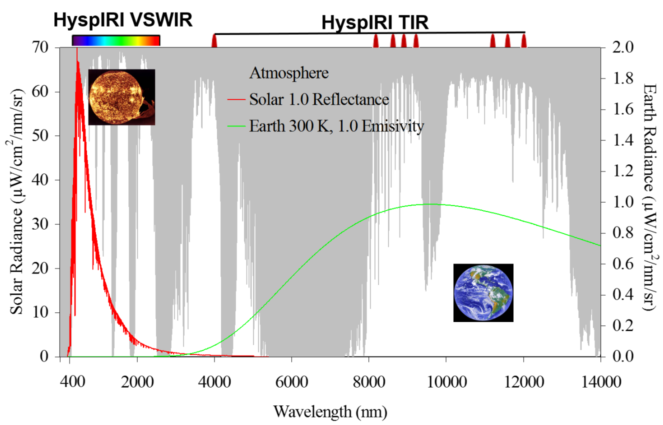
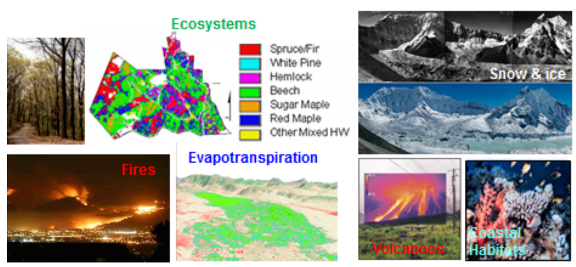
HyspIRI Comprehensive Development Report

HyspIRI Mission Concept Team





Prepared for

National Aeronautics and
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By

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Contents

Executive Summary

NASA's Hyperspectral Infrared Imager (HyspIRI) is a global mission focused on unique and urgent Earth science and applications objectives that are addressed by continuous spectral measurements in the visible to short-wavelength infrared (VSWIR: 380 to 2510 nm) portion of the spectrum and measurements from eight discrete multi-spectral bands in the thermal infrared (TIR: 3 to 13 microns) spectral range. A direct broadcast subset/processing capability is included in the HyspIRI mission to support near real-time applications and science.

Five key areas for HyspIRI science and applications are global terrestrial ecosystem composition and function; fire fuel, temperature, severity and recovery; vegetation evapotranspiration including agricultural lands; dust and black carbon in snow and ice; volcano composition and emissions; and coastal and inland water benthic habitats. These science and applications contributions are critical today and uniquely addressed by the combined imaging spectroscopy, thermal infrared measurements, and IPM direct broadcast capability of HyspIRI.

Two key climate contributions are: (1) the global HyspIRI spectroscopic measurements of the terrestrial biosphere delivering ecosystem composition and function to constrain and reduce the uncertainty in climate-carbon interactions and terrestrial biosphere feedback; and (2) the global 8 band thermal measurements to provide improved constraint of fire related emissions as well as the evapotranspiration status of terrestrial vegetation. In these climate science areas, the urgency and uniqueness of HyspIRI measurements is traced to the lack of an accurate global baseline of the terrestrial ecosystem composition and functional diversity that is required to accurately initialize the ecosystem models that underpin current climate models as well as the improved fire emission knowledge that derive from the revisit of multispectral thermal measurements fine spatial sampling.

The HyspIRI mission was designated in National Research Council (NRC) Decadal Survey: Earth Science and Applications from Space. In the Decadal Survey, HyspIRI is recognized as relevant to a range of Earth science and applications including climate: "A hyperspectral sensor (e.g., FLORA) combined with a multispectral thermal sensor (e.g., SAVII) in low Earth orbit (LEO) is part of an integrated mission concept [described in Parts I and II] that is relevant to several panels, especially the climate variability panel." To address its objectives, the HyspIRI instrumentation includes a visible-to-short-wave-infrared (VSWIR) imaging spectrometer that covers the range 380–2510 nm in 10-nm contiguous bands, and a multispectral imager that covers the range from 3–13 µm with 8 discrete bands across the mid- and thermal-IR (TIR) portion of the spectrum. Both instruments have a nominal spatial resolution of 60 m at nadir. The baseline VSWIR instrument has a revisit time of 19 days the TIR instrument will have a revisit time of 5 days. HyspIRI also includes an Intelligent Payload Module (IPM) that will enable a subset of the data to be processed onboard the satellite and downlinked to the ground in near real-time.

At the request of NASA in 2013, a VSWIR-Dyson imaging spectrometer concept using the latest technologies was studied that provides 30 m surface sampling and 16 revisit and is consistent with the 2013 NRC report: Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program. This VSWIR-Dyson architecture also meets the HyspIRI requirements.

HyspIRI is a global mission, developed to address a set of science and applications questions identified in the Decadal Survey. To develop options for the implementation of HyspIRI a mission concept team was appointed by NASA headquarters with leadership shared between JPL and GSFC. To provide science and applications guidance to the mission concept team a Science Study Group (SSG) was formed by

NASA Headquarters. In 2007, two SSG groups were formed one for each measurement type: imaging spectrometer and thermal infrared. In 2008 these groups were merged and the formal HyspIRI SSG formed. The SSG is intended to represent the broad scientific and applications community that is interested in science and applications research enabled by HyspIRI measurements. Members of the SSG include the disciplines of ecology, coastal and inland waters, volcanology, snow and ice hydrology, geology, the atmosphere, biomass burning and wild fires, agriculture, urban infrastructure and a range of applications. Table 1 gives the membership of the HyspIRI SSG. Since their inception the mission concept team and SSG have generated and number of reports to document status and evolution of the HyspIRI mission concept and enabled science and applications. Table 2 provides a summary of these documents that form the bulk of Appendix of this comprehensive development report. These documents can be accessed on line along with this executive summary at [http://hyspiri.jpl.nasa.gov/mission-report].

Table 1. Membership of the HyspIRI Science Study Group providing science and applications input on design and implementation options for the HyspIRI mission concept.

HyspIRI SSG Member	Home Institution
Mike Abrams	Jet Propulsion Laboratory
Rick Allen	University of Indiana
Martha Anderson	US Department of Agriculture
Greg Asner	Carnegie Institute of Washington
Paul Bissett	Florida Environmental Research Institute
Alex Chekalyuk	Lamont-Doherty
James Crowley	US Geological Survey
Ivan Csiszar	University of Maryland
Heidi Dierssen	University of Connecticut
Friedmann Freund	Ames Research Center
John Gamon	University of Alberta
Louis Giglio	University of Maryland
Greg Glass	John Hopkins University
Robert Green	Jet Propulsion Laboratory
Simon Hook	Jet Propulsion Laboratory
James Irons	Goddard Space Flight Center
John Mars	US Geological Survey, HQ
David Meyer	US Geological Survey, EROS
Betsy Middleton	Goddard Space Flight Center
Peter Minnett	University of Miami
Frank Muller Karger	University of South Florida
Scott Ollinger	University of New Hampshire
Thomas Painter	Jet Propulsion Laboratory
Anupma Prakash	University of Alaska, Fairbanks
Jeff Privette	National Ocean and Atmospheric Administration
Dale Quattrochi	Marshall Space Flight Center
Michael Ramsey	University of Pittsburg
Vince Realmuto	Jet Propulsion Laboratory
Dar Roberts	University of California, Santa Barbara
Dave Siegel	University of California, Santa Barbara
Phil Townsend	University of Wisconsin
Kevin Turpie	Goddard Space Flight Center
Steve Ungar	Goddard Space Flight Center
Susan Ustin	University of California, Davis
Rob Wright	University of Hawaii

Table 2. HyspIRI mission concept team and SSG documents generated in support the HyspIRI mission concept. These documents be accessed on line along with this executive summary at [http://hyspiri.jpl.nasa.gov/mission-report].

