HYTI: High Spectral and Spatial Resolution Thermal Imaging from a 6U CubeSat

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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, will demonstrate how high spectral and spatial long-wave infrared image data can be acquired from a 6U CubeSat platform. 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^{-1} resolution), at a ground sample distance of ~60 m. The HyTI performance model indicates narrow band NEΔTs of <0.3 K. 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 HOT-BIRD FPA technology. Launch is scheduled for no earlier than Fall 2021. 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.

In this presentation we will provide an overview of the HyTI measurement approach, the onboard data reduction approach and the spacecraft design.

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INTRODUCTION

Since the launch of the Landsat 4 Thematic Mapper, scientists interested in studying the long-wave infrared (LWIR) thermal properties of Earth's surface, atmosphere, and water bodies at high-to-moderate resolution 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 would yield an hitherto unattainable measurement record for Earth scientists. Applications include mapping the chemistry of rocks and minerals exposed at Earth's surface[1], the composition of volcanic gas and ash plumes[2], and quantifying soil moisture content and evapotranspiration[3].

The recently published Earth Science Decadal Survey[4] explicitly identifies the provision of high spatial and either multi- or hyper-spectral thermal infrared data as a candidate measurement approach for achieving the Surface Biology and Geology Targeted Observable, and suggests that CubeSat constellations and alternative mission architectures be explored in order to provide, or complement, these important data. The HyTI mission is supportive of this 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 6U platform.

THE HYTI MISSION

The HyTI imager and measurement approach

The HyTI imager is a novel, no-moving-parts hyperspectral imager that was originally developed using funding from DARPA and NASA. A prototype of the instrument (Fig. 1) has already been developed and flight tested in a light aircraft. 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). 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. Figure 2 illustrates the process.

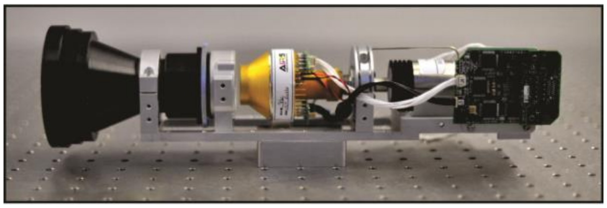

Figure 1: HyTI imager prototype

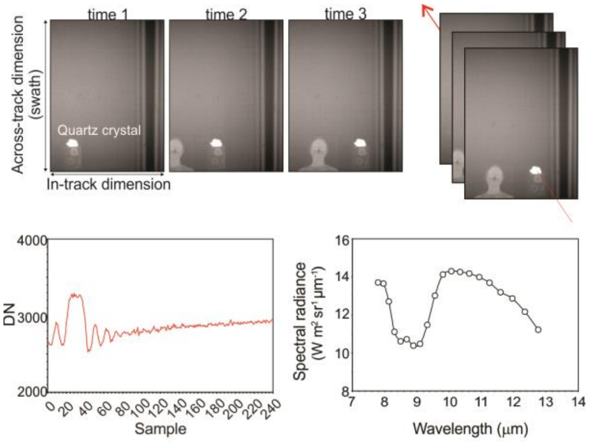

Figure 2: HyTI imaging approach

After co-registration of the image frames, standard Fourier Transform techniques[5] are used to produce a spectro-radiometrically calibrated image cube. The Fabry-Perot interferometer consists of two pieces of germanium (AR coated), with a sloped air-gap between. Reflection, transmission and eventual recombination of rays that traverse this gap produces interference that can be sampled at the array. The slope ensures that optical path difference (hence fringe period, Fig. 2) varies linearly across the air gap (the broad dark vertical stripe in these images denotes the point at which the pieces of Ge are contacted, where no modulation takes place). The spectral resolution of an interferometer is given by the ratio of the cut-off frequency to the number of samples in a single-sided interferogram[6], 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[7,8].

