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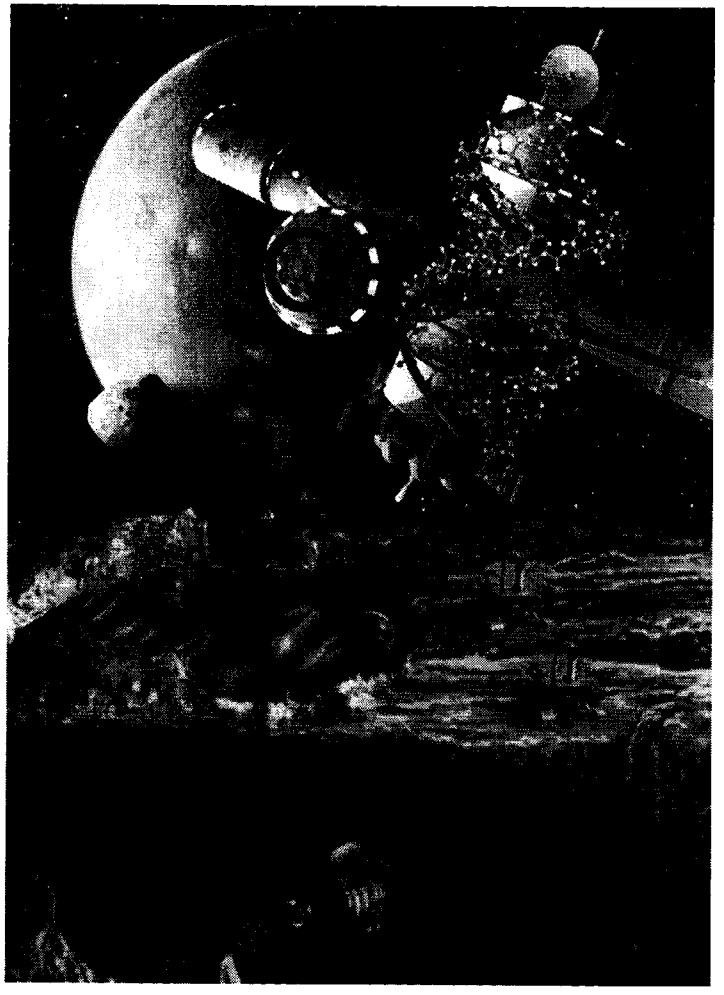


Advanced Sensor Development at JPL

Dr. Timothy Krabach

Program Manager
Life Detection Science & Technology

Jet Propulsion Laboratory

Breakthrough Sensors Thrust

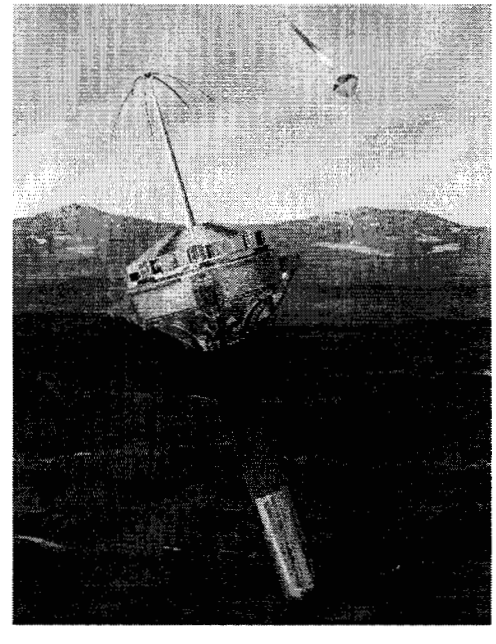
- **Scope of activities**
  - **Detectors and Focal Planes with quantum – limited sensitivity for all regions of the electromagnetic spectrum**
    - **Some areas of the EM spectrum (submillimeter, UV, Xray) are a unique NASA concern**
    - **Sensitivities required by NASA missions in all cases exceed those in the commercial and military sectors**
  - **Advanced components for active sensing instruments**
    - **Radar, lidar, metrology systems are core NASA capabilities**
    - **Key areas are laser development, photonic circuits, optics and antenna development**

Breakthrough Sensors Thrust

- **Scope of activities (continued)**
  - **Cryogenic systems**
    - **Advanced coolers are critical to enable operation of many novel detector and photonic devices**
    - **Cryogenic coolers are a huge impediment in current NASA mission planning**
  - **In situ sensors probing the physical, chemical, and biological properties**
    - **Missions landing on, boring under, and flying about other bodies in the solar system demand a suite of in situ sensors**
    - **Long term human exploration missions will need numbers of sensors to enable robust, low cost environmental control and medical care**
  - **Advanced Sensor Electronics**
    - **Need Mixed Signal, micropower, and communication capability capable of operating in severe environments**

In Situ Exploration: The next phase of deep space missions

The major focus of NASA planetary missions is on the surface, sub surface, and aerial exploration of the planets, moons, comets, and asteroids.



The unraveling of the physical, chemical, and biological properties of planetary bodies is leading NASA technology programs into new classes of vehicles and sensors, many of which have increasing relevance to earthly applications

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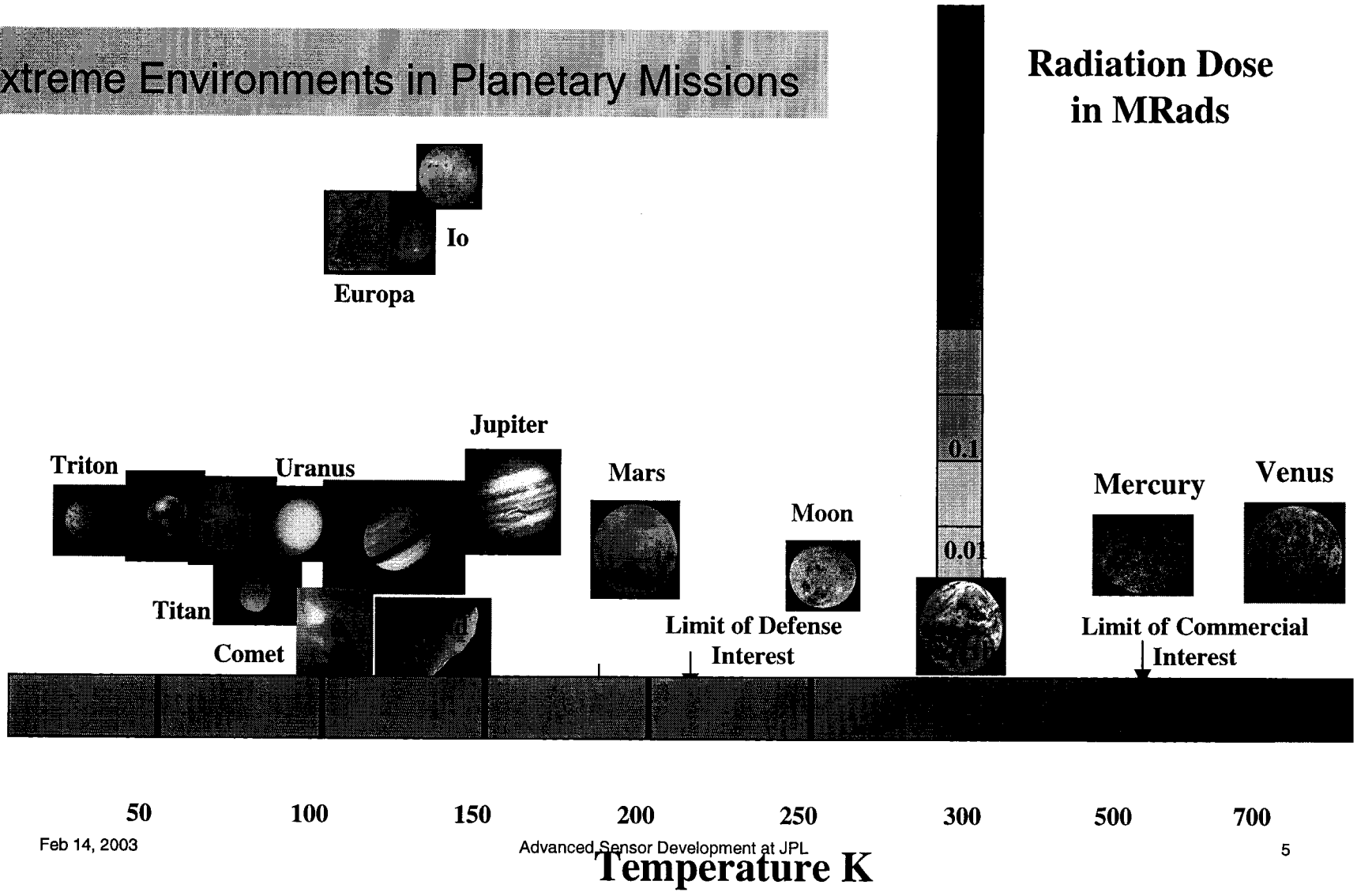
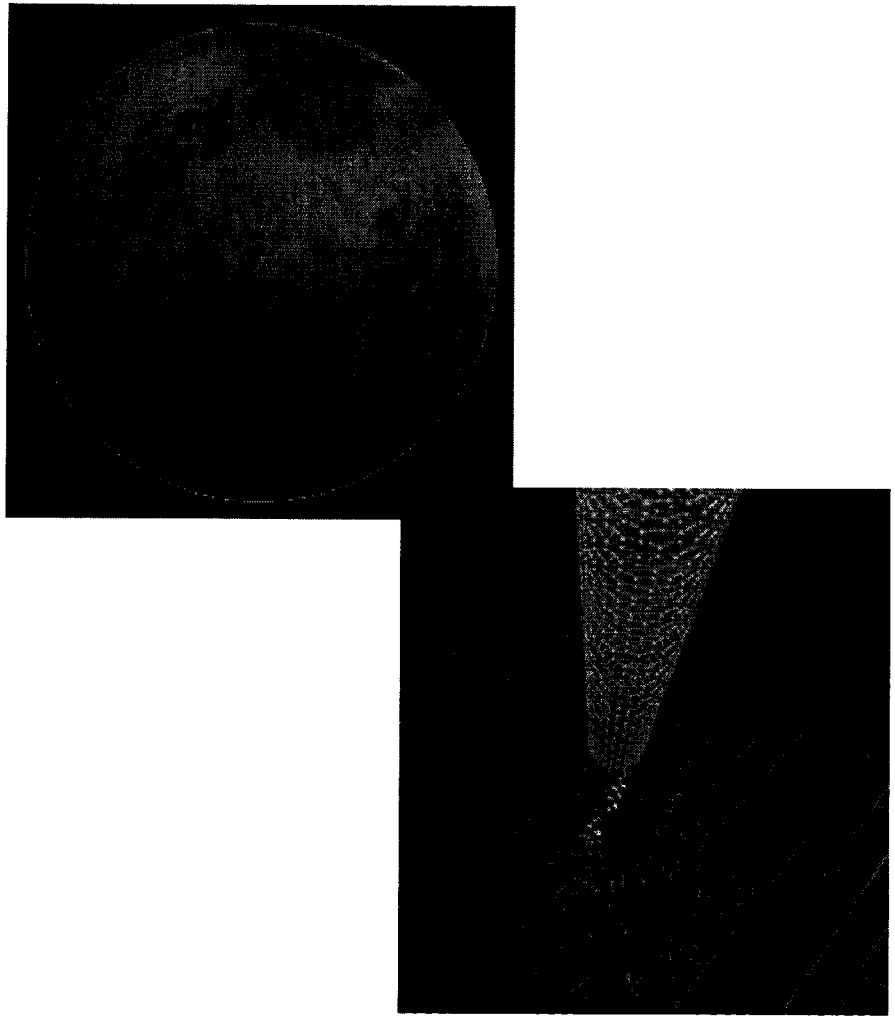
Challenges in Exploring the Solar System

