QWEST and HyTES: Two New Hyperspectral Thermal Infrared Imaging Spectrometers for Earth Science

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Abstract— **We have recently developed a laboratory prototype of an airborne thermal infrared imaging spectrometer termed the Quantum Well Earth Science Testbed (QWEST). Based on our experience with QWEST we are developing the airborne Hyperspectral Thermal Emission Spectrometer (HyTES). HyTES is scheduled for completion in 2011. Both instruments utilize several key components: slits, spectrometers, gratings and detectors developed at the Jet Propulsion laboratory. In particular, each design uses a Dyson spectrometer, an electron microbeam grating and a Quantum Well Infrared Photodetector (QWIP) focal plane array. The Dyson configuration uses a single monolithic prism-like grating design which allows for a high throughput instrument (F/1.6) with minimal ghosting, stray-light and large swath width. The configuration has the potential to be the optimal imaging spectroscopy solution for lighter-than-air (LTA) vehicles, unmanned aerial vehicles (UAV), manned airborne platforms and spaceborne platforms due to its small form factor and relatively low power requirements. The instrument specifications will be discussed as well as design trade-offs. Calibration results from QWEST (noise equivalent temperature difference, spectral linearity and spectral bandwidth) will be presented as well as some field results. Field testing of QWEST was performed to acquire data from a variety of standard minerals and these will be compared to laboratory measurements of the same minerals made with an FTIR spectrometer.**

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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) now 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[3,4] (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 currently under development which is 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 earth observing thermal infrared (EOTIR) is typically expressed as the wavelength range between 7 and 14 µm. Our current demonstration instrument operates between 7.5 – 9.5 µm and the planned airborne instrument 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 which was recently recommended by the National Research Council in their Decadal Survey. The EOTIR 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?

The QWEST testbed provides a means for testing enabling technology for the development of a fully operational airborne platform suitable for earth science studies. HyTES when fully operational 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[5,6] 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[7]. Subsequent work was also done by Kwo[8] and Lobb[9]. 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.

The Offner design is relatively large with our required throughput and would require a bulky temperature controlled dewar and large power supplies to maintain adequate thermal control for the EOTIR. J. Dyson[10] 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[11] proposed a Dyson design for microlithography in the visible and ultraviolet and Mouroulis[12,13] 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[14]. Kuester[15] 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 EOTIR. QWEST was designed to minimize smile and keystone distortion[16] 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 fabricated is shown in figure 2. Broadband area coatings are used on all applicable light transmitting surfaces. The coatings allow 99.5% or better EOTIR 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.

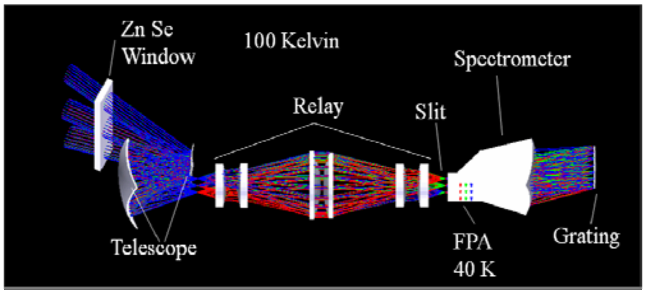


Figure 1. Conceptual layout of Dyson spectrometer and objective lens elements

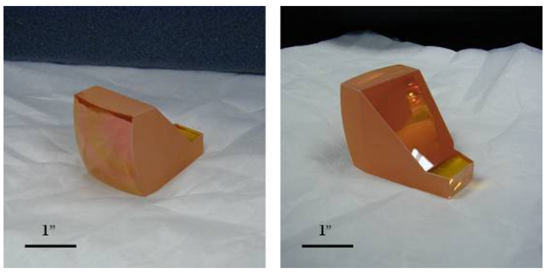


Figure 2. Monolithic ZnSe optical block with BBAR coatings used in double pass for the Dyson spectrometer

3. THE QWIP ARRAY

QWIP technology[17,18,19] 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 studies requiring accurately calibrated data.

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 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 as shown in figure 3.

