

An introduction to the NASA Hyperspectral InfraRed Imager (HyspIRI) mission and preparatory activities



Christine M. Lee^{a,*}, Morgan L. Cable^a, Simon J. Hook^a, Robert O. Green^a, Susan L. Ustin^b, Daniel J. Mandl^c, Elizabeth M. Middleton^c

^a NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, United States

^b University of California Davis, Davis, CA, United States

^c NASA Goddard Space Flight Center, Greenbelt, MD, United States

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ABSTRACT

In 2007, the NASA Hyperspectral InfraRed Imager (HyspIRI) mission was recommended in *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (Decadal Survey) to address critical science questions in multiple areas, in particular ecosystems and natural hazards. HyspIRI is comprised of two instruments, a visible to short-wavelength infrared (VSWIR) imaging spectrometer and a thermal infrared (TIR) multispectral imager, together with an Intelligent Payload Module (IPM) for onboard processing and rapid downlink of selected data. The VSWIR instrument will have 10 nm contiguous bands and cover the 380–2500 nm spectral range with 30 m spatial resolution and a revisit of 16 days. The TIR instrument will have 8 discrete bands in the 4–13 μm range with 60 m spatial resolution and a revisit of 5 days. With these two instruments in low Earth orbit, HyspIRI will be able to address key science and applications questions in a wide array of fields, ranging from ecosystem function and diversity to human health and urbanization.

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1. Introduction

In 2007, the National Research Council released *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (often referred to as the “Decadal Survey”), which reviewed and summarized the current state of Earth systems science in the context of societal challenges (NRC, 2007). The Decadal Survey recommended that NASA undertake several Earth science missions, including the Hyperspectral InfraRed Imager (HyspIRI) mission that would address specific science questions and societal needs. HyspIRI would be comprised of two instruments: a Visible/near infrared/Shortwave InfraRed (VSWIR) imaging spectrometer and a thermal infrared (TIR) multispectral imager, together with an Intelligent Payload Module (IPM) for onboard processing and rapid downlink of selected data. By operating in low Earth orbit (LEO), HyspIRI could provide global coverage every 5–16 days at high spatial resolutions (30–60 m) (Fig. 1). In response to this report, NASA Headquarters appointed Drs. Robert Green and Simon Hook from the Jet Propulsion Laboratory (JPL) to lead the development of the VSWIR and TIR instruments, respectively, and Dr. Betsy Middleton and Mr. Daniel Mandl from Goddard Space Flight Center (GSFC) to lead the development

of the IPM. NASA also appointed a Science Study Group (SSG) to advise on the scientific development of the mission and ensure that the questions outlined in the Decadal Survey would be addressed. Together with JPL and GSFC, the SSG developed a set of science and applications questions that would address needs outlined in the Decadal Survey and by the science community (Table 1, (Abrams & Hook, 2013)).

2. Mission architecture

2.1. VSWIR

The VSWIR instrument configuration was initially based upon the Offner spectrometer design, which has heritage with the Moon Mineralogy Mapper (M3) (Green et al., 2011). This instrument configuration required a 60 m ground sample distance and a revisit of 19 days. However, recent evaluations in collaboration with the Sustainable Land Imaging (SLI) program (NRC, 2013) indicated that the Dyson spectrometer design (Fig. 2, (Mouroulis, Green, & Chrien, 2000)) with newly available detector arrays could significantly improve the spatial and temporal resolution of the VSWIR instrument that will ultimately become part of HyspIRI's architecture. The Dyson configuration would have an improved spatial resolution of 30 m and a revisit of 16 days when the maximum sun elevation angle is $\geq 20^\circ$ (Fig. 1).

* Corresponding author at: 4800 Oak Grove Dr Pasadena, CA 91109.
E-mail address: christine.m.lee@jpl.nasa.gov (C.M. Lee).

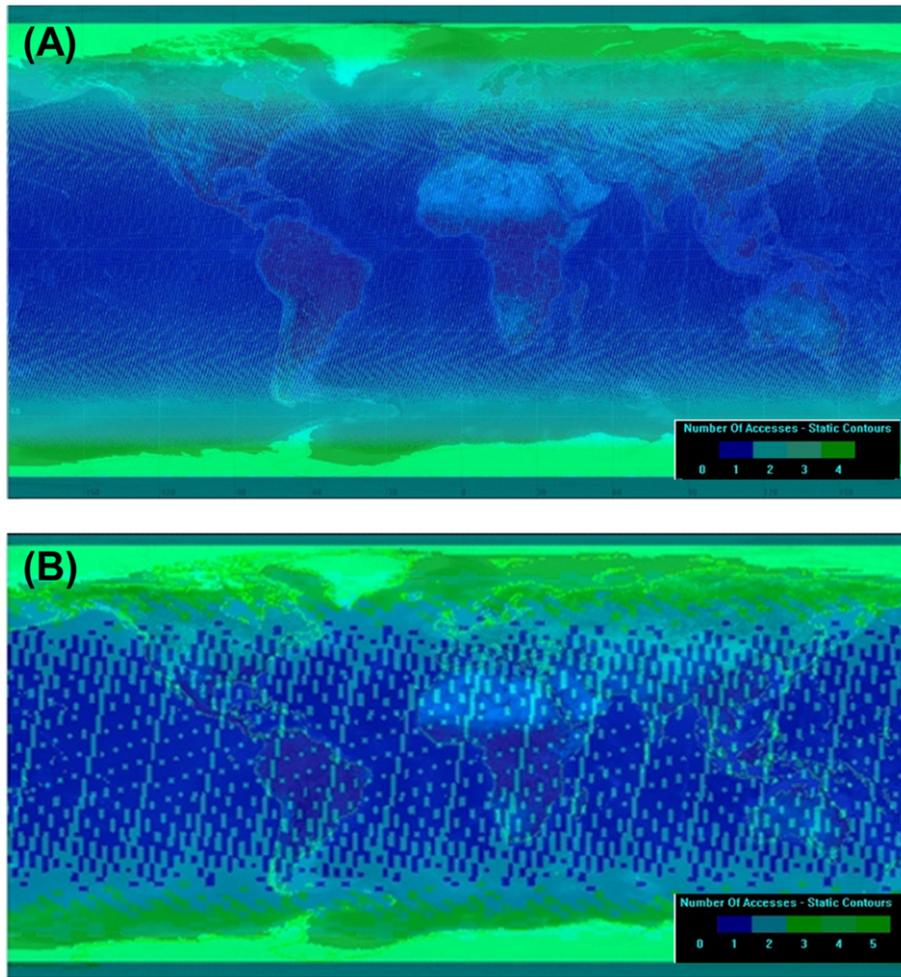


Fig. 1. HypsIRI planned global coverage. (A) 16-day VSWIR coverage. VSWIR would measure the terrestrial surface and the coastal areas every 16 days at 30 m spatial sampling. The oceans and ice sheet measurements would be returned at 1 km equivalent spatial sampling. (B) 5-day TIR coverage. The TIR would measure the terrestrial surface and the coastal areas every 5 days (day and night) at 60 m spatial sampling. The oceans and ice sheet measurements would be returned at 1 km spatial sampling.

