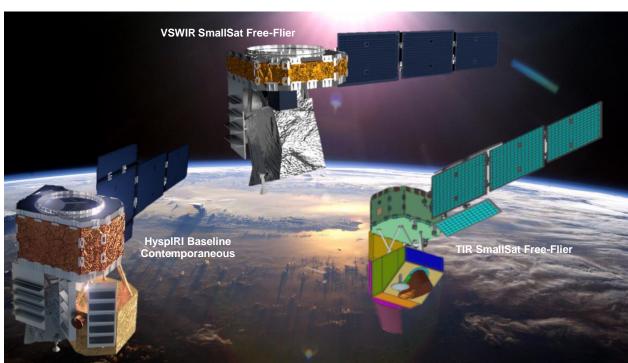


HyspIRI Final Report

HyspIRI Mission Concept Team



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Executive Summary

NASA's Hyperspectral Infrared Imager (HyspIRI) concept was the subject of a pre-formulation study focused on a global mission of important new Earth science and applications objectives. HyspIRI addresses those objectives with 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. In the 2013 timeframe the team developed a compact wide VSWIR Dyson spectrometer architecture to enable a wide swath and 30 m spatial resolution. The TIR technology investment in PhyTIR is now operating on the ISS as an Earth Venture Instrument (EVI) named ECOSTRESS. The Dyson VSWIR technology was selected in 2018 as an EVI named EMIT, and both EVI funded instruments represent a major risk reduction for the HyspIRI pre-formulation study and for measurement of observables of the HyspIRI type in the future.

Building on the 2007 Decadal Survey, HyspIRI developed six key science and application focus areas: (1) global terrestrial ecosystem composition and function; (2) fire fuel, temperature, severity and recovery; (3) vegetation evapotranspiration including agricultural lands; (4) snow and ice hydrology, albedo, dust, and black carbon; (5) volcano lava composition and emissions; and (6) coastal and inland water habitats. These important science and applications contributions fill gaps in current Earth measurements from space and are uniquely addressed by HyspIRI's combined imaging spectroscopy, thermal infrared measurements, and Intelligent Payload Module (IPM) direct broadcast capability. To demonstrate the feasibility of the HyspIRI science and applications contributions, Appendix A lists publications, by discipline, that have been produced as a result of the HyspIRI preparatory airborne activities. These activities enabled science teams to develop and test Level 2 and Level 3 algorithms and products to prepare for a future space-based mission of the HyspIRI type. While six key focus areas are identified, HyspIRI-type measurements contribute to a broad set of additional science and applications areas highlighted in Appendix A and in the white papers contributed to the 2017 Decadal Survey.

Two key science contributions of HyspIRI type measurements are: (1) the global 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 volcano and fire-related emissions, as well as the evapotranspiration status of terrestrial vegetation. In these science areas, the urgency and uniqueness of HyspIRI measurements is traced to the lack of an accurate global baseline of terrestrial ecosystem composition and functional diversity. Such a baseline is required to accurately initialize the ecosystem models that underpin current Earth system models. Improved fire emission knowledge is enabled by the frequent revisit of multispectral thermal measurements with fine spatial sampling.

The HyspIRI mission was identified in the 2007 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 combined with a multispectral thermal sensor 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. The 2017 HyspIRI TIR instrument has spatial resolution of 60 m at nadir, and the VSWIR has a spatial resolution of 30 m. The final architecture VSWIR instrument has a revisit time of 16 days; the TIR instrument has a revisit time of 5 days. HyspIRI also includes an IPM that enables a subset of the data to be processed onboard the satellite and downlinked to the ground in near real-time. Current space computer capabilities allow for onboard processing, compression, and cloud screening to enable direct broadcast of the VSWIR and TIR data sets via ground networks of satellite receiving stations.

A key update to the VSWIR imaging spectrometer occurred at the request of NASA in the 2013 timeframe. This was to develop an updated architecture to provide 30 m surface sampling and 16 day revisit, that was consistent with the 2013 NRC report: Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program. This led to the current VSWIR architecture that also meets the 2007 HyspIRI requirements. For this architecture, an optically fast and compact Dyson spectrometer is used. Investment in HgCdTe focal plane array technologies also moved the detector array dimensions from 1280 by 480 elements, to 3072 by 512 elements. Two of these larger detector arrays and the Dyson architecture allows for a Landsat class swath width of 185 km with 30 m spatial sampling.

As called for in the 2007 Decadal Survey, HyspIRI is a global mission, with full terrestrial and coastal aquatic coverage developed to address a set of new and important science and applications questions and objectives. To explore architectures 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 was 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 representatives from 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 a number of reports to document status and evolution of the HyspIRI mission concept and its enabled science and applications. These documents, along with workshop reports and content, contain more than 1000 pages and can be accessed online [http://hyspiri.jpl.nasa.gov/].

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
Jeffrey Luvall	Marshall 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

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). Table 2 gives the high level questions. The impetus behind these questions is discussed in Appendix B, with corresponding underlying detail.

Table 2. HyspIRI mission concept science and applications questions developed by the SSG, informed by guidance from the 2007 Decadal Survey.

Question #	Question
vq1	What is the global spatial pattern of ecosystem and diversity distributions and how do ecosystems differ in their composition and/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, and/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?

To advance the HyspIRI mission, the SSG has held regular telecons. In addition, workshops with the SSG and the broader science and applications community have typically been held twice a year. These have been designated the HyspIRI Science and Applications Workshop (hosted by JPL) and the HyspIRI Data Products Symposium (hosted by GSFC). These open meetings have facilitated communication between the broader communities and brought together the efforts of the HyspIRI mission concept team and the SSG. Figure 1 shows pictures from the workshops of 2014 as well as the final joint workshop in 2018. These workshop were held annually from 2008 through 2018. Reports and presentations from these meetings are maintained at the HyspIRI website [http://hyspiri.jpl.nasa.gov/].





Figure 1. 2014 HyspIRI Data Products Symposium in June at GSFC (left) and the 2014 Science and Applications Workshop in October at Caltech (right) and final joint workshop of 2018 at the Carnegie Institute of Science, Washington, DC.

While the 2007 HyspIRI mission concept activity ended in 2018, the 2017 National Research Council Decadal Survey recommended a new NASA "Designated" program element to address a set of five high-value Targeted Observables during the next decadal period. One of these is the Surface Biology and Geology (SBG) Targeted Observable that will enable improved measurements of Earth's surface characteristics to provide valuable information on a wide range of Earth system processes. The specific SBG targeted observables – surface biology and geology, functional traits of terrestrial vegetation and inland and near-coastal aquatic ecosystems, active geologic processes, ground and water temperature, gross primary production (GPP), and snow spectral albedo – are to be implemented with a maximum recommended development cost of \$650M (in FY18\$). An approach to achieve the SBG observable is high spectral resolution (or hyperspectral) imagery in the visible and shortwave infrared (VSWIR) and thermal infrared (TIR) provides the desired capabilities to address important geological, hydrological, and ecological questions; therefore, hyperspectral imagery with moderate spatial resolution (30-60m) and multispectral thermal IR at 60m resolution are identified as a priority for SBG implementation. To assess the feasibility of an SBG, a CATE evaluation of the HyspIRI concept found that the concept is technically mature and costs are well-understood.

Chapter 1: Decadal Survey

1.1: Summary of 2007 ESAS Decadal Survey Hyperspectral Infrared Imager (HyspIRI) Mission Concept

From the National Research Council. 2007. Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond:

"Ecosystems respond to changes in land management and climate through altered nutrient and water status in vegetation and changes in species composition. A capability to detect such changes provides possibilities for early warning of detrimental ecosystem changes, such as drought, reduced agricultural yields, invasive species, reduced biodiversity, fire susceptibility, altered habitats of disease vectors, and changes in the health and extent of coral reefs. Through timely, spatially explicit information, the observing capability can provide input into decisions about management of agriculture and other ecosystems to mitigate negative effects. The observations would also underpin improved scientific understanding of ecosystem responses to climate change and management, which ultimately supports modeling and forecasting capabilities for ecosystems. Those, in turn, feed back into the understanding, prediction, and mitigation of factors that drive climate change.

Volcanos are a growing hazard to large populations. Key to an ability to make sensible decisions about preparation and evacuation is detection of the volcanic unrest that may precede eruptions, which is marked by noticeable changes in the visible and IR, centered on craters. Assessment of soil type is an important component of predicting susceptibility to landslides. Remote sensing provides information critical for exploration for minerals and energy sources. In addition, such environmental problems as mine-waste drainage and unsuitability of soils for habitation, soil degradation, poorly known petroleum reservoir status, and oil-pipeline leakage in remote areas can be detected and analyzed with modern hyperspectral reflective and multispectral thermal sensors.

Background: Global observations of multiple surface attributes are important for a wide array of Earth system studies. Requirements for ecosystem studies include information on canopy water content, vegetation stress and nutrient content, primary productivity, ecosystem type, invasive species, fire fuel load and moisture content, and such disturbances as fire and insect damage. In coastal areas, measurements of the extent and health of coral reefs are important. Observations of surface characteristics are crucial to exploration for natural resources and for managing the environmental effects of their production and distribution. Forecasting of natural hazards, such as volcanic eruptions and landslides, is facilitated by observations of surface properties.

Science Objectives: The HyspIRI mission aims to detect responses of ecosystems to human land management and climate change and variability. For example, drought initially affects the magnitude and timing of water and carbon fluxes, causing plant water stress and death and possibly wildfire and changes in species composition. Disturbances and changes in the chemical climate, such as O3 and acid deposition, cause changes in leaf chemistry and the possibility of vulnerability to invasive species. The HyspIRI mission can detect early signs of ecosystem

change through altered physiology, including agricultural systems. Observations can also detect changes in the health and extent of coral reefs, a bellwether of climate change. Those capabilities have been demonstrated in space-borne imaging spectrometer observations but have not been possible globally with existing multispectral sensors.

Variations in mineralogical composition result in variations in the optical reflectance spectrum of the surface that indicate the distribution of geologic materials and the condition and types of vegetation on the surface. Gases from within the Earth, such as CO2 and SO2, are sensitive indicators of volcanic hazards. They also have distinctive spectra in both the optical and near-IR regions. The HyspIRI mission would yield maps of surface rock and soil composition that in many cases provide equivalent information to what can be derived from laboratory x-ray diffraction analysis. The hyperspectral images would be a valuable aid in detecting the surface expression of buried mineral and petroleum deposits. In addition, environmental disturbances accompanying past and current resource exploitation would be mapped mineralogically to provide direction for economical remediation. Detection of surface alterations and changes in surface temperature are important precursors of volcanic eruptions and will provide information on volcanic hazards over areas of Earth that are not yet instrumented with seismometers. Variations in soil properties are also linked to landslide susceptibility.

Mission and Payload: The HyspIRI mission uses imaging spectroscopy (optical hyperspectral imaging at 400-2500 nm and multispectral IR at $8\text{-}12~\mu\text{m}$) of the global land and coastal surface. The mission would obtain global coverage from LEO with a repeat frequency of 30 days at 45-m spatial resolution. A pointing capability is required for frequent and high-resolution imaging of critical events, such as volcanos, wildfires, and droughts.

The payload consists of a hyperspectral imager with a thermal multispectral scanner, both on the same platform and both pointable. Given recent advances in detectors, optics, and electronics, it is now feasible to acquire 'pushbroom' images with 620 pixels cross-track and 210 spectral bands in the 400- to 2,500-nm region. If three spectrometers are used with the same telescope, a 90-km swath results when Earth's curvature is taken into account. A multispectral imager similar to ASTER is required in the thermal IR region. For the thermal channels (five bands in the 8- to 12-µm region), the requirements for volcano-eruption prediction are high thermal sensitivity of about 0.1 K and a pixel size of less than 90 m. An optomechanical scanner, as opposed to a pushbroom scanner, would provide a wide swath of as much as 400 km at the required sensitivity and pixel size.

The HyspIRI mission has its heritage in the imaging spectrometer Hyperion on EO-1 launched in 2000 and in ASTER, the Japanese multispectral SWIR and thermal IR instrument flown on Terra. The hyperspectral imager's design is the same as the design used by JPL for the Moon Mineralogy Mapper (M3) instrument on the Indian Moon-orbiting mission, Chandrayaan-1, and so will be a proven technology.

Cost: About \$300 million.

Schedule: Mid-2015. Both sensors, the hyperspectral imager and the thermal-IR multispectral scanner, have direct heritage from the M3 and ASTER instruments, respectively. The technology is currently available, and so a 2015 launch is feasible."

Chapter 2: Mission Architectures

To provide options for implementation of HyspIRI, a set of mission architectures was examined and studied and updated from 2008 to 2018 and are described in the following sections.

2.1: Full HyspIRI Mission

The initial full HyspIRI mission combines the VSWIR and TIR instruments and addresses 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. This initial VSWIR had 60 m spatial sampling, a 150 km swath, and a less than 20-day revisit at the Equator (after 2013 this became 30 m and 16 day revisit), 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 this full HyspIRI mission spacecraft is 626 km at the Equator. The number of acquisitions for different parts of the Earth is shown in Figure 2. This figure is colorcoded 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.

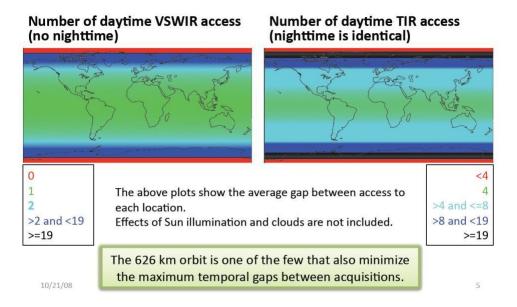
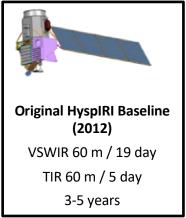


Figure 2: Number of image acquisitions in 19 days for early study of HyspIRI combined VSWIR, TIR, and IPM.

The VSWIR instrument measures spectra between 380 and 2510 nm with 10-nm contiguous spectral samples. The position of these samples will be calibrated to ≤0.5 nm uncertainty. 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 available at the HyspIRI website [http://hyspiri.jpl.nasa.gov/]. 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.