Extreme Environments in Planetary Missions



Challenges in Detection of Extant or Extinct Life on Other Bodies



- **Uncertainties in definitive signatures**
  - **Unlikely there will be a single silver bullet**
- **Need for Investigation across a wide spatial range**
  - **Likely require global to nano scale data collection**
- **Coordinating Multiple, Mixed Measurements and Instruments**

Mission Constraints

- **Need large reductions in total mass, power, volume over similar instruments on Earth**
- **Need large reductions in user-operator interactions for deployed systems**
- **Need tightly integrated systems approach for suites of sensors, platforms, and vehicles**

- **How does one guarantee calibrated operation after months (years) of storage during flight?**

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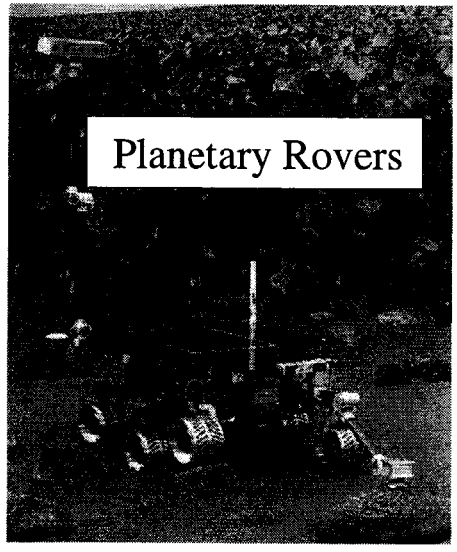
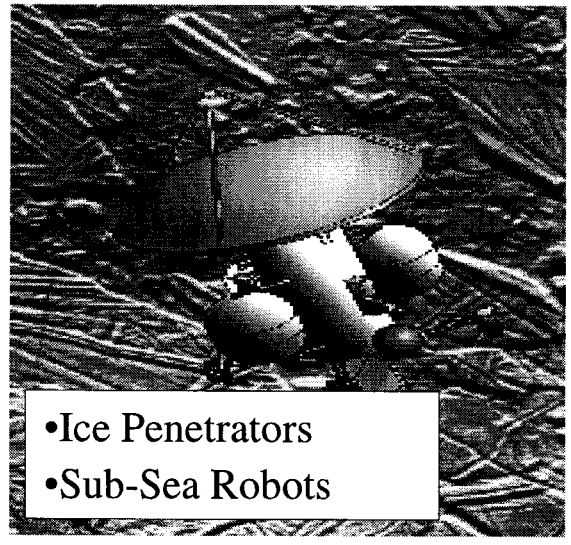
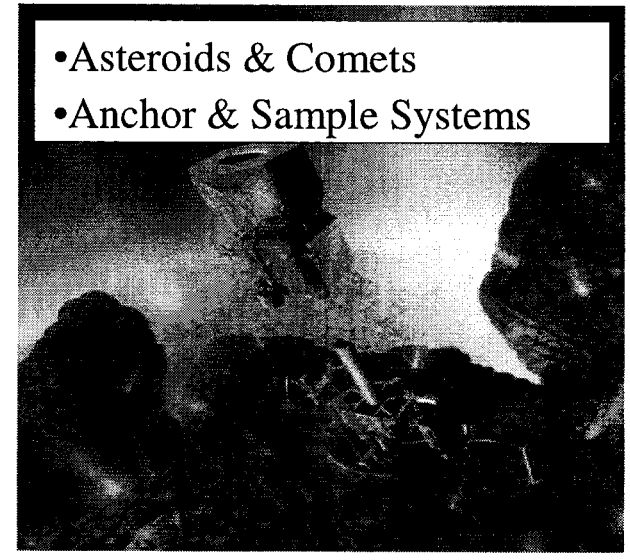
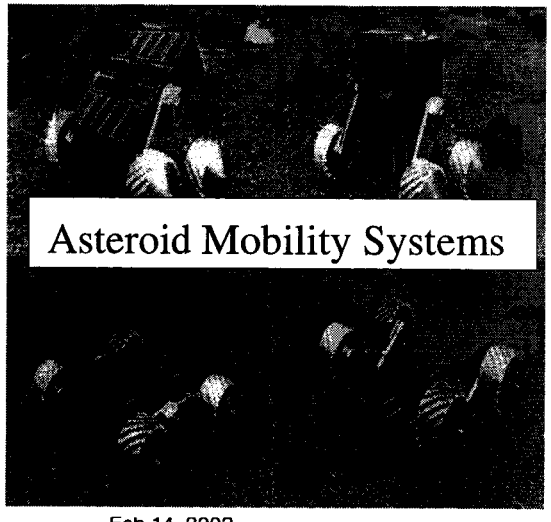
Advanced Sensor Deployment and Mobility Systems

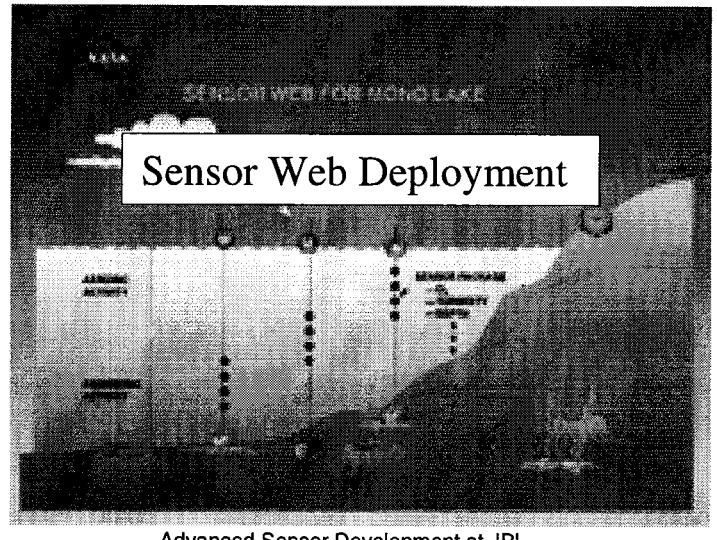
Robotic Exploration











Mars Microprobe (DS-2)

High – g (80,000g) impact packaging

Non-erosive, lightweight, single-stage atmospheric entry system

Microtelecommunications system with mixed digital/analog/RF ASICs

Power microelectronics with mixed digital/analog ASICs

Ultra low temperature lithium battery

Advanced 3D HDI microcontroller

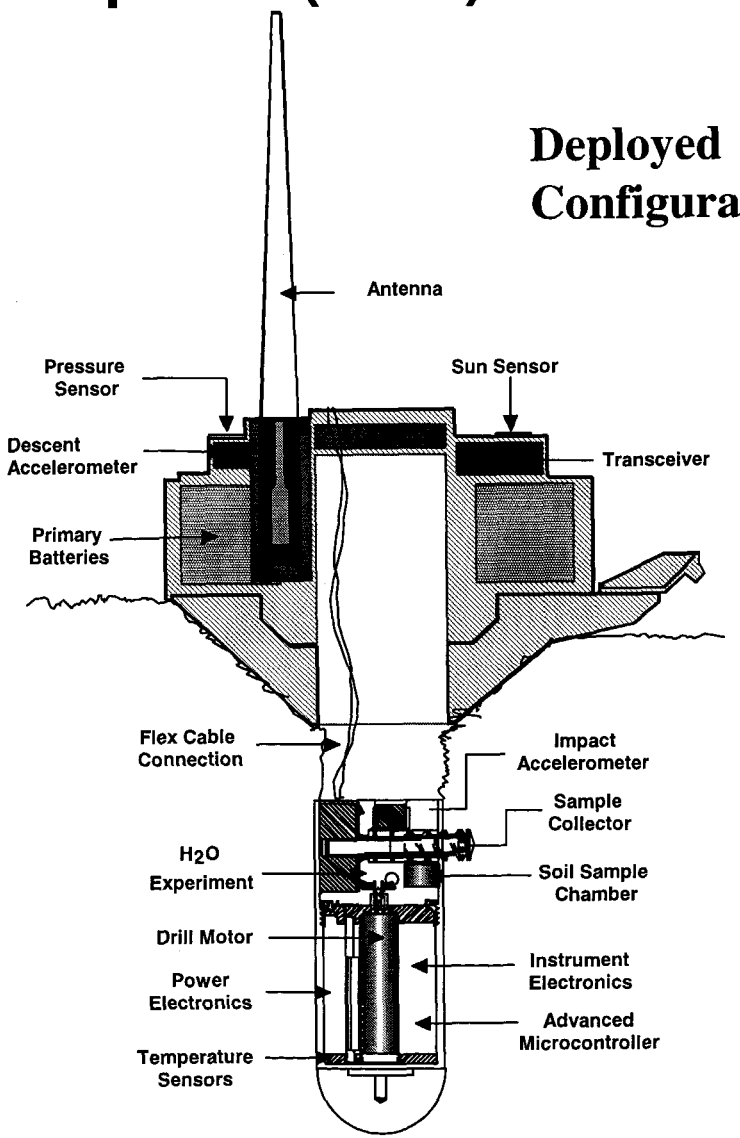
Flexible interconnects for system cabling

Meteorological high-g pressure sensor

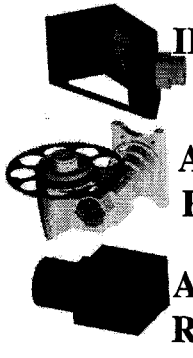
Soil conductivity high-g temperature sensor