VSWIR would cover 380 to 2510 nm in ≤ 10 -nm contiguous bands and include $>95\%$ spectral cross-track and $>95\%$ spectral instantaneous field of view (IFOV) uniformity. The absolute radiometric accuracy requirement is $>95\%$, and this would be maintained using monthly lunar views and periodic surface calibration experiments, with basic algorithm analyses orchestrated by the IPM. The signal-to-noise ratio (SNR) would be 700:1 at 600 nm and 500:1 at 2200 nm. The instrument design also minimizes polarization sensitivity and scattered light to allow for improved coastal ocean observations. To reduce the effect of sun glint from water surfaces, the instrument would be pointed 4° in the backscatter direction. The nominal data collection scenario involves observing the land and coastal zones to a depth of ≤ 50 m at full spatial and spectral resolution and transmitting these data to ground stations. Over the open ocean, data would be averaged to a spatial resolution of ~ 1 km.

2.2. TIR

The HypsIRI TIR instrument would continue the multi-decade legacy of measurements from prior sensors such as the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER, <https://asterweb.jpl.nasa.gov/>) and the Moderate Resolution Imaging Spectroradiometer (MODIS, <http://modis.gsfc.nasa.gov/>) (Abrams & Hook, 2013). The HypsIRI TIR instrument would have eight spectral bands, one in the mid-infrared (MIR) region at $4 \mu\text{m}$ and seven in the longwave infrared (LWIR) region between 7 and $13 \mu\text{m}$. Several TIR bands (Fig. 3) closely

match those of ASTER and MODIS (Table 2). The $4\text{-}\mu\text{m}$ band design has a high saturation limit (1200 K), whereas the longer wavelength bands would saturate at 400–500 K; this configuration enables identification of hotspots from fires, volcanoes and other thermal phenomena (Realmuto et al., 2015). The radiometric accuracy and precision of the instrument would be 0.5 K and 0.2 K respectively and all bands would be quantized to 14 bits. Calibration would utilize an on-board blackbody and a view to space that would occur with every rotation of the scan mirror. The HypsIRI TIR instrument would have 60 m spatial resolution and a revisit of 5 days at the equator.

2.3. Intelligent Payload Module

The Intelligent Payload Module (IPM) is an onboard processing system concept devised as a requirement in the formulation process of the HypsIRI mission to serve users working in time-critical or time-sensitive conditions, such as disaster response teams, drought monitoring, and ground-based field experiments and calibration/validation activities. The IPM concept for HypsIRI leverages the onboard processing architecture developed for the Earth Observing 1 (EO-1) technology demonstration satellite launched in 2000, which has two Mongoose processors, one for Command and Data Handling (C&DH) and the other for Science Data processing. By segregating the instrument data processing from C&DH, more flexibility is possible, with no risk to the health and safety of the satellite. The IPM would build upon this flexible configuration and also take advantage of the most current onboard processing

Table 1
Urgent and unique science and applications addressed by the HypSIIRI mission.

Field	Science questions	Applications
Terrestrial Systems	<ul style="list-style-type: none"> • Ecology – patterns and spatial distribution • Ecology – function, physiology, seasonal activity, phenology • Wildfires (changes to landscape/carbon budget) • Surface composition and change • Biodiversity/species distribution • Surface energy balances (e.g., assessing evapotranspiration) 	<ul style="list-style-type: none"> • Agricultural applications (e.g., drought mitigation, water use efficiency, water supply) • Impacts of and response to natural/anthropogenic disturbances • Management of wildfires (e.g., megafires) • Impacts of landscape and landscape changes to human health • Conservation practices
Aquatic Systems	<ul style="list-style-type: none"> • Understanding optically complex waters (e.g., turbid, coastal, estuarine) • Shallow water bottom composition • Inland aquatic environments • Marine ecology, coral reefs composition/extent • Wetlands extent • Submerged aquatic vegetation and species identification/distribution • Geomorphology (shoreline changes) • Groundwater discharge • Flooding • Ocean color/ocean biology 	<ul style="list-style-type: none"> • Water availability and quality (for human consumption or human use) such as tools for predicting onset and extent of (harmful) algal blooms • Tracking oil spills and other pollutants • Disasters assessment (e.g., for floods preparation or interventions) • Restoration and mitigation practices • Conservation practices • Impacts of and response to natural/anthropogenic disturbances
Biogeochemical	Carbon, water, nitrogen, oxygen, feedback into climate, carbon storage, and effects on ecosystem function/species populations	<ul style="list-style-type: none"> • Impacts on mitigation practices • Impacts on resource extraction, urbanization • Impacts on water quality (available water)
Atmosphere Geology	Atmospheric correction <ul style="list-style-type: none"> • Surface minerals composition • Geologic hazards such as earthquakes and as caused by volcanoes (prediction and plume detection) 	Applicable to all areas <ul style="list-style-type: none"> • Resource mapping and extraction • Earthquake damage extent or early warning? • Impacts on air quality and human health

technology, including space-qualified low power multicore processors and Field Programmable Gate Array (FPGA) co-processors. These processors would enable increased performance capability and larger data volume throughput, and address latency needs (Cappelaere et al., 2013; Mandl et al., 2013). For example, instrument data rates of up to 1 gigabits per second would be ingested by the IPM and passed through a data processing chain (Fig. 4) for Level 1 processing, Level 1 radiometric correction, atmospheric correction, geometric correction, and a data classification step via the Web Coverage Processing Service (WCPS).

Since the two HypSIIRI instruments would produce large data sets at rapid rates (Table 3), the IPM would enable essential data transfers at critical times. Although direct broadcast technologies have increased

rapid data delivery to local ground stations, the expected direct downlink rate is limited to about 10 megabits per second (Chien et al., 2013). The IPM would use this direct downlink for reduced volume for data products pre-determined by users that can be downlinked to those users on the ground in near real-time. The IPM can decide which data to downlink and when, using ground and flight automation software. Users would be able to specify and prioritize geographical regions of interest, which can be combined with predicted ground tracks to develop a schedule for onboard product generation and downlink (Chien, Silverman, & Davies, 2009). On-board automated analyses would be used to search for specific events or feature signatures of interest, such as a volcanic eruption or algal bloom. Data products from such events can be merged on a priority basis depending on CPU resources, band processing limitations, and downlink bandwidth. The Earth Observing One (EO-1) spacecraft has been utilized as a testbed for planning onboard product generation, and has established the utility of such techniques for the HypSIIRI Mission (Chien et al., 2013; Middleton et al., 2013).

3. HypSIIRI community outreach

The HypSIIRI mission concept team has actively engaged the science and application communities to prepare for the potential global mission that would routinely provide high quality VSWIR spectrometer and multi-band thermal data sets to address a wide variety of science and application needs. The most important mechanism to support this community involvement has been through annual HypSIIRI Science Symposia and HypSIIRI Science and Applications Workshops, initiated in 2009 and 2008, respectively. Both of these annual 2–4 day meetings address programmatic status, technology innovations, science questions, application demonstrations, and community outreach. Both meetings draw 100 or more academic, government, and industry participants, including members of the SSG and international partners who serve on the International Science Study Group. In 2014, these meetings were used to initiate and carry on discussions on HypSIIRI's role within SLI Program and also to engage the community for input and feedback to the Decadal Survey process.

