Sensor Development Overview

December 5, 2002

Valerie Duval – System

Marc Walch – Systems

Robert Green – Imaging Spectrometry

Mark Wadsworth – HIT

Ed Blaze – Program Manager

Sarath Gunapala – QWIP

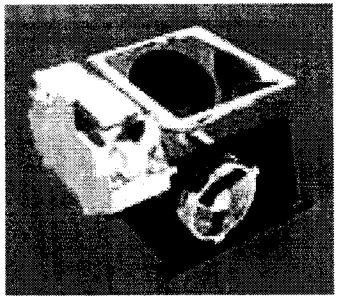
Tom Cunningham – APS

Mark Foote – Thermopiles

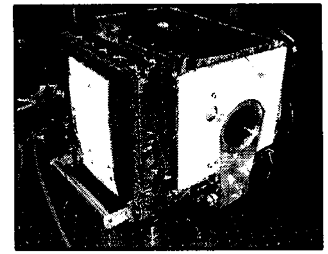
Instrument System Leadership

End-to-end responsibility for remote sensing instrument development—for both JPL's and for others' missions

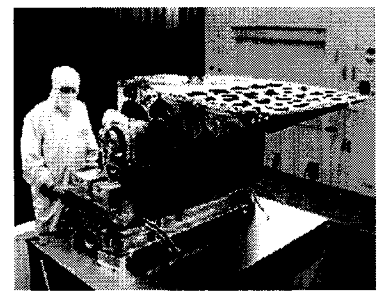
- *Airborne and Space-borne*
- *Planetary, Astrophysics*



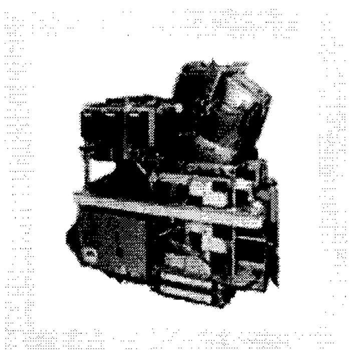
Cassini VIMS



MICAS for DS-1

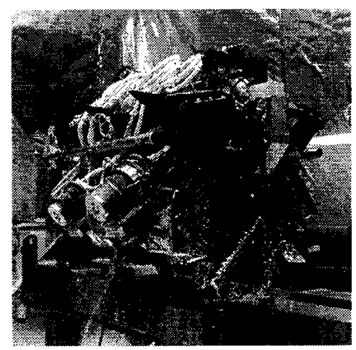


AIRS (Earth Observing System)

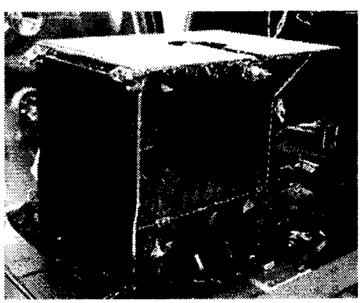


AVIRIS—Airborne (ER-2)

WF/PC-2 (Hubble Retrofit)

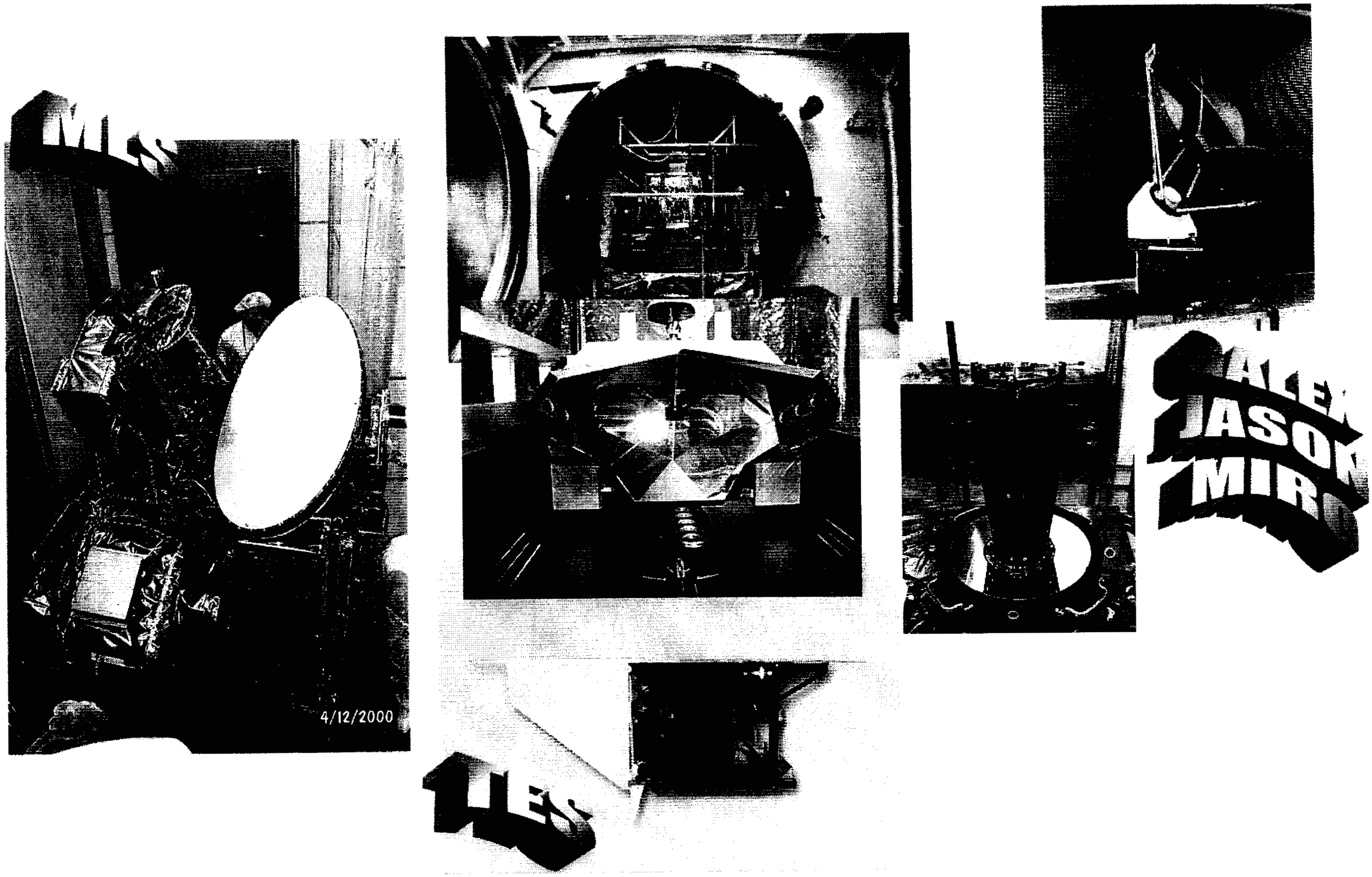


MISR (Earth Observing System)



TES (Earth Observing System)

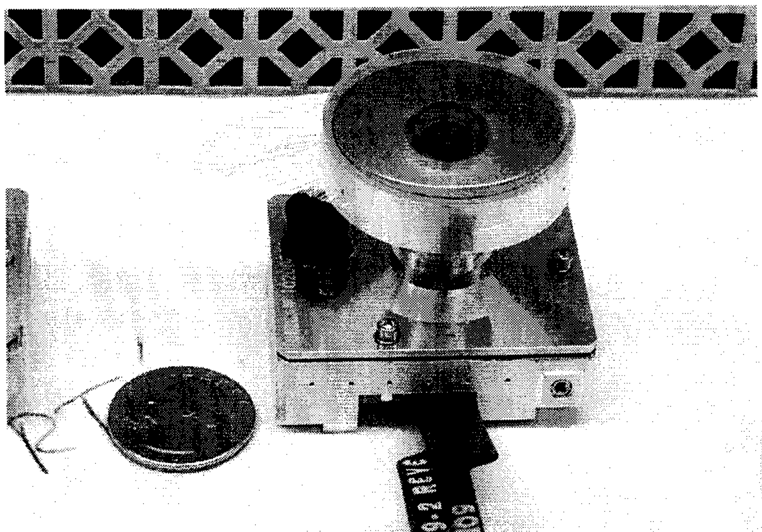
Instrument System Leadership



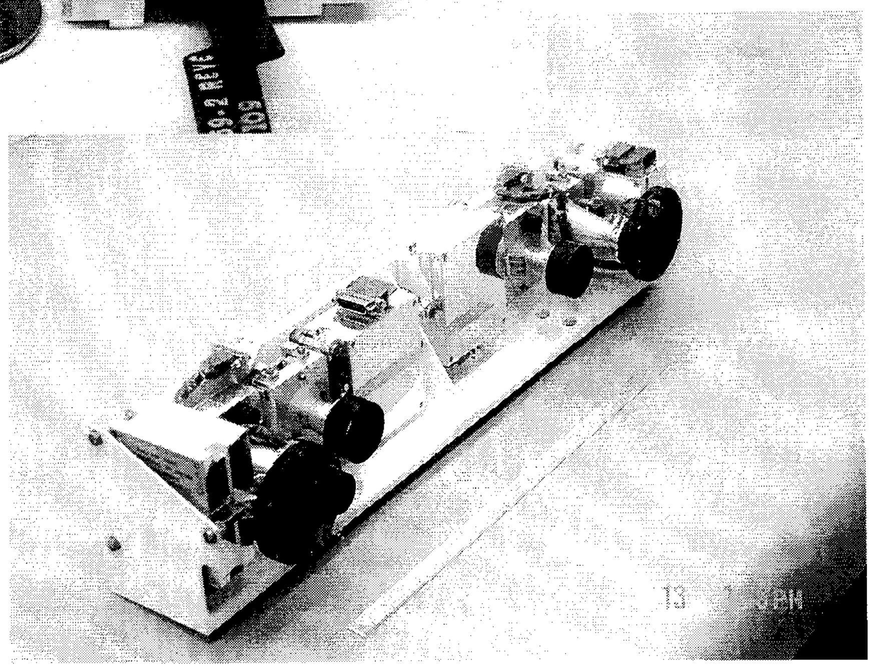
Specific Instrument Capabilities

- Instrument system design, fabrication, and integration, mirroring the JPL end-to-end capability
- Focal Planes
  - Focal Plane Arrays, packaging, system integration
- Optics
  - Design, analysis, and integration and test
- Electronics
  - Digital and analog, including focal plane readout
- Calibration and data utilization
- End-to-end science data systems