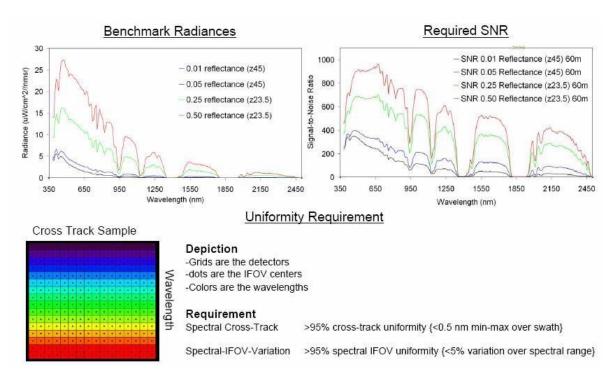


Figure 3. HyspIRI-VSWIR original baseline and key signal-to-noise and uniformity requirements.

Over the open ocean and the ice sheets, data is nominally averaged to a spatial resolution of 1 km. The VSWIR instrument has a swath width of 150 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 μ m, 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 3. 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 are typically used for split-window type applications (ASTER bands 12–14 and MODIS bands 31 and 32).

Table 3. Nominal characteristics of the HyspIRI 8 TIR spectral bands.

	Wavelength Spectral		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 500 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 ($60 \text{ m} \times 600 \text{ km}$) observed on the ground. There will also be periodic surface validation experiments and monthly lunar views.

2.2: ISS Demonstration Mission Options

Instrument studies were conducted using JPL's Team X with contributions from the GSFC team 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; thus, 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).

2.3: 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 and coasts at ±52 degrees latitude at 30m resolution. The tech demo would demonstrate the VSWIR detector with ≤380 to ≥2510 nm spectral range using >=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 4 shows some of the VSWIR science and applications that could be advanced with an ISS demonstration. Table 5 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 4. 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 5. 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		

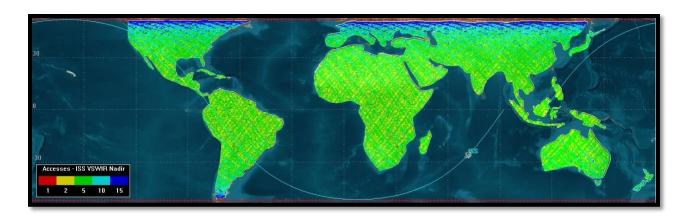


Figure 4. Measurement access offered from a VSWIR imaging spectrometer demonstration on the ISS.

2.4: EMIT (Earth Surface Mineral Dust Source Investigation) on the ISS

The Earth Surface Mineral Dust Source Investigation (EMIT) is an Earth Ventures-Instrument (EVI-4) Mission selected in 2018 to map the surface mineralogy of arid dust source regions via imaging spectroscopy in the visible and short-wave infrared. Currently the source region composition for the Earth's mineral dust cycle is poorly known. Source knowledge is required for Earth system models (ESM) and prediction of future conditions. EMIT has two objectives. 1) Constrain the sign and magnitude of dust-related radiative forcing at regional and global scales. EMIT achieves this objective by acquiring, validating, and delivering updates of surface mineralogy used to initialize ESMs. 2) Predict the increase or decrease of available dust sources under future climate scenarios. EMIT achieves this objective by initializing ESM forecast models with the mineralogy of soils exposed within at-risk lands bordering arid dust source regions. The maps of the source regions will be used to improve forecasts of the role of mineral dust in the radiative forcing (warming or cooling) of the atmosphere. The Earth's mineral dust cycle impacts many elements of the Earth system as shown in Figure 5. EMIT is scheduled for launch to the ISS in 2021. Elements of the EMIT mission are drawn from the science and technology of HyspIRI.

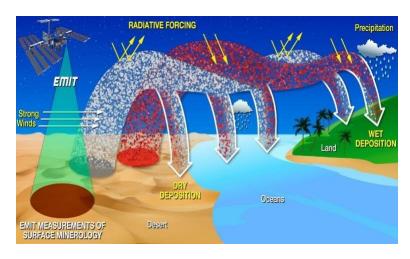


Figure 5. EMIT concept to measure the Earth's mineral dust source regions to advance Earth system modeling of the Earth's mineral dust cycle.

EMIT uses a VSWIR Dyson imaging spectrometer based on the HyspIRI concept as well as the CHROMA 1280 x 480 MCT detector array that are of the HyspIRI type. In addition, EMIT will use the lossless compression and cloud screening algorithms developed and tested for HyspIRI. The level 1 and level 2 VSWIR spectroscopy ground processing algorithms are also evolved from those developed for HyspIRI and tested during the HyspIRI airborne campaigns as shown in Figure 6.

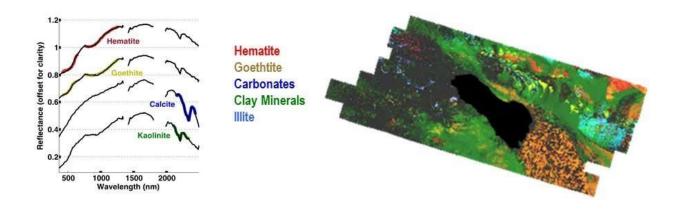


Figure 6. Example surface mineral mapping with spectroscopic measurements acquired as part of the HyspIRI airborne campaign.

2.5: TIR Concept Demonstration for the ISS

The HyspIRI 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 38m in-track resolution. The ISS tech demo would use a 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, and build new electronics for instrument control 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 demonstration on the ISS are given below. Table 6 gives a comparison of full mission vs Tech Demo parameters. Figure 7 shows the coverage offered from the ISS orbit.

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 combined mid and thermal infrared active fire measurements can be used to calculate carbon emissions. ISS orbit will allow us to characterize burning over a 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, the 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 6. 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)

Respective instrument reports were developed for the VSWIR and TIR instruments on the ISS and delivered to NASA headquarters. These reports are available at the HyspIRI website [https://HyspIRI.jpl.nasa.gov].

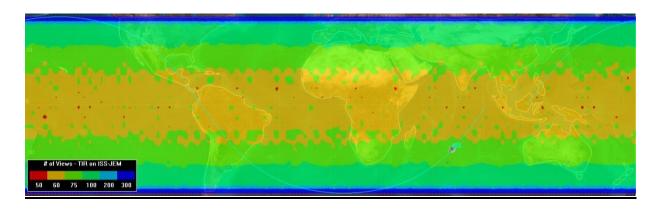


Figure 7. Measurement access offered from a TIR instrument demonstration on the ISS.

2.6: The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)

The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) is currently operating from aboard the International Space Station after a successful launch on June 29, 2018 from Cape Canaveral.

ECOSTRESS will address three overarching science questions:

How is the terrestrial biosphere responding to changes in water availability?

How do changes in diurnal vegetation water stress impact the global carbon cycle?

Can agricultural vulnerability be reduced through advanced monitoring of agricultural water consumption and improved drought estimation?

The ECOSTRESS mission will answer these questions by accurately measuring the temperature of plants. Plants regulate their temperature by releasing water through tiny pores on their leaves called stomata. If they have sufficient water they can maintain their temperature, but if there is insufficient water their temperatures rise and this temperature rise can be measured with a sensor in space. ECOSTRESS will use a multispectral thermal infrared radiometer to measure the surface temperature. The radiometer will acquire the most detailed temperature images of the surface ever acquired from space and will be able to measure the temperature of an individual farmer's field.

ECOSTRESS has nine total standard release products, summarized in the following table and on this website: https://ecostress.jpl.nasa.gov/products/science-data-products-summary-table.

Science Data Product Description, Resolution and Latency Table

by plone — last modified Jun 25, 2018 04:20 PM — History

Data Product	Description	Spatial Resolution (m)	Median Processing Latency** (hours)	Median Validation Latency*** (months)
L1A_RadioCal	Radiometric Calibration	38 x 69		6 post-IOC
L1B_GeoCal	Geometric Calibration			6 post-IOC
L2_LSTE	Land Surface Temperature and Emissivity			6 post-L1
L2_Cloud	Cloud mask			6 post-L2
L3_ET_PT- JPL	Radiometric Calibration (m) Latence (hours) Geometric Calibration 38 x 69 Geometric Calibration Land Surface Temperature and Emissivity			6 post-L2
L3_ET_ALEXI	Evapotranspiration (ALEXI model enhanced)	70 x 70	12 110410	6 post-L2
L4_ESI_PT- JPL				6 post-L3
L4_ESI_ALEXI		ndex derived from		6 post-L3
L4_WUE	Water Use Efficiency			6 post-L3

^{**} Delay associated with processing

Included in this product set are land surface temperature, evapotranspiration, evaporative stress index and water use efficiency.

In addition to its primary science and applications objectives, ECOSTRESS has demonstrated applicability for other areas of work as well. Since launch, ECOSTRESS has moved successfully into science operations and has yielded numerous preliminary findings related to both science and applications contexts, including successful capture of wildfires in the western United States over the summer (Fig 8) and day and nighttime acquisitions of land surface temperature during heat wave events in Los Angeles (Fig 9).

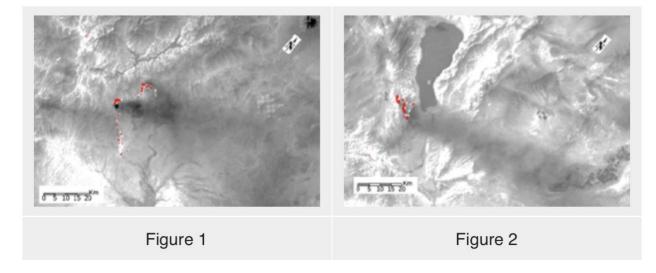


Figure 8. ECOSTRESS, NASA's new Earth-observing mission aboard the International Space Station, detected three wildfires burning in the western U.S. on July 28, 2018 -- the Carr and Whaleback fires in California, and the Perry Fire in Nevada. The fires can be seen in red.

^{***} Delay assoicated with validation of data (IOC - In-Orbit Checkout)

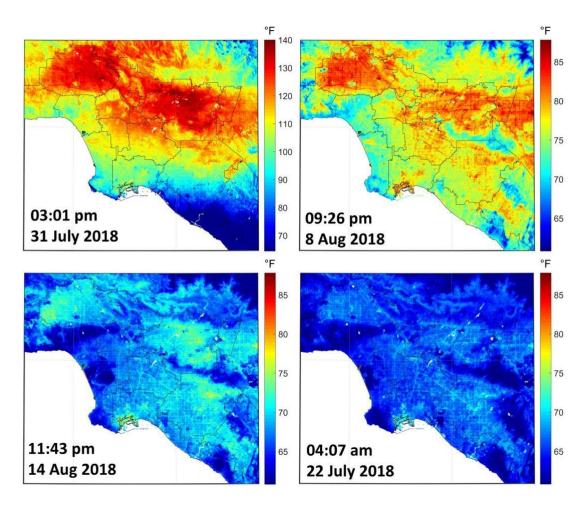
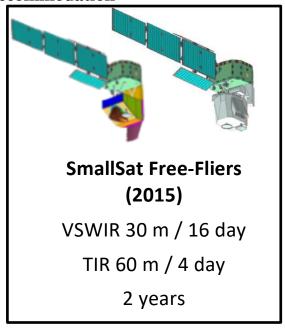


Figure 9. ECOSTRESS captured surface temperature variations in Los Angeles, California between July 22 and August 14 -- a period of extended heat -- at different times of day. The images show how different surfaces within the cityscape warm and cool throughout the day. They have been colored to show the hottest areas in red, warm areas in orange and yellow, and cooler areas in blue. The hottest areas are dark asphalt surfaces that have very little shade during the day and remain warm throughout the night due to their higher heat capacity. They include freeways, airports, oil refineries and parking lots. Clouds and higher-elevation mountainous areas were the coolest.

ECOSTRESS has also helped established an Early Adopters community and program that is a reflection of the interest, needs and utility of the TIR component of HyspIRI. Additional information can be found at ecostress.jpl.nasa.gov/applications.

2.7: Small Satellite Accommodation



In addition to the full HyspIRI 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 at the time, identified feasible mission architectures for the TIR and VSWIR each on their own small satellite. The number of smallsat spacecraft vendors is expanding each year. The studies were comprehensive and included analysis of mass, power, data link, data storage, and thermal and pointing performance. The studies showed that there are available smallsat solutions that meet all TIR and VSWIR requirements within appropriate margins. This implementation approach provides 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. These results are 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 10 shows example configurations of the smallsat VSWIR and TIR instrument, respectively.

Potential options exist to include the HyspIRI Intelligent Payload Module (IPM) for near realtime 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.

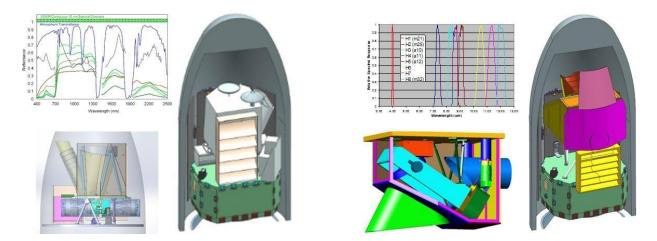
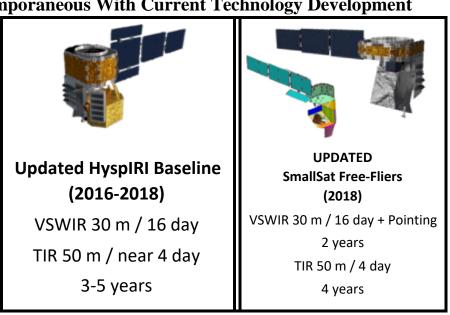


Figure 10. Example configurations of the VSWIR (left) and TIR (right) for standalone smallsat mission with the faring of a Pegasus launch vehicle. This 2014 concept for the VSWIR with 30 sampling and a 16 day revisit was achieved with a pair for Dyson imaging spectrometers and a single telescope. The TIR requirements are met with an evolved version of the PHyTIR IIP instrumentation developed from 2011 to 2014.

