed in the early 2000s and was recommended as a "Tier 2" mission in the National Research Council's 2007 review *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (the so-called "Decadal Survey"; National Research Council, 2007). HyspIRI was designed to address pressing questions about the world's terrestrial and aquatic ecosystems, as well as to investigate and provide crucial information on natural disasters such as volcanoes, wildfires, and drought. Other hyperspectral satellite missions (e.g., PRecursore IperSpettrale della Missione Applicativa, or PRISMA; Environmental Mapping and Analysis Program, or EnMAP) and thermal infrared satellite missions (e.g., Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station, or ECOSTRESS) are planned, but these will not have the global observational capability of HyspIRI. Moreover, HyspIRI is the only planned mission that combines hyperspectral measurements from a visible to shortwave infrared (VSWIR: 380–2500 nm) sensor with eight-channel multispectral measurements from a mid to thermal infrared sensor (TIR: 4–13 μm). The HyspIRI VSWIR sensor has a nominal ground sample distance of 30 m, while the HyspIRI TIR sensor has a nominal ground sample distance of 60 m. (HyspIRI VSWIR was originally proposed to have a 60 m ground sample distance, but the concept has evolved to a 30 m ground sample distance using a new spectrometer design. As a measure of how rapidly this evolution is occurring, a majority of the papers in this special issue only consider the 60 m case.) These spatial and spectral characteristics enable HyspIRI to successfully address the 17 mission concept science and applications questions developed by the HyspIRI Group (2009).

The eight years since the Decadal Survey have seen strong development and demonstrations of hyperspectral and thermal infrared remote sensing in general and the HyspIRI concept in particular. There have been significant advances in instrument design, as evidenced by the Carnegie Airborne Observatory (CAO), the National Ecological Observatory Network's Airborne Observational Platform (NEON AOP), Next Generation AVIRIS (AVIRISng), the Portable Remote Imaging Spectrometer (PRISM), and, in the thermal infrared, the Hyperspectral Thermal Emission Spectrometer (HyTES). HyspIRI's VSWIR instrument concept has been modified from its original Offner spectrometer to a Dyson design. There are recent, ongoing, and planned future airborne campaigns using AVIRIS and MASTER to simulate HyspIRI data and aimed at specific HyspIRI science objectives. Those campaigns have already yielded useful results, further demonstrating the potential for space-based VSWIR-TIR observations. The well-attended science symposia and applications workshops demonstrate clear support for HyspIRI among the scientific community.

This special issue follows from those science meetings, where presentations have covered a wide range of topics, from underlying algorithms and technologies to applied science. The included papers are by no means exhaustive with respect to the HyspIRI mission, but they offer a very good cross-section of relevant topics. Lee et al. (in this issue) provide a mission overview, describing the VSWIR and TIR sensors and giving a synopsis of the science underlying the mission objectives. This paper is the fundamental reference point for the broader HyspIRI mission concept. The papers that follow focus on individual aspects of HyspIRI science, from technical issues and algorithms to results for observations of terrestrial and aquatic ecosystem applications, and they merit some further mention.

2. Net radiation and high temperature phenomena

Surface net radiation is the difference between the downward and upward radiations across the shortwave (0.3–3.0 μm) and longwave spectrum (3.0–100.0 μm), and it is a key variable used to link the atmosphere and the land surface systems. Remote sensing using hyperspectral VSWIR and multispectral TIR measurements provides unique and abundant spectral information for quantification of the shortwave and longwave land surface radiation budget. In previous studies, only single broadband or multispectral data have been used to estimate the shortwave net radiation. He, Liang, Wang, Shi and Goulden (in this issue) have proposed two methods to estimate the instantaneous land surface net shortwave radiation with high spatial resolution using hyperspectral remote sensing observations from AVIRIS data. The first calculates the net radiation based on separate estimation of downward radiation and surface broadband albedo, which requires ancillary information for aerosol optical depth. The second method directly estimates the net radiation from the observed radiance.

In a similar study, Wang, Liang, He and Shi (in this issue) propose a new algorithm to estimate the clear-sky instantaneous all-wave net radiation over the land surface by combining VSWIR and TIR remote sensing data in a synergistic manner. The new method is based on extensive modeling of atmospheric radiative transfer over the entire solar spectrum. Validation with one-year measurements at seven Surface Radiation Budget Network (SURFRAD) sites demonstrate that the new method can accurately estimate clear-sky instantaneous all-wave net radiation with a root mean square error (RMSE) of 70.6 W m^{-2}, which is more accurate than the method of separating shortwave and longwave components.

