HYSPIRI 2012

TECHNOLOGY READINESS ASSESSMENT

FINAL DRAFT

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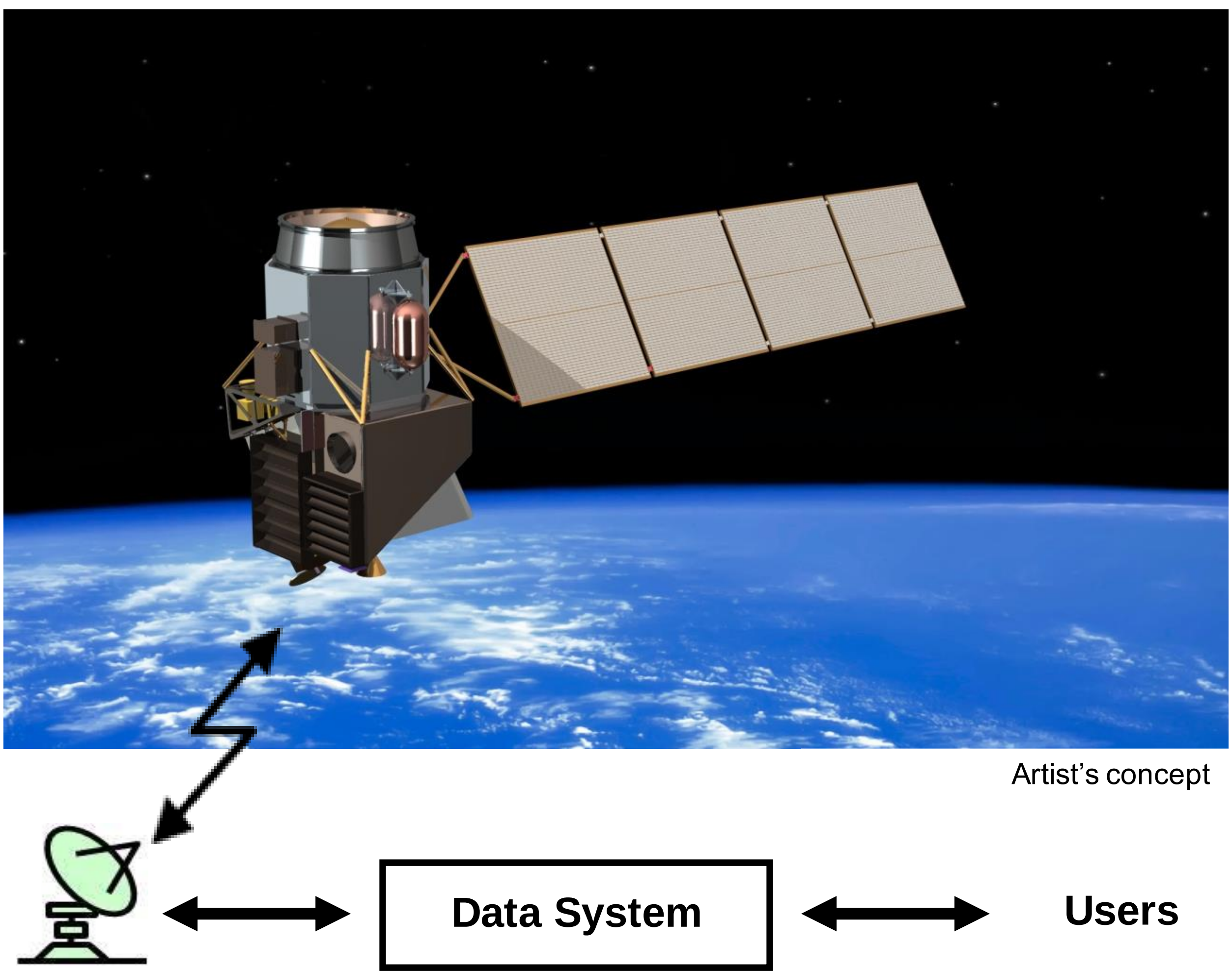


Artist's concept

HyspIRI Mission Concept Technology Readiness Assessment

0 Executive Summary 2
0.1 Key for TRL and Heritage Classification 5
1 Spacecraft 8
1.1 Spacecraft Telecom Subsystem (TT&C) 12
1.2 Guidance, Navigation and Control Subsystem (GN&C) 14
1.3 Command and Data Handling (CDH) Subsystem 16
1.4 Propulsion Subsystem 18
1.5 Electrical Power Subsystem 20
1.6 Structure and Mechanisms Subsystem 22
1.7 Thermal Control Subsystem 24
1.8 Spacecraft Bus Flight SW 26
1.9 (Alternative) X Band Telecom and SSR 28
2 Payload 34
2.1 VSWIR 34
2.2 TIR 49
2.3 IPM 63
3 Ground Systems 67
3.1 ATK Command And Control (C&C) Ground System 67
3.2 KSAT Ground System 67
3.3 (Alternative) SCAN Ground System 68
3.4 Science Data System Hardware 68
3.5 Science Data System Software 71
4 Assembly, Integration and Test Facility 73
4.1 ATK Facilities and ATLO Processes 73
4.1 JPL VSWIR and TIR Instrument Assembly Facility 74
4.2 JPL VSWIR and TIR Instrument Alignment and Calibration 74
4.3 JPL Thermal Vacuum Facility 77
5 Science Algorithms 77
5.1 Level-1 VSWIR Algorithms 77
5.2 Level-1B TIR Algorithm 78
5.3 Level-2 VSWIR Surface Reflectance Algorithm 78
5.4 Level-2 TIR Surface Radiance Algorithm 78
5.5 Level-2 Land Surface Temperature and Emissivity (LST&E) Algorithm 79
6 Calibration and Validation 80
6.1 VSWIR 80
6.2 TIR 81

0 Executive Summary

This report contains the HyspIRI mission concept's recent technology readiness survey which determined that every component in the HyspIRI mission is TRL 6 or greater except for the following three items which are TRL 5 and have a funded plan for becoming TRL 6: custom TIR HgCdTe based detector, TIR ROIC and TIR Focal Plane Assembly. All three of these developments are being funded by an ESTO IIP and will be TRL 6 in 2013.

The TRL assessment contained in this document has been reviewed and concurred by Mark Domen (ESM SEWG TRL Study Lead from GSFC), Raúl Romero (ESM SEWG JPL Lead) and Charles D. Norton (ESTO Associate at JPL).

This document itemizes the TRL of each subsystem of the HyspIRI Mission, backing up these TRL assertions with insight into the heritage of these subsystems. Although heritage and TRL are not always directly related, the heritage descriptions are used to provide a deeper understanding into the readiness of the HyspIRI mission for starting phase A.

The HyspIRI mission is leveraging significant existing experience in designs, software, operations and testing to achieve its science objectives. While the project does not take credit for cost reductions as a result of this extensive heritage, the broad range of experience described in this document will bring substantial risk reduction benefits to HyspIRI through the adoption of flight proven designs implemented by an experienced team.

Spacecraft Bus

The ATK (Alliant Techsystems Inc.) spacecraft bus is shown as an example, feasible, baseline design. The bus vendor has not yet been selected. Each subsystem of this bus is TRL 6 or greater (see Table 0-1).

The selection of this bus for HyspIRI has the additional advantage of being the same bus that was used for the ARTEMIS instrument. This TacSat-3 spacecraft (built for the Air Force Research Laboratory) demonstrated pointing knowledge better than that required by HyspIRI.

A few key modifications to the TacSat-3 spacecraft are required for HyspIRI. The primary one is different avionics. Although the same avionics used for TacSat-3 ("RSMB Avionics") is also under consideration, it would require an additional 1 Tbit SSR that was not part of TacSat-3. Therefore, the "HEAU" avionics with its included 1 Tbit SSR is the baseline design. A Phase A/B trade will decide between the RSMB and HEAU.

Other than the possibly different avionics (and SSR), the only other hardware changes from TacSat-3 are the change to a larger propulsion tank and the addition of an 800 Mbps X-Band system.

The SSR and high rate X-Band telecom (TT&C) proposed by ATK are flight proven and an alternate X-Band system and SSR by Surrey Satellite Technology Ltd (SSTL) is also shown. The Surrey system will be flight proven in 2012. A Phase A/B trade will decide between the two.

Table 0-1. Spacecraft TRL and Heritage

ATK Bus Technology Readiness Assessment		
	Primary Heritage Mission(s)	**Lowest component TRL**
TT&C	ORS-1, GeoEye-1, QuickBird, TacSat-4	9
GN&C	ORS-1, EO-1, TacSat-3	9
Avionics	WISE	6
Propulsion	ORS-1	9
Power	TacSat-3, ORS-1	7
Structure	TacSat-3, ORS-1	7
Thermal	TacSat-3, ORS-1	9
Harness	TacSat-3, ORS-1	8
Software	TacSat-3, ORS-1	7
(Alternative) X-Band and SSR	NigeriaSat 2	8

Payload: VSWIR, TIR and IPM

VSWIR builds on a long heritage with JPL, NASA and non-NASA imaging spectrometers including Hyperion, CRISM, M3 and ARTEMIS.

TIR builds on successful thermal infrared Earth-Observing instruments such as the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on the Terra satellite launched in 1999 as part of NASA's Earth Observing System (EOS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra and Aqua satellites.

The IPM is based on NPP's broadcast system. It contains no hardware below TRL 9 and no software below TRL 7. While there is a wide array of potential on-board algorithms that have been identified (anywhere from TRL 5-9), only those algorithms currently TRL 7 or higher are part of the baseline. Note that the IPM is an applications demonstration and not required to meet the mission's Level 1 requirements.

The spacecraft bus and instruments are summarized in Tables 0-2 through 0-4.

Ground System

The ground system is comprised of the ATK provided Command and Control, the KSAT (Kongsberg Satellite Services) provided stations and a JPL Science Data System (SDS).

The spacecraft is operated by an ATK team out of their Mission Operations Center (MOC) in Pasadena, California. This same team currently supports the operation of QuikSCAT, ACRIMSAT, JASON and OSTM/JASON-2 out of JPL's mission control center. ATK's MOC currently serves as the back-up to JPL's mission control center.

The large volume of science data (4.6 Terabits per day on average) passes directly from the satellite, through KSAT's tracking station and local buffer (sufficient for 1 week's data), across commercial fiber optic cables via FTP to the SDS at JPL. This approach is feasible because of HyspIRI's non-stringent data latency requirements. KSAT's stations are also used for S-Band TT&C up and downlinks.

An alternative feasible ground station provided by NASA's SCAN (Space Communications and Navigation) is also presented. An analysis performed by SCAN shows that their system will accommodate the data rates and volumes required by HyspIRI (assuming a baseline launch date in 2020).

Table 0-2. VSWIR TRL and Heritage

VSWIR Technology Readiness Assessment		
	Primary Heritage Mission(s)	**Lowest component TRL**
Focal Plane and Electronics	M3, ARTEMIS, CRISM	6
Mechanical	M3, OCO, ARTEMIS, HYPERION	7
Thermal	M3, AIRS	7
Optics	M3, ARTEMIS	7

Table 0-3. TIR TRL and Heritage

TIR Technology Readiness Assessment		
	Primary Heritage Mission(s)	**Lowest component TRL**
Focal Plane and Electronics	CrIS, M3, DIVINER, AIRS, MODIS, HIRDLS	5 (6 in 2013)
Mechanical	DIVINIR, MODIS, MER	7
Thermal	M3, AIRS	7
Optics	M3, ARTEMIS, DIVINIR	7

Table 0-4. IPM TRL and Heritage

	Primary Heritage Mission(s)	**Lowest component TRL**
Electronics	HST/RNS, MISSE7, and STP-H4	9
Mechanical / Thermal	FAST, IBEX	7
Telecom	NPP	9

The SDS uses the same architecture, Processing Control System (PCS) and Product Generation Executable (PGE) product lines as SMAP and CARVE. Although HyspIRI will process seventeen times the daily data volume of SMAP, the PCS and PGE product lines used in SMAP's SDS are designed such that they are well suited to scaling to HyspIRI's data volumes.

ATLO

The spacecraft bus is assembled, tested and integrated with the payload in the existing ATK facilities in Beltsville, Maryland. Environmental tests will be performed in nearby facilities at Goddard Space Flight Center (GSFC), Johns Hopkins University Applied Physics Laboratory (JHU-APL) or the Naval Research Laboratory (NRL).

The proposed VSWIR and TIR instruments are assembled and tested at JPL in facilities that have been used for the assembly and test of similar instruments in the past. Assembly and test of the VSWIR draws on experience gained on M3 and CAO, including precise calibration and alignment. Assembly and test of the TIR builds on experience gained on HIRDLS and AIRS, also including precise calibration and alignment.

The IPM will be assembled and tested at GSFC.

Launch Vehicle

The Taurus 3210 is identified as the baseline launch vehicle. HyspIRI requires the 92" fairing, different from the smaller 63" fairing that has failed on its last three launches in 2001, 2009 and 2011. These failures seem localized to the 63" fairing separation since one 92" fairing launched successfully in 2004.

HyspIRI is also compatible with the Minotaur IV which would save the project a considerable amount of money but has not been baselined because it is not part of the NASA Launch Services (NLS) II contract.

Science Data Processing Algorithms

All the algorithms required to bring the VSWIR and TIR data up through level 2 exist and have been published. HyspIRI will only provide up through Level 2 products consistent with the mission's Level 1 requirements "to collect and provide surface reflectance, water leaving radiance, thermal emissivity and surface temperature imaging measurements…"

Calibration and Validation

The VSWIR calibration is performed in the same manner as was done for Hyperion using in-situ and airborne measurements of a dry lake bed with simultaneous VSWIR measurements. A single excursion to a California dry lake bed during the on-orbit check-out phase of the mission will be sufficient to meet HyspIRI's science objectives.

The TIR calibration is performed in the same manner as was done for ASTER and TES using in-situ measurements at existing ground sites, lab measurements of samples from the calibration targets and airborne measurements of the calibration targets.

0.1 Key for TRL and Heritage Classification

TRLs were determined using NPR 7120.8 – Appendix J (TRL4-9 shown below) and reviewed and concurred by Mark Domen (ESM SEWG TRL Study Lead from GSFC), Raúl Romero (ESM SEWG JPL Lead) and Charles D. Norton (ESTO Associate at JPL).

TRL	Definition	Hardware Description	Software Description	Exit Criteria
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
6	System/sub-system model or prototype demonstration in a relevant environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully	Documented test performance demonstrating agreement with analytical predictions.

		conditions.	demonstrated.	
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results.

The level of heritage described in this document follows the guidance in the following table. Note that there is no explicit correlation between TRL and number of heritage categories that are listed as Full, Partial or None.

	Full heritage	Partial heritage	No heritage
Design	Identical	Minimal modifications	Major modifications
Manufacture	Identical	Limited update of parts and processes necessary	Many updates of parts or processes necessary
Software	Identical	Identical functionality with limited update of software modules (<50%)	Major modifications (>=50%)
Provider	Identical provider and development team	Different however with substantial involvement of original team	Different and minimal or no involvement of original team
Use	Identical	Same interfaces and similar use within a novel overall context	Significantly different from original
Operating Environment	Identical	Within margins of original	Significantly different from original
Referenced Prior Use	In operation	Built and successfully ground tested	Not yet successfully ground tested

1 Spacecraft

HyspIRI's bus is a high heritage design that leverages ATK's outstanding performance record.

ATK Space Experience

ATK Space has more than 27 years experience in providing Space Systems, Products and aerospace engineering services to NASA, DoD, and commercial customers. The ATK Space division is part of the ATK corporation which is an aerospace and defense company with more than 19,000 employees in 22 states, Puerto Rico and internationally, and revenues in excess of $4.5 billion.

Space Products include Solid Rocket Motors, precision structures, thermal systems, propellant tanks, deployable antennas, deployable booms and Solar Array assemblies. This experience spans the entire project life cycle from mission concept and feasibility studies; through concept definition; preliminary and detailed design; fabrication, assembly, integration, and test; to launch support, operations, and post-flight activities.

ATK has extensive experience in spacecraft system and subsystem and instrument development, in free-flying and attached payloads, and technology demonstration missions. The HyspIRI spacecraft fits well within ATK's Space capability and ATK has the infrastructure and depth of personnel to meet all requirements.

The majority of HyspIRI's bus heritage comes from the Responsive Space Modular Bus (RSMB). RSMB was used as the bus for ORS-1, and its components have extensive flight experience on EO-1, TacSat-3 and ORS-1. A few selected missions highlighting ATK's relevant experience are provided below.

TacSat-3

The TacSat-3 (JWS D2) is a technology mission of the Air Force Research Laboratory. The project is funded by the DOD's Office of Force Transformation as Phase II of a four-phased approach for developing modular spacecraft buses. TacSat 3's main payload is a hyperspectral sensor (ARTEMIS) and the satellite platform has a standardized avionics package whose development was managed by the Air Force Research Laboratory. It also features a Navy Secondary Data-X Payload for IP-Based Buoy Communications.

ATK Space Spacecraft Division announced in June 2006 that it had been awarded a new Task Order under its existing Indefinite Delivery Indefinite Quantity contract with the Air Force Material Command, Air Force Research Laboratory, Space Vehicles Directorate (AFRL/VS). Under this award, ATK designed, built and tested the Operationally Responsive Space Modular Bus (ORSMB) for the TacSat-3 mission. ATK delivered the Bus in October 2007 to AFRL for payload integration and software validation testing.

The Bus is a single string, three axis stabilized design with a lifetime mission goal of one year. The Bus was launched on the Minotaur-I Launch Vehicle and delivered to a Low Earth Orbit. The TacSat-3 bus launched two software experiments, 1) the On-Orbit Checkout Experiment – used to autonomously validate and report on the health of every bus component within the first few orbits; and 2) the Automatic Tasking Experiment – used as an autonomous scheduler capable of assessing the feasibility of completing the commanded mission prior to execution.

ATK Space was responsible for the development, procurement, integration and delivery of the TacSat-3 bus. The proposed spacecraft total mass was 348 kg and spacecraft orbit average power was 335W.

ATK managed a large number of contracts, fabricated a number of the subsystems in house, and developed the GNC and Flight Software in their Beltsville facility. ATK's experiences gained from the TacSat-3 program on development, integration, testing and delivery supports future spacecraft development efforts.

Figure 1-1: TacSat 3

Program resources were well managed and fairly stable throughout design cycle. Program cost increase was due to selection of higher reliability parts and extended I&T schedule. Overall mission cost with launch vehicle has been stated at $75M. Major subsystem costs are For Official Use Only (FOUO) per Security Classification Guide. Schedule changes (proposed launch Q4 2007, actual Q2 2009) were due to selections of higher reliability parts that led to delays with procurements and development; I&T environmental testing; software validation; realignment of Star Tracker Camera Head Units, and a GIDEP alert for a customer furnished component.

The ORS-1 Mission

ATK provided the bus for the Department of Defense's Operationally Responsive Space-1 (ORS-1) satellite. The ORS-1 space vehicle was declared fully operational on September 16th, 2011 following successful on-orbit deployment and checkout of all systems.

Launched from the Mid-Atlantic Regional Spaceport at NASA Wallops Flight Facility the ORS-1 is the first satellite in the DoD's Operationally Responsive Space program designed to support combatant command operations as an operational satellite. The ORS-1 mission focuses on the quick deployment of a small satellite with innovative sensor technologies to provide real-time support to commanders in the battlefield.

ATK's spacecraft bus met the ORS program goals of being operationally responsive with affordable technology and unprecedented rapid execution from design to launch. ATK built the bus in just 16 months at its Beltsville, Maryland facility and shipped it ahead of schedule to Goodrich Corporation, the prime contractor for the ORS-1 satellite.

The satellite bus is based on the design ATK developed for the successful TacSat-3 satellite (an earlier demonstration program) with the addition of a propulsion module. TacSat-3 launched in 2009, transitioned to full operation in October 2010, and continues to support the DoD (2 + years so far, with a design life of 1 year).