Category	Document
Reports and Whitepapers	Compiled Reports and Whitepapers from 2008-2014
Individual Report files	2014 HyspIRI Separate Platforms Whitepaper
	2014 PHyTIR Test Results
	2012 Workshop Report
	2012 TIR Band Study Report
	2011 Workshop Report
	2011 Symposium Report
	2011 Sun Glint Report
	2011 High Temperature Saturation Report
	2010 Workshop Report
	2009 Workshop Report
	2008 Whitepaper and Workshop Report
	TRL Assessment Report
HyspIRI Workshop Material	2014 Compiled Workshop
	2013 Compiled Workshop
	2012 Compiled Workshop
	2011 Compiled Workshop
	2010 Compiled Workshop
	2009 Compiled Workshop
	2008 Compiled Workshop
Individual Workshop files	2014 Workshop Agenda and Presentations
	2013 Workshop Agenda and Presentations
	2012 Workshop Agenda and Presentations
	2011 Workshop Agenda and Presentations
	2010 Workshop Agenda and Presentations
	2009 Workshop Agenda and Presentations
	2008 Workshop Agenda and Presentations

Category	Document
HyspIRI Symposium Material	2014 Compiled Symposium
	2013 Compiled Symposium
	2012 Compiled Symposium
	2011 Compiled Symposium
	2010 Compiled Symposium
Individual Symposium files	2014 Symposium Agenda and Presentations
	2013 Symposium Agenda and Presentations
	2012 Symposium Agenda and Presentations
	2011 Symposium Agenda and Presentations
	2010 Symposium Agenda and Presentations
TeamX ISS Accommodation	VSWIR ISS Study
	TIR ISS Study
2014 Small Spacecraft Vendor Presentation	2014 Small Spacecraft Vendor Presentation
Algorithm Theoretical Basis Documents (ATBDs)	TIR Level 2 Surface Radiance
	TIR Level 2 Surface Temperature and Emissivity
	TIR Cloud Mask
	VSWIR Level 2 Water Leaving Reflectance
	VSWIR Level 2 Land Surface Reflectance
Science Applications	
Summaries	Disasters
	Water Resources
	Health and Air Quality
Science Application White Papers	Hyspiri Volcanoes
	Public Health

To advance the HyspIRI mission, the SSG has held regular telecons and a large fraction of the membership of these two groups has met typically twice a year at the HyspIRI Science and Applications Workshop (hosted by JPL) and the HyspIRI Data Products Symposium (hosted by GSFC). The open meetings have facilitated communication between the broader scientific and applications communities and the efforts HyspIRI mission concept team and the SSG. Figure 1 shows pictures from these meetings in 2014. Reports and presentations from these meetings are found in the Appendix.

Figure 1. 2014 HyspIRI Data Products Symposium in June at GSFC (left) and Science and Applications Workshop in October at Caltech (right).

Early in the HyspIRI mission concept effort, the SSG identified key science and applications questions, consistent with the Decadal Survey, around which to formulate mission concepts and implementation options for NASA. These overarching thematic questions were separated into three groups referred to as the VSWIR questions (VQ), TIR questions (TQ), and Combined questions (CQ). These questions are shown in Table 3 with a summary of each question.

Table 3. HyspIRI mission concept science and applications questions developed by the SSG drawing from the guidance of the Decadal Survey.

Question #	Question
vq1	What is the global spatial pattern of ecosystem and diversity distributions and how do ecosystems differ in their composition or biodiversity?
vq2	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?
vq3	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?
vq4	How are disturbance regimes changing and how do these changes affect the ecosystem processes that support life on Earth?
vq5	How do changes in ecosystem composition and function affect human health, resource use, and resource management?
vq6	What are the land surface soil/rock, snow/ice and shallow-water benthic compositions
tq1	How can we help predict and mitigate earthquake and volcanic hazards through detection of transient thermal phenomena?
tq2	What is the impact of global biomass burning on the terrestrial biosphere and atmosphere, and how is this impact changing over time?
tq3	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?
tq4	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?
tq5	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?
cq1	How do Inland, Coastal, And Open Ocean Aquatic Ecosystems Change Due To Local and Regional Thermal Climate, Land-Use Change, And Other Factors?
cq2	How are fires and vegetation composition coupled?
cq3	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?
cq4	How do species, functional type, and biodiversity composition within ecosystems influence the energy, water and biogeochemical cycles under varying climatic conditions?
cq5	What is the composition of exposed terrestrial surface of the Earth and how does it respond to anthropogenic and non-anthropogenic drivers?
cq6	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?

These science questions are elaborated in the sections below.

VSWIR Science Questions

<u>VQ1. Pattern and Spatial Distribution of Ecosystems</u> Terrestrial and aquatic ecosystems represent an assemblage of biological and non-biological components and the complex interactions among them, including cycles and/or exchanges of energy, nutrients, and other resources. The biological components span multiple trophic levels and range from single-celled microbial organisms to higher order organisms,

including vegetation in forests and grasslands, and in coastal and other aquatic environments, as well as animals. Remote sensing represents perhaps the only viable approach for mapping the current distribution of these ecosystems globally, monitoring their status and improving our understanding of feedbacks among modern ecosystems, climate and disturbance. HyspIRI, as a high-fidelity imaging spectrometer with a 19-day repeat pass, has the potential for dramatically improving our ability to identify plant functional types/function groups, quantify species diversity, discriminate plant and phytoplankton species, and map their distribution in terrestrial and coastal environments.

VQ2. Ecosystem Function, Physiology and Seasonal Activity Vegetation dynamics express themselves across a wide range of time scales from diurnal to inter-annual. Although we well understand broad phenological patterns such as leaf emergence, more subtle patterns of vegetation activity reflecting underlying physiological dynamics are less well known and require the unique hyperspectral capabilities and frequent repeat cycles provided by HyspIRI.

