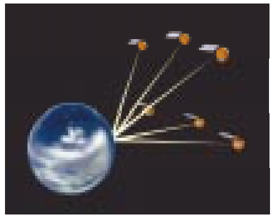
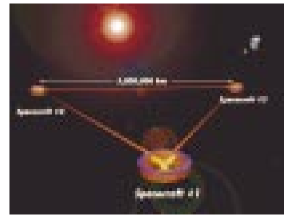
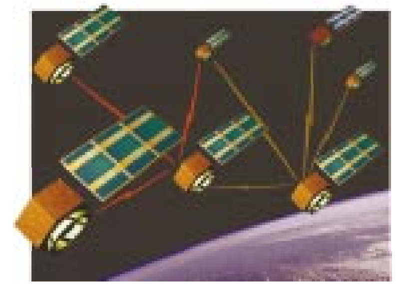
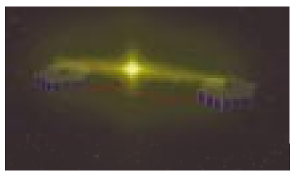


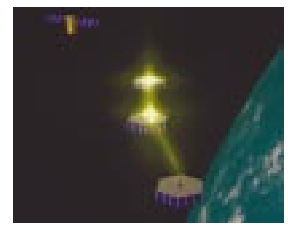




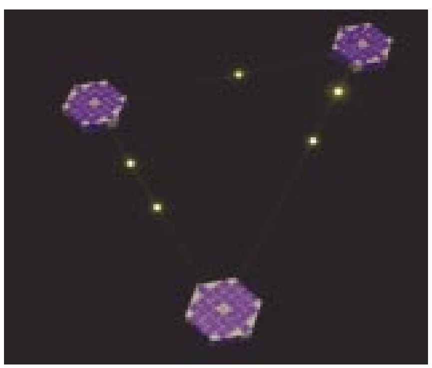
# Distributed Space Systems

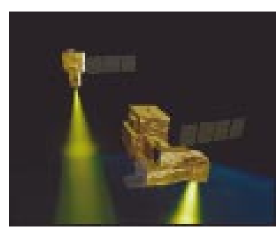
## ECT Distributed and Microspacecraft Element

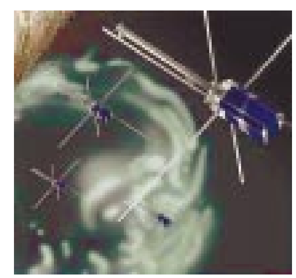




Dr. Jesse Leitner
**ECT D&MS Element Manager**
**Jesse.Leitner@gsfc.nasa.gov**
**301-286-2630**



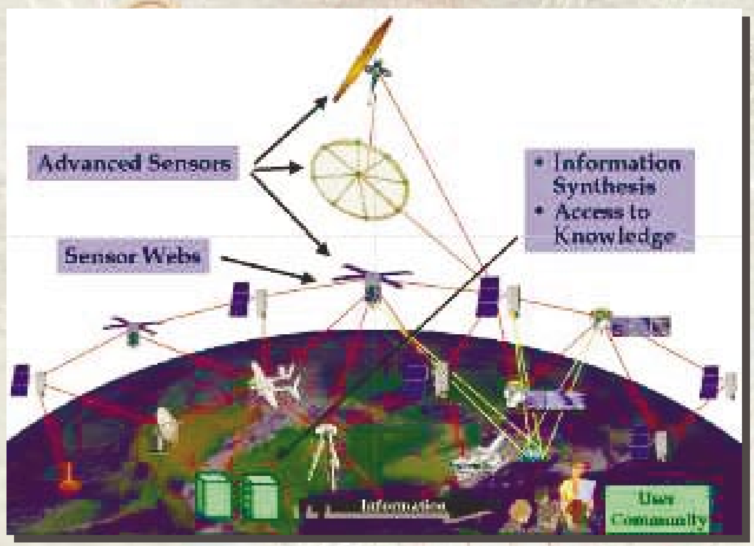




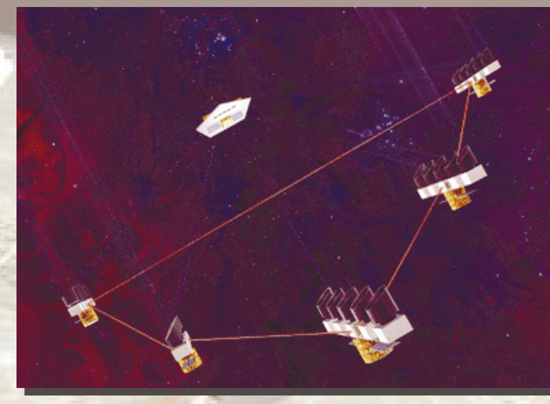
**May 23, 2002**

# Distributed Space Systems- Revolutionizing Earth & Space Science

Co-observation

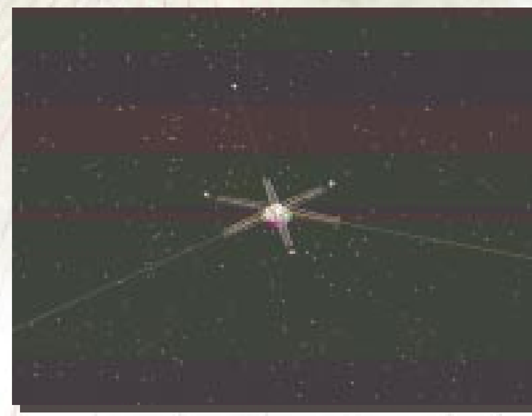



Coincidental Observations



Interferometry

Multi-point observation



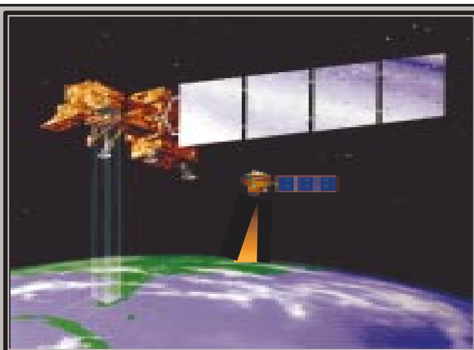
Tethered Interferometry

***A new era of space exploration will be enabled by cooperating spacecraft***

# Distributed Spacecraft Missions

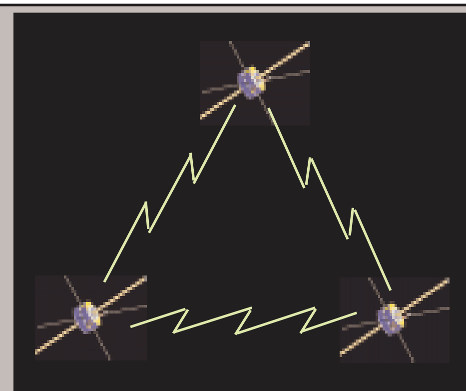
| Projected Launch Year | Mission Name | Mission Type |
|---|---|---|
| 00 | New Millennium Program (NMP) Earth Observing-1 (2) | Earth Science |
| 01 | Gravity Recovery and Climate Recovery (GRACE) (2) | Earth Science |
| 03 | University Nanosats (AFRL/GSFC) ORION nanosat mission (2) | Technology Demonstrator |
| 03 | University Nanosats (AFRL) 3 Corner Sat misson (3) | Technology Demonstrator |
| 03 | University Nanosats (AFRL/GSFC) ION-F mission (3) | Technology Demonstrator |
| 03 | Synchronized Position Hold Engage & Reorient Experimental Satellites | Technology Demonstrator |
| 03 | NMP ST-5 Nanosat Constellation Trailblazer (3) | Space Science |
| 04 | Techsat-21/AFRL (3) | Technology Demo |
| 04 | Auroral Multiscale Mission (AMM)/APL | Space Science/SEC |
| 04 | ESSP-3-Cena (w/ Aqua) (2) | Earth Science |
| 05 | Starlight (ST-3) (2)** (ground-based only at the moment) | Space Science/ASO |
| 05 | Magnetospheric Multiscale (MMS) (4) | Space Science/SEC |
| 06 | MAGnetic Imaging Constellation (MAGIC) (7, string of pearls) | Space Science |
| 06 | COACH (2-3) | Earth Science |
| 07 | Global Precipitation Mission (EOS-9) | Earth Science |
| 07 | Geospace Electrodynamic Connections (GEC) | Space Science/SEC |
| 08 | Constellation-X (4) | Space Science/SEU |
| 08 | Magnetospheric Constellation (DRACO) (50-100) | Space Science/SEC |
| 08 | Laser Interferometer Space Antenna (LISA) (3) | Space Science/SEU |
| 09 | DARWIN Space Infrared Interferometer/European Space Agency | Space Science |
| 10 | Leonardo (GSFC) (4-8) | Earth Science |
| 15 | Stellar Imager (SI) (10-30) | Space Science/ASO |
|  | Astronomical Low Frequency Array (ALFA)/Explorers | Space Science |
| 12 | MAXIM Pathfinder (2-3) | Space Science/SEU |
| 05+ | Living with a Star (LWS) (many) | Space Science |
| 05+ | Soil Moisture and Ocean Salinity Observing Mission (EX-4) | Earth Science |
| 05+ | Time-Dependent Gravity Field Mapping Mission (EX-5) | Earth Science |
| 05+ | Vegetation Recovery Mission (EX-6) | Earth Science |
| 05+ | Cold Land Processes Research Mission (EX-7) | Earth Science |
| 05+ | Hercules | Space Science/SEC |
| 05+ | Orion Constellation Mission | Space Science/SEC |
| 15 | Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) (3) | Space Science/SEU |
| 20+ | Planet Imager (PI) | Space Science/ASO |
| 20 | MAXIM X-ray Interferometry Mission (34) | Space Science/SEU |
| 15+ | Solar Flotilla, IHC, OHRM, OHRI, ITM, IMC, DSB Con | Space Science/SEC |
| 15+ | NASA Goddard Space Flight Center Earth Sciences Vision | Earth Science |
| 15+ | NASA Institute of Advanced Concepts/Very Large Optics for the Study of Extrasolar Terrestrial Planets | Space Science |

# DSS Technology Development Areas



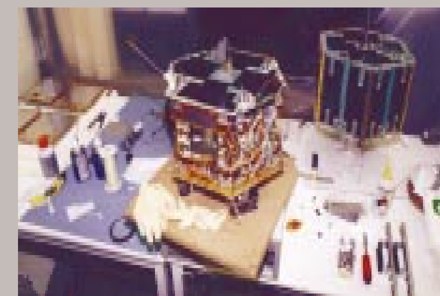
## Formation Sensing and Control

*Sensing, actuation, and algorithms required to maintain and/or understand vehicle position or orientation*



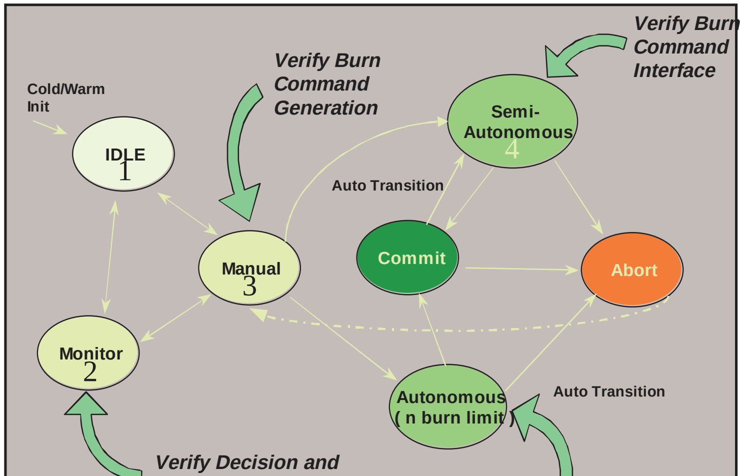
## Intersatellite Communications

*Hardware, software, and advanced coding and compression algorithms to satisfy unique DSS communications needs*



## Miniaturized Spacecraft Technology

*Approaches to reducing spacecraft bus infrastructure requirements in the areas of cost,mass, volume, and power*

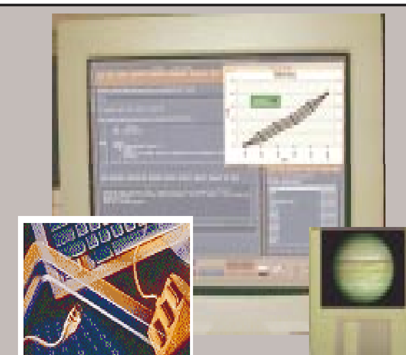



## Constellation Management and Mission Operations

*High-level control strategies to enable collaborative multi-spacecraft campaigns*