The THEMIS Mission

The THEMIS mission is the fifth NASA Medium-class Explorer (MIDEX). It was launched in February 2007 with the primary mission to determine the trigger and large-scale evolution of substorms. The THEMIS mission employs five, identical probes that fly independent and synchronized orbits around earth. The orbit periods are designed to produce a combined measurement set resulting from the apogee region conjunctions due to the natural evolution of the orbits. While the probes are highly autonomous, attitude and orbit determination is maintained by the ground operations center with all orbit and attitude maneuvers nominally taking place during ground contact.

ATK Space was responsible for the development, procurement, integration and delivery of five Buses, five separation systems and the Probe Carrier. In addition ATK was responsible for the design and building of multiple sets of Ground Support Equipment for Probe and Probe Carrier handling and integration. Spacecraft total wet mass was 128

Figure 1-2. ORS-1.

Figure 1-3. THEMIS.

kg; total fuel load 49 kg and spacecraft orbit average power was 40.4 watts The prime contract was with University California Berkeley (UCB) with mission management out of Goddard Space Flight Center. In this responsibility ATK managed a larger number of contracts, fabricated a number of the subsystems in house and integrated all systems in their Beltsville facility.

The EO-1 Mission

The Earth Observing-1 (EO-1) mission was developed in support of the NASA/Goddard Space Flight Center (GSFC) Mechanical Systems Center.

ATK Space served as the Prime Contractor for the EO-1 mission, with responsibility for spacecraft bus, mission integration, payload integration, system level testing and verification, ground support equipment, launch vehicle integration and post-flight operations. ATK Space fabricated or procured the spacecraft structural/mechanical subsystem, propulsion system, harness, attitude control system, solar array and data handling subsystem.

This work was performed under a Firm Fixed Price task order. The program, the first of the New Millennium missions, successfully demonstrated three new primary instruments and six new spacecraft technologies. This mission also represented the first use of the Delta Dual Payload Attach Fitting, with the Argentine spacecraft SAC-B as a dual-primary payload. This mission has exceeded all cost and technical performance goals and continues to operate beyond its required lifetime.

Figure 1-4: EO-1

EO-1 flies in a sun-synchronous, 705 km circular orbit, using enhanced formation flying techniques to stay one minute behind the LANDSAT-7 spacecraft. The 563 kg EO-1 spacecraft exceeded all requirements including a three-axis 0.02 degree, 3-sigma pointing requirement and the bus has performed flawlessly in orbit.

Spacecraft performance has exceeded all design requirements in mass, power, delta-v, and pointing. Of significant note is the addition of third imaging payload (Hyperion) 18 months into the program. Bus integration was halted and three months where allotted to retrofit the mechanical and electrical subsystems. This change increased the mass and power requirements that impacted costs to the NASA. Cost change (proposed cost: \$26M, actual cost: \$40.5M) was due to addition of safehold mode and GPS following PDR, Hyperion addition, launch delay and Solid State Recorder failure during I&T. Schedule change (proposed launch December 1998, actual launched November 2000) was due to Hyperion addition, launch delay and Solid State Recorder failure during I&T. While the lifetime requirement was 12 months, the program is still performing after eleven years on orbit. Science data collection events are received more than 10 times more frequently than baseline requirements.

FUSE

In June 1999, the FUSE satellite was successfully launched into a 768 km circular orbit on a Delta II launch vehicle. Johns Hopkins University (JHU) is the PI institution and is responsible for the mission management and also developed the instrument. The international development team consisted of four universities, Canadian and French space agencies and industrial partners, multiple domestic industrial partners, and a variety of subcontractors. ATK was the primary industrial team partner on the FUSE Satellite team and provided expertise in the areas of program management, systems engineering and management, science instrument management and engineering, satellite and Mission I&T management and engineering, launch vehicle interface and integration engineering/management, and ground antenna development/ installation management.

In addition, the ATK support items and deliverable subsystems included the UV, visible, and stray light optical engineering; contamination systems engineering; mechanical systems engineering; thermal control systems and hardware; instrument electrical/data harness design, fabrication, and integration development of the large high-stability composite metering structure (telescope and spectrograph); precision mirror adjust mechanisms, UV and visible stray light baffles, deployable aperture doors, electrical systems engineering, and the majority of the instrument and Mission I&T team staffing.

Figure 1-5: FUSE

Operating Environment Similarities to Past Experience

EO-1 flew in a sun synchronous orbit very similar to HyspIRI's orbit (at 80 km higher altitude). HyspIRI will benefit from ATK's previous experiences in the same radiation and thermal environment with a spacecraft that has exceeded its design lifetime by a factor of ten.

HyspIRI also draws on ATK's operation experience in satellite monitoring. ATK has provided the back-up control room for JPL's Earth Science Mission Center (ESMC) for over 10 years. ATK has been the primary back up for QUIKSCAT, ACRIMSAT, JASON, OSTM/JASON2, TOPEX, CALIPSO, and WISE.

HyspIRI Spacecraft Bus Status

The bus is ready to be produced for HyspIRI at a pace that fits within HyspIRI's overall mission schedule. As an example, for the ORS-1 program, the similar spacecraft bus was delivered just 17 months after receipt of order (ARO).

The bus ATK is proposing to use for HyspIRI is high heritage, as summarized in Table 1-1.

The maturity of the proposed bus can be observed in the following sections that detail each subsystem.

Table 1-1. Spacecraft TRL and Heritage

ATK Bus Technology Readiness Assessment		
	Primary Heritage Mission(s)	**Lowest component TRL**
TT&C	ORS-1, GeoEye-1, QuickBird, TacSat-4	9
GN&C	ORS-1, EO-1, TacSat-3	9
Avionics	WISE	6
Propulsion	ORS-1	9
Power	TacSat-3, ORS-1	7
Structure	TacSat-3, ORS-1	7
Thermal	TacSat-3, ORS-1	9
Harness	TacSat-3, ORS-1	8
Software	TacSat-3, ORS-1	7
Alternative X-Band and SSR	NigeriaSat 2	8

1.1 Spacecraft Telecom Subsystem (TT&C)

The HyspIRI TT&C subsystem consists of an 800 Mbps X-Band link for science data and a low rate S-Band link for telemetry and command.

Two Log-Spiral S-Band antennas are optimally located on the vehicle to provide omni-directional coverage and assured vehicle contact regardless of orientation. The TT&C design is very similar to that used on legacy ATK space programs. The combination of transponder power, antenna gain and associated RF hybrid network performance ensures that robust link margins exist to support HyspIRI command and control requirements.

The HyspIRI X-band Communications Subsystem is designed to support the downlink of two high data rate X-band carriers, each supporting ~400 Mbps, while employing orthogonal circular signal polarization. The two X-band transmitters are flight proven T-724A units from L-3Com and operate over a selectable portion of the 7.9 to 8.4 GHz range. These units employ Offset QPSK modulation as well as Reed-Solomon encoding and when combined with X-band horn antennas satisfy the required link margin. They are the next generation of the T722 transmitter, and have almost identical specifications. The antennas have previously been used in a simultaneous oppositely polarized configuration on TacSat-4 where one was transmit and one was receive.

The design utilizes mature flight-proven COTS-based components.

An alternative 800 Mbps X-Band subsystem is also presented (in Section 1.9). This alternative is provided by Surrey and will be TRL 9 in 2012.

Table 1-2. Spacecraft Telecom Subsystem

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
S-band Transponder		Full L3 CXS-810	Full Identical to ORS-1	Full Std Parts and Processes	Full Function and interfaces are unchanged	Full Orbit differences within margins	Full Flown on ORS-1	9
Hybrid RF Switch		Full ET Industries J-112-180	Full Identical to ORS-1	Full Std Parts and Processes	Full Function and interfaces are unchanged	Full Orbit differences within margins	Full Flown on ORS-1	9
S-Band Omni Antenna		Full EDO AS-48915	Full Identical to ORS-1	Full Std Parts and Processes	Full Function and interfaces are unchanged	Full Orbit differences within margins	Full Flown on ORS-1	9
X-Band Transponder		Full L3 T724A	Full No Changes Required	Full Std Parts and Processes	Full Function and interfaces are unchanged	Full Within margins	Full Flown on GeoEye-1	9
X-Band Antenna Gimbals		Full MOOG Type 22 BIAX	Full Change limited to brackets for antenna and RF rotary joint fitment	Full Std Parts and Processes	Full Function and interfaces are unchanged	Full Within margins	Full QuickBird, GLAST	9
X-Band Antenna		Full Antenna Research Associates - Seavey Division C0737-800	Full Change limited to brackets for fitment to gimbal	Full Std Parts and Processes	Full Function and interfaces are unchanged	Full Within margins	Full TacSat-4	9

1.2 Guidance, Navigation and Control Subsystem (GN&C)

The GN&C subsystem is very similar to TacSat-3's GN&C and is identical to ORS-1's GN&C. The key GN&C requirements for HyspIRI are all met and shown in Table 1-3.

ATK has baselined 4 reaction wheels for HyspIRI, however, EO-1 has operated successfully for over 10 years using three reaction wheels. ATK's study plan includes a trade analysis to ascertain the potential of using just three RWAs for the HyspIRI mission.

Also based on their experience with EO-1, ATK believes HyspIRI mission requirements can be satisfied with four course sun sensors.

Preliminary analysis indicates that the HyspIRI position requirements will be exceeded with the use of the cost effective SGR-07 GPS receiver. This instrument offers significant savings in mass, power and complexity over competing GPS options. Orbit knowledge and 1 PPS synch pulse are provided by the receiver, with a precision ephemeris propagator in the GN&C FSW as a backup to fly through any GPS outages. GPS real-time position knowledge of 10m will be attenuated further by ground processing GPS pseudo-range telemetry to achieve sub-meter (95 percentile) position knowledge.

Preliminary analysis shows that HyspIRI attitude stability requirements are met with this GN&C. Assuming a reasonable controller bandwidth of 0.01 Hz, the RSMB currently achieves 0.2 degrees versus the 0.5 degree HyspIRI requirement.

Additional trades are required during the initial HyspIRI study phase to establish a detailed GN&C design baseline. ATK suggests, at minimum, that the following three trades be explored.

Trade 1 – Star Trackers & IRU versus Star Trackers only

Given the slow SV rates, STs may provide adequate attitude knowledge however attitude accuracy and stability requirements need to be verified. A lower performance IRU could be introduced to support Safe-hold mode (Sun-acquisition).

Trade 2 – Two Camera Head Units (CHUs) versus Three CHUs

HyspIRI must have at least 2 CHUs at all times. All CHUs must be mechanically coupled to payload instruments to 2-3 arcsec over thermal variation. Analysis will determine if a third CHU is required.

Trade 3 – Four Reaction Wheel Assemblies (RWAs) versus Three RWAs

As discussed above, EO-1 has operated on 3 RWAs for over 10 years. ATK plans to trade reliability against cost, risk, power, and operating constraints to establish a best-value solution.

Table 1-4 shows that all GN&C components have already achieved TRL 9.

Table 1-3. GN&C Requirements and Expected Performance

	Requirement	ATK-Bus Capability	Comments
Pointing Stability (milli-rad/sec) (3σ)	0.1	0.07	0.03 per axis achieved on ORS-1 (has no Solar Array drive assembly, but has high rate slewing and tracking)
Pointing Knowledge (m) (3σ)	60	46	Hyperion instrument on board EO-1 recovered 30m. TacSat-3 recovered GSD <50m, <100m real time.
Pointing Control (deg) (3σ)	0.5 per axis	0.2 per axis	Calculated assuming reasonable controller bandwidth of 0.01 Hz
Precision Orbit Knowledge (m) (3σ)	60	10 (real time), <1 (after ground processing)	The < 1 meter is 95th percentile.

Table 1-4. GN&C.

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Reaction Wheels and Driver		Full Goodrich TW16B-200	Full	Full	Full	Full Orbit differences within margins	Full Flown on ORS-1	9
IRU		Full Honeywell MIMU	Full	Full	Full	Full Orbit differences within margins	Full Flown on ORS-1	9
Magnetometers		Full Billingsley TFM-100S	Full	Full	Full	Full Orbit differences within margins	Full Flown on ORS-1 (Similar to TacSat-3)	9
Torque Rods		Full Goodrich TR60CFR	Full	Full	Full	Full Can accommodate As-specified	Full Flown on ORS-1, Tacsat-3, EO-1	9
GPS Receiver and Antenna		Full SSTL SGR-07	Full	Full	Full	Full Orbit differences within margins	Full Flown on ORS-1 (Similar to SGR-20 flown on TacSat-3)	9
Coarse Sun Sensors		Full ComTech (Aero Astro) 3000-3100	Full	Full	Full	Full Orbit differences within margins	Full Flown on ORS-1, TacSat-3 (using EO-1 layout)	9
Star Tracker w/ 2 Camera Head Units		Full DTU mDPU w/ 2CHUs	Full	Full	Full	Full Orbit differences within margins	Full Flown on ORS-1, TacSat-3	9

1.3 Command and Data Handling (CDH) Subsystem

In support of HyspIRI mission requirements, ATK plans to complete a trade study between their two avionics architectures to establish the most cost effective solution.

The baseline HEAU avionics solution was co-developed by ATK and SwRI to meet more demanding mission requirements and orbits than typically required by a mission that would use the RSMB. The 50 Krad tolerant HEAU architecture integrates the processing, power control, and propulsion control functions into a single box while adding mission unique control features that can be adapted across a variety of demanding mission and payload types. The HEAU architecture is suitable for long life missions in LEO, HEO and GEO orbits. Elements of the HEAU have flown on a few missions including Kepler and WISE. The 1 Tb SSR has been developed for the MMS mission. It has so far completed environmental testing and is currently at TRL 6. HyspIRI's exact HEAU and SSR are the baseline for the ViviSat Mission Extension Vehicle (MEV) currently under development by ATK, with a planned launch in 2015.

The alternate avionics option is the RSMB, of which there are two versions: the existing RSMB and the next generation RSMB which would be used by HyspIRI.

The cost-effective, Responsive Space Modular Bus (RSMB) avionics architecture for Class B/C missions with design lives on the order of 1-2 years was developed around the flight proven 10 Krad tolerant AITech S950 single board computer, AITech S990 Gbyte flash memory card, associated AITech I/O cards, ATK developed and flight proven Power Control Electronics (PCE) and fully flight qualified Propulsion Control Unit (PCU). This modular avionics suite flew successfully on TacSat-3 (without the optional PCU) and on ORS-1 (including the propulsion feature).

In partnership with AITech, ATK is developing the next generation of RSMB C&DH electronics. The developmental AITech S960 is currently under test as an engineering flight model. This model has increased radiation tolerance 100Krad and preserves the cost effectiveness of the RSMB avionics suite. ATK expects this improved RSMB solution to be fully space qualified in time to support missions scheduled for 2015 and beyond.

The HEAU has been chosen as the current baseline because it is designed for handling HyspIRI's data volumes and for HyspIRI's lifetime. However, solutions exist for the RSMB avionics, including having the high rate science data bypass the avionics completely by using the SSTL telecom and SSR, or using the SSR slice from the HEAU in the same fashion with the baselined telecom. A detailed trade will be done to determine which solution optimizes technical performance, risk and cost.

Table 1-5. On-Board Data Handling and Storage Subsystem.

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
HEAU Avionics Suite		Full SWRI	Partial Small configuration differences	Full	Full	Full Orbit differences within margins	Full Elements of the HEAU Suite have flown on Kepler, Deep Impact, IMAGE, Calipso, WISE and Orbital Express	7
HEAU Avionics Suite's SSR		Full SWRI	Full Identical	Full	Full	Full Orbit differences within margins	Partial Has undergone environmental tests in preparation for a 2014 launch onboard MMS	6

1.4 Propulsion Subsystem

The propulsion subsystem is based on a simple and reliable blowdown design. This system is identical to that used on ORS-1 (with the exception of a larger tank), and ATK employed a similar system for the EO-1 spacecraft

The RSMB modular propulsion system utilizes an off-the-shelf 16.5 x 20 inch pressure vessel constructed of titanium, four thrusters, a pressure transducer and associated valves and plumbing. The solenoid latch valve and the dual-series seat thruster valves provide the three mechanical seats required by Range Safety. The selected propellant tank includes an elastomeric diaphragm, minimizing fuel sloshing and providing positive, gas-free hydrazine on demand. The baseline RSMB propulsion system design (based on a 500kg Space Vehicle) allows for a Delta-V of 138 m/s at a specific impulse (Isp) of 197 (lbf*s/lbm), with a modest 3:1 blow-down ratio. This is insufficient, so a larger tank has been identified that meets HyspIRI delta-V requirements. A separate Propulsion Control Unit (PCU) box provides power functions and a hardware commanded safe-mode response for the propulsion system.

Table 1-6. Propulsion Subsystem.

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Latching Valves		Full Vacco V1E10747-01	Full	Full	Full	Full Orbit differences within margins	Full Flown on ORS-1, AXAF, ROCSat, HS-376	9
Propellant Filter		Full Vacco F1D10767-01	Full	Full	Full	Full Orbit differences within margins	Full Flown on ORS-1	9
Pressure Transducer		Full Taber P3911C501AXEX2YX	Full	Full	Full	Full Orbit differences within margins	Full Flown on ORS-1, BSS GPS IIF	9
Tank		Full ATK 80526-01	Full	Full	Full	Full Orbit differences within margins	Full Flown on ORS-1, Skynet IV, CRSS, STEREO	9
Thrusters		Full AeroJet MR-103G	Full	Full	Full	Full Orbit differences within margins	Full Flown on ORS-1, Iridium, GPS IIR, OSC Star-2	9
Fill and Drain Valves		Full Vacco V1E10701-01	Full	Full	Full	Full Orbit differences within margins	Full Flown on ORS-1, BSAT-2C, GeoEye1	9
Tubing		Full Aerojet N/A	Full	Full	Full	Full Orbit differences within margins	Full Flown on ORS-1	9

1.5 Electrical Power Subsystem

The solar array and spacecraft battery are sized to meet the HyspIRI power resource requirements with adequate margin.

The 626 km sun-synchronous orbit defines the maximum orbit eclipse of 34 minutes during May, where ATK's analysis defines the battery size with the worst case spacecraft peak power of 620 watts. The Lithium-Ion battery sizing analysis resulted in a 48 Amp-Hour battery for the ATK HEAU approach.

The one axis rotational multipanel solar arrays are sized to the worse case End of Life (EOL) for solstice seasonal conditions with maximum losses from solar declination and sun incident angle. The solar array sizing results indicated 4.1 m^2 solar array area, with adequate power margin. The solar array consists of three panels on a single wing, which is equivalent to 1028 watts EOL of solar array output.

Table 1-7. Power Supply Subsystem.

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Solar Array		Full EMCORE	Full	Full	Full	Full Orbit differences within margins	Full Flown on TacSat-3 and ORS-1	9
Peak Power Tracker		Full Goodrich AN64541-001-01	Full	Full	Full	Full Orbit differences within margins	Full Flown on ORS-1	9
Auxiliary Electronics Box		Full ATK	Full	Full	Full	Full Orbit differences within margins	Full Flown on TacSat-3 and ORS-1	9
Battery		Full ABSL 48 A-Hr	Full	Full	Full	Full Orbit differences within margins	Full Flown on TacSat-3	9
Solar Cells		Full EMCORE BTJ	Full	Full	Full	Full Orbit differences within margins	Full Flown on ORS-1	9

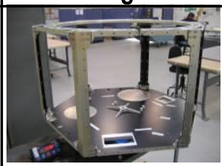
1.6 Structure and Mechanisms Subsystem

The ORS-1 payload was nearly identical to HyspIRI in mass and power accommodation requirements. However, HyspIRI has a slightly larger footprint that the RSMB will handle by offsetting the instruments from the bus on flexures.

Both the instrument and star tracker fields of view are simple and free of any obstructions by spacecraft appendages.

The principal drivers for the HyspIRI RSMB structure are the packaging in the launch vehicle, instrument accommodation and propulsion / tank sizing requirements.

Table 1-8. Structure and Mechanisms Subsystem.

