Hyperspectral Thermal Emission Spectrometer: Engineering Flight Campaign

William R. Johnson, Simon J. Hook, Steven S. Shoen and Bjorn T. Eng
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109
(818) 393-5470
William.R.Johnson@jpl.nasa.gov

Abstract - **The Hyperspectral Thermal Emission Spectrometer (HyTES) successfully completed its first set of engineering test flights. HyTES was developed in support of the Hyperspectral Infrared Imager (HyspIRI). HyspIRI is one of the Tier II Decadal Survey missions. HyTES currently provides both high spectral resolution (17 nm) and high spatial resolution (2-5m) data in the thermal infrared (7.5-12 µm) part of the electromagnetic spectrum. HyTES data will be used to help determine the optimum band positions for the HyspIRI Thermal Infrared (TIR) sensor and provide antecedent data for HyspIRI related studies. The first engineering flights were on a Twin Otter based in Grand Junction, Colorado. After a few local flights around Grand Junction, the HyTES flew to Burbank picking up data over additional sites on the way. Nighttime data were then acquired over a set of sites in and around Los Angeles, CA and the following day the plane flew back to Grand Junction acquiring data from more sites.**

HyTES includes several new technologies: a Dyson spectrometer, QWIP detector, precision slit and electron microbeam diffraction grating. The test flights allowed the successful demonstration of these technologies as well as a preliminary assessment of the end-to-end performance of the instrument. The instrument pre-flight performance is shown. Future work will focus on a detailed analysis of these datasets both from an engineering and science perspective. This will include the identification of potential improvements needed to make HyTES campaign-ready on a variety of aircraft. These improvements would allow HyTES data to be acquired at a variety of spatial resolutions on platforms with a greater range than the Twin Otter.

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1. INTRODUCTION

The Jet Propulsion Laboratory (JPL) has a long history in developing science-grade imaging spectrometers for remote sensing applications. Examples include the airborne visible infrared imaging spectrometer [1] (AVIRIS) and more recently a compact Offner type imaging spectrometer called the Moon Mineralogical Mapper [2] (M^3) which recently completed its mission in orbit around the moon onboard India's Chandrayaan-1.

In late 2006, JPL began the development of a breadboard thermal infrared pushbroom spectrometer named the Quantum Well infrared photodetector Earth Science Testbed (QWEST) as an end-to-end laboratory demonstration of both the thermal Dyson spectrometer as well as the quantum well infrared focal plane technology. The testbed is a precursor to the airborne version under development referred to as the hyperspectral thermal emission spectrometer (HyTES) and funded by the NASA Instrument Incubator Program (IIP). The current effort brings together numerous in-house specialties such as optical design and general spectrometer alignment optimization, precision slit fabrication, high efficiency and low scatter concave diffraction grating design and fabrication, precision mechanical and machining capability and quantum well infrared photo detectors (QWIP) focal plane arrays.

The long wave infrared (LWIR) is typically expressed as the wavelength range between 7 and 14 µm. Our current demonstration instrument operates from 7.5 to 9.5 µm and the planned airborne instrument will operate from 7.5 µm to 12 µm. Spectral information from this wavelength range is extremely valuable for Earth Science research. The airborne instrument will be used in support of the HyspIRI mission (hyspiri.jpl.nasa.gov) which was recently recommended by the National Research Council in their Decadal Survey. The LWIR component of the HyspIRI mission will address science questions in five main science themes:

Volcanoes

What are the changes in the behavior of active volcanoes? Can we quantify the trace gases (Sulfur dioxide, CO2) released into the atmosphere by volcanoes and estimate its impact on Earth's climate? How can we help predict and mitigate volcanic hazards?

Wildfires

What is the impact of global biomass burning on the terrestrial biosphere and atmosphere, and how is this impact changing over time? A LWIR sensor will allow us to measure temperature, emissivity, radiative flux, burn products, hot spots, etc.

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Water Use and Availability

As global freshwater supplies become increasingly limited, how can we better characterize trends in local and regional water use and moisture availability to help conserve this critical resource?

Urbanization

How does urbanization affect the local, regional and global environment? Can we characterize this effect to help mitigate its impact on human health and welfare?

Land surface composition and change

What is the composition and temperature of the exposed surface of the Earth? How do these factors change over time and affect land use and habitability?

The QWEST testbed is providing enabling technology for the development of a fully operational airborne platform suitable for earth science studies. It will have sufficient spatial and spectral resolution to allow scientists to acquire the necessary data to aid in the planning of future spaceborne missions.