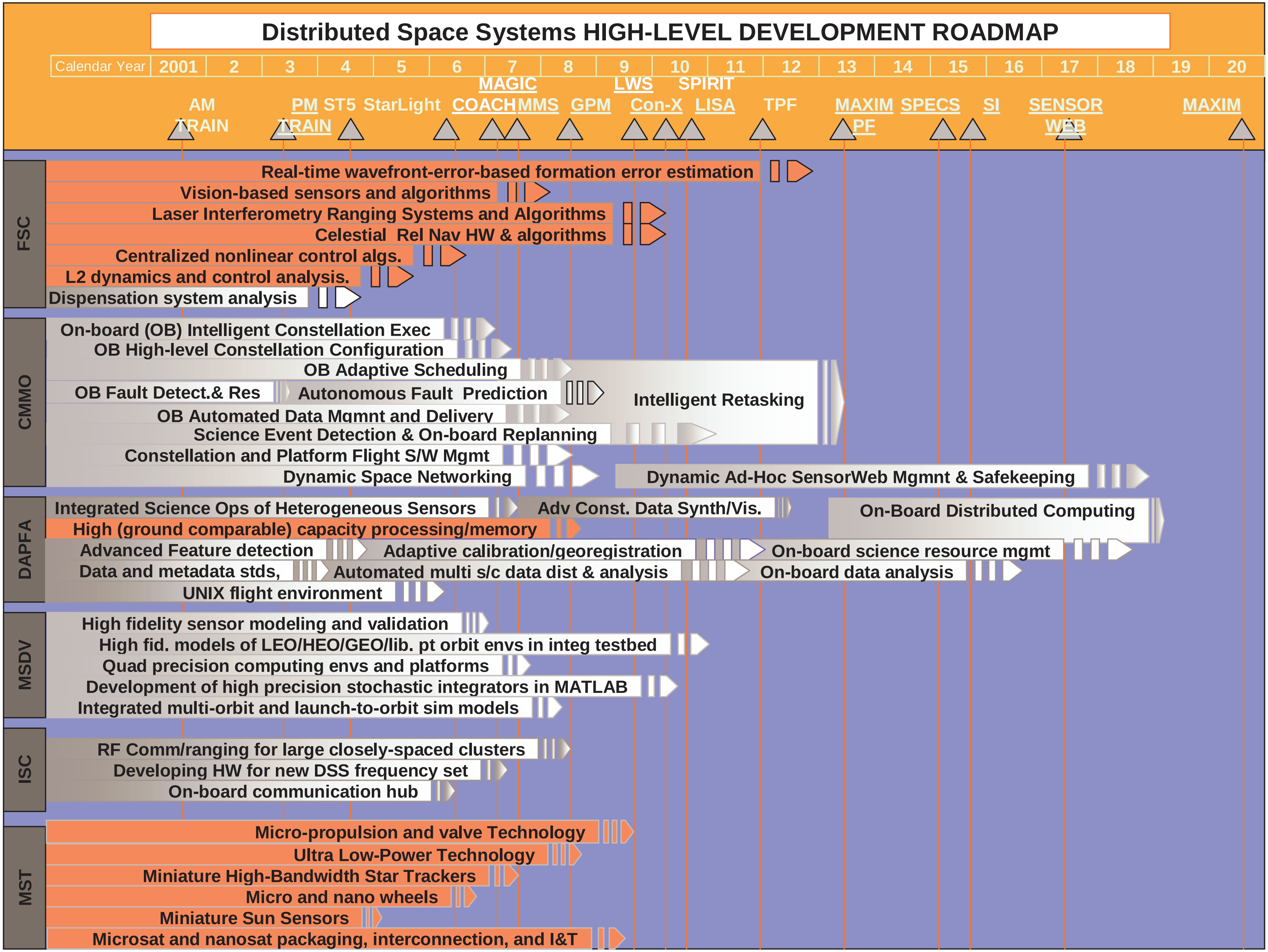
## Mission Synthesis, Design, and Validation

*The end-to-end DSS systems analysis*



## Data Acquisition, Processing, Fusion, and Analysis

*Data operations of the DSS E2E system in fulfilling the scientific objectives*



Distributed Space Systems HIGH-LEVEL DEVELOPMENT ROADMAP
Calendar Year
2001 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
AM TRAIN
PM TRAIN
ST5
StarLight
MAGIC COACH
MMS
GPM
LWS Con-X
SPIRIT LISA
TPF
MAXIM PF
SPECS
SI
SENSOR WEB
MAXIM
FSC
Real-time wavefront-error-based formation error estimation
Vision-based sensors and algorithms
Laser Interferometry Ranging Systems and Algorithms
Celestial Rel Nav HW & algorithms
Centralized nonlinear control algs.
L2 dynamics and control analysis.
Dispensation system analysis
CMMO
On-board (OB) Intelligent Constellation Exec
OB High-level Constellation Configuration
OB Adaptive Scheduling
OB Fault Detect.& Res
Autonomous Fault Prediction
Intelligent Retasking
OB Automated Data Mgmnt and Delivery
Science Event Detection & On-board Replanning
Constellation and Platform Flight S/W Mgmt
Dynamic Space Networking
Dynamic Ad-Hoc SensorWeb Mgmnt & Safekeeping
DAPFA
Integrated Science Ops of Heterogeneous Sensors
Adv Const. Data Synth/Vis.
On-Board Distributed Computing
High (ground comparable) capacity processing/memory
Advanced Feature detection
Adaptive calibration/georegistration
On-board science resource mgmt
Data and metadata stds,
Automated multi s/c data dist & analysis
On-board data analysis
UNIX flight environment
MSDV
High fidelity sensor modeling and validation
High fid. models of LEO/HEO/GEO/lib. pt orbit envs in integ testbed
Quad precision computing envs and platforms
Development of high precision stochastic integrators in MATLAB
Integrated multi-orbit and launch-to-orbit sim models
ISC
RF Comm/ranging for large closely-spaced clusters
Developing HW for new DSS frequency set
On-board communication hub
MST
Micro-propulsion and valve Technology
Ultra Low-Power Technology
Miniature High-Bandwidth Star Trackers
Micro and nano wheels
Miniature Sun Sensors
Microsat and nanosat packaging, interconnection, and I&T

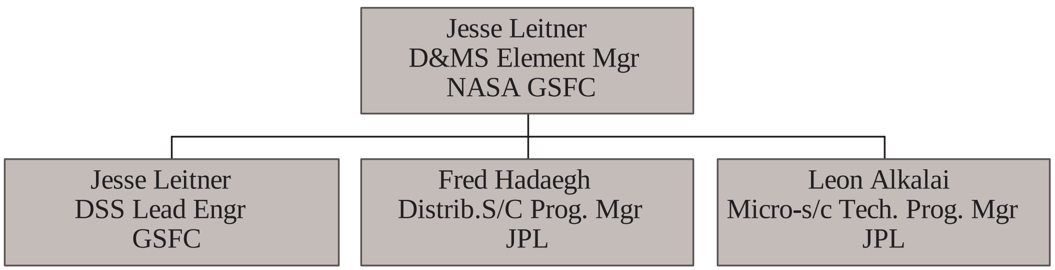
# Key Government Partnerships (outside NASA)

- **AFRL/VS - TechSat 21 - key demonstration on critical path to future formation flying missions**
  - NASA Technology infusion (rel nav and control algorithms, intersatellite communications)
  - Validation of key formation flying issues in formation flying testbed (formation flying algorithms, precise timing)
- **NRL - formation flying analysis and orbit design, communications and ranging, high precision formation sensing and metrology architectures**
- **AFRL/SN, NIST, other agencies - precise time transfer (leverages off of significant efforts which have taken place in DoD)**
- **US Naval Academy - support to formation control design efforts (high quality personnel and students available at very low-cost in summer)**

# DSS Code R Big Picture

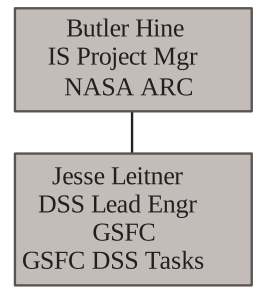
## ECT Program (Chris Moore)

D&MS Organization




## CICT Program (Eugene Tu)

Intelligent Systems Project




**Other Partners (government):**

**GRC: Space Comm (CICT) and propulsion (ECT) requirements specification**

**LaRC: Formation sensor development**

**NRL: Metrology system development, sensing architecture development**

**AFRL/SN, NIST, NRO: Timing and time transfer**

**AFRL/VS: TechSat 21**

**DARPA: MEMS technology**

# Technology Challenges

- Centimeter to nanometer control over S/C separations ranging from meters to 1000s of kilometers
- Precise and coordinated spacecraft pointing to sub-arc seconds
- Coordinated (simultaneous) Orbit/Attitude control of multiple spacecraft
- Tethered formation control
- Autonomous fleet reconfiguration, replenishment, upgrade, and repair
- Initialization of multi-spacecraft fleets: collision avoidance
- Autonomous ground operations for formations and constellations; extreme challenge is a mission consisting of 100's to 1000's of satellites
- Multiple spacecraft deployment systems : deployerships and release mechanisms
- Data management: Mb-Gb/sec of data in space-to-space communications networks
- Inter-spacecraft communications for fleet control
- Cross-calibration, data management/processing of distributed instruments
- Mass production and I&T of low-cost Microsat and Nanosat vehicles
- Modeling, simulation and testbed infrastructure

# Dominant Technology Drivers for NASA DSS Missions

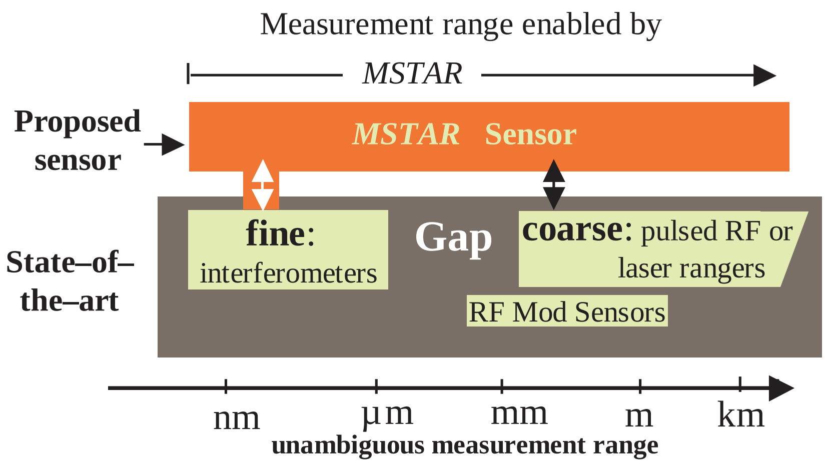
- **Cost!**
  - *MMS - need low-cost means of long range relative nav*
  - *Drives the need to push GPS to its limits*
- Span of coverage
  - *DRACO, MMS - Must cover large spatial region time-synchronously*
- Extremely low noise characteristics (high sensitivity of payload)
  - *LISA - Measurement would be lost in the most minimal gravitational or seismic disturbances*
- Long mission duration
  - *SI - Must last through entire solar cycle*
- "Awkward" Science Sensors
  - *MAGnetic Imaging Constellation - Each craft has 4 500 meter antennae*
- High required angular and spatial resolution
  - *SI, MAXIM - milli-micro arcsecond line-of-sight requirements*

# D&MS Components

- **Distributed Spacecraft work at Goddard**
  - Specialized formation sensors for synthetic Fizeau telescope missions
  - Lagrange point formation control
  - Six degree of freedom control at low-high altitudes
- **Formation Flying work at JPL**
  - Specialized formation sensors and metrology systems for precision formations
  - Precision formation flying architectures
  - Hardware in the loop simulation
- **Micro/nano spacecraft work at JPL**
  - Miniaturized GN&C
  - Micro-thrusters
  - Micro-power

Modulation Sideband Technology for Absolute Ranging
# (MSTAR) Sensor

## Product




## Product Objectives

Develop a range sensor with nanometer resolution and multi-kilometer absolute measurement range.

- A high-precision, high-dynamic range, flight-qualifiable interferometric absolute metrology gauge using Modulation Sideband Technology for Absolute Ranging (MSTAR) that will bridge the gap between the existing “fine” and “coarse” regions.
- A handoff approach between the interferometric gauge and the long range “coarse” RF sensor

## Participants & Customers

- Dr. Serge Dubovitsky, JPL, 346
- Dr. Oliver Lay, JPL, 335
- Prof. William H. Steier, USC
- Dr. Harrold Fetterman, Pacific Wave Industries, Inc.
- **Primary Enterprise Customer**: SSE
  Separated Spacecraft Interferometry: Terrestrial Planet Finder (TPF), Constellation-X, Life Finder (LI), Planet Imager (PI)
  Large Deployable Single Telescopes: Filled Aperture Infrared Telescope, FAIR), Space UV/Optical Telescope (SUVO)
- **Secondary Enterprise Customer**: ESE (EX5)

## Product Schedule & Funds

| **Product Milestones** | **02** | **03** | **04** |
|---|---|---|---|
| Demonstrate full performance | X | | |
| Demo. path to integration and insertion to flight system | | X | X |
| Code R ($K) | | | |
| Contracted Support (PWI) | 151 | 200 | 0 |
| USC | 150 | 150 | 0 |
| **Total ($K)** | **488** | **401** | **566** |

# RF Formation Flying Sensor

## roduct

## roduct bectives

Develop a Ka-band Formation Flying Sensor (FFS) to measure ranges and bearing angles between multiple spacecraft to a (2cm, 1 arcmin)-accuracy, at 30-1000m spacecraft separation, with near-4$\pi$-steradican coverage and no ground commands, for autonomous precision formation flying of multiple spacecraft.

•FY02: Prototype FFS; demonstrate technology.
•FY03: Develop calibration & acquisition techniques.
•FY04: Enhance formation flying sensor algorithms.

## articiants rstoers

**Participants:**

- Tracking Systems & Applications (335): G. Purcell, J. Tien, J. Srinivasan, L. Young, M. Gudim
- Spacecraft Telecomm. Equipment (336): L. Amaro
- Comm. Ground Systems (333): M. Ciminera, G. Walsh, D. Price, C. Foster

**Co-funding:**

- StarLight Mission

**Customers:**

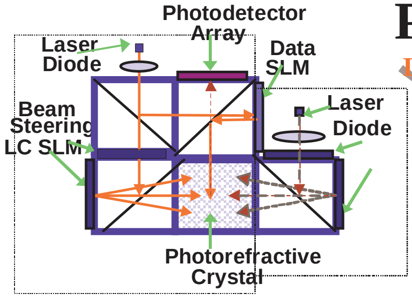
- Primary Enterprise Customer: StarLight mission
- Future Customers: TPF, Planet Imager, other future missions requiring precision formation flying.

