Advanced Sensor Development at JPL

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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.
Challenges in Exploring the Solar System

Extreme Environments in Planetary Missions

Radiation Dose in MRads

Temperature K
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?
Advanced Sensor Deployment and Mobility Systems
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
MUSES CN nanoRover

IR Spec
APS Camera
Filter Wheel
Alpha X-Ray Spec

Body, Mobility
L band
Transceiver Board

Front & Rear Solar Panels
Top & Bottom Solar Panels

RF antenna

Side Panel Radiators

1.3 kg; 14x14x7cm

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

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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):

- **Mesogyro**:
  - Size: <8 in³
  - Bias stability: 0.1 deg/h
  - Power: <1W

- **Microgyro**:
  - Size: <1 in³
  - Bias stability: <1 deg/h
  - Power: <1W

Performance Goals:

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 $\Rightarrow$ reliability $\Rightarrow$ 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

![Image of batteries on chip]

![Graph showing discharge capacity comparison between unannealed and annealed cells]

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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

- 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
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
High-performance One-chip CMOS Digital Imager

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)

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

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

Products & Funding

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<tr>
<th>Level 1 Milestone</th>
<th>FY'00</th>
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<td>Develop CMOS micro-fab. process</td>
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<td>Develop low-noise pixel</td>
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<td>Evaluate new process with test imagers</td>
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<td>Develop FPA compatible high precision ADC</td>
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<td>Develop large format digital imager</td>
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<td>Demonstrate proof-of-concept imager</td>
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Detectors and Focal Planes

Visible
Science Grade CCDs
CMOS Active Pixel Sensors

Ultraviolet
GaN Staring Hybrid FPAs
Delta-doped SiCCDs

X-ray
Transition Edge Calorimeters
CZT Staring Hybrid FPAs

CMOS APS “camera on a chip”

Delta-doped UVCCD

CZT X-ray focal plane

TES pixels
Detectors and Focal Planes

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

- **Far Infrared**
  - Si:As BIB arrays
  - Micromesh Bolometer Arrays

- **Submillimeter**
  - Superconducting SIS mixers
  - THz sources / amplifiers

- **QWIP pixels**
- **Twin slot SIS mixer**
- **Micromesh bolometer**
- **InP HEMT 200 GHz amp**

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Lasers and Photonics

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

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

2.04 μm TDL
0.5W Optical Amplifier

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

Individually Addressable Micro Mirror Arrays

Computed-Tomography Imaging Spectrometer with Diffractive Gratings

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In situ Sensors

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

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.
Nano and Quantum - based Technologies

Carbon Nanotube Scanning Tunneling Microscope

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

Performance

- High sensitivity & large dynamic range: 10 ppb - 10000 ppm
- Low power, mass, volume: < 2 W, 1.4 kg, 1700 cm³ 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
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)

Performance

- Mass range / resolution - 1 - 600 amu / 0.5 amu
- Dynamic range / crosstalk - $10^7 / 1$ part in $10^4$
- Sensitivity - $2 \times 10^{12} (10^{14})$ 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
  - $5 \times 10^{-9}$ 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 Fabricated Scroll Pump for Vacuum Roughing

- LIGA Micromachining
- Approximately 3 mm pole length
- 20 poles, 9 Quadrupoles
- Linear array
  (Wiberg, Chutjian, Orient, et al)

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

2002

Mission Complexity

In space nanoprobe

Solid body mapping

2004

Ultrasensitive detection & precision metrology

2006

NEMS flight system @ 1 uW

High-temp, radiation tolerant nano components

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

2011

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

Quantum-atomic gravity gradiometer: 1E3 higher sensitivity

Integrated smart nano sensor systems

Quantum limited EM detector: microwave to Gamma Ray

2016

High performance Nano Sensors

Capability

Microspacecraft for Harsh Environments

Carbon nanotube based chemical probes

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Advanced Sensor Development at JPL
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.