Mars Exploration Rover Cameras



HazCam



PanCams

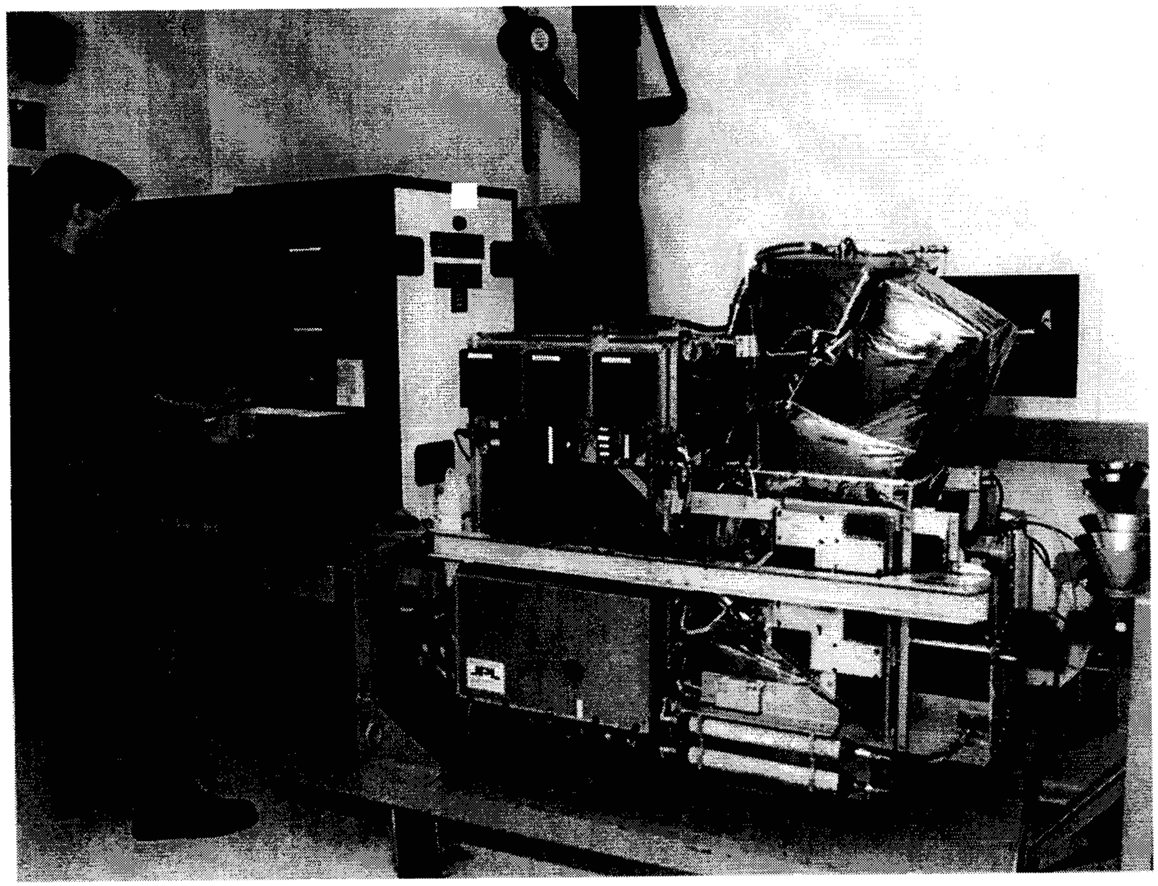
Camera specs

- Camera Types
  - PanCams (Stereo pairs)
  - Microscopic Imager
  - NavCams (Stereo Pairs
  - HazCams (Stereo Pairs)
  - SunCam

- Mass: 210 – 250 grams
- Power: 2.4W
- Detector Format: 1024^2
- Operating Temp: –55 to +5°C

Picture Taken by MER Camera—Mars lighting

AVIRIS Instrument



AVIRIS Data Set Example: Pearl Harbor, Hawaii

Spectral

Range	370 to 2500
Sampling	9.8 nm
Accuracy	0.5 nm

Radiometric

Range	0 to Max Lambertian
Sampling	12 bits
Accuracy	96 percent

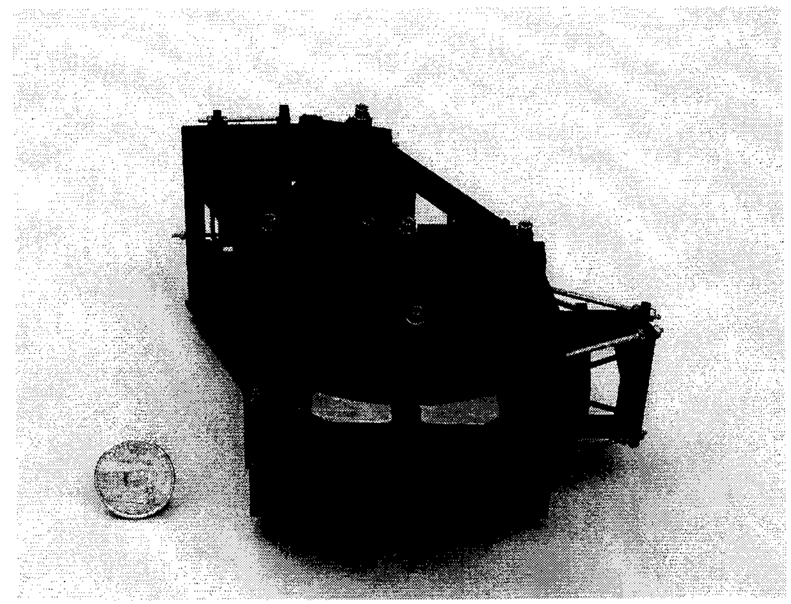
Spatial (ER-2 / Twin Otter aircraft)

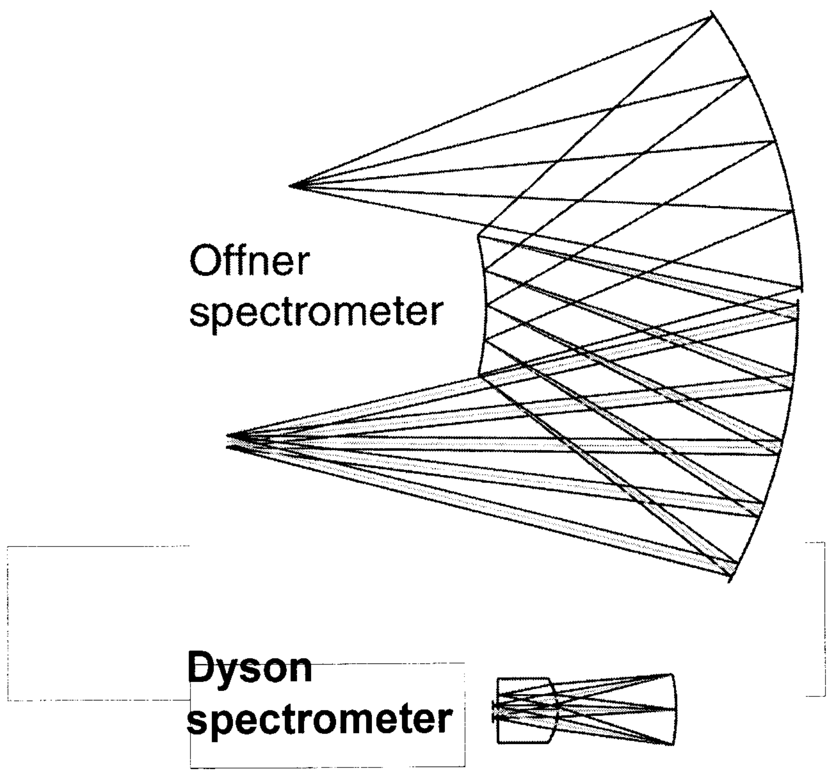
Swath	11/2.2 km ER-2/TO
Sampling	20/4 m ER-2/TO
Accuracy	20/4 m ER-2/TO

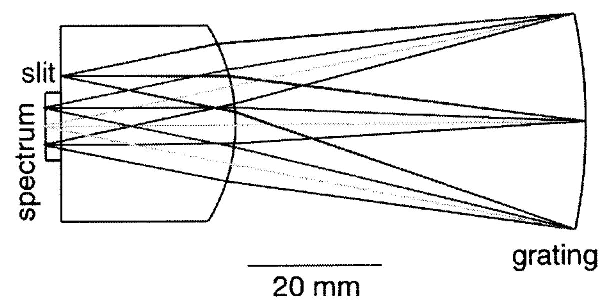
Full INU/GPS geo rectification

New Concepts in Imaging Spectrometry at JPL

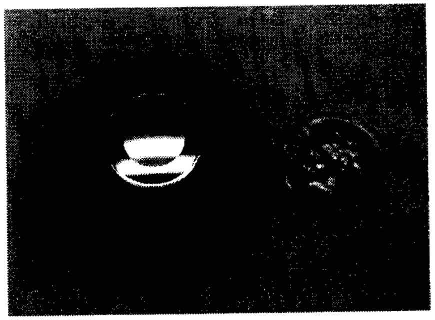
- **New system design can decrease size, mass, and power while maintaining AVIRIS capability**





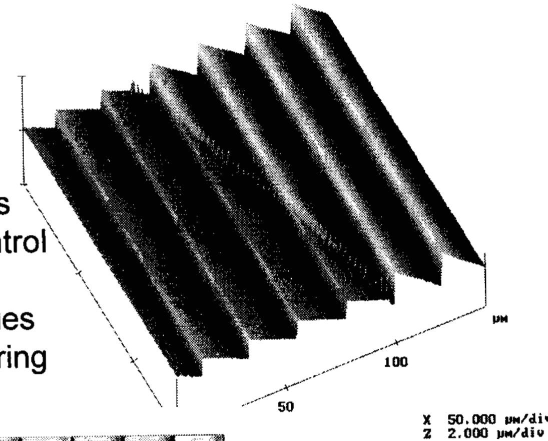


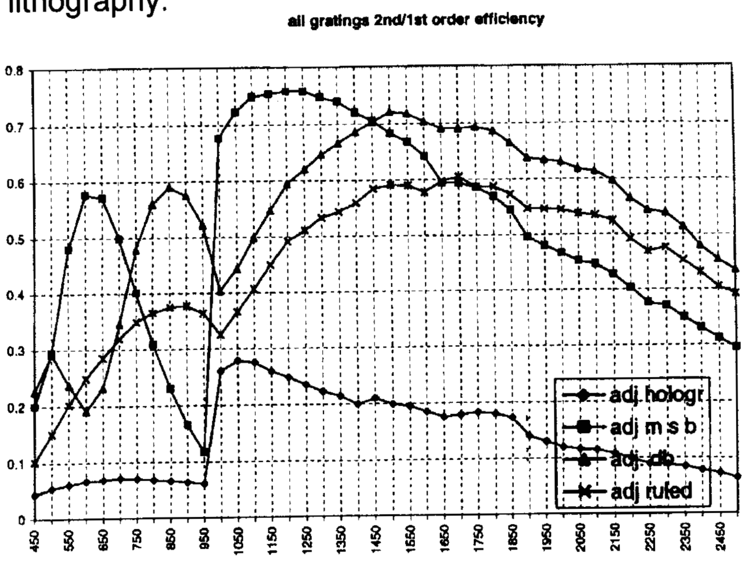
E-Beam Lithography Diffraction Gratings



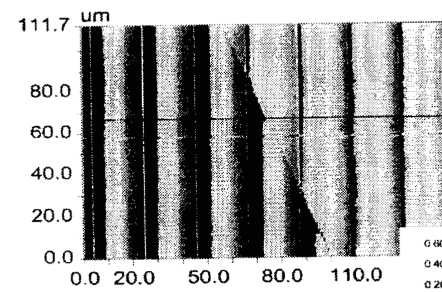
For the first time, JPL has fabricated high-performance *blazed gratings on convex substrates* by using E-beam lithography.

