# Long-wave infrared Dyson spectrometer

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## ABSTRACT

Preliminary results are presented for an ultra compact long-wave infrared slit spectrometer based on the dyson concentric design. The dyson spectrometer has been integrated in a dewar environment with a quantum well infrared photodetecor (QWIP), concave electron beam fabricated diffraction grating and ultra precision slit. The entire system is cooled to cryogenic temperatures to maximize signal to noise ratio performance, hence eliminating thermal signal from transmissive elements and internal stray light. All of this is done while maintaining QWIP thermal control. A general description is given of the spectrometer, alignment technique and predicated performance. The spectrometer has been designed for optimal performance with respect to smile and keystone distortion. A spectral calibration is performed with NIST traceable targets. A 2-point non-uniformity correction is performed with a precision blackbody source to provide radiometric accuracy. Preliminary laboratory results show excellent agreement with modeled noise equivalent delta temperature and detector linearity over a broad temperature range.

**Keywords:** imaging, spectroscopy, QWIP, pushbroom

## 1.1. INTRODUCTION

The Jet Propulsion Laboratory (JPL) has a long history in developing science-grade imaging spectrometers for remote sensing applications. Examples include the world renowned 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 will be eventually orbiting the moon on board India's Chandrayaan-1.

In late 2006, JPL began the development of a breadboard thermal infrared line-spectrometer dubbed the Quantum Well infrared photodetector earth science testbed (QWEST) as a laboratory demonstration of both the thermal dyson spectrometer as well as the quantum well infrared focal plane technology. The current end-to-end effort brings together numerous in-house specialties such as optical design and general spectrometer alignment optimization, precision slit fabrication, high efficiency and low scatter non-flat 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 atmospheric band between 8-14um. Our current demonstration instrument operates between 8-9um while an 8-12um version is still underdevelopment. This bandwidth is extremely important in understanding earth science. There are at least five main science themes from an earth science standpoint which a thermal infrared (TIR) spectrometer instrument would address:

**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?

The QWEST testbed will allow for a smoother transition to a fully operational airborne platform suitable for earth science. It will have enough spatial and spectral resolution to allow scientist to acquire the necessary data to plan future space borne missions.

### 1.2. Dyson Background & LWIR Optical Design

Concentric designs allow an idealized infinitely thin slit to be mapped perfectly from the input aperture 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]. Having a concentric design like the Offner compliments beautifully with a pushbroom slit spectrometer designs. Smile and keystone distortion are nearly eliminated using proper alignment techniques as well as non-idealized point spread function (PSF) properties.

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[8] published a paper in 1959 outlining a seidel corrected unit magnifier which was composed of a single lens and concave mirror. He outlined the higher order aberrations but his end result was to be used to project groups of lines for emulsion photography and also phase contrast microscopy.

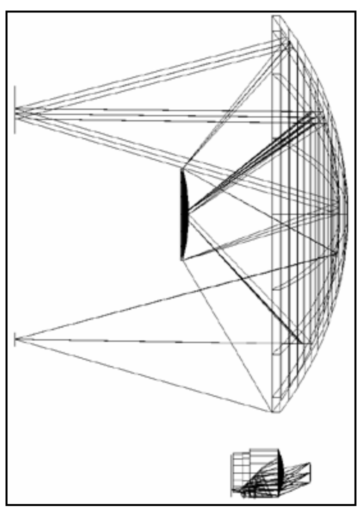


**Figure 1.** Optical design for LWIR Offner and Dyson comparing relative size. Both are F1/.6 with the same amount of dispersion and slit width.

Mertz also proposed the Dyson principle in the same paper in 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. Kuester[12] 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 F/# systems is dramatic as shown in figure 1. Our dyson spectrometer was deigned to minimize smile and keystone distortion[13] while virtually eliminating ghosting. The design requirements which stem from the science are a function of the detector pixel size. We're operating with a 50um effective pixel so smile and keystone distortion were kept to no more than 1-2% of this or ~2um. JPL can fabricate ultra precision slits 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 alignment hence it falls on the opto-thermo-mechanical design and fabrication to alleviate these concerns. As shown in figure 2, a single monolithic block is used in double pass where radiation 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 3. Broadband area coatings are used on all applicable light transmitting surfaces. The coatings allow 99.5% or better LWIR radiation to transmit.

