HYTI mission: Raw thermal instrument on-orbit data processing with SpaceCloud

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ABSTRACT

The HyTI (Hyperspectral Thermal Imager) mission, funded by NASA's Earth Science Technology Office InVEST (In-Space Validation of Earth Science Technologies) program, is the first US science satellite to leverage heterogenous SpaceCloud hardware with CPU and GPU acceleration. The mission will demonstrate how high spectral and spatial long-wave infrared image data can be acquired from a 6U CubeSat platform and perform advanced on-orbit real-time data processing and creating L1 and L2 products. The mission will use a spatially modulated interferometric imaging technique to produce spectro-radiometrically calibrated image cubes, with 25 channels between 8-10.7 µm, at 13 cm-1resolution) at a ground sample distance of ~60 m. The small form factor of HyTI is made possible via a no-moving-parts Fabry-Perot interferometer and JPL's cryogenically cooled HOT-BIRD FPA technology. The value of HyTI to Earth scientists will be demonstrated via on-board processing of the raw instrument data to generate L1 and L2 products, with a focus on rapid delivery of data regarding volcanic degassing, land surface temperature, and precision agriculture metrics. This presentation will provide an overview of the HyTI measurement approach, the onboard data reduction approach, and the spacecraft design. We will also update HyTI integration, testing, and future mission concepts based on the SpaceCloud Framework containerization of mission management and data applications.

1 INTRODUCTION

HyTI addresses the need for high spectral and spatial resolution long-wave infrared image data to quantify the chemical composition and temperature of the Earth's solid surface, oceans, and atmosphere [1]. Many critical phenomena, including evapotranspiration, volcanic degassing, and urban heat pollution, rely on such data, and repetitive, global-scale measurements are needed to quantify the critical physicochemical processes. Scientists increasingly require these data to be made available with low latency to allow their use in an operational capacity. Such data are currently unavailable to Earth scientists, with sensors such as Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) nearing the end of their life and planned Landsat mission offering most bi-spectral measurements in the longwave infrared (LWIR).

Scientists have been studying the long-wave infrared (LWIR) thermal properties of Earth's surface since the Landsat 4 Thematic Mapper launch. The studies have included atmosphere and water bodies at high-to-moderate resolution. They have been limited to making measurements at a 60-120 m ground sample (e.g., Landsat TM, ETM+) in no more than five spectral bands (e.g., Terra ASTER). This barely scratches the surface of the potential that the LWIR region of the spectrum has for quantifying Earth system processes. Operational acquisition of high spatial and spectral resolution

LWIR data from Earth orbit will allow mapping the chemistry of rocks and minerals exposed to Earth's surface [3], the composition of volcanic gas and ash plumes [4], and quantifying soil moisture content and evapotranspiration [5]. The recently published Earth Science Decadal Survey (ESDS) [6] explicitly identifies the provision of high spatial and either multi- or hyperspectral thermal infrared data as a candidate measurement approach for achieving the Surface Biology and Geology Targeted Observable and suggests that small satellites, e.g., CubeSat, constellations and alternative mission architectures be explored to provide, or complement, these critical data.

The amount of data generated by the LWIR sensor can easily overwhelm the communication link to the earth, and the data can be acquired over cloudy areas. To increase the scientific return, the HyTI mission is leveraging onboard heterogeneous computing using central processing units (CPU) and graphical processing units (GPU) to generate L1 and L2 products, significantly reducing the amount of data to be downlinked. The architecture can also allow cloud detection and removal to further optimize data management. The HyTI mission is supportive of the ESDS recommendation, as it will demonstrate how recent innovations in LWIR imaging technologies can be combined to provide high spatial and spectral resolution LWIR image data from a small 6U CubeSat platform.