2.8: HyspIRI Mission Concept Study 2018 Update: VSWIR, TIR, IPM Separate and Contemporaneous With Current Technology Development



The HyspIRI 2018 baseline contemporaneous concept update was based the latest developments in instrument, spacecraft and ground systems. It uses only mature technology: The Compact Wide-swath Imaging Spectrometer (CWIS) prototype has brought the latest VSWIR to >= TRL 6, PHyTIR, ECOSTRESS have brought latest TIR to >= TRL 6-9, IPM based on Space cube 2.0 >= TRL 6. The flight system, ground system and science data system all use existing technology. For this configuration, a 504 km Sun Synchronous Orbit (10:30 AM LMTDN) is optimal. The 2018 HyspIRI combined mission concepts provides VSWIR with 16 day repeat coverage at 30 m spatial resolution and a TIR with near 4 day repeat coverage at 50 m spatial resolution. These measurements are enabled by mature technologies, onboard data compression and cloud screening and proven Ka-Band link to ground. They build upon the ECOSTRESS EVI instrument on ISS and EVI-4 selected EMIT (ISS) TRL 6 technology as well as the HyspIRI Airborne Preparatory Campaign science, applications and data processing advances. Elements of the mission concept is shown below. Figure 11 and 12 show the global coverage.

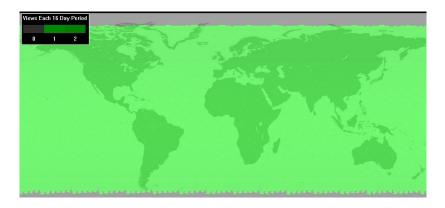


Figure 11. 2018 HyspIRI VSWIR 16-day global coverage.

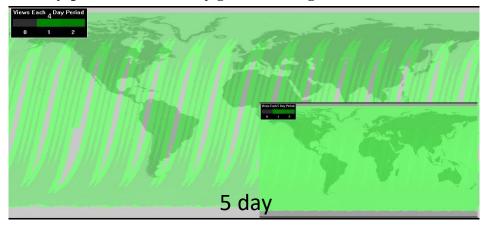


Figure 12. 2018 HyspIRI TIR 4-day near-global coverage with full coverage in 5 days

In this final 2018 concept, the HyspIRI VSWIR payload would consist of:

VSWIR: two CWIS-type Dyson spectrometers each with >3000 cross-track elements to give a combined swath of 185 km swath with 30 m spatial sampling. Configuration, optical design, and spectral coverage are shown in Figure 13 below.

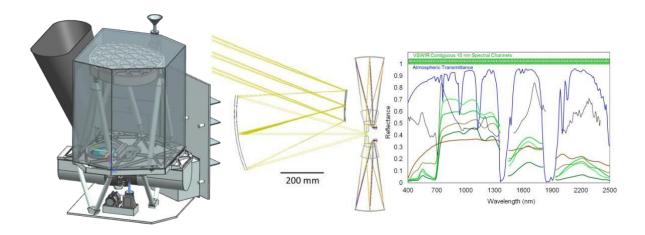


Figure 13. The VSWIR 2018 concept, optical design, and spectral coverage.

The 2018 HyspIRI TIR is based on PhyTIR Demo on ECOSTRES at 518 km swath with 50 m resolution. Configuration, optical design and spectral coverage of the 2018 TIR concept are shown in Figure 14 below.

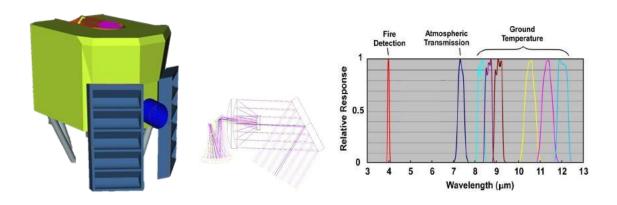


Figure 14. The HyspIRI TIR 2018 concept, optical design, and spectral coverage

Current IPM hardware to support on-board processing for the HyspIRI smallsat free-flier options is shown below in Figure 15 with 4-card flight unit and dimensions of 5 x 7 x 9 inches.







Figure 15. Key elements of the IPM hardware and prototypes that support the HyspIRI 2018 concepts.

SmallSat Free-Fliers

HyspIRI 2018 concept TIR SmallSat Free-Flier shown in Figure 16: All-reflective, compact telescope, Scanning mirror with 13.3-um HgCdTe, PHyTIR/ECOSTRESS ROIC, 8 thermal bands, FPA capability proven in ECOSTRESS ISS instrument. Instrument is integrated with a commercial bus launched into a 503 km orbit with a 4 day revisit and 50m nadir resolution.

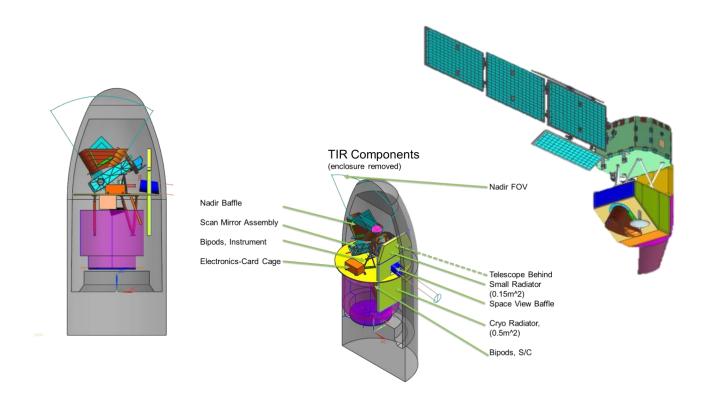


Figure 16. TIR Instrument Configuration Optics and Detector All-reflective, compact telescope, Scanning mirror, 13.3um HgCdTe, PHyTIR/ECOSTRESS ROIC. The

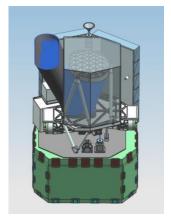
instrument electronics modeled after OCO-3 + ECOSTRESS. Thermal NGAS high efficiency cryocooler and electronics, passive radiator to cool FPA housing, larger radiator to reject cryocooler and instrument electronics heat, Ops heaters, survival heaters, PRTs. Mass of 102 kg w/ contingency. Power draw is 184 Watts w/ contingency. The data rate is ~55 Mbps orbit average data rate with ~0.546 Tb data volume worst-case per orbit.

Observational Scenarios of day and night land and coastal regions at 50 m resolution with Oceans at 1 km resolution are supported. The orbit is a nominal sun-synchronous (descending), overpass time 11:00 +/-30min. The Ground Network with utilize the 7.3m S/X/Ka-band KSAT stations at Svalbard and Trollsat. It employs lossless compressed data can be downlinked with two 7-minute passes per orbit, and the Compression algorithm in firmware. This uses a solution that is a subset of the NISAR implementation. The FPA is designed specifically for HyspIRI TIR instrument with the performance/capability demonstrated by ECOSTRESS instrument. The software heritage is from ECOSTRESS. Hardware will use standard interface cPCI, RS-422, which reduces bandwidth on the processor and bus.

VSWIR SmallSat Free-Flier

Two F/1.8 Compact Dyson-VSWIR Imaging Spectrometer (380 to 2510 nm) with CWIS like design shown in Figure 17. Two CHROMA-D ROIC $-3K \times 512$ pixels; 18 um pixel. Instrument is integrated with a commercial bus launched into a 429 km SSO. Pegasus XL with a 16-day revisit with a 185 km swath and a 30 m sampling





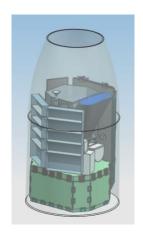


Figure 17. Shows the 2018 concept for the HyspIRI VSWIR.

The VSWIR configuration includes: Telescope assembly, 2 Dyson spectrometers, Single cryocooler and electronics, Thermal heaters/sensors, Passive radiator, IPM and instrument electronics. The mass is 129 kg with contingency power of 117 W. It will have a data rate 1

Gbps peak SSR write from C&DH unit (IPM read/write TBD) with ~375 Gbit/sec orbital average data accumulation rate. The Onboard Processing will have 4:1 Fast lossless compression, cloud screening using 0.45 and 1.25 μm channels. C&DH passes data from SSR to IPM for processing; writes level 2 science data products from IPM back to SSRS/C downlinks SSR-stored data to ground station. The ground processing for level 1, level 2 and selected level 3 algorithms has been demonstrated during the HyspIRI airborne preparatory campaign. The subsystem design, accommodation, interface, heritage, and technology readiness are at TRL 6 or greater: the CHROMA-D ROIC is based on the heritage designs from 6604A / CHROMA ROICs, the Electronics design based on EVI-4 selected EMIT Pointing of the smallsat provides the ability to select specific revisit targets (e.g., estuaries, lakes) and targets of opportunity (e.g., active volcanoes and forest fires).

2.9: 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 16day revisit version of the VSWIR imaging spectrometer. Figure 18 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.

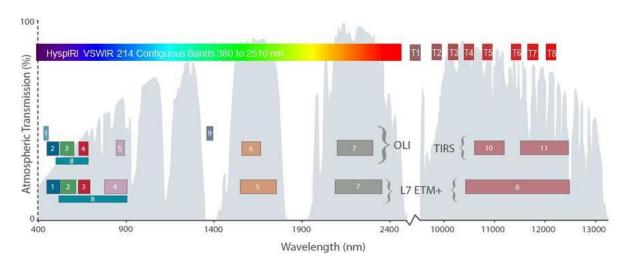


Figure 18. Spectral coverage of the HyspIRI VSWIR and TIR in comparison to Landsat 7 and 8. This is for the updated VSWIR instrument concept that provides 30 m surface sampling and a 16 day revisit.

As quoted from the NRC 2013 Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program report:

"It is important to recognize that while Landsat produces comprehensive coverage at several distinct wavelengths, additional and stronger characteristics about surface composition follow if the reflectance spectrum is known more completely. Imaging spectrometry acquires such data at hundreds of contiguous spectral bands simultaneously. Its value lies in its ability to provide a high-resolution reflectance spectrum for each pixel in the image. Many, although not all, surface materials have diagnostic absorption features that are only 20 to 40 nm wide. Therefore, spectral imaging systems that acquire data in 10-nm bands contiguously between 400 and 2,500 nm may be used to identify surface materials with diagnostic spectral absorption features. This feature is superior to multi- spectral remote sensing systems that acquire data in wider, often discontinuous bands. The SELIP would benefit from exploring the advantages and practicality of adding hyperspectral analysis to the planned Landsat acquisitions.

Earth's surface consists mainly of soil, vegetation, snow, ice, and water as well as areas of built structures. Each of these constituents has properties with distinct spectral signatures, which, when measured by a hyperspectral imager, convey information about such properties as productivity, nutrient limitation, water stress in vegetation, soil mineralogy related to locations of natural resources, snow grain size and dust or soot content, and sediment and plankton abundance in water.... NASA and the Department of Defense have operated airborne imaging spectrometers for more than two decades, and more recently, the National Science Foundation, commercial companies, and institutional laboratories have flown airborne instruments.

Among the recommendations in the 2007 NRC decadal survey for a flight around 2020 is HyspIRI, which combines optical imaging spectrometry with multispectral thermal imagery. HyspIRI has no projected launch date. Such data are valuable for quantification of land surface composition (chemical composition of foliage, mineralogy, and other properties) and provide unique information on plant biodiversity and invasive plants. Hyperspectral imagery is extraordinarily flexible because complete spectral coverage (typically in the visible through shortwave infrared regions) is available. This allows specific regions of the spectrum to be selected for current and future data products. Imaging spectroscopy has benefited from technology improvement over the past decades, with improved optics that allow for smaller and less expensive instruments, enhanced downlink capabilities allowing exploitation of the entire spectrum, and uniform detector arrays increasing measurement accuracy, precision, and spatial registration. Several technology demonstration spectrometers have flown in Earth orbit, allowing the evaluation of spaceborne imaging spectroscopy data products, and a high-performance imaging spectrometer has flown to the Moon, demonstrating the key aspects of the capability in a prolonged spaceflight environment."

Chapter 3: Technology Investments

Selected technology investments are presented here. Many additional investments have been made by NASA and other entities that mature the technologies that enable HyspIRI class measurements. Many of these have been reported at the workshop and in pre formulation reports to NASA. A subset of these are available at the HyspIRI website: [https://hyspiri.jpl.nasa.gov].

3.1: Intelligent Payload Module (IPM) Development

The purpose of the IPM is two-fold. The first is to supplement the HyspIRI full mission architectural concept with onboard processing that enables low-latency users to receive subsets of VSWIR and TIRS data along with small synthesized data products in a timelier manner. An example of a low-latency user is an emergency responder who needs situational awareness for a natural hazard to provide decision support. An IPM consists of onboard radiation hardened or radiation tolerant combination of CPUs and field programmable array fabric to enable band stripping of selected bands at 4 Gbps and possibly perform radiometric correction, atmospheric correction and georeferencing/orthorectification/co-registration at that speed. It also includes non-volatile storage separate from the spacecraft solid state recorder and a communications link to the ground separate from the main S-band and KA band links to ground stations. Figure 19 depicts the IPM as a branched processor system off of the main data feed that is able to filter out user selected data subsets and small data products. It can then can transmit those data subsets and data products rapidly to the users on the ground via direct broadcast or similar technology.

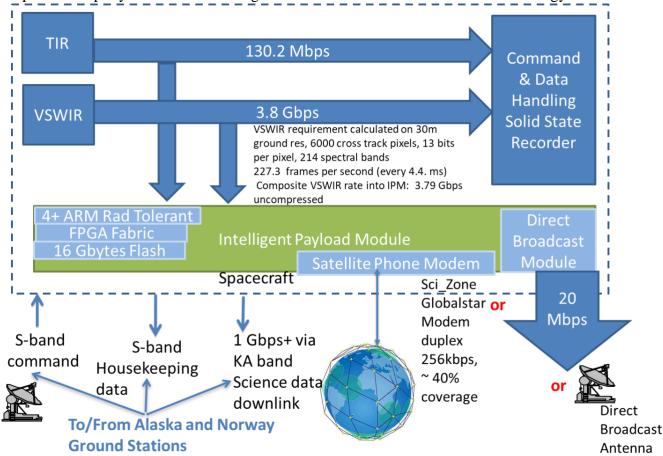


Fig 19. Operations concept for the use of IPM in the Full HyspIRI mission concept. Note that there are multiple ways to downlink from the IPM. In the case of the Globalstar modem, there is direct control of the IPM via the duplex link. In the direct broadcast

method, control would have to occur via the standard S-Band uplink and command and data handling processor link.