Modeling temperatures of wildfires and volcanic lava flows necessitates measurements of emitted radiance at 4 μm wavelength. The 60 m spatial resolution of the HyspIRI TIR sensor will allow more detailed analysis of high temperature phenomena, but also makes saturation of the 4 μm channel more likely than for previous coarser resolution sensors. Realmuto et al. (in this issue) review temperature retrievals from a variety of satellite and airborne sensor data, and provide new analyses of data acquired over fires and lava flows. They recommend a 1200 K saturation brightness temperature for the 4 μm channel, which is unlikely to saturate for wildland fires and lava flows filling an instantaneous field of view. The tradeoff for a higher saturation threshold is a higher noise equivalent delta temperature at background temperatures, but other HyspIRI TIR sensor channels will provide lower saturation thresholds and higher sensitivity.

3. Temperature emissivity separation and atmospheric correction

An on-going challenge in thermal remote sensing is temperature emissivity separation (TES), where measured radiance can vary either due to emissivity differences or to a change in land surface temperature (LST). TES is further complicated by the need to remove atmospheric effects, and precipitable water vapor is widely recognized as the most significant error source. Grigsby et al. (in this issue) evaluate five approaches for TES, including the standard MASTER TES algorithm using VSWIR-derived and scene-estimated water vapor, a single band inversion using VSWIR water vapor, and a water vapor scaling method proposed by JPL. Retrieved LST is validated using field measured values from grape vines in San Joaquin Valley, California. The authors find significant improvements in TES in both cases using water vapor scaling, with the most accurate retrievals using per-pixel AVIRIS-derived water vapor.

One of the challenges associated with an imaging spectrometer global mapping mission is providing consistent, accurate atmospherically-corrected products. Atmospheric effects must be corrected for hundreds of VSWIR bands spanning a wide range of wavelengths, accounting for surface reflectance and elevation, solar and view geometries, and atmospheric characteristics. Thompson et al. (in this issue) demonstrate improvements in the ATREM (Atmospheric Removal) algorithm for use on HyspIRI Preparatory Campaign data collected over large areas of California. New developments include retrieval of pressure altitude and three-phase water absorption to improve calculation of apparent surface reflectance. Application of the algorithm to multiple dates of airborne data reveals changes in the retrieved absorption paths for all three phases of water over elevation and time.

4. Terrestrial biochemistry and biophysics

Estimation of biochemical and functional characteristics of vegetation is a unique capability of imaging spectrometer data. Serbin et al. (in this issue) use imaging spectrometer data to estimate two important measures of vegetation photosynthetic capacity: the maximum rate of RuBP (Ribulose-1,5-bisphosphate) carboxylation (V_{cmax}) and activation energy (E_V), which indicates the sensitivity of V_{cmax} to temperature. Using Partial Least Squares Regression (PLSR), they create models to estimate pixel-level V_{cmax} and E_V for agricultural crops in California. Their models show strong relationships ($R^2 \geq 0.90$) between V_{cmax} and E_V measured remotely and in the field. Their results suggest that scalable methods for mapping photosynthetic capacity will be achievable using HyspIRI VSWIR data. The addition of HyspIRI TIR data could permit measurement of changes in photosynthetic capacity with temperature.

A majority of studies using spectroscopy to estimate foliar nitrogen (N) have focused on natural vegetation, primarily forests. However, N is also a fundamental ecosystem property in human-dominated landscapes, such as turf, pasture, hay and fallow, where N concentrations may vary depending on management practices. Pellissier, Ollinger, Lepine, Palance and McDowell (in this issue) apply PLSR to field spectroscopy and imaging spectrometry data to evaluate the potential for estimating N concentrations in cultivated grasslands with variable management regimes. Strong correlations are observed between measured and estimated N concentrations at both field spectra and image data spatial scales, suggesting that HyspIRI can be used to estimate N in cultivated grasslands, potentially leading to more accurate estimates of N export from these systems, and ultimately improving their management.

Sagebrush communities cover a large region of semi-arid North America, representing one of the most threatened ecosystems in North America. Mitchell, Shrestha, Spaete and Glenn (in this issue) first evaluate the utility of a combination of Light Detection and Ranging (lidar) and imaging spectrometry (HyMap) to estimate sagebrush shrub cover and height, using the random forests algorithm to select optimal variables, and validating remote sensing products against field observations. Second, they spatially degrade HyMap data to the originally proposed 60 m HyspIRI resolution, demonstrating that HyspIRI can provide high quality ($R^2 = 0.63–0.71$) estimates of shrub cover and height, primarily through a combination of narrow-band indices, in this case the red to green ratio and anthocyanin reflectance index.

5. Terrestrial biodiversity and species

An established strength of imaging spectroscopy is its ability to map vegetation species. Differences in leaf-to-canopy scale biochemistry and structure can create distinguishable differences in reflectance spectra. Somers et al. (in this issue) examine changes in tropical forest reflectance spectra across a precipitation gradient in Panama. They link coefficient of variation calculated from reflectance spectra to species richness, and a spectral similarity index to species overlap. Spectral variability was highest at a more biodiverse moist forest site and lowest at a dry forest site. Differences in spectral variability were most pronounced in the visible and shortwave infrared spectral regions. Their analysis demonstrates the potential for HyspIRI VSWIR data to estimate biodiversity in tropical forest ecosystems.