2 THE HyTI MISSION OVERVIEW

The HyTI mission is led by the University of Hawaii and will study Earth in the LWIR frequencies using a novel, no-moving-parts hyperspectral imager developed initially using funding from DARPA and NASA. Light from the scene is focused by a refractive lens and passed through a Fabry-Perot interferometer mounted directly above the focal plane array within the integrated dewar cooler assembly (IDCA). The small form factor of HyTI is made possible via the use of a no-moving-parts Fabry-Perot interferometer and JPL's cryogenically-cooled barrier infrared detector (BIRD) focal plane array (FPA) technology [2]. The forward motion of the platform allows interferograms of targets on the ground to be reconstructed, as each ground target is imaged at a succession of optical path differences as the fixed interference pattern is pushed along the ground in the in-track flight direction. The images are co-registered in orbit and followed by standard Fourier Transform techniques to produce a spectro-radiometrically calibrated image cube.

The ratio of the cut-off frequency gives the spectral resolution of an interferometer to the number of samples in a single-sided interferogram, and the fringe periodicity (number of samples) of HyTI is proportional to the design slope of the air-gap (although system f-number provides an ultimate constraint on the spectral resolution achievable with this design. The HYTI focal plane array (FPA) will be maintained at a temperature of 68 K. The AIM-Creare SF070 Cryocooler System directly enables these key technologies. The integration of a cryocooler into a 6U CubeSat bus has been a significant technical development in volume integration, power consumption, and exported vibration mitigation; the experience of the integration of a cryogenically cooled detector is now demonstrated with the HyTI bus [7]. The spectral sensitivity is 8-10.7 μm, assuming a worst-case quantum efficiency of 10%. For HyTI, an FPA of 640 × 512 elements will be used. From an assumed orbital altitude of ~400 km (i.e., ISS orbit the design ground sample distance of HyTI will be ~60 m. 25 spectral samples between 8-10.7 μm will be acquired (spectral resolution of 13 cm-1). Our performance model (Fig. 2) indicates that NEΔTs of <0.2 K are attainable (at this spectral resolution) for source temperatures in the range of 0-50 ºC. Calibration will be via intermittent deep-space looks (to calculate radiometric offsets) with pre-launch look-up tables of gain vs. FPA temperature vs. integration time. Validation will use periodic Lunar scans and vicarious calibration using Landsat and ASTER images.

HyTI is a technology demonstration, not a science mission. Nevertheless, a mission must be defined to demonstrate the applicability of HyTI's innovative technologies to making Earth science measurements [8]. The science focus of HyTI is a derivation of Landsat Surface Temperature (LST), volcanic sulfur dioxide emissions, and precision agriculture metrics. An illustration of the HYTI satellite is shown in Figure 2-1.

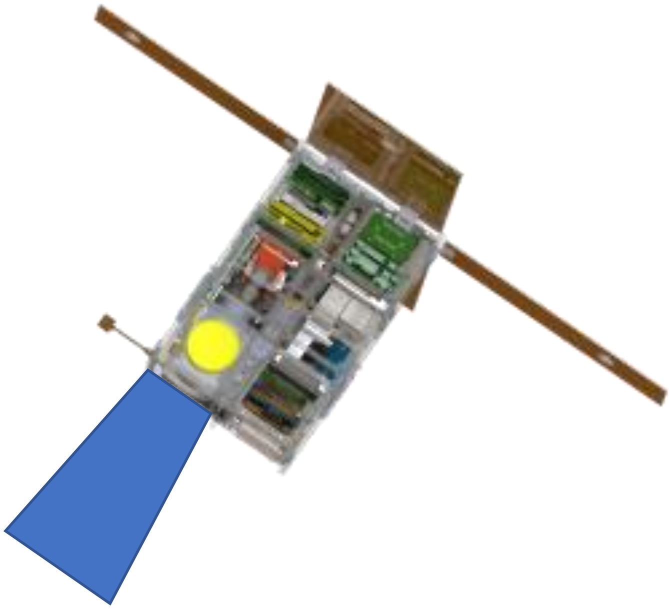

Figure 2-1. Rendering of the HyTI spacecraft and sensor acquisition.