## roduct Schedule rm unds

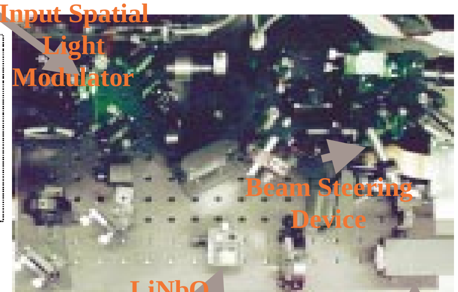
| **Product Milestones** | **02** | **03** | **04** |
|---|---|---|---|
| Prototype sensor Tech demo | X | | |
| Acq. & calibration algorithms | | X | |
| Integrated filtering algorithms | | | X |
| Code R ($K) | 300 | 400 | 400 |
| Code S ($K) | 670 | 800 | 800 |
| StarLight | 670 | 800 | 800 |
| **Total ($K)** | **970** | **1,200** | **1,200** |

# Compact Holographic Data Storage

## Products




System Schematic Diagram of a LC Beam Steering Based CHDS system




Current Book-sized CHDS breadboard developed at JPL

## Product Objectives

- A compact nonvolatile holographic memory with Ultra High data/image storage capability (1TB), High-speed random access data transfer (1GB/s)
- FY01 Demonstrated a book-sized CHDS 1-D breadboard using an innovative Liquid Crystal Beam Steering Devices data/image storage/retrieval; TRL 2
- FY 02 Integrate CHDS system breadboard for user interface and evaluation; TRL3

## Participants & Customers

- Tien-Hsin Chao, Jet Propulsion Laboratory (JPL)
- Demetri Psaltis (Cal Tech)
- Primary Enterprise Customer: HEDS, NGST, AIST
- Secondary Enterprise Customer: Mars Landers

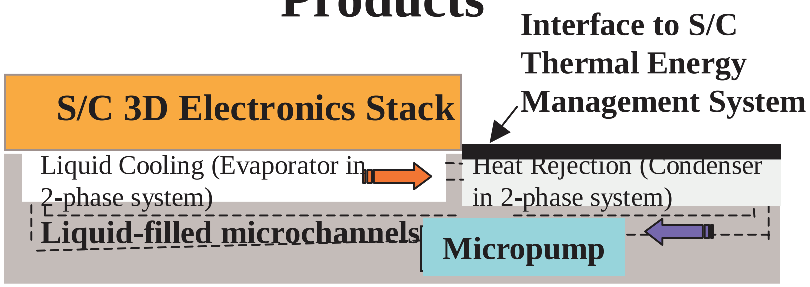
## Product Schedule & Funds

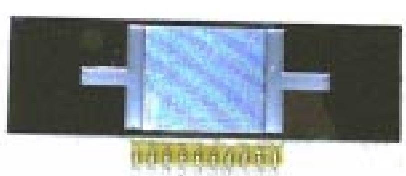
| Product Milestones | 00 | 01 | 02 |
|---|---|---|---|
| FY 00 Develop compact system architecture<br>FY 00 Proof-of-concept demo<br>FY01 1-D Subsystem breadboard<br>FY 02 CHDS system breadboard | | | |
| CETDP ($K) | 286 | 290 | 150 |
| Co-Funding ($K) | | | |
| Total ($K) | 286 | 290 | 150 |

Tien-Hsin Chao

# MEMS Pumped Liquid Cooling System for Highly Integrated Micro-Nano Sciencecraft

## Products



Microchannels device etched in silicon

Closed Loop test bed

## Overview

•Develop MEMS based liquid pumped cooling system for high power-density electronics & sensors used in future spacecraft. Develop cooling system (micropump and microchannel) as an integrated package that can remove over 25 W/cm$^2$

•FY00: Design and Fab microchannels; TRL 2/3

•FY01: Advanced microchannels and evaluate micropump technologies; TRL 2/3

•FY02: Design, fab, & test complete cooling system; TRL 3

## Participants:

•Jet Propulsion Lab – Dr. Gaj Birur (PI), Dr. Anthony Paris, Amanda Green, Siina Haapanen

•SAIC, San Diego - Dr. Tricia Sur

•Micro Device Labs (MDL) at JPL & Thermal Flight Systems & Technology Lab at JPL

•FY00 : NASA GSFC (Ted Swanson) & Stanford University (Prof. Tom Kenny)

## Customers:

• Primary Enterprise Customer: Code S, Solar System Exploration missions to Mars & other planets, SEC and small-sat missions (GSFC)

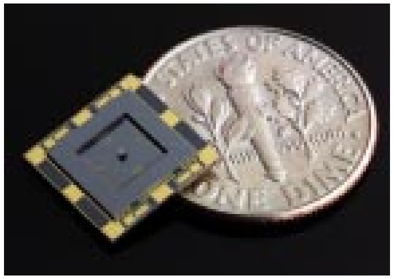
•Secondary Enterprise Customer: Code Y, advanced sensors, high power density payload (FPGA)

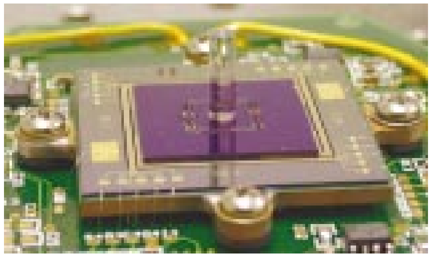
## Product Schedule & Funds

| Product Milestones | 00 | 01 | 02 |
|---|---|---|---|
| 1. Design & fab μchannel | ——— | ——— | → |
| 2. Eval μpump technologies | | ——— | → |
| 3. Integrate & test | | | ——→ |
| Code R ($K) | 355 | 300 | 140 |
| Co-Funding ($K) | 0 | 0 | 0 |
| Total ($K) | 355 | 300 | 140 |

# Miniature High Precision Gyro Development

## Products





**Micro Scale Gyro** **Meso Scale Gyro**

## Product Objectives

- To develop MEMS microgyros & micro inertial system technologies for space applications with
  - High Performance (<0.1 ˚/hr long term drift)
  - > 1000 X reduction in cost and size.
  - > 100 X reduction in power consumption
  - Increased functionalities and flexibility
- FY 02: **3 axis gyro breadboard demonstration** TRL 3
- FY 03 **3 axis IMU breadboard TRL 4**

## Participants & Customers

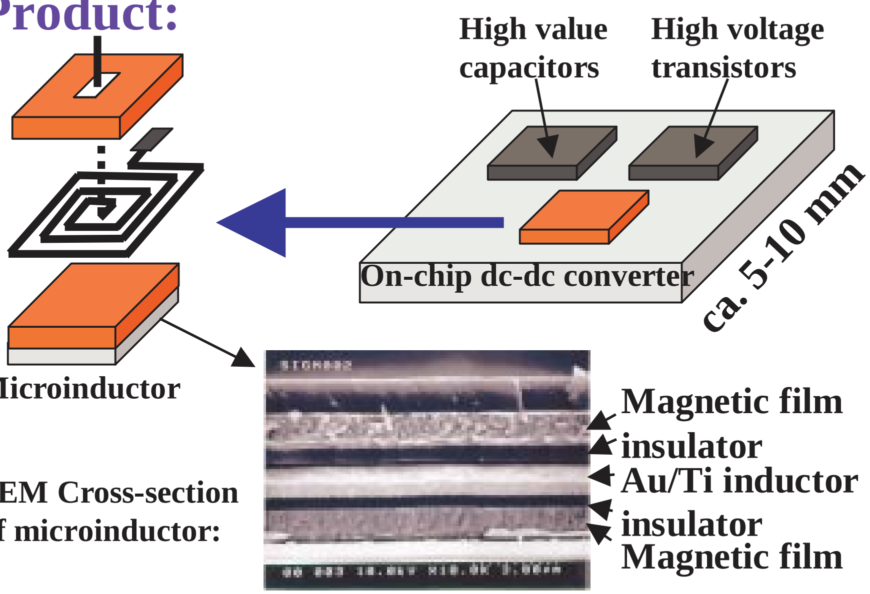
- Dean Wiberg, JPL
- Joel Gambino, GSFC
- Boeing Satellite Systems
- JPL Microdevices Laboratory & GSFC testing facilities
- Primary Enterprise Customer: Space Science, Aerospace
- Secondary Enterprise Customer: HEDS, Earth Science

## Product Schedule & Funds

| Product Milestones | 01 | 02 | 03 |
|---|---|---|---|
| FY 01 µgyro: Wafer scale fab to 1.0˚/hr bias drift | X | | |
| FY 02 3 axis gyro breadboard demonstration | | X | |
| FY 03 3 Axis IMU) breadboard demonstration | | | X |
| Code R ($K) | 390 | 300 | 300 |
| Co-Funding ($K) CISM//DARPA | 2100 | 1500 | 2000 |
| Total ($K) | 2390 | 1800 | 2300 |

# Micro Inductors for Integrated Power Electronics

## Product:




## Product Objectives

- Enable the miniaturization and integration of the power electronics/dc-dc converters through the development of high value integrated microinductors using silicon compatible processes
- Funding was leveraged with System-on-a-chip program support (FY00 and FY01)
- Will be used in conjunction with high value dielectric capacitors, high voltage transistors, and rechargeable microbatteries also under development

## Participants & Customers

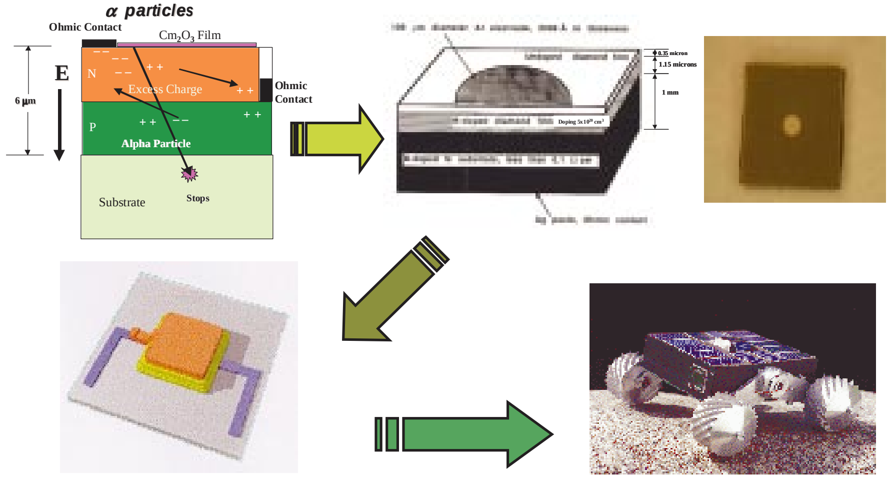
- NASA Goddard Space Flight Center/Nanosatellite Power Program
- Integral Wave Technologies
- University of Idaho
- Primary Enterprise Customer: Micro-Nano Sciencecraft Program , X-2000 Deep Space Systems Technology Program

## Product Schedule & Funds

| Product Milestones | 00 | 01 | 02 |
|---|---|---|---|
| FY 00 Prototype microinductor | X | | |
| FY 01 Materials development and optimization | | X | |
| FY 01 Primitive Element Fab | | X | |
| FY 02 Prototype converter | | | X |
| CETDP ($K) | 200 | 150 | 265 |
| Co-Funding ($K) - DSST (integrated passive components) | 400 | 600 | 0 |
| Total ($K) | 600 | 650 | 265 |

# Alpha Particle Power Source

## Products




On-Chip Power Source

## Product Objectives

- α-voltaic microdevices based on wide band gap radiation-hard semiconductors for $mW/mm^3$ power (vs. $mW/cm^3$)
- FY00: Initial device design, survivability studies and lifetime predictions; proof-of-principle device ; TRL 1
- FY02: Integrated alpha-voltaic on-chip power source with demonstrated long lifetime; TRL 3

## Participants & Customers

- Jagdish Patel (P.I.), Jean-Pierre Fleurial, Jet Propulsion Laboratory (JPL)
- Robert Averback, U. Illinois
- Takeshi Tachibana, Kobe Steel Ltd., Japan
- Oak Ridge National Laboratory (ORNL)
- Primary Enterprise Customer: *HEDS, Mars Exploration Program*
- Secondary Enterprise Customer: *Solar System Exploration Program*

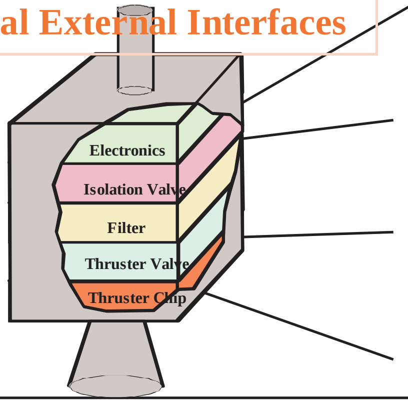
## Product Schedule & Funds

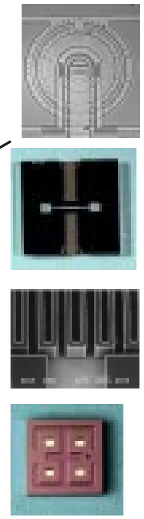
| Product Milestones | 00 | 01 | 02 |
|---|---|---|---|
| FY 00 Survivability studies | X | | |
| FY 00 proof-of-principle device | X | | |
| FY 01 Materials Selection | | X | |
| FY 01 Optimum Device Design | | X | |
| FY 02 Power source prototype | | | X |
| FY 02 Long-life demonstration | | | X |
| CETDP ($K) | 150 | 180 | 140 |
| Co-Funding ($K) | | | |
| Total ($K) | 150 | 180 | 140 |

# Integrated Micro-propulsion

## Products

**Goal:**
- **Micromachined Components**
- **Highly Integrated Modules**
- **Minimal External Interfaces**




## Product Objectives

- **Develop fully integrated propulsion systems that combine MEMS-based sub components with integrated microelectronics control circuits for future micro/nano Sciencecraft**
- **FY02: Demonstrate operation of propulsion components (VLM and MIV) with Driver Electronics; TRL 3.**
- **Continued performance mapping of VLM thruster, MIV filtration tests**

## Participants & Customers

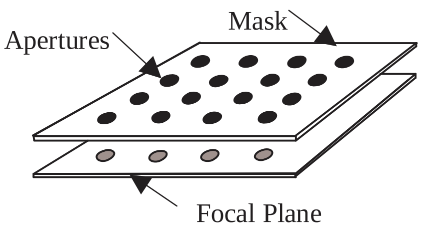
- Juergen Mueller (PI), Mohammad Mojarradi (Co) PI Jet Propulsion Lab (JPL). Amanda Green, David Bame Victor White (JPL). Prof. Harry Li ( University of Idaho), Prof. Ben Blalock (Mississippi State University)
- Unique facilities: 0.5 μN resolution thrust stand, Micro Devices Lab, Micropropulsion Design, Assembly and Test facility (MDAT) (under construction).
- Primary Enterprise Customer: Code S, Solar System Exploration Missions to Mars & other planets, SEC missions (GSFC), interferometry missions
- Secondary Enterprise Customer: Code Y, advanced sensors