VQ3. Biogeochemical Cycles The biogeochemical cycles of C, H, O, N, P, S, and dozens of other elements sustain life on Earth, are central to human well-being and are at the core of some of our most pressing environmental concerns. As these elements travel between the atmosphere, biosphere, hydrosphere, and lithosphere, they shape the composition and productivity of ecosystems, they influence the climate regulating properties of the atmosphere, and they affect the quantity and quality of water supplies. Because human livelihood has long been tied to the production of food, fiber, and energy, our activities have had particularly profound effects on cycles of carbon, nitrogen, and water. Issues such as climate change, nitrogen deposition, coastal eutrophication, groundwater contamination, and erosion represent human alterations of these basic biogeochemical cycles. The HyspIRI instrument stands to advance our understanding of biogeochemical cycling in a number of important ways.

VQ4. Ecosystem Response to Disturbance Ecological disturbance plays a central role in shaping the Earth system. Disturbances (such as extreme weather events, fire, forest thinning or dieback, rangeland degradation, insect and pathogen outbreaks, and invasive species) affect vegetation biochemical and physiological processes with cascading effects on whole ecosystems. Similar effects take place based on disturbances to aquatic ecosystems, such as sediment re-suspension, nutrient input, or storm events, among many others. These and other disturbances often occur incrementally at spatial scales that fall well within the pixel size of current global satellite sensors. Since disturbance often involves changes in vegetation function (physiology and biochemistry) and composition (e.g., the spread of introduced species) that may not be detectable with conventional satellite approaches, detection and quantification often requires the full spectral signatures available from imaging spectroscopy. HyspIRI's high-fidelity imaging spectrometer will facilitate the study of ecological processes in disturbed areas at a level not possible with current satellite sensors. HyspIRI will directly address a range of ecological disturbance-response questions central to predictions of future global change.

VQ5. Ecosystems and Human Well-being
Ecosystem condition affects the humans dependent on those ecosystems for life and livelihood. For example, measurements of ecosystem condition derived from hyperspectral imagery can provide important insights into how ecosystem health is related to water quality, and by extension to human health. Similarly, hyperspectral data have been demonstrated to be effective for mapping the presence of invasive or undesirable plant species, which in turn affect the production of natural resources for human use by displacing desirable species with species of comparably lower value. Additional linkages from ecosystem to human condition include the monitoring of changes to ecosystems that may influence disease spread, resource availability, and resource quality. In border areas and areas with high

human population densities, such information may provide insights into underlying causes of social, economic, or political conflict. Therefore, measurements of ecosystem condition from HyspIRI provide the potential to better characterize relationships between ecosystem health and human well-being.

VQ6. Surface and Shallow Water Bottom Composition The surface composition within exposed rock and soils of a wide range of materials is revealed in the solar reflected light spectroscopic signature from 400 to 2510 nm. HyspIRI will be able to measure the surface composition of those areas with 75% or less vegetation cover, which occur seasonally over 30% of the land surface of the Earth. These HyspIRI measurements will enable new research opportunities for mineral and hydrocarbon resource investigation and emplacement understanding as called for in the Decadal Survey. With reasonable water clarity in the shallow-coastal and inland water regions, the bottom composition may be derived with imaging spectroscopy measurements in the region from 380 to 800 nm. A high fraction of the world's population lives in close proximity to these shallow water regions. Measurement by HyspIRI globally and seasonally of the composition and change of these environments will support understanding of their condition and associated resources and hazards.

TIR Science Questions and Importance

TQ1. Volcanoes and Earthquakes Volcanic eruptions and earthquakes yearly affect millions of lives, causing thousands of deaths, and billions of dollars in property damage. The restless earth provides premonitory clues of impending disasters; thermal infrared images acquired by HyspIRI will allow us to monitor these transient thermal phenomena. Together with modeling, we will advance our capability to one day predict some natural disasters.

TQ2. Wildfires Both naturally occurring wildfire and biomass burning associated with human land use activities have come to be recognized as having an important role in regional and global climate change. There consequently exists a substantial need for timely, global fire information acquired with satellite-based sensors. In conjunction with its long-wave infrared channels, the specialized 4-µm channel of the HyspIRI thermal sensor will fill this void and permit reliable detection of fires at much higher spatial resolution than other current or planned sensors. The unprecedented sensitivity will enable the detection and characterization of small, often land-use-related fires that remain undetected by lower resolution sensors.

TQ3. Water Use and Availability Given current trends in population growth and climate change, accurate monitoring of the Earth's freshwater resources at field to global scales will become increasingly critical (DS 2007, WGA 2006, 2008). Land surface temperature (LST) is a valuable metric for estimating evapotranspiration (ET) and available water because varying soil moisture conditions yield distinctive thermal signatures: moisture deficiencies in the root zone lead to vegetation stress and elevated canopy temperatures, while depleted water in the soil surface layer causes the soil component of the scene to heat rapidly. With frequent revisit (< 7 days), high-resolution TIR imaging can provide accurate estimates of consumptive water use at the spatial scale of human management and time scale of vegetation growth, needed 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 et al. 2007).

TQ4. Human Health and Urbanization Excess deaths occur during heat waves on days with higher-than-average temperatures and in places where summer temperatures vary more or where extreme heat is rare (e.g., Europe, northeastern U.S.). Exposure to excessive natural heat caused a reported 4,780 deaths during the period 1979-2002, and an additional 1,203 deaths had hyperthermia reported as a contributing factor (CDC, 2005). Urban heat islands (UHI) may increase heat-related impacts by raising air temperatures in cities approximately 1–6 °C over the surrounding suburban and rural areas due to absorption of heat by dark paved surfaces and buildings; lack of vegetation and trees; heat emitted from buildings, vehicles, and air conditioners; and reduced air flow around buildings (EPA, 2006). Critical to understanding the extent, diurnal and energy balance characteristics of the UHI is having remote sensing data collected on a consistent basis at high spatial resolutions to enable modeling of the overall responses of the UHI to the spatial form of the city landscape for different urban environments around the world. Unfortunately, current satellite systems do not have adequate revisit times or multiple thermal spectral bands to provide the information needed to model UHI dynamics and its impact on humans and the adjacent environment. HyspIRI will have a return time, spectral characteristics, and nighttime viewing capabilities that will greatly enhance our knowledge of UHI's form, spatial extent, and temporal characteristics for urban areas across the globe.

TQ5. Earth Surface Composition and Change The emitted energy from the exposed terrestrial surface of the Earth can be uniquely helpful in identifying rocks, minerals, and soils (Figure 11). Spaceborne measurements from HyspIRI will enable us to derive surface temperatures and emissivities for a variety of Earth's surfaces. Between day and night, Earth surface composition remains the same, but temperature changes. Daytime and nighttime HyspIRI images will be used to map temperatures and extract further information about properties of the surface such as thermal inertia. Buried sources of high temperatures, (such as lava tubes, underground fires in coal seams and high temperature rocks) cause hot spots on the Earth's surface. The temperature profile across these hot spots holds clues to the depth of the heat source. HyspIRI data will be used to map temperature anomalies, extract thermal profiles, and numerically derive the depth to the hot sources.

