HYTI: HIGH SPATIAL AND SPECTRAL 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 a cryogenically-cooled HOT-BIRD (High Operating Temperature Barrier InfraRed Detector) focal plane array. Launch is scheduled for Fall 2022. 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, and land surface temperature.

1. 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+, and the most recent iteration, the Landsat 8 and Landsat 9 TIIRS sensor), in no more than five spectral bands (e.g., Terra ASTER). It can be argued that the ECOSTRESS mission [1] currently operating on the International Space Station represents the state-of-the-art for orbital moderate resolution thermal remote sensing, via the acquisition of five channels in the 8-12 μm interval at 69 × 38 m resolution. 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 [2], the composition of volcanic gas and ash plumes [3], and quantifying soil moisture content and evapotranspiration [4]. The recently published Earth Science Decadal Survey [5] explicitly identifies

the provision of high spatial and either multi- or hyper-spectral thermal infrared data as a candidate measurement approach for achieving the SBG 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.

2. THE HYTI PAYLOAD AND IMAGE MEASUREMENT TECHNIQUE

The HyTI imager is a novel, no-moving-parts hyperspectral imager that was originally developed 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).
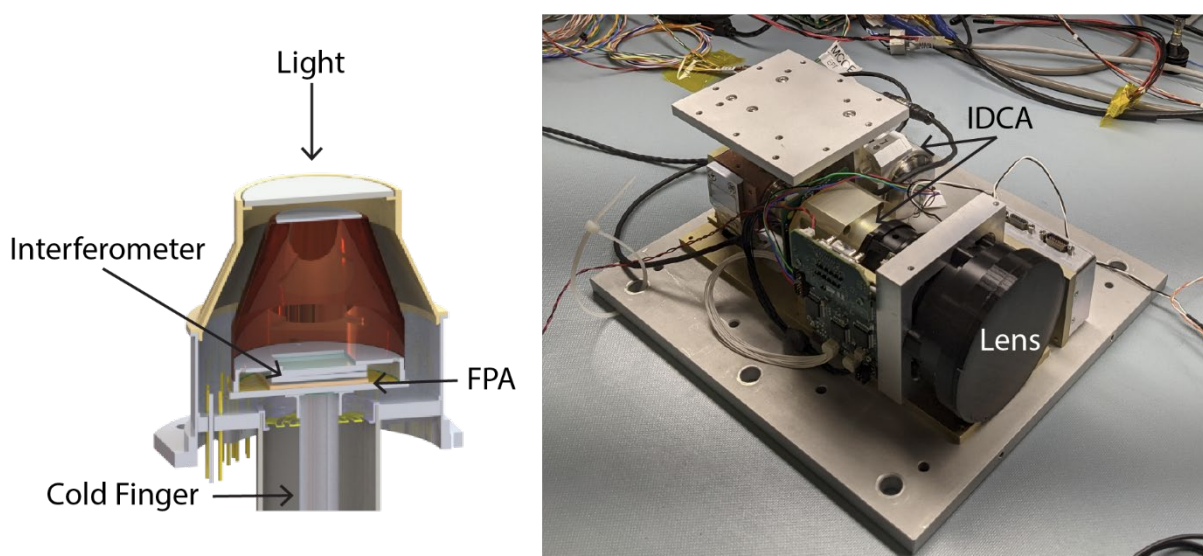

Figure 1. Right: HyTI payload. Left: detail of the HyTI interferometer and FPA within the dewar