In alternate scenarios, in which VSWIR and TIR are either hosted in smallsats or on ISS, the IPM architecture design changes a little. Figure 20 depicts an alternate operations concept in which VSWIR resides on Space Station and Landsat bands are convoluted from the VSWIR bands and then sent to the ground via the Space Station wireless interface.

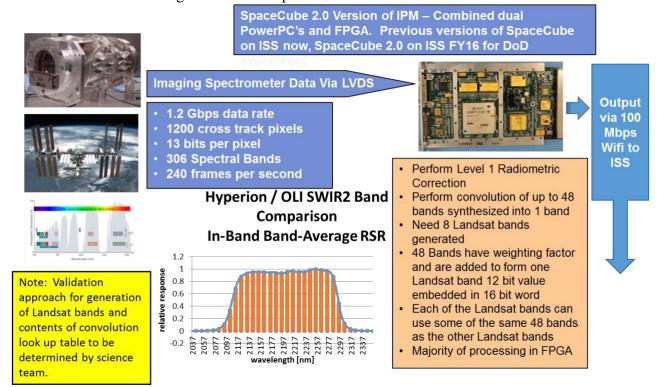


Fig 20. Primary operations concept for IPM-VSWIR (Dyson) on ISS, convolution of Landsat bands from hyperspectral bands.

One processor family targeted for onboard the IPM is the SpaceCube family along with the CHREC Space Processor being developed at GSFC. Figure 21 shows the evolution of the various SpaceCube boards and availability. Depending on when HyspIRI or something similar launches there are also other potential low power processor options such as NASA's High Performance Space Processor (NASA wide collaboration) and JPL's Data Compression and Support Electronics (DCSE).

ar to	Onboard Processor	FPGA/CPU Type	CPU Memory (DDR)	Fabric Memory Block Ram	Non- volatile storage	Cost of Flight Unit	Date TRL 7-9	Comment	Cubesat grade
Simil	CHREC Space Processor	Xynq/2 ARMs (667 Mhz)	1 Gbyte DDR2	612Kbyte	4 Gbyte	\$20-80K	now	radiation tolerant	Cu B
2	SpaceCube 2 (Defense)	2 x V5 rad tol 4 PowerPCs 400 Mhz	4 x 512 MB DDR2	2 x 1341 Kbytes	2 x 4 Gbytes	\$500K	now	Radiation tolerant	bps thru
Virtex	SpaceCube 2 (Radhard)	Virtex 5 softcore- N x Microblaze 75Mhz	4 x 512 MB DDR2	2 x 1341 Kbytes	2 x 4 Gbytes	\$600K	now	Radiation hardened	e <mark>ved 10 G</mark> grade
ex 8	SpaceCube 3	Kintex- /hardcore 4 PowerPC 1.2-1.8 Ghz	4Gbytes Processor/2 Gbytes FPGA-DDR3	4.75 Mbytes	1 x 16 Gbytes	??	TRL 6 2019 TRL 7-8 2020	Full missio grade-rad tol-meet R req	=
Vir	SpaceCube 3	Kintex- HPSC hardcore – 8 ARMs 1.2-1.8 Ghz	4Gbytes Processor/2 Gbytes FPGA-DDR3	4.75 Mbytes	1 x 16 Gbytes	??	2021+	Full mission grade-mee RT req	

Note: 2018- Delivering double Virtex 5 flight boards to Robotic Refueling Mission 3

Figure 21. SpaceCube processor family evolution, along with availability and ability to meet real-time mission requirements

A variety of software was tested and developed in conjunction with the IPM, either via parallel efforts or specifically for the IPM. Earth Observing 1's Autonomous Sciencecraft Experiment (ASE) also validated a number of IPM Technologies [Chien et al. 2013]. Another earlier software effort was an Earth Science Technology Office (ESTO)-funded effort conducted by JPL in which a cubesat called Intelligent Payload Experiment (IPEX) was launched December 6, 2013 with over 30,000 images taken to test out this configuration. Figure 22 depicts some of the onboard processing experiment which includes some artificial intelligence applications. Also, IPEX used CLASP ground-based planning and CASPER for onboard planning (e.g. same as Earth Observing 1's (EO-1's) Autonomous Sciencecraft Experiment (ASE)). Also, CLASP is being used for ECOSTRESS.

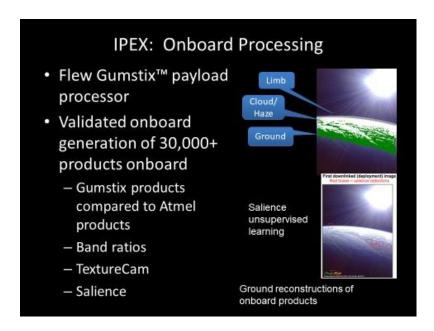


Figure 22. IPEX processing experiments, launched December 6, 2013.

On the GSFC side, the development of the IPM was primarily funded by NASA ESTO with some funds also supplied by the HyspIRI project. There has been an Advanced Information Systems Technology (AIST)-11 award which enabled prototyping an IPM hosted on airborne platforms to flush out basic concepts.

Figure 23 shows the basic onboard software configuration, which includes Core Flight Executive/Core Flight Software (cFE/cFS) that is operational on many missions launched by GSFC and has become one of the NASA standards.

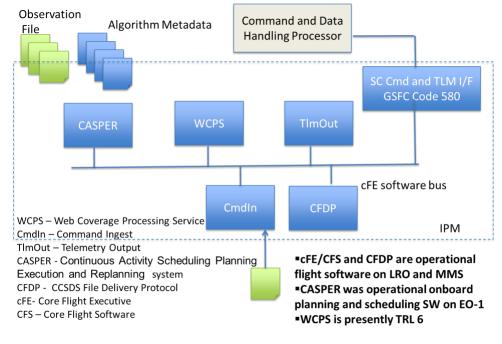


Figure 23. Targeted software that was used for IPM testing which includes as its base, cFE and cFS. Note that in this configuration, control of the IPM can either come from the ground if the IPM radio link allows, or could come from the Command Data Handling computer which controls the rest of the spacecraft. Thus, depending on whether a Globalstar modem or Direct Broadcast is chosen, control of the IPM would use different pathways.

In addition to the software mentioned, a variety of other relevant software efforts were conducted that could run on the IPM and the ground as follows:

- Onboard cloud screening Heritage onboard cloud screening developed for EO-1 in a collaboration between GSFC and MIT/LL. That software was integrated into Autonomous Sciencecraft Experiment in a collaboration between JPL and GSFC [Griffin et al]. D. Thompson developed a rapid cloud screening algorithm used on AVIRIS. Later a JPL team developed a machine learning technique for cloud screening using random decision forests which was validated on EO-1 in 2017.
- 2. Various relevant heritage classifiers onboard EO-1 included
 - a. Snow, Water, Ice, Land (SWIL) (using both manually derived decision trees and support vector machine learning classifiers
 - b. Surface water extent mapping (floods)
 - c. Thermal analysis (volcano, fires)
 - d. Sulfur detection
 - e. Unsupervised outlier analysis using visual salience
- 3. Hyperion to OLI band demonstration 2017–flight validated by JPL/GSFC
 - a. Landsat 8 using Hyperion data analysis by GSFC
- 4. EO-1 heritage
 - a. SensorWeb Opengeospatial Consortium (OGC) compatible Sensor Planning Service (SPS) to control EO-1 imaging. GeoBPMS was used to with SPS interface to control tasking requests for EO-1 from the Web.
 - b. Web Coverage Processing Service (WCPS) which allows users to specify algorithms that automatically execute onboard or on the ground with automatic configuration for the target environment (e.g., onboard or in a cloud). This was developed under an ESTO AIST-11 research grant [Mandl et al 2011][Cappelaere et al 2010]
- 5. Rapid onboard co-registration of Advanced Land Imager bands using Global Land Survey chips (ground validation) GSFC
- 6. Compact onboard orthorectification technique (ground validation) -GSFC
- 7. Various relevant heritage classifiers onboard EO-1 included
 - a. Snow, Water, Ice, Land (SWIL)
 - b. Surface water extent mapping (floods)
 - c. Thermal analysis (volcano, fires)
- 8. Hyperion to OLI band demonstration 2017-flight validated by JPL/GSFC

- a. Landsat 8 using Hyperion data analysis by GSFC
- 9. EO-1 heritage
 - a. SensorWeb Opengeospatial Consortium (OGC) compatible Sensor Planning Service (SPS) to control EO-1imaging. GeoBPMS was used to with SPS interface to control tasking requests for EO-1 from the Web.
 - b. Web Coverage Processing Service (WCPS) which allows users to specify algorithms that automatically execute onboard or on the ground with automatic configuration for the target environment (e.g., onboard or in a cloud). This was developed under an ESTO AIST-11
- 10. Rapid onboard co-registration of Advanced Land Imager bands using Global Land Survey chips (ground validation) GSFC
- 11. Compact onboard orthorectification technique (ground validation) GSFC

3.2: Prototype HyspIRI Thermal Infrared Radiometer (PHyTIR)

The Prototype HyspIRI Thermal Infrared Radiometer (PHyTIR) was developed as part of the risk reduction activities associated with HyspIRI. PHyTIR provides engineering risk reduction on key technical challenges of the HyspIRI Thermal Infrared Instrument. It demonstrated the focal plane array technology as well as the scanning technique. The PHyTIR push-whisk design has nearly 10000 cross track spatial pixels over a 50-degree field of view and 3 spectral bands placed at 4µm, 8 µm and 12µm in the thermal infrared (TIR) wavelength region. These bands span the passband of the HyspIRI-TIR sensor. In particular, the proposed design requires a high sensitivity and high throughput Focal Plane Array (FPA), combined with a scanning mechanism that requires stringent pointing knowledge. The scanning approach, and the high sensitivity and high throughput FPA, are required to meet the revisit time (5 days), the high spatial resolution (60m), and the number of spectral channels (8) specified by the Decadal Survey, and the HyspIRI Science Study Group for the mission.

The PHyTIR system is a complete end-to-end laboratory system. The system utilizes an existing Read-Out Integrated Circuit (ROIC) that has been developed as part of the HyspIRI Concept Study. The ROIC was mated with the detectors and filters, all located inside the PHyTIR vacuum assembly. The scanning mechanism operates at the same speed as the HyspIRI-TIR instrument and has the same pointing knowledge capability.

Preparatory Work – Analysis and Prototyping

A short design study was conducted to determine the best instrument rational to meet the HyspIRITIR science requirements. The trade was for push-whisk scanning versus pushbroom scanning as well as mercury cadmium telluride (MCT) versus quantum well infrared photodetectors (QWIP) and microbolometers. This is shown in figures 24 and 25, respectively. The trade basically describes how HyspIRI-TIR needs to have a push-whisk scan and use mercury cadmium telluride (MCT) detectors. The push-whisk as opposed to pushbroom scanning increases the swath hence minimizing the repeat time. As with MODIS, push-whisk also allows natural 2-point calibrations for each ground swath scan, since the mirror sweeps through a dark space view

as well as a slightly above ambient blackbody target each time it rotates a full cycle. Pushbrooming techniques would require gaps in the along-track scan for on-board calibrations.

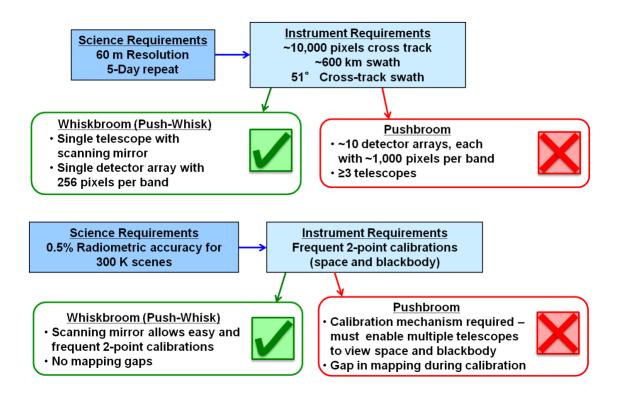


Figure 24. Rationale for choosing whiskbroom scanning for HyspIRI-TIR and the PHyTIR concept.

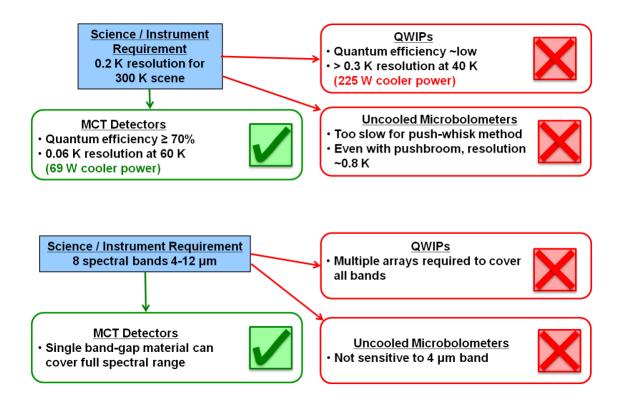


Figure 25. Rational for choosing MCT detectors for HyspIRI-TIR and the PHyTIR concept.

PHyTIR Instrument Description

The PHyTIR system is a complete end-to-end laboratory system. The system utilizes an existing ROIC that has been developed as part of the HyspIRI Concept Study. The ROIC was mated with the detectors and filters, all located inside the PHyTIR vacuum assembly. The scanning mechanism operates at the same speed as the HyspIRI-TIR instrument and has the same pointing knowledge capability.

Figure 26 top shows the PHyTIR instrument concept while the below shows a graphical representation of the scanning approach. The instrument utilizes a continuously rotating scan mirror to allow the telescope to view a 51° cross-track nadir strip, an internal blackbody target, and Space, every 2.1 seconds with a nadir resolution of 60m. The scan mirror rotates at a constant velocity which minimizes the possibility of introducing any vibrations and disturbances during measurements.