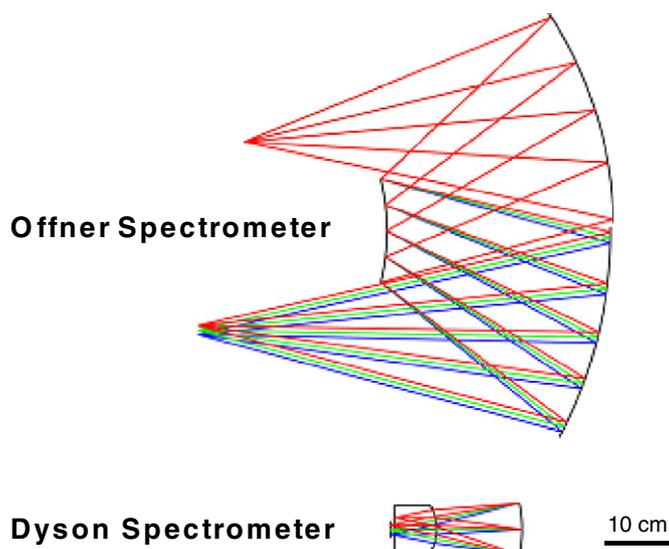


Fig. 2. Comparison of the Offner and Dyson imaging spectrometer designs for comparable performance adapted from (Mouroulis et al., 2000). The Dyson design is much more compact.

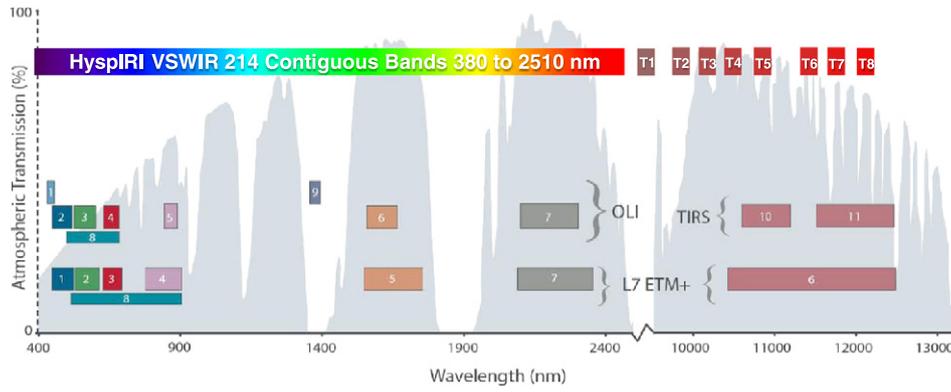


Fig. 3. Wavelength ranges and band locations of HypsIRI in comparison to Landsat 7 and 8. HypsIRI will include two instruments: visible to short-wavelength infrared (VSWIR) and thermal infrared (TIR).

4. Science questions and applications

The HypsIRI mission has the capability to address an unprecedented diversity of science and applications questions using the VSWIR and TIR instruments independently or together. These themes are summarized in Tables 1 and 4 and described in additional detail below.

4.1. Terrestrial ecosystems

4.1.1. Canopy biochemistry

Canopy biochemistry governs the fundamental processes of light absorption and photosynthesis and is a key component of biogeochemical cycles including carbon, water, and nutrients. Imaging spectroscopy has demonstrated the unique ability to measure leaf photosynthetic pigments, including chlorophyll a and b, carotenoids including xanthophyll pigments, and anthocyanins (Kokaly, Asner, Ollinger, Martin, & Wessman, 2009; Ustin et al., 2009). Water absorption is expressed in the near and shortwave infrared and can be used to retrieve leaf and canopy water content (Hunt, Ustin, & Riano, 2013; Ustin et al., 2009). Many studies have focused on measuring foliar nitrogen because of its importance in plant nutrition and nutrient cycling (Martin & Aber, 1997; Martin, Plourde, Ollinger, Smith, & McNeil, 2008; Ollinger et al., 2002; Ollinger et al., 2008; Townsend, Foster, Chastain, & Currie, 2003). More recently, Asner and colleagues using chemometric methods have shown that a much broader range of chemistry can be detected from leaf and canopy spectra than previously considered, such as phenolic compounds (Skidmore et al., 2010), leaf mass area and phosphorous content (Asner & Martin, 2011; Asner et al., 2011; Asner, Martin, Anderson, & Knapp, 2015). Thermal infrared imagery also may contribute to measures of cellulose, hemi-cellulose, cutin and other biochemicals in the 8–14 μm range (Da Luz & Crowley, 2007).

Table 2
Characteristics of the HypsIRI TIR instrument spectral bands.

Band	Wavelength (μm)	Spectral bandwidth (μm)	Nominal radiance and temperature (W/m ² /μm/sr)		Overlap with other TIR missions
			Min	Max	
1	3.98	0.08	14 (400 K)	9600 (1200 K)	MODIS Band 22
2	7.35	0.32	0.34 (200 K)	110 (500 K)	MODIS Band 28
3	8.28	0.34	0.45 (200 K)	100 (500 K)	ASTER Band 10
4	8.63	0.35	0.57 (200 K)	94 (560 K)	ASTER Band 11, MODIS Band 29
5	9.07	0.36	0.68 (200 K)	86 (500 K)	ASTER Band 12
6	10.53	0.54	0.89 (200 K)	71 (500 K)	ASTER Band 13
7	11.33	0.54	1.1 (200 K)	58 (500 K)	ASTER Band 14, MODIS Band 31
8	12.05	0.52	1.2 (200 K)	48 (500 K)	MODIS Band 32

4.1.2. Pattern and spatial distribution

Identifying plant functional types (Ustin & Gamon, 2010), assessing species diversity (Féret & Asner, 2014), and discriminating terrestrial plant species and communities (Baldeck et al., 2014; Roberts, Dennison, Roth, Dudley, & Hulley, 2015) could be advanced using HypsIRI VSWIR global 30-m pixel coverage. Previous work has demonstrated the unique capacity of imaging spectroscopy data for mapping detailed patterns of invasive species in habitats (Andrew & Ustin, 2010; Hestir et al., 2008; Khanna, Santos, Hestir, & Ustin, 2011; Underwood et al., 2006; Hestir et al., 2012). Monitoring invasive species is critical to understanding sustainability of ecosystem services and functionality (Santos et al., 2011). In a study of invasive trees, Asner et al. (2008) utilized hyperspectral imaging to map five invasive species in a lowland Hawaiian forest that significantly transformed the three dimensional forest structure and permanently changed its functionality despite all species belonging to the same broadleaf forest functional type. The HypsIRI mission has the potential to reveal many more examples of changing species distributions and ecosystem functionality.

4.1.3. Function, physiology, seasonal activity and diversity

While broad phenological patterns such as leaf emergence are well understood (Noormets, 2009; Zhang et al., 2003), more subtle patterns of vegetation activity associated with underlying physiological condition/changes are not as well-characterized (Forrest & Miller-Rushing, 2010). The unique spectroscopic capabilities and the 16-day repeat cycle of the HypsIRI VSWIR could enhance further studies of leaf phenological processes, such as using Photochemical Reflectance Index (PRI) (Garbulsky, Peñuelas, Gamon, Inoue, & Filella, 2011) to assess seasonal relationships between photosynthetic and light use efficiency to study carbon sequestration.

By measuring the biophysical and biochemical properties of vegetation, HypsIRI could also improve measures of plant physiological function through simultaneous estimates of surface temperature and plant biochemistry (Ustin, 2012) that link surface properties (e.g., albedo, leaf area index, leaf senescence and mortality, biochemistry of pigments, water and dry leaf matter) and energy balance parameters (Cammalleri et al., 2012). This information would support improved agricultural practices (Droogers & Bastiaanssen, 2002; Ishimwe, Abutaleb, & Ahmed, 2014; Thenkabail, Lyon, & Huete, 2011; Tits, Somers, Stuckens, Farifteh, & Coppin, 2013) such as selection of crops (Thenkabail et al., 2013), water use practices (Cheng, Riaño, & Ustin, 2014), and mitigation strategies in response to drought (Zarco-Tejada, González-Dugo, & Berni, 2012). Emerging research demonstrates the ability of imaging spectroscopy to map photosynthetic capacity (Serbin et al., 2015).