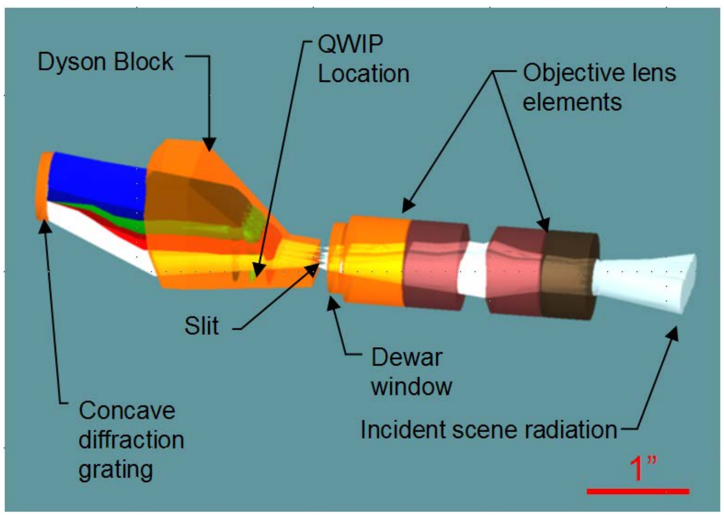



**Figure 2.** Conceptual layout of Dyson spectrometer and objective lens elements

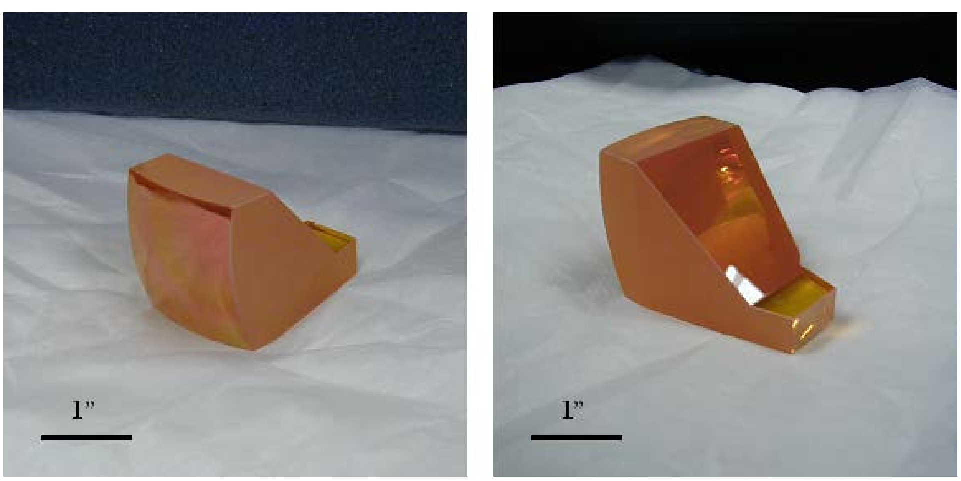



**Figure 3.** Monolithic ZnSe optical block with BBAR coatings used in double pass for the Dyson spectrometer

The main dyson block was fabricated from ZnSe, a robust material with a transparent wavelength region from 0.4 ~ 23um and a very low absorption coefficient between $10^{-3}$cm and $10^{-4}$cm. It's used commonly for optical elements and dewar windows. It's produced in a chemical vapor deposition (CVD) chamber by reacting zinc vapor with selenium vapor and high temperature and pressure. By controlling the physical process parameters, very high quality ZnSe can be produced in large blocks with very low defects. Large ZnSe disk used for lens elements are common, but it's not so common to find a block with significant length in 3-dimensions. Some level of effort was given in finding the necessary material and a fabrication house willing to take on the precision diamond tuning, cutting, polishing and coating necessary for the Dyson to work at the required performance level.