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Primary Structure	 ORS-1	Full ATK	Partial Minor Scaling and Equipment Accommodation Changes	Full	Partial Qualification Required, Similar to EO-1, TacSat-3, ORS-1 Designs	Full Orbit and LV differences within margins	Partial Qualification Required, Similar to EO-1, TacSat-3, ORS-1 Designs	7
Secondary Structure		Full ATK	Partial Payload Accommodation Changes	Full	Partial Qualification Required	Full Orbit and LV differences within margins	Partial Qualification Required	7
Brackets and Fasteners		Full ATK	Full	Full	Partial Qualification Required, Similar to EO-1, TacSat-3, ORS-1 Designs	Full Orbit and LV differences within margins	Partial Qualification Required	7

1.7 Thermal Control Subsystem

The HyspIRI instrument interfaces to the top deck of the bus via flexures. These flexures isolate any thermal distortions of the aluminum bus structure from the precision pointing requirements of the instrument.

The thermal design employs passive structural panels, which can be thermally coupled to create a near isothermal bus. Modular MLI is then applied on a mission specific basis to minimize thermal control heater power. A single modular bus mechanical design simplifies integration by building the same bus each time with minimal tailoring of modular MLI.

The thermal design has three key components (Note that the heritage of these components is included under "Primary Structure" in Table 1-8): 1) Structural elements with local thermal conduction, 2) Isothermal panels with an embedded heat pipe, 3) Isothermal bus with short external cross-strap heat pipes that thermally couple adjacent panels. This Isothermal Bus meets all mission requirements.

Isothermal panels are constructed by embedding a Constant Conductance Heat Pipe (CCHP) into an Aluminum honeycomb panel. The CCHP spreads heat across the entire panel maximizing area efficiency and permits unrestrained placement of thermal components, sensors, heaters, and MLI. Two sets of short external cross-strapping heat pipes thermally couple adjacent panels, permitting thermal loads, environmental views, and structural thermal capacitance to cascade around all surfaces. This minimizes thermal excursions in response to transient conditions. The thermal design configuration will be optimized for the HyspIRI orbit.

Table 1-9 shows that the TCS components, are already TRL 9 and are being used in missions with similar requirements to those of the HyspIRI mission.

Table 1-9. Thermal Control Subsystem.

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
MLI		ATK SAI-SPEC-055	Full	Full	Full	Full Orbit differences within margins	Full Flown on TacSat-3 and ORS-1	9
Thermistors		Full 44902 GSFC Space Qualified Thermistors	Full	Full	Full	Full Orbit differences within margins	Full Flown on TacSat-3 and ORS-1	9
Thermostats		Full Honeywell 650 Series	Full	Full	Full	Full Orbit differences within margins	Full Flown on TacSat-3 and ORS-1	9

1.8 Spacecraft Bus Flight SW

The Flight Software (FSW) runs on the VxWorks operating system, and is a modular software architecture with a combination of legacy, Commercial Off-The Shelf (COTS), and mission specific tasks. The FSW manages:

- Software tasks,
- Payload, ADCS, command and telemetry, discrete, and torque rod interfaces,
- CCSDS uplink and downlink,
- Time distribution,
- On board memory and files.

ADCS software executes as a task in the FSW. It operates the spacecraft using commands, telemetry and uploadable tables. A Real Time Executive (RTE) provides high level access to C&DH and ADCS functions by commanded, event-driven, and time tagged execution of scripts written in the Spacecraft Control Language (SCL). The RTE controls fault protection, constraint enforcement, power management, and routine operations. All decisions can be observed in telemetry on the ground.

ATK has developed a large repository of heritage flight software highly suited to meet the wide range of RSMB requirements expected over varying mission types, for example the ORS-1 and TacSat-3 program used the same C&DH computer and avionics and required similar guidance, navigation, and control algorithms for significantly different mission CONOPS.

As ORS-1 and TacSat-3 both employed fixed solar arrays, GN&C FSW planned enhancements include the addition of SADA control algorithms to steer the solar array to the Sun. ATK has design heritage with SADA control on several proprietary programs. A magnetic field model will be added to manage momentum during science operations. GN&C supervisory functions, such as mode logic, fault logic, and gains database, will be updated to reflect mission operational requirements. Minor modifications are expected in the Sun sensor processing and reaction wheel processing to reflect modification in the quantity of those H/W components. Proportional control logic may be adjusted to improve attenuation of disturbance torques by feed-forwarding these torques to RWAs.

ATK's modular software approach allows them to meet HyspIRI software requirements with code that is 70% from heritage projects. In addition to this heritage code base, ATK has assembled the processes, tools, and infrastructure necessary to develop the remaining mission unique software both quickly and efficiently. ATK's use of strict coding standards, automatic code generation, and custom tools allow models and tests developed at the earliest prototyping stages to evolve into test-bed software, verified flight software, and verification scripts. ATK's focus on using automated processes to flow the outputs from the earliest development phases all the way through to the final product enable ATK to both develop highly reliable flight software cost effectively and to quickly adapt heritage code to meet new or changing requirements.

Use of the same SW flown on previous missions allows the minimization of risk and development time.

Table 1-10. Spacecraft Bus SW.

Title	Design	Manufacture	Use	Prior Use
Subsystem Functionalities				
Basic Libraries	Partial Minor modifications for HyspIRI Payload accommodation	Full	Full	Full Previous use on TacSat-3 and ORS-1
Orbit Propagation	Full	Full	Full	Full Previous use on TacSat-3 and ORS-1
Attitude Determination	Full	Full	Full	Full Previous use on TacSat-3 and ORS-1
Sensor Data Processing	Full	Full	Full	Full Previous use on TacSat-3 and ORS-1
Actuator Commanding	Full	Full	Full	Full Previous use on TacSat-3 and ORS-1
FDIR Rules	Partial Minor modifications for HyspIRI Payload accommodation	Full	Partial Minor modifications for HyspIRI Payload accommodation	Full Previous use on TacSat-3 and ORS-1

1.9 (Alternative) X Band Telecom and SSR

An alternative to ATK's proposed X Band telecom subsystem and SSR is described in this section. Future work will be done to trade this system with the telecom and SSR proposed by ATK.

Surrey has extensive experience designing, building and operating their own spacecraft (including payloads). The two spacecraft most relevant to this X-Band Telecom and SSR subsystem are NigeriaSat-2 and TechDemoSat.

NigeriaSat-2

Nigeria's National Space Research and Development Agency (NASRDA) contracted Surrey to develop and build NigeriaSat-2, the related ground infrastructure and image processing facilities. Also included in the contract was an extensive on-the-job training program for Nigerian engineers who observed Surrey throughout the process. NigeriaSat-2's medium and high resolution imaging supports Nigeria's food supply security, agriculture and geology research, mapping and security applications, development of the national GIS infrastructure and builds on the data being generated by NigeriaSat-1.

The 268 kg satellite is based on Surrey's SSTL-300 bus. It has a design lifetime of 7 years (with a goal of up to 10 years). It is 3-axis stabilized with the ability for rapid slew (body pointing) of +/- 45 degrees. The sensor has a 20 km footprint and its data is geolocated to an accuracy of < 35 m without the use of ground control points. NigeriaSat-2 flies in a 668 km Sun Synchronous Orbit.

The spacecraft has two, two axis gimbaled antennas (Antenna Pointing Mechanism (APM)), each connected to a transmitter capable of 105 Mbps downlinks. Since the two antennas have opposite circular polarizations (one antenna is LHCP and the other is RHCP), up to 210 Mbps can be down linked at any one time. However, the mission only requires 105 Mbps and the second string acts as cold redundancy.

The spacecraft launched in August of 2011 and is currently operational and in good health.

TechDemoSat

TechDemoSat is a UK government funded satellite designed to raise the TRL of key UK space technologies. It is funded by the Technology Strategy Board (TSB) and the South East England Development Agency (SEEDA). The satellite is based on the SSTL-150 bus with modifications and upgrades to accommodate the eight payloads. It is on schedule to launch in late 2012.

The 150 kg satellite is roughly 1 meter cubed and will carry payloads from industry and academia. These include: A maritime sensor suite, a space environment sensor suite, an infrared remote sensing radiometer, and a platform technology suite that will include a de-orbit sail and a Cubesat ACS suite. In addition to the payloads, Surrey will include some of their newer technologies like the FMMU and XTX 400 to raise their TRLs to 9.

Surrey Subsystem Design Experience

Surrey has been designing and manufacturing subsystems for in-house platforms and as stand-alone items for the past decade. All systems used in the alternative X Band Telecom and SSR are based on heritage designs and most have extensive flight experience. From telecommunication systems to propulsion, power, ACS, data handling and navigation, Surrey offers many components for a range of missions needs.

Surrey Lessons Learned from Telecom Subsystems on Past Similar Missions

Surrey flew an X-band transmitter with a fixed antenna on UK-DMC2 and was able to provide 80 Mbps of data to the ground; a very high rate for a 120kg, sub $10M mission. Surrey has looked to capitalize on this design by providing the same transmitter but with antenna pointing capability. This allows the same transmitter to achieve higher effective rates by using a more directed beam antenna. Further changes to coding and modulation have brought the capability up to 400 Mbps.

Operating Environment Similarities to Past Experience

Almost all of Surrey's missions operate in the LEO environment. The components used are all readily available and low cost, with demonstrated reliability. The 5 satellite RapidEye constellation, UK-DMC2, TOPSAT and an array of other small missions have shown these parts' ability to operate beyond mission lifetimes.

Figure 1-6. NigeriaSat - 2 being fueled at the launch site.

Regimen

Surrey builds all its components, subsystems and full-up platforms on previous flight proven designs. Reliability and heritage comes from flight performance and selective analysis and test. This is a successful method proven over 10 years of mission success.

Surrey will perform environmental and acceptance tests on all parts and components as follows using their established processes and procedures:

- Random Vibration in each axis to test workmanship
- Thermal cycling (-20degC to +50degC, three cycles, one hour dwell. Functional test performed after dwell at temperature extremes of first and last cycle and at ambient before and after cycling)
- 300 hours of burn-in and electrical acceptance testing
- EMC conducted and radiated, emissions and susceptibility testing with the test setup and test levels defined in MIL-STD-461E, and appropriately tailored for EMC testing of the specific units

Surrey will also provide:

- FMECA analysis for the subsystem. The analysis is performed down to the functional/block level. ECSS-Q-30-02A will be used as a reference/guideline document for the analysis.
- EEE Parts list
- Materials and Processes List
- Finite Element Model
- Thermal Analysis

Subsystem Overview

The Surrey X-band telecom and SSR is a catalogue item. It includes the transmitter, antenna and gimbals, buffer and mass memory. NigeriaSat 2 (launched 2011, see Figure 1-6) is currently flying two chains (2 HSDRs, 2 XTx105s and 2 APMs) with one chain as primary and the other as back-up, demonstrating that the components of the subsystem work together (minus the FMMU). TechDemoSat-1 will demonstrate the full two-chain system on orbit in 2012 with the same simultaneous two-chain architecture and data rates as HyspIRI would require. This system will also fly on the Kazakh MRES mission in 2013.

Buffer and Packetizer

The HSDR has flown on UK-DMC-2, Deimos-1 (launch 2009), and NigeriaSat-2, and will fly on Surrey's TechDemoSat-1, Kazakh MRES, the DMC-3 constellation and two undisclosed 3rd party missions. The HSDR's FPGA has the capability for CCSDS formatting, but needs to be programmed for HyspIRI to perform this function.

Mass Memory

The FMMU will fly on TechDemoSat-1 (2012) and the DMC-3 Constellation. TechDemoSat's FMMU is a new board layout; however all of its components except the flash memory chips have flown before on other Surrey missions. The FMMU has passed functional tests and will be flight qualified by the end of 2011, on track for its 2012 launch.

Test results on SEE and TID radiation susceptibility for the class of NAND Flash used are available in the literature and meet HyspIRIs EOL storage, longevity and bit error requirements with EDAC and minimal shielding as determined to be required through detailed analysis in Phase B.

The following single event latchup (SEL) mitigations are implemented:

- Each memory bank has latch up protection circuit, enabling it to be turned off on the event of a latch-up or an anomaly

The following single event upset (SEU) mitigations are implemented:

- File system memory is TMR protected

- Payload flash memory uses block hamming code, providing 1 bit correct and 2 bits detect capability per 512 bytes of memory

Computer

The OBC 750 is an on-board computer being used as a translator between the spacecraft's 1553 and the CAN bus used by all the PTS components. It is currently flying on NigeriaSat-2 and will fly on TechDemoSat-1. In-flight data from these two missions will be used to determine what level of shielding, if any, will be required to meet HyspIRI's requirements.

PDU

The Power Distribution Unit (PDU) has significant flight heritage, having been used on over 13 Surrey missions. The PDU will provide switched unregulated power supplies to the payload modules and provide a switched regulated 5 V power supply to the APM. The PDU will accept a 28 V unregulated input from the platform.

Transmitter

The X-band transmitter upon which the XTx 400 is based has flown on multiple missions (see Table 1-11) demonstrating an 80 Mbps data rate. It is currently flying on NigeriaSat-2 and NigeriaSat-X demonstrating 105Mbps.

The XTx400 is due to fly on TechDemoSat-1, the Kazakh MRES Mission and the DMC-3 constellation. The XTx 400 has been demonstrated on the ground and flight qualified for its flight aboard TechDemoSat-1 in late 2012. Key components have undergone TID tests to verify that they are acceptable for use in a 5 kRAD environment. The XTx 400 uses the same GaAs MESFET technology as the previous generation XTx (XTx105).

Antenna and Gimbal

HyspIRI will fly the same APM as used on NigeriaSat-2, TechDemoSat-1 and the DMC-3 constellation.

Two X-Band transmitter and APM chains can be used simultaneously because each antenna has different circular polarization (RHCP and LHCP) and each antenna has a low axial ratio over the narrow beamwidth. Two transmitter-APM chains will be used simultaneously on TechDemoSat-1 and the DMC-3 constellation.

The APM has been qualified to over 300,000 cycles. HyspIRI requires only 25,000 cycles for the baseline mission.

Table 1-11. Alternative X Band and SSR.

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Antenna and Gimbal (APM)		Full Surrey	Full Identical design (including electronics, mechanisms and horn).	Full Manufactured according to Surrey standard PA Plan. Processes unchanged.	Full Identical interfaces and functionality	Full Standard Surrey LEO mission environment (inc thermal, structural & radiation)	Full Currently flying on NigeriaSat-2 APM will also fly on TechDemoSat-1 (2012), Kazakh MRES (2013) and the DMC-3 Constellation (2014)	9
Transmitter		Full Surrey	Full HyspIRI's transmitter is identical to TechDemoSat-1's (uses same 8PSK coding and 2/3 TCM)	Full Manufactured according to Surrey standard PA Plan.	Full HyspIRI's transmitter is identical to TechDemoSat-1's	Full Standard Surrey LEO mission environment (inc thermal, structural & radiation)	Partial (Full in 2012) Flown on MDA's RapidEye constellation (2008), UK-DMC-2 (2009), Deimos-1 (2009), NigeriaSat-2 (2011), and NigeriaSat-X (2011). XTx 400 will fly on TechDemoSat-1 (2012), Kazakh MRES (2013) and DMC-3 constellation (2014).	8 (9 in 2012)

Table 1-11. Alternative X Band and SSR.

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
CCSDS Packetizer and Buffer (HSDR)		Full Surrey	Full The hardware design is unchanged	Full Manufactured according to Surrey standard PA Plan. Processes unchanged.	Full Identical interfaces and functionality	Full Standard Surrey LEO mission environment (inc thermal, structural & radiation)	Full Used on UK-DMC-2 (2009), Deimos-1 (2009), NigeriaSat-2 (2011), NigeriaSat-X (2011). To be used on: TechDemoSat-1 (2012), Kazakh MRES (2013) and DMC-3 (2014).	9
Memory (FMMU)		Full Surrey	Full HyspIRI's FMMU is identical to TechDemoSat-1	Full Manufactured according to Surrey standard PA Plan	Full HyspIRI's FMMU is identical to TechDemoSat-1	Full Standard Surrey LEO mission environment (inc thermal, structural & radiation)	Partial (Full in 2012) Has passed functional tests. To be used on TechDemoSat-1 2012	8 (9 in 2012)
Bus Translator Computer (OBC 750)		Full Surrey	Full HyspIRI's OBC is identical to NigeriaSat's (NigeriaSat's OBC is a new module. A number of components have flight heritage from use in different Surrey products)	Full Manufactured according to Surrey standard PA Plan	Full Identical use (although not all capabilities are used for HyspIRI)	Full Standard Surrey LEO mission environment (inc thermal, structural & radiation)	Full Currently flying on NigeriaSat-2 (2011). Will also fly on TechDemoSat-1 (2012)	9

Table 1-11. Alternative X Band and SSR.

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Power Distribution Module		Full Surrey	Full Identical design	Full Manufactured according to Surrey standard PA Plan. Processes unchanged.	Full Identical use (although not all capabilities are used for HyspIRI)	Full Standard Surrey LEO mission environment (inc thermal, structural & radiation)	Full Used on over 13 missions including RapidEye Constellation (5 units) (2008), DMC-2 (2009), Deimos-1 (2009), NigeriaSat 2, (2011) Will be used on TechDemoSat-1 (2012), Kazakh MRES (2013), DMC-3 (2014)	9

2 Payload

2.1 VSWIR

The overall instrument system builds on a long heritage with JPL, NASA and non-NASA imaging spectrometers including Hyperion, CRISM, M3 and ARTEMIS. The operating environment is completely enveloped by the heritage suite.

The VSWIR instrument draws the majority of its design heritage from the M3 instrument which was successfully flown on the recent Chandrayan1 mission to the moon. The VSWIR architecture is very similar to M3 but is a factor of 3 larger in size. It uses a very similar structural, optical, and thermal design. Mature space-proven technologies are used throughout the instrument. This heritage is described in Tables 2-2 through 2-5.

The first JPL imaging spectrometer, the Airborne Imaging Spectrometer (AIS), shown in Figure 2-1, was proposed in 1979 and first flew in 1982 with a cryogenic MCT area array detector. Following AIS, the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) was designed and developed at JPL to cover the full 2.5 octaves of spectrum from 0.4 to 2.5 µm with 10 nm sampling. In the same timeframe with development and operation of AVIRIS, JPL developed the Near Infrared Mapping Spectrometer (NIMS) that was flown to Jupiter as part of the Galileo mission. Subsequently, the Visual and Infrared Mapping Spectrometer (VIMS) was developed and flown to Saturn as part of the Cassini Mission.

Between 1997 and 2000, JPL was part of the EO-1 Hyperion space imaging spectrometer effort providing design input as well as the Offner spectrometer enabling electron-beam lithography gratings for this space pushbroom instrument. For the MRO CRISM effort, JPL provided support as well as the two enabling gratings and calibration equipment, experience, and analyses. From 2003-2005, JPL developed the airborne Mapping Reflected energy Spectrometer (MaRS) that is shown in Figure 2-2. This is a high uniformity and high signal-to-noise ratio pushbroom Offner imaging spectrometer using two 6604a detector arrays and operated with the detector and spectrometer in a vacuum vessel at 80 K.

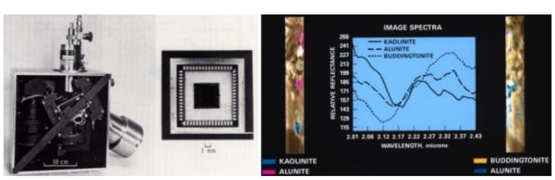


Figure 2-1: Airbone Imaging Spectrometer (AIS) was JPL's first grating pushbroom imaging spectrometer (1979-1985).