Combined Science Questions and Importance

CQ1. Coastal, Ocean and Inland Aquatic Environments: the oceans and inland aquatic environments are a critical part of global climate, the hydrologic cycle, and biodiversity. HyspIRI will allow for greatly improved separation of phytoplankton pigments, better retrievals of chlorophyll content, more accurate retrievals of biogeochemical constituents of the water, and more accurate determination of physical properties [GEO 2007].

CQ2. Wildfire, Fuel and Recovery: The 4 nm channel will greatly improve determination of fire temperatures, since it will not saturate like almost all other sensors with a similar wavelength channel. Coupling the multispectral TIR data with the VSWIR data will improve understanding of the coupling between fires and vegetation and associated trace gas emissions [Dennison et al 2006].

CQ3. Volcanoes and Surface Signatures HyspIRI's TIR channels will allow combined measurement of temperature, surface composition, and SO_2 emissions. These three parameters are critical to understand changes in a volcano's behavior that may herald an impending eruption. Fumaroles, lava lakes, and crater lakes often undergo characteristic increases in temperature associated with upwelling magma; SO_2 emissions both increase and decrease before some eruptions. Prediction of lava flow progress depends entirely on knowledge of effusion rate and temperature [Wright et al 2008].

CQ4. Ecosystem Function and Diversity HyspIRI will provide improved measures of plant physiological function through simultaneous estimates of surface temperature and plant biochemistry, improved estimates of surface biophysical properties (e.g., albedo, crown mortality) and energy balance and improved discrimination of plant species and functional types. No current sensor can simultaneously retrieve canopy temperature and quantify physiological or compositional changes in response to stress.

CQ5. Land Surface Composition and Change Combining information from the hyperspectral VSWIR and TIR scanners will greatly improve our ability to discriminate and identify surface materials: rocks, soils and vegetation. This is the first step to be able to quantitatively measure change of the land surface, whether naturally caused or of anthropogenic origin. Change detection, monitoring, and mapping forms the basis for formulating numerous policy decisions, from controlling deforestation to open-pit mining. HyspIRI will provide a greatly improved tool to make more informed and intelligent decisions.

CQ6. Human Health and Urbanization It appears that the world's urban population will grow by over 60% by 2030 [UNIS 2004]. Because of its enhanced hyperspectral capabilities in the VSWIR bandwidths and its multiple channels in the TIR, HyspIRI will provide much better data to improve measurement and modeling of urban characteristics around the world. One of the issues that has been problematic in the past is retrieving accurate measurements of temperature, albedo, and emissivity for specific surfaces across the complex and heterogeneous urban landscape. HyspIRI has the spatial resolution, spectral coverage, and repeat cycle to greatly improve these retrievals.

A core activity of the mission concept team to address the HyspIRI science and applications, under the guidance of NASA headquarters, has been to explore at different mission approaches, including a full satellite mission (VSWIR & TIR combined), independent instruments aboard the International Space Station (ISS), and small satellite accommodation options. Other significant activities such as detector and instrument prototype development as well as the HyspIRI preparatory campaign are discussed following this mission architectures section.

Mission Architectures

To provide options for implementation of HyspIRI and set of mission architectures were examined and studied and are described in the following sections.

Full HyspIRI Mission

The full HyspIRI mission combines the VSWIR and TIR instruments and answers the full set of science questions. The dedicated HyspIRI satellite is designed for a Sun synchronous, low Earth orbit. The overpass time is nominally 10:30 a.m. ± 30 minutes. The VSWIR has a 19-day revisit at the Equator, and the TIR has a 5-day revisit at the Equator. The TIR measures both day and night data with 1 daytime image and 1 nighttime image every 5 days. The concept altitude for the full mission spacecraft is 626 km at the Equator. The number of acquisitions for different parts of the Earth in a 19-day cycle is shown in Figure 2. This figure is color-coded such that areas that are green meet the requirement and areas that are light blue, dark blue, and black exceed the requirement. Examination of the TIR map indicates that as one moves poleward the number of acquisitions exceeds the requirements with daily coverage at the poles. The slightly more poleward extension of the TIR instrument is due to its larger swath width. VSWIR data acquisitions are also limited by the maximum Sun elevation angle with no data being acquired when the Sun elevation angle is less than 20 degrees.

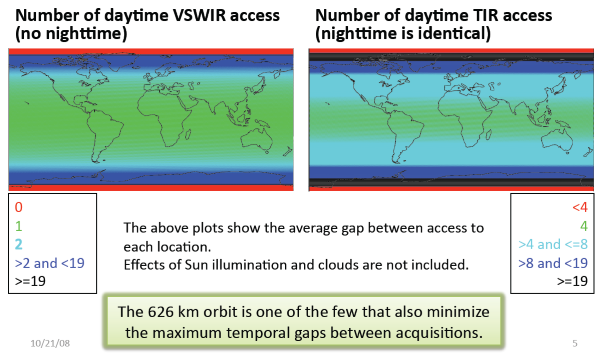

Figure 2: Number of image acquisitions in 19 days.

The VSWIR instrument will acquire data between 380 and 2510 nm in 10-nm contiguous bands. The position of these bands will be known to 0.5 nm. The instrument signal-to-noise ratio performance was modeled for a range of benchmark radiance levels designated by the SSG. These are shown in Figure 3. The VSWIR imaging spectrometer is designed to have low polarization sensitivity and low scattered light to enable coastal ocean habitat science and applications. To reduce the impact of sun glint the VSWIR instrument is pointed 4 degrees in the backscatter direction. A sun glint report is given the appendix of this document. The nominal data collection scenario involves observing the land and coastal zone to a depth of < 50 m at full spatial and spectral resolution and transmitting these data to the ground.

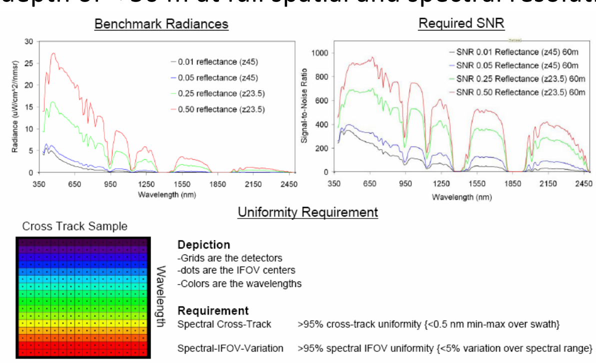

Figure 3. HyspIRI-VSWIR Key Signal-to-Noise and Uniformity Requirements

Over the open ocean and the ice sheets, data will be averaged to a spatial resolution of 1 km. The VSWIR instrument has a swath width of 153 km with a pixel spatial sampling of 60 m at nadir resulting in a temporal revisit of 19 days at the Equator. The nominal overpass time is 10:30 a.m. The absolute radiometric accuracy requirement is greater than 95%, and this will be maintained by using an onboard calibrator as well as monthly lunar views and periodic surface calibration experiments.