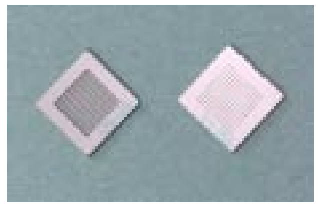
## Product Schedule & Funds

| Product Milestones | 00 | 01 | 02 |
|---|---|---|---|
| Design & Fab Micro Propulsion Comp. | X | | |
| Perf. Demo/Charact. of VLM/MIV | | X | |
| Map propulsion Cells into 0.35um | | | X |
| Demonstrate operation of VLM and MIV with Driver Electronics | | | X |
| CETDP ($K) | 500 | 500 | 500 |
| Co-Funding ($K), DRDF | 300 | TBD | TBD |
| Total ($K) | 800 | 500 | 500 |

# Sun Sensor On A Chip

## Product



Mask

## Product Objectives

• To develop a low mass (<8 grams) and low power (<25 mW) sun sensor (12x17 mm) with larger than 128° field of view and better than 0.02° accuracy for next generation nanorovers and nanospacecraft navigation applications

• FY 00 Milestone: Package a prototype MEMS mask and CCD focal plane. (TRL 3)

• FY 01 Milestone: Compact (25x25x8 mm & ~11.5 gm) fully functional sun angle sensor breadboard validated in laboratory environment. (TRL 3-4)

## Participants & Customers

• Principle Investigator: Dr. Sohrab Mobasser, JPL Power and Precision Conversion Systems and Technology

• Co-Investigator : Dr. Carl Christian Liebe, JPL Avionics Equipment Section

• Primary Enterprise Customer: Aerospace Technology

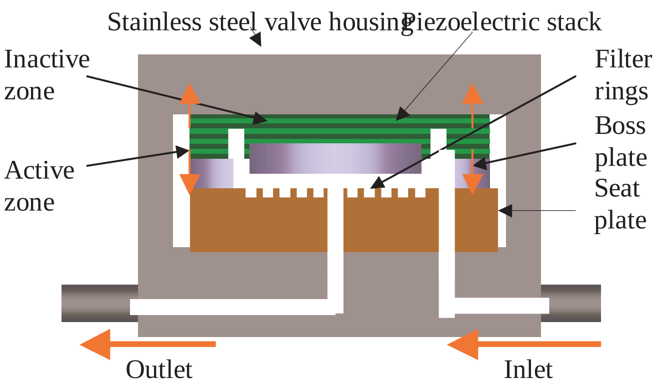
• Secondary Enterprise Customer: Space Science

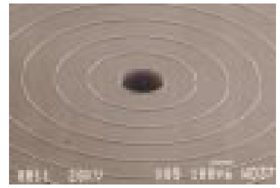
## Product Schedule & Funds

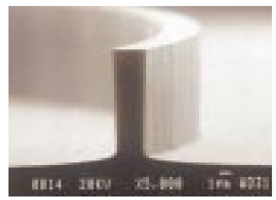
| Product Milestones | 00 | 01 | 02 |
|---|---|---|---|
| Prototype System Design<br>Mask Fab & Test<br>Detector and Solar Filter<br>Breadboard Fab & Test<br>Compact Breadboard Fab & Test | | | |
| CETDP ($K) | 200 | 170 | 150 |
| Co-Funding ($K) | | | |
| Total ($K) | 200 | 170 | 150 |

# Piezoelectric MEMS Microvalve

## Products





## Product Objectives

- Long term: Ultra leak-tight, fast response, high differential pressure piezoelectric microvalves with low power consumption for micropropulsion and bioengineering applications
- FY02: Actuated, leak tight piezoelectric microvalves at TRL 3

## Participants:

Dr. Eui-Hyeok Yang (PI), JPL (3842)
Dr. Juergen Mueller, JPL (3534)
Dr. Gajanana C. Birur, JPL(3530)
Dr. Mohammad Mojarradi, JPL (3460)

## Potential Customers:

**NASA/JPL:**
- Micro Mars Programs
- New Millennium
- Interferometry Missions
- Inflatable Spacecraft (ARISE)

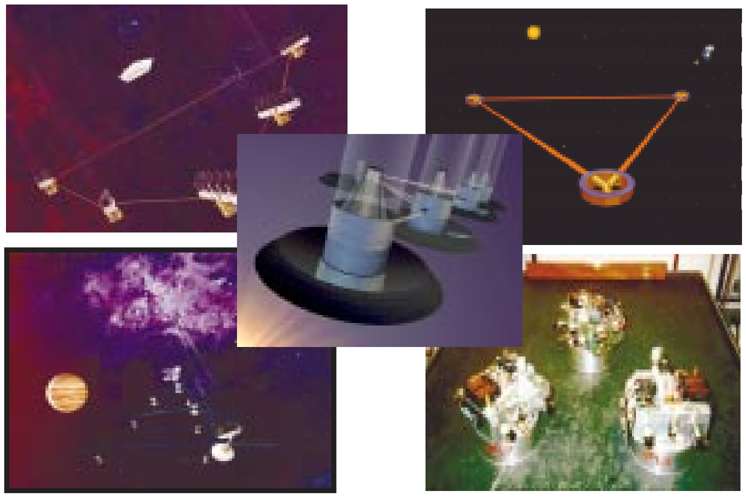
**Outside:**
- Air Force
- DARPA
- BMDO
- NRO

## Product Schedule & Funds

| Product Milestones | 02 |
|---|---|
| •Design & fabrication of the valve structures | X |
| •Assembly and test of piezoelectric actuators | X |
| •Leak and flow test of the actuated valve | X |
| •*Pressure-balanced valve design* | X |
| •*Pressure-balanced valve fabrication & test* | |
| CETDP ($K) | 320 |
| Total ($K) | 320 |

# Formation Flying Control

## Products



## Product Objectives

- A system of methods, architectures, algorithms and software for autonomous precision control (mm-cm, arcsec-arcmin) of constellations, fleets and formation flying spacecraft.
- FY02: Demonstrate re-configurable control within scaleable architecture and high fidelity simulation.
- FY03: Demonstrate integrated FF guidance & control algorithms in an end-to-end visual demonstration of formation maneuvers, in a distributed simulation environment

## Participants & Customers

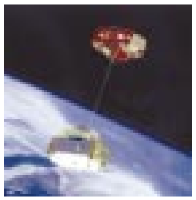
- Dr. Fred Y. Hadaegh, NASA - JPL
- Prof. Paul K.C. Wang, UCLA; Prof Roy Smith, UCSB, Prof. David C. Hyland, Univ. of Michigan, Ann Arbor
- **Primary Enterprise Customer**: SSE (Origins S1, Structure of Universe S2); Starlight, TPF, MAXIM, SPECS, LISA, LIRE, LATOR
- **Secondary Enterprise Customer**: ESE: Sensor Webs (E2); EOS-9, EX4 -7

## Product Schedule & Funds

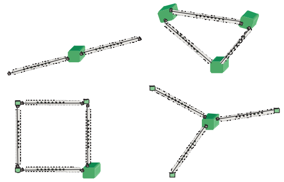
| **Product Milestones** | **02** | **03** | **04** |
|---|---|---|---|
| Re-configurable control demo | X | | |
| End-to-end FF G&C in distrib. sim. | | X | |
| Integrated distrib. real-time demo. | | | X |
| Code R ($K) | 300 | 400 | 400 |
| University Grants ($K) | 180 | 350 | 350 |
| Code S ($K) | 400 | 650 | 650 |
| StarLight | 250 | 250 | 250 |
| TPF | 150 | 400 | 400 |
| NRA | 150 | 150 | 0 |
| SBIR I, II | 400 | 250 | 0 |
| **Total ($K)** | **1,250** | **1,450** | **1,050** |

# Tethered Spacecraft Formation

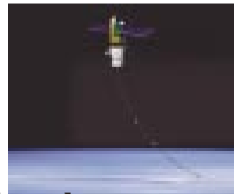
## roduct



Precision LEO Spinning Interferometer



Tethered Formation Control Technology



Distributed sensors For Planetary Science

Smart Tether

MEMS based Tethered Nano-Picosat

## roduct bectives

- eelo a system of ethods to siulate and control foration flying tethered system architectures hich ill ae the ay to future classes of lighteight sacecraft
- nable Tethered Sace nterferometers orations of Tethered Sensor ebs istributed Sacecraft
- odeling and control algorithms for smart tether deeloed ointing retargeting odels deeloed ose ground testing TR
- delivery of integrated siulation tool ground testing deeloment of ey technologies TR
- seeortunity for roosing flight deo

## articiants ustomers

rincial nestigator Marco uadrelli ASA et roulsion ab asadena A arcoquadrelli nasa.gov

SE icro Sat MMS eeriment Tethered Synthetic Aerture Radar

ASE T tethered interferometer for lanet imaging

SE S tethered foration for sub astronomy

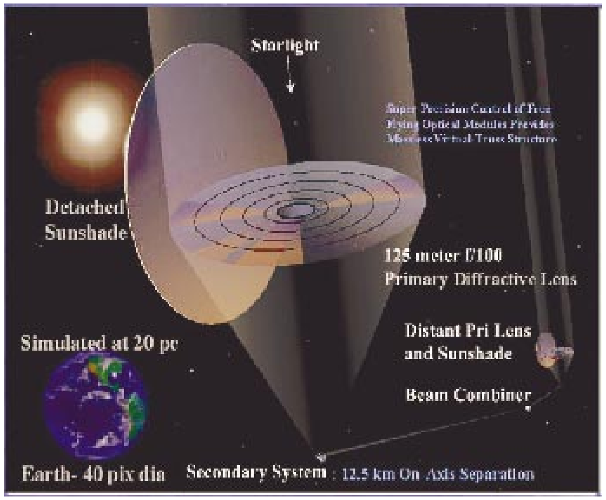
SS uter lanets loration lanetary Atoshere Magnetoshere eodesy Missions

## Schedule unding

| Product Milestones | 02 | 03 | 04 |
|---|---|---|---|
| Pointing/targeting control alg.<br>LEO formation control alg.<br>LEO flight demo proposal | X | <br>X | <br><br>X |
| Code R ($K) | 150 | 230 | 260 |
| grant ($K) | 50 | 100 | 100 |
| Total ($K) | 150 | 230 | 260 |

# Formation Flying System Analysis

## Product




## Product Objectives

- FY02: Develop formation metrology & control architectures, methods of control for image acquisition & tracking. Develop sensing, actuation, and control requirements
- FY03: Design 3D simulation for super precision control of separated optical modules for benchmark telescope configurations. Incorporate system dynamics, metrology observability and actuation constraints.
- FY04: Super-precision (sub-mm) formation control feasibility will be evaluated for benchmark optical telescope systems. Perform technology assessments for metrology, actuation, and control methods.

## Participants Customers

- Mr. Edward Mettler, Dr. David Bayard, Dr. Marco Quadrelli – G&C Group
- Mr. Bill Breckenridge - Autonomy & Control Staff
- Dr. Serge Dubovitsky – Optical Metrology

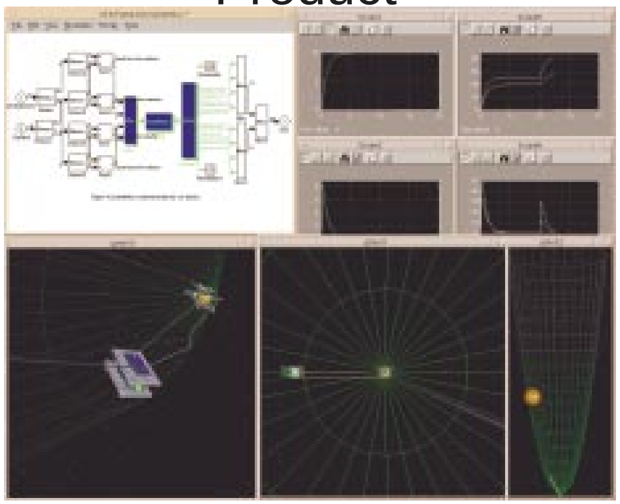
- **Primary Enterprise Customer:** OSS Astrophysics
- **Secondary Enterprise Customer:** ESE: Sensor Webs
- Benefits: Methods, tools, analyses, and 3D simulations will be developed to enable feasibility of super-precision control of benchmark arch. of distributed telescope optical systems.

## Product Schedule & Funds

| **Product Milestones** | **02** | **03** | **04** |
|---|---|---|---|
| Formation Control Architecture | X | | |
| Metrology/Control Reqmts. | X | | |
| Analyze dynamics & control | | | |
| Devel. 3-D simulation | | X | |
| Tech. Assessment/feasibility | | | X |
| Code R ($K) | 150 | 200 | 250 |
| Code S ($K) | 0 | 100 | 150 |
| TPF | 0 | 100 | 150 |
| **Total ($K)** | **150** | **300** | **400** |

# Computing for Formation Flying

## Product



## Product Objectives

- To develop advanced high fidelity & performance computational algorithms, modeling techniques and simulation architectures for precision formation flying.
- Develop methodology for high speed distributed simulation of formation flying spacecraft and instrument systems.
- Demonstrate distributed simulation capability in real-time context, and develop techniques for multiple-resolution modeling.