2. OPTICAL DESIGN

Concentric designs allow a point to be mapped perfectly to a focal plane array. Past and future planned imaging spectrometer systems have successfully implemented the Offner [3,4] design. The idea behind the Offner concentric design was to provide a relay unit magnifier to alleviate distortion and third order system aberrations while having an accessible object and image plane. The first published supplementary idea for an all reflecting or 2-mirror concentric imaging spectrometer was cast by Thevenon and Mertz [5]. Subsequent work was also done by Kwo [6] and Lobb [7]. A concentric design like the Offner is well-suited to pushbroom spectrometers. Smile and Keystone distortion are nearly eliminated using proper alignment and design techniques.

The Offner design would be relatively large and would require a bulky temperature controlled dewar and large power supplies to maintain adequate thermal control for the LWIR. Dyson [8] published a paper in 1959 outlining a Seidel-corrected unit magnifier which was composed of a single lens and concave mirror. It was to be used to project groups of lines for emulsion photography and also phase contrast microscopy. Mertz also proposed the Dyson principle in the same paper where he discussed the Offner. Wynne [9] proposed a Dyson design for microlithography in the visible and ultraviolet and Mouroulis [10,11] et al. considered Dyson designs for visible spectrometry and for coastal ocean applications. A thorough treatment of these designs as well as an operational thermal infrared system is described in a work by Warren et al [12]. Kuester [13] et al. discuss an airborne platform which uses a visible transmitting Dyson.

Our effort uses the same principle but extends the Dyson design to work optimally with the LWIR. The savings in physical size for similar low F/# systems is dramatic. QWEST was designed to minimize smile and keystone distortion [14] while simultaneously virtually eliminating ghosting. The slit width is 50 µm, which corresponds to two detector pixels. Smile and keystone distortions were kept to no more than 1-2% of this or ~2µm. JPL fabricates ultra precision slits using reactive ion etching which can be kept straight to an order of magnitude better than this. For this reason the slit straightness is not typically the limiting factor in spectrometer performance.

As shown in Figure 1, a single monolithic block is used in double pass where light from the slit enters at a narrow optical passageway and is transmitted through the rear power surface, diffracts off the grating and re-enters the block to totally internally reflect off the back surface which guides the spectrally dispersed radiation to focus at the QWIP location. This design minimizes the travel and form factor of the system. The actual block fabricated is shown in Figure 2. Broadband area coatings are used on all applicable light transmitting surfaces. The coatings allow 99.0% or better LWIR light to transmit. The block was fabricated from ZnSe, a robust material with a transparent wavelength region from 0.4 ~ 23 µm and an absorption coefficient between $10^{-3}cm^{-1}$ and $10^{-4}cm^{-1}$. The ZnSe slab is produced by chemical vapor deposition.

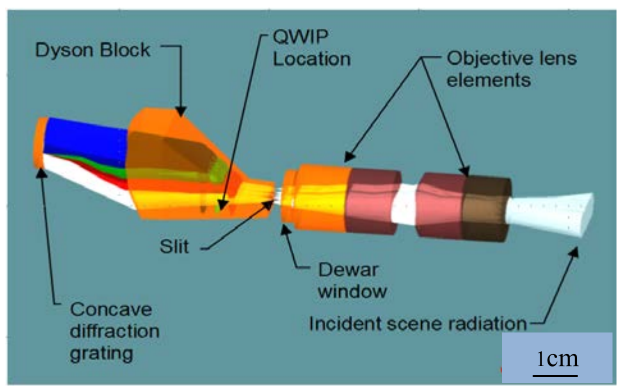


Figure 1. Conceptual layout of Dyson spectrometer and objective lens elements

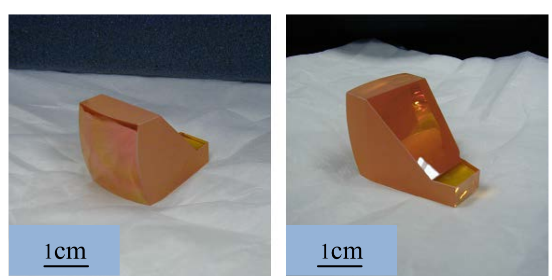


Figure 2. Monolithic ZnSe optical block with BBAR coatings used in double pass for the Dyson spectrometer

3. THE QWIP ARRAY

QWIP technology [15,16,17] utilizes the photoexcitation of electrons between the ground state and the first excited state in the conduction band quantum well (QW). QWIPs have been successfully integrated into commercial handheld field units for more than a decade. This is the first integration of a 2-band QWIP with a spectrometer system for earth science studies requiring accurately calibrated data. A schematic of the layout is shown in Figures 3. There's a relative height difference between the two bands as shown in Figure 4.