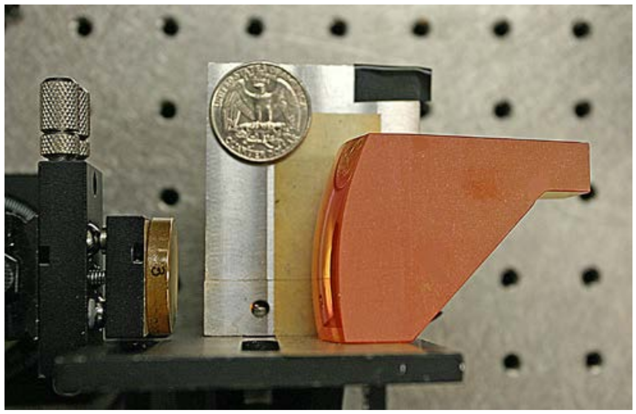


**Figure 4.** Test set-up showing dyson block and concave diffraction grating.

### 1.3. QWIP

QWIP technology[14,15,16] 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 25 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 640x512 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 nomuniformity, 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. The QWEST system is currently at 40K to have a signal-to-noise ratio advantage. The QWIP is known for its high spatial uniformity (<0.02%). This is a clear advantage over other detector technologies such as HgCdTe and InSb. A custom made LCC and FPA clamp was designed to accommodate the close proximity (~mm's) of the FPA with the ZnSe dyson block as shown in figure 5.

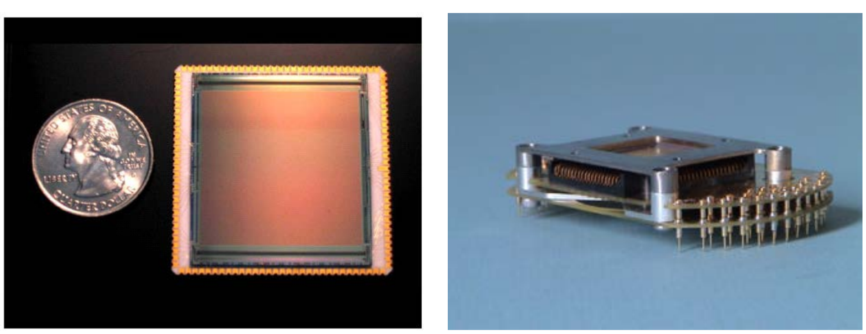
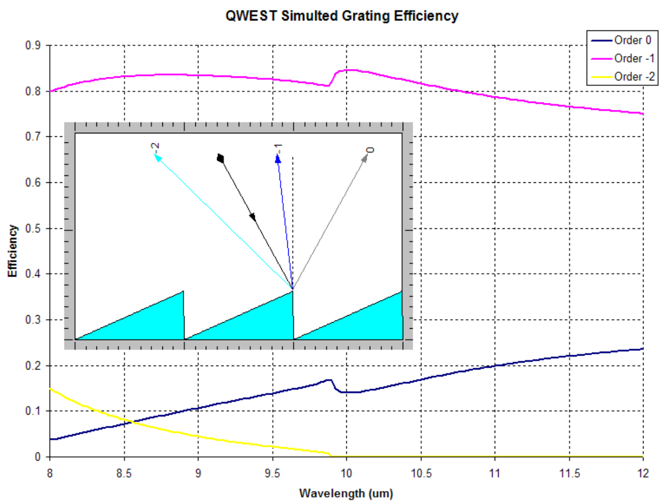


**Figure 5.** QWIP and custom made clamp assembly to hold QWIP and leadless chip carrier (LCC)

### 1.4. Diffraction Grating

Diffraction grating design and fabrication is a key enabling technology for JPL[17]. Specifically, writing gratings on non-flat substrates enables high performance spectrometers. JPL is in possession of an e-beam which has been specially modified by the manufacturer to allow writing on substrates with approximately 3.5 mm of height variation. Accurate E-beam exposure on non-flat substrates is possible because the beam has significant depth of field (10's of µm) in its focus and pattern distortion parameters. The LWIR Dyson single blazed grating design is optimized for maximum efficiency in the -1 order while the other orders are relatively weak as shown in figure 6.