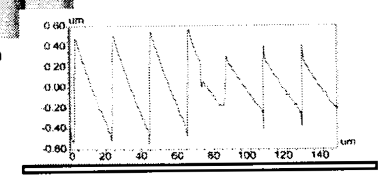
The Ultra-precise lithography process allows orders of magnitude finer control over grating surface finish than conventional manufacturing techniques - providing >10x reductions in scattering and ghosting



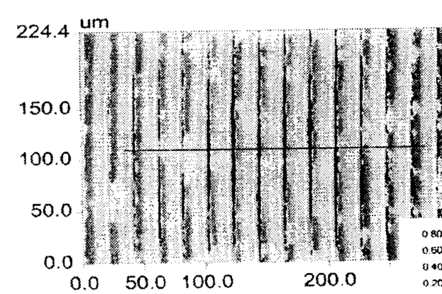


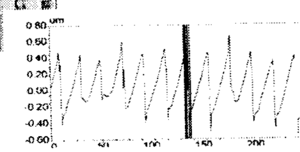
E-beam gratings offer 2-3x efficiency advantage and design flexibility over holographic and ruled gratings





Dual-Blaze E-beam Grating (EO-1 GIS Flight Grating)





Ruled Grating (EO-1 Flight Candidate)

HIT--Hybrid Imaging Technology Selected for Mars'05 Op-Nav Camera

This camera will demonstrate high accuracy (1 km or 0.1 degree flight path entry angle, both 3 sigma) approach navigation. JPL is currently working with LMA to configure it on the '05 MRO spacecraft. It is a level 1 mission requirement, as the use of HIT helped reduce the system mass to 2.5 kg and the power usage to 3 watts.

Upcoming Projects Which Baseline HIT

- 2007 CNES orbiter called Premier
- 2007 G. Marconi Italian sample canister detection orbiter
- 2007atmospheric entry Scout mission
- 2009 Mars Smart Lander

HIT - Hybrid Imaging Technology

Small, low power, scientific-quality digital cameras for visible, UV and IR applications

Photon Detection Capability Rivaling Scientific CCDs

- System Level Integrability Rivaling CMOS
- Power < 25 mW
- Linearity > 99.6%
- Physical Size < 5 cm per side, Mass < 100 grams

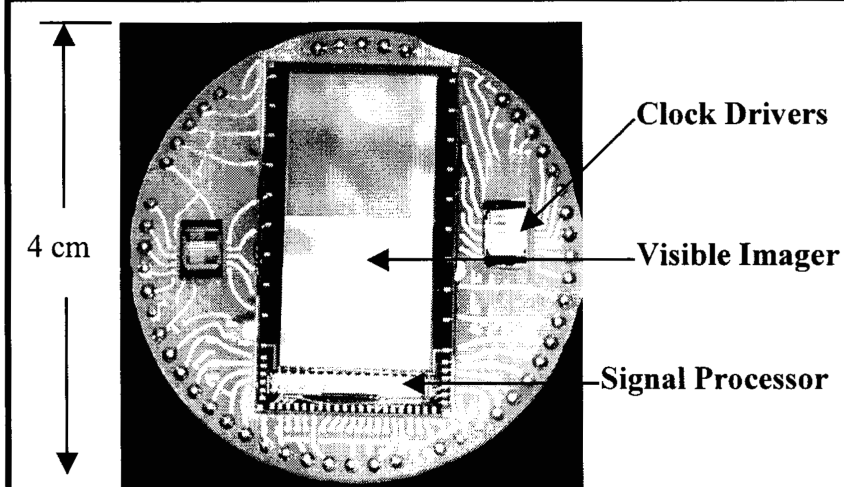
HIT was recently licensed to an imaging company for commercial development

Compare HIT Op-Nav to Viking Op-Nav Camera

	MRO HIT Camera	Viking Camera
Mass	2.5 kg	20 kg
Power	3 watts	23 watts
Aperture	6 cm	13 cm
Noise Level	5 e- (rms)	1000 e- (rms)
Navigational Accuracy	2 microradians	10 microradians

The Viking Camera was the last camera used for optical navigation at Mars. HIT revives the capability.

1k x 1k Pixel HIT Optical Navigation Camera



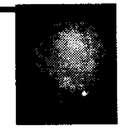
Detector Array Technology

- Quantum Well Infrared Photodetectors (QWIPs)
- Thermopile Detectors
- Active Pixel Sensors (APS)
- Delta Doped Charge Coupled Devices (CCDs) and APS
- Curved Focal Plane Arrays
- MEMS Devices

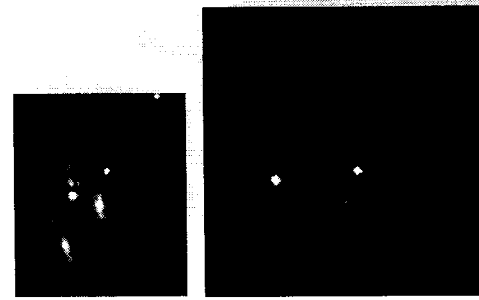
ADVANCES IN QWIP TECHNOLOGY AT JPL

SEEING THE UNIVERSE IN A NEW LIGHT USING QUANTUM TECHNOLOGY

Total Eclipse of the Moon taken with QWIP Camera 20 January 2000



Courtesy: Arnold Goldberg Army Research Laboratory

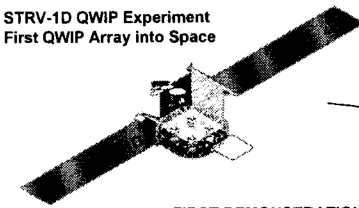


8.5 μm mid-infrared image, obtained with a QWIP focal plane array at primary focus of the Palomar 200-inch Hale telescope.

The S106 region displays vigorous star-formation obscured behind dense molecular gas and cold dust, and extended nebular emission from dust heated by starlight. QWIP-infrared images are used to assess the prevalence of warm dusty disks surrounding stars in such regions. Formation of these disks are an evolutionary step in the development of planetary systems.

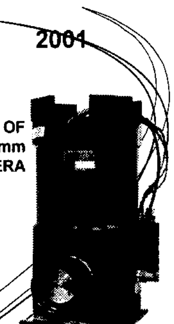
200-inch Hale Telescope, Palomar Observatory

STRV-1D QWIP Experiment First QWIP Array into Space



2001

FIRST DEMONSTRATION OF 8-9 AND 14-15 mm DUALBAND QWIP CAMERA



2000

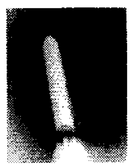
640 x 486 LWIR QWIP CAMERA

1999

FIRST DEMONSTRATION OF PALMCORDER SIZE QWIP CAMERA

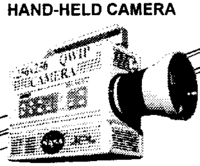
1998

IMAGE OF DELTA II LAUNCH TAKEN WITH 8-9 μm JPL QWIP CAMERA



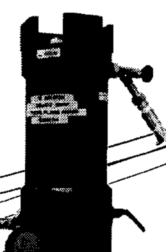
ADVANTAGE OF LWIR QWIPs DETECTING COLD HARD BODIES AGAINST HOT PLUME

FIRST DEMONSTRATION OF HAND-HELD CAMERA



1996

FIRST DEMONSTRATION OF 15 MICRON 128 X 128 QWIP FOCAL PLANE ARRAY CAMERA

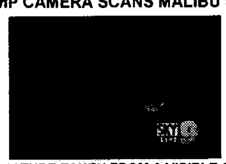


199

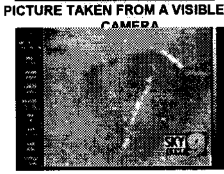
THERMAL INFRARED IMAGING IS USED TO DETECT FAULTY TRANSFORMERS

Courtesy of QWIP Technology

QWIP CAMERA SCANS MALIBU FIRES



PICTURE TAKEN FROM A VISIBLE CCD CAMERA



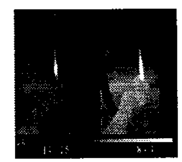
LONG-WAVELENGTH ALLOWS THE QWIP CAMERA TO SEE THROUGH SMOKE AND PINPOINT LINGERING HOTSPOTS (PICTURE ON LEFT) WHICH ARE NOT NORMALLY VISIBLE (PICTURE ON TOP)

THE EVENT MARKED THE QWIP CAMERA'S DEBUT AS A FIRE OBSERVING DEVICE.