## articiants ustoers

- Abhi Jain, B. Martin, G. Sohl JPL
- DARTS Lab JPL
- Ben Leimkuhler, Univ. of Kansas
- Jay Laurent, Univ. of Iowa
- J. Leitner, GSFC
- Primary Enterprise Customer: SS (TPF, LISA)
- Secondary Enterprise Customer: ES (GRACE, EO), HEDS (Operations)

## Product Schedule & Funds

| **Product Milestones** | **02** | **03** | **04** |
|---|---|---|---|
| High-accuracy simulation alg. | X | | |
| FF distributed simulations | | X | |
| Multi-resolution modeling | | | X |
| Integrated FF simulation | | | X |
| Code R ($K) | 300 | 400 | 400 |
| Code S ($K) | 200 | 400 | 400 |
| StarLight | 100 | 100 | 100 |
| TPF | 100 | 300 | 300 |
| Total ($K) | 500 | 800 | 800 |

# New Efforts in FY03 and beyond

# ECT DSS 02 Overall Thrust Objective

- **The 02 task plan in DSS for the ECT area most closely addresses the Highly Distributed with secondary objectives addressed being Evolvable, Resilient, Self-Sufficient, and Ultra-Efficient**
  - Highly-distributed: By definition, this area is centered on the process of synthesizing an unrealizably-large aperture through dozens of realizable sub-apertures. Hence an unsurmountable problem is solved through an efficient and precise interaction of more reasonable tasks. The scope of this task essentially provides the precision glue to enable several key future missions and to enhance an even larger number of missions a few years down the road.
  - Resilient and Evolvable: One out of the large number of sub-aperture spacecraft can fail and be removed from the constellation with minimal performance lost, and the constellation can be reconfigured to adapt to changing environments or circumstances.
  - Ultra-efficient: by using small spacecraft to replace an impossible-to-realize monolithic spacecraft aperture, the ration of performance to mass, power, and volume is maximized.

# ECT/DSS Tech. Dev. Task 1 - Development of Relative Representation for Control Analysis and Design of Libration point orbiting spacecraft formations

- **Development of close proximity relative equations of motion for large (5-30 S/C) formations near the L2 libration point**
  - FY03 milestone: linear representation for zeroth order analysis, formation design, and preliminary control design ($120k)
    - Metrics: validation against simulation in linear regime (with 100 km of L2 point), facility of use for linear control design (qualitative comparison to Hill's equations for earth-orbiting systems)
  - FY04 milestone: nonlinear representations including first order perturbations ($160k)
    - Metric: validation against simulation in large region about L2
  - FY05 milestone: high-fidelity nonlinear relative representation with substantial perturbations to handle nanometer accuracy ($180k)
    - Metric: precise validation against nonlinear simulation
  - FY06 milestone: refinement of equations and validation against space flight data ($300k)
    - Metric: Facility of use for nonlinear control design

# ECT/DSS Tech. Dev. Task 2 - Relative Attitude determination for Earth-Orbiting formation flying missions

- **Long-term goal is integrated sensor and algorithm system, exploiting GPS and other low-cost sensors to the greatest amount possible for relative attitude determination on formations of 2-10 spacecraft.**
  - FY03 - algorithm development for 2-spacecraft LEO missions using GPS only. Implementation with GPS receivers in high-fidelity GPS RF signal simulator ($80k)
    - metric - degrees of precision for relative attitude in three axis
  - FY04 - extension to HEO Missions which extend outside of the GPS constellation and demonstration with GPS Receivers and RF signal simulator. Initial development of 3+ spacecraft algorithms. ($150k)
    - Metrics - degrees of precision for rel. att, worst case (highest) apogee/perigee combination
  - FY05 - development of architectures and algorithms suitable for the n-satellite problem. Integration and fusion with other sensors for high-altitude problems. Initial closed-loop assessments in the formation flying testbed. ($150k)
    - Metric - Closed-loop attitude control performance
  - FY06 - Integration with advanced relative navigation algorithms for 6 DOF sensing at low through high orbits. ($200k)
    - Metrics - simplicity, cost of implementation, rel. att. precision
  - FY07 - Transition into early stages of development for Stellar Imager, MAXIM, MAXIM pathfinder, and Gamma Ray Telescope missions ($140k)
    - Metric - dynamic range of applicability to several missions

# ECT/DSS Tech. Dev. Task 3 - Visual APS/LED coarse-acquisition formation sensor development

- **Development of a sensor required for synthetic aperture formation initialization (6 DOF relative for each spacecraft) in low-gravity environments entirely outside of range of GPS. Concept has a star-tracker-like APS sensor on a mothership with a FOV large enough to just encompass the formation of daughter spacecraft. Each daughter spacecraft has 3 or more LED beacons. Concept is derived from VISNAV work that has been done by Texas A&M funded by CETDP.**
  - FY03 - Laboratory (blackroom) experiments with 3-5 daughter spacecraft concept (static) ($360k)
    - Metric - ability to capture all spacecraft in FOV
  - FY04 - Dynamic laboratory experimentation ($400k)
    - Metric - duration sensor can maintain lock on all spacecraft
  - FY05 - Nominal flight experiment integrated with formation flying testbed analysis ($400k)
    - Metric - duration sensor can maintain lock, accuracy of measurement against truth
  - FY06 - Shuttle space experiment with 3-5 daughter ships ($600k)
    - Metric - duration sensor can maintain lock, accuracy of measurement against truth
  - FY07 - Demonstration on low-gravity piggy-back ride ($500k)
    - Metric - duration sensor can maintain lock, accuracy of measurement against truth

# ECT/DSS Tech. Dev. Task 4 - High-accuracy laser interferometric ranging system for clusters of extended bodies

- **Development of a precision ranging system to take formation from coarse acquisition down to handoff point of wavefront error control. This is a long-term activity targeting goal of micron order ranging by 2010 and sub-nanometer by 2015.**
  - FY03 - Survey of laser ranging capabilities and state of the art. Development of advanced interferometric design which integrates successful elements of current technology programs (SBIRs, etc), Starlight mission elements, and DoD capabilities ($120k) - metric: throughness of study
  - FY04 - Optical bench design of ranging system. Evaluations over short ranges. Assessment of realistic capability. ($320k) - metric- positioning accuracy
  - FY05 - Performance of long-range (10s - 100s of meters) tests and development of 5 year strategy for improving the technology. ($850k)- metrics- positioning accuracy, range of validity
  - FY06 - Development of testbed for dynamic measurement evaluation. Study data rates, integrity, resolution in noisy environments. Integrate basic control loops for closed-loop analysis. ($600k) - metric - closed loop performance, size of disturbances which can be attenuated.
  - FY07 - Development of initial flight experiments to prove out in realistic dynamic environment. ($600k) - metrics - open- and closed-loop performance

# ECT/DSS Tech. Dev. Task 5 - Real-scene wavefront error sensing for fine formation control

- **Concept development for integrating the science imaging activity with the ultra-high precision relative navigation of a formation or cluster of satellites. This is likely the only solution for the fine sensing element of the extended scene interferometric imaging missions.**
  - FY03 - Development of tools (including integration of existing optical and dynamics analysis tools) for high-fidelity modeling of an optical wavefront and associated wavefront error sensors (and concepts for wavefront error sensors). Will leverage off of NGST work, extending the concepts to non-contiguous, sparse formations of free-flying sub-apertures. ($240k) - metric - qualitative validation of tool
  - FY04 - Analysis of current wavefront sensors and sensing concepts, development of new sensing schemes and initial design of suitable wavefront sensors for formations. Develop initial linear algorithms for determining individual aperture errors as a function of wavefront errors (WFE inversion). ($250k) - metric - simulated performance
  - FY05 - Extend laboratory experimental setups to handle the sparse, dynamic formation problem. Enhance WFE inversion algorithms to incorporate nonlinear effects. ($650k)
    - Metric - lab performance against truth
  - FY06 - Develop breadboard prototype wavefront sensor specific to the formation flying problem, which uses candidate 2-3 spacecraft distributed aperture interferometer (Michelson or Fizeau). ($900k) - metric - laboratory performance and precision
  - FY07- Dynamic laboratory testing of wavefront sensor with WFE Inversion algorithms. Design of candidate flight experiments. ($1.4M) - metric - laboratory performance in open and closed loop

# Backup Materials

# Compact Holographic Data Storage

Tien-Hsin Chao

April, 2002

# Motivation, Challenge, and Benchmark

## Motivation

### Space Science Enterprise

- Current data storage capacity onboard spacecraft is limited (100's MB), it is far less than that
  required for real-time recording of video imageries during fly-by or planet orbiting
  (e.g. Neptune Orbiter With Triton Flybys ; Saturn Ring Observer; Mars missions)
- No current data storage technology is survivable in *radiation-intensive* environment such as that over the Europa

### Earth Science Enterprise

- Current Earth orbiting satellites (for EOS) requires 10's of Terabytes onboard storage capacity for buffer storage of data from high-rate sensors (SAR, LADAR, etc) prior their downlink to Earth.
- Magnetic data storage system is far inadequate due to its high mass and high volume

Enable onboard data storage on EOS satellite (requiring up to 1 TB data storage per day)

Enable intelligent data search/retrieval using cross-association capability of holographic memory

## Challenges

Develop high-capacity, high-transfer rate, nonvolatile, radiation-resistant holographic data storage system with low mass, low volume and low power consumption

# Motivation, Challenge, and Benchmark - Continued

## STATE-OF-THE-ART HOLOGRAPHIC MEMORY TECHNOLOGIES

| | Rockwell | MIT | Lucent | JPLÕs ÒHDS Goal |
|---|---|---|---|---|
| volume | 9Óx9Óx5Ó | CD Ğdisk Drive size | CD-disk Drive size | Sugarcube module |
| capacity | 1GB | 2Gb breadboard | 1Gb/breadboard | 100GB/cube 1TB/board |
| read/write | read only | Read only | read only | read/write |
| Moving pts | No | Yes | Yes | No |
| volatility | volatile | less volatile | volatile | nonvolatile |

BENEFIT TO NASA

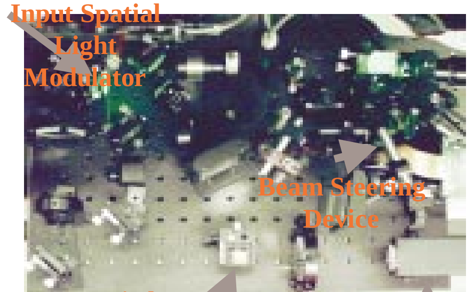
- NASA's 21st century missions will
  - require the storage of large volumes of data
  - be subject to long-duration exposure to the space radiation environment
- be based on integrated miniature systems
  - This system is envisioned to be smaller than 1 $cm^3$ in volume.
- *Holographic data storage technology* will simultaneously satisfy NASA's missions requirements in non volatility , high-density, high-transfer rate, low-power/volume, and and radiation-hardened.

## PERFORMANCE METRICS OF READ/REWRITABLE NONVOLATILE MEMORY TECHNOLOGIES

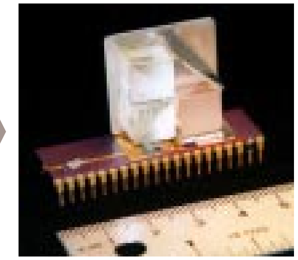
| Feature | Magnetic | Flash | Holographic |
|---|---|---|---|
| Non-volatile | Yes | Yes | yes |
| Data Retention | > 10 yrs | > 10 yrs | > 10 yrs |
| Endurance (Erase/write Cycles) | $10^5$ | $10^6$ (commercial) | unlimited |
| Data Transfer rate | 10 Mb/sec | 160 Mb/sec | > 1 Gb/sec |
| Power Consumption | 1Gb/Watt | 10 Gb/watt | 100 Gb/watt |
| Current Package | 6 x 3.5-in disk<br>< 100 GB | 256 Mb &<br>512 Mb (per die)<br>100's Gb (MCM) | 100 Gb/$cm^3$ cube.<br>1 Tb/card |

## Objective

- **Develop innovative holographic data storage technology to enable nonvolatile high-density, high-transfer rate, read/rewritable of image and digital data in a space environment**
- **Demonstrate through flight-test the key capabilities:**
  - **Ultra High data/image storage capability (1TB)**
  - **High-speed random access data transfer (1GB/s)**
  - **Radiation-hardened**



**A BOOK-SIZED CHDS BREADBOARD DEVELOPED AT JPL (2002)**


**PRODUCT GOAL: MARK-UP MODEL OF A CUBIC CHDS SYSTEM**

## Schedule/Deliverables

**Initial system integration and proof-of-concept functionality demo: Aug '01**

**Lab compact breadboard data storage/retrieval performance evaluation demo: Sep '02**

**JPL'S SOLUTION – COMPACT HOLOGRAPHIC DATA STORAGE (CHDS)**

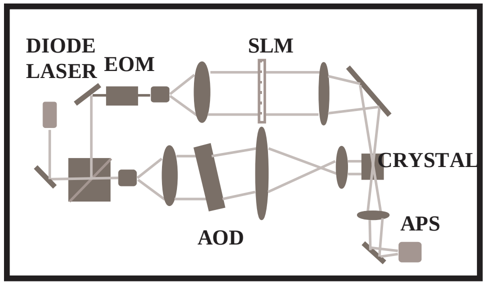
- Record digital/imagery data in photorefractive (PR) crystal directly in imagery form with high-speed (1 Gbits/sec) , random access, read/write capabilities
- Up to 2x $10^5$ pages of data has been stored in a 1 $cm^3$ PR crystal
  - **More than 1 tera bytes per cubic crystal**
- JPL developed an innovative electro-optic beam steering devices to achieve, for the first time, high data transfer rate with no moving parts

## Application/Mission

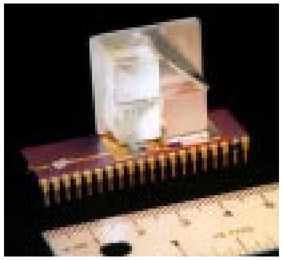
Data intensive missions, including:

- Earth Science Missions, e.g., EOS, PM-2A, CHEM-2, NPOESS, METOP.
- Other data intensive missions, e.g., HEDS, SIM, EUROPA ORBITOR

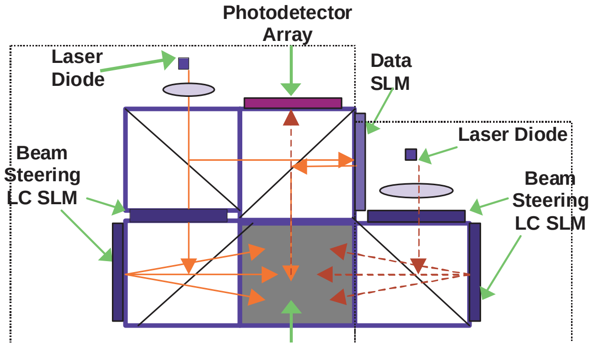
# Comparison of CHDS Technologies




Previous JPL CHDS using
Acousto-optic scanner



Cubic Holographic memory using
VECSEL array (Caltech approach)