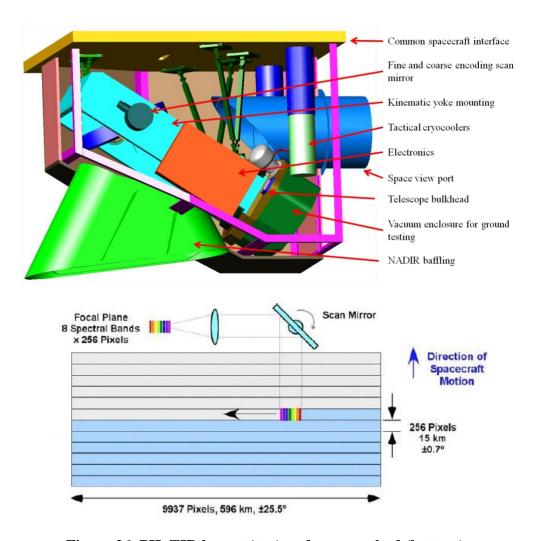


Figure 26. PHyTIR layout (top) and scan method (bottom).

The 5-day revisit requirement necessitates a wide swath, which is realized by the scan method. The scan mirror sweeps the image of the focal plane across a 51° swath perpendicular to the spacecraft motion. Each point in this strip is sampled by detectors in all 8 spectral channels (only 3 used in PHyTIR due to the limited funding). The sweep rate is such that, as the spacecraft moves, the full 51° swath is sampled, with a small overlap between strips. The relatively fast sweep rate requires a fast frame-rate focal plane.

MCT Detector

PHyTIR uses a Mercury Cadmium Telluride (HgCdTe) detector array (JW Beletic et al. 2008). These IR sensors are hybrid complementary metal-oxide semiconductor (CMOS) arrays, with

HgCdTe used for light detection and a silicon integrated circuit for signal readout. The detector array and readout integrated circuit (ROIC) was developed at Teledyne Scientific Imaging in Camarillo, California. HgCdTe is the industry standard long wave photo detection material. It's been used in the commercial and military market for many decades. It's also been used in numerous space based missions during the same time period. The detector pixel pitch of the FPA is 40 µm. Indium bumps were evaporated on top of the detectors for hybridization with a custom HyspIRI-TIR developed silicon ROIC. The PHyTIR FPAs were hybridized (via indium bump-bonding process) to a 256x256 pixel CMOS ROIC. At temperatures below 72 K, the signal-to-noise ratio of the system is limited by array nonuniformity, readout multiplexer (i.e., ROIC) noise, and photocurrent (photon flux) noise. At temperatures above 72 K, the temporal noise due to the dark current becomes the limitation. The system is operated at 60K to have a SNR advantage. MCT isn't known for its high spatial uniformity; hence the PHyTIR scanning mechanism (similarly to the HyspIRI-TIR scanner) allows full 2-point recalibration for gain and bias of the system on the order of every 2s. This calibration feature allows HgCdTe to be useable for space applications while having a clear signal to noise advantage over other detector technologies (e.g. microbolometers, quantum well infrared photodetectors QWIP). A graphical representation of the HyspIRI-TIR ROIC which is used in PHyTIR is shown in figure 27. The ROIC is custom designed with different well sizes under each spectral filter. The well sizes are complementary to the expected saturation temperature under normal operating conditions.

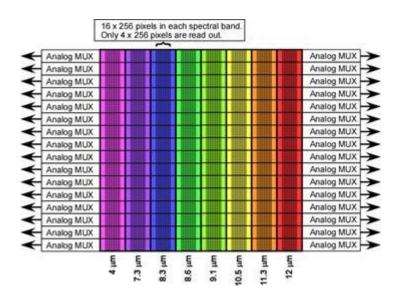


Figure 27. HyspIRI-TIR ROIC pixel design utilized by PHyTIR - 32 analog multiplexers (MUX) are used to readout the array at 12.5MHz. This allows operation of 4 TDI samples under each of the 8 spectral channels at 32 micro seconds well time.

The HgCdTe focal plane has a long wavelength cut off of 13.5 microns and has sensitivity down to nearly 2 microns. Figure 28 shows the packaged PHyTIR Focal Plane Array and analog readout board. The board was custom designed to fit within the system with minimal thermal

and structural impact, hence there was a need for alignment holes and packaging mounts. The connector interface on the right hand side of the image is used for the flex cable interface. A flex cable was delivered All-flex was delivered. It has the correct cryogenic properties and is based upon standard practices providing minimizing thermal impact while maintaining adequate electrical contact.

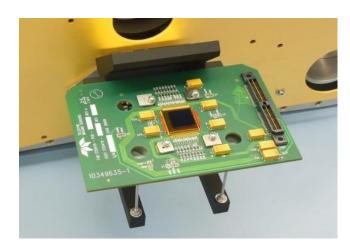


Figure 28. PHyTIR focal plane array analog electronics. It is mounted securely to the bulkhead using thermal standoffs.

In terms of instrument development, PHyTIR was a success completing all goals on time and within budget. PHyTIR was critical in the timely development and ultimate deployment of ECOSTRESS.

3.3: VSWIR Related Technology Advancements

CHROMA-A detector array with analog output: Early in the HyspIRI mission concept it was realized an improved detector array would be required. Investments were made with Teledyne Imaging Sensor (TIS), Inc. to develop the Configurable Hyperspectral Readout for Multiple Applications (CHROMA) read-out-integrated-circuit (ROIC) that could be scaled to meet the HyspIRI VSWIR measurement requirements. This ROIC is evolved from the TMC 6604a device that flew on CRISM, ARTEMIS, and the Moon Mineralogy Mapper (M3). The analog version of the CHROMA-A support detector array sizes of 1280 by 480 for up to 1280 crosstrack spatial samples and 480 spectral channels. The detector pitch is 30 microns. At least two of these arrays would be required for the early configuration of the HyspIRI VSWIR imaging spectrometer with 60 m ground sampling and a 150 km swath. The CHROMA-analogy has been in production for more than 5 years and tested at JPL (Sullivan et al., 2017). It is currently used

or planned for a wide range of imaging spectrometers. Figure 29 shows a CHROMA device with test results.

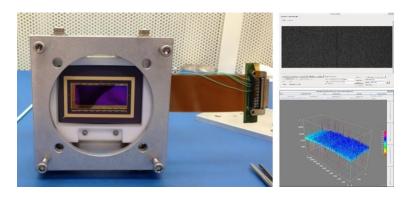


Figure 29. Shows a CHROMA-A 1280 by 480 MCT detector array and test results at JPL. The CHROMA is snap shot read and integrate while read to support imaging spectrometers. This device is substrate removed HgCdTe to provide sensitivity from 380 to 2510 nm. Following testing this device showed 99.97 % operable detectors.

Compact Wide-swath Imaging spectrometer (CWIS): With the realization that the HyspIRI VSWIR requirements could be achieved with an imaging spectrometer with the nominal Landsat swath, ground sampling, and revisit, investments were begun in the Dyson design from imaging spectrometer (Mouroulis et al., 2000). The Dyson offers the capability of high optical throughput with lower size and mass. These investments led to the design (Van Gorp, et al, 2014). and development (Van Gorp et al., 2016) of the CWIS prototype imaging spectrometer. Figure 30 shows CWIS during vibration testing at JPL along with some spectral measured by CWIS at the required cryogenic temperatures following alignment and calibration.

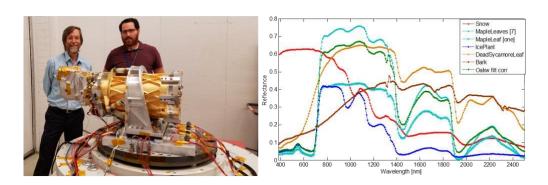
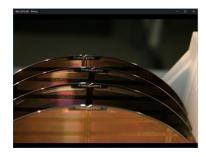


Figure 30. The Compact Wide-swath Imaging Spectrometer (CWIS) a HyspIRI VSWIR Dyson imaging spectrometer prototype in vibration testing configuration (left). Spectra measured by CWIS following alignment and calibration in full cryogenic operation.

<u>Lossless compression:</u> An enabling technology for the HyspIRI VSWIR imaging spectrometer especially in the latter Landsat swath configuration (Mouroulis et al., 2015) is on-board lossless configuration. Effort for lossless imaging spectrometer compression have been a focus for more than a decade (Klimesh, 2005, 2006, 2010, Aranki et al., 2009ab). This algorithm has been tested in an FPGA implementation with the AVIRIS-NG airborne instrument (Keymeulen, 2014). The algorithm has also been adopted as CCSDS 123.0-B-1 standard (Kiely, 2012).

<u>Cloud Screening:</u> For the HyspIRI mission concept that is focused on surface composition an on-orbit cloud screening algorithm provide increased data downlink efficiency. A cloud screening algorithm has been developed and tested on AVIRIS-NG (Thompson et al., 2014) and implemented in a FPGA. This algorithm is baselined in the EMIT EVI-4 mission.

<u>CHROMA-D:</u> To enable the Landsat swath option of the HyspIRI VSWIR with the Dyson imaging spectrometer, an evolved version of the CHROMA detector array was required. Teledyne Imaging Sensors (TIS) Inc. has been developing several devices of this type. One is designated the CHROMA-D and can support dimension of 3072 by 512 elements. Two of these in the 2018 HyspIRI VSWIR design provide the 185 km swath, 30 m ground sampling, and 16 day revisit required. Figure 31 shows a set of CHROMA-D ROICs, MCT detectors, and package design in development that will meet the 2018 HyspIRI VSWIR requirements.





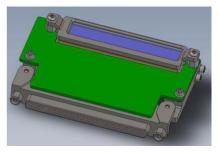


Figure 31. CHROMA-D detector array elements form 2016 for a 3072 by 512 digital out detector array to enable the Landsat swath VSWIR imaging spectrometer for the HyspIRI mission concept.

<u>VSWIR atmospheric correction processing:</u> Routine atmospheric correction is required for the HyspIRI VSWIR mission concept. The HyspIRI airborne campaign have been essential to test and develop these algorithms. The AVIRIS-NG campaigns to India have also provided stressing atmospheres to test these algorithms. Based on a series of recent tests and demonstrations atmospheric corrections are being routinely applied to a range of imaging spectrometer data sets at the imaging spectrometer science data system and elsewhere (Thompson et al., 2015, Bue, et al., 2015, Thompson et al., 2018).

Chapter 4: HyspIRI Preparatory Activities

In the past decade, NASA has invested in a wide range of direct and indirect activities for technology, science, and applications that advance a range of objectives in support of future observations of the HyspIRI type. A subset of these are described here. Additional reports related to these activities can be found at the HyspIRI website: [https://HyspIRI.jpl.nasa.gov] and elsewhere.

4.1: Analysis of Existing Data Sets

Early on in the 2007 Decadal Survey HyspIRI mission concept study, NASA created two opportunities to advance HyspIRI related science and applications through analysis of existing data sets. The first resulted in six investigations that are listed below.

Michael Abrams/Jet Propulsion Laboratory: HyspIRI Preparatory Data Sets for Volcanology

Petya Campbell/NASA Goddard Space Flight Center: Assessing Ecosystem Diversity and Urban Boundaries Using Surface Reflectance and Emissivity at Varying Spectral and Spatial Scales

Fred Kruse/University of Nevada Reno: Characterization of Hydrothermal Systems Using Simulated HyspIRI Data

Lin Li/Indiana University-Purdue University at Indianapolis: Remote Sensing of Global Warming-Affected Inland Water Quality: Challenge, Opportunity and Solution

Philip Townsend/University of Wisconsin-Madison: Detection of Key Leaf Physiological Traits Using Spectroscopy and Hyperspectral Imagery

Richard Vaughan/USGS: Simulated HyspIRI Data for Global Volcano Monitoring: Measuring Volcanic Thermal Features with a Wide Range of Temperatures

The second opportunity resulted in the following five investigations

Andrew French/U.S. Arid Land Agricultural Research Center: Monitoring Arid Land Cover Change with Simulated HyspIRI Data

Rasmus Houborg/NASA Goddard Space Flight Center Combining Observations in the Reflective Solar and Thermal Domains to Improve Carbon, Water and Heat Fluxes Simulated By a Two-Source Energy Balance Model

Alexander Koltunov/University of California, Davis: Toward monitoring the Relationship Between Vegetation Conditions and Volcanic Activity with HyspIRI Dar Roberts/University of California, Santa Barbara: Evaluation of Synergies Between VNIR-SWIR and TIR Imagery in a Mediterranean-climate Ecosystem

Prasad Thenkabail/US Geological Survey: Water Use and Water Productivity of Key World Crops using Hyperion-ASTER, and a Large Collection of in-situ Field Biological and Spectral Data in Central Asia

Together these sets of investigations explored the HyspIRI related science and applications that could be pursued with previously existing data sets and made the case for subsequent new HyspIRI-like data acquisitions with combined VSWIR and TIR measurements.

4.2: California Campaign

To support the development of the HyspIRI mission and prepare the community for HyspIRIenabled science and applications research, NASA sponsored the HyspIRI preparatory airborne campaign. In ROSES 2011 a call for proposals was issued titled: HyspIRI Preparatory Airborne Activities and Associated Science and Applications Research (NNH11ZDA001N - HYSPIRI).

From the 2011 Call, The National Aeronautics and Space Administration (NASA) Earth Science Division within the Science Mission Directorate solicited proposals using airborne measurements resulting from planned airborne campaigns in FY2013 and FY2014. For these campaigns, NASA planned to fly the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and the MODIS/ASTER Airborne Simulator (MASTER) instruments on a NASA high-altitude aircraft to collect precursor datasets in advance of the HyspIRI mission. NASA solicited proposals that would use these airborne data to address one, or more, science or applications research topics aligned with the science questions for the HyspIRI mission. A goal of this solicitation was to generate important science and applications research results that are uniquely enabled by HyspIRI-like 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.

For this activity, NASA selected 14 investigations, summarized in Table 7. Measurements for these investigations are acquired by the AVIRIS and the 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 six large areas is shown in Figure 32 and Figure 33 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 demonstrate the HyspIRI level 1 and level 2 processing algorithms for the VSWIR and TIR instruments and advance their maturity for the HyspIRI mission. The three seasonal data sets (spring, summer and autumn) were collected in 2013, 2014 and 2015. Beginning in 2016, a single season of the California data sets were collected in the early summer every year up through 2018.