HyTI allows for high spatial and spectral resolution LWIR imaging by combining the multiplex advantage common to all interferometers with the sensitivity of JPL's Barrier Infra-Red Detector FPA technology[9]. Based on III-V compound semiconductors, the BIRD detectors offer a breakthrough solution for the realization of low cost (high yield), high-performance FPAs with excellent uniformity and pixel-to-pixel operability. These antimony (Sb) compound-based BIRD detectors outperform existing TIR detectors including Quantum Well Infrared Photodetectors (QWIPs). To achieve acceptable dark current levels (see below), the FPA will be maintained at a temperature of 68 K, although our performance model indicates that requirements are met if the FPA runs at 72 K. The spectral sensitivity is in the range 8-10.7 μm, and we assume a worst case quantum efficiency of 10%. For HyTI an FPA of 640 × 512 elements will be used. The HyTI ROIC cannot read the entire array at the required frame rate (139 Hz), and so HyTI will use a window of 256 detectors to define the field of view (swath), with 320 detectors used to sample the interference pattern generated by the Fabry-Perot interferometer (the in track direction). A frame rate of >139 Hz allows for oversampling in the in-track dimension at orbital velocity.

From an assumed orbital altitude of ~400 km (i.e., ISS orbit the design ground sample distance of HyTI will be ~70 m. To achieve this a multi-element refractive lens will be used, with an IFOV of 0.15 mrad, and an f-number of 3.44 (240 mm focal length). 25 spectral samples between 8-10.7 μm will be acquired (spectral resolution of 13 cm^{-1}). Our performance model (Fig. 3) indicates that NEΔTs of <0.3 K are attainable (at this spectral resolution), for source temperatures in the range 0-50 ºC. T2SLS detectors are very stable in time. 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 intermittent Lunar scans, and vicarious calibration using Landsat and ASTER images.

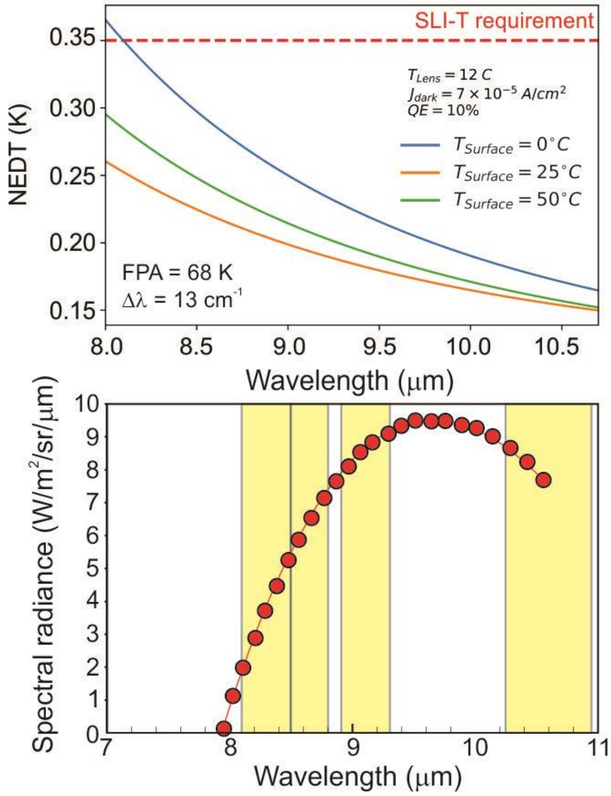

Figure 3. NEΔT predictions for HyTI, assuming a QE of 10%, with measured dark current (top). Illustration of the HyTI band count, compared to that of the Terra ASTER sensor.