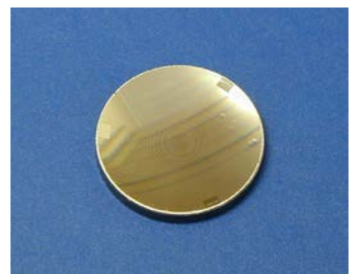



**Figure 6.** a) Blaze grating etched in PMMA on a concave surface using e-beam lithography. Blaze is coated with gold to maximize thermal reflectance. Gratings fabricated in this manner provide ultra-low scatter combined with high efficiency. B) Dyson grating as fabricated. The rectangular markings near the edge are non-exposure regions due to the mount which holds the grating during fabrication.

### 1.5. System Specifications and Results

The main goal of this effort was to show as a proof of concept that high quality data can be obtained using the combination of Dyson spectrometer with QWIP detector. Total system isolation from stray light past the spectrometer slit was established by cryogenically cooling all opto-mechanical structures to 40K. This is reasonable for the testbed due to its small form factor. First light data reductions are presented and look very promising. Excellent spectral signal linearity as well as spectral noise equivalent delta temperature (NEdT) are observed for the peak QWIP sensitivity region surrounding 8.3um while these response characteristics over the entire band are very reasonable considering the QWIP quantum efficiency (QE) fall-off on either side.

The basic specifications of QWEST are shown in figure 7a with a schematic of the instrument in figure 7b. QWEST uses a large format detector and has a large spatial swath width. The current optical design and grating works for the entire 8-12um regime but the existing QWIP which is being used for preliminary testing is sensitive from 8-9um. The broadband (8-12um) QWIP installation is currently underway and results will be presented in future publications. The close proximity of all electro-optical components can be appreciated in figure 8. This shows the dyson block and hardware in nearly its final configuration.