Tunable Diode Laser Spectrometer Sample/water experiment

Deployed Configuration



MUSES CN nanoRover



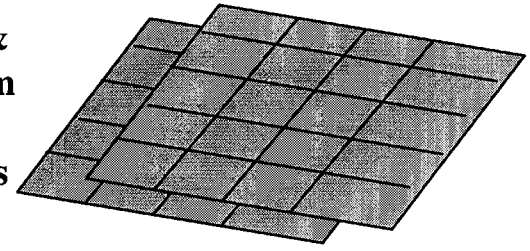
IR Spec

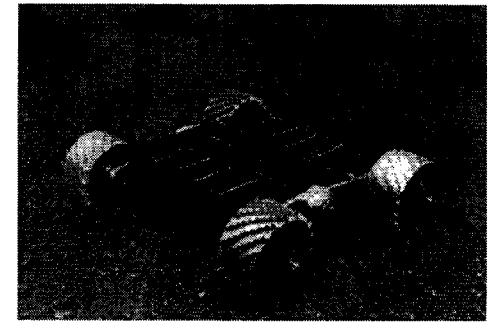
APS Camera Filter Wheel

Alpha X-Ray Spec

RF antenna

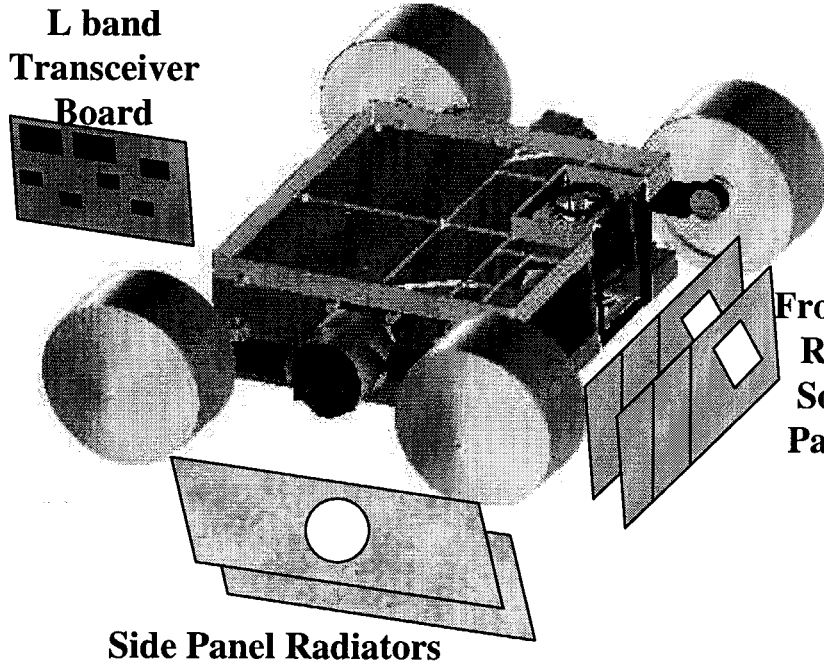
Top & Bottom Solar Panels





1.3 kg; 14x14x7cm

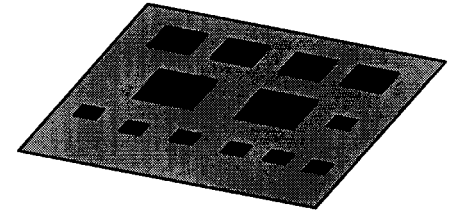
L band Transceiver Board



Body, Mobility

Front & Rear Solar Panels

Side Panel Radiators



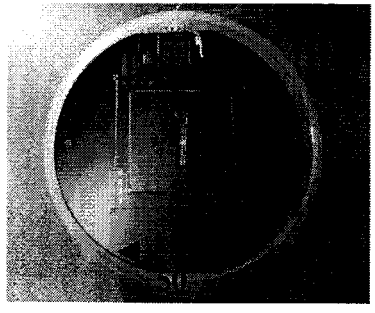
Mongoose CPU, SRAM, EEPROM, Digital/Analog I/O, Power supplies/switches

Robotic Vehicle Subsystem Technologies

- **Power**
  - **Advanced Batteries, Fuel Cells, Distribution Systems, Solar Arrays, Thermoelectrics, In situ fuel generation**
- **Guidance, Navigation, and Control**
  - **MEMS accelerometers and gyroscopes, star trackers, Precision GPS, sun sensors, fiber optic and free space metrology**
- **Avionics**
  - **Low Temperature processors, ASICs, system – on – chip (SoC) integrated systems w/comm**
- **Autonomy**
  - **Long term self directed behavior, cooperative robotic systems, fault tolerant and repairable systems**

Miniaturized Gyroscopes

Two key technology lines (Micro and Meso scales):



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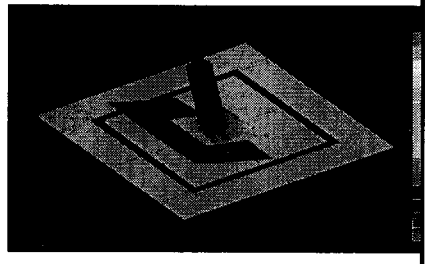
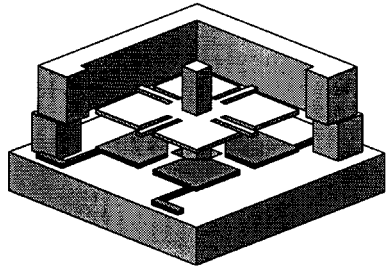


Mesogyroscope



Microgyroscope

Performance Goals:

- **Mesogyro:**
  - Size: <8 in^3
  - Bias stability: 0.1 deg/h
  - Power: <1W
- **Microgyro:**
  - Size: <1 in^3
  - Bias stability: <1 deg/h
  - Power: <1W

Four principal thrusts directed at precision performance:

1. Precision fabrication
2. Electronic tuning
3. Statistical correlation
4. Mechanical tuning

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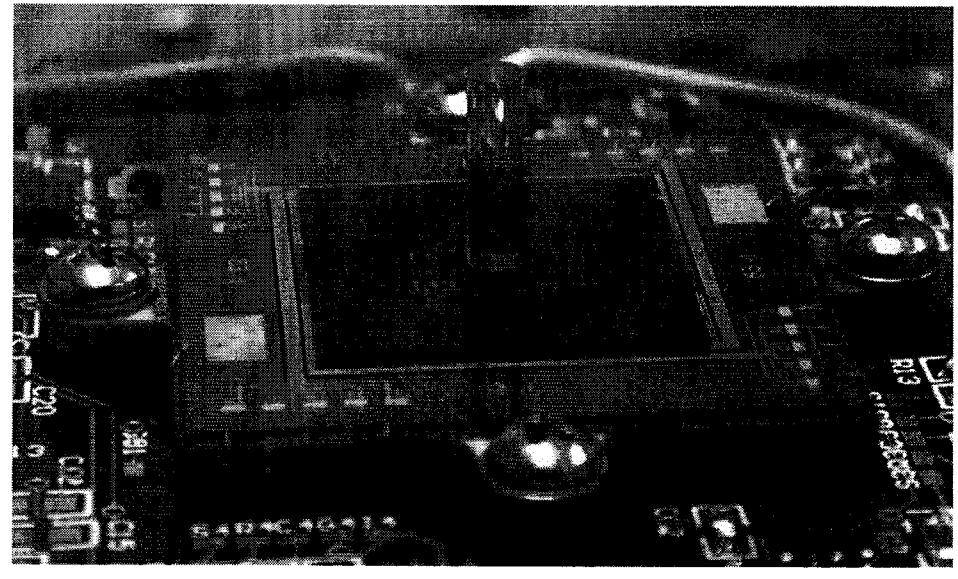
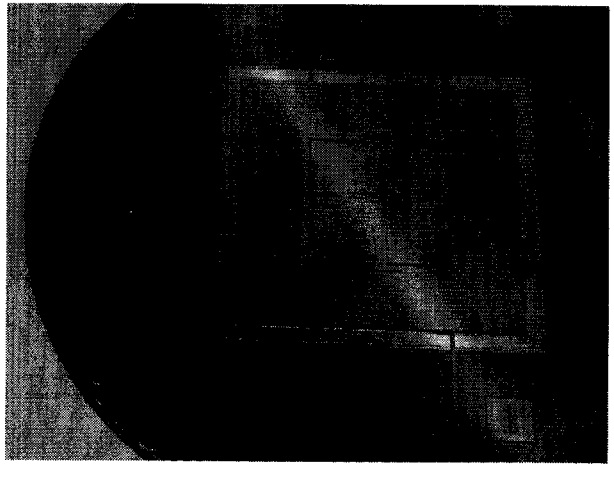
Mesogyroscope

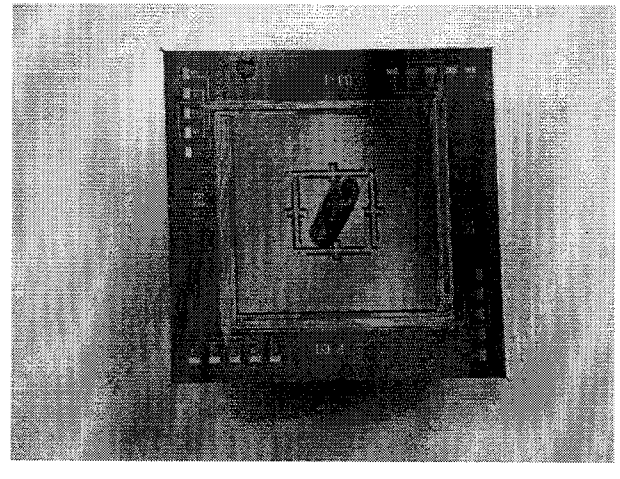
Current Results :

- Bias stability: 2 deg/hr bias
- Angular Random Walk: 0.03 deg/ rt-hr
- First thermal characterization
- Advanced vacuum package being developed by Cincinnati Electronics
- Control Electronics: advanced digital ASICs as well as conventional mixed signal on board design

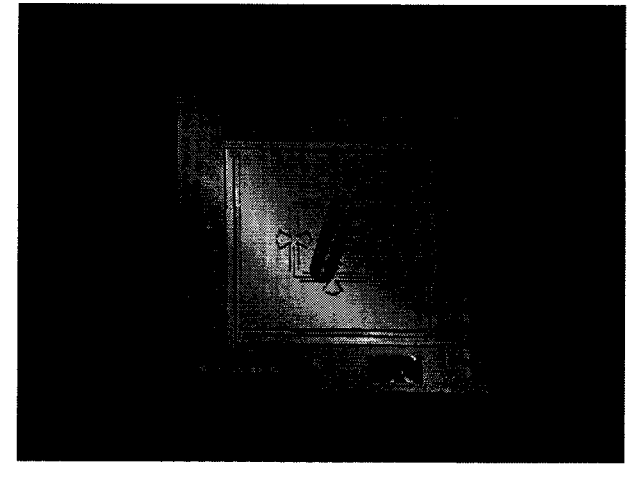




Baseline Design



"X" wing Design



"A" Wing Design

Micro Power Sources

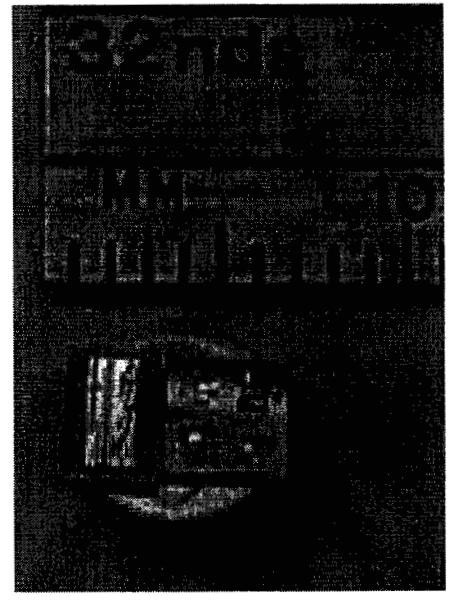
Develop low mass/volume power sources, in concert with the development of low power electronics/MEMS devices.