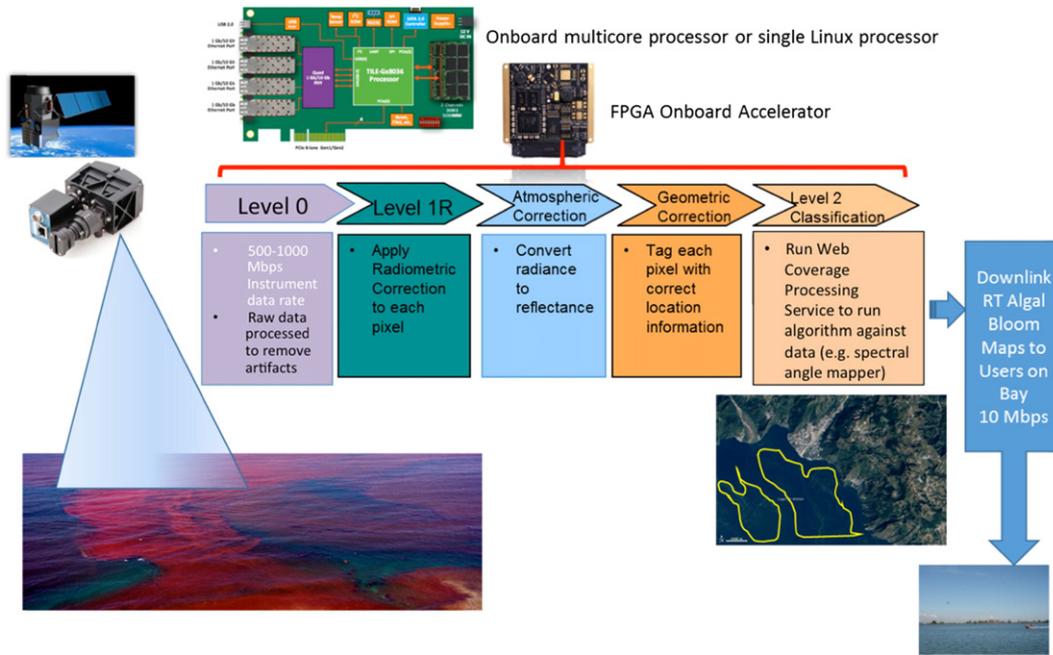


Fig. 4. The IPM data processing chain is diagrammed for a target operations scenario in which an orbital hyperspectral imager performs onboard processing in real time or near real time. This example used in this figure reflects the data processing flow for detecting algal blooms and relaying the resulting data products to rapid latency users in the field.

4.1.4. Biodiversity estimates and discrimination of plant species and communities

Many studies using imaging spectroscopy have shown excellent success for species mapping over a wide range of ecosystems such as mixed hardwood forests (Townsend et al., 2003), diverse tropical rain forests (Clark, Roberts, & Clark, 2005), montane rainforests (Somers & Asner, 2012), mixed dry sclerophyll communities (Youngentob et al., 2011), savannas (Baldeck et al., 2014), shrublands (Dennison & Roberts, 2003; Dudley, Dennison, Roth, Roberts, & Coates, 2015; Roberts et al., 2015), and semi-arid shrub-grasslands (Noujdina & Ustin, 2008). In addition, Da Luz and Crowley (2007) showed that broadleaf plant species have distinct reflectances in the thermal infrared (between 7 and 14 μm) that could improve mapping of species distributions. Imaging spectroscopy has also enabled the study of linkages between canopy biochemical diversity, species diversity, and spectral diversity across a wide range of species in tropical forests (Asner & Martin, 2011; Asner et al., 2008; Carlson, Asner, Flint Hughes, Ostertag, & Martin, 2007; Féret & Asner, 2014; Somers et al., 2015).

4.1.5. Plant functional types and plant trait strategies

The current paradigm for understanding ecosystem functionality (photosynthesis, transpiration, respiration) is to define classes based on

plant functional types (PFTs), which can be studied using remote sensing (Asner et al., 2015; Homolová, Malenovský, Clevers, García-Santos, & Schaepman, 2013; Homolová et al., 2014; Santos, Hestir, Khanna, & Ustin, 2012). Many PFT traits (which are assumed to indicate similar functionalities) are uniquely detectable with spectroscopy – especially the growth form (grass, herb, shrub, and tree), leaf longevity (deciduous vs. evergreen) and phylogeny (angiosperms vs. gymnosperms). These attributes, however, are only partially correlated with ecosystem functionality. Over the last 15 years, ecologists have amassed extensive databases of plant traits (Kattge et al., 2011; Wright et al., 2004), in part enabled by use of imaging spectroscopy, to better assess the linkages between PFT attributes and plant function.

The apparent convergence of leaf characteristics found by Wright et al. (2004) were expanded to nearly 70,000 species in Kattge et al. (2011); this expansion supports the idea that leaf optical properties can be used to infer plant function (Ustin & Gamon, 2010). Formulations that represent trait variation as a continuous variable, rather than distinct categories, bear promise for applications with imaging spectroscopy (Homolová et al., 2013). This finding reinforces the utility of developing vegetation databases that relate spectral properties to leaf and canopy traits such as Spectral Input/Output (SPECCHIO) (Hueni, Nieve, Schopfer, Kneubühler, & Itten, 2009), and the Ecosystem Spectral Information System (EcoSIS) (<http://ecospectra.org/>).

Table 3

Comparison of the full HypsIRI VSWIR and TIR instrument mission parameters to the current and proposed ISS demonstrations (VSWIR-Dyson and ECOSTRESS).

Parameter	Full HypsIRI VSWIR	Proposed VSWIR-Dyson demonstration	Full HypsIRI-TIR	ECOSTRESS
Orbital altitude	626 km (LEO)	400 km	626 km (LEO)	400 km
Ground spatial resolution	30 m	30 m	60 m	38x69 m
Land surface coverage	Full Earth (<16-day revisit)	$\pm 52^\circ$ latitude with range of revisit periods	Full Earth (<5-day revisit)	$\pm 52^\circ$ latitude with range of revisit periods
Time-of-day coverage	10:30 AM and 10:30 PM	All times of day	10:30 AM and 10:30 PM	All times of day
Spectral bands	Contiguous (10 nm), 380–2500 nm	Contiguous (10 nm), 380–2500 nm	8	5
Average data downlink	300 Mbit/s	9.1 Mbit/s	24 Mbit/s	3 Mbit/s
Swath width	185 km	30 km	51° 596 km	51° 384 km
Mission duration (goal)	3 yrs (5 yrs)	0.5 yr (2 yrs)	3 yrs (5 yrs)	0.5 yr (1 yr)
In-flight calibration	Onboard calibrator, monthly lunar views and periodic surface cal.	Radiometric cal. from vicarious, automated targets and pseudo invariant; spectral from atmosphere; spatial from surface targets	Space and internal blackbody	2 internal blackbodies

Table 4
HyspIRI mission concept science questions drawn from the Decadal Survey.