Dudley, Dennison, Roth, Roberts and Coates (in this issue) explore a new technique for mapping dominant vegetation species across spatial and phenological gradients using imaging spectrometer data. They construct a multi-temporal spectral library, and then select endmembers from the library to minimize confusion between species. The resulting species-level classifications from a single set of endmembers applied to five image dates have similar accuracies to single-date classifications. Since this type of approach does not require a consistent phenology over time or space, multitemporal spectral libraries may prove useful for mapping species using HyspIRI VSWIR data.

Most previous species classification efforts have been limited to a small number of sites. Roth et al. (in this issue) compare multiple species classification approaches in five different North American ecosystems. Classification accuracies varied by site and vegetation functional type, with maximum accuracies for each site ranging between 61% and 92%. Linear discriminant analysis provides higher average accuracy compared to multiple endmember spectral mixture analysis (MESMA), and dimension reduction techniques show promise for maintaining or increasing classification accuracy. Since HyspIRI is a global mapping mission, the work described in Roth et al. (in this issue) is critical for determining which techniques are likely to be useful for mapping species across larger scales.

Roberts, Dennison, Roth, Dudley and Hulley (in this issue) take advantage of the full spectrum capabilities that HyspIRI will provide. They examine differences across multiple species using measurements from both an imaging spectrometer and a thermal infrared multispectral sensor, similar to the VSWIR/TIR combination of HyspIRI. They use MESMA to map dominant vegetation species, achieving a 75% polygon-level overall accuracy. Many species are found to cluster uniquely in the space defined by green vegetation fraction and land surface temperature, indicating potential differences in species environmental controls, water availability, and transpiration. Based on these results, the combination of HyspIRI VSWIR and TIR data should provide valuable information on functional differences between plant species.

Urban areas represent bio-diverse landscapes in which tree species diversity is often greater than neighboring natural ecosystems and where individual tree crowns cannot be resolved by moderate resolution sensors, such as the proposed HyspIRI mission. Gu, Singh and Townsend (in this issue) utilize non-metric multidimensional scaling (NMDS) to represent compositional gradients of dominant tree genera in Madison, Wisconsin. They relate plot-based NMDS factors (similar to principal components) to suites of trait-based vegetation indices (e.g., the photochemical reflectance index, PRI) derived from AVIRIS and structurally-based indices derived from lidar, finding strong correlations between AVIRIS-derived indices. They utilize these relationships to map gradients of tree genera across the urban forests of Madison, illustrating some of the potential of HyspIRI for mapping plant taxa and associated foliar traits in urban landscapes.

6. Inland waters and wetlands

Hestir et al. (in this issue) provide a comprehensive overview of the potential and need for a global hyperspectral imaging mission for mapping freshwater ecosystems. They specifically focus on spatial, spectral, temporal and radiometric requirements for retrieving freshwater biophysical, biochemical and plant functional information. They illustrate some of the potential through three case studies focused on Mantua Lake, in northern Italy. In the first case study, they demonstrate the spectral requirements for mapping cyanobacteria. In the second, they focus on temporal requirements needed to capture seasonal variation in wetland vegetation using the Operational Land Imager (OLI), and in the third, they evaluate the spatial requirements needed to estimate chlorophyll concentrations in the lake. All three studies illustrate that the proposed HyspIRI sensor meets the spectral, temporal and spatial requirements to quantify dynamics in this lake system, none of which are fully met by any single existing sensor.

Cyanobacterial blooms represent a significant threat to water quality in inland waters. Imaging spectrometry, through detailed sampling of the visible and near-infrared, offers the potential to discriminate harmful from non-harmful cyanobacteria genera. Kudela et al. (in this issue) use field spectroscopy and data from the Hyperspectral Imager for the Coastal Ocean (HICO) and MASTER to discriminate harmful *Microcystis* cyanobacteria from non-harmful *Aphanizomenon* at several water

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bodies in California using spectral shape-based algorithms. They conclude that seasonal changes in the abundance of these two cyanobacteria can be determined and harmful levels identified at the spatial and spectral resolutions of HyspIRI without optimized atmospheric correction. Finer temporal sampling could be achieved in combination with other sensors.