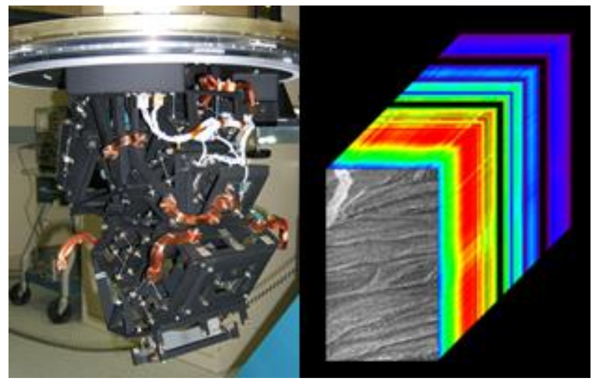


Figure 2-2: The Mapping Reflected energy Spectrometer (MaRS). MaRS is an airborne Offner pushbroom imaging spectrometer using an electron-beam lithography grating and slit as well as two 6604a detector arrays operating in a vacuum at 80 K. It was developed at JPL from 2003 to 2005. An early test flight image is shown on the right.

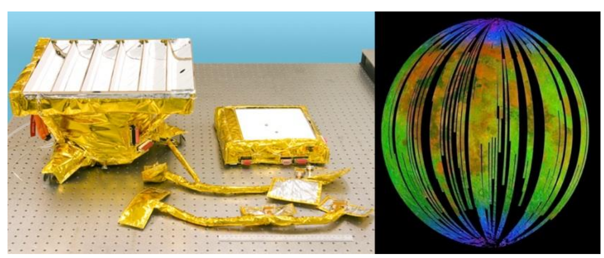


Figure 2-3: NASA Discovery Moon Mineralogy Mapper (M3) that is an Offner pushbroom imaging spectrometer using electron lithography grating, uniform slit, 6604a MCT detector array, detector electronics, and passive radiator. M3 was developed from 2005 to 2007 and flown from 2008 to 2009. A partial M3 mosaic of the Moon with hydroxyl/water absorption in blue is shown on the right.

In the period from 2005 to 2007 developed the space M3 imaging spectrometer that was integrated and launched on Chandrayaan-1 in 2008 and operated through 2009. The M3 imaging spectrometer is shown in Figure 2-3 prior to shipment for integration with the spacecraft. In this same time frame JPL was part of the ARTEMIS space imaging spectrometer effort and provided the spectrometer design, grating, slit and critical calibration sources. ARTEMIS also used a MCT 6604a detector array.

Between 2009 and 2011, JPL developed and delivered to the Carnegie Institute of Washington Airborne Observatory (CAO). CAO is a high uniformity and high SNR pushbroom airborne imaging spectrometer. This instrument is of the M3-type with a single 2.5 octave spectrometer and Teledyne 6604a MCT detector array. The detector and spectrometer operate in a vacuum vessel at cryogenic temperatures. Figure 2-4 shows the CAO with the vacuum vessel removed and an early test image.

In the period from 2010 to 2012 JPL has developed the space qualifiable Ultra Compact Imaging Spectrometer (UCIS) that is a high uniformity and high SNR pushbroom imaging spectrometer operating a MCT 6604a detector array and spectrometer at cryogenic temperatures. UCIS is shown during integration and test in Figure 2-5.

Through these efforts and with a strong institutional commitment, JPL has demonstrated a sustained focus for the development and delivery of science research class imaging spectrometers using five key capabilities: (1) optimized high uniformity, high SNR imaging spectrometer designs; (2) unique electron-beam lithography grating fabrication to create efficient, low-polarization, and low-scatter gratings; (3) ultra-uniform electron-beam air slits, that permit the uniformity values inherent in the design; (4) component mounts allowing adjustments at the 0.25 μm level and locking for space flight; (5) an unmatched suite of calibration and alignment sources as well as the vetted procedures and analysis tools for delivery of aligned and calibrated imaging spectrometers. In addition, the imaging spectrometer team at JPL has both the long standing and recent experience and expertise, including lessons learned, to develop and deliver high fidelity imaging spectrometers.

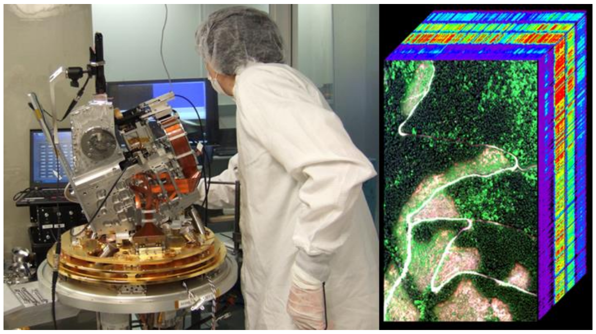


Figure 2-4: CAO airborne Offner imaging spectrometer developed between 2009 and 2011. This instrument is of the M3-type with an electron-beam lithography grating, slit and uses a 6604a MCT detector array and 14 bit drive electronics. A first light test flight image is shown on the right.

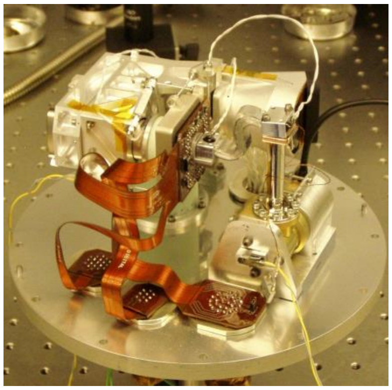


Figure 2-5: The UCIS space qualifiable Offner pushbroom imaging spectrometer with electron-beam lithography grating, slit and 6604a MCT detector array with 14 bit drive electronics. UCIS was developed between 2010 and early 2012.

The extensive component and architectural heritage embodied in the HyspIRI VSWIR instrument provides for a cost-effective, low-risk development. JPL's prior experience with all aspects of development for this type of instrumentation is the principal reason that they are able to propose a 36-month instrument development schedule

This heritage is described in Tables 2-2 through 2-5 and summarized in Table 2-1.

Table 2-1. VSWIR TRL and Heritage

VSWIR Technology Readiness Assessment		
	Primary Heritage Mission(s)	Lowest component TRL
Focal Plane and Electronics	M3, ARTEMIS, CRISM	6
Mechanical	M3, OCO, ARTEMIS, HYPERION	7
Thermal	M3, AIRS	7
Optics	M3, ARTEMIS	7

Optical

Elements of heritage in the optical subsystem include:

- The classic Offner spectrometer design used on VSWIR is related to that used on the Hyperion, CRISM, M3 and ARTEMIS space imaging spectrometers.
- The HyspIRI telescope has heritage in a number of space optical systems including OCO.
- Aluminum mirrors have successfully flown in the CRISM, M3, Hyperion and ARTEMIS space imaging spectrometers.
- Protected silver was flown on ARTEMIS and in the M3 spectrometer.
- A similar e-beam slit is currently utilized by ARTEMIS. JPL e-beam gratings have flown on Hyperion, CRISM, M3 and ARTEMIS.

Focal Plane and Electronics

The architecture and implementation of the VSWIR electronics are derived primarily from M3 using space qualified components. Elements of heritage in the electronics subsystem include:

- Full spectral range HgCdTe detectors were flown on M3 and ARTEMIS. The VSWIR detector array is the direct descendent of the TMC 6604a that was used in the CRISM, M3 and ARTEMIS space imaging spectrometers.
- The three zone order sorting filter fabricated by Barr Associates Inc is similar to that flown on M3.
- The electronics are all TRL 7 except for the digital electronics due to the Virtex 5 not yet having flight heritage. The Virtex 5 is currently in space aboard a cubesat and its team is trying to regain communication. If the mission is successful, the digital electronics will be raised to TRL 7.
- The lossless compression algorithm implemented on the FPGA was developed for imaging spectrometer data and was tested and ported to an FPGA for the ARTEMIS mission. This algorithm was ready for ARTEMIS, but was descoped due to other mission constraints. Recent tests of this algorithm with the CAO VSWIR airborne full spectral range Offner imaging spectrometer on diverse data sets (forest, desert, water, cloud) shows compression ratios of 4X lossless for 13 bit data. (Note that the HyspIRI data storage and downlink have been sized using a conservative 3X lossless compression).

Mechanical / Thermal

HyspIRI mechanical designs draw heavily from previous space assemblies designed and built by JPL. Elements of heritage in the optical subsystem include:

- The spectrometer and telescope benches are Investment Cast aluminum like the optical bench of OCO. The focal plane assembly, slit mount, and grating mount are derived from those used in the M3 instrument.
- The grating and detector array mount are derived from M3 designs. The blaze of the grating is multi-facet to optimize the efficiency across the spectrum as was done for M3 and ARTEMIS.
- The HyspIRI instrument is an all aluminum design. This inherently athermal design and approach draws heritage directly from M3.
- The calibration cover is modeled on that flown with Hyperion.
- The focal plane arrays and spectrometer are cooled to 160K and 200K, respectively, using a scaled version of the M3 passive cooler. The M3 passive cooler is 0.41m x 0.43m x 0.08m and weighs 1.2kg. The

HyspIRI scaled version of this design is 0.9m x 1m x 0.12m and weighs 4kg.

Table 2-2. VSWIR Focal Plane & Electronics.

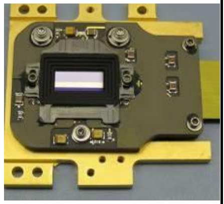
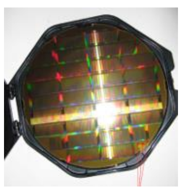
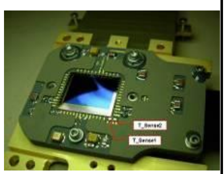
Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Full Range Mercury-Cadmium-Telluride (HgCdTe) Detector Material	 M3	Full Teledyne provided previous detector (ARTEMIS, M3) and will provide this detector	Partial Identical material as used on ARTEMIS and M3. Dimensions enlarged to accommodate 6604b ROIC.	Partial Manufacturing processes are 90% similar to those used for ARTEMIS and M3.	Full Function is unchanged from prior uses and interfaces are identical.	Full Material Flown in 400 km LEO, a harsher environment and Lunar orbit at detector temperatures of 140 K to 180 K. HyspIRI operates at 160 K.	Full Material flown on ARTEMIS and M3.	7
6604B ROIC		Full Teledyne provided previous detector (ARTEMIS, CRISM, M3) and will provide this detector	Partial 6604a dimensions are enlarged to accommodate 1280 x 480 elements. 6604a had 640 x 480 elements.	Partial Manufacturing processes are 90% similar to those used for 6604a.	Partial Function is unchanged from 6604a, it is still a snapshot, integrate with well read unit cell. Interfaces are minimally modified.	Full Material Flown in 400 km LEO, a harsher environment and Lunar orbit at detector temperatures of 140 K to 180 K. HyspIRI operates at 160 K.	Full 6604a flown on ARTEMIS, M3 and CRISM.	6
Detector Package	 M3	Full AdTech Ceramics who providedM3 ceramic detector package	Partial M3 design expanded to accommodate larger 6604b dimensions	Full Same processes used as for M3	Full Function is unchanged, it is still a ceramic package. Interfaces are identical.	Full Material Flown in 400 km LEO, a harsher environment and Lunar orbit at detector temperatures of 140 K to 180 K. HyspIRI operates at 160 K.	Full Flown on M3	7

Table 2-2. VSWIR Focal Plane & Electronics.

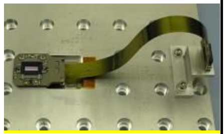
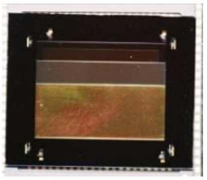
Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Flex Print Cable	 M3	Full Accurate Engineering Inc. who provided M3 Flex Print Cable	Partial M3 design expanded to accommodate larger 6604b dimensions	Full Same processes used as for M3	Full Function is unchanged. Interfaces are identical.	Full Material Flown in 400 km LEO, a harsher environment and Lunar orbit at detector temperatures of 140 K to 180 K. HyspIRI operates at 160 K.	Full Flown on M3, OCO, CRISM	7
Order Sorting Filter		Full Barr Associates, who provided Filter for ARTEMIS, M3	Partial Identical materials and techniques to prior spaceborne OSFs. Modifications are to accommodate larger size of 6604b.	Full Manufacturing processes are identical to what was used for ARTEMIS and M3.	Full Function is unchanged from ARTEMIS and M3.	Full Material Flown in 400 km LEO, a harsher environment at detector temperatures of 140 K to 180 K. HyspIRI operates at 160 K.	Full Prior flown on ARTEMIS and M3.	7

Table 2-2. VSWIR Focal Plane & Electronics.

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Digital Electronics		Full JPL In House Build	Partial Upgrade FPGA's from Virtex 1 to Virtex 5 because of Virtex 1 obsolescence. Simplify design by removing SSR.	Full Manufacturing processes are identical to those used for prior spaceborne missions.	Full Function is still to control the Detector, Control the instrument, interface with the S/C and compress and edit science data. Interfaces and function unchanged.	Full LEO is more benign than Lunar Orbit, and so within the specifications of M3's design	Partial Heritage electronics flown on M3. Virtex 5 qualified for space but has not yet been demonstrated in space. It was launched into space in Oct 2011 on an ESTO funded University of Michigan Cubesat called M-Cubed, however, as of Feb 2012, the Cubesat is not yet responding to commands but does appear to be in good health.	6
Compression Algorithm Used in Digital Electronics		Full JPL In House	Full Algorithm was designed for VSWIR. Version tested on breadboard is the same that will fly	N/A	Full Algorithm was designed for VSWIR.	N/A	Partial Algorithm has been tested on Virtex 5 breadboard in the laboratory and benchmarked with data from AVIRIS, MaRS and Next Gen Imaging Spectrometer (of the HyspIRI Architecture)	6
Signal Chain	 M3	Full JPL In House Build	Partial identical topology with improved ADC	Full Manufacturing processes are identical to those used for prior spaceborne missions.	Full Function is still to digitize science data from the detector and interfaces are minimally modified to deal with 8 signal chains in each spectrometer instead of 4	Full LEO is more benign than Lunar Orbit, and so within the specifications of M3's design	Full Flown on M3	7

Table 2-2. VSWIR Focal Plane & Electronics.

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Housekeeping	 M3	Full JPL In House Build	Partial Identical parts and topology new PCB design to fit configuration	Full Manufacturing processes are identical to those used for prior spaceborne missions.	Full Function is still to make low rate housekeeping measurements. Interfaces are identical	Full LEO is more benign than Lunar Orbit, and so within the specifications of M3's design	Full Flown on M3 as well as Artemis, CRISM, and OCO	7
Power Sub System	 MIRI	Full JPL In House Build	Partial Identical DC to DC converters with different voltages to suit HyspIRI	Full Manufacturing processes are identical to those used for prior spaceborne missions.	Full Function is still to provide instrument DC voltages Interfaces are minimally modified.	Full LEO is less benign than Earths' L2 point, but not outside the acceptable operating realm of this Power Sub System	Partial Will fly on MIRI, which is a completed spaceflight qualified instrument on JWST	7

Table 2-3: VSWIR Mechanical Structure.

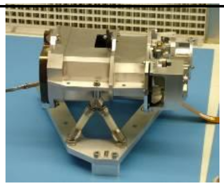
Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Thermal Shield	 M3	Full JPL, in-house build	Partial Similar to M3, using aluminum honeycomb structure similar to Integrated Structure Assembly flown on Mars Pathfinder	Partial Similar substrates built by JPL, Canyon Composites, MDA Information Systems.	Partial Similar to Integrated Structure Assembly flown on Mars Pathfinder	Partial Aluminum honeycomb structures are common thermal control material	Full Thermal shield approach identical to M3, implementation similar to Integrated Structure Assembly flown on Mars Pathfinder	7
Telescope Bench	 OCO	Full JPL, in-house build	Partial Investment Cast Aluminum structures designed and built for OCO	Full Identical to fabrication process by Nu-Cast for OCO	Full Identical to OCO Optical bench	Partial Operates colder than OCO but identical dimensional stability thermal cycle	Full Similar design has flown on OCO-1	7
Spectrometer Bench	 M3	Full JPL, in-house build	Partial Designed similar to M3, but using Investment Cast Aluminum manufacturing approach used for OCO	Full Identical to fabrication process by Nu-Cast for OCO	Full Identical to OCO Optical bench	Partial Operates colder than OCO but identical dimensional stability across thermal cycles	Full All aluminum Spectrometer Bench designs have flown on M3 and ARTEMIS	7

Table 2-3: VSWIR Mechanical Structure.

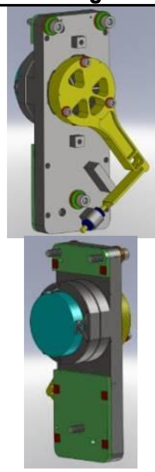
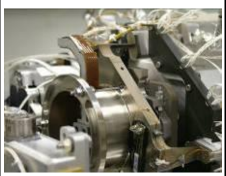
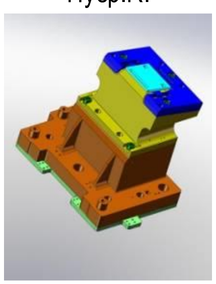
Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Grating Mounts	 HyspIRI	Full JPL, in-house build	Partial Modified from M3 to I/F to larger Spectrometer Bench	Full Typical manufacturing techniques, as were used for M3	Full Identical to M3	Partial Within the operating environment of M3	Full Grating mount designs have flown on M3	7
Focal Plane Assembly mounts	 M3	Full JPL, in-house build	Partial 6 DOF Moore Mount modified from M3 to I/F to larger Spectrometer Bench	Full Typical manufacturing techniques. Focal plane alignment and thermal control techniques identical to M3	Full Identical to M3	Full Within the operating environment of M3	Full Focal plane mount designs have flown on M3	7
Slit mounts	HyspIRI 	Full JPL, in-house build	Partial 4 DOF Moore Mount modified from M3 to I/F to larger Spectrometer Bench	Full Typical manufacturing techniques. Slit alignment techniques identical to M3	Full Identical to M3	Full Within the operating environment of M3	Full Slit mount designs have flown on M3	7

Table 2-3: VSWIR Mechanical Structure.

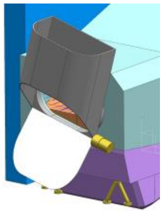
Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Calibration Cover	HyspIRI   Hyperion	None JPL, in-house build. JPL did not build HYPERION cover, but has extensive experience with mechanisms for similar missions (e.g. MCS, Diviner Lunar Radiometer).	None Evolved design specific for HyspIRI. Based on HYPERION design.	Full Standard manufacturing techniques	Full Identical to HYPERION	Full Same LEO environment as HYPERION (700km altitude vs 626 km altitude SSO)	Full Calibration cover flown on HYPERION	7
Calibration Cover Actuator Aeroflex 16229 Stepper motor		Full JPL, in-house build	Partial Build to print with minor modifications	Full Standard manufacturing techniques	Full Actuator exceeds functional requirements for this use	Full JPL draws on extensive launch and LEO environmental qualifications and flights	Full Many actuators of this precision flown on many JPL missions	9

Table 2-4. VSWIR Thermal.

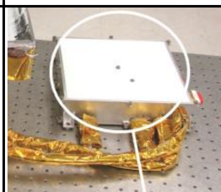
Title	Image	Provider	Design	Manufacture	Use	Thermal Environment	Prior Use	TRL
Passive Cooler	 M3	Full JPL, in-house build	Partial Aluminum k-core radiator blades, G10 reflectors and aluminum structure. 3X scaled version of M3 passive cooler	Partial Same as for M3 except for different tooling to handle larger size.	Partial Different thermal environment and heat loads.	Full M3 Moon mission at 100km much more severe thermal environment	Full M3	7
Electronics Radiators	 M3	Full JPL, in-house build	Partial Similar to M3, TES, AIRS, MICAS, MLS and MISR with different configurations	Full Standard materials and processes	Full Radiator sizing requires analysis for environment to meet AFT requirements	Full Low Earth Polar Orbit like TES, AIRS, MLS, and MISR	Full M3, TES, AIRS, MLS, MICAS, and MISR	7
Heaters/ Controllers	 M3	Full Tayco custom heaters, Minco & Honeywell 700 series components	Full Identical to M3, TES, AIRS, MLS, and MISR instruments	Full Standard parts and processes	Full Previously on M3, TES, AIRS, MLS AND MISR. HyspIRI actuation set points are similar temps	Full Low Earth Polar Orbit like TES, AIRS, MLS, and MISR	Full M3, TES, AIRS, MLS, MICAS, and MISR	9
Temp Sensors	 M3	Full NASA type 311P-18-10S-7R6; Goodrich 118 series PRTs	Full Identical to M3, TES, AIRS, MLS, and MISR instruments	Full Standard parts and processes	Full Previously on M3, TES, AIRS, MLS AND MISR	Full Low Earth Polar Orbit like TES, AIRS, MLS, and MISR	Full M3, TES, AIRS, MLS, MICAS, and MISR	9

Table 2-4. VSWIR Thermal.