SPACECRAFT

InVEST is targeted towards platforms exclusively in the 1U to 6U form-factor. HyTI will use a 6U bus, provided by ISISpace. Figure 4 shows a conceptual rendering of the HyTI spacecraft. The payload comprises an the IDCA (provided by American Infrared Solutions), the cryocooler (AIM SF070), the multi-element refractive lens (provided by New England Optical Systems), and the payload on-board computer (Unibap Deep Delphi iX5). The cryocooler electronics (drive and current ripple filter) are provided by Creare. The Fabry-Perot interferometer will be provided by LightMachinery. Communication will be via X-band for primary downlink (Syrlinks EWC27) with an ISISspace S-band for both redundant Tx and Rx. A Globalstar duplex and simplex are included to provide backup communications, and act as a beacon.

Four solar panels provide a peak of 40 W, with a battery capacity of 76 Wh. Attitude control is provided by CubeSpace CubeADCS (star tracker, reaction wheels, magnetometers, earth and sun sensors). Although the Unibap DDiX5 will be required for payload data processing, and ISIS iOBC will support the remainder of the spacecraft.

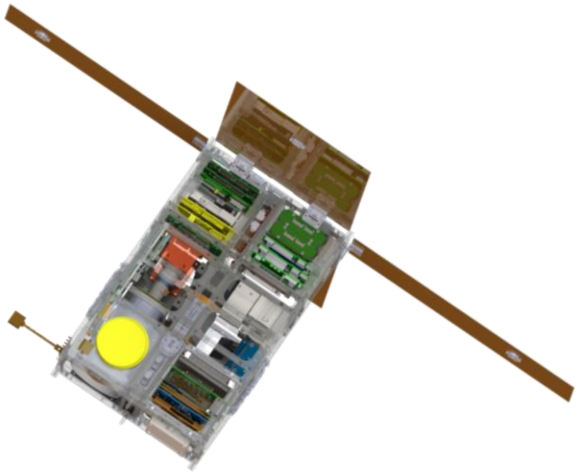

Figure 4. Rendering of the HyTI spacecraft

Maintaining the FPA at 68-72 K imposes constraints on the heat rejection temperature for the IDCA. The HyTI thermal design includes sinking the IDCA to radiators occupying the two 3×2 surfaces of the spacecraft using two graphite flex straps (from TAI) Model results show that the FPA can be cooled to operational temperature with substantial margin.

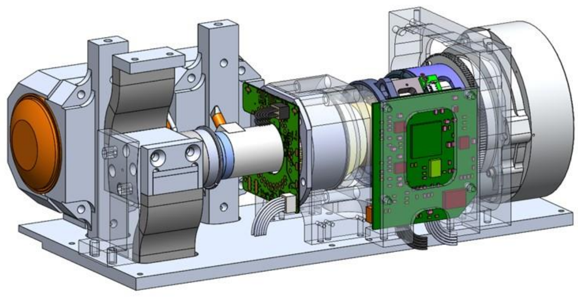

Figure 5. Rendering of the HyTI payload

MISSION OPERATIONS AND SCIENCE FOCUS

HyTI is a technology demonstration, not a science mission. Nevertheless, to demonstrate the applicability of HyTI's innovative technologies to making Earth science measurements, a mission must be defined. The science focus of HyTI is derivation of Landsat Surface Temperature (LST), volcanic sulfur dioxide emissions, and precision agriculture metrics.

The HyTI data rate is high, requiring onboard processing of the raw frames to the final Level 1 calibrated radiance cubes (i.e., Figure 2); this achieves a ×10 reduction in data volumes even before lossless (3:1) compression. To achieve this, HyTI will demonstrate onboard processing from L0 to L1 (i.e. frame-to-frame co-registration, FFT and spectral calibration) using the Unibap Deep Delphi iX5 heterogeneous computer platform, which offers CPU, GPU and FPGA capability. Test results indicate that using the GPU capabilities, 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 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 (SO2, in ppm.m; LST in K) using ~150 operations per pixel (rather than performing a full radiative transfer inversion). The results of the approach are illustrated below, using the volcanic gas plumes from Kilauea volcano, Hawaii, as an example. The PLSR-based retrieval compares favorably with a full RT inversion applied to airborne MASTER (MODIS-ASTER Simulator).

