Title: The Hyperspectral Thermal Emission Spectrometer (HyTES): preliminary results
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Abstract:
The Hyperspectral Thermal Emission Spectrometer (HyTES) is being developed as part of the risk reduction activities associated with the Hyperspectral Infrared Imager (HyspIRI). HyspIRI is one of the Tier 2 Decadal Survey Missions. HyTES will provide information on how to place the filters on the HyspIRI Thermal Infrared Instrument (TIR) as well as provide antecedent science data. The pushbroom design has 512 spatial pixels over a 50-degree field of view and 256 spectral channels between 7.5µm to 12µm. HyTES includes many key enabling state-of-the-art technologies including a high performance convex diffraction grating, a quantum well infrared photodetector (QWIP) focal plane array, and a compact Dyson-inspired optical design. The Dyson optical design allows for a very compact and optically fast system (F/1.6). It also minimizes cooling requirements due to the fact it has a single monolithic prism-like grating design which allows baffling for stray light suppression. The monolithic configuration eases mechanical tolerancing requirements which are a concern since the complete optical assembly is operated at cryogenic temperatures (~100K). The QWIP allows for optimum spatial and spectral uniformity and provides adequate responsivity or D-star to allow 200mK noise equivalent temperature difference (NEDT) operation across the LWIR passband. Assembly of the system is nearly complete. After completion, alignment results will be presented which show low keystone and smile distortion. This is required to minimize spatial-spectral mixing between adjacent spectral channels and spatial positions. Predictions show the system will have adequate signal to noise for laboratory calibration targets.

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). The current effort involves completing the Hyperspectral Thermal Emission Spectrometer (HyTES) which is being developed under the NASA Instrument Incubator Program (IIP). HyTES 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.

HyTES will operate between 7.5 and 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. This mission was recommended by the National Research Council in their Earth Science Decadal Survey. The HyspIRI mission includes a visible shortwave infrared (SWIR) spectrometer and a multispectral thermal infrared (TIR) imager. Data from the HyspIRI mission will be used to address key science questions related to the Solid Earth and Carbon Cycle and Ecosystems focus areas of the NASA Science Mission Directorate. More specifically, 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 amount of material 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?

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?

HyTES will allow scientists to acquire data with sufficient spatial and spectral resolution to plan future space borne missions. Table 1 lists the instrument specifics. The Quantum Well Earth Science Testbed (QWEST) is a JPL internally funded laboratory demonstration vehicle. It allows testing of components at the system level.

Table 1. QWEST and HyTES specifications. QWEST is a laboratory technology demonstration testbed while HyTES is the IIP funded airborne sensor.

Instrument Characteristic	QWEST	HyTES
Number of pixels x track	320	512
Number of bands	256	256
Spectral Range	8-12 um	7.5-12 um
Integration time (1 scanline)	30 ms	30 ms
Total Field of View	40 degrees	50 degrees
Calibration (preflight)	Full aperture blackbody	Full aperture blackbody
QWIP Array Size	640x512	1024x512
QWIP Pitch *	25 um	19.5 um
QWIP Temperature	40K	40K
Spectrometer Temperature	40K	40K
Slit Width	50 um	39 um
Pixel size at 2000 m flight altitude	4.5 m	3.64
Pixel size at 20,000 m flight altitude	45 m	36.4
	Operational	Summer 2011

Instrument Deisgn:

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[4,5] design. The Offner concentric design provides a relay unit magnifier which alleviates 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[6]. Subsequent work was also done by Kwo[7] and Lobb[8]. A concentric design like the Offner is well-suited to pushbrooom spectrometers. Smile and keystone distortion are nearly eliminated using proper alignment and design techniques.

Although an excellent performer, for the TIR the Offner design would be relatively large and would require a bulky temperature controlled dewar and large power supplies to maintain adequate thermal control. J. Dyson[9] 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[10] proposed a Dyson design for microlithography in the visible and ultraviolet and Mouroulis[11,12] 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 work by Warren et al[13]. Kuester[14] 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. HyTES was designed to minimize smile and keystone distortion[15] 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 can fabricate 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 with grating fabricated is shown in figure 2. Broadband area coatings are used on all applicable light transmitting surfaces. The coatings allow 99.5% 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 and 10^{-4}cm. The ZnSe slab is produced by chemical vapor deposition.