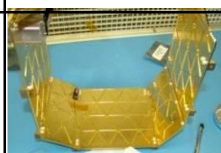
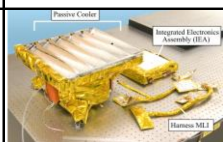
Title	Image	Provider	Design	Manufacture	Use	Thermal Environment	Prior Use	TRL
Flexible Thermal Straps	 M3	Full Space Dynamics Laboratory, high purity aluminum	Full Identical to M3, TES, AIRS, and CheMin instruments	Full Standard parts and processes	Full Previously on M3, TES, AIRS, and CheMin	Full Low Earth Polar Orbit like TES, AIRS, and CheMin	Full M3, TES, AIRS and CheMin	7
Finishes/ Coatings	 M3	Full JPL, in-house build	Full Identical to M3, TES, AIRS, MLS and MISR instruments	Full Standard parts and processes	Full Previously on M3, TES, AIRS, MLS AND MISR	Full Low Earth Polar Orbit like TES, AIRS, MLS, and MISR	Full M3, TES, AIRS, MLS, MICAS, and MISR	9
MLI	 M3	Full JPL, in-house build	Partial Similar to M3, TES, AIRS, MLS and AIRS with dimensional changes	Full Standard materials and processes	Full Previously on M3, TES, AIRS, MLS AND MISR	Full Low Earth Polar Orbit like TES, AIRS, MLS, and MISR	Full M3, TES, AIRS, MLS, MICAS, and MISR	9

Table 2-5: VSWIR Optics.

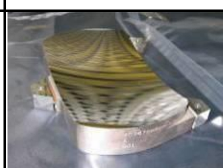
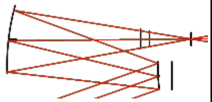
Title	Image	Provider	Design	Manufacture	Use	Operational Environment	Prior Use	TRL
Grating	M3   ARTEMIS	Full JPL provided previous grating (Hyperion, CRISM, M3, ARTEMIS) and will provide this grating	Partial Identical materials and techniques as used for M3 and ARTEMIS. Modifications made are different blaze angles and increased diameter.	Partial Manufacturing processes are 90% similar to those used for M3 and ARTEMIS.	Full Function is unchanged from M3 and ARTEMIS.	Full Grating flown in 400 km LEO (ARTEMIS), a harsher environment and Lunar orbit (M3).	Full Flown on M3 and ARTEMIS.	7
Slit	 ARTEMIS	Full JPL provided previous slit (ARTEMIS) and will provide this slit	Partial Design uses same approach as for ARTEMIS, but length of slit is larger to accommodate 6604b.	Full Manufacturing process unchanged.	Full Function unchanged	Full Slit flown in 400 km LEO (ARTEMIS).	Full ARTEMIS	7
Aluminum Mirrors	 M3 Spectrometer Mirror	Partial Several possible providers, e.g. Axsys, Tinsley, Corning	Partial Larger size for one telescope mirror, other mirrors full.	Full No new processes	Full Function and interfaces unchanged	Full M3, ARTEMIS	Full Flown on M3 and ARTEMIS	7

Table 2-5: VSWIR Optics.

Title	Image	Provider	Design	Manufacture	Use	Operational Environment	Prior Use	TRL
Two Mirror Telescope Architecture		Full JPL	Full This architecture has been fabricated, aligned and flown on CAO at 140 K in a vacuum in May 2011	Partial Optical architecture same, mechanical changes due to larger size.	Full Same function and optical interfaces	Partial CAO version could be flown in space	Full Flown on aircraft in a vacuum vessel at 140 K in May 2011 with successful imaging of calibration site in Nevada Desert	7

2.2 TIR

Measurements of temperature and emissivity from space have a long heritage. Dating back to the 1970's MSS and AVHRR have provided thermal imaging of the earth from space. The data and instruments have improved greatly over the decades. Thermal radiometers are the work horse for atmospheric, land and sea surface temperature measurements. Like ASTER, the HyspIRI TIR will build upon its predecessors to extend the measurements of temperature and emissivity from space. The TIR will provide a combination of spatial sampling (60 meters), global repeat (5 days) with 8 spectral bands to monitor the earth surface temperatures, fires and volcanic activity.

The TIR instrument draws upon the heritage of MODIS, HIRDLS, AIRS and other sensors to provide the highest quality measurement with state-of-the-art technology. Currently funded technology development from ESTO will demonstrate the custom HgCdTe based detector, a key component of the TIR system. This work is done through the IIP funded PHyTIR program, a system level demonstration of the TIR instrument that will be completed in 2013.

JPL has been involved in thermal infrared spectral imaging since the late 1970's, when it was using and interpreting data from a Bendix 24 channel infrared imager flown over Utah, Cuprite, Nevada and Death Valley, California. In the mid 1980's, JPL collaborated with others to develop and calibrate the Thermal Infrared Multispectral Scanner (TIMS). TIMS was an aircraft scanner providing six-channel spectral capability. A photo of the instrument and a JPL data set is shown in Figure 2-6. TIMS operated in the thermal infrared atmospheric window region (8 - 12 µm) with a sensitivity of approximately 0.1°C. In the same timeframe with development and operation of TIMS, JPL developed the Near Infrared Mapping Spectrometer (NIMS) that was flown to Jupiter as part of the Galileo mission. Subsequently, the Visual and Infrared Mapping Spectrometer (VIMS) was developed and flown to Saturn as part of the Cassini Mission. Both of these instruments had some sensitivity in the thermal infrared.

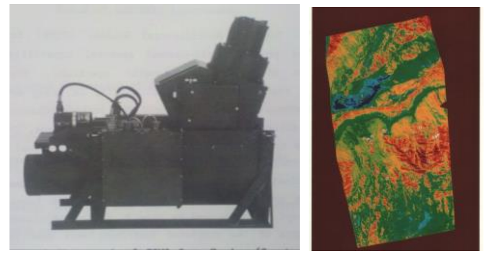


Figure 2-6: Left) Thermal Infrared Multi-spectral Scanner (TIMS) was used extensively by JPL (1985-2000) Right) color coded thermal inertia plot from TIMS

TIMS operated for nearly 15 years. During this time, the pressure modulator infrared radiometer (PMIRR) was designed, assembled and aligned at JPL to do limb and nadir sounding of the Martian atmosphere, using filter and gas correlation radiometry. In 1998, the Mars orbiter (MO) failed an orbit insertion but the JPL instruments would have been set to provide high vertical resolution profiles of temperature, aerosols and water vapor as a function of atmospheric pressure over a Martian year. A second PMIRR instrument was built, but lost in the Mars Climate Orbiter (MCO) mishap. The work done developing PMIRR was used in later years to successfully build other planetary thermal instruments. In 1999, JPL lead the calibration and validation effort for MODIS/ASTER airborne simulator (MASTER) shown in Figure 2-7. This system was developed to support scientific studies by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Moderate Resolution Imaging Spectroradiometer (MODIS) projects. This instrument allowed JPL to acquire the expertise in temperature/emissivity separation algorithms.

In 2004, JPL launched the Tropospheric Emission Spectrometer (TES). It was successfully launched into polar orbit aboard NASA's third earth Observing Systems spacecraft (EOS-Aura), shown in Figure 2-8. TES was designed and built by JPL and consists of a Fourier transform spectrometer of the Connes type. It utilizes a Cassegrain optical system with gimbaled pointing mirror. It has a sophisticated thermal control system which uses pulse tube cryocoolers to operate the detectors at 65K, step-down thermal zones at

180K to minimize parasitic loading, passive coolers and radiators with thermal pipes to deposit excess heat into deep space, and blackbody calibration source to maintain detector absolute accuracy.

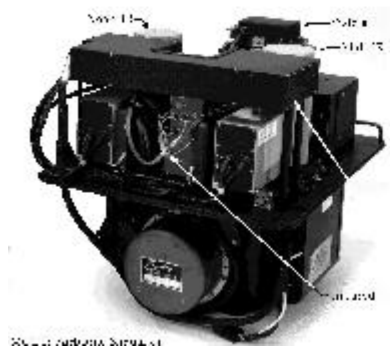


Figure 2-7: The MODIS/ASTER (MASTER) airborne simulator is a joint development involving the Airborne Sensor Facility at the Ames Research Center, the Jet Propulsion Laboratory and the EROS Data Center. The primary objective of the MASTER activity is to support the ASTER and MODIS instrument teams in the areas of algorithm development, calibration and validation.

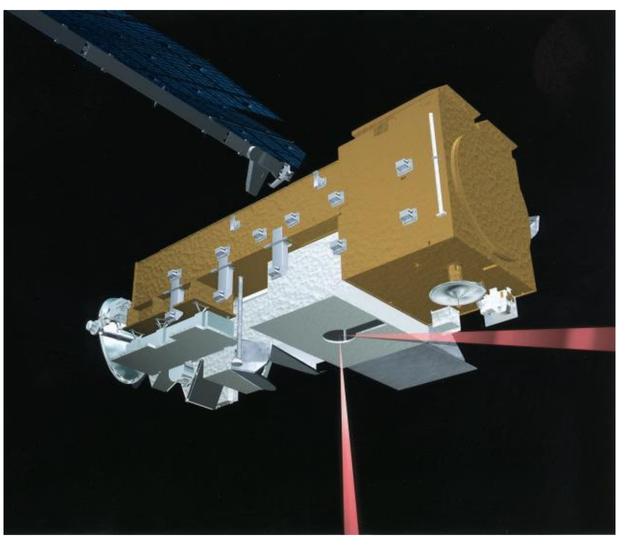


Figure 2-8: Computer-aided design view of the EOS Aura platform on orbit. The TES is the instrument slightly to the right of center. The keyhole-shaped entrance aperture permits both downward and limb views to be obtained (indicated by the rays emanating from the aperture).

JPL designed and built the Mars Climate Sounder (MCS, Figure 2-9) instrument for the Mars Reconnaissance Orbiter (MRO) mission to recover the atmospheric science lost when the two missions carrying PMIRR instruments failed. MCS contains JPL-developed uncooled thermopile detector arrays that have flat spectral sensitivity from 0.3 microns to beyond 200 microns. Nine spectral channels from 0.3 to 45 microns allow the instrument to measure atmospheric temperature, water vapor, dust and ice as a function of altitude, as well as polar albedo. MCS has now been making Mars climate measurements for over 5 years.

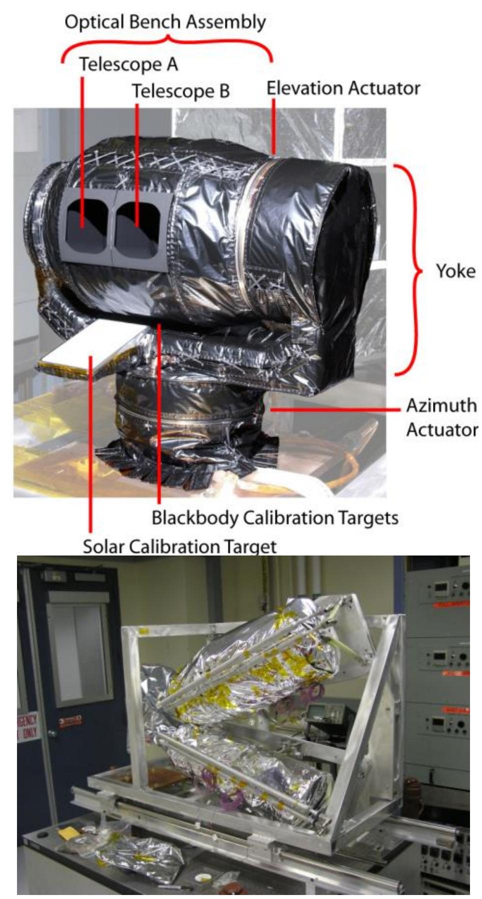


Figure 2-9: Top) The Mars Climate Sounder (MCS) is a spectral radiometer with one visible/near infrared channel (0.3 to 3.0 μm) and eight far infrared (12 to 45 μm) channels. These channels were selected to measure temperature, pressure, water vapor and dust levels. Bottom) Target projector/blackbody calibration sources.

JPL also developed the Diviner instrument for the Lunar Reconnaissance Orbiter (LRO) mission. Diviner is a near copy of MCS, but is nadir looking and has spectral channels ranging from 0.3 to 200 microns to thermally map the Moon's surface. Diviner's very stable detectors have allowed it to measure surface temperatures as low as 25 K at the Moon's poles, the coldest temperature measured to date in the solar system.

In the period from 2009 to 2011 JPL developed an airborne thermal infrared pushbroom imaging spectrometer named the Hyperspectral Thermal Emission Spectrometer (HyTES). It operates with quantum well infrared photodetecotrs at 40K and an optics package at 100K. When flown at low altitude later in 2012 the system will provide 200mK thermal noise equivalent delta temperature for ambient ground targets, 0.5 K absolute accuracy, and 256 spectral channels with about 3m ground resolution over a 1.5km swath.

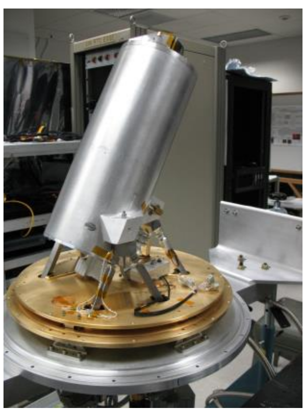


Figure 2-10: HyTES airborne cryogenic platform. This uses QWIP detector technology, state of the art pushbroom imaging optics and multiple zone cryogenic thermal system. HyTES was developed between 2009 and early 2011.

Through these efforts and with a strong institutional commitment, JPL has demonstrated a sustained focus for the development, delivery, calibration and validation of science-grade \ thermal instruments using five key capabilities: (1) thermal detector expertise, both with in-house development and management and testing of out-of-house work (2) cutting edge science calibration and validation both using airborne and space systems (3) design of complex thermal control system required for cryogenic space applications; (4) advance thermal optical system design and baffling control (5) an unmatched suite of calibration, alignment sources as well as the vetted procedures and analysis tools for delivery of aligned and calibrated thermal imaging spectrometers. In addition, the thermal instrument team at JPL has both the long standing and recent experience and expertise, including lessons learned, to develop and deliver high fidelity thermal instruments.

The extensive component and architectural heritage embodied in the HyspIRI TIR instrument provides for a cost-effective, low-risk development. JPL's prior experience with all aspects of development for this type of instrumentation is the principal reason that we are able to propose a 36-month instrument development schedule.

This heritage is described in Tables 2-7 through 2-10 and summarized in Table 2-6.

Table 2-6. TIR TRL and Heritage

TIR Technology Readiness Assessment		
	Primary Heritage Mission(s)	**Lowest component TRL**
Focal Plane and Electronics	CrIS, M3, DIVINER, AIRS, MODIS, HIRDLS	5 (6 in 2013)
Mechanical	DIVINIR, MODIS, MER	7
Thermal	M3, AIRS	7
Optics	M3, ARTEMIS, DIVINIR	7

Focal Plane and Electronics Subsystem

The detector material, ROIC and Focal Plane Assembly will be demonstrated to TRL 6 as part of the PHyTIR program, a Prototype HyspIRI TIR. Elements of heritage in the detector and electronics subsystem include:

- Focal plane assembly and detector material with slightly different doping flown on CrIS.

Detector material with identical doping will be demonstrated in 2013 as part of PHyTIR.

- ROIC will be demonstrated to TRL 6 by PHyTIR program in 2012.
- Flex print cable, digital and housekeeping electronics modified from what flew on M3
- Signal chain electronics are based on those used by M3 with upgraded ADC.
- Digital electronics are based on those used by M3 with upgraded FPGA (Rad hard Virtex 5). The Virtex 5 is currently in space aboard a cubesat and its team is trying to regain communication. If the mission is successful, the digital electronics will be raised to TRL 7.
- Similar butcher block filters flew on CRISM, M3 and DIVINIR.
- Power subsystem is based off the MIRI subsystem that has been successfully tested and will fly on JWST

Mechanical Subsystem

The mechanical subsystem draws heavily from JPL experience with common structural elements found on such missions as M3, MER, and DIVINIR.

- The scanning mechanism flew on GIFTS and WISE. The same motors, encoders, structure and mirror technology will be used on TIR however the mirror is changed from one sided SiC to two sided SiC and the limited range of motion oscillating operation is changed to continuously rotate in a single direction.
- The focal plane assembly mounts are very similar to M3 and DIVINIR mounts.
- The telescope bench is a scaled version of the DIVINIR telescope bench that uses the same materials.
- The enclosure is a standard in-house structure build for JPL's engineers and draws heritage from MER's Warm Electronics Box

Thermal Subsystem

The thermal subsystem is high heritage and draws on JPL's experience with multiple similar systems on OCO, OCO-2, M3, and AIRS. The elements of the thermal subsystem include the following:

- The cryocooler is build-to-print by NGST and has flown on ABI and was recently used by JPL on OCO-2.
- The passive radiator is a larger version of the M3 passive radiator
- Electronics radiators, heat pipes and a focal plane enclosure that have flown in different configurations on AIRS (and other missions).
- The other components are common and high heritage with extensive flight history

Optics Subsystem

The optical elements have high heritage and draw on JPL's experience on M3, ARTIMIS and DIVINIR. Furthermore, similar telescopes have flown on VIMS-IR, MODIS, VIIRS, ASTER and AVHRR/3. The elements of the optical subsystem include:

- The three mirror anastigmatic optical architecture is common and most recently used on DIVINIR.
- Diamond turned aluminum mirrors of slightly different shape and smaller size than flew on M3 and ARTEMIS
- The blackbody is a larger version of what flew on DIVINIR

Table 2-7. TIR Focal Plane & Electronics.

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Mercury-Cadmium-Telluride (HgCdTe) Detector Material		Full Teledyne	Partial Similar material used on CrIS but with slightly longer cutoff wavelength (13.5 µm on TIR versus 15.4 µm on CrIS)	Full Manufacturing processes are the same as those used for CrIS and TES.	Full Function is unchanged from prior uses and interfaces are identical. Used to detect earth IR at similar radiance.	Partial HyspIRI TIR operates at 60K, colder than CrIS (80K). TES had same material at 65 K.	Full Heritage detector material flown on CrIS. Exact TIR material doping and temperature will be demonstrated by 2012 in PHyTIR ground tests, **currently funded by ESTO IIP**.	5 (6 in 2012)
ROIC		Full Teledyne provided ROIC for previous detectors (ARTEMIS, CRISM, M3, JWST and WISE) and will provide this ROIC	Partial Custom ROIC currently undergoing test for use on PHyTIR. TIR's whiskbroom requires similar pixel rate to heritage pushbroom spectrometers. Design based on Teledyne's extensive experience with ROICs. Same amplifier as CRISM and M3.	Full Manufacturing processes are identical to those used for JWST, WISE, ARTEMIS, CRISM and M3.	Partial Function and interfaces are customized for similar pixel rate. TIR's function and interfaces will be tested on PHyTIR. GIFTS focal plane (not from Teledyne) is very similar to TIR's.	Partial TIR operating environment (60K) is warmer than JWST and WISE (~45K) and cooler than ARTEMIS, CRISM, M3 (~120K).	Partial ROIC will be demonstrated (to TRL 6) as part of PHyTIR in 2012 **currently funded by ESTO IIP**. AIRS, GIFTS and HIRDLS (not provided by Teledyne) also have LWIR multiplexed detectors.	5 (6 in 2012)

Table 2-7. TIR Focal Plane & Electronics.