Onboard processing raw sensor frames to the final Level 1 calibrated radiance cubes is achieved with a ×10 reduction in data volumes even before lossless (3:1) compression. This is achieved by onboard processing from L0 to L1 (i.e., frame-to-frame co-registration, FFT, and spectral calibration) using the SpaceCloud iX5-100 heterogeneous computing platform.
The SpaceCloud iX5-100 analytics computer incorporates edge computing, storage, and cloud software at a weight of approximately 600 grams, dimensions of 100 x 100 x 50 mm3, and up to 20 W of power at load. The HYTI software can use CPU, GPU, and FPGA resources together with 256 GB of solid-state storage. The iX5-100 compute resources are provided by AMD 64-bit system-on-chip CPU and GPU and Microsemi FPGA.

Ground-based benchmarking on the flight processing unit indicates that using the GPU capabilities, the data can be processed from L0 to L1 in real-time (i.e., 1 sec of L0 camera data at 139 Hz can be processed to its L1 equivalent). L2 processing will also be done onboard. We will derive volcanic sulfur dioxide concentrations and LST onboard using a Partial Least Squares Regression-based technique to allow us to convert L1 (radiance) to L2 (SO_2, in ppm.m; LST in K) using ~150 operations per pixel (rather than performing a full radiative transfer inversion).

HyTI will be launched to orbit via the NASA CubeSat Launch Initiative. The 6U CubeSat is planned for deployment from the ISS into a 51.6° ~400 km orbit. The baseline mission includes a 3-month mission life with a possible extension to a 1-year goal. The Hawaii Space Flight Laboratory at the University of Hawaiʻi at Mānoa is the lead system integrator. JPL is Co-Prime, primarily responsible for the enabling focal plane array (FPA) technology. West Coast Solutions is the lead on the Cryocooler System Engineering; AIM provides the Cryocooler Thermo Mechanical Unit (TMU), and Creare/WCS provides the Cryocooler Control Electronics (CCE), including an Input Ripple Filter to reduce extreme currents oscillations on the spacecraft bus. HyTI will use a 6U bus with subsystems provided by Innovative Solutions In Space (ISISpace), CubeSpace, Syrlinks, and other space-qualified components vendors for CubeSats. Fig. 2-1 shows a conceptual rendering of the HyTI spacecraft with the spacecraft configuration shown in Figs. 2-2 and 2-3. The payload uses 3.5U of the 6U available, which includes the IDCA (provided by American Infrared Solutions; https://www.go-airs.com/), the cryocooler (AIM SF070; https://www.aim-ir.com), the multielement refractive lens (provided by New England Optical Systems; http://www.neos-inc.com/), and the payload onboard computer (Unibap SpaceCloud iX5-100 (DD-iX5); https://unibap.com/). The Fabry-Perot interferometer is provided by LightMachinery (https://lightmachinery.com/). Payload data downlink will be via a Syrlinks X-band. (S-band redundant) with S-band up (S-band redundant.