Type	Question
VSWIR instrument questions	<ol style="list-style-type: none"> 1) What is the global spatial pattern of ecosystem and diversity distributions and how do ecosystems differ in their composition or biodiversity? 2) What are the seasonal expressions and cycles for terrestrial and aquatic ecosystems, functional groups, and diagnostic species? How are these being altered by changes in climate, land use, and disturbance? 3) How are the biogeochemical cycles that sustain life on Earth being altered/disrupted by natural and human-induced environmental change? How do these changes affect the composition and health of ecosystems and what are the feedbacks with other components of the Earth system? 4) How are disturbance regimes changing and how do these changes affect the ecosystem processes that support life on Earth? 5) How do changes in ecosystem composition and function affect human health, resource use, and resource management? 6) What are the land surface soil/rock, snow/ice and shallow-water benthic compositions
TIR instrument questions	<ol style="list-style-type: none"> 1) How can we help predict and mitigate earthquake and volcanic hazards through detection of transient thermal phenomena? 2) What is the impact of global biomass burning on the terrestrial biosphere and atmosphere, and how is this impact changing over time? 3) How is consumptive use of global freshwater supplies responding to changes in climate and demand, and what are the implications for sustainable management of water resources? 4) How does urbanization affect the local, regional and global environment? Can we characterize this effect to help mitigate its impact on human health and welfare? 5) What is the composition and temperature of the exposed surface of the Earth? How do these factors change over time and affect land use and habitability?
Combined instrument questions	<ol style="list-style-type: none"> 1) How do Inland, Coastal, And Open Ocean Aquatic Ecosystems Change Due To Local and Regional Thermal Climate, Land-Use Change, And Other Factors? 2) How are fires and vegetation composition coupled? 3) Do volcanoes signal impending eruptions through changes in the temperature of the ground, rates of gas and aerosol emission, temperature and composition of crater lakes, or health and extent of vegetation cover? 4) How do species, functional type, and biodiversity composition within ecosystems influence the energy, water and biogeochemical cycles under varying climatic conditions? 5) What is the composition of exposed terrestrial surface of the Earth and how does it respond to anthropogenic and non-anthropogenic drivers? 6) How do patterns of human environmental and infectious diseases respond to leading environmental changes, particularly to urban growth and change and the associated impacts of urbanization?

4.1.6. Response to disturbance

Ecological disturbance (such as those that occur due to extreme weather, fire, forest thinning and dieback, rangeland degradation, insect and pathogen outbreaks, and invasive species) affects vegetation biochemical and physiological processes with cascading effects on whole ecosystems (Hansen et al., 2001; Harley et al., 2006). These disturbances often involve long-term changes in vegetation function and composition, and the VSWIR instrument will produce full spectral signatures that would facilitate disturbance applications. Examples of applications include mitigation of impacts from drought, infestations, and monitoring restoration.

4.2. Aquatic ecosystems

4.2.1. Ocean color and optical properties

HyspIRI's VSWIR would enable improved studies of ocean color and optical properties (Devred et al., 2013), and build upon previous studies of optical properties of water (Fichot, Sathyendranath, & Miller, 2008; Lee, Rhea, Arnone, & Goode, 2005) including chlorophyll concentrations (Gitelson, Gao, Li, Berdnikov, & Saprygin, 2011; Moses et al., 2012), phytoplankton functional types (Bracher et al., 2009; Moisan, Moisan, & Linkswiler, 2011) and species (Ryan, Davis, Tuffillaro, Kudela, & Gao, 2014; Simis, Ruiz-Verdú, Domínguez-Gómez, Peña-Martinez, Peters, & Gons, 2007), suspended sediment (Li, Kaufman, Gao, & Davis, 2003; Volpe, Silvestri, & Marani, 2011) and colored dissolved organic matter (Brezonik, Olmanson, Finlay, & Bauer, 2015; Kutser, Pierson, Kallio, Reinart, & Sobek, 2005). HyspIRI could also lead to improved monitoring of pollution and water quality (Brando & Dekker, 2003; Koponen, 2002; Olmanson, Brezonik, & Bauer, 2013), including particle-associated biogeochemical constituents (Brando & Dekker, 2003; Fichot et al., in preparation) and groundwater discharge into the ocean (Johnson, Glenn, Burnett, Peterson, & Lucey, 2008). The HyspIRI mission, with its continuous spectral coverage in the VSWIR and 30-m spatial resolution, would be highly complementary to upcoming satellite missions such as Pre-Aerosol Clouds and Ocean Ecosystem (PACE), which has coarser spatial resolution (1 km) but higher temporal resolution (1–2 day global coverage). HyspIRI could also complement observations from the

GEOstationary Coastal and Air Pollution Events (GEO-CAPE) mission, which would provide measurements every 0.5–3 h from a geostationary orbit at 250–375 m resolution for ocean color. Further information about the role HyspIRI would play in advancing ocean color data products for coastal science research and applications is described in the HyspIRI Aquatic Studies Group report (Turpie et al., 2015a).

4.2.2. Wetland environments

HyspIRI's VSWIR has considerable potential to improve how wetlands are studied, from wetland extent, to wetland cover classification and species distributions, to hydrological processes (Turpie, Klemas, Byrd, Kelly, & Jo, 2015). Imaging spectroscopy has already been used to evaluate vegetation functional types (Klemas, 2013a; Klemas, 2013b), map estuarine wetlands (Li, Ustin, & Lay, 2005; Rosso, Ustin, & Hastings, 2007) and mangrove environments (Hirano, Madden, & Welch, 2003), and species distributions, including invasive species (Hestir et al., 2008; Khanna et al., 2011; Pengra, Johnston, & Loveland, 2007). HyspIRI could also build upon studies of wetland biochemical and biophysical parameters (Byrd, O'Connell, Di Tommaso, & Kelly, 2014; Mutanga & Skidmore, 2004), and hydrological and hydro-meteorological processes using TIR (Banks, Paylor, & Brian Hughes, 1996; Mohamed, Bastiaanssen, & Savenije, 2004) and VSWIR products (Davranche, Poulin, & Lefebvre, 2013).

4.2.3. Water surface features and algal blooms

HyspIRI could also be used to improve characterizations of water surface features. Coarser resolution multispectral data have been used to locate and study aggregations of *Sargassum* (Gower, Hu, Borstad, & King, 2006), *Trichodesmium* (Hu, Cannizzaro, Carder, Muller-Karger, & Hardy, 2010), *Ulva prolifera* (Hu et al., 2010) as well as the toxin-producing *Karenia brevis* (Stumpf et al., 2003). Finer resolution hyperspectral imagery has demonstrated potential for discrimination between types of floating plant matter (Dierssen, Chlus, & Russell, 2015) and for *Sargassum* biomass estimates (Hu, Feng, Hardy, & Hochberg, 2015). Discrimination of optically active algal bloom pigments (Li et al., 2010; Randolph et al., 2008) using hyperspectral data also point to the potential utility of the HyspIRI VSWIR instrument.

4.2.4. Bathymetry

Knowledge of shallow water bathymetry is vital for shipping, environmental management, and monitoring change in the coastal zone. Remote sensing has been long established as a useful tool to estimate bathymetry for shallow waters (Lyzenga, 1978), with multispectral sensors providing reasonably accurate retrievals to ~20 m depth in clear water (Lyzenga, Malinas, & Tanis, 2006). Algorithms have been developed for hyperspectral retrievals (Lee, Carder, Mobley, Steward, & Patch, 1998; Mobley et al., 2005), and retrieval accuracy increases with increasing spectral resolution (Lee & Carder, 2002). Recent work by Ma et al. (2014) shows accurate bathymetry retrievals to ~30 m depth in clear water using Hyperion, which points to the strong potential for HypSPIRI in this application.