640 x 486 QWIP IMAGE

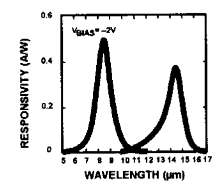
Features of 640 x 486 QWIP Camera

Array Size =	311,040 pixels
Spectral Bandpass=	8-9 μm
Quantum Efficiency=	4.5%
Operability =	99.98%
NEΔT =	36 mK
FPA Uniformity=	99.95%



SIMULTANEOUS 8-9 AND 14-15 μm DUALBAND IMAGE OF A FLAME

SIMULTANEOUSLY MEASURED RESPONSIVITY SPECTRUMS OF A DUALBAND DETECTOR



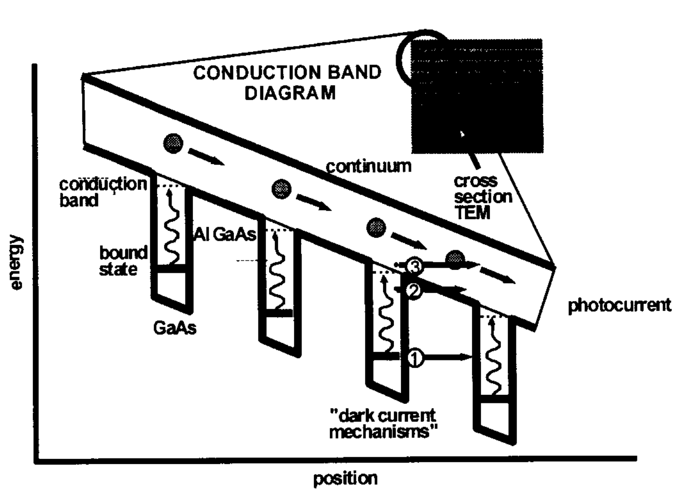
DUALBAND FOCAL PLANE ARRAY DATA

DETECTIVITY (cm√Hz/W) (300K BACKGROUND WITH f/2 STOP, T = 40K)	2.9×10^{10}	1.1×10^{10}
NEΔT (mK)	29	44
OPERABILITY (<100 MK)	99.7%	98%
NON-UNIFORMITY	0.03%	0.05%

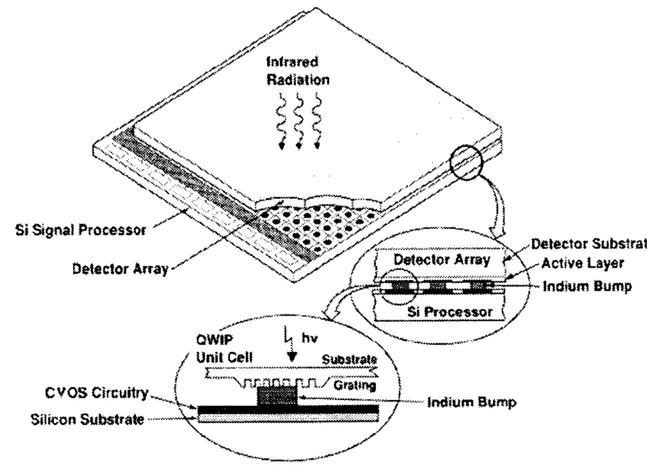
- OVER 100 PUBLICATIONS IN QUANTUM AND NANO TECHNOLOGY
- ORGANIZED QWIP 2000 WORKSHOP
- 18 PATENTS FILED (4 APPROVED, 14 PENDING)
- DELIVERED OVER 100 FOCAL PLANE ARRAYS

Reference: Sarath D. Gunapala, et al., *IEEE Trans. Electron Devices*, **44**, pp. 45-57, 1997; **45**, 1890 (1998); **47**, pp. 326-332, 2000; **47**, pp. 963-971, 2000

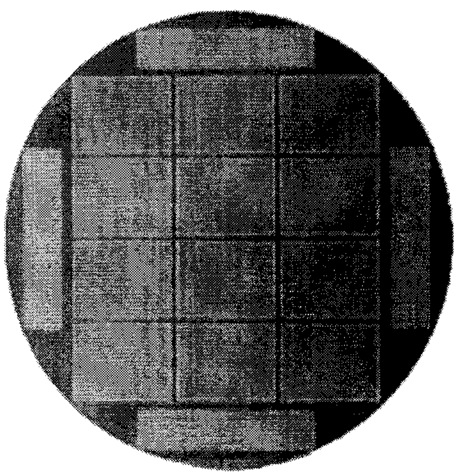
640 x 512 Pixel Focal Plane Array



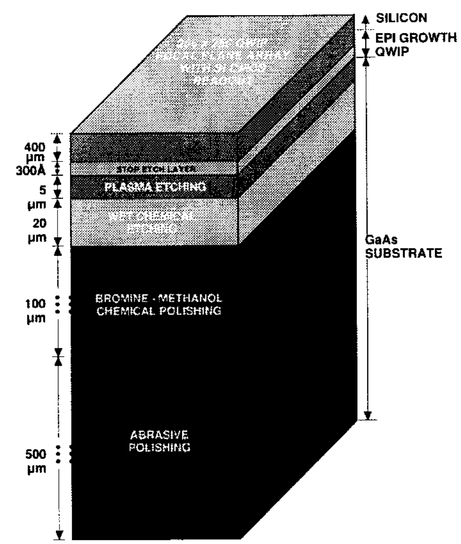
BOUND-TO-QUASIBOUND QWIP



INDIUM BUMP BONDING PROCESS



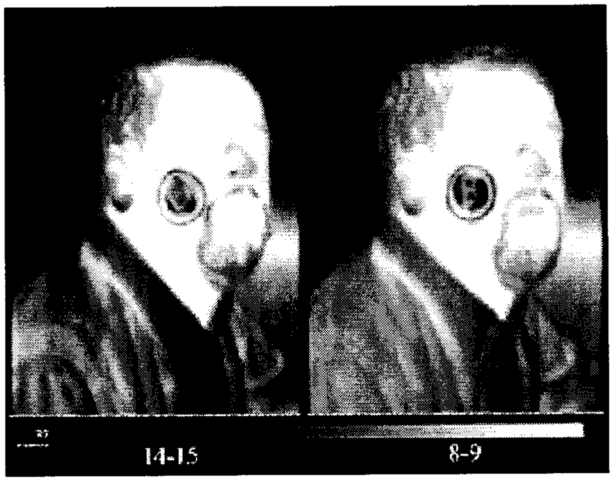
TWELVE 640x512 QWIP FOCAL PLANE ARRAYS (FPAs) ON 3 inch GaAs WAFER

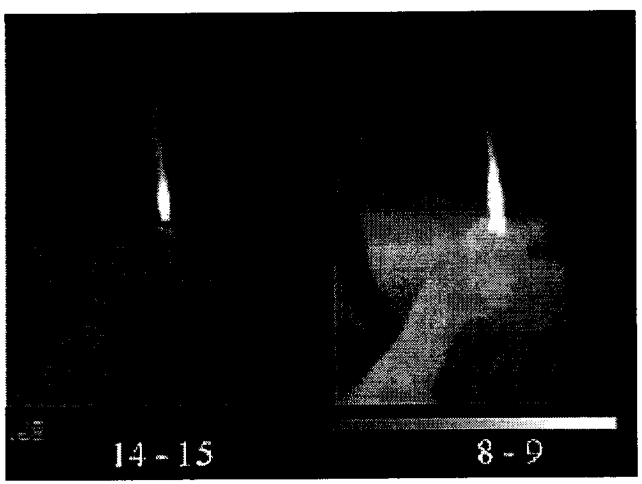


FPA THINNING PROCESS

Dualband Focal Plane Arrays

SIMULTANEOUS 8-9 AND
14-15 μm DUALBAND IMAGERY

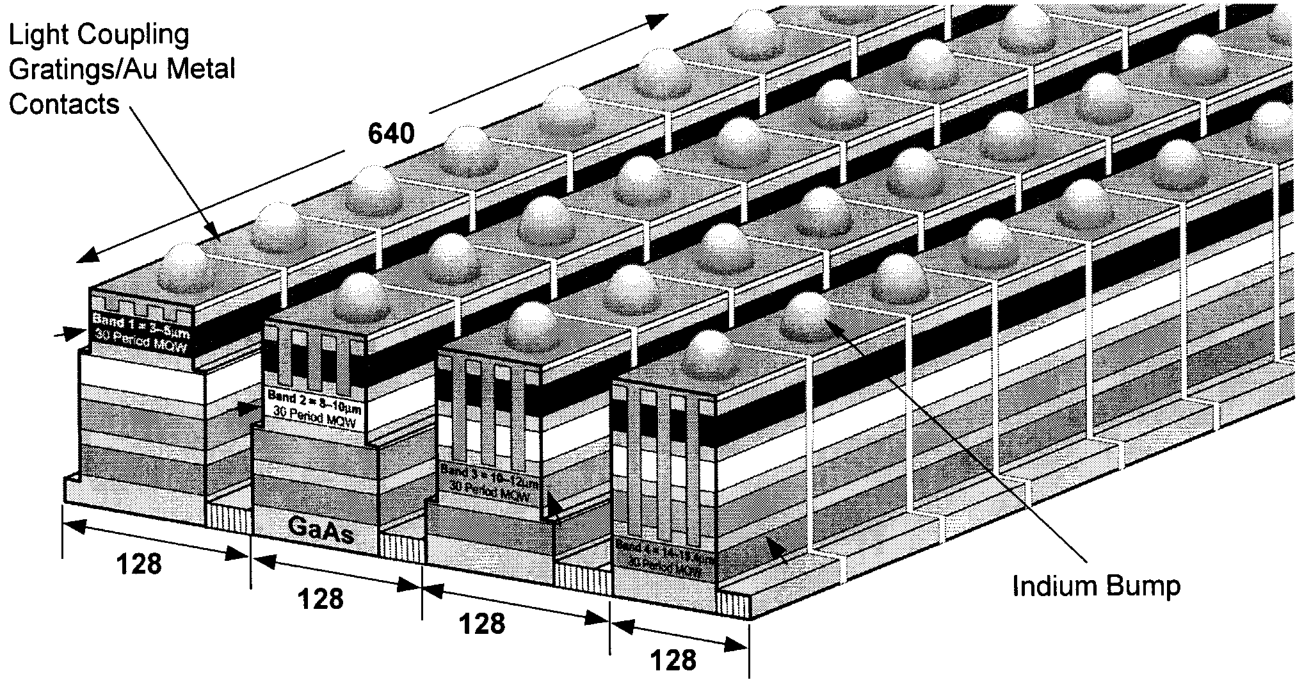


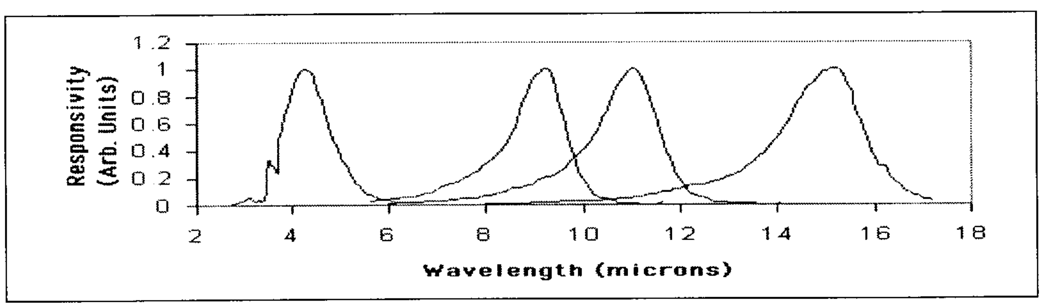


ARRAY SIZE	640X486	
50% SPECTRAL BAND	8-9 μm	13.5-15 μm
CUTOFF (μM)	9.1	15
$\Delta\lambda/\lambda$	16%	10%
ABSORPTION QE	12.9%	8.9%
GAIN (AT V_B = -2V)	1.38	0.25
DETECTIVITY (cm√Hz/W) (300K BACKGROUND WITH f/2 STOP, T = 45K)	2.9×10^{10}	1.1×10^{10}
NEΔT (mK)	29	44
OPERABILITY (<100 mK)	99.7%	98%
NON-UNIFORMITY	0.04%	0.03%