Table 7. Investigations selected as part of the HyspIRI CA 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	
hunlin Liang U Maryland Characterizing surface energy budget of different surface types under v		
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	CHANGE BY TO CHANGE BY THE CHA	

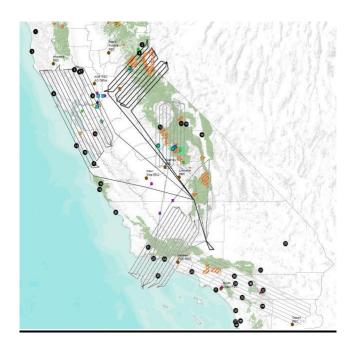


Figure 32: Map of HyspIRI CA flight lines, with the University of California Reserves labeled with black dots.

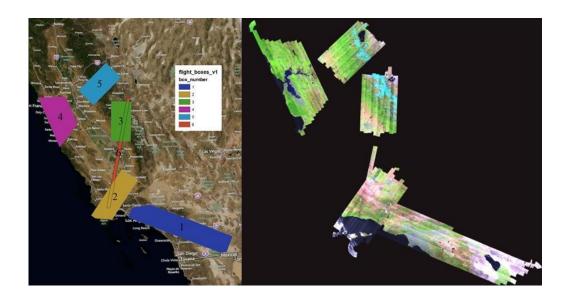


Figure 33. HyspIRI CA preparatory airborne campaign measurement collection areas.

These 6 large areas were measured in three seasons of 2013, 2014 and 2015. The 14 investigations have been pursued to advance the maturity of HyspIRI science and applications.

The large, multi-season, and multi-year data sets were also used to test and mature HyspIRI level 1 and level 2 processing algorithms.

4.2: Hawaii Campaign

Although there are many diverse ecosystems in California, two major goals of the HyspIRI mission concept are not observable in California: to measure active volcanoes and coral reefs. So in 2014, a ROSES call for proposals titled HyspIRI Preparatory Airborne Activities and Associated Science: Coral Reef and Volcano Research (NNH14ZDA001N-HYSP) was issued. From the 2014 call, the National Aeronautics and Space Administration (NASA) Earth Science Division within the Science Mission Directorate solicited proposals using airborne measurements resulting from a planned airborne campaign in 2016 in the Hawaiian Islands for volcano and coral reef research. For this campaign, NASA planned to fly the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and the MODIS/ASTER Airborne Simulator (MASTER) instruments on a NASA high-altitude aircraft to collect precursor datasets in advance of the Hyperspectral Infrared Imager (HyspIRI) mission. NASA solicited proposals that would use these airborne data to address one or more of the science questions for the HyspIRI mission relevant to volcano or coral reef research. A goal of this solicitation was to generate important science and applications research results that are uniquely enabled by HyspIRI-like data, taking advantage of the contiguous spectroscopic measurements of the AVIRIS, and the full suite of MASTER.

Eleven investigations were selected for the Hawaii mission, as shown in Table 8. The goal of the mission was to test Level 1 and 2 products for VSWIR and TIR HyspIRI-type measurement for coral reefs and volcano research. Additionally, a goal was to advance the maturity of higher level products and related algorithms. In January 2017 the ER-2 deployed for six weeks to Marine Corps Base Hawaii (MCBH) on the island of Oahu with AVIRIS and MASTER for collections over the Hawaiian Island chain. Data was collected from the mid Northwest Islands through the main chain islands for coral reef studies. The Big Island of Hawaii was flown to capture data over the Mauna Loa Summit and the Kilauea Crater for volcano studies. There was a mission requirement to collect both day and night underflights of ASTER over the volcano. Due to base closures, weather, instrument failures and aircraft maintenance issues only one daytime underflight of ASTER was achieved. Additional funding was identified to return for a 4 week deployment in January 2018 to support the mission requirement of a day/night ASTER underflight. Additional funding was also secured to support flying more coral reef locations in the main island chain.

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

Principal Investiagtor		Investigation
Dierssen, Heidi		Hyperspectral remote sensing of coral reefs: Assessing the potential for spectral discrimination of coral symbiont diversity

Steven Ackleson	Naval Research Laboratory	Assessing Simulated HyspIRI Imagery for Detecting and Quantifying Coral Reef Coverage and Water Quality Using Spectral Inversion and Deconvolution Methods
Kyle Cavanaugh	University of California, Los Angeles	Using HyspIRI to Identify Benthic Composition and Bleaching in Shallow Coral Reef Ecosystems
Paul Haverkamp	University of California Davis	Modeling of Environmental Variables and Land- Use/LandCover Change Influence on Declining Hawaiian Coral Reef Health Since 2000 Using HyspIRI-Like Images
Eric Hochberg	Bermuda Institute of Ocean Science Inc.	Coral Reef Condition Across the Hawaiian Archipelago and Relationship to Environmental Forcing
ZhongPing Lee	University Of Massachusetts, Boston	Evaluation and Application of the AVIRIS Data for the Study of Coral Reefs
David Pieri	Jet Propulsion Laboratory	In Situ Validation of Remotely Sensed Volcanogenic Emissions Retrievals Using Aerostats and UAVs
Ramsey, Michael	University of Pittsburgh	Quantifying Active Volcanic Processes and Mitigating their Hazards With HyspIRI Data
Vincent Realmuto	Jet Propulsion Laboratory	Mapping the Composition and Chemical Evolution of Plumes from Kilauea Volcano
Vaughan, Greg	USGS	Simulating HyspIRI data for global volcano monitoring: Specifically, measuring volcanic thermal features with a wide range of temperatures
Chad Deering	Michigan Technological University	Understanding Basaltic Volcanic Processes by Remotely Measuring the Links Between Vegetation Health and Extent, and Volcanic Gas and Thermal Emissions Using HyspIRI-Like VSWIR and TIR Data

4.3: Level 2 Data Processing

Through the California and Hawaii campaign data collections, a systematic approach was developed for handling large volumes of VSWIR and TIR data which were made readily available to the science team for both investigations via internet downloads. Both AVIRIS-C (VSWIR) and MASTER TIR teams established data pipelines to handle the routine collections from 2013 up through 2018. For the VSWIR data a standardized Level 2 reflectance product was produced and automated for both terrestrial and aquatic targets [Thompson et al 2015]. All level 2 AVIRIS-C products can be downloaded via the data portal at: https://aviris.jpl.nasa.gov/alt_locator/, and AVIRIS-NG level 2 products can be downloaded at: https://avirisng.jpl.nasa.gov/alt_locator/. The TIR level 2 product pipeline for TIR now produces Land Surface Temperature (LST) and Emissivity. The Level 2 MASTER products are available at: https://masterprojects.jpl.nasa.gov/L2 Products. The HyspIRI Preparatory Airborne Activities enabled this major progression in the field, and is allowing for products for both ECOSTRESS and EMIT. This foundational work is also progressing the field of Level 3 product generation for both the VSWIR and TIR.

4.4: HyTES HyspIRI TIR Megabox

As a follow-on for the 2018 California collection, HyTES with AVIRIS-C and MASTER collected a simulated HyspIRI scene over California, Nevada, and Oregon (Figure 34). The megabox was collected with the NASA ER2 during the summer of 2018. The 600 km x 600 km box was designed to be the same dimensions of a HyspIRI TIR scene. The box consisted of 52 HyTES flight lines, and all data was collected with the AVIRIS-C and MASTER sensors. The line spacing was based on the 50 degree field of view of HyTES (AVIRIS FOV is 34 degrees and MASTER is 78 degrees). The data collection began in May 2018 and ended in September 2018. Quicklooks from all of the data is available on the hytes.jpl.nasa.gov (Figure 35).



Figure 34: HyTES TIR Megabox planned flight lines

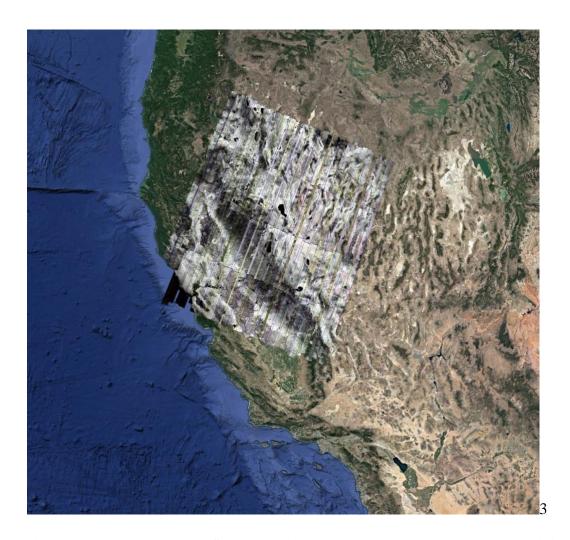


Figure 35. Nearly all HyTES megabox lines have been processed. The remaining few lines should be completed within the next month.

4.5: Additional Campaigns

During the HyspIRI Study timeframe, there were multiple international campaigns that focused on collecting VSWIR data that advanced the HyspIRI Study. These international campaigns included the second Ice, Cloud and Land Elevation Satellite (ICESat-2) laser risk reduction campaign to Greenland with AVIRIS-NG. The AVIRIS-NG sensor also collected data over the Indian Subcontinent twice with the Indian Space Research Organization (ISRO) on joint campaigns with NASA in 2016 and 2018. The Portable Remote Imaging Spectrometer (PRISM) conducted a campaign over the Southern Oceans and Antarctica with the NSF Gulfstream V as part O₂/N₂ Ratio and CO₂ Airborne Southern Ocean (ORCAS) Study. ORCAS was an NSF-sponsored airborne field campaign with research flights from Punta Arenas, Chile during January and February of 2016. PRISM was also selected as the primary instrument of the Earth Ventures Suborbital (EVS-2) Coral Reef Airborne Laboratory (CORAL). CORAL flew

missions in Australia, Guam, Palau, Hawaii and Florida. The University of Zurich and the European Space Agency (ESA) sponsored a 2018 AVIRIS-NG campaign to Europe. The primary objective was a Sentinel 3B Calibration and Validation effort, with data collections to support the future ESA FLEX and CHIME missions.

Chapter 5: Science and Applications

5.1: Summary of Science and Applications Linked to HyspIRI Type Observables

The new and important science and applications enabled by HyspIRI type measurements have expanded and matured over the past decade. This has been fostered by NASA investments as well as by the broad advance of science and application research. The best summary of the current status is provided by the two rounds of white papers provided to the 2017 Decadal Survey. These were prepared with the involvement of the SSG and the broad communities that require this class of measurement.

The authors and titles of the first set of HyspIRI related white papers submitted to the Decadal Survey in 2015 are given below. The full white paper can be found at the HyspIRI website [https://Hyspiri.jpl.nasa.gov].

Joshua Fisher: Evapotranspiration: A Critical Variable Linking Ecosystem Functioning, Carbon and Climate Feedbacks, Agricultural Management, and Water Resources

Jeffery Luvall: Human Health / Water Quality

Duane Waliser: Advancing the Science and Societal Benefits of Subseasonal to Seasonal (S2S) Environmental Prediction

Natalie Mahowald: Closing the Earth Surface Dust Source Composition Gap for Earth System Understanding and Modeling

Phillip Dennison: Burning Questions: Critical Needs for Remote Sensing of Fire Impacts on Ecosystems

Andrew Thorpe: Mapping atmospheric constituents at high spatial resolution to understand their influence on Earth's climate

Wendy Calvin: Key Questions and Challenges in Dynamic Earth Processes, Natural Resources, and Hazards linked to Geologic and Soil Surface Composition

Kevin Turpie: New Need to Understand Changing Coastal and Inland Aquatic Ecosystem Services

Thomas Painter: Monitoring Cryospheric Albedo in a Changing World: Filling the knowledge void on a key climate parameter

Robert Wright: Predicting Changes in the Behavior of Erupting Volcanoes to Reduce the Uncertainties Associated with their Impact on Society and the Environment

The second set of science and applications white paper inputs provided to the Decadal Survey in 2016 are listed below. This second set responded to a new set of requests and are in many cases more refined. All of these are available from the HyspIRI website [https://Hyspiri.jpl.nasa.gov]

Dale Quattrochi: High Spatial, Temporal, and Spectral Resolution Instrument for Modeling/Monitoring Land Cover, Biophysical, and Societal Changes in Urban Environments

Wendy Calvin: Earth Surface Geochemistry and Mineralogy: Processes, Hazards, Soils, and Resources

Philip Dennison: Global Measurement of Non-Photosynthetic Vegetation

Heidi Dierssen: Assessing Transient Threats and Disasters in the Coastal Zone with Airborne Portable Sensors

Riley Duren: Understanding anthropogenic methane and carbon dioxide point source emissions

Joshua Fisher: EVAPOTRANSPIRATION: A Critical Variable Linking Ecosystem Functioning, Carbon and Climate Feedbacks, Agricultural Management, and Water Resources

Steve Greb: Inland Waters

Robert Green: Science and Application Targets Addressed with the 2007 Decadal Survey HyspIRI Mission Current Baseline

Eric Hochberg: Coral Reefs: Living on the Edge

Simon Hook: Carbon Emissions from Biomass Burning

Jeffrey Luvall: A Thermodynamic Paradigm For Using Satellite Based Geophysical Measurements For Public Health Applications

Natalie Mahowald: Measuring the Earth's Surface Mineral Dust Source Composition for Radiative Forcing and Related Earth System Impacts

Frank Muller-Karger: Monitoring Coastal and Wetland Biodiversity from Space

Thomas Painter: Understanding the controls on cryospheric albedo, energy balance, and melting in a changing world

Tamlin Pavelsky: From the Mountains to the Sea: Interdisciplinary Science and Applications Driven by the Flow of Water, Sediment, and Carbon II

Ryan Pavlick: Biodiversity

David Pieri: Enabling a global perspective for deterministic modeling of volcanic unrest

E. Natasha Stavros: The role of fire in the Earth System

Philip Townsend: Global Terrestrial Ecosystem Functioning and Biogeochemical Processes

Kevin Turpie: Global Observations of Coastal and Inland Aquatic Habitats

Robert Wright: Predicting Changes in the Behavior of Erupting Volcanoes, and Reducing the Uncertainties Associated with their Impact on Society and the Environment

These white papers broadly capture the current state of the science and applications requirements for the class of measurements provided by the HyspIRI mission concept.

5.2: HyspIRI Applications

HyspIRI's impact in advancing diverse science questions extends into its potential benefit to address diverse science applications. The HyspIRI applications team has been working to build community awareness and engagement for HyspIRI-like datasets to support science applications within various management contexts. This ties in closely to the applications work that has been done for ECOSTRESS.