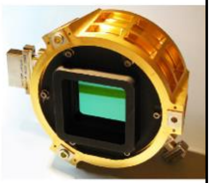
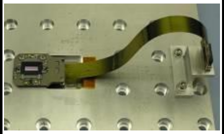
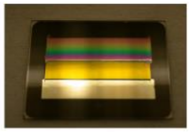
Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Focal Plane Assembly	 JWST FPA	Full Teledyne	Partial Similar hybrid and analog boards with similar materials, adhesives, paints, mounting plate and finishes.	Full Same processes used as for M3, JWST, WISE and CRISM	Partial Function is unchanged from CRISM. Interfaces are different (bond path and mounting locations, filter interface, trace design). HIRDLS, GIFTS and AIRS FPA (not from Teledyne) are very similar to TIR's.	Partial TIR operating environment (60K) is warmer than JWST and WISE (45K) and cooler than ARTEMIS, CRISM, M3 (120K).	Partial Heritage Focal Plane Assembly flown on CrIS. Correct speed and temperature will be demonstrated in 2013 in PHyTIR ground tests, **currently funded by ESTO IIP**.	5 (6 in 2013)
Flex Print Cable	 M3	Full Accurate Engineering Inc. who provided M3 Flex Print Cable	Partial M3 design expanded to accommodate more outputs.	Full Same processes used as for M3	Full Function is unchanged. Interfaces are similar	Partial M3 cable at 140K to 180 K, TIR runs at 60 K on one side to room temperature on the other.	Full Flown on M3	7
Butcher Block Filter		Full Barr Associates, who provided Filter for CRISM and M3	Partial Identical materials and techniques to prior missions. In same wavelength range (long IR). Different specific wavelengths.	Full Manufacturing processes are identical to what was used for CRISM, HIRDLS and M3.	Full Function is unchanged from CRISM and M3.	Partial TIR operates at 60 K, which is colder than the CRISM and M3 versions (120K).	Full Similar filters flown on CRISM and M3.	7

Table 2-7. TIR Focal Plane & Electronics.

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Digital Electronics		Full JPL In House Build	Partial Upgrade FPGA's from Virtex 1 to Virtex 5 because of Virtex 1 obsolescence. Simplify design by removing SSR.	Full Manufacturing processes are identical to those used for prior spaceborne missions.	Full Function is still to control the Detector, Control the instrument, interface with the S/C and compress and edit science data. Interfaces and function unchanged.	Partial LEO is more benign than Lunar Orbit, and so within the margins of M3's design. Virtex 5 is designed for expected radiation environment.	Partial Heritage electronics flown on M3. Virtex 5 qualified for space but has not yet been demonstrated in space. It was launched into space in Oct 2011 on a University of Michigan Cubesat called M-Cubed, however, as of Jan 2012, the Cubesat is not yet responding to commands but does appear to be in good health.	6
Compression Algorithm Used in Digital Electronics		Partial JPL In-House with consultation with ASTER team	Partial ASTER is 12 bits and 5 bands, TIR is 14 bits and 8 bands. Both TIR and ASTER use 2:1 compression. Modifications are made to handle extra bands and bits.	N/A	Partial ASTER is 12 bits and 5 bands, TIR is 14 bits and 8 bands. Modifications are made to handle extra bands and bits.	N/A	Full Flown on ASTER	6
Signal Chain	 M3	Full JPL In House Build	Partial Similar topology with different ADC (RHF1401) providing faster throughput.	Full Manufacturing processes are identical to those used for prior spaceborne missions.	Partial Function is still to digitize science data from the detector, however it is done 10 times faster.	Full LEO is more benign than Lunar Orbit, and so within the specifications of M3's design	Full Flown on M3	6

Table 2-7. TIR Focal Plane & Electronics.

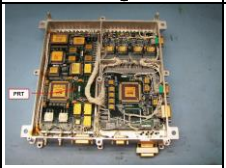
Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Housekeeping	 M3	Full JPL In House Build	Partial Identical parts and topology new PCB design to fit configuration	Full Manufacturing processes are identical to those used for prior spaceborne missions.	Full Function is still to make low rate housekeeping measurements. Interfaces are identical	Full LEO is more benign than Lunar Orbit, and so within the specifications of M3's design	Full Flown on M3.	7
Power Sub System	 MIRI	Full JPL In House Build	Partial Identical DC to DC converters with different voltages to suit HyspIRI TIR	Full Manufacturing processes are identical to those used for prior spaceborne missions.	Full Function is still to provide instrument DC voltages Interfaces are minimally modified.	Full LEO is less benign than Earths' L2 point, but not outside the acceptable operating realm of this Power Sub System	Partial Will fly on MIRI, which is a completed spaceflight qualified instrument on JWST.	7

Table 2-8: TIR Mechanical Structure.

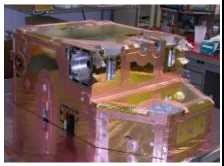
Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Enclosure with Baffles	 MER WEB	Full JPL, in-house build	Partial New aluminum honeycomb substrate design similar to those used on parts of MER and MSL.	Full Uses the same standard processes used to build part as MER and MSL.	Full Same function and interfaces	Full Aluminum honeycomb structures are common structural materials in LEO	Full Enclosure is built with common mechanical elements flown on many missions including MER (Warm Electronics Box and Rover Equipment Deck), and MSL (Belly Pan).	7
Telescope Bench		Full JPL, in-house build	Partial Same materials and off-axis two mirror design as DIVINIR. Three times larger telescope diameter than DIVINIR	Full Identical to fabrication process used on DIVINIR. Standard JPL processes for precision aluminum structures.	Full Identical to telescope on DIVINIR	Full Identical to DIVINIR	Full Flown on DIVINIR.	7
Focal Plane Assembly mounts	 M3	Full JPL, in-house build	Partial 6 DOF Moore Mount modified from M3 to I/F to larger Spectrometer Bench	Full Typical manufacturing techniques. Focal plane alignment and thermal control techniques identical to M3 and DIVINIR	Full Identical to M3	Partial ~60 K colder than M3	Full Focal plane mount designs have flown on M3 and DIVINIR	7

Table 2-8: TIR Mechanical Structure.

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
Scanning Mirror Assembly (Motor, encoder, structure, mirror)		Full L3	Partial The heritage one-sided SiC mirror will be changed into a two sided SiC mirror. The heritage design is an oscillating design. TIR will rotate at a constant speed in one direction. The heritage mechanism exceeds TIR's resolution and speed requirements.	Full Standard manufacturing techniques	Partial Similar to GIFTS, WISE. Resolution exceeds TIR requirements. Oscillating mirror with limited swing must be changed to continuously rotate.	Full Operating in vacuum. WISE operated at 11 K, much colder than TIR which operates at room temperature	Full Heritage mechanism flew on GIFTS and WISE	7

Table 2-9. TIR Thermal.

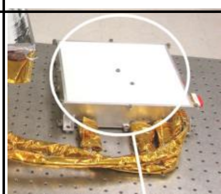
Title	Image	Provider	Design	Manufacture	Use	Thermal Environment	Prior Use	TRL
Cryocooler + Electronics	NGST HEC	Full NGST	Full Unchanged build-to-print from OCO-2 and ABI.	Full Standard materials and processes	Full One stage crycooler performs same cooling function at similar temperatures and power draw as heritage missions	Full LEO orbit like heritage missions. Cooling to similar temperature.	Full Flown on ABI. Has also been demonstrated during OCO-2 environmental tests. OCO-2 launches in 2012.	9
Electronics Radiators	M3	Full JPL, in-house build	Partial Similar to M3, TES, AIRS, MICAS, MLS and MISR with different configurations	Full Standard materials and processes	Full Radiator sizing requires analysis for environment to meet AFT requirements	Full Low Earth Polar Orbit like TES, AIRS, MLS, and MISR	Full M3, TES, AIRS, MLS, MICAS, and MISR	7
Heaters/ Controllers	M3	Full Tayco custom heaters, Minco & Honeywell 700 series components	Full Identical to M3, TES, AIRS, MLS, and MISR instruments	Full Standard parts and processes	Full Previously on M3, TES, AIRS, MLS AND MISR. HyspIRI actuation set points are similar temps	Full Low Earth Polar Orbit like TES, AIRS, MLS, and MISR	Full M3, TES, AIRS, MLS, MICAS, and MISR	9
Heat Pipes		Full ATK	Partial Same technology demonstrated on many spacecraft (ammonia heat pipe). Used on OCO, AIRS, Cloudsat	Full Standard parts and processes	Full Same use as for heritage missions	Full Low Earth orbit. Similar heat throughputs as OCO, AIRS and Cloudsat	Full Flown on AIRS and Cloudsat. Tested on OCO. Will fly on OCO-2 in 2012	7

Table 2-9. TIR Thermal.

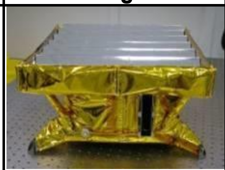
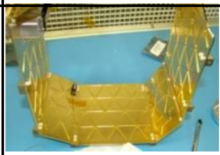
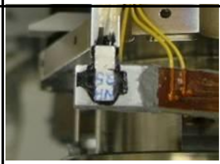
Title	Image	Provider	Design	Manufacture	Use	Thermal Environment	Prior Use	TRL
Passive Cooler	 M3	Full JPL, in-house build	Partial Aluminum k-core radiator blades, G10 reflectors and aluminum structure. 2X scaled version of M3 passive cooler	Partial Same as for M3 except for different tooling to handle larger size.	Partial Different thermal environment and heat loads.	Full M3 Moon mission at 100km much more severe thermal environment	Full M3	7
Focal Plane Thermal Enclosure + Vent	 M3	Full JPL, In-house build	Partial Common aluminum enclosure. Similar to M3	Full Standard materials and processes	Full Same use previously on M3	Full Minimal temperature differences from M3. Difference does not affect design.	Full Flown on M3, AIRS	7
Temp Sensors	 M3	Full NASA type 311P-18-10S-7R6; Goodrich 118 series PRTs	Full Identical to M3, TES, AIRS, MLS, and MISR instruments	Full Standard parts and processes	Full Previously on M3, TES, AIRS, MLS AND MISR	Full Low Earth Polar Orbit like TES, AIRS, MLS, and MISR	Full M3, TES, AIRS, MLS, MICAS, and MISR	9
Flexible Thermal Straps	 M3	Full Space Dynamics Laboratory, high purity aluminum	Full Identical to M3, TES, AIRS, and CheMin instruments	Full Standard parts and processes	Full Previously on M3, TES, AIRS, and CheMin	Full Low Earth Polar Orbit like TES, AIRS, and CheMin	Full M3, TES, AIRS and CheMin	7
Finishes/ Coatings		Full JPL, in-house build	Full Identical to M3, TES, AIRS, MLS and MISR instruments	Full Standard parts and processes	Full Previously on M3, TES, AIRS, MLS AND MISR	Full Low Earth Polar Orbit like TES, AIRS, MLS, and MISR	Full M3, TES, AIRS, MLS, MICAS, and MISR	9

Table 2-9. TIR Thermal.

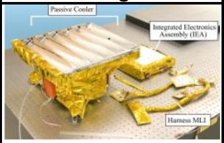
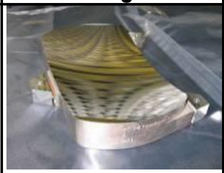
Title	Image	Provider	Design	Manufacture	Use	Thermal Environment	Prior Use	TRL
MLI	 M3	Full JPL, in-house build	Partial Similar to M3, TES, AIRS, MLS and AIRS with dimensional changes	Full Standard materials and processes	Full Previously on M3, TES, AIRS, MLS AND MISR	Full Low Earth Polar Orbit like TES, AIRS, MLS, and MISR	Full M3, TES, AIRS, MLS, MICAS, and MISR	9

Table 2-10: TIR Optics.

Title	Image	Provider	Design	Manufacture	Use	Operational Environment	Prior Use	TRL
Aluminum Mirrors	 M3 Spectrometer Mirror	Partial Several possible providers, e.g. Axsys, Tinsley, Corning	Partial Largest 8" mirror is much smaller than largest heritage mirrors on Artemis. However, conic constant is different	Full No new processes	Full Function and interfaces unchanged	Full Operates at room temperature like M3, ARTEMIS	Full Flown on M3 and ARTEMIS	7
Three Mirror Anastigmatic Architecture		Full JPL	Partial Same design as DIVINIR but scaled to larger size	Full Standard manufacturing processes	Full Same function and interfaces as DIVINIR	Full Operates at room temperature, just like DIVINIR	Full DIVINIR.	9
IR Cal Blackbody		Full JPL	Partial Similar temperature as DIVINIR, but larger size (8" across vs 4" across)	Full Standard manufacturing processes	Full As an IR calibration target	Full DIVINIR and TIR blackbodies operate at room temperature	Full DIVINIR	7

2.3 IPM

The IPM draws on GSFC's experience providing NPP's direct broadcast system, with specific components coming from other missions as shown in table 2-11.

Table 2-11. IPM Hardware TRL and Heritage

	Primary Heritage Mission(s)	Lowest component TRL
Electronics	HST/RNS, MISSE7, and STP-H4	9
Mechanical / Thermal	FAST, IBEX	7
Telecom	NPP	9

Table 2-12. IPM Software TRL and Heritage

	Primary Heritage Mission(s)	Lowest component TRL
Ground Operations	EO-1, HyspIRI IPM Prototype	7
Flight Software	EO-1	8
Onboard Algorithms	EO-1, MODIS, ASTER, ETM, ETM+, SeaWifs, AVIRIS	7-9

2.3.1 IPM H/W

Electronics Subsystem

The architecture and implementation of the IPM electronics are SpaceCube 1.0 which flew on HST/RNS, MISSE7, and STP-H4.

Mechanical / Thermal Subsystem

IPM mechanical and thermal designs draw heavily from previous space flight hardware designed and built by GSFC. It uses common materials, methods and designs.

Telecom Subsystem

The telecom subsystem is the same direct broadcast system that is flying on NPP.

2.3.2 IPM S/W

The IPM Software has 3 components:

Ground System for automated operations of the IPM

This is very mature having already been demonstrated in prototype form for the baseline IPM design and performance on a simulated HyspIRI orbit.

Flight Software for basic algorithm upload and operations.

The baseline for this flight software is the onboard science processing software infrastructure currently in operation on EO-1. Specifically, HyspIRI would use the EO-1 R5 flight software version that has been in flight for over 2 years.

Onboard science and applications processing algorithms

Onboard science and applications processing algorithms are discipline dependent. A number of high value user requested low latency products have been identified. The algorithms to achieve these products fall into two categories: high heritage and maturity, and medium heritage and maturity. These are shown in Table 2-15 and 2-16.

The heritage and maturity evaluation relates specifically to the level of algorithm analysis in the flight context. Many of the moderate heritage and maturity algorithms have been in use in the ground for a significant period but have ancillary inputs that make flight deployment more complex. Further study could mature these if desired. They are not part of the baseline mission.

Table 2-13. IPM Electronics.

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use	TRL
SpaceCube 1.0 Processor and Memory		Full - Copy of HST/RNS, MISSE7, STP-H4 units	Full - Copy of HST/RNS, MISSE7, STP-H4 units	Full - Standard parts and processes	Full - Copy of HST/RNS, MISSE7, STP-H4 units	Full - Similar environment	Full - Copy of HST/RNS, MISSE7, STP-H4 units	9
SpaceCube 1.0 Power Card		Full - Copy of HST/RNS, MISSE7, STP-H4 units	Full - Copy of HST/RNS, MISSE7, STP-H4 units	Full - Standard parts and processes	Full - Copy of HST/RNS, MISSE7, STP-H4 units	Full - Similar environment	Full - Copy of HST/RNS, MISSE7, STP-H4 units	9

Table 2-14: IPM Telecom.

Title	Image	Provider	Design	Manufacture	Use	Operational Environment	Prior Use	TRL
L3 T-718 X-Band Transmitter		Full L3 Cincinnati	Full Unchanged off-the-shelf	Full Unchanged off-the-shelf	Full Used on NPP for similar direct broadcast system	Full Used on NPP in similar LEO	Full Flown on NPP	9
Antenna and Mount			Full Unchanged off-the-shelf	Full Unchanged off-the-shelf	Full Used on NPP for similar direct broadcast system	Full Used on NPP in similar LEO	Full Flown on NPP	9
Filter			Full Unchanged off-the-shelf	Full Unchanged off-the-shelf	Full Used on NPP for similar direct broadcast system	Full Used on NPP in similar LEO	Full Flown on NPP	9

Table 2-15. High Heritage Onboard Processing Algorithms (TRL 7-9)

Algorithm	V = VSWIR, T = TIR, B=Both	Heritage (G = Ground, F = Flight)
Volcano Thermal	V	F – EO-1/ASE
Volcano Thermal	T	G - MODVOLC
Cryosphere	V	F – EO-1/ASE
Cryosphere	B	G – MODIS Ice
Flooding	V	F – EO-1/ASE, G –EO-1
Flooding	B	G – MODIS Surface Water
Active Fire Mapping	T	F – EO-1/ASE G – MODVOLC, ASTER, ETM+
Burn Scar Evaluation	V	G – Landsat, ALI, Aviris

Table 2-16. Moderate Heritage Onboard Processing Algorithms (TRL 5-6) – Not part of baseline mission

Algorithm	V = VSWIR, T = TIR, B=Both	Heritage (G = Ground, F = Flight)
Ocean pollutants	B	G - MODIS
Sea Surface Temperature	T	G - MODIS
Ocean Biological	V	G – Seawifs, MODIS
Volcanic Plumes	B	G - MODIS, ASTER

3 Ground Systems

3.1 ATK Command And Control (C&C) Ground System

ATK's Mission Operations Center (MOC), located in Pasadena, CA will directly communicate with the KSAT Integrated Network Operations Center (TNOC). The MOC has served as the back-up to JPL's Earth Science Mission Center (ESMC) for over ten years. A back-up facility in Beltsville, MD will supply the necessary redundancy.

QuikSCAT, ACRIMSAT, JASON and OSTM/JASON-2 are currently supported by ATK's Space Mission Operations Organization staff. TOPEX, CALIPSO and WISE were previously supported.

The ATK Space Mission Operations organization consists of four operations teams:

The Flight Control Team (FCT) is responsible for maintaining the satellite health, safety, configuration of the ground system and the verification of all commands sent to HyspIRI via the KSAT TNOC. This team is responsible for real-time monitoring and commanding, as well as being the first response to any spacecraft anomaly. The team is also responsible for ensuring the integrity of received data.

The Science Data Team (SDT) is responsible for production, archival, and distribution of all science products during mission operations. The SDT manager provides the technical and operational interface, and is responsible for all aspects of the science production operations. These include mission reporting, problem management and resolution, support planning, documentation, and hardware and software systems required to perform the science production operations. The team performs delivery of "quick-look" science data upon receipt, and it maintains the science database and archives all data from the beginning of the mission. The SDT operates the hardware and software that is called the Science Data System (SDS).

The Mission Planning and Sequencing Team (MPST), in conjunction with KSAT, is responsible for the scheduling of ground communications network support as well as processing, managing, and distributing the on-board planned sequence for the mission. MPST coordinates the request from the science, payload, and spacecraft teams and develops command scripts to meet mission requirements.

The Satellite Analysis and Engineering Support (SA) Team consists of cross-trained spacecraft subsystem engineers. The Thermal and Power subsystem engineers monitor battery and thermal conditions on-board the spacecraft. The Command and Data Handling engineers monitor the Solid-State Recorder, and the Navigation engineers monitor the spacecraft orbit solution and execute planned maneuvers as needed.

ATK envisions utilizing off-the-shelf software packages for HyspIRI's mission operations needs such as AGI Corporation's STK tool and MATLAB for maneuver preparation and execution, and ITOS for payload and spacecraft monitoring and control, as well as satellite development, test and operations.