The detector pixel pitch of the FPA is 19.5 μm and the actual pixel area is 23x23 μm. Indium bumps were evaporated on top of the detectors for hybridization with a silicon readout integrated circuit (ROIC). These QWIP FPAs were hybridized (via indium bump-bonding process) to a 1024x1024 pixel complementary metal-oxide semiconductor (CMOS) ROIC and biased at VB = –1.25 V. At temperatures below 72 K, the signal-to-noise ratio of the system is limited by array nonuniformity, readout multiplexer (i.e., ROIC) noise, and photocurrent (photon flux) noise. At temperatures above 72 K, the temporal noise due to the dark current becomes the limitation. We are currently running the system at 40K to have a SNR advantage. The QWIP is known for its high spatial uniformity (<0.51%). This is a clear advantage over other detector technologies such as HgCdTe and InSb. A custom made LCC and titanium FPA clamp was designed to accommodate the close proximity (~mm's) of the FPA with the ZnSe block.

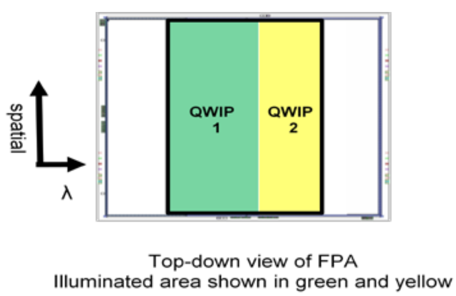


Figure 3. Two QWIP sensor regions on are hybridized on a standard Santa Barbara Focal Plane 9803 read out integrated circuit.

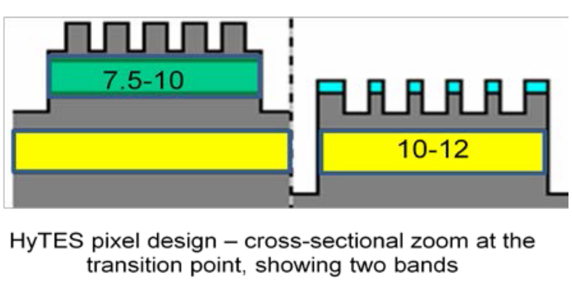
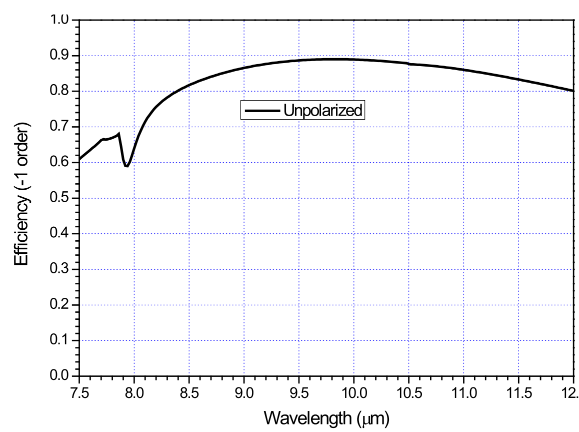


Figure 4. A schematic (not to scale) of the QWIP material structure for 2-band system. Each band is fine tuned for different wavelength regions within the LWIR.

4. DIFFRACTION GRATING

Diffraction grating design and fabrication is a key enabling technology for these spectrometers. JPL has developed electron-beam lithography techniques that allow fabrication of precisely blazed gratings on curved substrates having several millimeters of height variation [18,19,20]. Gratings fabricated in this manner provide high efficiency combined with low scatter. The blazed grating for this LWIR Dyson spectrometer was fabricated in a thin layer of PMMA electron-beam resist coated on a diamond-turned concave ZnSe substrate. After exposure and development to the desired blaze angle, the resist was overcoated with gold for maximum infrared reflectance. A photograph of the grating and the simulated efficiency of the fabricated grating are shown in Figures 5a and 5b, respectively. The design was optimized for maximum efficiency in the -1 order, and the other orders remain relatively weak across the band.