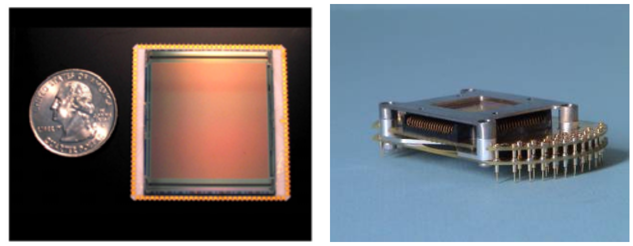
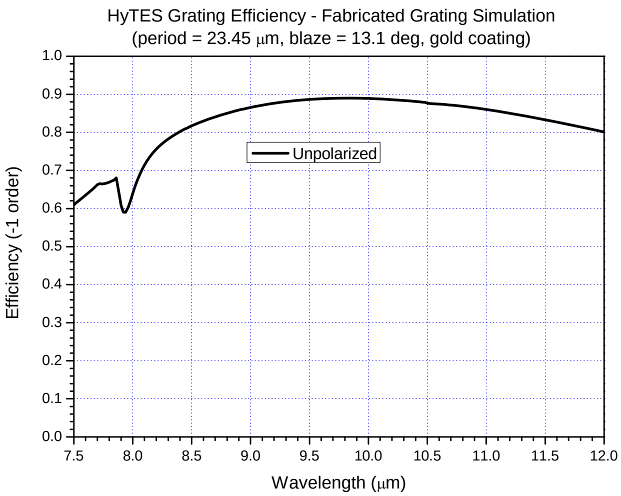


Figure 3. QWIP and custom made clamp assembly to hold QWIP and leadless chip carrier (LCC)

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.[20,21,22] Gratings fabricated in this manner provide high efficiency combined with low scatter. The blazed grating for this EOTIR 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 Fig. 4a and 4b, respectively. The design was optimized for maximum efficiency in the -1 order, and the other orders remain relatively weak across the band. The grating in correct system orientation is shown in figure 6.

(a)



(b)

Figure 4. 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. SYSTEM SPECIFICATIONS AND RESULTS

Both QWEST and HyTES total system isolation from stray light past the spectrometer slit was established by cryogenically cooling all opto-mechanical structures to 40K/100K. This is reasonable due to the small form factor of the system. Stray light analysis using FRED (Photon Engineering, LLC) shows the HyTES optical design to have spurious background signal at least 4 orders of magnitude below input signal level. A plot of this is shown in figure 5. This is reasonable due to the expected dynamic range of the system. It also showed the elimination of spatial and spectral ghosts from the sensor region of interest.

Current data reductions are presented here for QWEST and look very promising. Excellent spectral signal linearity as well as spectral noise equivalent delta temperature (NEdT) are achieved. The QWIP appears to have more than adequate spectral quantum efficiency (QE) for typical EOTIR temperatures. Push-brooming allows the integration time to be a manageable 30ms.

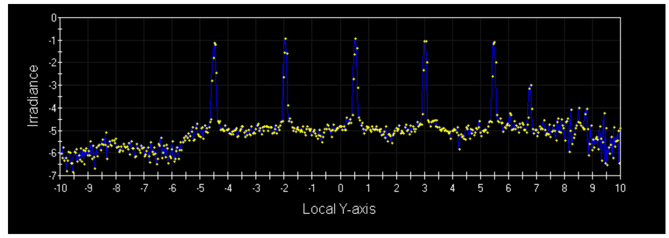
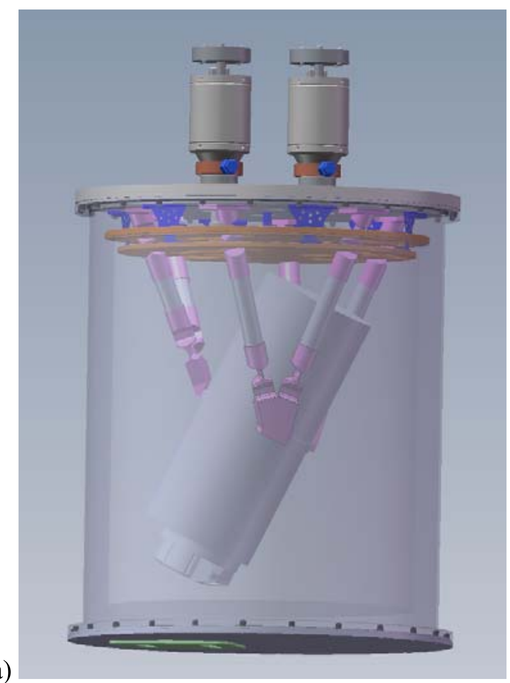


Figure 5. Stray light analysis performed showing background spurious signal for this design to be at least 4 orders of magnitude below signal.