Example Applications:

- Autonomous/Distributed Sensing
- Rad-hard CMOS memory
- Isolation of analog sensors from digital noise
- Distributed power: point-of-use

Benefits:

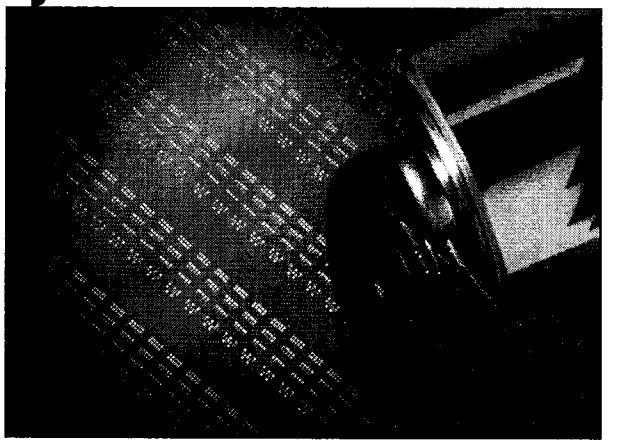
- Affords greater level of integration
- Allows for redundancy ⇒ reliability ⇒ safety
- Leverages high reliability associated with microelectronics revolution
- Changes paradigm of spacecraft architecture
  - Power woven into the entirety of the vehicle

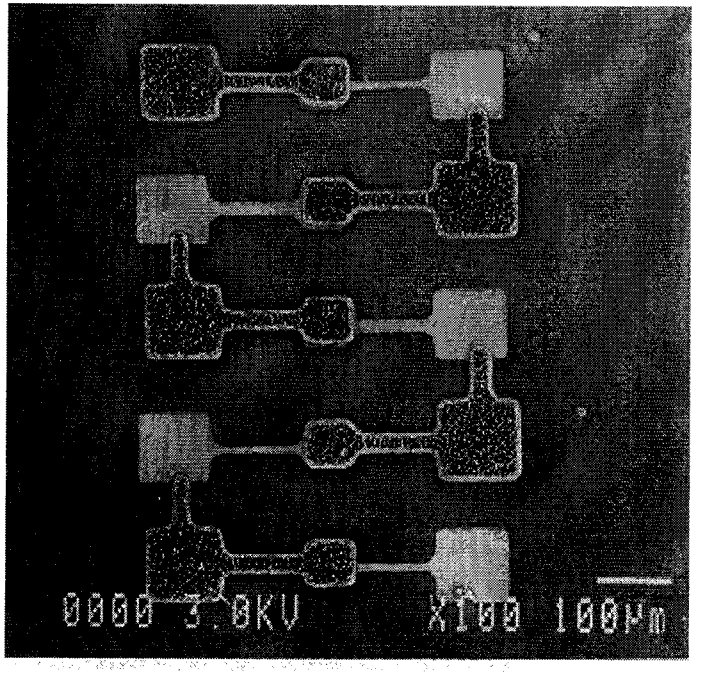


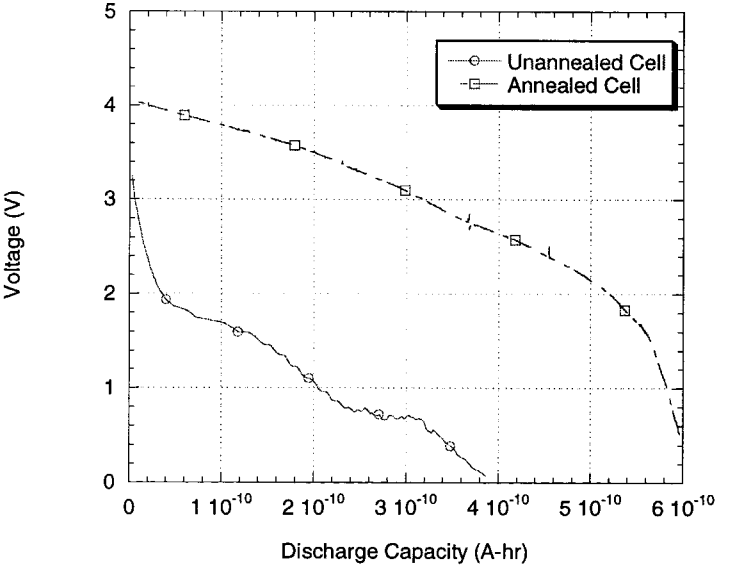
U. C. Berkeley optical transmitter array on a coin cell
(http://robotics.eecs.berkeley.edu/%7Epister/SmartDust/)

Thin Film/Micro-Battery

- Integrate batteries on chip with CMOS
- Can fabricate 20,000 batteries on a 4" wafer with footprints (50-100 μm)^2
- Can design cells in parallel/series arrangement for higher voltage/current







Thin Film/Micro-Battery Collaborators

University Collaborators:

•Caltech: Prof. B. Fultz
Materials characterization (XRD, TEM, SEM, EELS, Auger, ICP-MS)

•Auburn University: Prof. J. Williams
Materials characterization (RBS)

• Stanford Synchrotron Radiation Laboratory
High-resolution diffraction studies of individual layers/interfaces (novel effort)

•University of Idaho: Prof. H. Li
Circuit design, charger integration

•Mississippi State University: Prof. B. Blalock
Circuit design, charger integration

NASA Centers:

•Johnson Space Center: G. Studor
Integration of micro-power source with micro-wireless integrated sensor (μ-WIS)

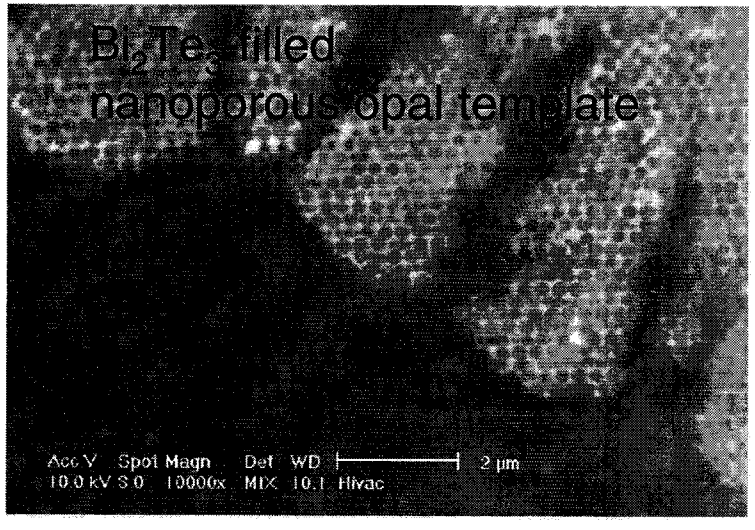
•Goddard Space Flight Center: T. Yi
Device testing and mission insertion consultation

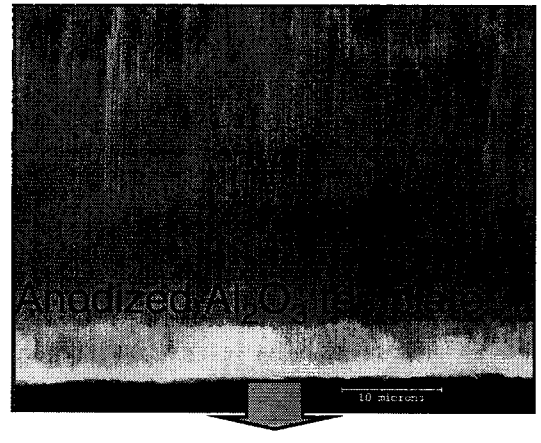
Industry Collaborator:

• Chemat Technology: Dr. Y. Huang, Dr. I. Ball
Sol-gel electrolyte development, supercapacitor development

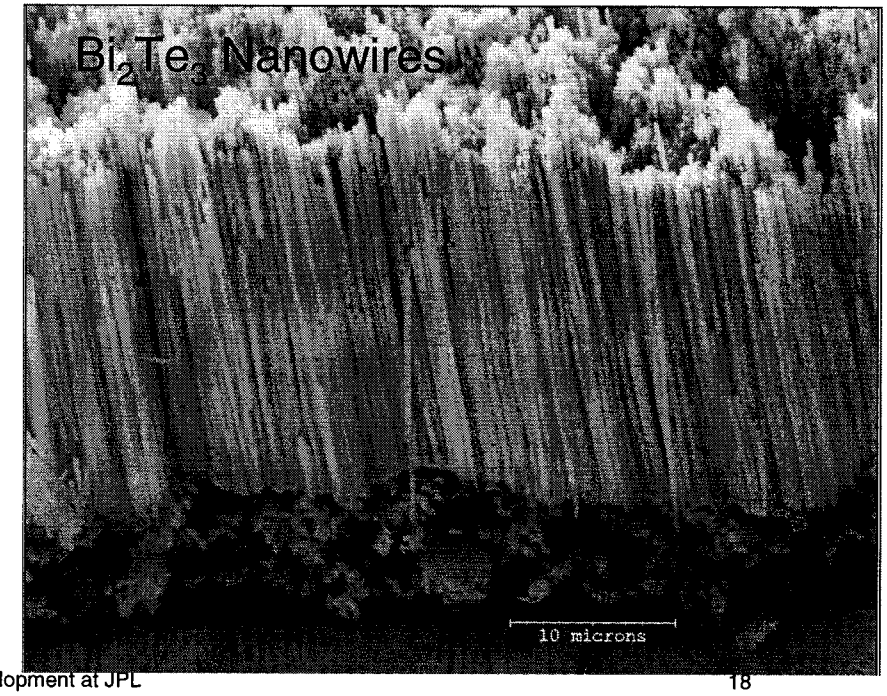
Thermoelectric Nanostructures

(template from Allied Signal)





(template from MIT)



- Technique could lead to novel TE devices
  - Low dimensionality could lead to:
    - Higher Seebeck coefficients
    - Use in new "nano" devices such as self-powered sensor arrays
  - Should be easier to integrate into devices than superlattice-type structures
    - Key issue for device performance is thermal shunt from template
    - Requires high porosity

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Sensor and Instrument Technologies for In situ Exploration