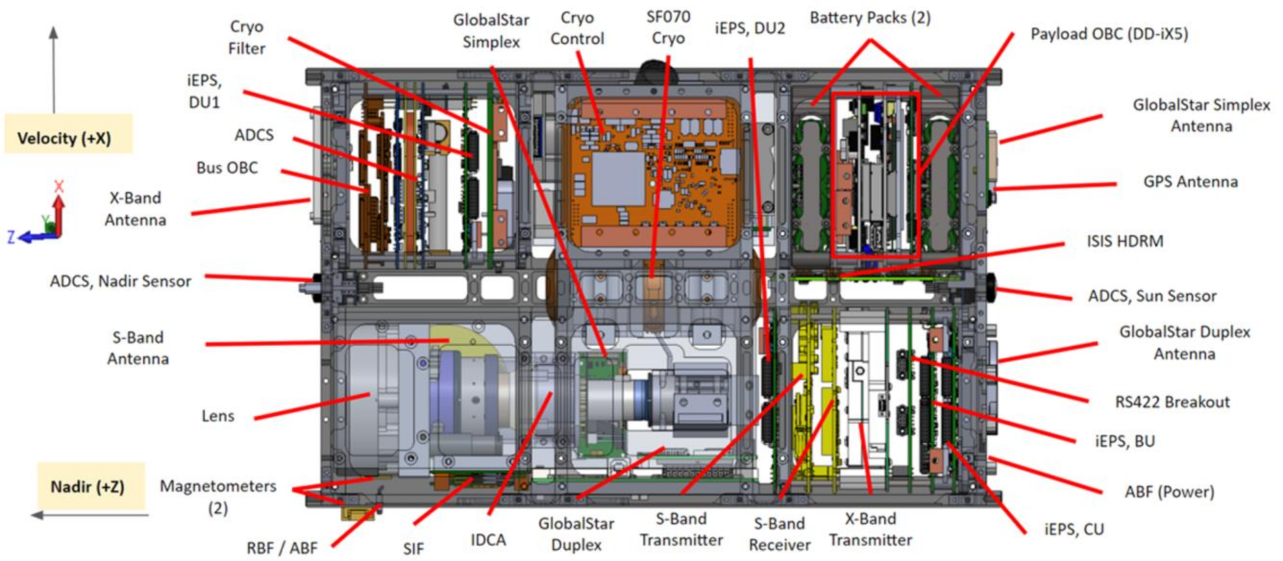

Figure 2-2. HyTI configuration. -Y face.

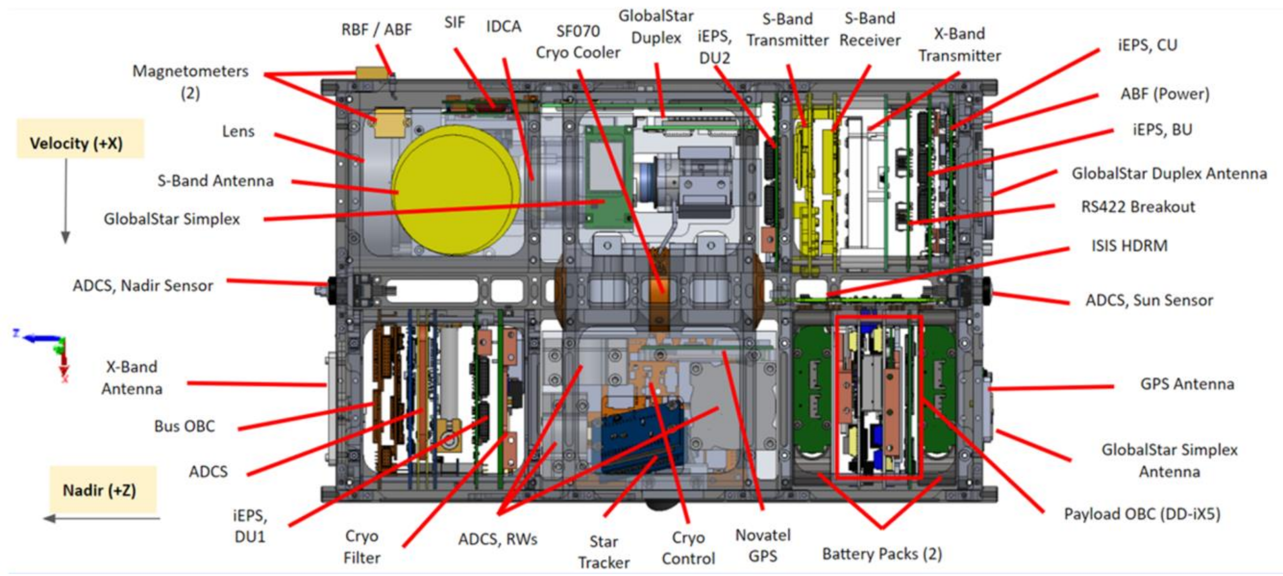

Figure 2-3. HyTI configuration. +Y face.

Figure 2-4 shows a photograph of the SpaceCloud iX5-100 cloud computing solution with a sample flight chassis.