(a)

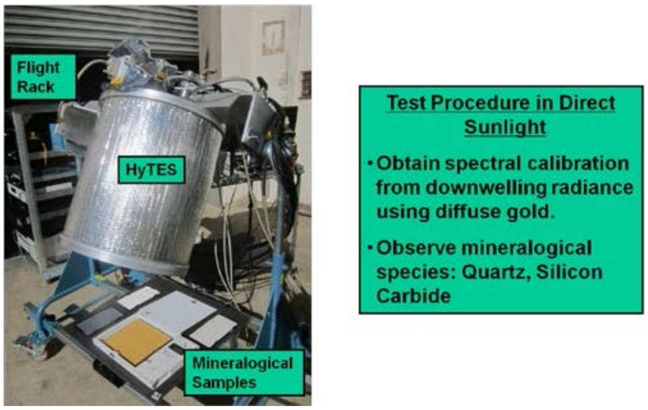


(b)

Figure 5. HyTES spectrometer grating: (a) photograph of fabricated grating (annular E-beam focus zones are visible due to slight variation in scattering; unexposed rectangular areas near edge are due to the E-beam mount), (b) simulated efficiency (calculated using PCGrate 6.1 software).

5. ENGINEERING FLIGHT RESULTS

HyTES flew on a Twin Otter aircraft out of Grand Junction, Colorado as shown in Figure 6. Pre flight tests show very good results in terms of the spectral alignment and spatial resolution. The following results should better quantify this.

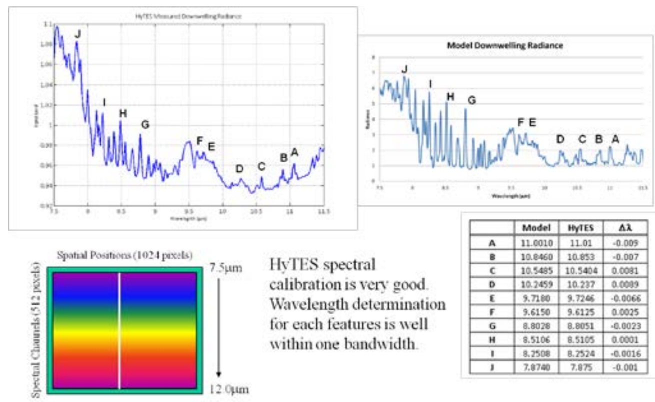


a)

b)

Figure 6. a) HyTES shown outdoors undergoing testing before being installed on the Twin Otter and b) Final system loaded onto Twin Otter. System is shown during a brief stop at the Burbank airport facility.

HyTES measured noise equivalent delta temperature (NEDT) was measured to be at 200mk for most of the spectral bandwidth and was <200mk for many channels near 10µm. A spectral calibration was performed using a monochromator coupled to a thermal target projector. This is an easy way to determine the position of the spectral bands and verify the full width at half maximum. For radiometric performance, a National Institute of Standards and Technology (NIST) traceable transfer calibration is performed on our electro-optic blackbody to verify its performance between the two end bracket temperatures of 4C and 40C. JPL has multiple NIST traceable blackbodies with a stability at 25 C of +/- 0.0007 C and a thermistor standard probe with an accuracy of 0.0015 ° C over 0-60 ° C and stability/yr of 0.005. A transfer calibration of the NIST traceable blackbody with the one used for the tests was performed in a ramp and soak mode where the blackbody temperature is increased by a set interval and allowed to soak for several minutes and then the temperature is measured. We use a 2-point non-uniformity correction [21,22,23] where 5C and 45C are used to bracket the temperature range. The blackbody is ramped from 5C to 45C and then is left to drift in 5C increments to finally end up back at 5C. Frames are taken at each interval to check for both temporal artifacts as well as single frame noise equivalent temperature difference per spectral band as well as determining any spectral non-linearity.

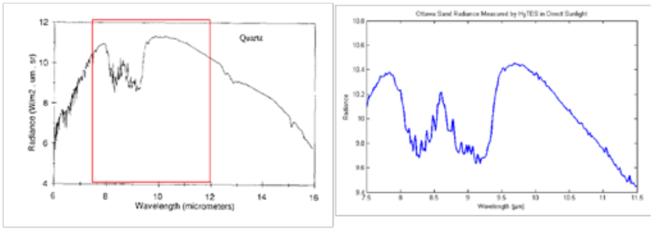


	Model	HyTES	Δλ
A	11.0010	11.01	-0.009
B	10.8460	10.853	-0.007
C	10.5485	10.5404	0.0081
D	10.2459	10.237	0.0089
E	9.7180	9.7246	-0.0066
F	9.6150	9.6125	0.0025
G	8.8028	8.8051	-0.0023
H	8.5106	8.5105	0.0001
I	8.2508	8.2524	-0.0016
J	7.8740	7.875	-0.001

Figure 7. Excellent spectral alignment measured using atmospheric water line spectra as compared with 2cm^{-1} MODTRAN downwelling radiance model.