Tidal wetlands provide vital habitat to diverse plants and wildlife, and they play an important role in biogeochemical cycles. These ecosystems are under threat from both local human activities and global change, and there is a pressing need for widescale monitoring that can only be accomplished through satellite remote sensing. These ecosystems are both terrestrial and aquatic at the same time, which presents certain challenges to their study from space, e.g., glint contamination. Turpie, Klemas, Byrd, Kelly and Jo (in this issue) review the scientific and management issues surrounding wetlands and discuss the capabilities and limitations of HyspIRI to measure key wetland ecological properties. HyspIRI's combined high-resolution TIR and VSWIR sensors should enable a plethora of applications, from hydrology and evapotranspiration to biomass and species composition. The ability to generate global, multitemporal data sets raises the potential for observing and evaluating ongoing wetland change.

7. Coastal waters

Giant kelp is the foundation species for another coastal ecosystem that is important worldwide. Kelp forests exhibit tremendous seasonal and interannual variation, and remote sensing has been key to monitoring their biomass. Bell, Cavanaugh and Siegel (in this issue) demonstrate the potential for HyspIRI to not only measure biomass, but also photo-physiological condition in the form of a spectral index that empirically relates to the kelp's chlorophyll:carbon ratio. HyspIRI's temporal coverage of kelp areas is expected to be on the order of 1–5 cloud-free acquisitions per season, giving HyspIRI great potential to generate new understanding of kelp system physiological and ecological dynamics.

Sargassum spp. are brown macroalgae that serve a critical ecosystem function in pelagic regions such as the Gulf of Mexico and the Atlantic. Hu, Feng, Hardy and Hochberg (in this issue) evaluate the spatial and spectral requirements needed to discriminate *Sargassum* from spectrally similar materials including other marine algae, marine garbage and oil emulsions. They evaluate this potential using observations from a diversity of multispectral and hyperspectral systems imaging *Sargassum*, including data acquired by MODIS, Landsat, and WorldView-2 broad band systems, as well as hyperspectral data acquired by HICO and AVIRIS. To evaluate minimum cover limits for detection and identification, they employ a mixing model, finding that *Sargassum* identification requires a minimum of 20–30% cover, but only 1–2% cover to detect the presence of the marine algae. HyspIRI, with improved spectral, spatial and radiometric properties (signal-to-noise ratio), provides a good compromise between spatial coverage, and spatial resolution with the wavelengths needed for discrimination.

Dierssen, Chlus, and Russell (in this issue) also explore the issue of floating vegetation, but focus on nearshore areas where seagrass wrack contributes a large part of the floating material. Based on spectral measurements of *Sargassum* and the seagrass *Syringodium filiforme*, both in laboratory mesocosms and from the air using the Portable Remote Imaging Spectrometer, the authors find that a simple "Sargassum Index" of reflectance at 650 and 630 nm can discriminate between the two vegetation types. Age of the wrack could be estimated based on its water absorption feature at 930–990 nm. The authors conclude that hyperspectral imagery is necessary to simultaneously discriminate among floating vegetation and to assess its age. Because wrack typically organized in windrows with 5–35 m spacing, HyspIRI offers good spectral and spatial capability to study nearshore floating vegetation.

8. Oceans

Moving toward the realm of more traditional ocean color, hyperspectral data enable discrimination between phytoplankton functional types and may provide better estimates of phytopigment concentrations. However, the ocean is a much darker target than the land, which increases the necessity for good signal-to-noise and robust atmospheric correction. Lorenzoni et al. (in this issue) explore the relationship between in-water spectral absorption, phytoplankton community structure, and phytoplankton photophysiology (pigments and carbon) for a complex coastal system in the Cariaco Basin, off Venezuela. The authors find seasonality in all aspects of their data. Pigment concentrations and the amount of particulate organic carbon are correlated with phytoplankton community structure. Absorption spectra cluster in the same pattern as the phytoplankton communities, but the pigments themselves cannot be identified from absorption spectra using higher-order derivative analysis.

Palacios et al. (in this issue) also investigate the link between spectral data and phytoplankton functional type in the coastal zone, in this case Monterey Bay, California, utilizing ship-based and AVIRIS observations as part of the HyspIRI Preparatory Flight Campaign. The standard ocean color algorithm OC-3 provides accurate estimates of in-water chlorophyll *a* for ship-based spectral measurements but is less accurate when applied to the airborne data. Estimates of phytoplankton community structure are not robust with either AVIRIS or ship-based data, suggesting that the limiting factor was the algorithm (Phytoplankton Detection with Optics, or PHYDOTax). Closer examination of the AVIRIS data highlights the ocean color requirements of (1) rigorous sensor calibration, especially at blue wavelengths, (2) high sensor signal-to-noise, and (3) accurate atmospheric correction.

9. Summary

As demonstrated by the preceding summaries, this special issue cuts across most of HyspIRI's science objectives. The papers are also a snapshot of the current state of research being conducted by the hyperspectral and thermal infrared remote sensing communities. We think the information gathered in this volume represents a stepping stone from which the HyspIRI community can move forward technically and scientifically. We are very pleased to have had the opportunity to oversee this process, and we hope the discovery and development process continues to a successful HyspIRI mission.

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