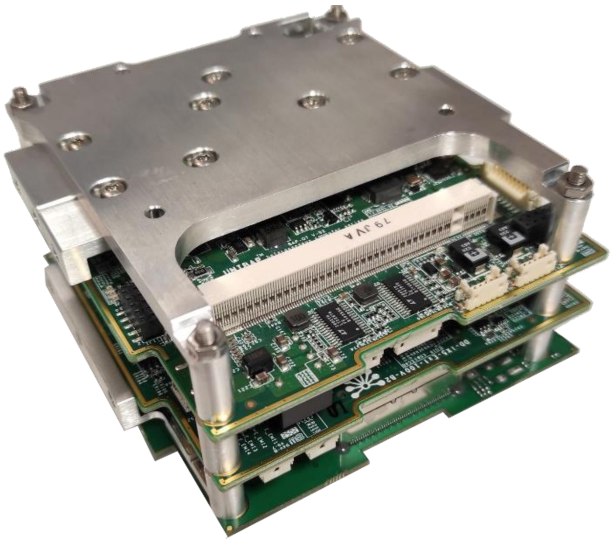

Figure 2-4. Photograph of SpaceCloud iX5-100 radiation-tolerant cloud computing solution.

3 HyTI DATA ACQUISITION AND PROCESSING

The nature of the HyTI data acquisition system requires a complex interaction between software processes and the payload hardware, requiring a large amount of data collection and a significant amount of processing. For a typical data take (typically up to 10 min), it is necessary to:

- Prepare the spacecraft sufficiently in advance at an appropriate LVLH (Local Vertical, Local Horizontal) attitude to be ready for imaging operations
- Prepare the instrument for image acquisition by cooling the FPA with the SF070 cryocooler. This needs to be done approximately 10 minutes before the FPA is set at the target temperature for imaging operations.
- Maintain the cryocooler at the target temperature during image acquisition, start the camera for image acquisition, monitor the system, and cease operations to protect the detector if an anomaly is detected.
- Measure the temperature of the lensing system and set the appropriate motorized focus position
- Maintain the spacecraft at the appropriate LVLH attitude and keep it under the attitude drift requirements, make position and attitude information available to the data acquisition process.
- Collect 28 GB of data at a rate of 46 MB/sec and store this data for later processing, or process it in real-time, while acquiring data.
- Collect and embed all relevant telemetry as part of the data stream.