The TIR instrument acquires measurements in eight spectral bands, seven of these are located in the thermal infrared part of the spectrum between 7 and 13 µm, and the remaining band is located in the mid infrared part of the electromagnetic spectrum around 4 um. The center position and width of each band is given in Table 4. The exact spectral location of each band was based on the measurement requirements identified in the science-traceability matrices, which included recognition that other sensors were acquiring related data such as ASTER and MODIS. HyspIRI will contribute to maintaining a long time series of these measurements. For example the positions of three of the TIR bands closely match the first three thermal bands of ASTER, and the positions of two of the TIR bands of MODIS typically used for split-window type applications (ASTER bands 12–14 and MODIS bands 31 and 32).

Table 4. Nominal characteristics of the HyspIRI 8 TIR spectral bands.

	Wavelength	Spectral Bandwidth	Min Nominal Radiance and Temperature	Max Nominal Radiance and Temperature
	(microns)	(microns)	(W/m^2/micron/sr)	(W/m^2/micron/sr)
Band 1	3.98	0.08	14 (400 K)	9600 (1400 K)
Band 2	7.35	0.32	0.34 (200 K)	110 (500 K)
Band 3	8.28	0.34	0.45 (200 K)	100 (500 K)
Band 4	8.63	0.35	0.57 (200 K)	94 (560 K)
Band 5	9.07	0.36	0.68 (200 K)	86 (500 K)
Band 6	10.53	0.54	0.89 (200 K)	71 (500 K)
Band 7	11.33	0.54	1.1 (200 K)	58 (500 K)
Band 8	12.05	0.52	1.2 (200 K)	48 (500 K)

A key science objective for the TIR instrument is the study of hot targets (volcanoes and wildfires), so the saturation temperature for the 4-µm channel is set high (1400 K) whereas the saturation temperatures for the thermal infrared channels are set at 400 K. The temperature resolution of the thermal channels is much finer than the mid-infrared channel, which (due to its high saturation temperature) will not detect a strong signal until the target is above typical terrestrial temperatures. All the TIR channels are quantized at 14 bits.

The TIR instrument will have a swath width of 600 km with a pixel spatial resolution of 60 m resulting in a temporal revisit of 5 days at the equator. The instrument will be on both day and night, and it will acquire data over the entire surface of the Earth. Like the VSWIR, the TIR instrument will acquire full spatial resolution data over the land and coastal oceans (to a depth of < 50 m), but over the open oceans the data will be averaged to a spatial resolution of 1 km. The large swath width of the TIR will enable multiple revisits of any spot on the Earth every week (at least 1 day view and 1 night view). This is necessary to enable monitoring of dynamic or cyclical events such as volcanic hotspots or crop stress associated with water availability.

The radiometric accuracy and precision of the instrument are 0.5 K and 0.2 K, respectively. This radiometric accuracy will be ensured by using an on-board blackbody and view to space included as part of every row of pixels (60 m × 600 km) observed on the ground. There will also be periodic surface validation experiments and monthly lunar views.

ISS Demonstration Mission Options

Instrument studies were conducted using JPL's Team X to analyze the feasibility of deploying the VSWIR and TIR instrument on the International Space Station (ISS). The ISS orbits at a nominal altitude of ~400 km and an inclination of 51.6 degrees with an orbital period of 91 minutes. This provides earth viewing capabilities for the VSWIR and TIR ranging from -52° to +52° latitudes across all longitudes. An inclined orbit provides variable diurnal sampling vs. sun-synchronous orbit. This variable illumination and observation geometry has elements in common with the long record of precursor airborne measurements that are acquired with variable flight line orientations and at different times of day. The impact of deploying the HyspIRI instruments on the ISS is science question dependent, in some cases it is possible to go beyond the original question, e.g. to examine the impact of the diurnal cycle, whereas in other cases the question could not be addressed e.g. if the question required observations from high latitude regions.

VSWIR Concept Demonstration for the ISS

The VSWIR technology demo on the ISS would demonstrate early HyspIRI VSWIR Science results for a large fraction of the terrestrial surface & coasts at ±52 degrees latitude at 30m resolution. The tech demo would demonstrate the VSWIR detector with ≤380 to ≥2510 nm spectral range using a >=1000 cross track elements; Slit uniformity and performance in space; Grating performance to HyspIRI requirements; 4x lossless data compression and cloud screening; On-board calibration; Low cost Thales cryocoolers; Detector and Electronics; as well as IPM onboard storage and processing. Table 5 shows some of the VSWIR science and applications that could be advanced with an ISS demonstration. Table 6 compares the mission capabilities of the full HyspIRI VSWIR and the ISS demonstration, while Figure 4 shows the global access for VSWIR measurements from the ISS.

Table 5. VSWIR Science and application advanced with ISS demonstration.

Science and Applications
Ecosystem Measurement for Climate Feedback
Pattern and Spatial Distribution of Ecosystems and their Components
Ecosystem Function, Physiology, Diversity and Seasonal Activity
Biogeochemical Cycles
Ecosystem Disturbance
Fires: Fuel, Severity, Recovery, and Carbon Release
Black Carbon/Dust Effects on Snow and Ice
Ecosystem and Human Health
Earth Surface Composition
Coral reefs and Coastal Ocean Habitats

Table 6. Comparison of mission parameters between the full HyspIRI VSWIR and an ISS demonstration.

	DS Mission Flight Instrument	ISS Tech Demo Instrument
Orbit	LEO, Sun Sync.	51.6 north and south latitude
Mission Duration	3 years with goal of 5 years	6 months with goal of 2 years
FOV	12 degrees	5.67 degrees
Data rate	300 mbps	9.1 mbps
Coverage	Global and shallow coastal	25% of land mass
Revisit	19 days	~6 months
Parts	Class C	COTS
Swath	145 km	30 km
Resolution	60m	30 m
Spatial	2400 pixels	~1000 pixels

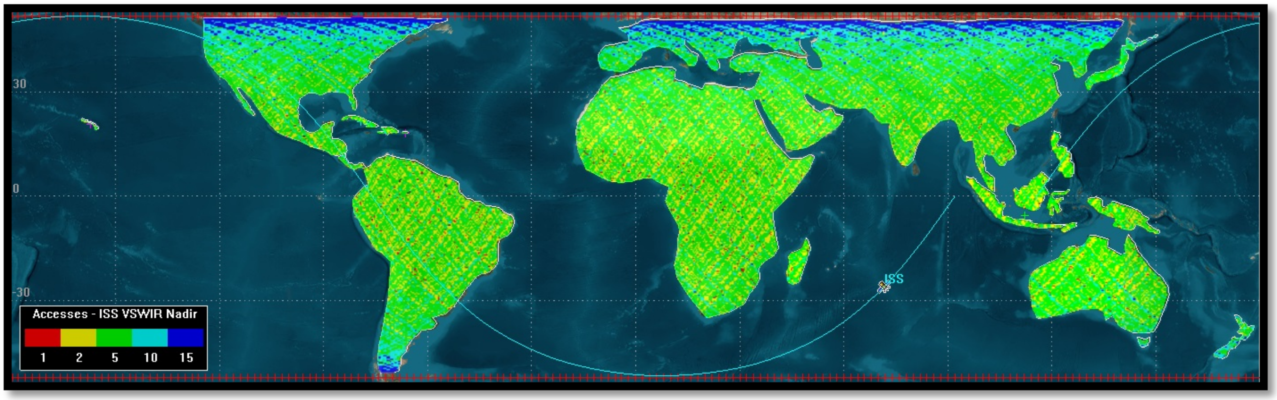

Figure 4. Measurement access offered from a VSWIR imaging spectrometer demonstration on the ISS.