The same C&C Ground System team and equipment currently used by ATK on QuikSCAT, ACRIMSAT, JASON and OSTM/JASON-2 will be used by HyspIRI. Using this experienced team and existing equipment will minimizes non-recurring set up costs and reduce risk. Note that there is not currently an ATK SA Team, but it would be made up of engineers with the appropriate experience and skillset.

3.2 KSAT Ground System

Kongsberg Satellite Services (KSAT) is an experienced and trusted ground station owner and operator with more than 10,000 satellite contacts per month in 2010 across its entire network of stations. They provide downlink and TT&C services for NASA, JAXA, ESA and others. The long term contracts that they have with the world's leading space agencies ensure continual business for their stations in Norway (Svalbard, Tromsø, Grimstad), and Antarctica. By 2016, there will also be stations in Alaska, South Africa, Dubai, India and Singapore.

The KSAT ground system has been operating 800 Mbps X band links to LEO satellites since September 2007.

KSAT is committed to providing the service HyspIRI requires. They have the capability and the capacity. See their letter of commitment and quote provided with this document.

Customizations will exist in the specific CCSDS decoding algorithms that are supplied by ATK and will be implemented by KSAT.

The station in Svalbard and the planned station in Alaska are sufficient for HyspIRI's downlink needs.

KSAT's system is provided as the baseline since their stations have the higher heritage, having been providing 800 Mbps X-Band downlinks since 2007. However, SCAN is also presented as an alternative and no final decision has been made one way or the other.

3.3 (Alternative) SCAN Ground System

SCAN's Near Earth Network (NEN) can provide 800 Mbps X-Band through their stations in Svalbard, Poker Flats and Antarctica. This capability is currently being installed and will be operational by the end of 2012. NEN has existing stations at these three locations, however the electronics is being upgraded to handle 800 Mbps X-Band.

The antennas and tracking platforms exist and have extensive heritage in their use. The supporting electronics and software is new for SCAN. However, the technologies used in these electronics and software have been in operation by KSAT and other organizations since September 2007.

SCAN is a NASA entity with decades of experience providing downlink and TT&C. SCAN is forecast to have 800 Mbps X-Band links operational by the end of 2012. However, since this capability is not yet implemented, no heritage currently exists for the SCAN 800 Mbps X Band Ground Stations.

See the details of the quote from SCAN in the attached documentation. SCAN would provide all required ground station services for the mission (uplink, S-Band and X-Band downlink and Launch and Early Ops tracking) for $100k cost to the project. The price is based on the required software licenses for the 8PSK link and for link analysis and the RF ICD. A QPSK link would be cheaper because QPSK capability already exists and so no software licenses need to be purchased. The rest of the costs incurred by SCAN to support HyspIRI come from SCAN's own budget.

3.4 Science Data System Hardware

The HyspIRI Science Data System (SDS) hardware design is based on recent missions including CARVE and SMAP. CARVE is a Ventures (EV1) mission that is currently going through engineering flight evaluation and scheduled to be operational in spring of 2012.

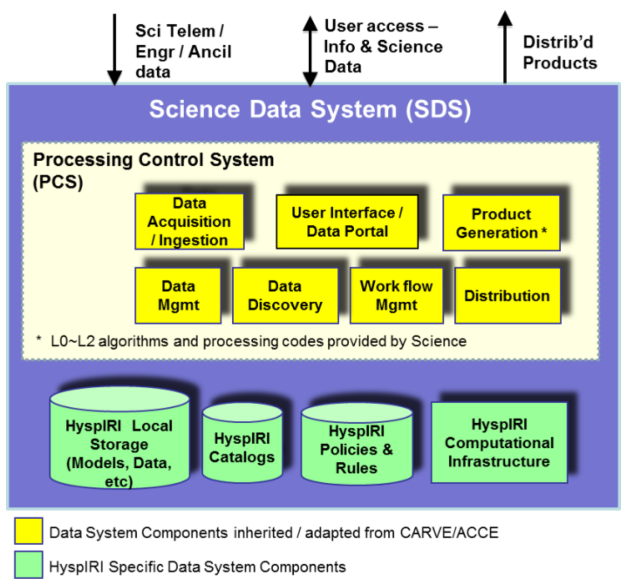


Figure 3-1. Science Data System - Functional Architecture and Components

SMAP is a first-tier earth decadal survey mission currently in development, scheduled for launch in 2014.

HyspIRI shares a common SDS functional architecture with SMAP and CARVE, as shown in Figure 3-1. All SDS components are implemented on commodity COTS computing hardware. This hardware performs the computationally intensive product generation functions.

By adopting a proven architecture, the non-recurring engineering costs of the SDS are reduced. In addition, the ability to use commodity COTS hardware allows HyspIRI to fully benefit from the ever-improving cost-performance ratio delivered by the COTS hardware industry.

The SMAP SDS Testbed shown in Figure 3-2 is 1/4th the size of the HyspIRI SDS based on present day COTS hardware technology. SMAP SDS Testbed is built upon the current 1U form-factor dual quad-core 3GHz Linux server technology.

Figure 3-2. SMAP Testbed – 1/4th the size of HyspIRI's SDS hardware using today's technology.

Table 3-1. SDS Hardware

Title	Provider	Design	Manufacture	Software	Use	Operating Environment	Prior Use
SDS Hardware	Full COTS H/W vendors / providers used, same as CARVE and SMAP	Full Same as to CARVE and SMAP	Full Same as CARVE and SMAP	Full Same as CARVE and SMAP. Uses standard operating system and diagnostic tools.	Full Same as CARVE and SMAP	Full Same as CARVE and SMAP (Commercial-grade computing facility/ environment used)	Partial (Full by 2014) CARVE SDS (airborne mission) in pre-operations validation phase. First deployment in 2012. SMAP SDS completing Phase B development. Launch in 2014

3.5 Science Data System Software

The HyspIRI SDS has heritage from prior missions including CARVE and SMAP. This high heritage approach represents significant savings in development cost and schedule, reduction in development risks, and improvement in operations reliability.

There are three major areas of science data system software for HyspIRI: processing infrastructure, product generation, and instrument/science algorithms. The HyspIRI processing infrastructure is based on the processing control system (PCS), the HyspIRI product generation is carried out by product generation executables (PGE), and the instrument and science algorithm and software is provided by the instrument and science teams respectively.

HyspIRI shares a common SDS functional architecture with SMAP and CARVE as depicted in Figure 3-1. The SDS software is a modular design and is configured with mission specific tailoring of workflow rules and data production policies. Tailoring is accomplished using configuration and parameter file inputs.

Figure 5-1 depicts the SDS processing infrastructure shared by CARVE, SMAP, and HyspIRI. The PCS-PGE interfaces are adopted from CARVE and SMAP for use by HyspIRI with little or no modification. For HyspIRI, processing algorithms for both instrument and science products are well developed and mature. Further details regarding instrument and science algorithm are in Section 5.

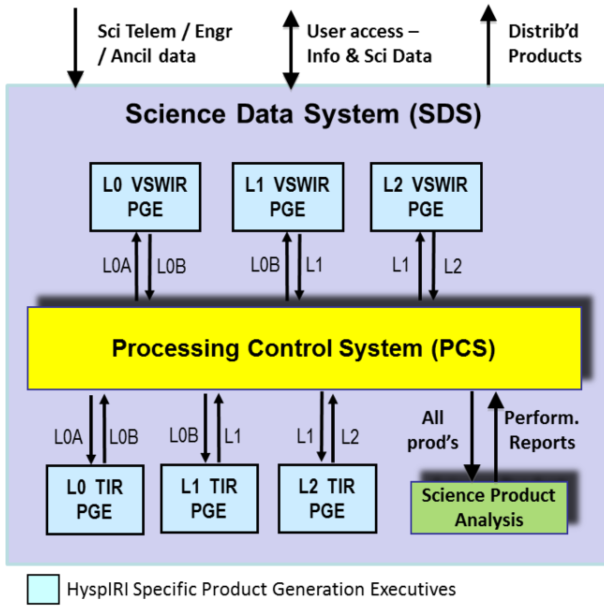


Figure 5-1. Science Data System - Data Processing Infrastructure

Table 5-1. SDS Data Processing Infrastructure Components

Title	Design	Manufacture	Use	Prior Use
Data Processing Infrastructure				
PCS (Processing Control System) Components				
Data Acquisition/Ingestion	Full Identical to CARVE and SMAP	Full Inherited from JPL productline, same as CARVE and SMAP	Full Same function and interfaces as CARVE and SMAP	Partial CARVE SDS in pre-operations validation phase SMAP SDS completing Phase B development
Data Management	Full Identical to CARVE and SMAP	Full Inherited from JPL productline, same as CARVE and SMAP	Full Same function and interfaces as CARVE and SMAP	Partial CARVE SDS in pre-operations validation phase SMAP SDS completing Phase B development
Data Discovery	Full Identical to CARVE and SMAP	Full Inherited from JPL productline, same as CARVE and SMAP	Full Same function and interfaces as CARVE and SMAP	Partial CARVE SDS in pre-operations validation phase SMAP SDS completing Phase B development
Workflow Management	Full Identical to CARVE and SMAP	Full Inherited from JPL productline, same as CARVE and SMAP	Full Same function and interfaces as CARVE and SMAP	Partial CARVE SDS in pre-operations validation phase SMAP SDS completing Phase B development
Distribution	Full Identical to CARVE and SMAP	Full Inherited from JPL productline, same as CARVE and SMAP	Full Same function and interfaces as CARVE and SMAP	Partial CARVE SDS in pre-operations validation phase SMAP SDS completing Phase B development
Product Generation	Full Processing Control System (PCS)-Product Generation Executable (PGE) based processing infrastructure, same as CARVE and SMAP Product generation algorithm and software provided by Instrument and Science teams, same arrangement as CARVE and SMAP	Full Inherited from JPL productline, same as CARVE and SMAP	Full Same function and interfaces as CARVE and SMAP	Partial CARVE SDS in pre-operations validation phase SMAP SDS completing Phase B development
User Interface/Data Portal	Full Identical to CARVE and SMAP missions	Full Inherited from JPL productline, same as CARVE and SMAP	Full Underlying interface framework is identical to CARVE and SMAP SDS.	Partial CARVE SDS in pre-operations validation phase SMAP SDS completing Phase B development

4 Assembly, Integration and Test Facility

4.1 ATK Facilities and ATLO Processes

ATK's existing facilities will be used for HyspIRI. No facility modification will be needed to support HyspIRI.

ATK integrates HyspIRI class spacecraft and space vehicles in its assembly, integration and test (AI&T) facility located in Beltsville, Maryland. ATK typically will utilize environmental test facilities at Goddard Space Flight Center (GSFC), Johns Hopkins University Applied Physics Laboratory (JHU-APL) or the Naval Research Laboratory (NRL), all in close proximity to Beltsville.

ATK's manufacturing and AI&T facilities have extensive capability to meet the needs for HyspIRI class missions. Their primary integration facility in Beltsville is their "5015" facility previously used for the FUSE payload structure integration, EO-1 bus, and THEMIS programs. In addition, ATK recently opened a larger AI&T facility used for the TacSat-3 and ORS-1 programs which is also suitable for HyspIRI class missions.

ATK facilities include ESD certified fabrication and test areas, Class 100K clean rooms with adjacent AI&T control rooms, mechanical and electrical staging areas and labs, controlled and bonded flight hardware storage, adhesive labs, electrical harnessing labs, and a wide assortment of general purpose and mission specific test equipment. ATK also maintains component-level thermal vacuum chambers and has access to numerous local vibration-only test facilities.

ATK has developed a database of detailed integration procedures from previous programs. This facilitates quick customization of integration processes.

ATK's ATLO approach for the HyspIRI class programs is straight forward with the primary goal of minimizing overall cost and risk while delivering a mission ready spacecraft to the launch site. Upon successful completion of the space vehicle Comprehensive Performance Test (CPT), a Pre Environmental Test Review is conducted. Space vehicle configuration management, both physical (red tag/green tag) and software/firmware configurations shall be confirmed and presented as well. Upon a successful review, the space vehicle and EGSE/MGSE shall be packaged up for transportation to the environmental test facility.

Upon arrival, the space vehicle is unpackaged and the EGSE / MGESE is staged. The EGSE is re-certified and connected to the space vehicle for a post shipment functional test.

Upon a successful functional test, the environmental test program begins. The following flow is a notional example of what a HyspIRI class mission flow typically consists of:

- Modal Survey
- 3 Axis Sinusoidal Vibration Test
- Random Vibration Test
- Separation Shock Test
- Acoustics Testing
- Thermal Vacuum/Thermal Cycling Testing
- EMI/EMC Testing
- RF Compatibility Testing with space/ground segment
- Mass Properties Testing

Upon a successful completion of the environmental test program, a launch site pre-ship CPT is conducted to validate the space vehicle is fully intact and mission qualified. Upon successful completion of the CPT, a Pre-Ship Review is conducted. The results and evaluation of the environmental test program and pre-ship CPT test data are presented for review. Space vehicle configuration management, both physical (red tag/green tag) and software/firmware configurations are again confirmed as well. Upon a successful review, the space vehicle and EGSE/MGSE is packaged for transportation to the launch site facility.

ATK has performed or supported multiple spacecraft launch operations. The EO-1 program was a dual launch configuration with the SAC-C spacecraft and the THEMIS program was the first NASA science constellation consisting of five satellites launched simultaneously. Both programs have relevance to the HyspIRI in regards to launch operations. Of particular note is the planning for fueling.

After the space vehicle and EGSE / MGSE have arrived at VAFB, the space vehicle is unpacked in a clean room. The EGSE is set up and post shipment certification testing is conducted. The AI&T EGSE is integrated to the space vehicle and a post shipment functional check is preformed to demonstrate the vehicle is qualified for flight. The space vehicle is then prepared for fueling.

In parallel to encapsulation operations, launch support EGSE is configured and the interface between the launch vehicle and space vehicle is validated pin for pin.

VAFB support services transports the encapsulated space vehicle to the launch vehicle for "stacking." The final "Red Tag / Green Tag" walk-down of the spacecraft shall be conducted by ATK.

From the mission control facility, ATK initiates power up of the space vehicle and conduct the requisite pre-launch functional test. The battery is verified and fully charged. Upon successful completion of the pre-launch functional test, the data results and the status of the vehicle are presented at the Pre-Launch Readiness Review. This review is to include the readiness status of the launcher as well.

Upon successful completion of the PLRR, the final countdown for launch may commence.

4.1 JPL VSWIR and TIR Instrument Assembly Facility

The VSWIR and TIR instrument including the passive cooler will be fully assembled in a class 10,000 clean room with 2200 sq. ft. of available floor space. A class 1000 laminar flow bench within this clean room facility will be used for the assembly of small optical components. An optical table 4ft by 8ft on vibration isolation mounts inside this facility will be used as the main work space in the assembly process (see Figure 6-1).

This JPL facility was used for the assembly of the complete M3 instrument. The laminar flow bench is ideally suited for the assembly of the HyspIRI VSWIR and TIR spectrometers with all their optics components and focal plane mounts. This facility is dedicated for the integration of small optical instruments and has been in service for over 10 years. All the required procedures and processes are in place including experienced technical personnel to handle and assemble the instrument. This facility requires no modifications to support HyspIRI.

4.2 JPL VSWIR and TIR Instrument Alignment and Calibration

Imaging spectrometer alignment and calibration involves establishing the required alignment of all components including all mirrors, filters, the spectrometer grating and the detector array. Once aligned the full spectral, radiometric, spatial, and uniformity calibration characteristics are determined with respect to NIST traceable and relevance absolute standards (spectral emission lines).

JPL has led alignment and calibration efforts for a series of imaging spectrometers extending back more than a decade including the spacebourne Galileo NIMS and Cassini VIMS instruments and the airborne AIS and AVIRIS instruments. More recently JPL aligned and calibrated the airborne MaRS in 2005 and the space M3 instrument in 2007. JPL also played roles in the alignment and calibration of Hyperion, CRISM and ARTEMIS.

Figure 6-1. JPL clean room assembly facility for small optical instruments

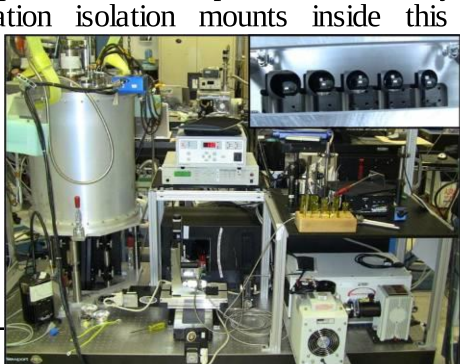


Figure 6-4. JPL Beam Injection Platform for spectral and spatial alignment and calibration.

Figure 6-2 shows JPL alignment and calibration sources used with ARTEMIS. Figure 6-3 shows use of the JPL laser sphere for spectral alignment and calibration. Figure 6-4 shows the Beam Injection Platform (BIP).

In 2011, JPL aligned and calibrated the airborne CAO VSWIR imaging spectrometer. MaRS, M3, and CAO VSWIR are all pushbroom architecture imaging spectrometers of the HyspIRI type. A practiced set of procedures exists for using this suite of alignment and calibration equipment.

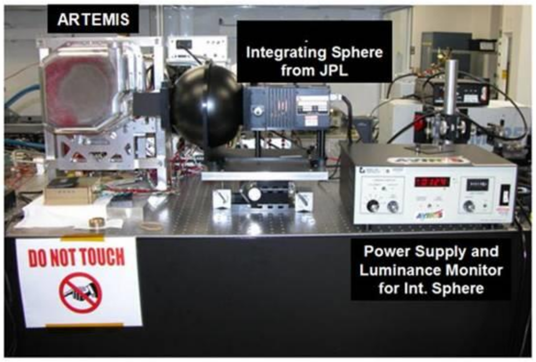


Figure 6-2. JPL calibration sourced used in ARTEMIS calibration

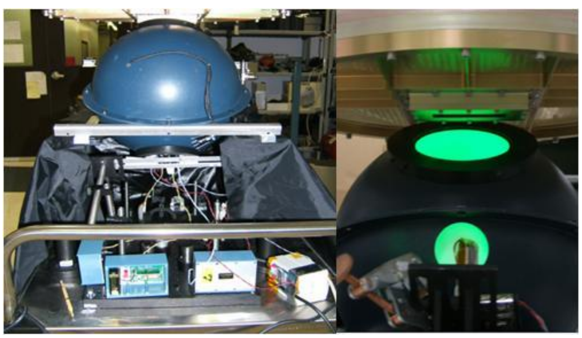


Figure 6-3. JPL eight wavelength laser sphere spectral alignment calibration source.

In addition, TIR will require NIST traceable blackbody sources, a target projector and monochromator for calibration. Existing blackbody calibration systems used on other space missions are available. JPL will build a similar blackbody system for TIR with a slightly larger entrance port. A photo is shown in Figure 6-5. These thermal calibration systems have a long history of being used to calibrate space flight instruments. The blackbodies and target projectors were originally built for the PMIRR and have been used on numerous instruments including PMIRR II, TES, MCS and Diviner.

HyspIRI uses existing spectral, radiometric, spatial, and uniformity alignment and calibration sources and equipment. The spectral response functions, the radiometric range, linearity and SNR, the spatial along-track and cross-track response functions can be determined along with the HyspIRI uniformity properties. The existing procedures and documentation for these sources and support equipment provide further maturity benefit for HyspIRI. HyspIRI benefits broadly form the development of these resources over the past decade and from the understanding for how to best use these elements to meet the alignment and calibration requirements of HyspIRI.

The HyspIRI instrument will be aligned with these existing resources to meet the specified requirements. However the sources, equipment and procedures will be adapted as needed to meet the HyspIRI alignment and calibration requirements. This is approach that has been employed in the previous JPL imaging spectrometer efforts.