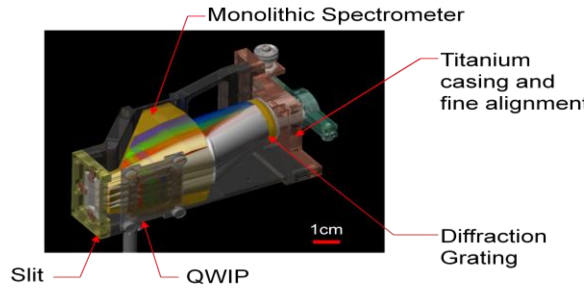

Figure 1. Model of Dyson spectrometer showing all major components. Thermal radiation passes through the slit and is dispersed by the grating. The dispersion is reimaged ultimately back at the focal plane array.

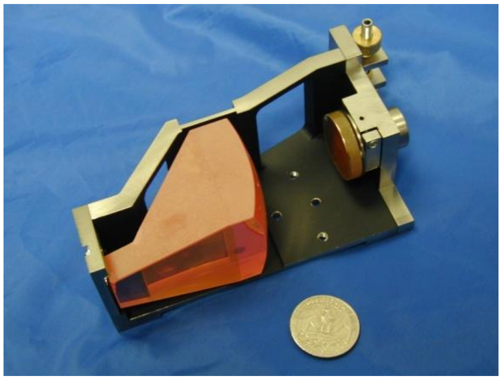

Figure 2. Monolithic ZnSe optical block with BBAR coatings used in double pass for the Dyson spectrometer

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.[16,17,18] 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 Figure 4. The design was optimized for maximum efficiency in the -1 order, and the other orders remain relatively weak across the band.

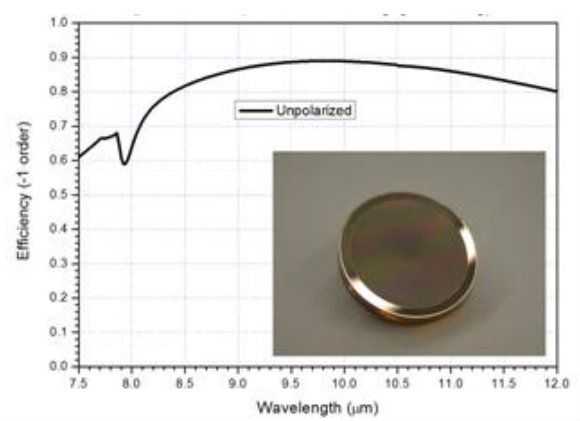

Figure 3. QWEST spectrometer grating: (a) photograph of fabricated grating (annular E-beam focus zones are visible due to slight variation in scattering; unexposed rectangular areas near edge are due to the E-beam mount), (b) simulated efficiency (calculated using PCGrate 6.1 software).

A relay assembly is used prior to the spectrometer housing. This minimizes stray light and allows for a fixed aperture stop position for the telescope. A photo of the relay is shown in figure 4. The assembly uses 6 total lens elements. All surfaces are coated with high transmissive interference layers in order to maximize light throughput. The lens elements are held in a kinematic mount to minimize distortions during flight operation.

Figure 4. HyTES opto-mechanical relay assembly.

QWIP technology[19,20,21] 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 the QWIP with a spectrometer system for earth science applicability.

The detector pixel pitch of the FPA is 20 μm and the actual pixel area is 19.5x19.5 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 (<1%). This is a clear advantage over other detector technologies such as HgCdTe and InSb. QWIP's are typically known to be narrow band in nature hence why multiple stacks are used to cover the extended bandwidth requirements of HyTES. Figure 5 shows the packaged HyTES FPA and flex cable attachment. The QWIP focal plane split into two regions to cover the system bandwidth requirements. Region one is sensitive to the 7.5um – 10um region while region 2 is sensitive to the 10um – 12um region.

Figure 5. HyTES focal plane array analog electronics.

System integration is currently underway. The vacuum chamber is shown in figure 6. The chamber supports airborne operation while maintaining rigidity of its inner precision optical components. Two cryocoolers are used. One maintains adequate focal plane temperate and control while the other reduces parasitics using multi layer insulation. Multi-layer insulation keeps the sensor at the required 40K while the optics are held at 100K. This minimizes background signal hence optimizing each spectral channel dynamic range.