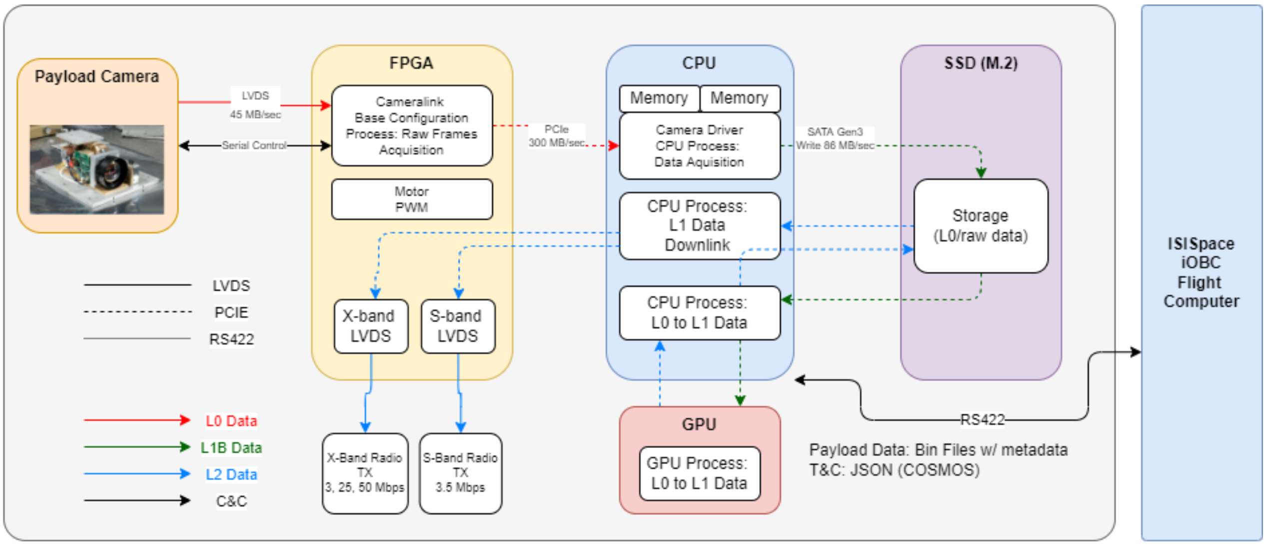

Figure 3-1. HyTI Data Processing Flow Diagram on Unibap iX5

The complexity and intensity of this process make full use of a combination of system and user-level multi-threaded programs, working in concert. The hardware is fully exercised, simultaneously working multiple CPU cores, GPU cores, and Digital I/O, LVDS lines, Serial, I2C, and PCI Express interfaces. This level of interaction and multi-tasking would not be possible without using a fully implemented Linux system. Figure 3-1 shows the data flow from the payload camera to the FPGA, to the CPU, SSD storage, and into the radios for data downlink.

The basic process to acquire an image cube consists of:

- A system-level thread that controls the Cryocooler, accepting commands for operation and providing state of health information
- A system-level thread that holds cryo power, accepts commands for operation, and providing state information
- A system-level thread that controls the Attitude Determination and Control System (ADCS), accepting commands for operation and providing state information
- A system-level thread that controls Commanding, accepting requests for immediate or queued processing
- A system-level thread that controls Communications, accepts incoming requests, and performs outgoing file transfers
- A user process commands the camera, acquiring frames that are then interpolated both spatially and interferometrically. These data can either be written to disk for later processing or sent directly to a data reduction process. This process is also responsible for controlling power to the focus system and the camera and collecting information from the ADCS and the Cryocooler. This is achieved through inter-process communication with their relevant threads.
- A user process reduces the data, first converting from interferogram space to spectral space and then performing intensity calibrations. This process makes extensive use of calculations on both the CPU and GPU cores.
- A user process that queues any desired files for transfer to the ground using the Communications thread

The complex, multi-featured nature of the Unibap makes it particularly suited to process the hyperspectral image cubes. The FPGA is matched for high-speed interfaces such as the Camera Link. However, access to this link would have been challenging without the straightforward use of existing video libraries in the Unix kernel that allowed this data to be captured like any standard video stream. High-speed control of the S-Band and X-Band radios was also implemented through the FPGA, with access being made transparent through Linux kernel devices. The FPGA also controls the PWM controller for the focus motor and the Hall Effect sensor to report the lens position. Access to these functions is available through the Linux kernel on the iX5.

Using the HSFL Middleware "Comprehensive Open-architecture Solution for Mission Operations Systems (COSMOS)" software suite, allows to tie together this low-level hardware access with the higher-level processes and threads described above. Serial, I2C, and Digital device libraries provided by COSMOS allowed us to embed control of these various pieces of hardware. In contrast, COSMOS's higher-level inter-process communications features permitted the sharing of telemetry and commands between the different programs [9-11]. The onboard processing flow to process the data cubes is summarized in the steps defined in Table 1:

Table 1. Data processing steps on HYTI

Data Processing Steps	**Algorithm Steps**
Step 1. L0 data acquisition and pre-processing (CPU)	● L0 data from IDCA to CameraLink to RAM ● Dark subtraction ● Replace bad pixels ● 2 Bytes × 320 columns × 512 rows × 139 frames/s ● Resulting data volume is ~93 GiB/day
Step 2. Co-register L0 frames, recover interference record, store result (CPU)	● RAM to disk ● Reorder data into interferometrically stacked HyTI Image Tiles (HITs) of coregistered data, resampled to 60 m postings ● 2 bytes × 320 columns × 667 rows × 512 planes per HIT ● Resulting data volume is ~86 GiB/day
Step 3. Generate interferogram and transform (GPU)	● Disk to RAM ● Generate interferogram for each pixel ○ Cubic spline interpolation ○ Zero mean subtraction ○ Triangular apodization ○ Discrete cosine transform ● 2 bytes × 320 columns × 667 rows × 25 spectral channels per HIT
Step 4. Radiometric calibration (GPU)	● RAM to disk ● Multiply and add each spectrum by column specific transfer function ● 2 bytes × 320 columns × 667 rows × 25 spectral channels per HIT
Step 5. L1 storage (CPU)	● Store HITs for subsequent downlink ● ~4.2GiB per day
Step 6. Downlink (CPU)	● Downlink accumulated tiles ● ~1.7 GiB per day (2.5:1 lossless compression)

Using a combination of CPU and GPU, the full processing stack has been implemented for a simulated 7-minute data set. Using the steps described above implemented in the iX5 heterogeneous compute architecture HSFL have been able to process the data reliably in under 7 minutes using only CPU and GPU capabilities. The authors are therefore confident in ascribing a 1:1 ratio to the data collection and processing event. A good replication of both spatial and spectral features have been achieved. In addition, there is a significant amount of cross-track motion that is properly handled.

4 CURRENT STATUS

HyTI is scheduled for delivery in the Summer of 2022, for launch to the ISS, via the CubeSat Launch Initiative, in the fall of 2022 or the first quarter of 2023. Currently, the flight hardware is integrated into the spacecraft bus configuration with the engineering model camera. The HSFL team is running system checkouts and software development to prepare for integrating the flight model camera (Fig. 4-1).

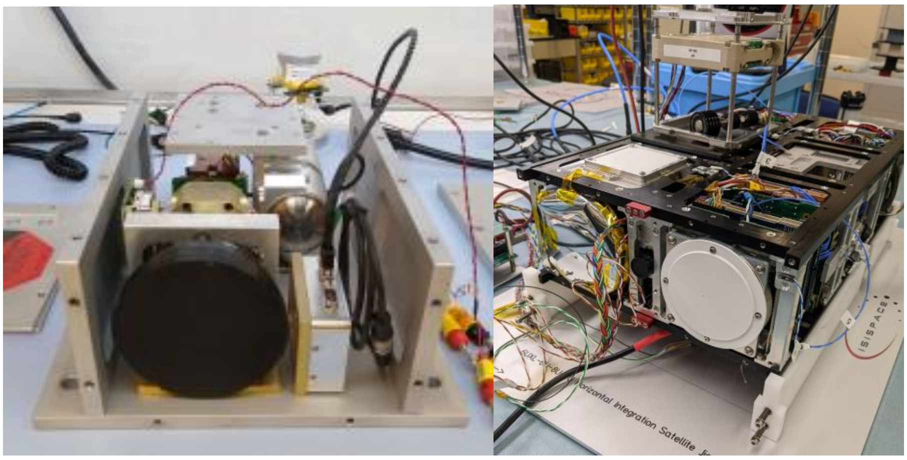

Figure 4-1. Top: HyTI payload. Bottom: HyTI Flat Sat

5 PREPARING FOR CLOUD COMPUTING AND SOFTWARE REUSE

SpaceCloud framework is riding on top of a tailored Ubuntu Linux distribution. Hence, most x86-64 “PC” compatible software may be used. Figure 3-1 illustrates the SpaceCloud software stack with standard Linux compatible libraries and specific ones. An example of a particular software package is L3Harris Geospatial’s ENVI®/IDL® geospatial software suite. This is not always available, but it was included for demonstration on the D-Orbit Wild Ride SCV-003 mission [12]. The processes described in section 3 will be converted into a containerized package with the SpaceCloud framework. The process will involve the exchange of raw frames from the Camera link driver converting L0 data and the production of compressed data files, the resulting output of the containerized process with L1 data. Other containers can then utilize the L1 data and process it into L2 data according to the mission needs; an relevant example will be SaraniaSat’s weak signal detection algorithms to demonstrate the derivation of L2 products onboard HyTI and low latency delivery of those products to stakeholders. Using the Partial Least Squares Regression-based technique another container will implement the derivation of volcanic sulphur dioxide concentrations. Once the L2 data files are exported to disk, any other process can transfer the files to the radios or another flight computer, depending on the mission needs.