Imaging Sensors

- **Focal Plane Sensors**
  - **Are at the heart of all remote sensing and many in situ instruments**
  - **Are critical for many navigation sensors in space and ground platforms**
  - **Improvements in focal planes (sensitivity, size, etc.) offer an extremely high science payoff, and offer both performance and miniaturization benefits for mobile platforms**

- **NASA R&D on focal plane technology spans the electromagnetic spectrum**

Common Characteristics of NASA Image Sensor R&D

- **Emphasis on high performance within a sensors range of application**
  - **Demand from needs of science instruments for NASA missions**
- **Solutions providing high stability, low drift, low noise**
  - **Driven by requirements for excellent calibration, and stand alone operation (few tweaks)**
- **Focal Plane technologies that simplify overall sensor and instrument implementation**

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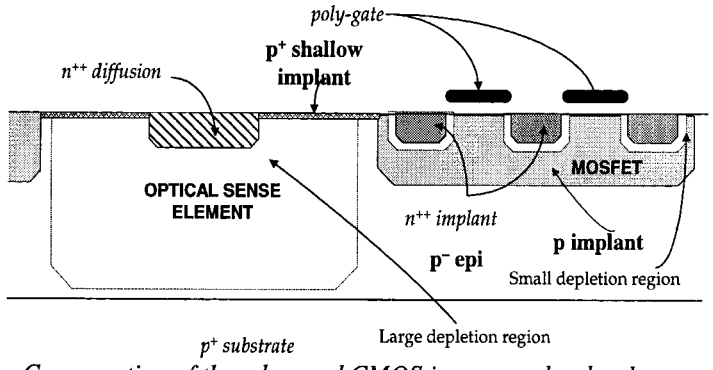
High-performance One-chip CMOS Digital Imager

Products



Cross-section of the advanced CMOS imager under development

Goal: develop high quality imager in CMOS technology

High QE (>80%), low cross-talk (< 0.5%), low read noise (< 10e$^-$), High linearity (99.9%), low power (<20 mW), & digital (>12 bits)

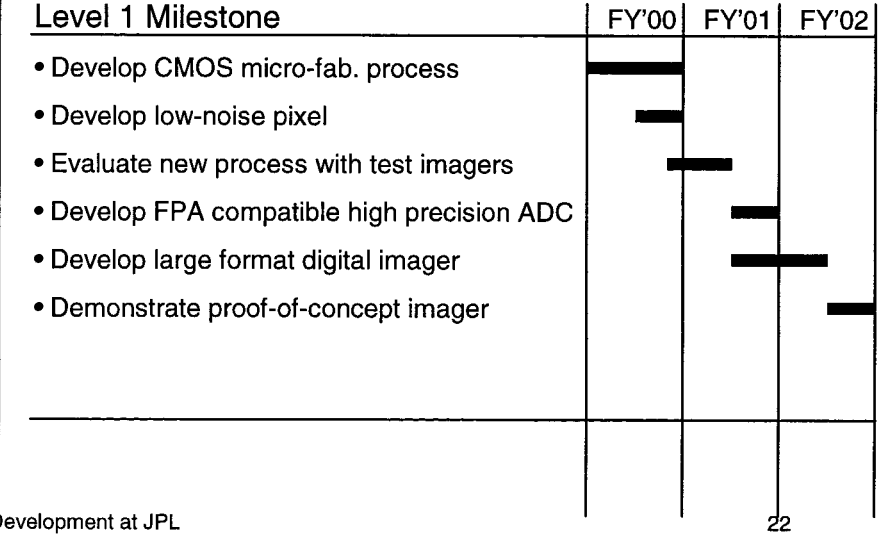
Product Objectives

- Develop new sub-micron CMOS micro-fabrication process capable of integrating sub-micron transistors and high-performance photo-sensitive element
- Develop photodiode pixel with low read noise, low-cross-talk, and high quantum efficiency
- End of FY00: Demonstrate low-noise pixel, and imaging compatible CMOS process; TRL level of 1
- End of FY 01: Develop high precision ADC and develop large format camera-on-a-chip
- End of FY 02: Demonstrate first high-precision, low-power, digital, compact, scientific quality CMOS imager; TRL level of 3

Participants & Customers

- PI: Bedabrata Pain, JPL
- Co-I: Guang Yang, JPL
- Collaborator: David Meyer, Lockheed-Martin
- Facilities: Advanced imager lab., JPL, Design Hub, JPL, VLSI fabrication lab, Lockheed-Martin, Manassas
- Primary Enterprise Customer: NASA Space Sciences (Code S)
- Secondary Enterprise Customer: NASA Earth Sciences (Code Y), and HEDS

Products & Funding



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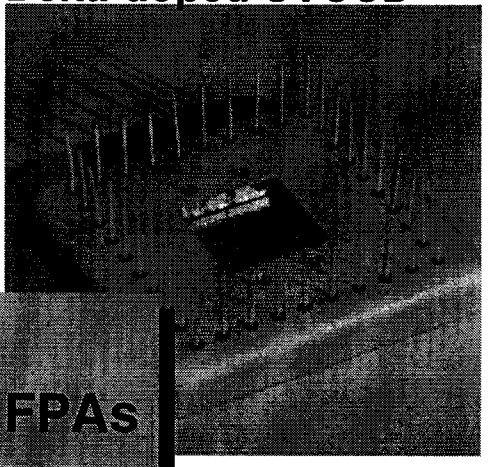
Detectors and Focal Planes

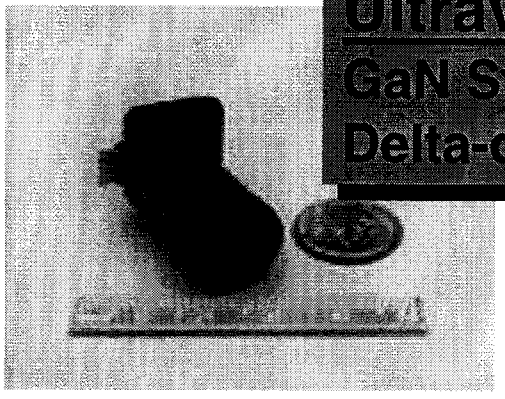
Visible
Science Grade CCDs
CMOS Active Pixel Sensors

Delta-doped UVCCD



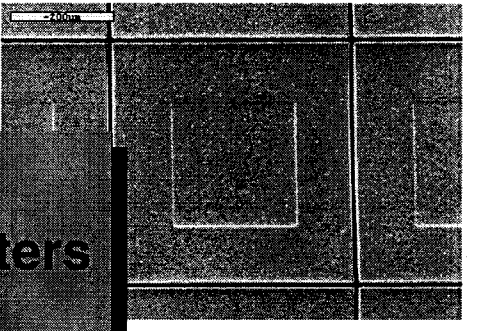
CZT X-ray focal plane

Ultraviolet
GaN Staring Hybrid FPAs
Delta-doped SiCCDs



CMOS APS "camera on a chip"

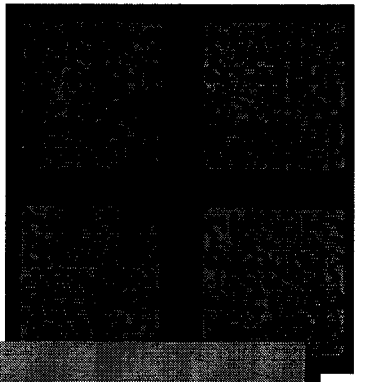
X-ray
Transition Edge Calorimeters
CZT Staring Hybrid FPAs



TES pixels

Detectors and Focal Planes

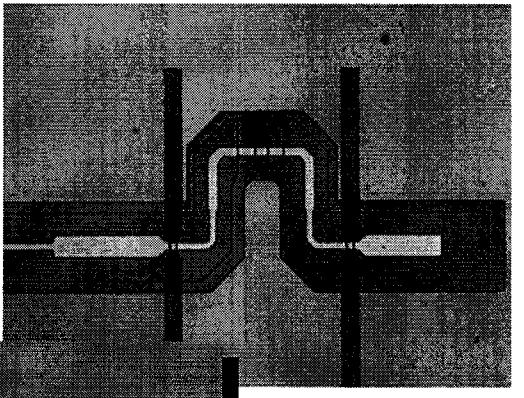
MW/LW Infrared
Low-noise InSb FPAs
Quantum Well focal planes