TIR Concept Demonstration for the ISS

The Team X TIR study determined that it would be feasible to leverage the existing PhyTIR instrument on the ISS JEM module as a technology demo to demonstrate TIR Science results for the terrestrial surface ±52 degrees latitude at 57-m nadir cross-track resolution and 38-m in-track resolution. The ISS tech demo would use core of PHyTIR (optical and scan system, focal plane, cryocoolers, focal-plane interface electronics) with minor changes, use commercial Thales coolers, as are used in PHyTIR, build new electronics for control of instrument and interface to ISS. The JEM module cooling loop would be used to dump heat from cryocoolers and electronics eliminating the radiator and passive cooler. Goddard's Intelligent Payload Module (IPM) would also be included as data interface to ISS. The key science and applications that can be achieved by a TIR demonstrations on the ISS are given below. Table 7 gives a comparison of full mission vs Tech Demo parameters

TIR Science and Applications from the ISS:

- Volcanoes: Tech demo will demonstrate we can quantitatively measure hot spots and gas emissions and measure lava composition. Due to the limited duty cycle we will not be able to characterize the behavior of all active volcanoes. Reduced number of spectral bands will impact our ability to discriminate certain geological materials. Higher spatial resolution from the ISS of 57x38m (Nadir x in-track) will improve material discrimination compared with planned 60m spatial resolution for HyspIRI-TIR.
- Wildfires: Tech demo will allow us to demonstrate that measurements of combined mid and thermal infrared active fire measurements can be used to calculate carbon emissions. ISS orbit will allow us to characterize burning over diurnal cycle. Due to limited duty cycle we will not be able to fully characterize each fire regime.
- Water Use and Availability: Tech demo will allow us to characterize ecosystem "hot spots" and quantify and understand variations in consumptive water use over irrigated systems. Tech demo will not allow continuous global coverage. Higher spatial resolution from the ISS (57x38m) will improve discrimination of evapotranspiration (ET) at the field scale. ISS orbit will enable ET to be studied over full diurnal cycle.
- Urbanization/Human Health: Tech demo will allow us to characterize urban areas and urban heat islands. Reduced numbers of bands will limit our ability to discriminate urban materials and limited duty cycle will impact our ability to systematically characterize urban areas. Higher

spatial resolution from the ISS (57x38m) will improve material discrimination compared with planned 60m for HyspIRI-TIR.

- Earth surface composition and change: For geological and soil mapping reduced number of bands will limit our ability to discriminate materials. Limited duty cycle will impact our ability to obtain cloud-free data. Higher spatial resolution on ISS will improve material discrimination as noted above.

Table 7. Comparison of mission parameters between the full HyspIRI TIR and an ISS demonstration.

Parameter	Full HyspIRI-TIR	ISS TIR
Orbital Altitude	626 km	400 km
Ground Spatial Resolution	60 m	57x38m (Nadir x in-track)
Land Surface Coverage	Full Earth <5-day revisit	±52° latitude with range of revisit periods. Subset of data downlinked.
Time-of-Day Coverage	10:30 AM and 10:30 PM	All times of day
Spectral Bands	8	5 (4 µm for fire detection; 8.3, 8.6, 9.1, and 11.3 µm for temperature measurement)
Average Data Downlink	24 Mbits/s	3 Mbits/s
Swath Width	51° 596 km	51°, 384 km; may be reduced based on ISS JEM accommodations
Mission Duration	3 years	1 year (goal)
In-Flight Calibration	Space and internal blackbody	2 internal blackbodies (reliable space view not available)

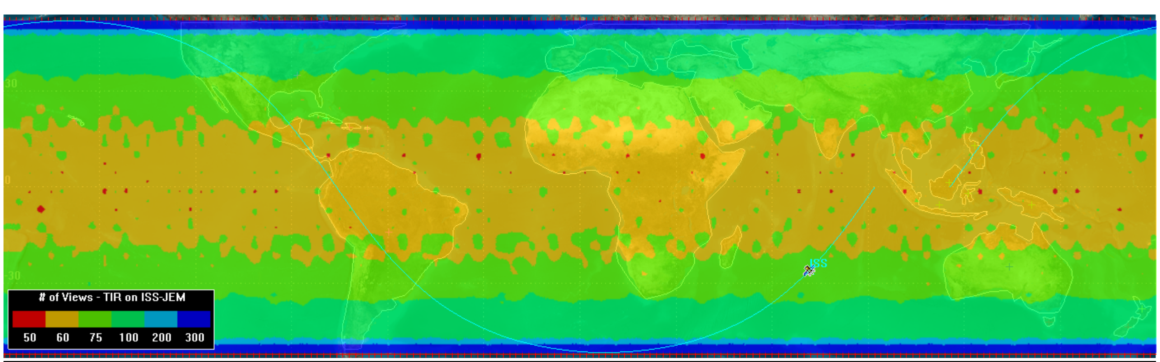

Figure 5. Measurement access offered from a TIR instrument demonstration on the ISS.

Respective instrument reports were developed for the VSWIR and TIR instruments on the ISS and delivered to NASA headquarters. These reports are also included as appendices of this report.

Small Satellite Accommodation

In addition to the full mission and ISS demonstration options, studies were performed to assess smallsat options for the VSWIR and TIR on separate platforms. These studies, with three separate spacecraft vendors (names withheld because of potential future competition), identified feasible mission architectures for the TIR and VSWIR each on their own small satellite. The studies were comprehensive and included analysis of mass, power, data link, data storage, thermal and pointing performance. The studies showed that there is at least one solution that meets all TIR and VSWIR requirements within JPL Design Principle margins. This implementation approach would cost roughly the same as a single satellite full mission but provide flexibility to fund and launch the instruments separately.

For the VSWIR instrument, the smallsat option takes advantage of advances in spectrometer design and detector technology to provide 30 m spatial sampling and a 16 day revisit that is more closely aligned with the traditional LandSat spatial and temporal coverage characteristics and consistent with the report: “Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program.”