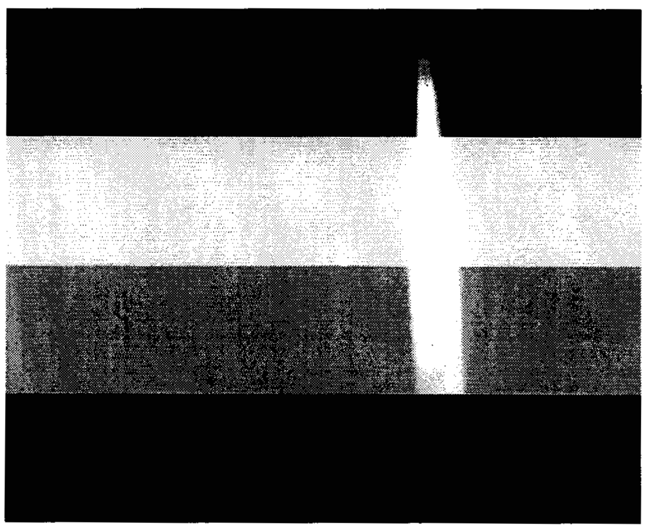
FINAL SYSTEM DELIVERED TO AFRL

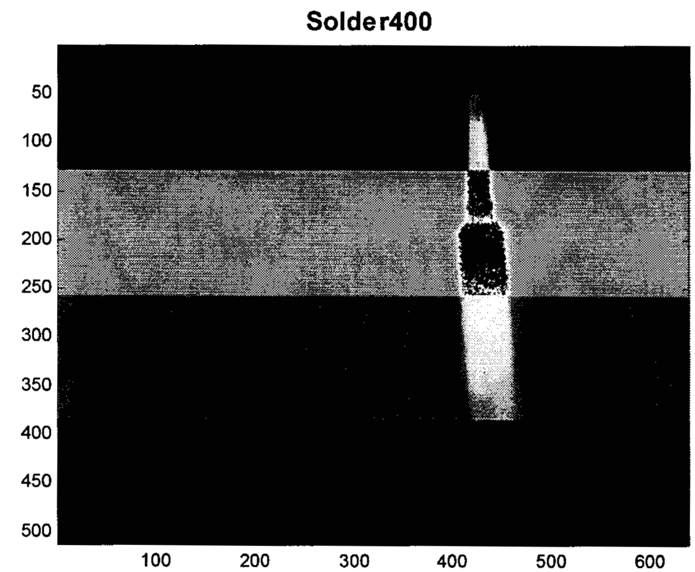
640 X 512 Four Band QWIP FPA





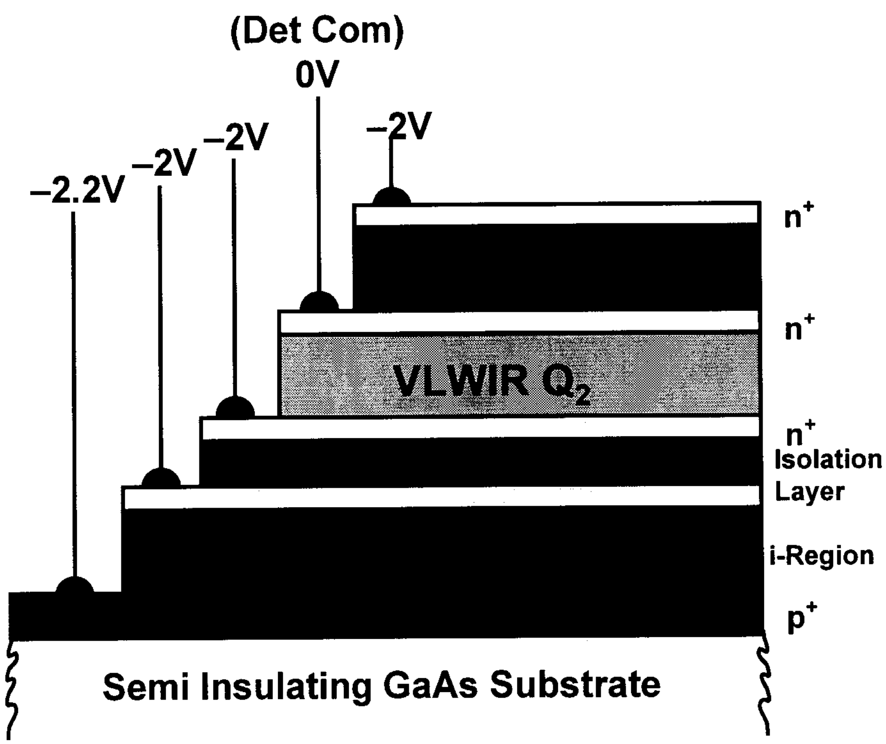
640 X 512 Pixel 4-Color QWIP FPA

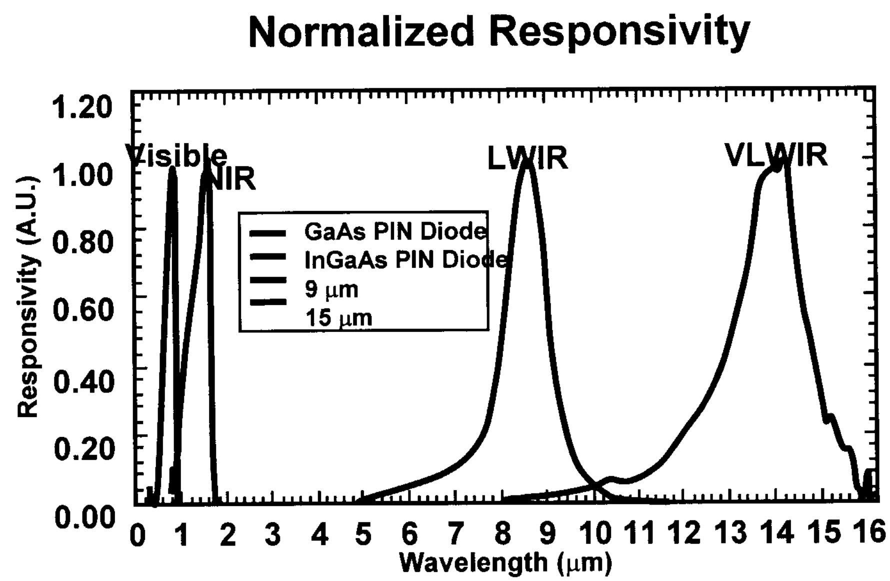




TWO 640X512 PIXEL 4-COLOR FOCAL PLANE ARRAYS DELIVERED TO NASA GSFC's HYPER-SPECTRAL IMAGING SPECTROMETER PROJECT

Triple Band (NIR, LWIR, & VLWIR) Detector



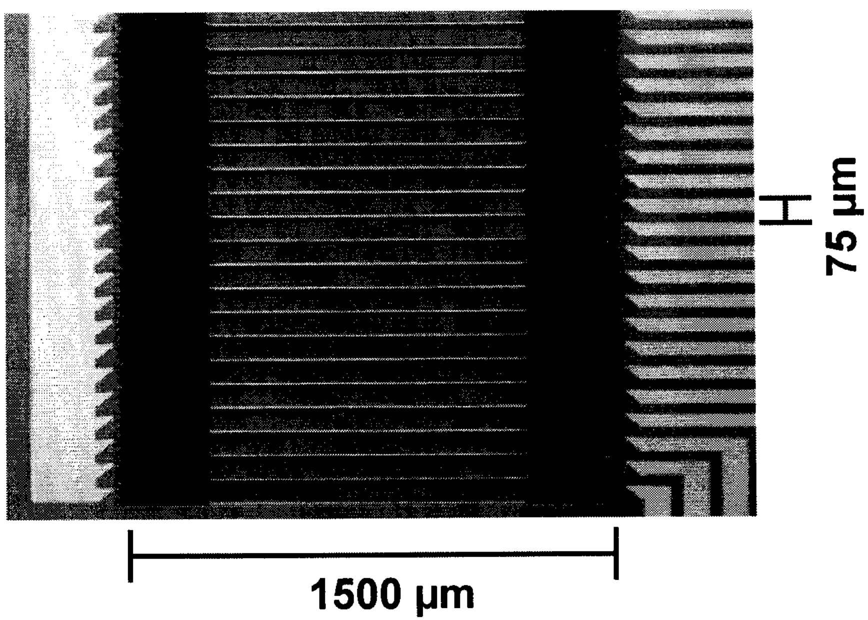


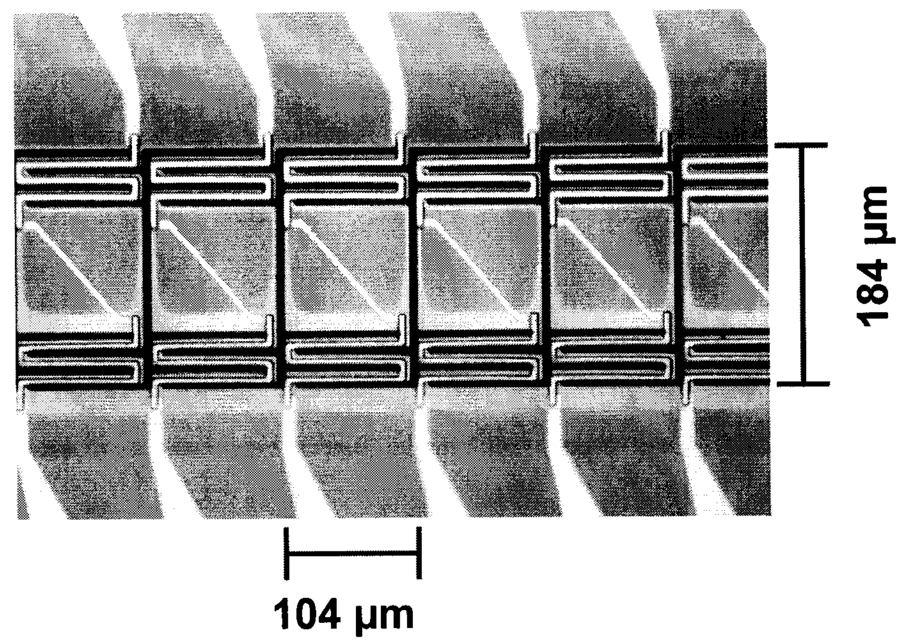
Thermopile Detectors

- Thermocouples measure temperature difference between absorber and substrate
- No optical chopping needed
- No bias required
- Large operating temperature range
- Tolerant of temperature drifts, so T stabilization not needed
- Highly linear - best choice for radiometry

➜ Minimal system requirements and high linearity make thermopiles ideal for many scientific and commercial applications