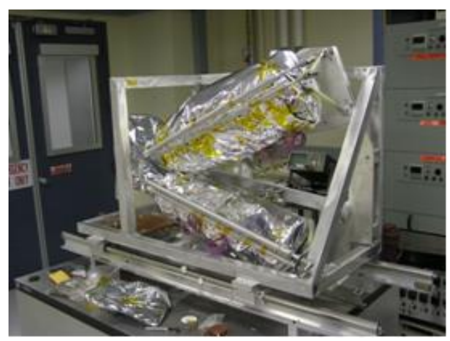


Figure 6-5. Existing thermal calibration equipment. TIR will require one slightly larger but with exactly the same design philosophy.

Table 6-1. Instrument Alignment and Calibration Equipment

Title	Image	Provider	Design	Manufacture	Use	Operating Environment	Prior Use
Alignment + Calibration GSE	 BIP	Full JPL In House Build	Partial Identical parts and basic layout, small changes to detailed layout to suit HyspIRI	Partial Injection mirror and mirror manifold are identical, instrument mounting plate and pupil mount are modified to handle different hardware	Full Identical function as Bi-stimulus injection platform (BIP)	Full Used in the same class 10,000 clean room.	Partial Similar to Bi-stimulus injection platform (BIP) used for airborne imaging spectrometers

4.3 JPL Thermal Vacuum Facility

The VSWIR spectrometer and passive cooler will undergo thermal vacuum testing in a 4-ft diameter vacuum chamber specifically designed for testing optical instruments (Figure 6-5). The chamber facility includes cryogenic cold targets needed for testing passive coolers and standard cold shrouds to simulate cold space. The facility is fully flight certified and it is located in a class 10,000 clean room with 1720 sq. ft. of floor space available. Facility services include GN2 purge gas, continuous LN2 supply and ambient air with relative humidity control.

This JPL facility was used for thermal vacuum and balance testing of the fully assembled M3 instrument with its passive cooler. More recently, the OCO-2 instrument heat rejection system underwent subsystem thermal vacuum and balance testing as part of the flight qualification process.

This facility requires no modifications for HyspIRI. Procedures, processes and thermal test equipment exist and are available for use by HyspIRI. Specialized MGSE for handling the spectrometer and passive cooler will be developed for installing and supporting this hardware inside the vacuum chamber.

Figure 6-5. JPL thermal vacuum chamber facility for small optical instruments

5 Science Algorithms

5.1 Level-1 VSWIR Algorithms

The VSWIR algorithms are based on research extending across 20 years of imaging spectrometer measurements for ecosystem science research. The instruments used include AIS 1982 to 1986, AVIRIS 1986 through present, Hyperion in space 2000 through present and a range of other airborne imaging spectrometers. AVIRIS (in high altitude flight) and Hyperion successfully use the algorithms with effectively the full atmospheric column.

The conversion of the recorded digitized signal to units of measure at sensor radiance for imaging spectrometers extends back to the AIS airborne instrument flown from 1982 to 1987 and through AVIRIS (Green et al., 1998) flown from 1986 to present as well as with Hyperion, CRISM and M3. JPL contributed to the L1B algorithm for Hyperion (Green et al., 2003) and CRISM (Murchie et al., 2007) and led the full L1B algorithm for M3. For AVIRIS, JPL has led the L1B calibration activity from 1986 to present. JPL also developed the baseline L1B algorithm for the MaRS airborne imaging spectrometer. These algorithms basically subtract the dark signal levels and apply the radiometric calibration coefficients and associate the correct spectral, radiometric and uniformity calibration files.

The spectral, radiometric and uniformity calibration files are generated using results from the calibration and validation methodology described in section 6.1. They account for molecular and aerosol scattering as well as transmittance through the eight atmospheric gases that produce observable absorption features in imaging spectrometer data over a range of 400 nm to 2500 nm with a spectral resolution between 1 and 20 nm: water vapor (H_2O), carbon dioxide (CO_2), ozone (O_3), nitrous oxide (N_2O), carbon monoxide (CO), methane (CH_4), oxygen (O_2), and nitrogen dioxide (NO_2).

Orthorectification of the VSWIR measurements is also part of the L1B algorithm. VSWIR Co-I Dr. Joseph Boardman has broad experience with orthorectification of imaging spectrometer data. Boardman's algorithms are used for AVIRIS (Boardman et al., 2007), MaRS and space M3 (Boardman et al., 2011) instrument as well as for the ARTEMIS imaging spectrometer. The orthorectification algorithm established the latitude longitude and elevation for each spectrum measured. This is calculated based upon the position and pointing of the imaging spectrometer in conjunction with the camera model of the instrument and an appropriately accurate surface DEM.

The basic L1B algorithms for VSWIR will be derived directly from the calibration algorithms of these precursor imaging spectrometers. The L1B algorithm will be adapted for the wider swath of VSWIR and adapted to take advantage of the parallel nature of the VSWIR cross-track measurements. The principle adaptation of the existing algorithms will be to: update the spectral, radiometric, spatial, uniformity and camera model calibration files to those required for HyspIRI's VSWIR and to format the algorithms to run in a parallel computing mode.

5.2 Level-1B TIR Algorithm

Algorithms for the conversion of Digital Number (DN) to sensor radiance have already been well established for thermal infrared imagers such as ASTER (Fujisada 1998) and MODIS (Xiong et al. 2005) and airborne instruments such as MASTER and TIMS. HyspIRI will derive it's algorithm heritage primarily from the ASTER L1B algorithm (Fujisada 1998), in which DN values are scaled to radiance values by applying the appropriate radiometric calibration and geometric correction coefficients.

The L1B data generated for HyspIRI will be the thermal infrared geolocated radiance at sensor. The data will not be orthorectified in that we will know the latitude and longitude for any given pixel, but the image pixels will be resampled to be on a defined grid and of equal size. The L0 through L2 products will be treated as standard products (i.e., produced for all scenes), whereas the L3 and above products will be considered as special products, i.e., produced for a limited time or region. The L0 through L2 data will be produced at the Science Data System and will be stored at a Distributed Active Archive Center (DAAC). The Science Data System will be developed later in the project.

The L1B data will be stored, along with the Metadata in separate SDS, Vgroup, and Swath layout in one HDF file, and will follow closely the ASTER L1 data structure format with some modifications (Fujisada 1998). For example, the L1B algorithm will be adapted for the wider swath of the TIR data and adapted to take advantage of the parallel nature of the TIR cross-track measurements.

5.3 Level-2 VSWIR Surface Reflectance Algorithm

The L2 algorithm of VSWIR is the correction of the L1B at sensor radiance to the surface reflectance. VSWIR Co-I Dr. Bo-Cai Gao developed the ATREM atmosphere correction algorithm (Gao et al., 1993, 2004, 2009). This algorithm has been used for AVIRIS, Hyperion and the HICO imaging spectrometers. An optically thick cloud screening algorithm is also part of VSWIR L2 (Griggin et al., 2003, Hartzell et al., 2009). Over the past 10 years with Hyperion these algorithms have been broadly applied and validated with respect to data sets acquired over a range of surface, atmospheric and latitude conditions.

The ATREM algorithm and optically thick cloud screening algorithm have been developed and implemented for the spaceborne Hyperion and HICO imaging spectrometers. These existing algorithms for space imaging spectrometer L2 data products are directly applicable to the VSWIR requirements for atmospheric correction and optically thick cloud screening.

These algorithms will be directly adapted to meet the L2 VSWIR requirements. Modification will be made to implement these algorithms in parallel for the VSWIR mission. These adapted algorithms will accept the appropriate spectral, radiometric, spatial and orthorectification parameters required for processing of VSWIR measurements.

5.4 Level-2 TIR Surface Radiance Algorithm

The thermal infrared (TIR) radiance at sensor measured by the HyspIRI TIR instrument will include atmospheric emission, scattering, and absorption by the Earth's atmosphere. These atmospheric effects need to be removed from the observation in order to isolate the land-leaving surface radiance contribution. The atmospheric correction approach planned for HyspIRI is based on the

ASTER algorithm which uses a Radiative Transfer (RT) approach to account for atmospheric effects (Palluconi et al. 1999). Additionally, a more advanced Water Vapor Scaling (WVS) method will be used to improve the accuracy of the atmospheric correction under more difficult humid conditions (Tonooka 2001, Tonooka 2005).

The physical-based RT approach was chosen over the more traditional split-window SW) correction approach for HyspIRI for three primary reasons: 1) The HyspIRI TIR bands 3–8 have been placed in the clearest regions of the atmospheric window; 2) the emissivity of the land surface is in general heterogeneous and is dependent on many factors, including surface soil moisture, vegetation cover changes, and surface compositional changes; and 3) split-window algorithms are inherently very sensitive to measurement noise between bands. The most important benefit of using a RT approach is that the surface spectral emissivity can be dynamically retrieved simultaneously with the surface temperature for all bands.

The surface radiance algorithm will be directly adapted to meet the L2 TIR product requirements. Modifications will be made depending on the availability of atmospheric profile data during the course of the HyspIRI mission, and also with regard to the most updated version of the MODTRAN RT model. Improvements made to the WVS algorithm will also be incorporated.

5.5 Level-2 Land Surface Temperature and Emissivity (LST&E) Algorithm

The two primary Level-2 products that will be generated by the HyspIRI TIR surface radiance product are the land surface temperature and emissivity (LST&E). The Earth emits energy at thermal wavelengths we cannot normally see, and that energy is a function of the LST&E of the surface. The LST&E products will be generated from the six HyspIRI spectral bands between 8 and 12 µm (Bands 2-6). For the 6 HyspIRI TIR bands between 8 and 12 µm there will be 6 measurements and 7 unknowns (6 band emissivities and 1 temperature) resulting in a non-deterministic solution. Various approaches have been proposed to solve this ill-posed problem, one being the Temperature Emissivity Separation (TES) algorithm currently used by ASTER (Gillespie et al. 1998). Because HyspIRI and ASTER will have very similar instrument characteristics, and band placements, the TES algorithm will be adapted for use with HyspIRI data.

An additional constraint is needed to An additional constraint is needed to separate temperature and emissivity from the observed thermal infrared radiance signal, independent of the data itself. There have been numerous theories and approaches over the past two decades to solve for this extra degree of freedom. For example, the ASTER TES Working Group (TEWG) analyzed ten different algorithms for solving the problem (Gillespie et al. 1999). Most of these relied on a RT model to correct at-sensor radiance to surface radiance and an emissivity model to separate temperature and emissivity. Other approaches include the SW algorithm which uses the differential absorption of water vapor between two nearby longwave TIR bands. However, using the SW algorithm leads to unreasonably large errors over barren regions where emissivities have large variations both spatially and spectrally (Hulley and Hook 2009). The ASTER TES algorithm was chosen for HyspIRI since it has the ability to dynamically retrieve spectral emissivity and surface temperature, and capitalizes on the strengths of previous algorithms with additional features (Gillespie et al. 1998).

The TES algorithm will meet the L2 requirements for generating spectral emissivity and surface temperature for HyspIRI TIR bands with an accuracy of 1 K. Analysis of atmospheric effects, a quality assurance and diagnostics assessment, and sensitivity analysis simulations still need to be performed pre-launch in order to fully characterize uncertainties associated with the TES algorithm. Validation strategies of the TIR products have already been fully developed and are based on methods used by ASTER, and also MODIS.

6 Calibration and Validation

6.1 VSWIR

Operational calibration and validation (cal/val) of the VSWIR level 1 data is performed with data taken over dry lake beds by the on-orbit instrument, in-situ sensors and an airborne sensor such as AVIRIS. The exact same methodology was used to calibrate and validate Hyperion with data taken over the Salar de Arizaro in Argentina (Green et al. 2003, Green et al. 1997). For HyspIRI, a single excursion to a California dry lake bed during the check-out phase of operations will be sufficient.

In-situ measurements are made of the cal target, a uniform area of the dry lake bed. Measurements are made of surface spectral reflectance (using a Full Range Spectrometer like that provided by Analytical Spectral Devices), and a carefully leveled reflectance standard (using a Spectralon like that provided by Labsphere Inc.). These two measurements are used to calculate the average spectral reflectance of the calibration target (with compensation for the bidirectional reflectance distribution function of the Spectralon standard at the illumination zenith angle at the time of the VSWIR overpass).

Solar intensity is also measured at the cal target, measured from local sunrise to local noon using a ten channel tracking solar radiometer like that offered by University of Arizona (the "Reagan Instrument"). These measurements are used with the Langley Method (Reagan et al, 1987) to derive instantaneous atmospheric optical depths. The 940 nm channel is used with a modified Langley Algorithm to calculate the total column water vapor.

The spectral reflectance, atmospheric optical depth and total column water vapor are used with MODTRAN to model the upwelling radiance incident at VSWIR (Anderson et al. 1995, Berk et al. 1989). This is compared to the measured radiance by VSWIR and is one of the six cal/val results used to calibrate the Level 1 data.

Airborne measurements of the cal target are taken by a sensor like AVIRIS. These are propagated to the top of the atmosphere (top of atmosphere (TOA) radiance) using spectral upward transmittance of the atmosphere along with path scattered radiance of the atmosphere (both calculated with MODTRAN). The close but not identical acquisition times between AVIRIS and VSWIR are accounted for using a ratio of the cosine of the two solar zenith angles. The AVIRIS TOA radiance is compared with the VSWIR measured radiance and this is the second of the six cal/val results used to calibrate the Level 1 data.

Radiometric precision is determined in two parts: dark signal and bright signal.

Dark signal radiometric precision is determined by measuring the noise equivalent delta leaving radiance (NEdL), which is the standard deviation across each cross-track sample when looking at the closed calibration cover. Because of the effects of photon noise, NEdL increases as signal increases, so this method cannot be used for determining bright signal radiometric precision. This is the third of the six cal/val results used to calibrate the Level 1 data.

Bright signal radiometric precision is determined as the ratio of the average over the standard deviation for the most homogeneous area of the cal target (an 11 x 11 sample region looking at 642-672 nm was used for Hyperion). This ratio is an estimate of the SNR for a bright target. This is the fourth of the six cal/val results used to calibrate the Level 1 data.

Cross track radiometric response is assessed by forming the ratio of the airborne to the VSWIR data and seeing if the variation is within the uncertainty of the registration. The airborne and VSWIR datasets are first registered using ground control points. Airborne data is scaled relative to the changing solar zenith angle over the duration of the flight's transect across the entire VSWIR swath. The results of this exercise are the fifth of the six cal/val results used to calibrate the Level 1 data.

The spectral calibration is determined by examining the absorption at 760 nm (oxygen absorption), 1140 nm (water absorption) and 2010 nm (carbon dioxide absorption) and comparing this to a MODTRAN modeled radiance using VSWIR's calibration parameters, which were determined in the laboratory as the central wavelength position and full width half maximum (FWHM) for an equivalent Gaussian spectral response function. This is possible because in the vicinity of the strong atmospheric absorption features, the shape of the radiance spectrum is sensitive to the position and the FWHM. This sensitivity has been successfully used to investigate and derive the operational spectral calibration of AVIRIS and Hyperion (Conel et al, 1988, Goetz et al. 1995, Green and Pavri 2002). The results of this exercise are the sixth and final cal/val result used to calibrate the Level 1 data.

The average spectral reflectance calculated from the in-situ measurements of surface spectral reflectance and the carefully leveled reflectance standard is compared with the Level 2 surface reflectance product. The results of this comparison are used to cal/val the data.

6.2 TIR

In-flight cal/val are essential for maintaining accuracy and precision of the instrument. The two most common types of cal/val methods are ground-based (in-situ) and aircraft-based. In ground-based cal/val, the surface radiance is measured by a ground-based radiometer, and the at-sensor radiance is forward modeled by estimating the atmospheric effects using atmospheric profiles with a radiative transfer model. The predicted at-sensor radiance is then compared to the observed radiance. For the aircraft-based method, data from an airborne sensor are acquired simultaneously with a satellite overpass, and a radiative transfer model is used to propagate this radiance to predict the at-satellite radiance. The aircraft measurements need to be well calibrated in order for this method to be successful. It is expected that cal/val of HyspIRI TIR Level 1 and 2 data will involve a combination of these two “vicarious” calibration methods. The validation of the atmospheric correction method is closely tied to the calibration of the instrument, since correction for atmospheric effects needs to be performed before at-surface radiance measurements can be compared to those at sensor.

In-situ data from a variety of ground sites covering the majority of different land cover types defined in the International Geosphere-Biosphere Programme (IGBP) will be used for validation. The sites will consist of water, vegetation (forest, grassland, savanna, and crops), and barren areas. The primary calval site will be Lake Tahoe in California/Nevada, an automated validation site where measurements of skin temperature have been made every two minutes since 1999 and are used to validate the mid and thermal infrared data and products from ASTER and MODIS (Hook et al. 2007). Water targets are ideal for calval activities because they are thermally homogeneous and the emissivity is generally well known. Further advantages of Tahoe are that the lake is located at high altitude, which minimizes atmospheric correction errors, and it is large enough to validate sensors from pixel ranges of tens of meters to several kilometers.

The LST product from ASTER has been validated using in situ data from dedicated field campaigns over lakes, agricultural lands and playas (Coll et al. 2005, Hook et al. 2007, Tonooka and Palluconi 2005), while fewer studies have attempted to validate the surface emissivity product (Hulley et al. 2009, Schmugge et al. 2003, Schmugge and Ogawa 2006). The ASTER LST product is currently being validated at the Lake Tahoe cal/val facility that has been providing continuous, well-calibrated measurements since 2000, and will continue to provide data through the HyspIRI mission. Currently, the most comprehensive emissivity validation of the ASTER product was performed in validating the North American ASTER Land Surface Database (NAALSED) v2.0 emissivity product (Hulley et al. 2009). NAALSED was validated over arid/semi-arid regions using nine pseudo-invariant sand dune sites in the western/southwestern USA.

Validation of emissivity data from space ideally requires a site that is homogeneous in emissivity at the scale of the imagery, allowing several image pixels to be validated over the target site. Typically sand samples are collected at each site, and the directional hemispherical reflectance of the samples is then measured in the lab at Jet Propulsion Laboratory (JPL) using a Nicolet 520 Fourier transform infrared (FT-IR) spectrometer at 4 cm^{-1} spectral resolution from 2.5-15 µm. The reflectance is then converted to emissivity using Kirchhoff's law. The uncertainty associated with the FT-IR lab emissivities is 0.002 (0.2 %) (Korb et al. 1999). Uncertainties in validation for HyspIRI will be small due to its high spatial resolution of 60 m, making it unique amongst other spaceborne sensors that provide emissivity products at much coarser spatial resolutions, such as MODIS (1 km). The nine established pseudo-invariant sand dune validation sites chosen for the ASTER study and planned for use with HysPIRI are: Great Sands National Park, Colorado; White Sands National Monument, New Mexico; Kelso Dunes, California; Algodones Dunes, California; Stovepipe Wells Dunes, California; Coral Pink Sand Dunes, Utah; Little Sahara Dunes, Utah; Killpecker Dunes, Wyoming; and Moses Lake Basalt Dunes, Washington.

Two methods have been established for the validation of LST data; a Temperature-based (T-based) and Radiance-based (R-based) method. For both methods, uncertainties not exceeding 1 K are generally considered good enough for validation studies. In the T-based method, radiometers are typically positioned a few meters above the surface being observed to measure the land leaving radiance, which is then corrected for emissivity effects and reflected sky radiation to obtain the LST. In the R-based method (Wan and Li 2008), accurate surface emissivity data are combined with atmospheric profiles in a radiative transfer model to simulate the TOA brightness temperatures (BT) in a clear window region of the atmosphere. An estimate of the true LST is then obtained by varying the input retrieved LST value until the calculated TOA BTs match the observed BT from the sensor.

We plan to use in-situ LST data from a variety of ground sites covering the majority of different land cover types defined in the International Geosphere-Biosphere Programme (IGBP). The sites will consist of water, vegetation (forest, grassland, and crops), and barren areas. In situ data from Lake Tahoe and Salton Sea cal/val site will be used for water surfaces (Hook et al. 2007); a combination of data from the Surface Radiation Budget Network (SURFRAD), FLUXNET, and NOAA-CRN sites will be used over vegetated areas, and over the pseudo-invariant sites a radiance-based LST method will be used in conjuction with the lab-measured sand samples (Wan and Li 2008).