The processing steps in Table 1 can be reconstructed into orchestratable SpaceCloud applications for simple reusability. This is also the case of the COSMOS framework which can be run a separate SpaceCloud container. If this software packaging change is performed, the same software containers can be run on other SpaceCloud framework compatible satellites, such as D-Orbit ION SCV-003 launched in June 2021 and ION SCV-004 launched in January 2022.

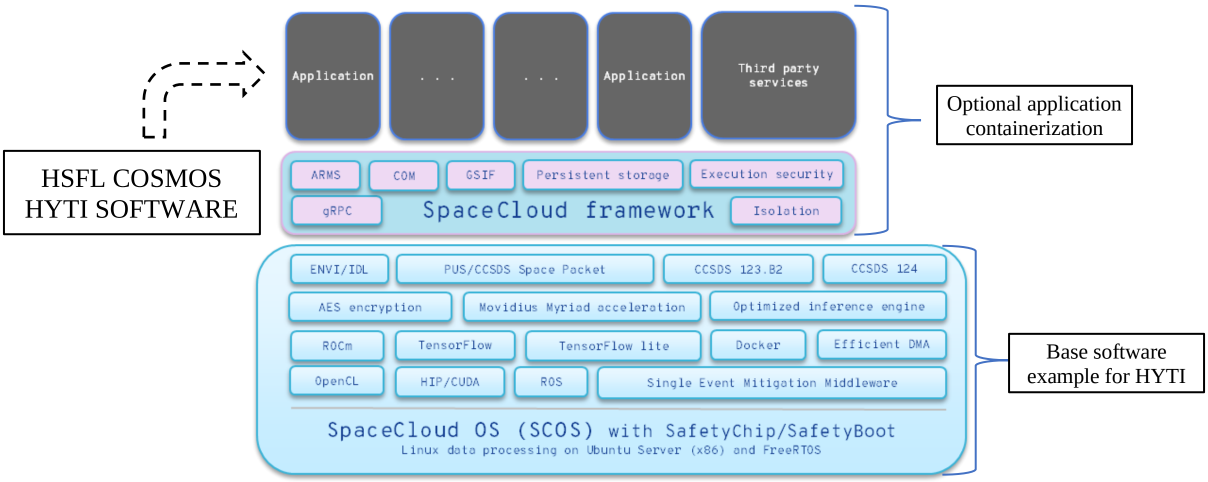

Figure 3-1. Illustration of an expanded HYTI software stack with SpaceCloud science application containerization. HFSL COSMOS software stack illustrated in parallel to SpaceCloud Framework.

6 CONCLUSION AND NEXT STEPS

The HyTI (Hyperspectral Thermal Imager) mission will demonstrate how high spectral and spatial long-wave infrared image data can be acquired and processed in-orbit on a 6U CubeSat platform. Using the onboard heterogeneous SpaceCloud computing hardware with the Unibap iX5 architecture, the mission will use a spatially modulated interferometric imaging technique to produce Spectro radiometrically calibrated image cubes, with 25 channels between 8-10.7 µm, at a ground sample distance of ~70 m. The HyTI performance model indicates narrow band NEΔTs of <0.2 K. Processing the large amount of data produced daily (in the order of ~100 GB) is only made possible with the iX5 heterogeneous solution with the combination of FPGA, CPU, GPU, and optional Neural Network Accelerators/Vision Processing Units and SSD storage. Flight integration is ongoing and delivery to NASA CSLI is planned for Fall 2022 with a target launch date in late 2022. The HyTI team is also expanding the work of HyTI for other applications, for Lunar missions that would enable very high ground resolution data of the Moon [13,14].

7 ACKNOWLEDGEMENTS

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