4.2.5. Shallow water ecosystems and characteristics

Satellite remote sensing is the only tool capable of enabling global study of coral reefs and other shallow benthic systems, such as seagrass habitats (Mumby, Green, Edwards, & Clark, 1999; Phinn, Roelfsema, Dekker, Brando, & Anstee, 2008). HypSPIRI is the only planned satellite with the combined spatial and spectral resolutions suitable for atmosphere (Gao, Montes, Li, Melita Dierssen, & Davis, 2007) and water column (Lee & Carder, 2002) corrections and bottom-type discrimination (Hochberg, Atkinson, & Andréfouët, 2003) required for processing and interpreting imagery of these systems. With repeat global coverage, HypSPIRI offers the potential to dramatically enhance our understanding of shallow water benthic processes. The Decadal Survey specifically recommends HypSPIRI for study of coral reefs.

4.2.6. Response to disturbances (oil spills, floods)

HypSPIRI could improve processes for mapping disturbance, monitoring impact and quantifying recovery of aquatic ecosystems that have been affected by discrete events such as oil spills (Leifer et al., 2012) and floods as well as disturbances occurring over an extended period of time, such as the introduction and spread of invasive species. Kokaly et al. (2013) used hydrocarbon absorptions detectable in short-wave infrared imaging spectrometry data to map the extent of oil contamination in Barataria Bay following the Deep Water Horizon oil spill, and Khanna et al. (2013) tracked the recovery of salt marsh vegetation following the spill. The extent and impact of invasive species can also be evaluated by leveraging the VSWIR and imaging spectroscopy capability to conduct species discrimination and mapping in aquatic ecosystems (Hestir et al., 2008; Khanna et al., 2011; Pengra et al., 2007).

4.3. Earth surface composition and change

The energy reflected and emitted from the exposed terrestrial surface of the Earth can be uniquely helpful in identifying rocks, minerals, and soils (Ben-Dor et al., 2009; Calvin, Littlefield, & Kratt, 2015). The composition of these exposed rock and soils can be obtained by analyzing reflectance and emissivity measurements. In addition, thermal data measurements will provide daytime and nighttime temperatures, which can be used to map temperatures and extract information such as thermal inertia. Buried sources of high temperatures (lava tubes, underground fires in coal seams, high temperature rocks, etc.) cause hot spots on the Earth's surface, which can then be used to understand the depth and potential flow profile (Ganci, Vicari, Cappello, & Del Negro, 2012). HypSPIRI TIR data would be used to map temperature anomalies (Peltier, Finizola, Douillet, Brothelande, & Garaebiti, 2012), extract thermal profiles, and numerically derive the depth to the hot sources by informing models (Berthelote, Prakash, & Dehn, 2007). These measurements would enable new research and applications opportunities for mineral and hydrocarbon resource investigation (van der Meer et al., 2014) and emplacement understanding as called for in the Decadal Survey (NRC, 2007) and more recent work (Ramsey & Harris, 2013).

Combining information from the HypSPIRI VSWIR and TIR data could greatly improve our ability to discriminate and identify surface materials including rocks, soils and vegetation (Da Luz & Crowley, 2007; van der Meer et al., 2014). This is the first step to quantitatively measure change of a land surface, whether naturally caused or of anthropogenic origin. Change detection, monitoring, and mapping form the basis for formulating numerous policy decisions, from controlling deforestation to open-pit mining. HypSPIRI could improve applications to enable more informed decisions in this regard.

4.4. Extreme events, natural disasters, and human health

4.4.1. Volcanoes and earthquakes

Volcanic eruptions and earthquakes affect millions of lives each year, causing thousands of deaths and billions of dollars in property damage. TIR could detect precursors to impending geologic events (Kruse et al., 2014), including transient thermal phenomena. For example, changes in temperature and the abundance of sulfur dioxide (and possibly other gasses) often precede volcanic eruptions and other seismic activity (Tramutoli et al., 2013; Worden, Dehn, Ripepe, & Donne, 2014). Characteristic changes in SO₂ emissions and/or temperature can be used to track eruptions or upwelling magma activity from fumaroles, lava lakes, and crater. Prediction of lava flows depends on effusion rate and temperature (Wright, Garbeil, & Harris, 2008), which would be produced by the HypSPIRI VSWIR and TIR instruments working in concert. These data can also be ingested into models to potentially improve predictions of some natural disasters (Ganci et al., 2012; Kruse et al.,

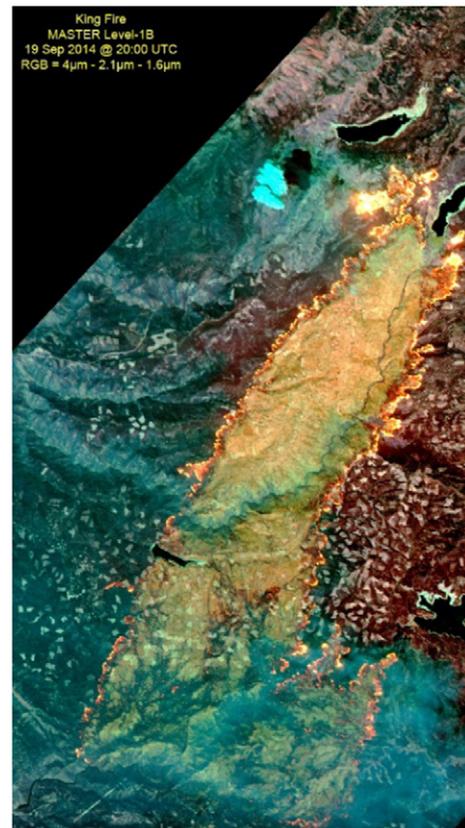


Fig. 5. MODIS-ASTER (MASTER) airborne simulator image over the 2014 King fire in California, USA, with a spatial resolution similar to that which HypSPIRI will provide. RGB = 4 μm; 2.1 μm; 1.6 μm, respectively. The active fire front can be clearly distinguished by using the 4-μm band (red).

2014) and used to develop applications to assess the extent and impact of these events on aviation practices, health and air quality, and disaster assessment and response.

4.4.2. Wildland fires

Wildfire is an increasingly important process in determining carbon flux and emissions from vegetated ecosystems, and fire regimes are likely to be altered with changing climate (Krawchuk, Max, Moritz, Van Dorn, & Hayhoe, 2009). VSWIR and TIR sensors offer complementary capabilities for increasing understanding of global fire processes. Combining multispectral TIR and VSWIR data could lead to improved understanding of the coupling between fires, vegetation and associated trace gas emissions (Dennison, Charoensiri, Roberts, Peterson, & Green, 2006).

Active fires can be characterized based on their emitted radiance (Fig. 5), and HypsIRI will provide improvements in spatial resolution, sensitivity, and saturation. The higher sensitivity TIR bands will allow measurement of smaller, land-use related fires that can remain undetected by coarser spatial resolution sensors. The 4- μm band has lower sensitivity but a 1200 K saturation threshold that is 2–3 times higher than saturation threshold provided by other satellite sensors, allowing characterization of large, hot fires (Realmuto et al., 2015). 4- μm radiance can be used to calculate fire radiative power (Wooster, Roberts, Perry, & Kaufman, 2005), which in turn can be used to estimate carbon emissions (Kaiser et al., 2012) at a finer spatial resolution than previously possible. Fire temperature can be retrieved from combinations of shortwave, mid- and thermal infrared channels (Dennison & Matheson, 2011), with VSWIR imaging spectrometer data providing an ability to distinguish small hotter fires from large cooler fires (Matheson & Dennison, 2012). Imaging spectroscopy can be used to map complex patterns of fire impacts on vegetation and soil, offering improved means of measuring fire severity (van Wagtenonk, Jan, Root, & Key, 2004; Kokaly, Rockwell, Haire, & King, 2007; Veraverbeke, Natasha Stavros, & Hook, 2014). Combined use of VSWIR and TIR data can further improve estimates of fire severity (Veraverbeke, Hook, & Harris, 2012). Imaging spectroscopy can also contribute significantly to monitoring vegetation recovery following fire (Mitri & Gitas, 2013; Riaño et al., 2002).