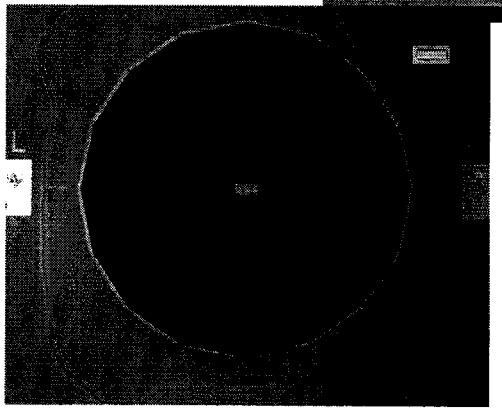


QWIP pixels

Far Infrared
Si:As BIB arrays
Micromesh Bolometer Arrays

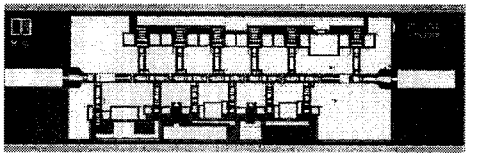
Twin slot SIS mixer





Micromesh bolometer

Submillimeter
Superconducting SIS mixers
THz sources / amplifiers

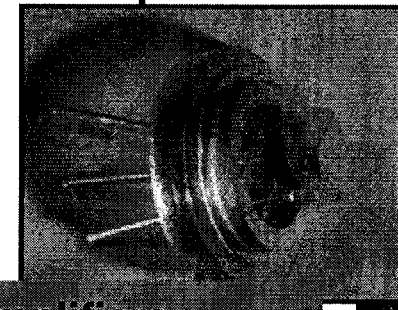


InP HEMT
200 GHz amp

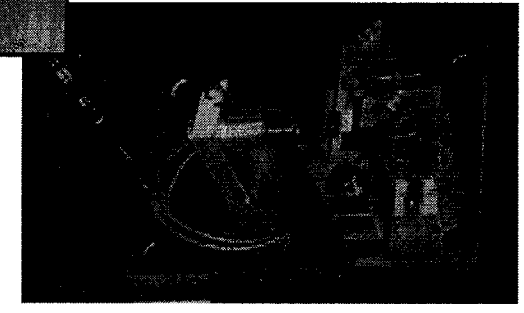
Lasers and Photonics

Tunable Diode Lasers
2.04 & 1.37 µm TDL for Mars
LWIR quantum cascade lasers

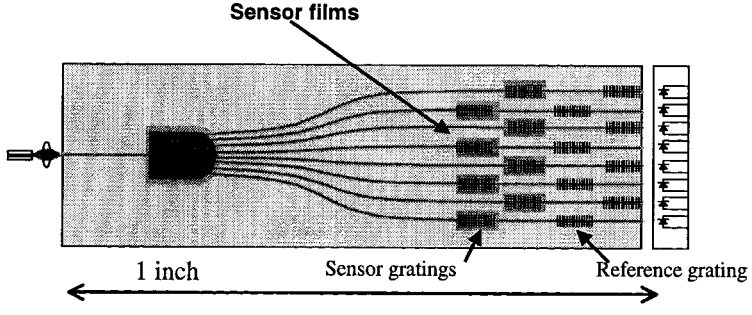
2.04 µm TDL



0.5W Optical Amplifier

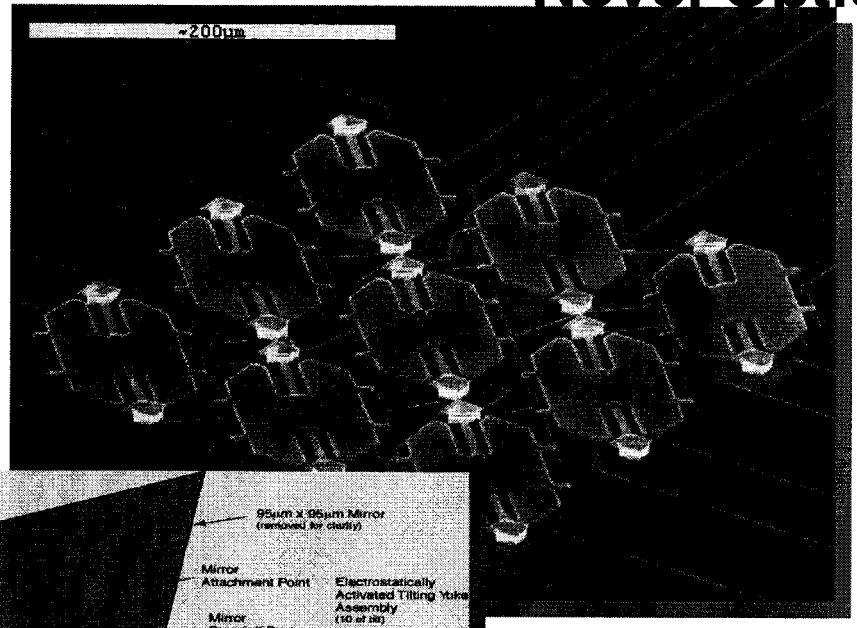


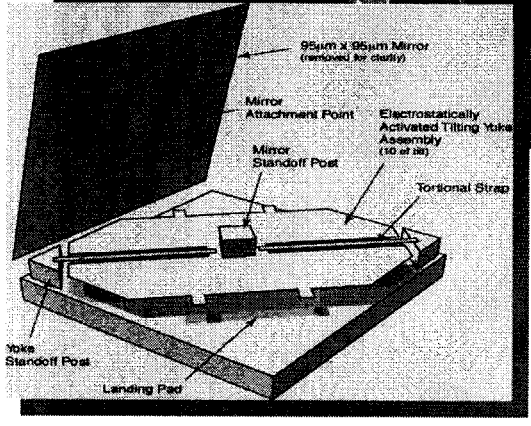
Fiber Laser / Amplifiers
944 nm microlidar source
2 µm eye safe fiber laser lidar



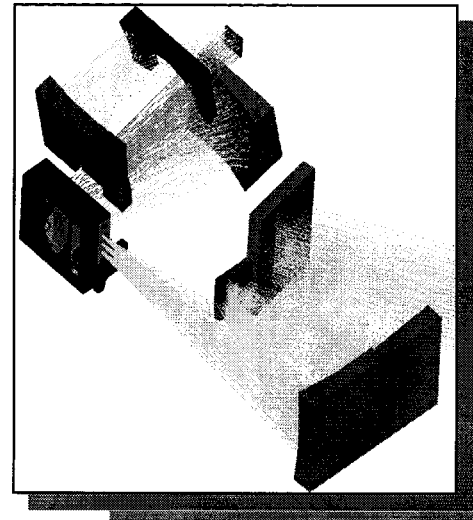
Photonic Waveguide Devices
Ultrastable diode lasers (<100kHz)
Waveguide biosensor arrays
Widely tunable lasers for Raman

Novel Optical Elements

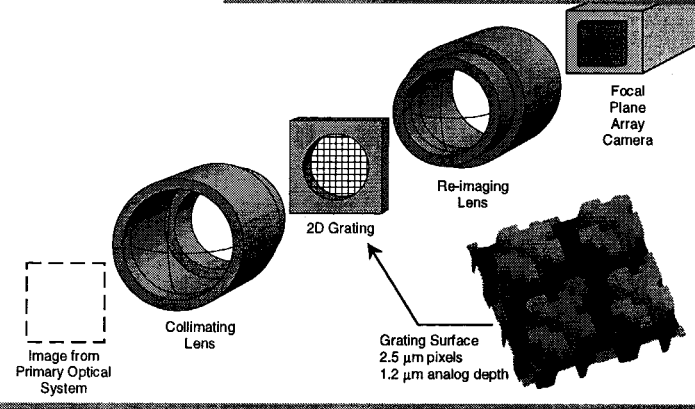




Individually-Addressable Micro Mirror Arrays



Miniature Infrared Hyperspectral Imaging



Computed-Tomography Imaging Spectrometer with Diffractive Gratings

In situ Sensors

Miniaturized Sensors Probing the Physical, Chemical, and Biological Properties of Samples

MEMS – based NMR spectrometer

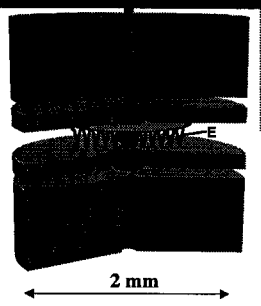
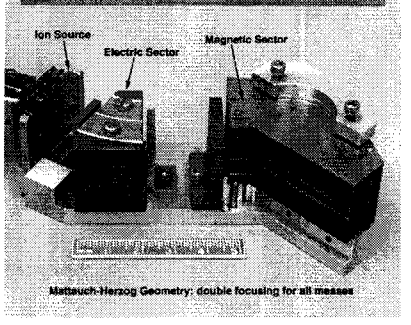
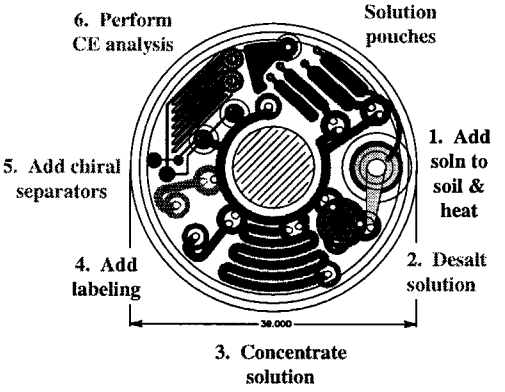


Figure 1: Schematic diagram of the microfabricated, force-detected nuclear magnetic resonance spectrometer. The key component is a mechanical oscillator made up of the sensor magnet C mounted on a silicon "diving board" or membrane D. The sample F sits in the cavity of an RF micro-coil E.

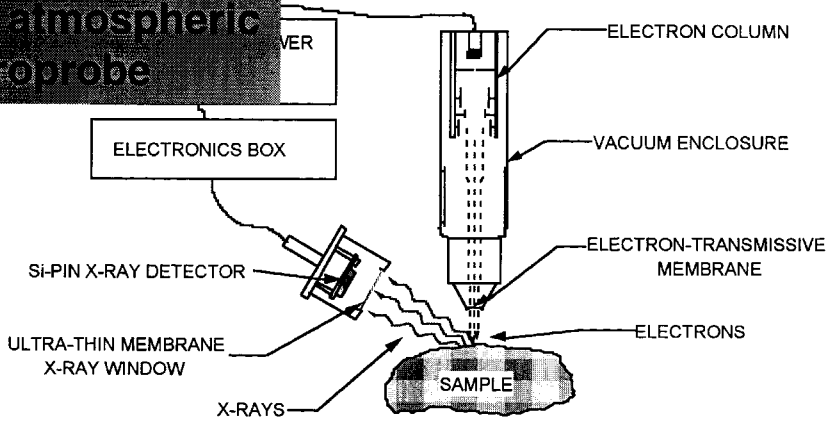
Miniature mass spectrometer



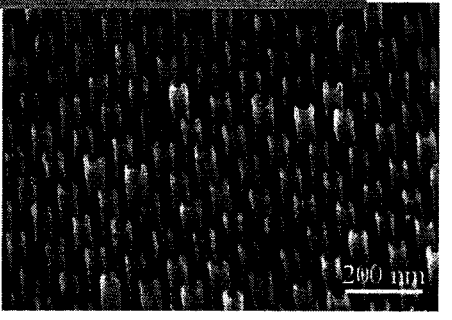
Microfluidic Sample Preparation



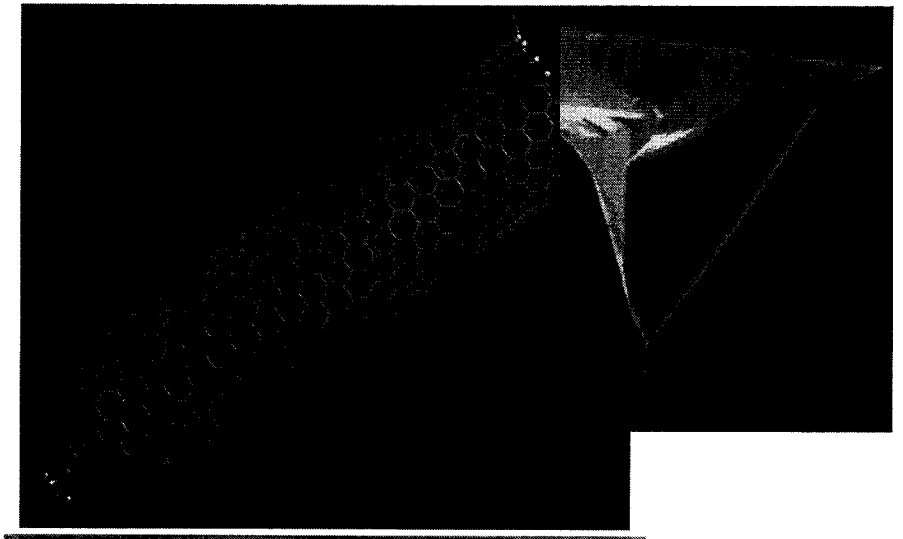
Miniaturized atmospheric Electron microprobe