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. 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) varies linearly across the air gap. A single frame of data (top left, Figure 2) records light emitted from each scene element modulated at one OPD per column of the array, and the broad dark vertical stripe on the right hand side of these images denotes the point at which the pieces of Ge are contacted, where no modulation takes place, with interference fringes extending from this point. As such, each column of the array contains aportion of an interferogram for each scene element in each column. By translating the interference across the scene (using forward motion of the platform; HyTI is a pushbroom imager, and the design frame rate oversamples in the interference pattern in the in-flight direction) light emitted from each scene element is modulated at each OPD. After co-registration of the image frames, standard Fourier Transform techniques [6] are used to produce a spectro-radiometrically calibrated image cube. 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 [7], and the fringe periodicity (number of samples) for 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 [8, 9].
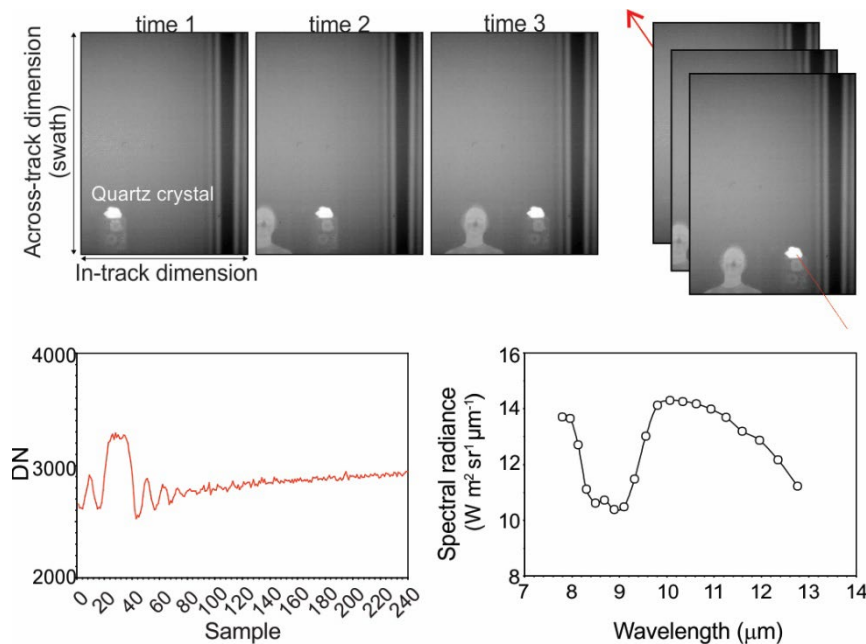

Figure 2. Top left: images of a quartz cube acquired at successive time steps, as the interference pattern is scanned across the scene. Co-registration of the frames (top right) allows an interferogram (lower left) to be obtained for each pixel in the image cube, from which a radiance spectrum (lower right) can be retrieved.

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 [10]. Based on III-V compound semiconductors, the BIRD detectors are 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, 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 ~60 m. 25 spectral samples between 8-10.7 μm will be acquired (spectral resolution of 13 cm^{-1}). The HyTI performance model (Figure 3) indicates that NEΔTs of <<0.3 K are attainable (at this spectral resolution), for source temperatures in the range 0-50 ºC. HyTI will ahve no on-board calibration targets, given the volume constraints of the 6U platform. T2SLS detectors are very stable in time [11]. 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.
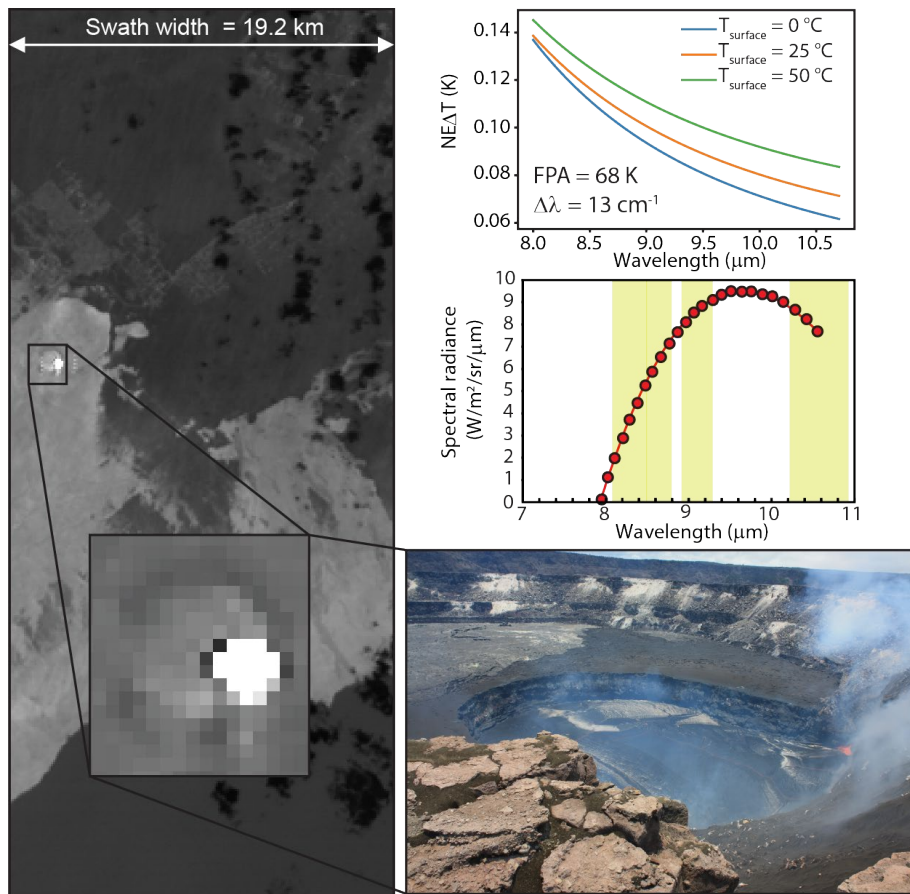
Figure 3. Left: illustration of HyTI image swath and ground resolution, using a Landsat ETM+ band 6 image of Kīlauea volcano, Hawai'i. Top right: predicted NEΔT of HyTI for a range of ground temperatures, and HyTI band count (red dots) compared to ASTER band count over the same spectral interval (yellow bars)