4.4.3. Drought, water use and availability

Given trends in population growth and climate change, accurate monitoring of the Earth's freshwater resources at field to global scales will become increasingly critical (GEOS, 2014; NRC, 2007). Land surface temperature, in combination with VSWIR estimates of Leaf Area Index, are valuable metrics for estimating evapotranspiration and available water (Anderson & Kustas, 2008). Remote sensing has been shown to be highly valuable in understanding drought conditions in the U.S. (Svoboda et al., 2010) and internationally (Verdin, Funk, Senay, & Choularton, 2005; Heim & Brewer, 2012). Moisture deficits in root zone soil can be reflected in vegetation stress (Ritchie, 1998) and canopy temperatures (Gonzalez-Dugo et al., 2012; Jackson, Idso, Reginato, & Pinter, 1981), while depleted water in the soil surface layer causes the soil component of the scene to heat rapidly (Wardlow, Anderson, & Verdin, 2012). With frequent revisits (5–16 days) and high spatial resolution, the HypsIRI instruments would provide accurate estimates of consumptive water use at the spatial scale of human management and timescale of vegetation growth. This information can support applications to monitor irrigation withdrawals, estimate aquifer depletion, evaluate performance of irrigation systems, plan stream diversions for protection of endangered species, and estimate historical water use for negotiating water rights transfers (Allen, Tasumi, Morse, & Trezza, 2005).

4.4.4. Human health threats and urbanization

Currently, more than 50% of global population lives in urban areas and these numbers are forecast to increase to 66% by 2050 (UN, 2014). Urban areas, although representing only a small fraction of the Earth's surface, have a significant ecological footprint in terms of

residential water use, carbon emissions, airborne pollutants and waste products (Grimm et al., 2008). Remote sensing can contribute significantly to an improved understanding of urban biophysical properties that govern the exchange of energy, trace gasses and urban hydrology. Of these, improved maps of impervious cover fraction, vegetation and urban temperatures (the Urban Heat Island Effect: UHI) are particularly important (Weng & Lu, 2008). HypsIRI, with its enhanced spectral capabilities in the VSWIR and its multiple channels in the TIR, has the potential of providing improved measures of impervious surface fraction, urban green cover, surface albedo, emissivity and LST (Roberts, Quattrochi, Hulley, Hook, & Green, 2012). VSWIR spectroscopy is particularly important because urban areas are highly diverse, consisting of numerous surfaces that cannot be discriminated using broad band systems (Herold, Gardner, & Roberts, 2003). VSWIR spectroscopy, by accounting for immense spectral diversity, provides more accurate measures of cover (Okujeni, van der Linden, & Hostert, 2015; Roberts et al., 2012). With multiple thermal spectral bands, frequent revisits, and nighttime viewing capabilities, the HypsIRI TIR instrument would provide unprecedented measures of the temporal and spatial properties of the UHI over all of the world's major cities.

4.4.5. Vector-borne diseases

HypsIRI TIR can provide thermal infrared data over the globe every five days, which will be key to quantifying many of the factors that influence the vector life cycle. Information from the VSWIR can be used in habitat definition, estimating leaf area index, type of land cover and other factors related to crop pathogen outbreaks (Mahlein, Oerke, Steiner, & Dehne, 2012) and disease vectors like mosquitos (Midekisa, Senay, Henebry, Semuniguse, & Wimberly, 2012; Mohan & Naumova, 2014). In acquiring improved products for soil moisture and type, temperature (water, air, surface), land surface characteristics, community composition, ecosystem distribution and phenology, vector habitats can be mapped to predict the emergence, extent, and potential impact of these diseases and build on previous works in this area (Ceccato, Connor, Jeanne, & Thomson, 2005; Hay & Lennon, 1999).

4.4.6. Response to oil spills

HypsIRI could improve processes for mapping disturbance, monitoring impact and quantifying recovery of aquatic ecosystems that have been affected by discrete events such as oil spills (Leifer et al., 2012) and floods (Davranche, Poulin, & Lefebvre, 2013) as well as disturbances occurring over an extended period of time, such as the introduction and spread of invasive species. Kokaly et al. (2013) used hydrocarbon absorptions detectable in shortwave infrared imaging spectrometry data to map the extent of oil contamination in Barataria Bay following the Deep Water Horizon oil spill, and Khanna et al. (2013) tracked the recovery of salt marsh vegetation following the spill. The extent and impact of invasive species can also be evaluated by leveraging the VSWIR and imaging spectroscopy capability to conduct species discrimination and mapping in aquatic ecosystems (Hestir et al., 2008; Khanna et al., 2011; Pengra et al., 2007).

5. Preparatory HypsIRI activities: risk reduction and technology demonstrations

5.1. Airborne HypsIRI campaign

For the last three years, NASA has supported and conducted annual airborne campaigns to demonstrate the important science and applications research that is uniquely enabled by HypsIRI-like data sets. The campaigns involve two instruments: the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (Green et al., 1998; Vane et al., 1993) and the MODIS/ASTER Airborne Simulator (MASTER) (Hook, Myers, Thome, Fitzgerald, & Kahle, 2001). Both are flown on a NASA ER-2 research aircraft at an altitude of 20 km over large diverse regions of the western United States (Fig. 6). Data sets from these instruments

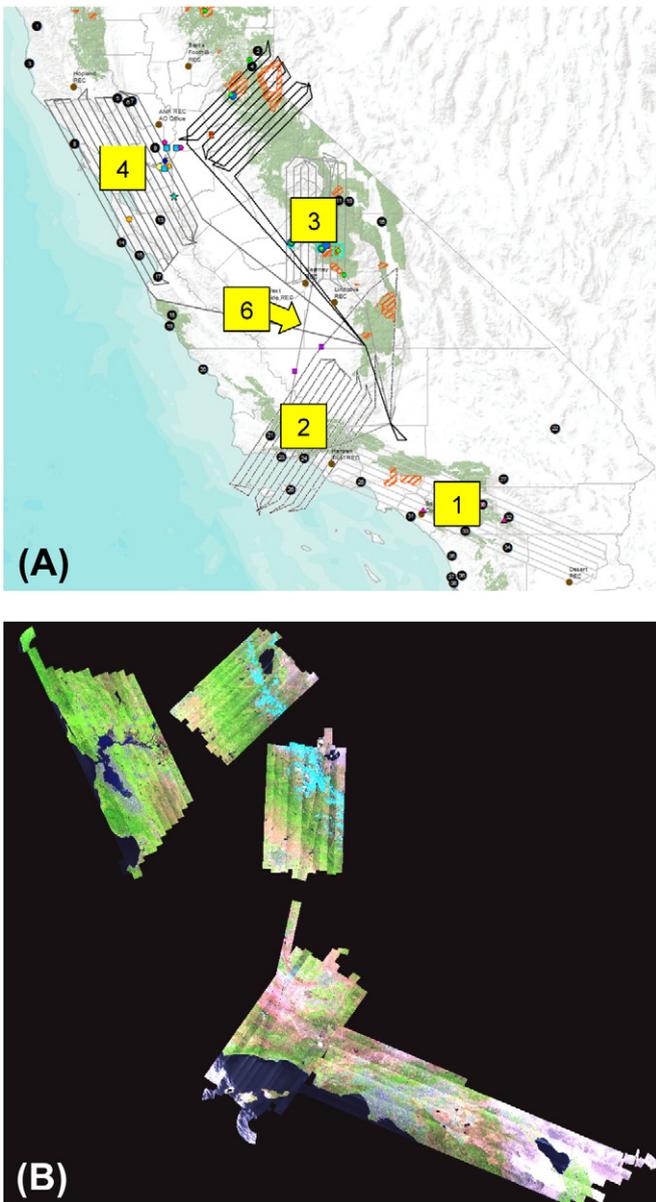


Fig. 6. (A) California boxes flown by AVIRIS and MASTER since 2013 as part of the HypSPiRI Airborne Campaign: (1) Southern California, (2) Santa Barbara, (3) Yosemite, (4) San Francisco Bay Area, (5) Lake Tahoe, and (6) Soda Straw. (B) Mosaic of flightlines from each box.