Current JPL innovative approach
using BS scanning devices

## Pros

- AO device mature
- High-speed
- Medium density (x1 AO)

## Cons

- Bulky (AO device requires lens set for beam forming)
- High-density storage requires 2 cascaded AO, very difficult for miniaturization

## Pros

- Very compact using VECSEL array for multiplexing
- High-speed
- Medium density

## Cons

- High-density storage requires high-density VECSEL array
  - 10 x 10 array available to date
  - with only 4 mW power for each laser source (1/20 of needed power

## Pros

- Very compact using BS device
- High-speed
- High density achievable with using 2 cascaded BS devices
- Use 2 single diode laser (commercially available)
- BS device is an emerging technology with a road map for performance optimization

ROADMAP FOR CHDS DEVELOPMENT PLAN

- CHDS advanced system development: To develop and demonstrate a compact, nonvolatile, holographic data storage system for onboard data storage and support of intelligent system
  - **Miniaturization**
    - **Utilized OEIC technology to integrate key components (VECSL laser array, spatial light modulator, active pixel sensor, and MEMS micro-mirror into a 1 inch$^3$ holographic memory module.**
  - **Non-volatility**
    - **Replace current 1-dopant photorefractive recording material (e.g. Fe:$LiNbO_3$ with emerging 2-dopant materials (e.g. Fe:Mn: $LiNbO_3$, Cr:Cu: $LiNbO_3$, and Fe:Tb:$LiNbO_3$, and Ce:Mn: $LiNbO_3$ ) to *extend the holographic data storage shell life from months to decades***

MAJOR APPLICATIONS

- **Enable onboard data storage on EOS satellite (requiring up to 1 TB data storage per day)**
- **Enable real-time continuous recording of video imageries during fly-by or planet orbiting**
  - **Neptune Orbiter With Triton Flybys ; Saturn Ring Observer; Mars missions**
- **Enable high-density data storage onboard deep-space spacecraft in *radiation-intensive* environment**
  - **EUROPA mission**
- **Enable intelligent data search/retrieval using cross-association capability of holographic memory**

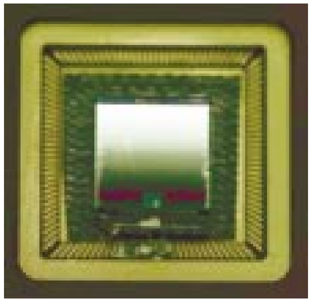
# Schedule and Milestones: Schedule and Budget

| Product Milestones | FY00 | FY01 | FY02 |
|---|---|---|---|
| Develop compact system architecture | ↔ | | |
| Proof-of-concept demo | ↔ | | |
| 1-D subsystem breadboard demo | | ↔ | |
| 2-D system breadboard demo | | | ←⋯ |

## Budget:

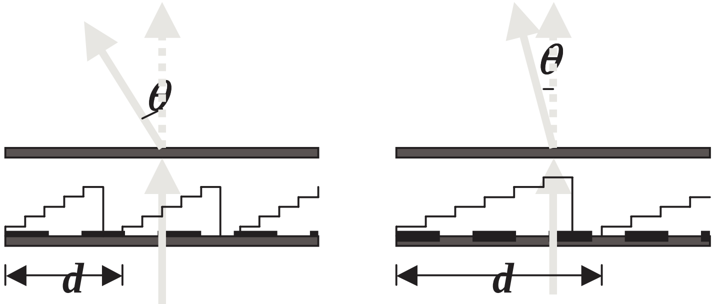
| Budget ($K) | FY00 | FY01 | FY02 |
|---|---|---|---|
| | 286 | 290 | 150 |

# Accomplishments to Date



Picture of a liquid crystal Beam steering device

Surface phase-modulation profile of a beam steering device




Optical phase profile (quantized multiple-level phase grating) repeats every 0-to-2$\pi$ ramp w/ a period $d$ which determines the deflection angle $\theta$

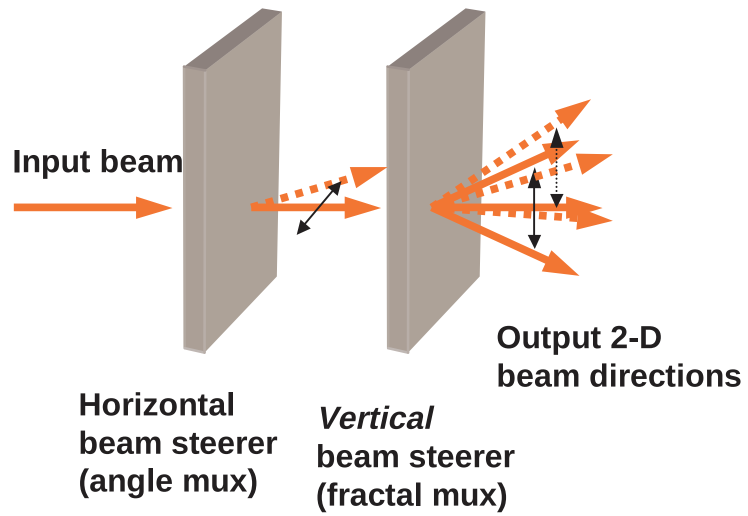
- Developed a new Electro-optic beam steering device
  - **Custom designed a liquid crystal beam steering device operational at 514 nm**
  - **Fabricated this device at Boulder Nonlinear system Inc.**
  - **Designed a LabView-based phase array profile controller**
  - **Achieved a more than 75% diffraction efficiency**
  - **128 resolvable scanning spots with the current design**
    - **Can be increased by 10-fold with larger aperture size**
  - **Capable of storing more than 15,000 pages of holographic data can be stored using a pair of orthogonally cascaded beam steering devices**
    - **Storage capacity up to 250 Gb per holographic memory cube**

## 2-D (Fractal-)Angle multiplexing using cascaded SLM beam steering devices

- Demonstrated, for the first time, 2-D (fractal-) angle multiplexing based on SLM beam steering (BS) device

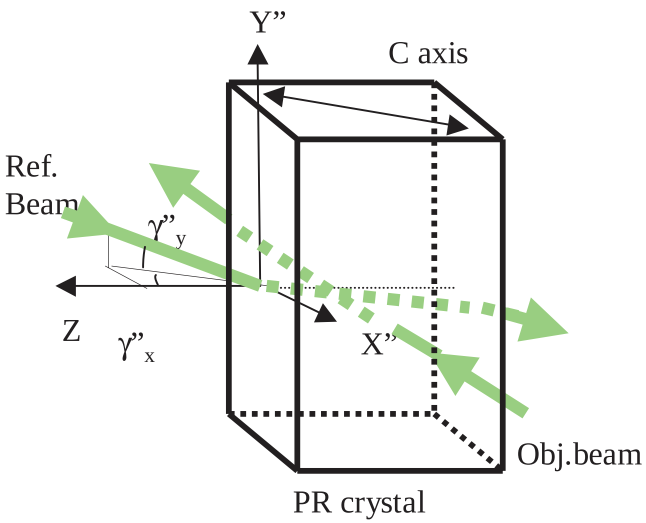
  ***Currently we have demonstrated recording of 20 (H) x 20 (V) holograms using BNS SLM BS devices; The number would be increased to, upon full system integration, a total of 128 x 128 = 16,384 holograms.***

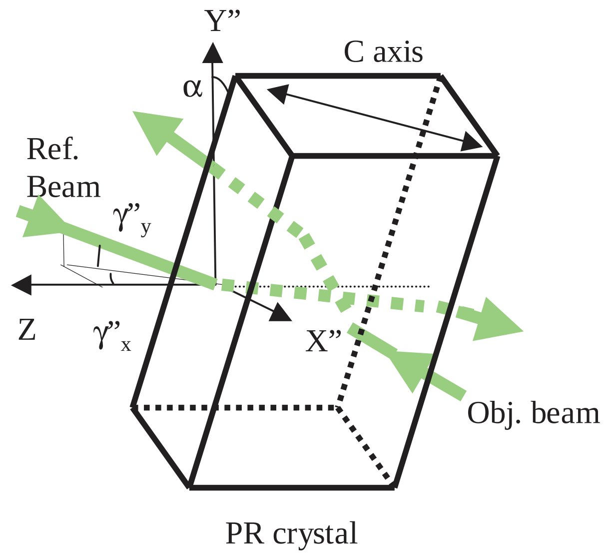
- Benefits of this new multiplexing technique:
  - **Better utilization of SBP-limited BS devices as well as associated optics**
  - **No mechanical moving parts**
  - **Randomly accessible beam steering**
  - **High Speed, low voltage / power consumption**




**Schematic of cascading two SLM-based BS devices to achieve 2-D (fractal-)angle mutliplexing recording**

# New $LiNbO_3$ PR Crystal Orientation Optimizing 2-D Holographic Data Recording Density



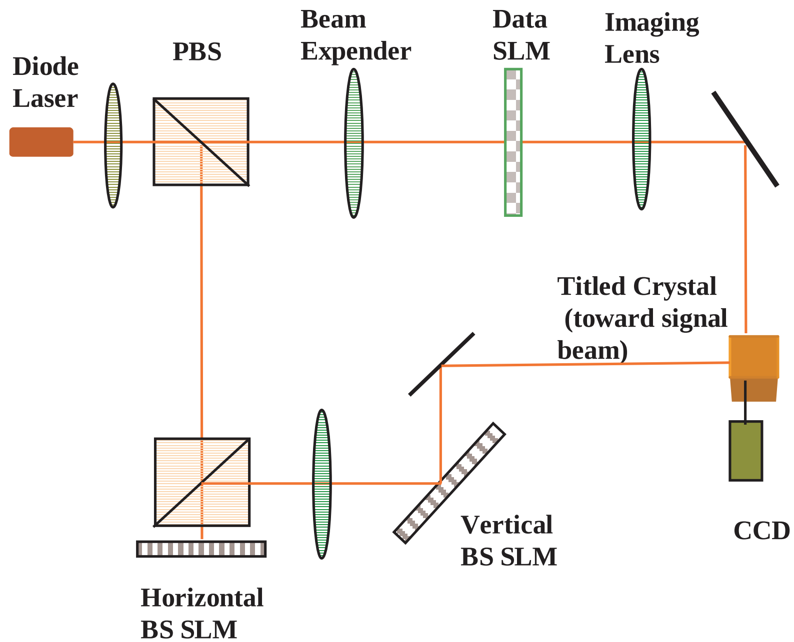




- **Original photorefractive crystal orientation**
  - **Optimum recording density only with reference beam steered around one axis (X’’-axis, as shown)**
  - **Number of holograms recorded in x”direction is *10* times larger than that recorded in Y’’ (or the fractal direction)**
- **New PR crystal orientation**
  - **Crystal tilted by 20 degree (α≈20°) off the Y”-axis**
  - **Permit propagating waves be decoupled and form two set of gratings that optimizing recording density in both X’’ and Y’’ direction two wave decoupling**
  - **Result in equal number of holograms recordable in both X’’ and Y’’ direction**
  - **Increase recording density by 10 folds**

- Optimized the crystal recording orientation:

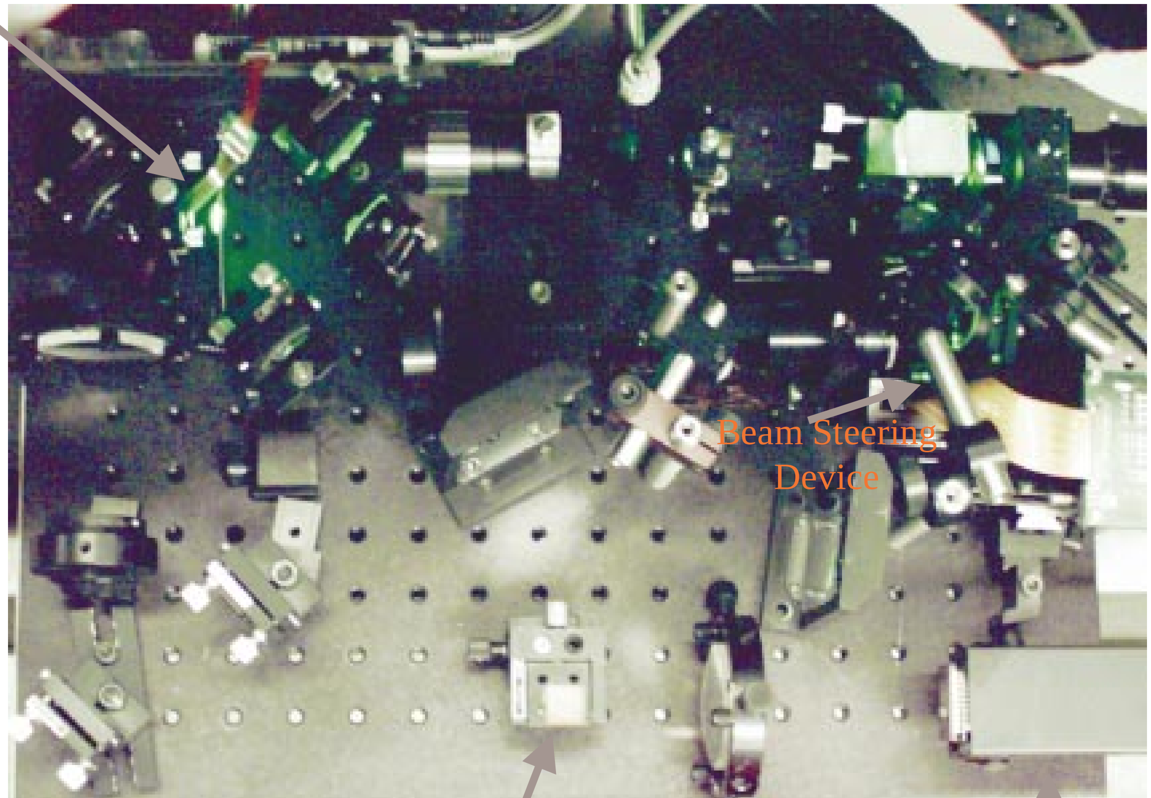
  *Crystal titled about 20$^{O}$ toward the signal beam has been found optimal in terms of minimizing the cross-talk in vertical direction.*

  ==> **Increased number of holograms recordable in the vertical direction by 10 folds**




**System architecture of 2-D (fractal-)angle multiplexing recording**

# Book-sized Holographic Memory Breadboard




**Photograph of a JPL compact holographic memory breadboard developed under NASA sponsorship**

**Experimental results showing retrieved holographic images of a Toutatis Asteroid**

## Accomplishments to Date

Recent Publications and Conference Presentations

1. Tien-Hsin Chao, Hanying Zhou, George Reyes, JPL "Compact Holographic Data Storage System," Proceedings of Eighteenth IEEE Symposium on Mass Storage Systems in cooperation with the Ninth NASA Goddard Conference on Mass Storage Systems and Technologies, April. 2001

- Tien-Hsin Chao, Hanying Zhou, and George Reyes, "Compact Holographic Data Storage," Presented to NASA Forum on Innovative Approaches for Outer Planetary Exploration 2001-2020, Feb 21-22 at Houston, TX.
- Tien-Hsin Chao, George Reyes, Hanying Zhou, Danut Dragoi, and Jay Hanan, "High-density Holographic Data Storage," Proceedings of International Symposium on Optical memory 2001 PP.248-249, Taiwan, Oct.2001.
- Tien-Hsin Chao, George Reyes, Hanying Zhou, Danut Dragoi, and Jay Hanan, "Nonvolatile Rad-Hard Holographic Memory," Proceedings of Non-volatile memory Technology Symposium 2001, pp. 12-17, San Diego Ca, Nov. 2001.