3. SUMMARY

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 ~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 BIRD FPA technology.

4. ACKNOWLEDGEMENTS

5. REFERENCES

[1] Fisher, J. B., Lee, B., Purdy, A. J., Halverson, G. H., Dohlen, M. B., Cawse-Nicholson, K., et al. (2020). ECOSTRESS: NASA's Next Generation Mission to measure evapotranspiration from the International Space Station. *Water Resources Research*, 56, e2019WR026058. https://doi.org/10.1029/2019WR026058

[2] Hall, J. L., Hackwell, J. A., Tratt, D. M., Warren, D. W. and Young, S.J (2008). Space-based mineral and gas identification using a high-performance thermal infrared imaging spectrometer. *Proceedings of SPIE,* 7082, 70820M.

[3] Gabrieli, A., Porter, J., Wright, R., and Lucey, P (2017). Validating the accuracy of SO_2 gas retrievals in the thermal infrared (8-14 μm). *Bulletin of Volcanology*, 80, https://doi.oeg/10.1007/s00445-017-1172-2, 2017.

[4] Anderson, M. C., Norman, J. M., Kustas, W. P., Houborg, R., Starks, P. J., and Agam, N. (2008). A thermal-based remote sensing technique for routine mapping of land-surface carbon, water and energy fluxes from field to regional scales. *Remote Sensing of Environment*. 112 (12), 4227-4241.

[5] National Academies of Sciences, Engineering, and Medicine, (2018). *Thriving on Our Changing Planet A Decadal Strategy for Earth Observation from Space.* The National Academies Press. https://doi.org/10.17226/24938.

[6] Mertz, L. (1965). *Transformations in Optics.* Wiley.

[7] Griffiths P.R. and DeHaseth, J.A. (1986). *Fourier Transform Infrared Spectrometry*. Wiley.

[8] Lucey, P. G., and Akagi, J. (2011). A Fabry-Perot interferometer with a spatially variable resonance gap employed as a Fourier transform spectrometer. *Proceedings of SPIE*, 8048, 80480K-1.

[9] Lucey, P.G., Hinrichs, J.L., and Akagi, J. (2012). A compact LWIR hyperspectral system employing a microbolometer array and a variable gap Fabry-Perot interferometer employed as a Fourier transform spectrometer. *Proceedings of SPIE*, 8390, 83900R-1.

[10] Ting, D., Soibel, A., Khoshakhlagh, A., Rafol, S. B., Keo, S. A., Höglund, L., Fisher, A. M., Luong, E. M., and Gunapala, S. D. (2018). Mid-wavelength high operating temperature barrier infrared detector and focal plane array. *Applied Physics Letters*, 113, 021101.

[11] Arounassalame, V., Guenin, M., Caes, M., Hoglund, L., Costard, E., et al. (2021). Robust Evaluation of Long-Term Stability of an InAs/GaSb Type II Superlattice Midwave Infrared Focal Plane Array. *IEEE Transactions on Instrumentation and Measurement*, 70, pp.5001108. ⟨10.1109/TIM.2020.3024406⟩.