Thermopile Linear Arrays

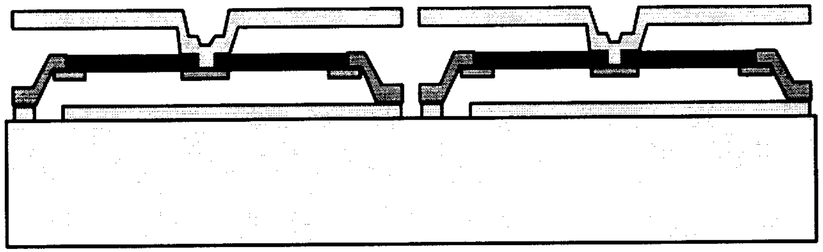




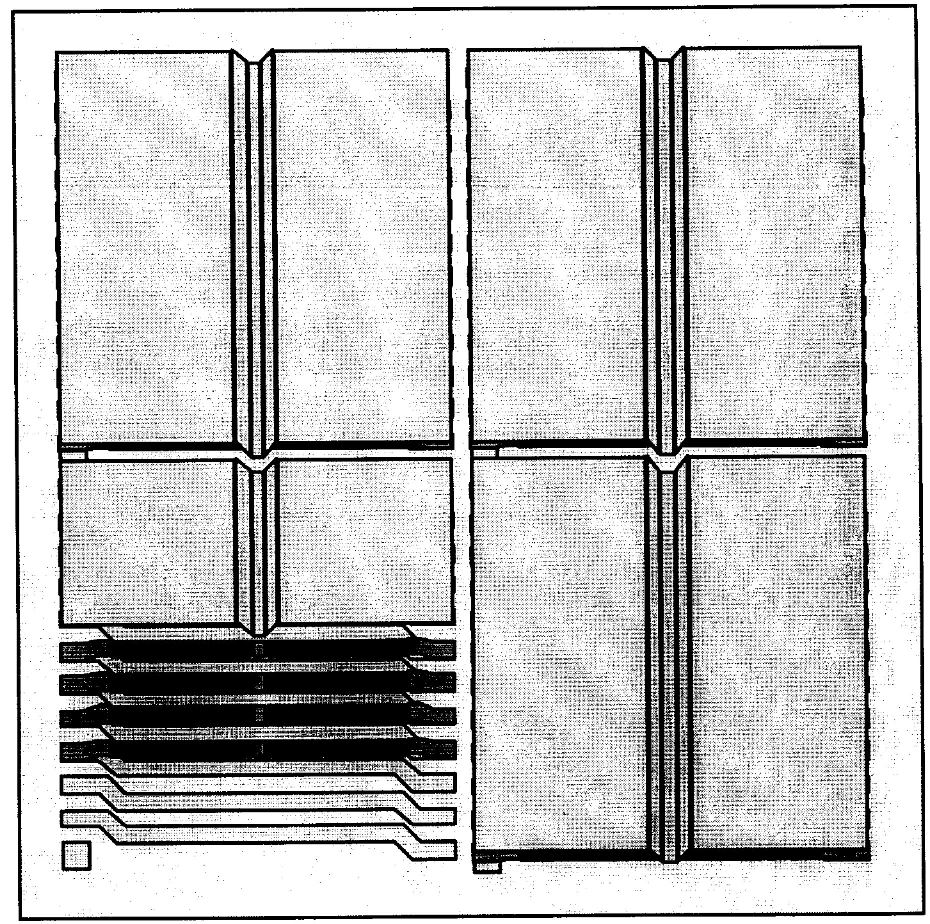
- Bi-Te and Bi-Sb-Te thermoelectric materials
- Bulk micromachining - silicon substrate removed from the back
- D* values 1-2x10^9 cmHz$^{1/2}$/W, significantly higher than other thermopile arrays

Thermopile 2-D Pixel Design

Side View



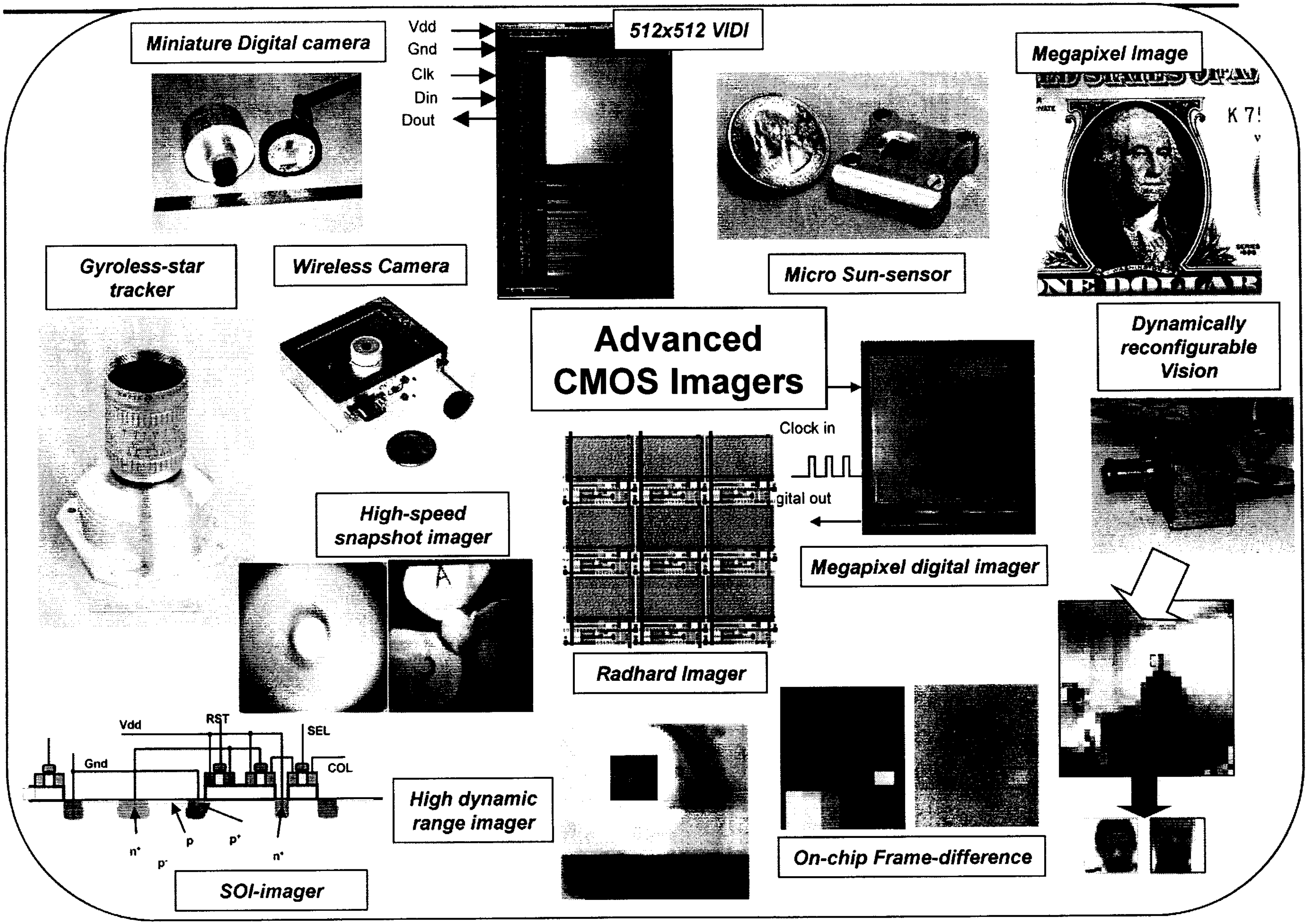
Top View



Features

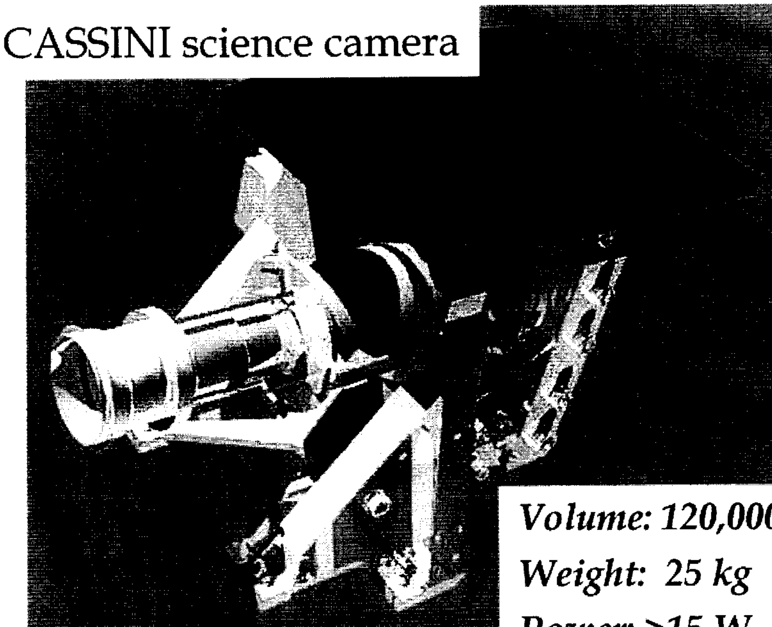
- Bi-Te and Bi-Sb-Te thermoelectric materials
  - High figure of merit at room T
- No dielectric in support legs
  - eliminates parasitic thermal losses
- Three level structure
  - Near 100% fill factor
  - Many thermocouples per pixel for high response
- Readout in each pixel
  - Electronically chopped amplifier, integration
  - Provides low 1/f noise and narrow electrical bandwidth

Active Pixel Sensor Visible Imagers



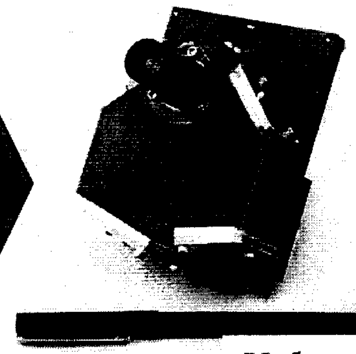
Imaging Needs In Next Generation Space Exploration

CASSINI science camera

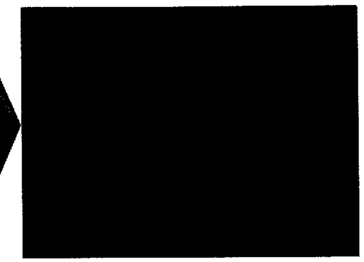


Volume: 120,000 cm^3
Weight: 25 kg
Power: >15 W

Near-future imager



Volume: 50 cm^3
Weight: 2 kg
Power: >100 mW



CURRENT DEVELOPMENT
Mars : ***Rover & Science cam***
(needs miniature digital cameras with 4 wire/camera, < 50 mW power, < 50 cm^3)

Driving forces in space-exploration:

- **miniaturization**
- **low-power**
- **multi-function: support science, laser-comm., tracking, guidance, object ID**
- **easily configurable: "smart imagers"**
- **low cost**

Rad Hard Risk Reduction Motivation

Issues

Conventional CCDs do not generally possess radiation immunity.