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

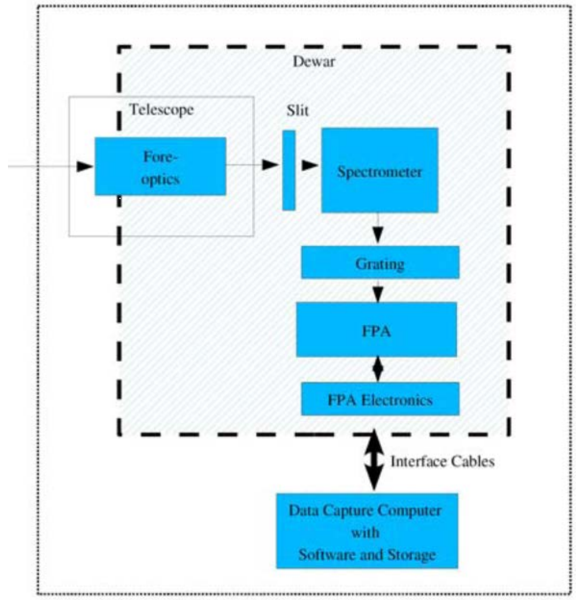



**Figure 7.** a) Final system specifications and b) schematic concept of dyson spectrometer

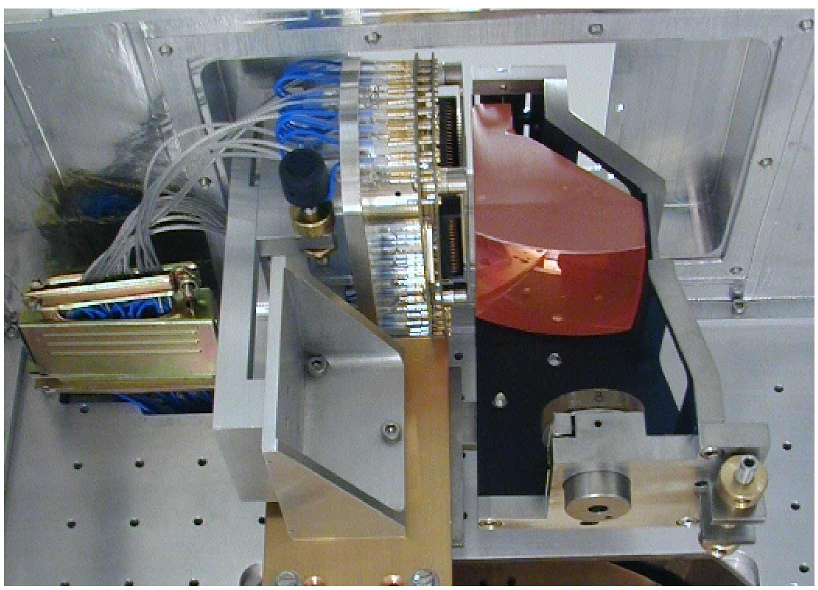


**Figure 8.** Dyson spectrometer testbed in totally isolated dewar environment.

A spectral calibration is performed using narrowband interference filters. This is an easy way to determine the position of the spectral bands and verify the full width at half max Gaussian filter function as shown in figure 9. A few test room temperature pushbroom scans are shown in figure 10 to verify the spatial resolution performance. Handheld rocks and minerals in plastic containers are shown. For radiometric performance, a NIST traceable transfer calibration is performed on our electro-optic blackbody to verify its performance between the two end bracket temperatures of 5C and 30C. 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. Calibration 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[18,19,20] where 5C and 30C are used to bracket the temperature range. The blackbody is ramped from 5C to 30C 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's.

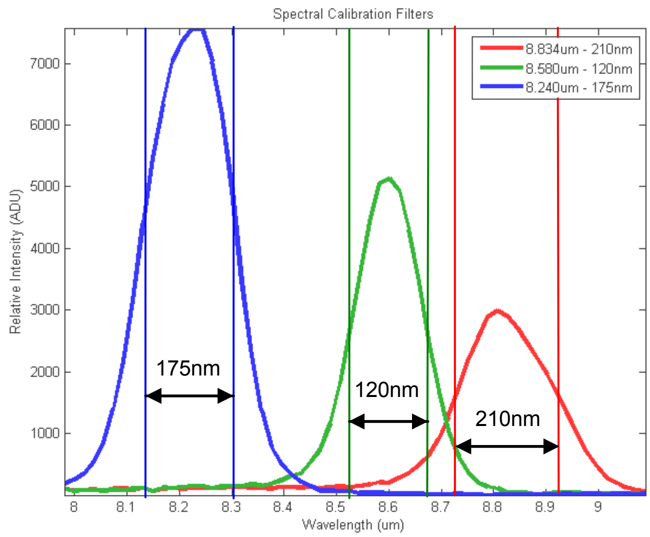



**Figure 9.** Narrowband spectral calibration filter response.

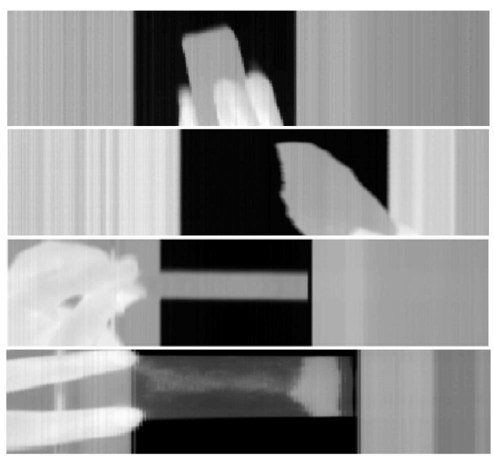
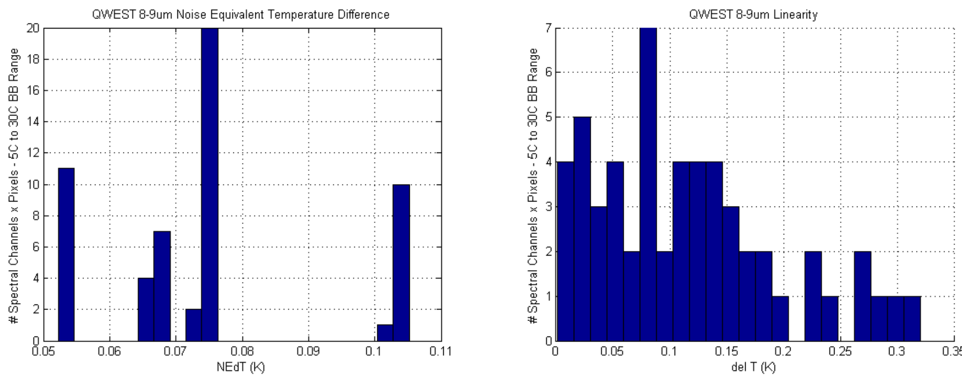