Courtesy of P. Dennison.

that together simulate HypSPiRI-like measurements are collected at regular intervals to obtain seasonal coverage. In 2013 NASA funded 14 proposals to support participation in these campaigns over three years. The PIs of these investigations have presented their work at annual HypSPiRI Science Symposia and HypSPiRI Science and Applications Workshops. For more information, see the HypSPiRI website (<http://hypspiri.jpl.nasa.gov/>).

In addition to these campaigns, a new HypSPiRI-relevant Research Opportunities in Space and Earth Sciences (ROSES) solicitation recently closed in April 2015 entitled “HypSPiRI Preparatory Airborne Volcano and Coral Reef Campaign”. This call requested proposals for volcano and coral reef research for a single campaign of flights in 2016 to the Hawaiian Islands by the ER-2 with the AVIRIS and MASTER instruments. Volcano and coral reef research were identified as especially relevant for the HypSPiRI mission in the Decadal Survey.

5.2. Prototype HypSPiRI Thermal Infrared Radiometer (PHyTIR)

As part of the risk reduction activities for HypSPiRI, a laboratory prototype of the HypSPiRI TIR instrument, termed PHyTIR, was developed under the NASA Earth Science Technology Office Instrument Incubator Program (Hook, Johnson, Foote, Eng, & Jau, 2011). The goal of the PHyTIR activity was to demonstrate key components of the HypSPiRI-TIR instrument. PHyTIR consisted of a push-whisk (whiskbroom) scanning (Fowler, 2014), multi-band filter radiometer with 8 spectral bands between 8 and 12.5 μm . However, only 3 of the 8 bands were populated and the electronics for reading the data from the bands was only suitable for laboratory use with the data recorded on a laboratory computer rather than a space-qualified data system. However, PHyTIR demonstrated that the HypSPiRI-TIR measurement requirements could be met and this activity matured the required technology to Technology Readiness Level (TRL) 5/6.

5.3. Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)

In 2014, a proposal was selected under the NASA Earth Ventures program to upgrade the PHyTIR radiometer for spaceflight and use it for the ECOSTRESS mission. The ECOSTRESS mission is focused on answering key questions related to water use and plant dynamics including: (1) How does the terrestrial biosphere respond to changes in water availability? (2) How do changes in diurnal vegetation water stress impact the global carbon cycle? and (3) Can agricultural vulnerability be reduced through advanced monitoring of agricultural water consumptive use and improved drought estimation? This mission leverages the successful design, assembly, and testing of PHyTIR and will essentially upgrade PHyTIR to have five spectral bands between 8 and 12.5 μm and enable space-flight electronics to be developed for it. ECOSTRESS will be deployed on the International Space Station (ISS) in a $\pm 52^\circ$ orbit and have a spatial resolution of 38 m (in track) by 69 m (cross track). ECOSTRESS has an improved spatial resolution and unique time of day coverage compared to plans for the HypSPiRI TIR instrument, since the ISS is in a precessing orbit, allowing data to be acquired at different times of day (Table 3). ECOSTRESS is planned for launch in 2017 with a mission lifetime of one year although the mission may be extended if the instrument continues to function as planned.

The core products of the ECOSTRESS mission include Land Surface Temperature (LST) and Emissivity, Evapotranspiration (ET), Evaporative Stress Index (ESI), and Water Use Efficiency (WUE). Several approaches will be utilized to derive the ET products including Atmospheric-Land Exchange Inverse (ALEXI) ET (M. C. Anderson, Norman, Mecikalski, Otkin, & Kustas, 2007) and Priestly–Taylor–Jet Propulsion Laboratory ET product (PT-JPL) (Fisher, Tu, & Baldocchi, 2008).

5.4. Proposed VSWIR-Dyson and ISS accommodation

In 2014, JPL developed a full range VSWIR-Dyson spectrometer (380–2510 nm range with ≤ 10 nm sampling, with a full width half max (FWHM) value of ≤ 12 -nm) as part of a proposed technology demonstration for ISS accommodation (Table 3). The VSWIR-Dyson leveraged the successes and design of the Portable Remote Imager SpectroMeter (PRISM) Visible Near InfraRed (VNIR) Dyson (<http://prism.jpl.nasa.gov/>). Essentially, at a comparatively modest cost and rapid schedule, deployment of this high signal-to-noise ratio (SNR) optical fast imaging spectrometer on the ISS would enable 30-m spatial sampling; furthermore, together with ECOSTRESS, the VSWIR-Dyson could generate early HypSPiRI science for a large fraction of Earth’s terrestrial surface.

To leverage the development of the VSWIR-Dyson, a proposed pathway to enable ISS-accommodation of this instrument is being explored and would include the following goals: (1) reduce risk and validate the VSWIR-Dyson imaging spectrometer architecture to support future

options for the SLI, HypsIRI and other NASA programs; (2) deliver Landsat bands with on-orbit convolution of imaging spectroscopy measurements at 30 m spatial resolution; (3) demonstrate low distortion, low stray light, high SNR, VSWIR-Dyson (380–2510 nm) imaging spectrometer with 30 m spatial resolution; (4) demonstrate on-orbit $\geq 4\times$ lossless spectral compression (CCSDS, 2013) and cloud screening; (5) cross-calibrate with Landsat and other multispectral instruments; (6) begin to address HypsIRI VSWIR and VSWIR + TIR Science and Applications objectives (Tables 1, 4).

6. Conclusions

The true value of HypsIRI is its potential to make significant contributions to a multitude of societally important science questions and applications (Tables 1, 4). With contiguous spectral measurements in the VSWIR and eight spectral bands in the TIR, and the IPM direct broadcast capability, HypsIRI enables near-term global mapping of changing ecosystems, both aquatic and terrestrial, and can be used to address societal needs related to land use and urbanization, public health, water availability and demand, and to potentially support response to environmental hazards such as volcanoes, earthquakes and wildfires.

We continue to advance the technology for the HypsIRI VSWIR, TIR and IPM objectives. These advances will lower the cost and reduce risks associated with HypsIRI mission planning. ECOSTRESS, which emerged from the HypsIRI risk-reduction instrument PHYTIR, will be installed on the ISS by 2017. This is a key example of the utility of the HypsIRI planning and mission concept activities. New airborne measurements with HypsIRI-like data sets (VSWIR and TIR) will continue to push forward the state of the science and applications and the maturity of the science data processing systems. The case for truly global HypsIRI measurements of the Earth for science and applications research continues to expand.

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