Their problems have severe affects on star trackers, particularly:

Displacement induced charge transfer efficiency degradation

- cannot shield Proton, alpha, etc;

Radiation induced dark current increase - can cool

Challenges

Optimize Rad Hard CMOS APS Imager Performance via:

Improvements in Rad Hard CMOS foundry process fabrication (w/joint BAE/LM resources),

Optimize Design of RH APS with different parametric pixel variations, choose best

Develop new Rad Hard architectures for analog and digital design choose best

Context

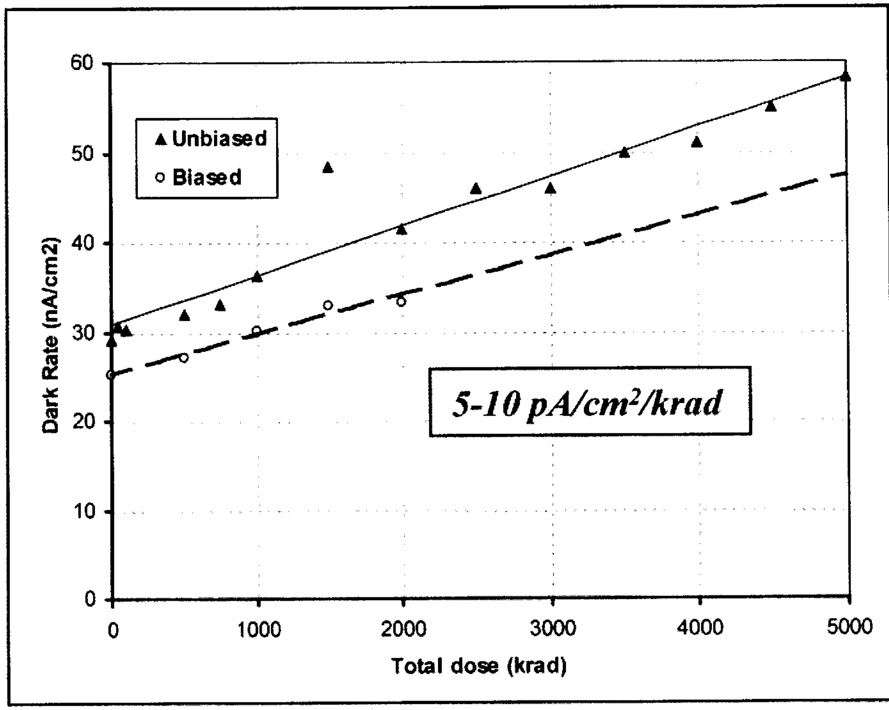
Various Users (NASA, Defense, etc.) need Rad Hard imagers and better Rad Hard CMOS analog circuit designs:Outer Planet moon (Europa) exploration

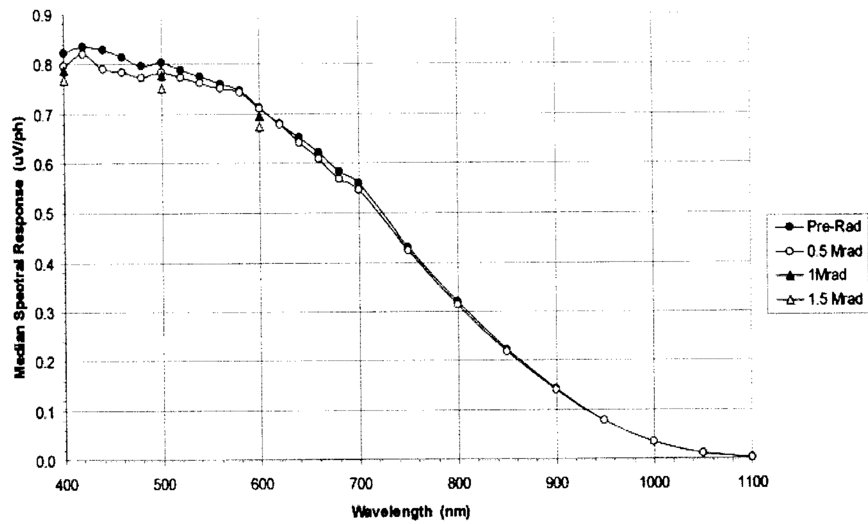
Earth Orbit / Earth Observing, Planetary lander/rovers w/RTGs

Theater, National Missile Defense

Commercial Communication satellites in radiation stressing MEO/GEO constellations

LOT-1 Results





Proton dose @, RT ~ 80 K

5.5 Mrad Total Dose @, T= ~ 81 K

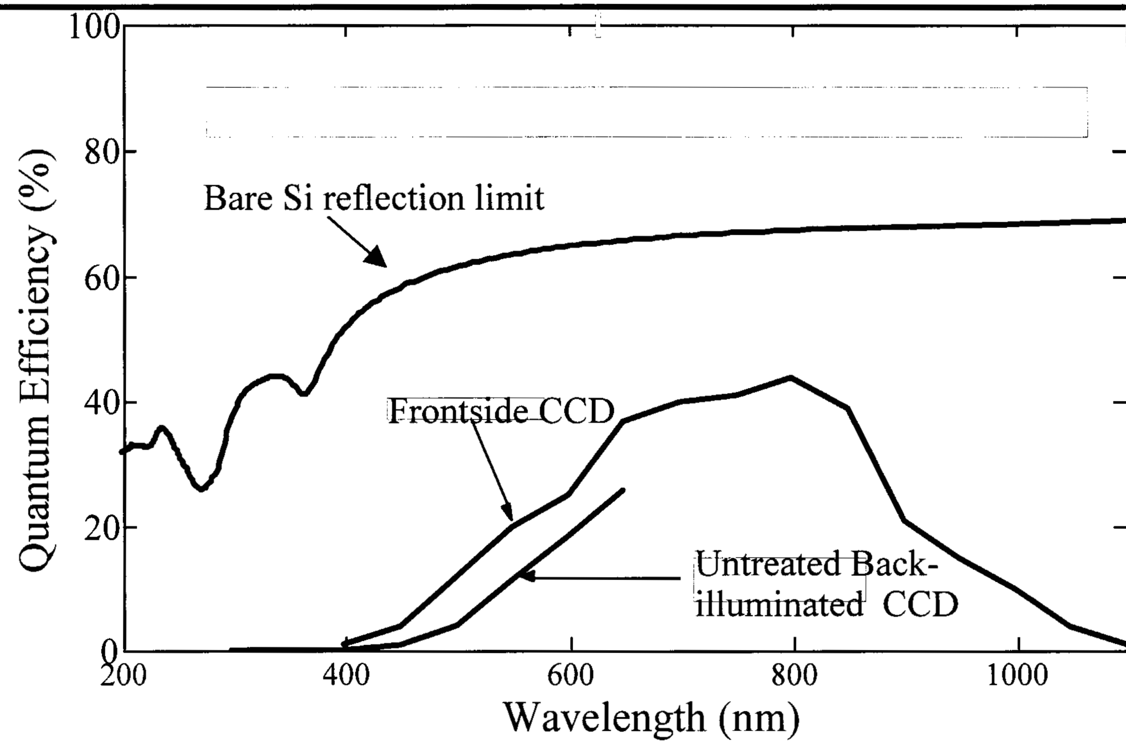
In-Situ Radiation Test Apparatus

- Imager is operating during radiation
- More difficult to do with CCDs due to their need for greater support electronics

Radiation Hardened APS Status

- **Lot-1**: demonstrated radiation-hardened CMOS imager, albeit with high pre-rad dark current & hot-pixels
- **Lot-2**: radiation-hardened CMOS imager with acceptable dark current levels;
  - Significant device level testing carried out
  - More SEU testing needed
- **Lot 3**: large format, low-noise, higher speed, improved linearity, optimized pixel imager under fabrication
  - Testing to be carried out
- **Next generation**: develop next gen. radiation-hard digital CMOS imager in the new BAE 0.25 μm process
  - Bring up imager-compatible process
  - New pixel design
  - Radiation-hard ADC design

UV Response of Standard CCDs or CMOS Arrays



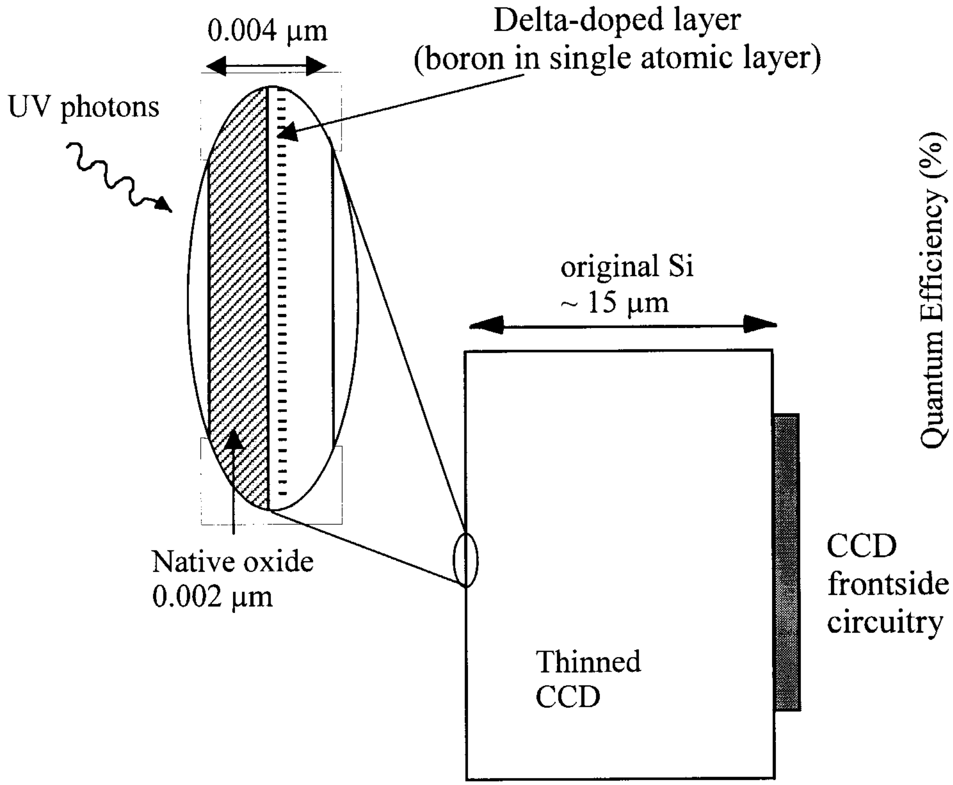
- Ultraviolet has applications in many fields: defense, biomedical, criminology, astrophysics, life detection, industrial sites, semiconductor process control, security/identification, etc.