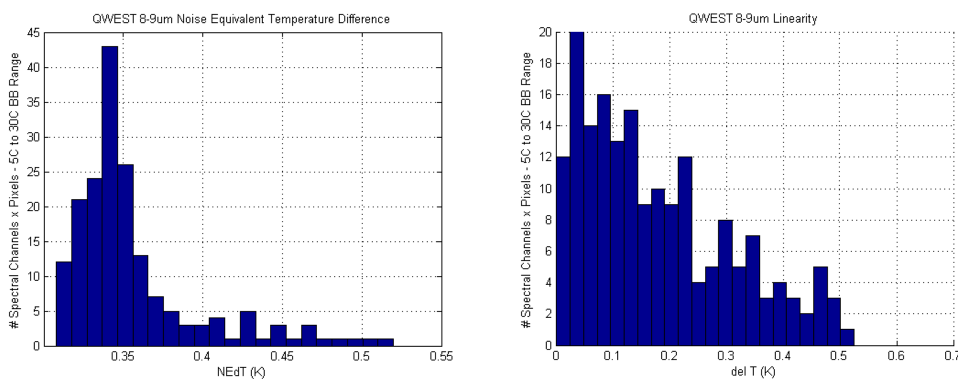
**Figure. 10.** Laboratory Pushbroom scans of various minerals.

Plots are shown for 2 scenarios. One shows spectral NEdT while the other shows spectral linearity. Figure 11 is for all bands near the peak of the QWIP response (i.e. $QE_{QWIP} > 20\%$), while figure 11b shows all the spatial and spectral data irrespective of detector QE. These two scenarios are differentiated as *best* and *worst* case scenarios for the 8-9um QWIP. We define the two performance metrics due to the response which is expected once the broadband QWIP is installed. It is expected that the spectrometer performance results using the broadband QWIP should approach that of 11a over the entire LWIR bandpass (i.e. 8-12um: $QE_{QWIP} > 20\%$ for 7.8-11.5 um).




a)

**Mean Spectral NEdT: 74.7mK**
(Minimum error: 52.3mK - maximum error: 105.2mK)
**Mean Linearity Error: 0.1149K**
(Minimum error: 0.00082K - maximum error: 0.3204)




b)

**Mean Spectral NEdT: 356mK**
(Minimum error: 308mK - maximum error: 520mK)
**Mean Linearity Error: 0.179K**
(Minimum error: 0.0011K - maximum error: 0.5253)

**Figure 11.** Noise equivalent temperature difference and detector linearity as measured for two scenarios. a) Narrowband response near peak of 8-9um QWIP, b) Broadband response from full 8-9um band. When implemented, the full LWIR QWIP will have peak response (>20% QE) over 7.8-11.5 um. It's expected the performance of the system should approach that shown in (a).

### 1.6. REMARKS

We've demonstrated the operation of a small form factor long wave infrared Dyson spectrometer using a QWIP focal plane array. The main advantage of the QWIP technology is its excellent spatial uniformity. The NEdT and linearity are excellent for the range of QE > 20%. The same spectrometer performance over the nominal LWIR bandpass is expected once the broadband QWIP installation is completed. Strain-layer super lattice detectors[21] which are also being fabricated at JPL have the potential of offering similar uniformity but with a higher operating temperature and higher QE. Future dyson platform may be able to take advantage of this technology as well.

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