The smallsat TIR instrument is the same 60 m GSD, 5 day revisit updated to include the latest design iterations resulting from the PHyTIR effort. Figure 6 shows example configurations of the smallsat VSWIR and TIR instrument respectively.

Potential options exist to include the HyspIRI IPM for near real-time processing and downlink for both the VSWIR and TIR smallsat solutions. However further study is required to identify the optimal approach for incorporation of the IPM.

These smallsat implementation studies were pursued to provide NASA additional options and more flexibility for pursuing the most urgent and unique of the HyspIRI science and applications objectives.

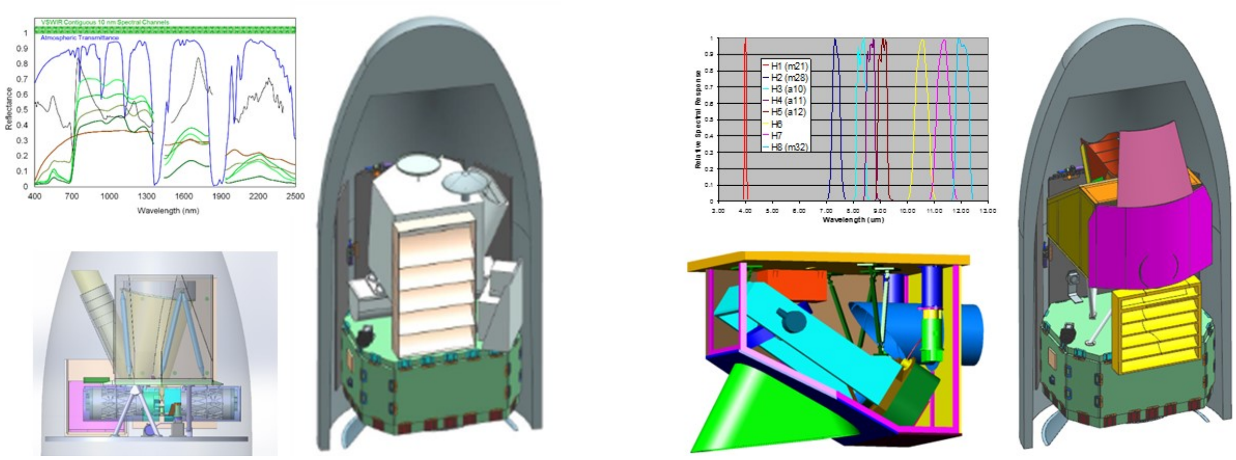

Figure 6. Example configurations of the VSWIR (left) and TIR (right) for standalone smallsat mission with the faring of a Pegasus launch vehicle. This 2014 concept if for the VSWIR with 30 sampling and a 16 day revisit achieved with a pair for

Dyson imaging spectrometer and a single telescope. The TIR requirements are met with an evolved version of the PHyTIR IIP instrumentation developed demonstration from 2011 to 2014.

Airborne Campaigns

To support the development of the HyspIRI mission and prepare the community for HyspIRI-enabled science and applications research, NASA sponsored the HyspIRI preparatory airborne campaign. For this activity, NASA has selected 14 investigations that are summarized in Table 7. Measurements for these investigations are acquired by the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and the MODIS/ASTER Airborne Simulator (MASTER) instruments on the NASA ER-2 high-altitude aircraft. These data acquisitions cover 6 large areas that capture significant climatic and ecological gradients. In addition, each of the large areas is measured in the spring, summer and autumn seasons to begin to simulate the seasonal capability of the HyspIRI flight mission. A geographical representation of the 6 large areas is shown in Figure 7 along with an example of one of the airborne data sets collected in 2013. A goal of this activity is to demonstrate important science and applications research results that are uniquely enabled by HyspIRI-type data, taking advantage of the contiguous spectroscopic measurements of the AVIRIS, the full suite of MASTER TIR bands, or combinations of measurements from both instruments. An additional goal of this preparatory airborne campaign is to test and demonstration the HyspIRI level 1 and level 2 processing algorithms for the VSWIR and TIR instrument and advance their maturity for the HyspIRI mission. Two full years of data have been acquired in 2013 and 214, a third year is planned for collection in 2015.

Table 8. Investigations selected as part of the HyspIRI preparatory airborne campaign.

Principal Investigator	Investigation Title
Paul Moorcroft, Harvard University	Linking Terrestrial Biosphere Models with Imaging Spectrometry Measurements of Ecosystem Composition, Structure, and Function
Dar Roberts, U. C. Santa Barbara	HyspIRI discrimination of plant species and functional types along a strong environmental-temperature gradient
Philip Townsend, U. Wisconson	Measurement of ecosystem metabolism across climate and vegetation gradients in California for the 2013-2014 NASA AVIRIS/MASTER airborne campaign
Susan Ustin, U. C. Davis	Identification of Plant Functional Types By Characterization of Canopy Chemistry Using an Automated Advanced Canopy Radiative Transfer Model
Matthew Clark, Cal. State Sonoma	Spectral and temporal discrimination of vegetation cover across California with simulated HyspIRI imagery
Bo-Cai Gao, Naval Research Laboratory	Characterization and Atmospheric Corrections to the AVIRIS-Classic and AVIRISng Data to Support the HyspIRI Preparatory Airborne Activities
Bernard Hubbard, USGS	Using simulated HyspIRI data for soil mineral mapping, relative dating and flood hazard assessment of alluvial fans in the Salton Sea basin, Southern California
George Jenerette, U. C. Riverside	Assessing Relationships Between Urban Land Cover, Surface Temperature, and Transpiration Along a Coastal to Desert Climate Gradient
Thomas Kampe, NEON	Synergistic high-resolution airborne measurements of ecosystem structure and process at NEON sites in California
Raphael Kudela, U. C. Santa Cruz	Using HyspIRI at the Land/Sea Interface to Identify Phytoplankton Functional Types
Ira Leifer, Bubbleology	Hyperspectral imaging spectroscopic investigation of California natural and anthropogenic fossil methane emissions in the short-wave and thermal infrared
Shunlin Liang U Maryland	Characterizing surface energy budget of different surface types under varying climatic conditions from AVIRIS and MASTER data
Jan van Aardt, Rochester Institute of Techology	Investigating the impact of spatially-explicit sub-pixel structural variation on the assessment of vegetation structure from HyspIRI data
Wendy Calvin, U Nevada	Energy and Mineral Resources: Surface composition mapping that identifies resources and the changes and impacts associated with their development

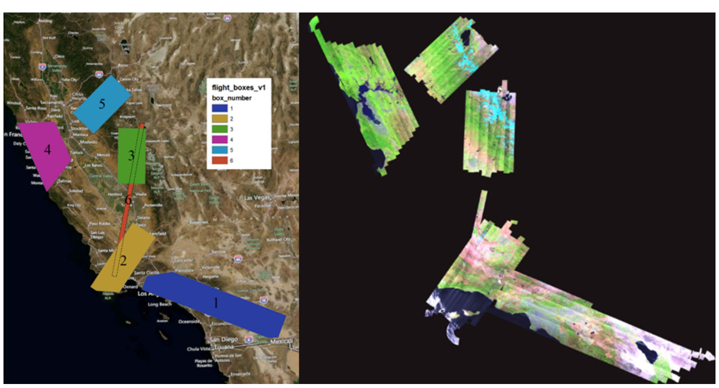

Figure 7. HyspIRI preparatory airborne campaign measurement collection areas. These 6 large area have been measured in three seasons of 2013 and 2014 and are planned to be collected in the 2015. The 14 investigations are selected to advance the maturity of HyspIRI science and applications. The large, multi season, and multi year data sets are being used to test and mature HyspIRI level 1 and level 2 processing algorithms.