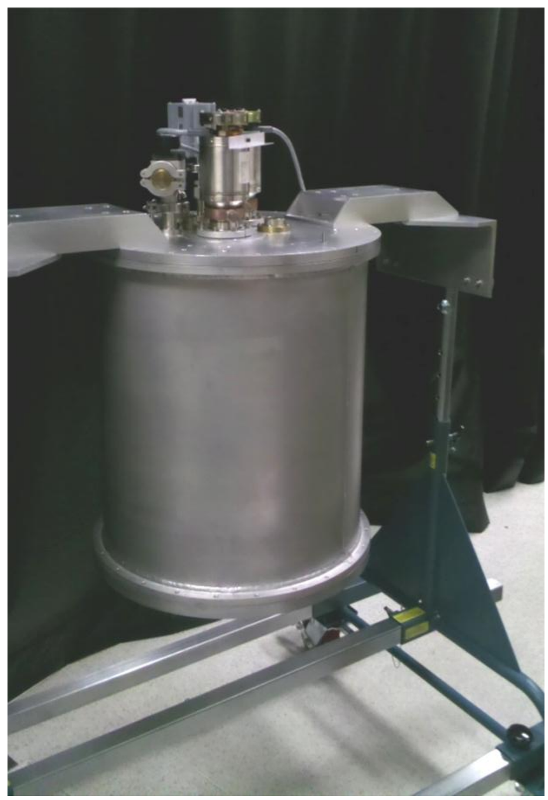

Figure 6. HyTES dual cryocooler vacuum chamber on integration and testing mount

When fully completed, HyTES will be a state-of-the-art mechanically cooled imaging spectrometer for the thermal infrared. Figure

7 shows a radiometric performance simulation of the noise equivalent delta temperature (NEDT). The system is expected to have adequate performance to determine the precise wavelengths required of future space borne missions. Preliminary results obtained by the QWEST components testbed show that the measured NEdT and linearity are excellent. The same spectrometer performance over the nominal LWIR band pass (8-12um) is expected once the broadband QWIP installation is complete. The IIP07 activity will end with the completion and testing of HyTES in the laboratory. This will determine whether the system and, in particular, QWIP has adequate performance for airborne use. Further work will then focus on making the instrument air-worthy and acquiring airborne measurements. HyTES will be a versatile airborne system since it uses mechanical cryocoolers to assist in parasitic suppression and active heat suppression.

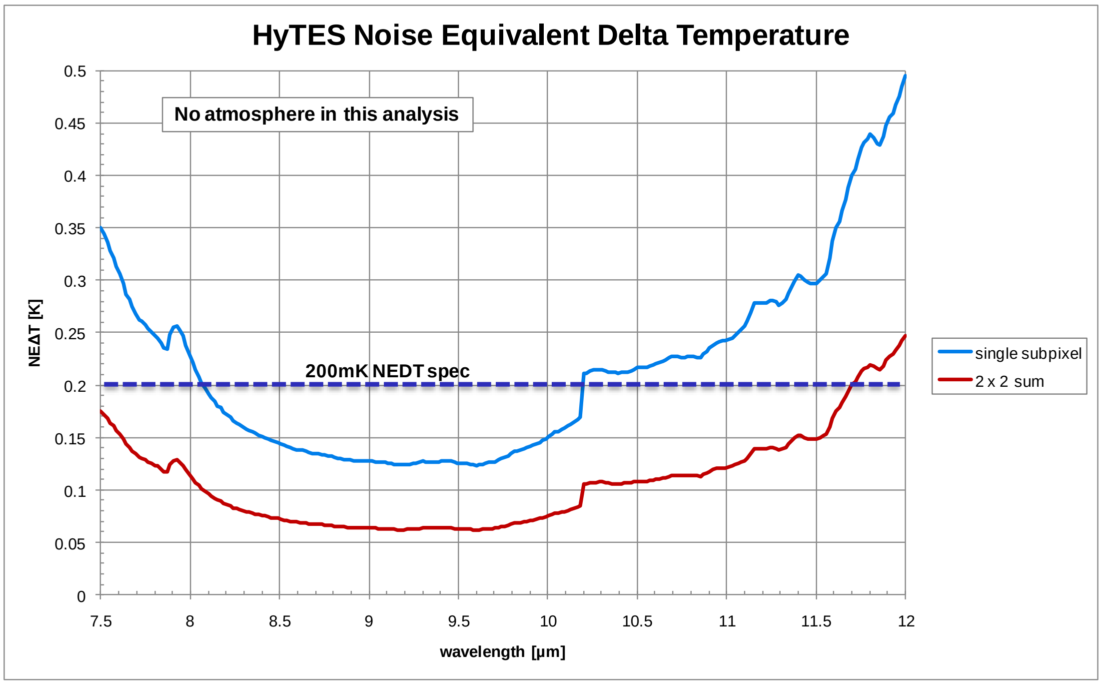

Figure 7. HyTES expected detector performance.

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