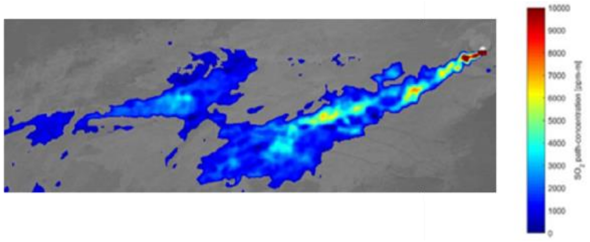

Figure 6. PLSR-based retrievals of volcanic SO_2 from airborne MASTER data

SaraniaSat's weak signal detection algorithms will also be implemented on the Unibap DD iX5, to demonstrate derivation of L2 products onboard HyTI, and low latency delivery of those products to stake-holders.

Current mission is to image mainly when HyTI is over the lower 48 states of the USA, with volcanic targets of opportunity outside of this region. This equates to HyTI acquiring data on ~five orbits per day, for an average of six minutes per pass. We estimate that this raw data can be processed to calibrated radiance cubes in a further two orbits, with subsequent downlink (via KSAT) to receiving stations in Spain, Chile, and New Zealand. Data collection, data processing, and data transmission cannot occur simultaneously due to the power constraints imposed by the 6U bus. Figure 7 shows a day-in-the-life simulation for HyTI which shows that the 40 W available via the four deployable solar panels and the 76 Wh battery allows this mission to be achieved. Approximately 50% of CONUS orbits will be obtained (average pass duration of 6 minutes, maximum of 10 minutes).

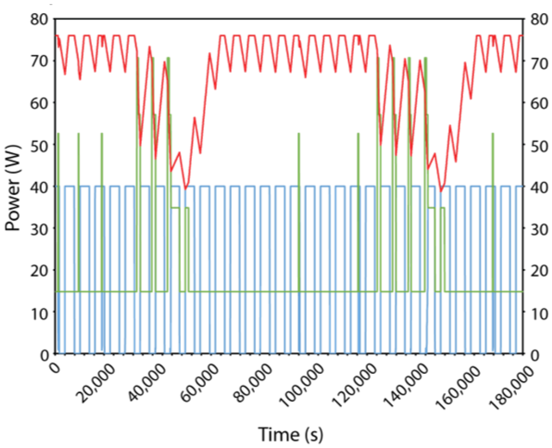

Figure 7. Day-in-the-life power budget for HyTI baseline mission. Blue is power generation, green is power consumption, and red is battery capacity

Power constraints mean that data cannot be processed while it is collected. The chart below shows the worst case power usage to acquire data, process L0 to L2, and downlink the data. In reality, these tasks will be performed on separate orbits.

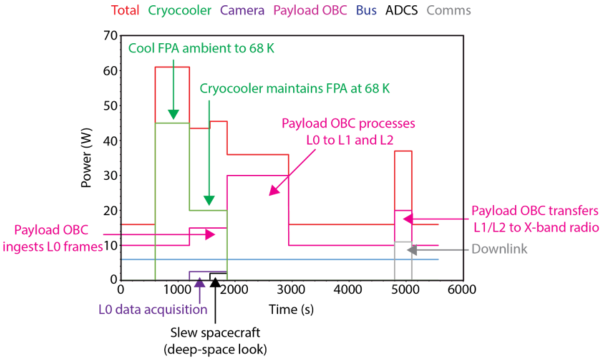

Figure 8. Power consumption during data acquisition, processing and downlink, assuming all took place in a single orbit

A proposal has been accepted for HyTI to the NASA CubeSat Launch Initiative.

CONCLUSIONS

The HyTI (Hyperspectral Thermal Imager) mission will demonstrate how high spectral and spatial long-wave infrared image data can be acquired from a 6U CubeSat platform. 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 <0.3 K. 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 BIRD FPA technology. Launch is scheduled for no earlier than Fall 2021.

Acknowledgments

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