# Resources & Interdependencies

Synergy

| Sponsor Name | Start & End Dates | FY'02 $ | $ to Date | Competed |
|---|---|---|---|---|
| [NASA ESTO] | [2000 - 2002] | [250] K$ | [650] K$ | [yes, AIST NRA] |

## Team/Research Assets

**Professor Demetri Psaltis of Caltech**

- New doubly doped photorefractive crystal for nonvolatile data storage

Dr. Fai Mok of Holoplex Inc.

- compact holographic data storage system packaging

## Links to Other Programs

A work plan for conducting space flight test/validation of the CHDS technology has been submitted to New Millennium ST-8 program for review

# Anticipated Products & Infusion Opportunities

| Technology Product | Current TRL | Final TRL/Date | Transition Opportunities |
|---|---|---|---|
| [Product/capability description] | [2] | [4/FY05] | Earth Science Missions, e.g., PM-2A, CHEM-2, NPOESS, METOP.<br>Other data intensive missions, e.g., HEDS, SIM |

- **JPl will collaborate with Caltech and Academia todevelop two-photon doubled doped photorefractive material for long-term nonvolatile data storage (increase the memory shelf life from months to decades)**
  - **Recently, more doping ions have been investigated for nonvolatile performance in a doubly-doped (2-color) $LiNbO_3$ crystal**
    - **Iron group (Ti, Cr, Mn, Cu)**
    - **Rare-earth element ions (Nd, Tb)have been investigated for nonvolatile performance in a $LiNbO_3$ crystal. To date, it has been reported that doubly doped $Cr:Cu:LiNbO_3$ as well as $Fe: Tb:LiNbO_3$ are effective in nonvolatile holographic recordings.**
  - **Comprehensive radiation test of the new photorefractive material to validate its radiation-resistance**
- **JPL will insert the new nonvolatile 2-photon PR crystals (e.g.** $Fe:Mn:LiNbO_3$, $Cr:Cu: LiNbO_3$, and $Fe:Tb:LiNbO_3$, and $Ce:Mn: LiNbO_3$) **material into the CHDS breadboard to demonstrate nonvolatile data storage.**
- **JPL will investigate the extend the use of holographic memory technologies for muti-channel demultiplexing in telecommunication systems**
  - **The inherent wavelength selectivity will enable new massively parallel optical communication system development**

## Summary

(We have developed a new 2-D (Fractal-)Angle multiplexing using 2 cascaded Liquid Crystal Spatial Light Modulator Beam Steering devices to enable high-speed, random access beam steering for angularly multiplexed hologram recording without any moving parts

- We have developed a compact CHDS breadboard and demonstrated grayscale holographic data storage/retrieval
- The CHDS breadboard design will enable the storage capacity up to 16,000 pages of holograms in a 1 $cm^3$ cube.
  - Storage capacity is 16 GB for 1-Meg pixel input (1k x 1k)
  - Storage capacity is 400 GB for 25-Meg pixel input (5k x 5k)
  - Storage capacity will be up to 4 TB by stacking 10 cubic PR crystal in a memory card

•Holographic data storage, upon full development, will simultaneously satisfy all space data storage reqireemnts in nonvolatility (decades), radiation-resistance, high-density (TBs), low volume (regular memory card-size), high transfer rate (1 GB/sec),, read/rewritable, random access W/O moving parts

# MEMS Pumped Liquid Cooling System for Highly Integrated Micro/Nano Sciencecraft

Gaj Birur (PI), Section 353
Tony Paris, Section 353
Amanda Green, Section 384
Siina Haapanen, Section 353
Tricia Waniewski Sur (SAIC, San Diego)

**Motivation**

# Motivation, Challenge, and Benchmark

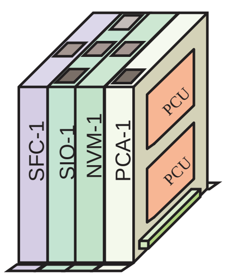
• The state-of-the-art thermal control technology is not adequate to meet the requirements of the high power density advanced electronics and science payload that is being considered for future spacecraft The high temperatures in electronics result in unacceptable reliability for the electronics

•Develop light weight compact heat removal system for high power density electronics used in microspacecraft and large spacecraft for Code S and Code Y missions

• The efficient thermal control system will enable the high power density electronics and science payload to be used on spacecraft used in deep space and earth orbiting missions. Enormous benefits are offered by compact 3-D electronics in terms of flexibility, compactness, and capability

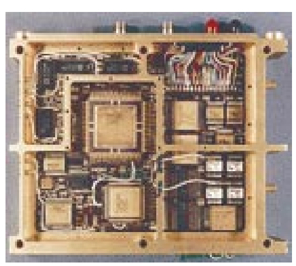
2000

**Avionics, Mission Data System**



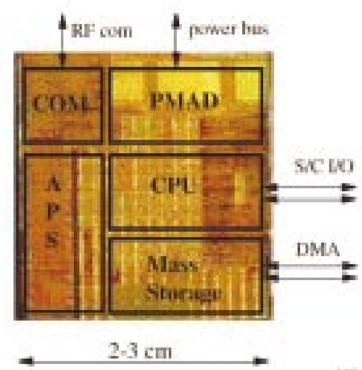

2004

**Deep Space Transponder**



2008

**System on a Chip**



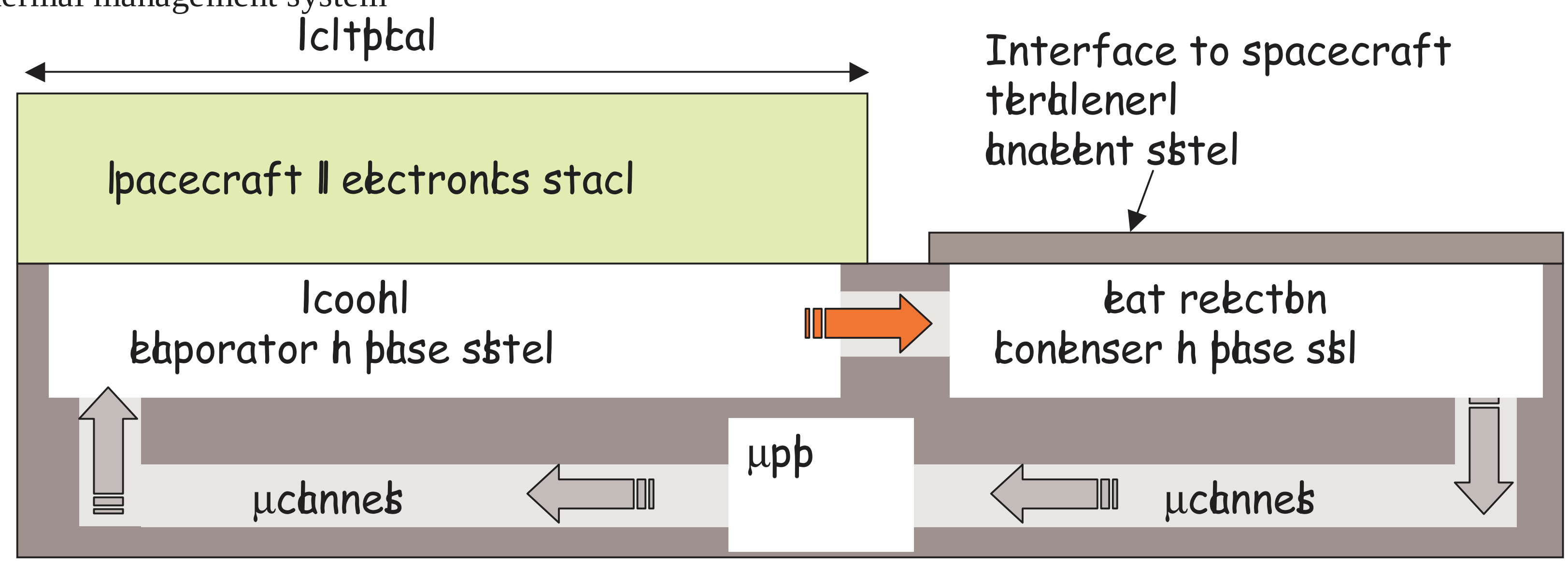
# Motivation, Challenge, and Benchmark

## Challenges

- Development of MEMS-based pumped liquid microchannel heat sinks with good hydraulic and thermal performance for removing heat flux over 25 W/sq cm
- Development of micropumps that meet the performance and can be integrated into the microchannel
- Actual integration of the micropumps with the microchannel devices to develop an integrated package

## Benchmark

- High thermal conductivity materials, micro heatpipes embedded in electronics, and two-phase cooling loops
- The proposed system offers several advantages over competing technologies – high heat transfer over long distances, simplicity, and robustness compared to two-phase systems, and ability to be integrated with the spacecraft thermal management system



# Schedule and Budget

## Schedule and Milestones:

| | Year 1 | Year 2 | Year 3 |
|---|---|---|---|
| 1. Optimization of microchannels. | Microchannel specs. | | |
| 2. Selection of working fluid. | Working fluid spec. | | |
| 3. Fabrication and testing of microchannels. | 1st generation microchannels | 2nd generation microchannel test data | |
| 4. Evaluation of micropump technologies. | | Selected micropump technology | |
| 5. Fabrication and testing of micropumps. | | Prototype micropump performance test data | |
| 6. Integration of microcooling system. | | | 1. Integrated micropump & microchannel system<br>2. Performance data from tests |

## Changes to original schedule:

•During the beginning of the second year (FY01), two of the co-investigators left JPL (Dr. Linda Miller and Dr. Tricia Sur). Some of the work on the micropump was delayed to FY02 due to non-availability of personnel. Dr. Anthony Paris joined the team in June 2001as replacement and is designing and testing 2nd generation microchannels.

# Schedule and Budget

## Budget:

| | FY00 | FY01 | FY02 |
|---|---|---|---|
| CETDP Funds Allocation | **$370K (Requested)**<br>**$353K (allocated)** | **$390K (Reqd.)**<br>**$300K(allocated)** | **$370K (Requested)**<br>**$140K (allocated)** |
| Budget plan<br>Funds actually costed | $353K (plan)<br>$ 350 K (actual) | $303 K(plan)<br>$285K (actual) | $155 (plan)<br>$ 45K (Feb/Mar 02) |
| Anticipated Co-Funding | | | 1. DSST Future Deliveries (**$150K** in FY03)<br>2. SOAC (**$150k** in FY03) |
| Sci/Eng. (Sec. 353)<br>Sci/Eng. & Tech (Sec. 346)<br>Admin (Sec. 353)<br>GSFC Civil Service*<br>**Workforce** (FTE) | 0.75<br>0.75<br>0.1<br>(0.2)<br>**1.6 Total** | 0.75<br>0.95<br>0.1<br>(0.2)<br>**1.8 Total** | 0.75<br>0.75<br>0.1<br>(0.2)<br>**1.6 Total** |

* $30 K/yr  for testing

## Changes to the original budget:

- In FY01 the actual funds allocated was lower ($300K vs $390K)
- The actual spending was lower ($285K vs $300K) due to eight-month gap between Tricia Sur leaving JPL and hiring of Tony Paris.  Most of the work on micropump was delayed to FY02
- FY02 funds allocated is significantly lower, current plan assumes stopping work in July 02 if no additional funds provided

# FY00 (First Year):

## Accomplishments:

- Designed and assembled an experimental set up at JPL Thermal Lab (B18-101A) for testing microchannel heat sink devices
- Updated microchannel simulation model MICROHEX for the optimization studies of the thermal and hydraulic performance of the pumped cooling system
- Granted a subcontract to Stanford University for the development of micropump technology and procurement of microchannel test fixture
- Designed and fabricated the first generation microchannel devices
- Calibrated the temperature sensors implanted in the microchannel devices