C nanotube arrays

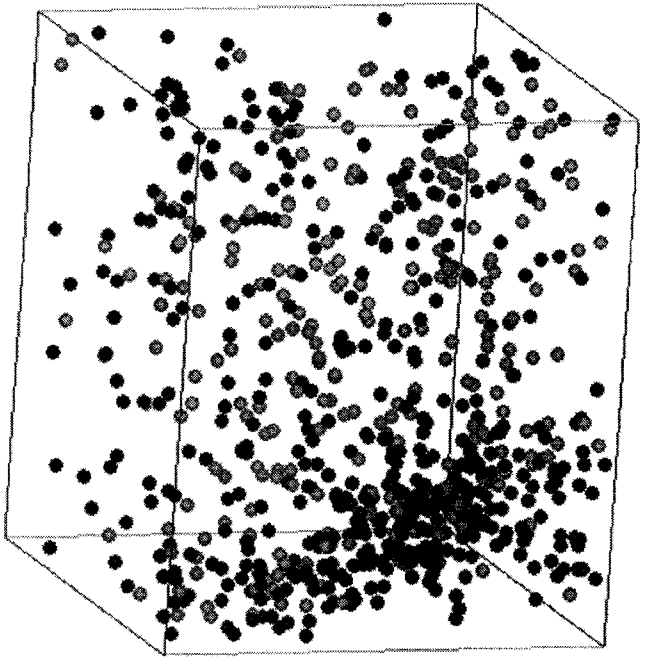


Nano and Quantum – based Technologies

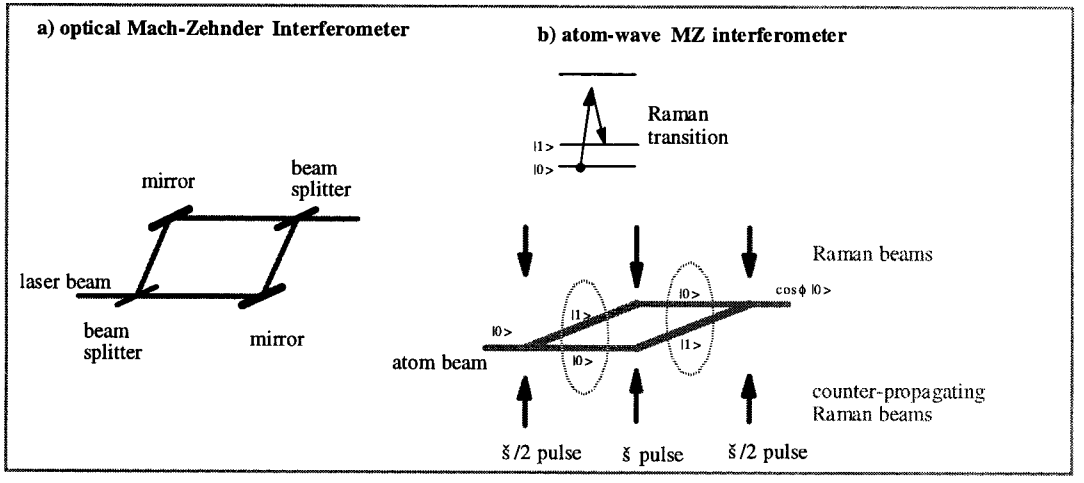


Carbon Nanotube Scanning Tunneling Microscope

3 dimensional atomic resolution image - Local Electrode Atomic Probe (LEAP)

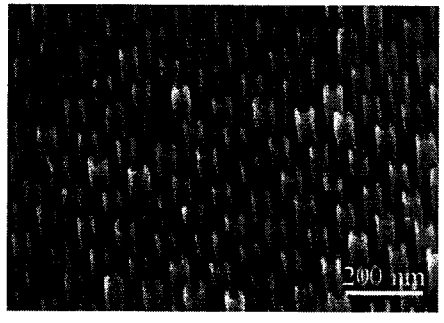


Coherent Atom Interferometry



Nano Sensors

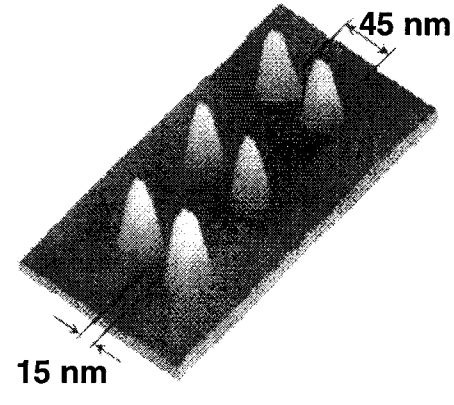
Carbon Nanotube – based Sensors



- Electrophoresis sieve for molecular separations
- Cold Cathodes for THz nano vacuum tubes
- Nano Mechanical Resonators for RF filters

Quantum Dot – based Sensors

- High Temperature Infrared Sensors
- Tunable Diode Lasers (IR thru UV)
- Biochemical Sensor Arrays
- QD Computing on Wire
- Radiation Hard Nonvolatile Memory

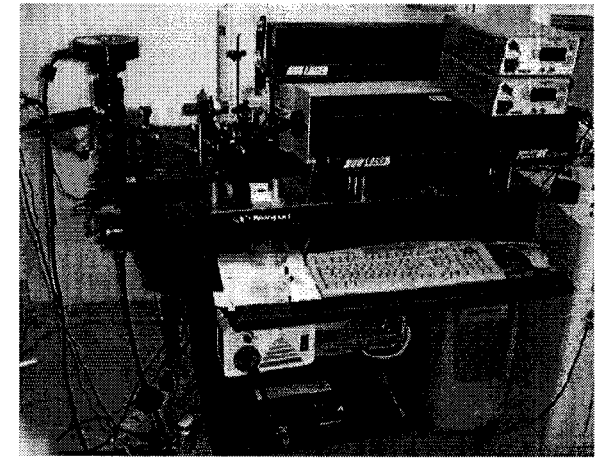


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Portable DUV Fluorescent Imaging / Raman Spectroscopy System

- Leverages work for Astrobiology and Planetary Protection
- Can be used both for bacterial detection and sterilization
- Applicable to water quality and surface sterilization

Old Specifications:



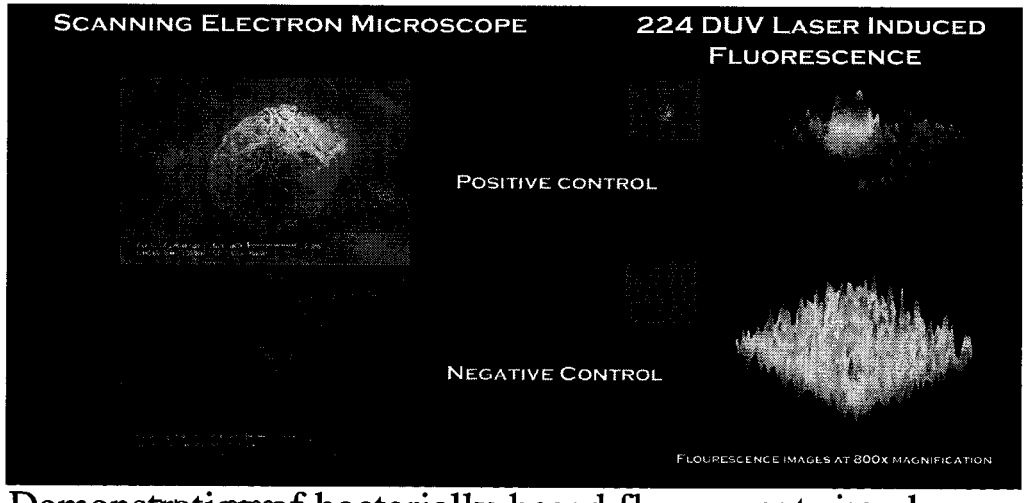
New Specifications:

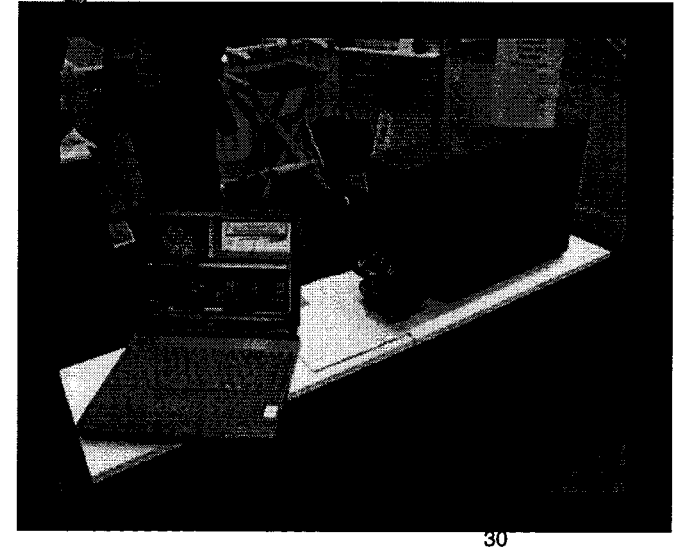
Size - 20cm x 25cm x 50.8cm

Weight - 10kg

Wavelengths - 1-3

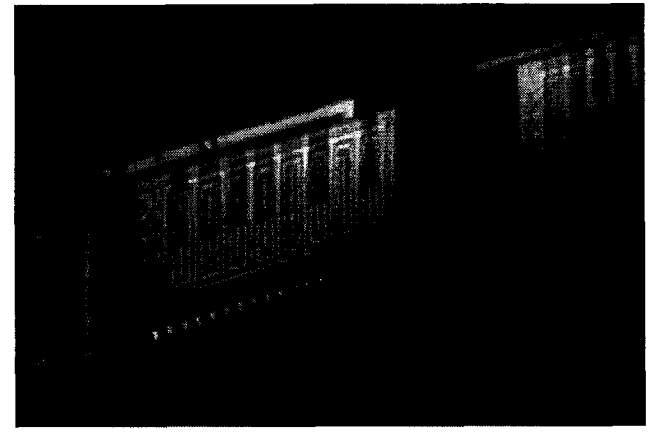
Power Req. - <100W





Demonstration of bacterially-based fluorescent signal

Electronic Nose



Technology

- Based on arrays of conducting polymers whose conductivity changes with exposure to different gases
- Chemicals identified by pattern of response across the array, in analogy to biological nose
- Flight experiment on STS 95 (1998) was the first ever continuous monitoring of any occupied spacecraft.