<u>Disasters</u>

HyspIRI would be able to make telling contributions to quantifying the hazards presented by volcanoes and wildfires. The TIR instrument would make measurements of the energy emitted by Earth's surface at 60 m resolution, at middle infrared wavelengths (approximately 4 micrometers), as well as seven spectral bands in the thermal infrared (8-12 micrometers). Targets that have high temperatures emit prodigious amounts of energy at 4 micrometers, making the identification of pixels that contain active lavas or vegetation fires relatively easy using the data

that HyspIRI would provide. As this channel is being designed with a wide measurement range, the intensity of the thermal emission can also be accurately quantified, to determine where the most active lavas (or the most active fires) are to be found. It is the combination of high spatial resolution, high temporal resolution, and global day-and-night mapping, using a dedicated "hotspot" detection waveband, that would make HyspIRI unique with respect to other earth observation missions in this regard.

Potential stakeholders.

- Federal Emergency Management Agency
- USGS Volcano Hazards program
- Federal Aviation Administration
- U.S. Environmental Protection Agency
- Red Cross

Water Resources and Ecological Forecasting

Drought Response and Management. Evapotranspiration (ET) is the key climate variable linking the water, carbon, and energy cycles, controlled both through the atmosphere and the biosphere. Plants regulate water loss (transpiration) by closing the pores on their leaves, but at the expense of shutting off CO2 uptake for photosynthesis and risking carbon starvation. Transpiration also performs the same cooling function as sweat—if plants cannot adequately cool themselves, they risk overheating and mortality due to dehydration.

The Evaporative Stress Index (ESI) describes temporal anomalies in evapotranspiration (ET), highlighting areas with anomalously high or low rates of water use across the land surface. Here, ET is retrieved via energy balance using remotely sensed land-surface temperature (LST) timechange signals. LST is a fast-response variable, providing proxy information regarding rapidly evolving surface soil moisture and crop stress conditions at relatively high spatial resolution. The ESI also demonstrates capability for capturing early signals of "flash drought", brought on by extended periods of hot, dry and windy conditions leading to rapid soil moisture depletion. With HyspIRI, we would be able to measure the ET from individual fields and provide actionable information to farmers so they can obtain the maximum benefits from often dwindling water supplies.

Potential stakeholders.

- U.S. Department of Agriculture
- National Oceanic and Atmospheric Administration
- U.S. Geological Survey
- U.S. Forest Service
- U.S. Bureau of Reclamation
- U.S. Army Corps of Engineers
- Western States Water Council and State Water Resources Departments
- U.S. Agency for International Development

- World Bank
- Red Cross

Water Quality.

Monitoring optical properties of water using imaging spectroscopy could be transformative for water quality monitoring and management, especially for water bodies that are chronically impacted by contaminants. For example, harmful algal blooms (HABs) pose a significant health risk to both human and animal populations. HAB occurrence is affected by a complex set of physical, chemical, biological, hydrological, and meteorological conditions making it difficult to isolate specific causative environmental factors. HAB's cause significant reduction in water quality through algal production of toxins potent enough to poison both aquatic and terrestrial organisms. The Great Lakes are the nation's single most important aquatic resource. They are the largest freshwater source in the world and contain 90% of U.S. surface water supply and provide drinking water to 40 million U.S. and Canadian citizens.

The HyspIRI mission would provide hyperspectral visible to shortwave infrared and multispectral thermal data products that would significantly enhance the capacity to monitor and predict algal blooms events and extent and their potential impact on human health. The 60 m resolution hyperspectral data and its repeat provided from HyspIRI would allow spectroscopy at a spectral accuracy of < 0.5 nm and an absolute radiometric accuracy of > 95% from water surfaces. These data would significantly enhance the ability to identify the toxic cyanobacteria species and sub-species along with their distribution within the water column and the spatial variability in the surface waters throughout the Great Lakes. HyspIRI's thermal infrared multispectral data would also have 60-meter spatial resolution but a 5-day repeat pattern that greatly enhances the ability to obtain timely and adequate thermal data. HyspIRI's NEdT (Noise Equivalent delta Temperature) precision of < 0.2 Kelvin would produce day- night pairs of calibrated surface temperatures for use in determining surface water temperature. The combination of both the visible-shortwave infrared and thermal wavelengths would significantly enhance the ability identify the toxic cyanobacteria species and provide water temperature to help understand the HAB population dynamics.

Potential stakeholders.

- National Oceanic and Atmospheric Administration
- U.S. Environmental Protection Agency
- U.S. Bureau of Reclamation
- Western States Water Council and State Water Resources Departments
- Water Utilities
- U.S. Agency for International Development
- World Bank
- U.S. Fish and Wildlife Service

Public Health

Vector borne Disease. The availability of HyspIRI-like data can significantly advance characterization of important environmental parameters significant in disease vector life cycles. Factors such as soil moisture and type, soil organic matter content, surface, air and water temperatures, and vegetation phenology and species community composition are important in controlling the geographical extent and timing of disease vector life cycles. Year to year population variability responds strongly to climate and weather cycles. The initiation of many disease vector life cycles is triggered by the start of the rainy season. The best currently available thermal data from MODIS is at a 1km resolution, which does not quantify the fine scale habitat variability important in determining the disease vector's niche. Landsat provides better spatial resolution, but a 16-day repeat cycle makes it difficult to obtain data in many areas due to cloud cover. In addition, currently there are no satellites that provide routine global hyperspectral measurements critical in providing plant phenology/physiology measurements important in monitoring disease vector habitat or life cycle processes.

The HyspIRI mission would provide hyperspectral visible and multispectral thermal data products enabling structural and functional classification of ecosystems and the measurement of key environmental parameters (temperature, soil moisture). HyspIRI 's 60-meter spatial resolution and approximately 5-day repeat pattern greatly enhances the ability to obtain timely and adequate thermal data. HyspIRI's NEdT (Noise Equivalent delta Temperature) precision of < 0.2 Kelvin would produce day-night pairs of calibrated surface temperatures for use in determining soil moisture, evaporation, and microclimate. The multispectral thermal bands would provide the capability of using wavelength dependent emissivity differences of minerals to map soil mineral composition, clay and organic matter content. The thermal measurements are particularly useful in providing approximately 5-day and day-night pairs of measurements of surface thermal environments.

Potential stakeholders.

- Centers for Disease Control
- National Institutes of Health
- State and local public health agencies
- U.S. Agency for International Development
- Bill and Melinda Gates Foundation
- Red Cross

Wildfires

Accurate predictions of fire behavior (e.g. fire intensity and spread) are crucial to support operational fire management and firefighting decisions. Fire behavior depends on topography, weather, and fuels. Fire behavior predictions are based on relationships with these environmental variables. High spatial resolution measurements of fire intensity are required to evaluate and improve these relationships in order to effectively protect real estate and human lives at the wildland-urban interface. For proactive fire management, we must understand how

fuels affect fire behavior. Fuels can be characterized by amount, condition (e.g., live or dead), and fuel moisture content. We can derive fuel characteristics using spectral information from visible to thermal infrared (0.38 to 12 μ m) measured by HyspIRI. By understanding how fuels relate to fire behavior we can manage the land and fuels accordingly, thus providing fuel breaks and fire corridors directing fires away from areas we wish to protect.

HyspIRI would provide unprecedented global measurements of fire intensity based on fireemitted radiance in the 4 μ m region with high spatial resolution (60 m) across ecosystems and fire types. The 60 m resolution would allow characterization of nearly pure active fire pixels, and thus the flaming front of the fire, which is currently impossible from coarser scale sensors. The saturation temperature for the 4 μ m channel is optimized for hot target characterization and set high at 1200 Kelvin. These high-quality fire intensity measurements would allow optimized relationships between environmental factors and fire behavior, ultimately providing better predictions of fire behavior and aiding active fire management. HyspIRI would also continuously monitor fuel conditions. HyspIRI's imaging spectrometer in the visible to shortwave infrared (0.38 to 2.5 μ m) would allow detailed characterization of fuel types and composition, while the multispectral thermal (4 to 12 μ m) imager would provide information on drought stress and fuel moisture content. This detailed information on fuel conditions from before the fire can then be linked to active fire characteristics.

Potential stakeholders.

- National Oceanic and Atmospheric Administration
- U.S. Environmental Protection Agency
- U.S. Forest Service
- U.S. Fire Administration
- State Fire Response and Management Departments
- Federal Emergency Management Agency
- Water Utilities

5.3: Coastal and Inland Aquatic Science and Applications

Coastal and inland ecosystems are extremely important to humans worldwide and highly vulnerable in a changing world, global study of these regions are both urgent and compelling. However, remote sensing of these aquatic subjects are particularly challenging and require careful dialogue between aquatic remote sensing scientist and mission architects and instrument engineers to determine the range of aquatic applications a given mission design can achieve. To that end, HyspIRI mission designers made special efforts to facilitate that discourse wherever possible.

Early in the mission concept pre-formulation, the coastal and inland aquatic remote sensing community actively contributed to the development of the HyspIRI science questions through aquatic scientists the SSG. They also provided input regarding requirements and architectural

trades studies. In particular, a special Sun Glint Working Group was formed to study the effects of surface specular reflectance given the HyspIRI tilt and orbital configuration. In that study, the working group simulated glint effects and determined that corrections could be applied to greatly improved glint contaminated data. However, such corrections must be spectrally based given spatial resolution and would likely need to be coupled with the atmospheric correction algorithm, especially with respect to calculations of aerosol contributions. It was also determined that aquatic data products that are dependent on classification algorithms were relatively robust and could recover information unless the specular signal was strong enough to overwhelm the atsensor signal. However, it was also found that data products that depended on retrieving the optical properties of the water were likely much more sensitive to glint (Hochberg et al., 2008). Aquatic remote sensing scientists also expatiated on the effects to aquatic science and applications of flying VSWIR and thermal instruments on separate orbital platforms. In that study, the community noted that the temporal separation between VSWIR and thermal observations could be problematic dynamic aquatic systems.

During the HyspIRI preparatory campaigns, one aquatic remote sensing team was selected to mature algorithms that discriminate coastal phytoplankton functional types (Kudela et al., 2015) during the flights over California using AVIRIS. Later, several teams were also selected to look at remote sensing of corals and related studies during flights over Hawaii using PRISM. Both studies are still producing results, however, they underscored the instrument performance and calibration requirements and the need for good atmospheric correction. During the two campaigns over Hawaii, several observations were also made over the Marine Optical Buoy (MOBY), which is an in-water hyperspectral spectrometer used for aquatic remote sensing vicarious calibration. It is hoped that these measurements will help with further development of atmospheric correction algorithms using hyperspectral data.

To strengthen and better organized community input, NASA established a special community of practice in 2012 called the Aquatic Studies Group (ASG). The objective of the ASG was to support the HyspIRI coastal and inland aquatic remote sensing community, compiling community input regarding data products, science and applications to formulate recommendations and guidance to NASA and the HyspIRI mission. The ASG has coordinated or published several white papers and dozens of peer-review literature articles related to HyspIRI; hosted several community forums, town halls, and international teleconferences and webinars; and worked directly with project management to convey community input. In addition, the ASG kept the community aware of research opportunities provided by NASA and other resources and promoted activities of the community at HyspIRI meetings, highlighting work in the development and demonstration imaging spectroscopy in aquatic environments.

The ASG reached out to other organizations to foster mutual benefit in aquatic remote sensing. They worked to coordinate activities and resources between related missions, including particularly the Phytoplankton, Aerosols, Clouds, ocean Ecology (PACE) and Geosynchronous GEOstationary Coastal and Air Pollution Events (GEO-CAPE) mission.

They also worked towards collaborations with the Group on Earth Observations (GEO) initiatives to build broader, international context. The ASG lead also represented NASA in a

Committee on Earth Observing Satellites (CEOS) feasibility study for a coastal and inland sensor for observations of aquatic ecosystems and water quality. The ASG also work collaboratively with applications scientists in areas such as assessing or predicting water borne diseases.

From 2012 to 2015, the ASG developed a white paper identifying key data products that were needed by the community and could be facilitated by the HyspIRI concept. In addition, the group strongly focused on prioritizing these products based on their relevance to the HyspIRI mission concept and the 2007 Decadal Survey, their urgent and compelling nature, and their feasibility and heritage. Because of the low temporal resolution of the HyspIRI mission concept, the report prioritized mapping the extent and distribution of sessile, habitat-forming species (e.g., sea grasses, corals, marsh and mangrove vegetation) and estimating the conditions of these habitats. In-water and surface phenomenon (e.g., phytoplankton blooms) were of interest in particular if they were related to persistence patterns.

At town halls and aquatic forums, the ASG identified the need to discuss instrument tilt options, a science-driven coastal mask, the need for good data for algorithm development, and how to set priorities for data products. In addition, during a special forum on atmospheric correction over coastal and inland waters, it was determined that the key challenges included absorbing gases (e.g., H₂O, O₃, NO₂) and aerosols and their variability in coastal regions; separating spatially resolved glint from the aerosol signal; shallow and turbid water; adjacency effects; UV reflectance uncertainty (e.g., solar irradiance variability, instrument calibration uncertainty); and other effects that play a role in moderate to high spatial resolution imagery (e.g., cirrus, surface foam).

By the close of the HyspIRI mission, the group has grown to over 100 affiliates with international and domestic institutions, including government, university, research and application organizations. The ASG remains poised to continue as a community of practice, promoting and advancing the coastal and inland sciences by connecting community requirements to aquatic remote sensing resources for the SBG mission.

Chapter 6: 2017 Decadal Survey

6.1: 2017 Decadal Survey: A Path to HyspIRI Type Observables

While the 2007 HyspIRI concept did not advance to a mission, the advances in understanding what new and important science and applications could be achieved from these measurements were provided to the 2017 Decadal Survey process in the form of white papers. Based in part on these and other factors, a set of observables in family with those of HyspIRI are identified in the 2017 Decadal Survey.

From the NRC 2017 Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space

"Targeted Observable: Surface Biology and Geology

Science/Applications Summary: Earth surface geology and biology, ground/water temperature, snow reflectivity, active geologic processes, vegetation traits and algal biomass.