Two tests were performed to characterize the instrument performance. Test one was for spectral linearity while the other determined the spectral NEdT. The data shows that HyTES has very good linearity with many temperature measurements showing absolute errors below 0.1C. The noise equivalent delta temperature for spectral channels at blackbody temperatures between 5C and 45C are within the requirement of 200mk. This implies that for a given temperature between this range HyTES has a mean NEdT of 200mK.

The current system is being operated outdoors under direct sunlight to understand and characterize the science usefulness of the instrument towards remote sensing earth science applications. The data shown is using an integration time of 30ms and observed at roughly noon time (Pacific Standard Time). Figure 7 shows radiance calculated for a gold standard. This plot shows atmospheric water band absorption and appears to be both spectrally and radiometrically accurate when compared to the MODTRAN simulation and previously deployed Fourier transform imaging spectrometers (FTIR), respectively.



Previously measured field radiance of Quartz (micro-FTIR)

HyTES radiance measurement of Ottawa sand in direct sunlight.

Figure 8. Radiance of Ottawa sand shows strong quartz signature and compares favorably with previously measured data.

The atmospheric data, as shown in figure 7, is then used in part to further reduce mineralogical data taken with the system in direct sunlight. As shown in Figure 8, Quartz deposits within Ottawa sand are found to have the an apparent emissivity which compares favorably with previously taken data [24].

HyTES flew over Cuprite and Death Valley. Geo-rectification is still on-going. Current results, as shown in Figure 9, show reasonable differentiation of mineralogical features.

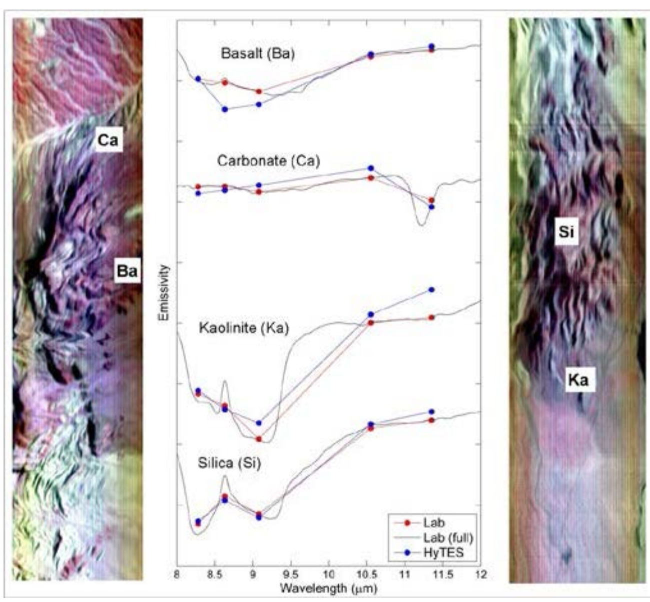


Figure 9. Two segments over Cuprite showing reasonable mineralogical differentiation. Emissivity spectra acquired from the data is shown superimposed on top of lab spectra.

Future science flights will include flying over regions such as Tahoe and Salton Sea to compare HyTES temperature retrievals with in-situ sensors on the ground as well as flying over naturally occurring methane sites. It is felt that HyTES has enough sensitivity and spectral resolution to discriminate between the plume and background.

6. Remarks

The HyTES study was a success. The HyTES instrument was built and flown on a twin otter aircraft over various sites in the southwestern USA. Results from the engineering flights are promising, and further flights are scheduled for the summer of 2013. Current results indicate that HyTES will be able to provide precursor data suitable for the HyspIRI mission and for the earth science community in general.

A compact, low cost, broad swath and flight worthy infrared spectrometer is not common. A typical spectrometer of this nature (e.g. FTS) are complicated and use sensitive mechanisms during operation, numerous passive and active optical elements and an abundance of post acquisition (onboard or on the ground) data processing. A HyTES spectrum is available immediately, and the design naturally has a slit which allows pushbrooming over a very width swath.

7. ACKNOWLEDGEMENTS

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Biography

William R. Johnson is an Optical Engineer and Technologist at the Jet Propulsion Laboratory. He completed his M.S. degree at the University of Arizona and has been employed at JPL ever since. He works on developing advanced imaging spectrometers.

Simon J. Hook received his B.Sc. in 1982 from the University of Durham, England, M.Sc. in 1985 from the University of Edmonton, Canada, and PhD., in 1989 from the University of Durham, England all degrees were in geology.

He is a principal scientist at the Jet Propulsion Laboratory JPL. His research is focused on improving our understanding of geologic and hydrodynamic processes on Earth and other planets.