The basic specifications of QWEST and HyTES are shown in figure 6b with a model view of the HyTES instrument in figure 6a. Both systems will use large format detectors and have large spatial swath widths. The current optical design and grating works for the entire 7.5-12μm regime but the existing QWIP FPA which is being used for preliminary testing in QWEST is only sensitive from 7.5-9.5μm. The close proximity of all electro-optical components can be appreciated in figure 7. This shows the ZnSe block and hardware in nearly its final configuration.

a) 

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
QWIP Temperature	40K	40K
Spectrometer (Dyson) 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

b)

Figure 6. a) Instrument design model showing opto-mechanical system in vacuum chamber and b) Final system specifications for QWEST and expected for HyTES

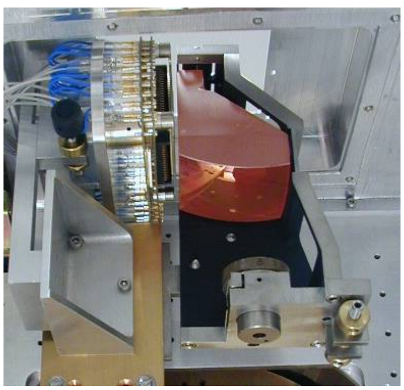


Figure 7. Dyson spectrometer testbed in dewar environment.

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 5C 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[23,24,25] 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..

Two tests were performed in the laboratory to characterize the instrument performance. Test one was for spectral linearity while the other determined the spectral NEdT. The system was shown to have very good linearity with many temperature measurements showing absolute errors below 0.1C. Figure 8 shows the spectral noise equivalent delta temperature for a 25C blackbody.

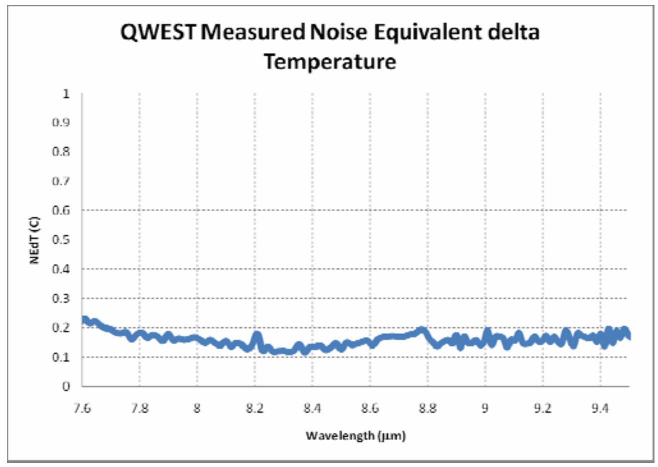
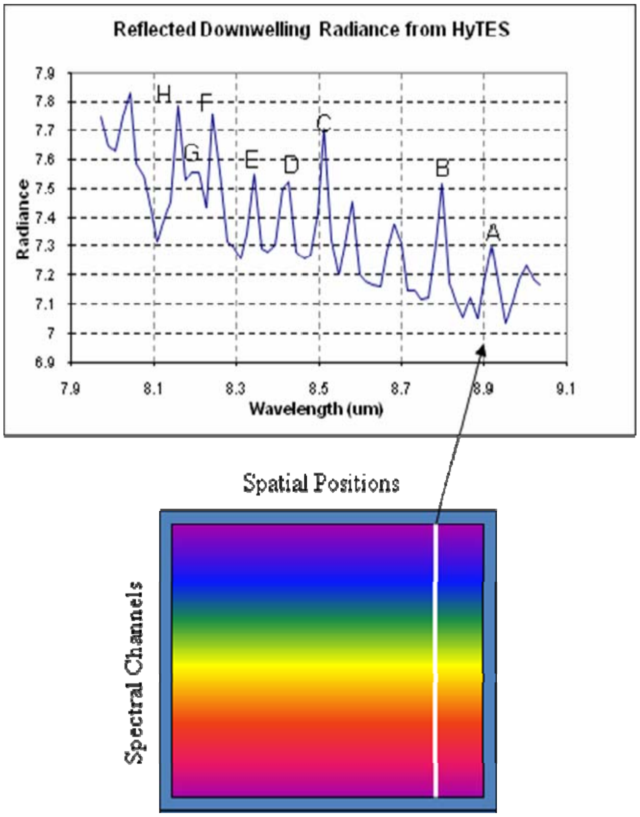


Figure 8. Noise equivalent temperature difference. The distribution is shown for all spectral channels irrespective of blackbody temperature measured. Measurements were made for a calibrated blackbody between 5C and 40C.

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 9 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 output from MODTRAN and previously deployed Fourier transform imaging spectrometers (FTIR), respectively.