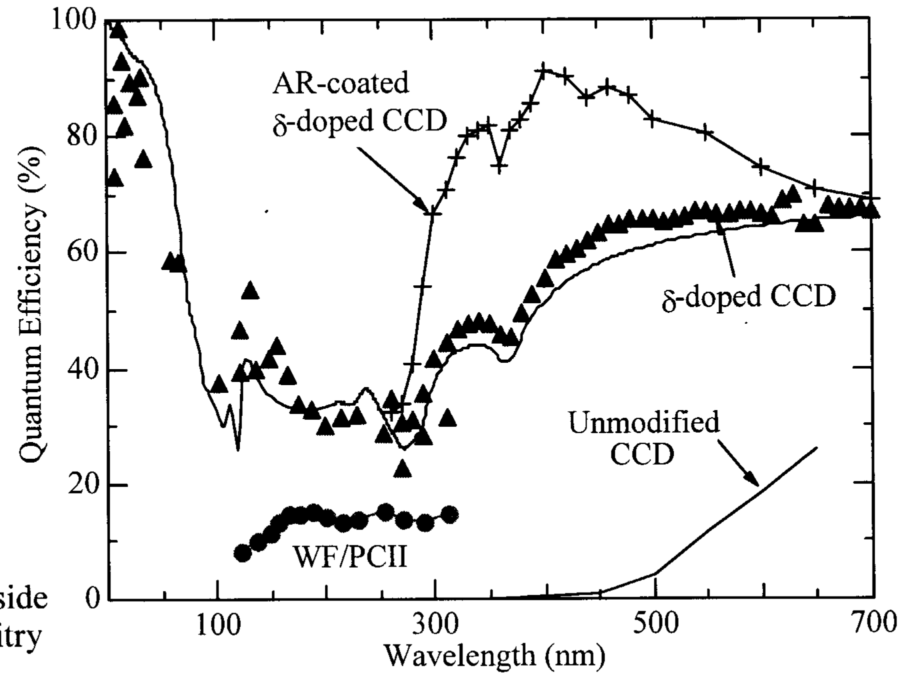
- Silicon CCDs and CMOS arrays are attractive imagers for their high resolution, low-noise, and maturity of technology

- Back-illuminated imagers potentially have the highest quantum efficiency (bare Si transmittance) in silicon arrays

- However, untreated thinned, back-illuminated (and conventional frontside) imagers are blind to UV

Delta Doping Technology

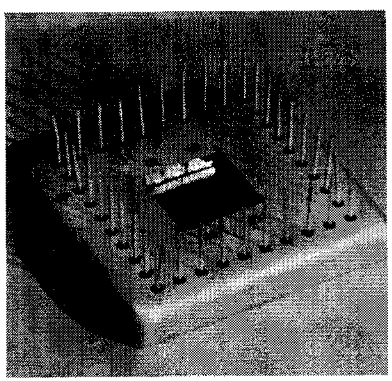




- 100% internal quantum efficiency, uniform, and stable
- Compatible with AR and filter coating: response can be tailored for different regions of the spectrum

Portable, High-Frame Rate UV camera

Portable UV CCD camera



δ-doped CCD with a structurally supported membrane, essential for robustness and applications using fast optics

Path of Development

- Former BMDO interested in compact, high frame rate UV camera
- Worked with Dalsa/SMD to develop custom electronics for CCD designed at JPL
- Full end-to-end CCD technology in-house leverage from NASA programs
- In-house thinning, delta doping (UV treatment with 100% internal QE), packaging and testing
- Our capabilities are compatible with commercial CCDs and can modify CCD or CMOS arrays for UV and visible

Curved Focal Plane Arrays

- Curved focal plane arrays (CFPAs) can dramatically increase throughput, resolution, and sensitivity

- CFPAs can reduce the complexity of optical system and, enable more compact wide FOV systems

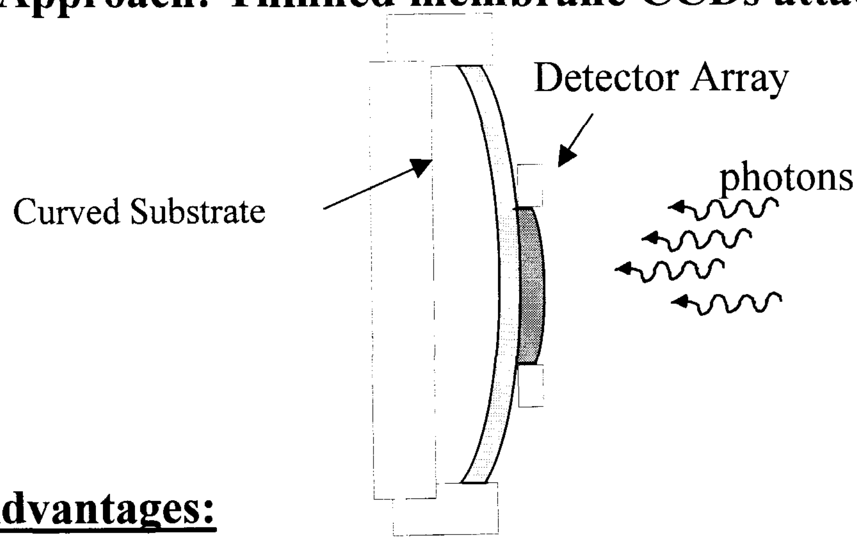
- Curved MCPs have been used to enable missions such as FUSE and Rosetta, however, curved solid state detectors are more compact, efficient, do not require high voltage, and can potentially be easier to manufacture.

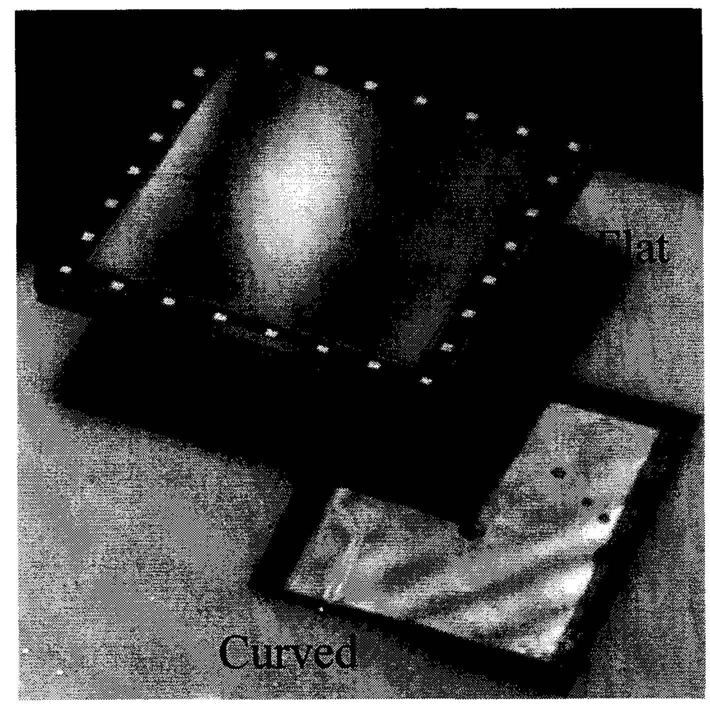
- Example; Rover Panoramic Camera, a CFPA can remove 3-4 elements which improves

  Throughput (~order of magnitude)
  Efficiency
  Field of view (factor of 2)
  Image quality (aberration is introduced by each field flattener)
  Simplicity.........

Curved Focal Plane Arrays

Approach: Thinned membrane CCDs attached to curved substrates





1024x1024, 12 µm pixel CCDs thinned and attached to flat and curved substrates. ROC=250 mm

Advantages:

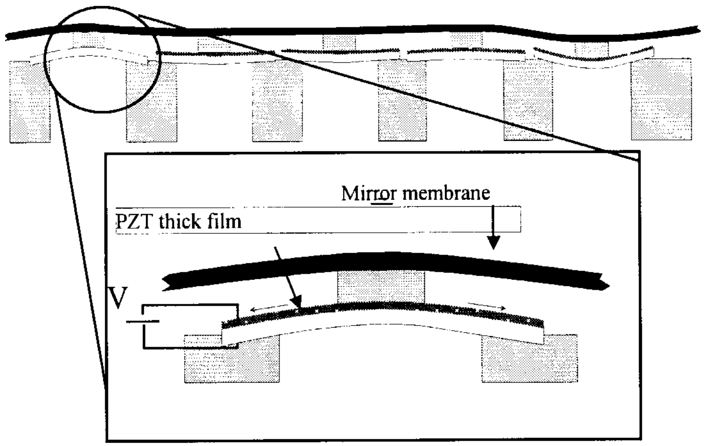
- **Simple Approach**
- **Applicable to *front or back* illuminated devices**
- **Decouples device fabrication from curvature of device**
- **Compatible with delta doping for high and stable efficiency**

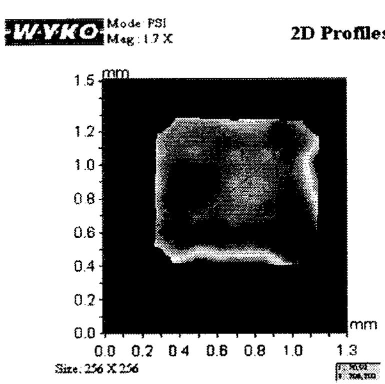
Challenges:

- **Limits of silicon membrane deformation**
- **Field effects**

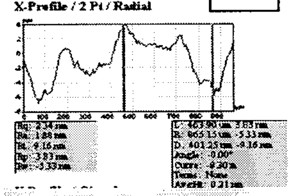
Large-Stroke MEMS Deformable Mirror for Future Ultra-Large Space Telescopes

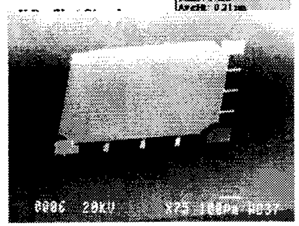
Products:





2D Profiles





Objectives:

Development of a large-stroke MEMS deformable mirror technology with precision surface deformation, low power, high areal density for astrophysical imaging and visual science applications

Applications:

- Wavefront correction for ultra-large, lightweight space telescopes
- Low cost wavefront corrector for retinal imaging
- Potential NASA customers: ORIGINS missions,SUVO, SAFIR, and Planet Imager.

Accomplishments

- Developed high-stroke piezoelectric unimorph actuator concept incorporated with the membrane transfer technology.

- Demonstrated a wafer-scale membrane transfer technique for the fabrication of optical quality mirror membrane.

- Developed a 3-D mechanical model for estimating mirror performance.