Candidate Measurement Approach: Hyperspectral imagery in the visible and shortwave infrared, multi- or hyperspectral imagery in the thermal IR.

Basis For Being Foundational: Key to understanding active surface changes (eruptions, landslides and evolving landscapes); snow and ice accumulation, melting, and albedo; hazard risks in rugged topography; effects of changing land-use on surface energy, water, momentum and carbon fluxes; physiology of primary producers; and functional traits and health of terrestrial vegetation and inland and near-coastal aquatic ecosystems. Further contributes to managing agriculture and natural habitats, water use and water quality, and urban development as well as understanding and predicting geological natural hazards and land-surface interactions with weather and climate. Depending on implementation specifics, the Targeted Observable may also contribute to hyperspectral ocean observation goals. Addresses many "Most Important" objectives of the Ecosystem, Hydrology, and Solid Earth Panels, and addresses key components of the Water and Energy Cycle, Carbon Cycle, and Extreme Events integrating themes....

The Surface Biology and Geology Targeted Observable, corresponding to TO-18 in the Targeted Observables Table ..., enables improved measurements of Earth's surface characteristics that provide valuable information on a wide range of Earth system processes. Society is closely tied to the land surface for habitation, food, fiber and many other natural resources. The land surface, inland and near-coastal waters are changing rapidly due to direct human activities as well as natural climate variability and climate change. New opportunities arising from enhanced satellite remote sensing of Earth's surface provide multiple benefits for managing agriculture and natural habitats, water use and water quality, and urban development as well as understanding and predicting geological natural hazards. The Surface Biology and Geology observable is linked to one or more Most Important or Very Important science objectives from each panel and feeds into the three ESAS 2017 integrating themes: water and energy cycle, carbon cycle, and extreme event themes.

Science Considerations. This Targeted Observable will likely be addressed through hyperspectral measurements that support a multi-disciplinary set of science and applications objectives. Visible and shortwave infrared imagery addresses multiple objectives: active surface geology (e.g., surface deformation, eruptions, landslides, and evolving landscapes); snow and ice accumulation, melting, and albedo; hazard risks in rugged topography; effects of changing landuse on surface energy, water, momentum and carbon fluxes; physiology of primary producers; and functional traits of terrestrial vegetation and inland and near-coastal aquatic ecosystems. Thermal infrared imagery provides complementary information on ground, vegetation canopy, and water surface temperatures as well as ecosystem function and health. Depending on implementation specifics, the Targeted Observable may also contribute to hyperspectral ocean observation goals. However, such goals are met to a large degree by POR elements, in particular the hyperspectral PACE mission, and are not considered a priority for

additional implementation (and thus are not recommended if they drive cost). Observations of the Earth's surface biology and geology, with the ability to detect detailed spectral signatures, provide a wide range of opportunities for Earth system science parameters across most of the panels and integrating themes. As such, this Targeted Observable maps to some of the highest panel priorities as well as the Integrating Themes.

Candidate Measurement Approaches. High spectral resolution (or hyperspectral) imagery provides the desired capabilities to address important geological, hydrological, and ecological questions, building on a successful history of past and ongoing multispectral remote sensing (e.g., MODIS). Consequently, hyperspectral imagery with moderate spatial resolution (30-60m) is identified as a priority for implementation.

CATE Evaluation. The CATE evaluation considered the HyspIRI concept, which was developed by SMD following a recommendation from the 2007 ESAS decadal survey, and found that the concept is technically mature and costs are well-understood, supporting a recommendation for early implementation....

Budgetary Guidance. In keeping with the guidelines of the designated program element and this report's Recommendation 3.3, the *Surface Biology and Geology* Targeted Observable has a maximum recommended development cost of \$650M (in FY18\$)."

Chapter 7: 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 by providing 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 assessed and matured where feasible.

The Hyperspectral Infrared Imager (HyspIRI) mission was proposed to be the first satellite system with the capability to provide global, repeat coverage across the visible and shortwave infrared spectrum, as well as eight channels in the midwave and thermal infrared. HyspIRI has stated objectives to address a host of pressing earth science questions, from radiation budgets to ecosystem functions. A sizable science community has grown to support the mission, and their ongoing research demonstrates HyspIRI's potential to greatly expand our knowledge of the Earth system. In response to the need for global measurements across the visible to thermal infrared, the concept for HyspIRI was developed in the early 2000s and was recommended as a "Tier 2" mission in the National Research Council's 2007 report Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (NRC 2007). HyspIRI was designed to address pressing questions about the world's terrestrial and aquatic ecosystems, as

well as to investigate and provide crucial information on natural disasters such as volcanoes, wildfires, and drought.

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

In 2013 the NRC released the report, Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program. This report identified 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 final report that consists of this document and appendices.

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Appendix A: List of Publications Sorted by Topic Areas

Overview Papers and Documents

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Appendix B: Details Underpinning HyspIRI Science Questions

VSWIR Science Questions

VQ1. Pattern and Spatial Distribution of Ecosystems 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.

<u>VQ2. Ecosystem Function, Physiology and Seasonal Activity</u> 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.

<u>VQ3. Biogeochemical Cycles</u> 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.

<u>VQ4. Ecosystem Response to Disturbance</u> 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.

<u>VQ6.</u> 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

<u>TQ1. Volcanoes and Earthquakes</u> 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.

<u>TQ2. Wildfires</u> 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-userelated 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), highresolution 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

<u>CQ1. Coastal, Ocean and Inland Aquatic Environments</u>: 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].

<u>CQ2. Wildfire, Fuel and Recovery</u>: 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].

<u>CQ3. Volcanoes and Surface Signatures</u> HyspIRI's TIR channels will allow combined measurement of temperature, surface composition, and SO₂ 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; SO₂ 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].

<u>CQ4. Ecosystem Function and Diversity</u> 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.

<u>CQ6. Human Health and Urbanization</u> 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.

Appendix C: HyspIRI Applications Traceability Matrix

HyspIRI Application TM



			Applied Sciences		Mission Data	E .		
Application question How do we schedule water release & determine evaliability for frigation use?	Application Concept The major pathway of water transport in the hydrologic cycle is evaportampiration(IFI); it sifficults measure directly for large area and determination of IF relies on a combination of models and surface parameterizations. Accurate determination of surface temperatures is critical in model parameterizations.	Application Measurement Locals Spatial variability of landscape elements necessaite fine spicial resolution measurements – Son. Repeat measurements of approximately 5 days are required to constrain ET models.	Category Water Management Agriculture	Potential nost agency Western Governor Association 1600 Broadway Suite 1700 Denver, 0.0 80020 309 823-9378 1772 Picasso Avenue Suite E Davis, California Davis, California	Product Surface temperature	Measure surface temperature within 0.5 K, 50 m resolution and 5 day repeat cycle.	SEBAL, oti 9 indentifica solls	Ancillary weakurements SEBAL, other ET models, agricultural crop indentification/management info, stream flow, ppt, sols
What is the species diversity and habitat of key water resources. Focused studies at specific locations e.g. Comportensitive Everglades Restoration Plan (CERP)	Characterize ET patterns and functional classification of ecosystems (carbon binding& storage, species diversity), and land-use/type	30-60m spatial resolution, 3-5 day thermal measurements (0.5%)	Water Management Ecological Forecasting	ir) Biologist Office of – SE Area sy Orlando,	Surface temperature Hyperspectral radiance measurements	Measure surface temperature within 0.5 K, 60 m resolution and 26 day repeat cycle. Provide hyperspectral radiance measurements at 60 m resolution on a 15 day repeat cycle.	6 structural	ppt, stream flow, weather stations, ecosystem structural studies, physiological measurments
What is the extent and the condition of coral reefs ecosystems?	Characterize the physical, chemical, and biological status of coastal and estuarine environments and ecosystems worldwide.	Hyperspectral measurements of coastal areas to provide spacial & spectral information for models & management.	Ecological Forcasting Oceans	NOAA's Center for Coastal Monitoring and Assessment	Hyperspectral radiance measurements	Provide hyperspectral radiance measurements at 60 m resolution on a 19 day repeat cycle.	Historical & NOAA's Cen Assessment	Historical & current habitat mapping data from NOAA's Center for Coastal Monitoring and Assessment
What are the abiotic environmental factors are important in determining the distribution of diesase-causing vectors and their life-cycles? Mentioning targeted tropical diseases for elimination-ropegress & micketors. Generate disease risk maps reliable to the date when the epidemiological survey occurs and to only the areas covered with the survey.	HypiRi observations can be merged through a Land Data Assimilation System (LDAS) be used to drive spatially-explicit ecological models of MTD vertors distributes & life cycles. Assimilations will be driven by observational data LDAS and satellite-derived meteorological forcing data, parameter datasets, and assimilation observations.	Spatial variability of landscape elements necessaite fine spacial resolution measurements ~ 60m. Repeat measurements of approximately 5 days are required for environmental measurements. 13 days for hyperspectral vegetation mapping/physological status.	Public Health-vector born diseases	PanAmerican Health Organization (PAHO), Steven Auft, (202 974 3996, autistev@ paho.org) Swiss Tropical Institute Wendepee Vountation Wountary, perelopee, vountation@ unitas. ch) interamerican nibas. ch) interamerican Development Bank	Hyperspectral radiance measurements & surface temperatures	Measure surfice temperature within 0.5 K, 60 m resolution and 5 day repeat cycle. Provide Phyperspectral radiance measurements at 60 m resolution on a 15 day repeat cycle.	Assimilations will B LDAS and statelline data, parameter did observations, included observations, included land Gover Type fr Soil Moisture from SimAP and Hyspilal. Terrestrial Water Soil Surface temperatu. Area index, and can Topography from	Assimilations will be driven by observational data LOLS And statisfies derived meteorological forcing data, parameter datasets, and assimilation observations, including-freschiption from TRMM, and GRM. Soil Moisture from Hyspilat Soil Moisture from AMSR-E (where applicable), Soil Moisture from AMSR-E (where applicable), Soil Moisture from AMSR-E (where applicable), Soil Action of Soil Action Hyspilation Station of Soil Action Hyspilation Station of Soil Action Hyspilation Station of Soil Action Soil Ac
What is the composition of dust sources globaly and what role does surface mineralogy and bloic crusts play in accessing the impact of dust in human health.	Global transport of dust is well documented. The health impacts from microgalisms and minerallogs are is now beginning to be understood. The source of the dust is significant in determining its possible health effects. MyspIRI hyperspectral measurements would provide global measurements of surface miner along and bostic cruss. MyspIRI surface thermal mineraling and bostic cruss. MyspIRI surface thermal measurements would also help identify the variability of dust sources due to surface moisture conditions and map mineralings.	Spatial variability of landscape elements necessalte film espacial expedition measurements "Gon Repeat measurements of approximately 5 days are required for environmental measurements [soil moisture]. 19 days for hyperspectral mineral mapping.	Public Health-Air Quality	US Department of Defense, Corps of Engineers, Public health agencies, World of metorologist Organization (WMOI) Sand and Dust SSORM Warning Advisory and Assessment System (Bill Sprigg (714) 289-	Hyperspectral radiance measurements & surface temperatures	Provide hyperspectral radiance measurements at 60 m resolution on a 19 day repeat cycle.	Detailed c 6 samples. I samplers.	Detailed chemical & biological analysis of source samples. Particle size distributions, ground based samplers.
What is the land-use and productivity of the intercoastal waters & barrier islands, e.g. Monitoring Gulf Novico - spawning cycles, migration, land-use, productivity.	Characterize the physical, chemical, and biological status of coastal and extuarine environments and ecosystems.	Spatial variability of bandscape elements necessalte fine spacial expedition measurements. Gen Repeal measurements of approximately 6 days are required for environmental measurements. 19 days for hyperspectral vegeration mapping/physiological status.	Ecological Forcasting	ulf Islands thew nps.gov	Hyperspectral radiance measurements & surface temperatures	Measure surface temperature within 0.5 k, 60 m resolution and 6 day repeat cycle. Provide hyperspectral radiance measurements at 60 m resolution on a 19 day repeat cycle.	6 hydrolab i	Ecosystem structural & functional measurments, hydrolab water chemistry measurements.
How does surface water temperature affect manatee migration	Characterize patterns and trends in fine spacial scale river, estuarine, and near coastal water temperatures.	30-60m spatial resolution, 3-5 day thermal measurements (0.5K). At least 1 nightime measurement within the 3-5 dya window.	Ecological Forcasting	Dauphin Island Sea Lab Ruth Carmichael rcarmichael@disl.org. (251) 861 7555	Surface temperature	Measure surface temperature within 0.5 K , 60 m resolution and 5 day repeat cycle	6 Bouy tem	Bouy temperatures
What are the abiotic environmental factors are important in determining the distribution of disease-causing vectors and their life-cycles?	Research/America's global health program advocates for funding and policies that spur research to develop vitally important global health technologies.	Spatial variability of landscape elements necessaite fine spotal resolution measurements ~ 60m. Repeat measurements of approximately 5 days are required for environmental measurement. 13 days for hyperspectral vegetation mapping/physological status.	Public Health	Alexandra FrankAlexandra Frank Senior Program Manager, Global Health Ray Research Annerica 703-339-257 (min) 571-48.2-2707 (direct.)	Hyperspectral radiance measurements & surface temperatures	Measure surface temperature within 0.5 k, 60 m resolution and 5 day repeat cycle. Provide Phyperspectar in dilance measurements at 50 m resolution on a 19 day repeat cycle.	Assimilations drive and statilitie-derive parameter of dataset parameter of dataset including-Precipital Land Cover Type it Soil Moisture from Fig. Soil Moisture from Fig. Surface temperated Area in Mex. and ca Topography from targed diseases. We testing for diseases.	Assimilations driven by observational data LDAS and selected the depocked meta-objectal forcing data, and selected datasets, and assimilation observations, including-free cipitation from TPRAMs, and GPM Land Cover Type from MysRAR, Ewhere applicable). Soil Mostsure from AMSR-E (where applicable). MoMA and MysRAR, Ewhere applicable). Soil Mosture tremperature, Vegetation Fraction/Leaf Sorface temperature, Vegetation Fraction/Leaf Sorface temperature, Vegetation Fraction/Leaf Sorface temperature. Repleasing from SRIM. Epidemiological surveys of targed diseases. Vector population sampling & texting for disease organism.