	Model	QWEST	Delta
A	8.92061	8.9179	0.00271
B	8.79894	8.7995	-0.00056
C	8.51426	8.5121	0.00216
D	8.4246	8.4276	-0.003
E	8.34725	8.3431	0.00415
F	8.25082	8.2418	0.00902
G	8.20345	8.208	-0.00455
H	8.16327	8.1573	0.00597

Figure 9. Radiance of gold standard with superimposed atmospheric bands as measured in direct sunlight.

This data is then used in part to further reduce data taken with the system in direct sunlight. As shown in figure 10, Quartz deposits within Ottawa sand are found with the following apparent emissivity. This compares favorably with previously taken data[26].

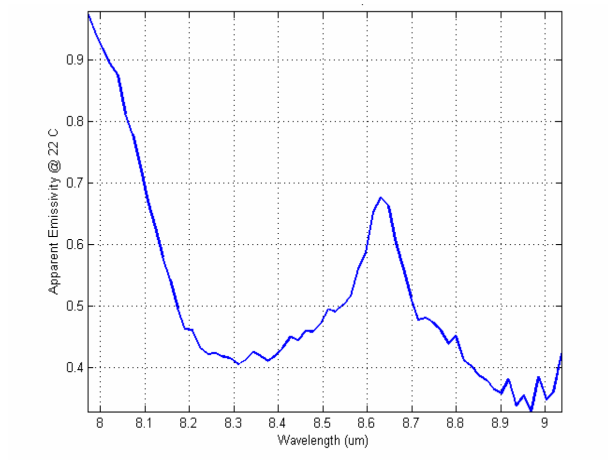


Figure 10. Apparent emissivity of quartz as measured by QWEST in direct sunlight.

6. REMARKS

QWEST which consists of an infrared Dyson spectrometer using a QWIP focal plane array has shown to be a success. We fully expect the airborne implementation, HyTES, to follow suit. The main advantage of the QWIP technology is its excellent spatial non-uniformity (< 0.5%). Results presented here show measured NEdT and linearity to be excellent. The same spectrometer performance over the nominal EOTIR bandpass (7.5-12□m) is expected once the broadband QWIP installation is completed.

Strain-layer super lattice detectors[27] 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 platforms may be able to take advantage of this technology as well.

7. ACKNOWLEDGEMENTS

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BIOGRAPHY

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.

Dr. Sarath D. Gunapala received his PhD in physics from the University of Pittsburgh in 1986. Since then he studied infrared properties of III-V compound semiconductor hetero-structures and the development of quantum well infrared photodetectors (QWIPs) for infrared imaging at AT&T Bell Laboratories. He joined NASA's Jet Propulsion Laboratory at California Institute of Technology in 1992. There, he leads the Infrared Focal Planes & Photonics Technology Research Group. Also, he is a senior research scientist and a principal member of the engineering staff at NASA Jet Propulsion Laboratory. Dr. Gunapala has authored over 250 publications, including several book chapters on infrared imaging focal plane arrays, and holds seventeen patents. He is a SPIE Fellow and Senior Member of IEEE.

Pantazis Mouroulis is a graduate of the University of Athens _BSc in physics 1976 and the University of Reading MSc and PhD in optics 1981. He is at present a senior research scientist and principal engineer at the Jet Propulsion Laboratory JPL, where he supervises an optical technology group. His recent research interests focus on instrumentation for imaging spectroscopy.

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 advance imaging spectrometer devices and data reduction techniques with a specific interest in the generalized problem of quantitative spatial and spectral modulation.

Dr. Daniel W. Wilson received the PhD in electrical engineering from the Georgia Institute of Technology in 1994. He is currently a principal engineer in the Microdevices Laboratory at Jet Propulsion Laboratory, California Institute of Technology. His research interests include the design, modeling, and electron-beam fabrication of diffractive optical components and instruments. Since joining JPL, he has contributed to the successful development of high performance convex diffraction gratings, coronagraph occulting masks, transient-event imaging spectrometers, and particle velocity sensors.

Dr. Cory Hill received his B.S. degree in physics from the University of Southern California in 1996, and the M.S. and Ph.D. in applied physics at the California Institute of Technology in 2001. He is a senior member of the engineering staff at the Jet Propulsion laboratory. His research activities include device *design and molecular beam epitaxial growth of III-V AS and Sb based materials for mid-ir lasers, ir focal planes and avalanche photodiodes.*

Jason Mumolo received his B.S. degree in electrical engineering from polytechnic University of California, Pomona in 2001. He joined the Jet propulsion Laboratory, California Institute of technology in Pasadena in 1997 as an undergraduate part-time student. He's current work and interest is in developing and fabrication of QWIP devices and other advance focal plane arrays for camera systems.