E-nose on board STS 95

Performance

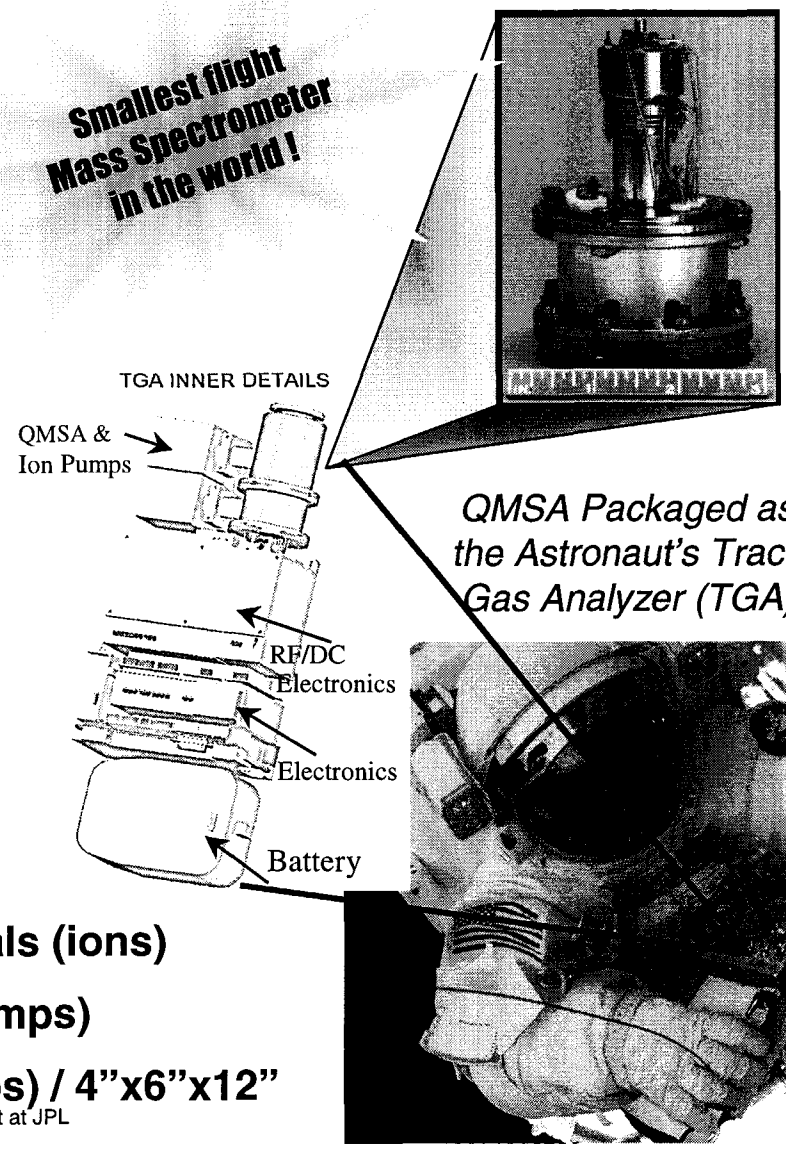
- High sensitivity & large dynamic range: 10 ppb - 10000 ppm
- Low power, mass, volume: < 2 W, 1.4 kg, 1700 cm^3 for complete system
- Real time event monitor: analysis in minutes
- Rapid response and recovery of sensors: seconds
- Can detect the presence of unanticipated chemicals
- Trainable to identify new chemicals

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Miniature Mass Spectrometer

Technology

- **Miniaturized quadruple mass spectrometer maintains the mass range, resolution, precision & stability comparable to larger units with a sensitivity corresponding to ~ 500 ppb**
- **Improved ionizer development expected to yield explosives detector with 100x sensitivity of existing technologies**
- **Currently on board ISS to detect coolant leaks (ammonia), and propellant condensation (hydrazine)**



QMSA Packaged as the Astronaut's Trace Gas Analyzer (TGA)

Performance

- **Mass range / resolution - 1- 600 amu / 0.5 amu**
- **Dynamic range / crosstalk - 10^7 / 1 part in 10^4**
- **Sensitivity - $2x10^{12}$ (10^{14}) counts/torr-sec neutrals (ions)**
- **Power - 15 W at 150 amu (incl. electronics & pumps)**
- **Weight / size - 1400 g (incl. Electronics & pumps) / 4"x6"x12"**

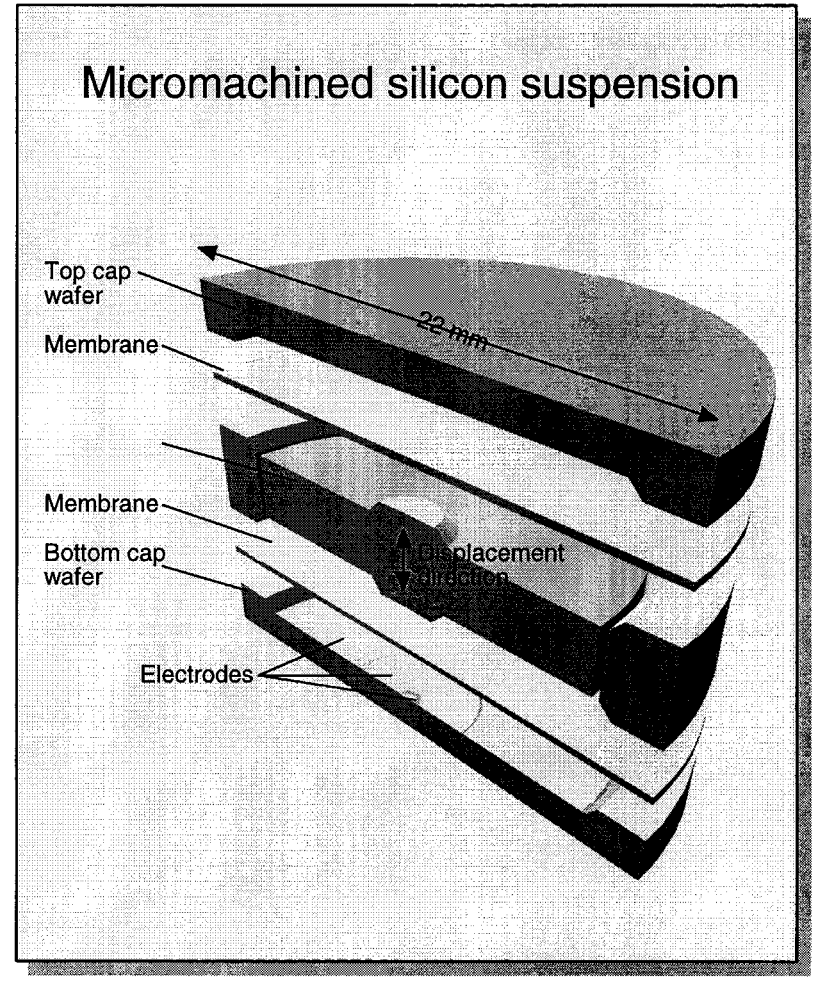
Micro Seismometer

Performance Goals:

- **Mass: < 50 g (transducer)**
- **Volume: cylinder Ø 30 mm x 20 mm**
- **Operating Power: < 20 mW**
- **Sensitivity:**
  - **better than 10^{-8} m/sec^2/√Hz over entire band**
  - **5 X 10^{-9} m/sec^2/√Hz at 10 Hz**
- **Bandwidth: 0.05-100 Hz**
- **Shock: 1000g, 100 ms half-sine**
- **Operating temperature: -80°C - +40 °C**

Areas of Development:

- **Suspensions - production of compact, robust, structures.**
- **Transducers - ultrasensitive, low-power position sensors.**
- **Control - electronically self centering, flat response, low noise**

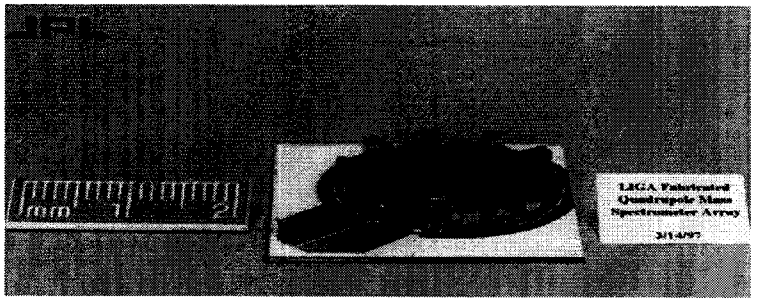


Micro GC/MS Components

JPL Fabricated Miniaturized Quadrupole Mass Filters

- **Electro-Discharge Machining (EDM)**
- **Approximately 7 mm pole length**
- **4 poles, 1 Quadrupole**

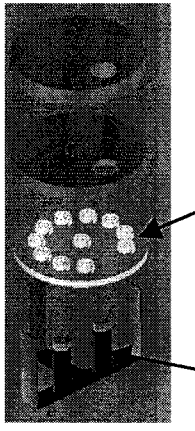
(Fuerstenau, Chutjian, Orient, et al)



- **LIGA Micromachining**
- **Approximately 3 mm pole length**
- **20 poles, 9 Quadrupoles**
- **Linear array**

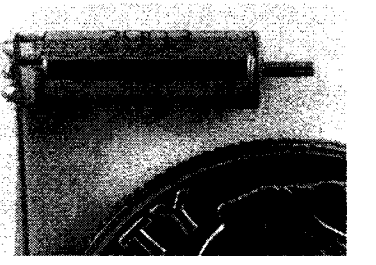
(Wiberg, Chutjian, Orient, et al)

LIGA Fabricated Scroll Pump for Vacuum Roughing



Scroll Pump Assembly

Unit Cell



Drive Motor

Unit Cell Parameters:	
Outside diameter	5 mm
Number of spirals	2.5
Wall thickness	0.2 mm
Pump height	2 mm
Estimated pumping speed	70 ml/s
Compression ratio	10:1

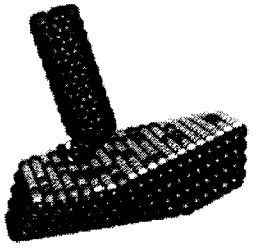
Sensors and Spacecraft Components

Impact on Space Transportation, Space Science and Earth Science

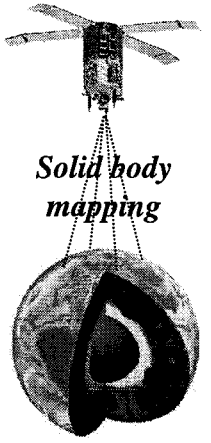
National Aeronautics and Space Administration
Jet Propu
California

2002 2004 2006 2011 2016

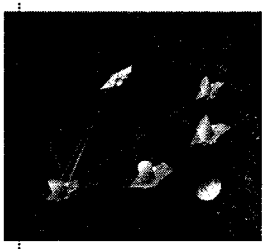
Mission Complexity



In space nanoprobes



Solid body mapping



Ultrasensitive detection & precision metrology

Nanosensor based bio explorer

NEMS flight system @ 1 uW

High-temp, radiation tolerant nano components

Quantum navigation sensors: 1E3 improvement in gyros, accelerometers & timing

High performance Nano Sensors

Nano flight system components
- Precision actuators: sub Å
- Propulsion: nano emitters
- Power: 40% efficiency

Integrated smart nano sensor systems

Quantum limited EM detector: microwave to Gamma Ray

Microspacecraft for Harsh Environments

Quantum-atomic gravity gradiometer: 1E3 higher sensitivity

Carbon nanotube based chemical probes

Capability

Summary

The search for life and the origins of biology in the solar system is pushing for detailed, fine scale investigation of Mars, Europa, Titan, comets, and any other place where water does or can exist

The future of robotic space exploration involves getting dirty in the fine dust, wet in water and methane oceans, and flying in smoggy and acidic air of the planets and moons of the solar system