Sustainable Land Imaging

In 2013 the NRC released the report: Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program. This report includes future measurements options that are consistent with the HyspIRI TIR instrument in conjunction with a 30 m surface sampling and 16 day revisit version of the VSWIR imaging spectrometer. Figure 8 shows the spectral coverage overlap between the HyspIRI VSWIR and TIR and the Landsat series of instruments. With guidance from NASA, the HyspIRI mission concept team has worked to evolve the mission concept to become compatible with this element of the Landsat and Beyond report by evolving the baseline VSWIR instrument to provide a 30 m sampling and 16 day revisit capability.

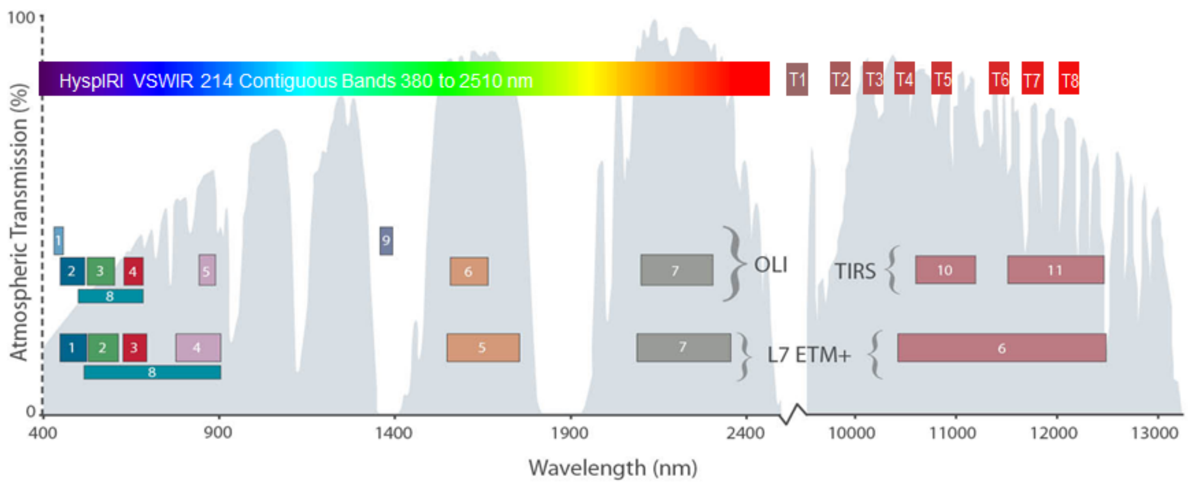

Figure 8. Spectral coverage of the HyspIRI VSWIR and TIR in comparison to LandSat 7 and 8. This is for the updated VSWIR instrument concept that provides 30 m surface sampling and a 16 day revisit.

Conclusion

Beginning in the 2007/2008 timeframe with release of the NRC Decadal Survey: Earth Science and Applications from Space the HyspIRI mission concept team and HyspIRI science study group have worked to support the NASA program office and provided options to implement the HyspIRI mission. These efforts have included broad community engagement with a Data Product Symposium and a Science and Applications Workshop held each year. In parallel, a series of mission concept implementation options have been provided including a full mission, demonstration missions on the ISS, and separate instrument smallsat missions. In concert with these activities the technologies necessary to implement HyspIRI have been and assessed and matured where feasible.

In 2013 the NRC released the report: Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program. This report identifies measurements that are consistent with the HyspIRI TIR instrument and with a 30 m surface sampling VSWIR imaging spectrometer with 16 day revisit. The HyspIRI concept team has worked to evolve the mission concept to support the guidance from both NRC reports. For both the Decadal Survey and the Landsat and Beyond report, the HyspIRI effort has been guided by the broad range of science and applications that are described in these reports.

Over the period from 2007 to present a significant volume of documentary material has been generated and made broadly available via the HyspIRI website. These efforts are summarized in this Comprehensive Development Report that consists of this executive summary and wide ranging set of appendices.

Appendix

Category	Document
Reports and Whitepapers	Compiled Reports and Whitepapers from 2008-2014
Individual Report files	2014 HyspIRI Separate Platforms Whitepaper
	2014 PHyTIR Test Results
	2012 Workshop Report
	2012 TIR Band Study Report
	2011 Workshop Report
	2011 Symposium Report
	2011 Sun Glint Report
	2011 High Temperature Saturation Report
	2010 Workshop Report
	2009 Workshop Report
	2008 Whitepaper and Workshop Report
	TRL Assessment Report
HyspIRI Workshop Material	2014 Compiled Workshop
	2013 Compiled Workshop
	2012 Compiled Workshop
	2011 Compiled Workshop
	2010 Compiled Workshop
	2009 Compiled Workshop
	2008 Compiled Workshop
Individual Workshop files	2014 Workshop Agenda and Presentations
	2013 Workshop Agenda and Presentations
	2012 Workshop Agenda and Presentations
	2011 Workshop Agenda and Presentations
	2010 Workshop Agenda and Presentations
	2009 Workshop Agenda and Presentations
	2008 Workshop Agenda and Presentations

Category	Document
HyspIRI Symposium Material	2014 Compiled Symposium
	2013 Compiled Symposium
	2012 Compiled Symposium
	2011 Compiled Symposium
	2010 Compiled Symposium
Individual Symposium files	2014 Symposium Agenda and Presentations
	2013 Symposium Agenda and Presentations
	2012 Symposium Agenda and Presentations
	2011 Symposium Agenda and Presentations
	2010 Symposium Agenda and Presentations
TeamX ISS Accommodation	VSWIR ISS Study
	TIR ISS Study
2014 Small Spacecraft Vendor Presentation	2014 Small Spacecraft Vendor Presentation
Algorithm Theoretical Basis Documents (ATBDs)	TIR Level 2 Surface Radiance
	TIR Level 2 Surface Temperature and Emissivity
	TIR Cloud Mask
	VSWIR Level 2 Water Leaving Reflectance
	VSWIR Level 2 Land Surface Reflectance
Science Applications	
Summaries	Disasters
	Water Resources
	Health and Air Quality
Science Application White Papers	Hyspiri Volcanoes
	Public Health