## Deviation from the original Plan:

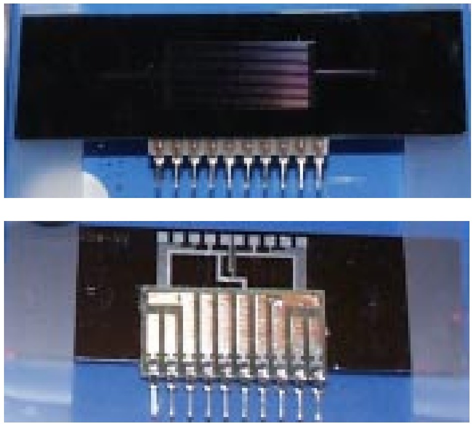
- None

## •Publications and Conference Presentations:

- None

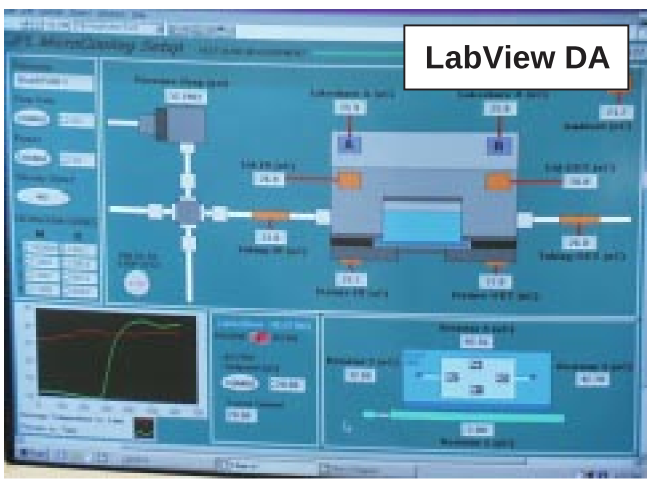
## Accomplishments to Date (cont’d)

## FY00 (First Year):

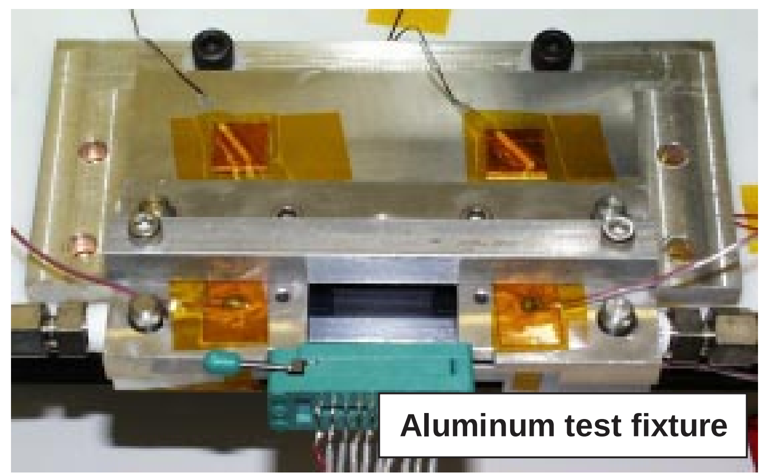


1st generation microcoolers

Open-loop test bed



LabView DA



Aluminum test fixture

# FY01 (Second Year):

## Accomplishments:

- Completed performance tests on 1st generation microchannel heat sinks
- Correlated the MICROHEX model with test data
- Performed optimization studies on microchannel heat sink geometry using MICROHEX model
- Evaluated several working fluids for the MEMS-based pumped loop
- Designed 2nd generation microchannel devices and started fabrication process.
- Performed a survey of micropump technologies suitable for MEMS-based pumped cooling system
- Designed and fabricated an improved test fixture for use with microchannel heat sinks
- Designed and assembled a closed-loop test bed for evaluating microchannels and micropumps

## Deviation from original plan:

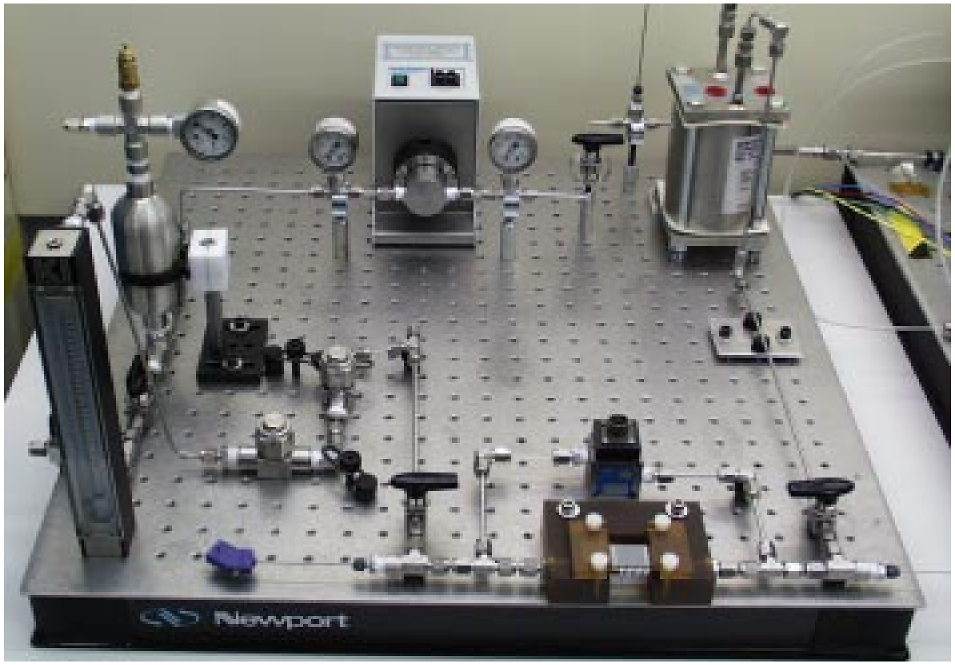
• Experimental evaluation of micropump technologies were postponed to FY02 due to unavailability of suitable working MEMS-based micropumps

## Publications and conference presentations:

•G. Birur, P. Shakkottai, and T. Sur, "MEMS based pumped liquid cooling system for Micro/Nano Spacecraft Thermal Control," International Conference on Nano/Microtechnology for Space and Biomedical Applications – NanoSpace 2001 on March 15, 2001 at Galveston, Texas

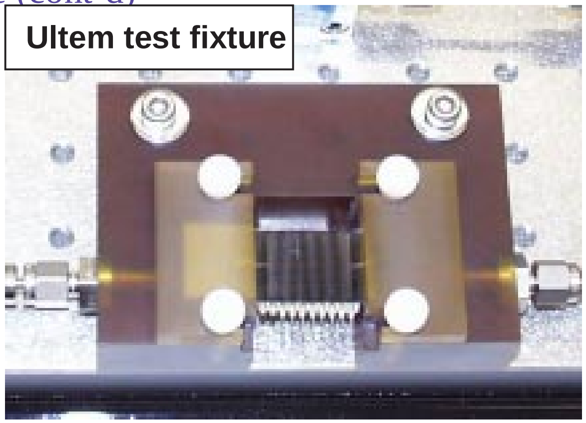
## FY01 (Second Year):

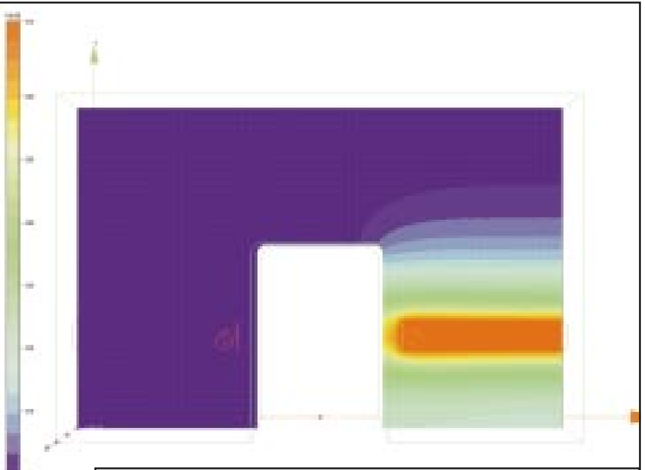
Accomplishments to Date (cont'd)




Closed-loop test bed

Ultem test fixture

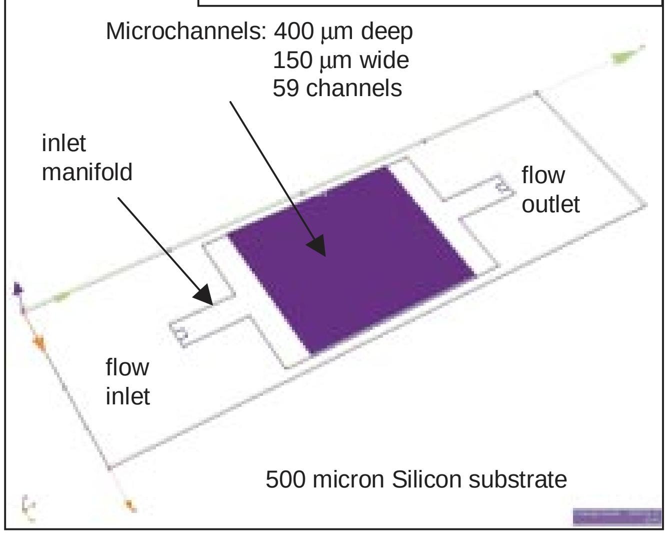




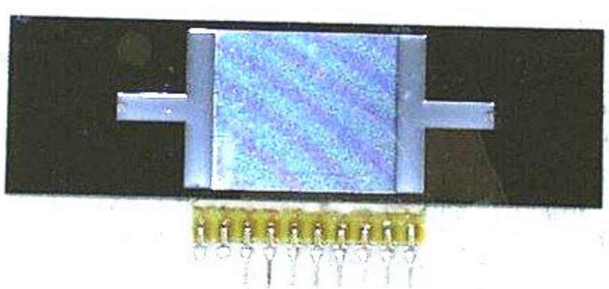
Fixture temperature distribution

# FY01 (Second Year): Accomplishments to Date (cont'd)

**2nd generation microcoolers**



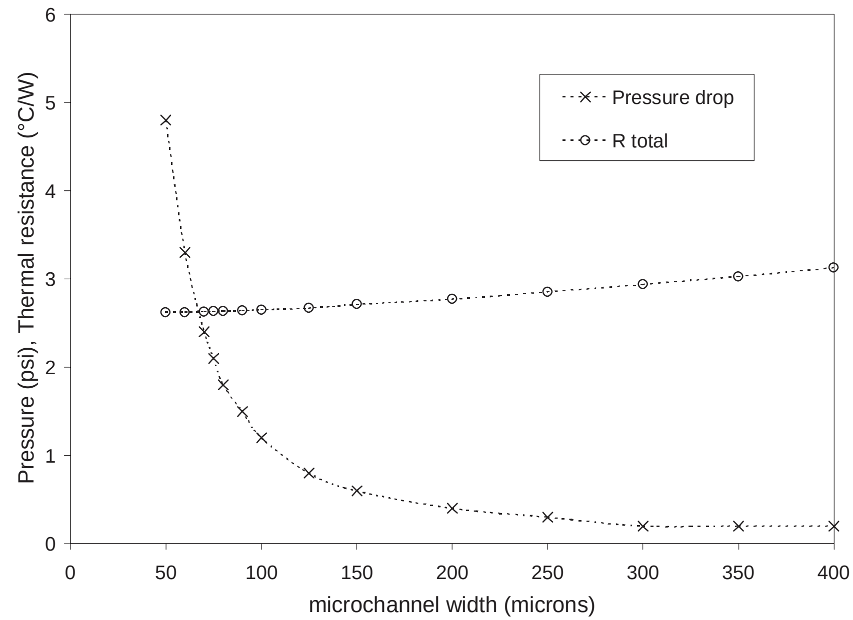

6.5 cm

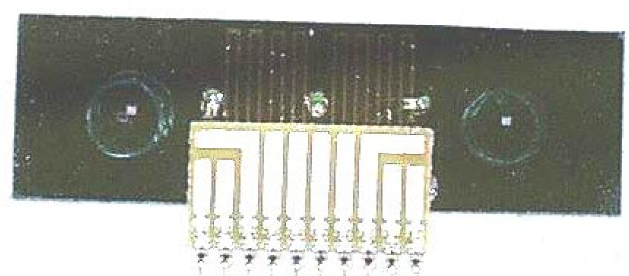


5 cm

**Top side (channels)**

**MICROHEX model predictions**



**Back side (heater and temp sensors)**

# FY02 (Third Year):

## Accomplishments:

- Installed and calibrated Platinum RTDs onto 2nd generation microchannel heat sinks
- Completed testing on the 2nd generation microchannel heat sinks
- Designed 3rd generation microchannel heat sinks with improved hydraulic performance using CFDesign software
- Began fabrication of the 3rd generation microchannel heat sinks
- Selected piezo-actuated micropump technology for the MEMS micropump
- Collaborating with Dr. E.H. Yang of MDL on the fabrication of the piezo-actuated micropump

## Deviation from the original Plan:

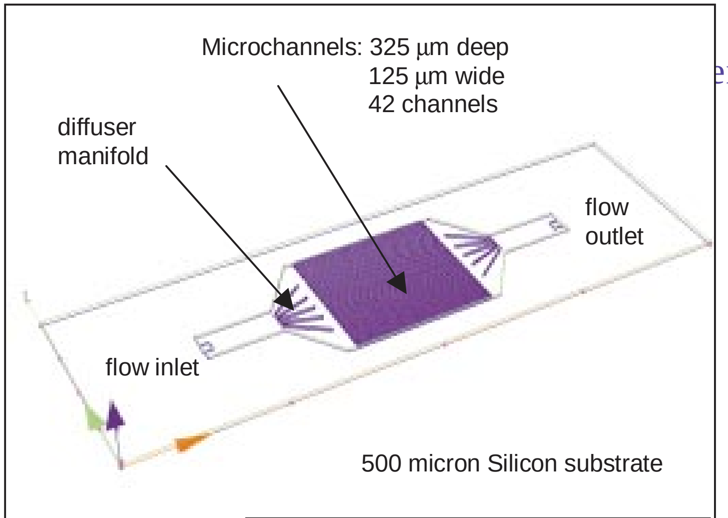
- Addition of 3rd generation microchannel heat sink design and fabrication
- Design and fabrication of micropump (moved from FY01 plan)

## • Publications and Conference Presentations:

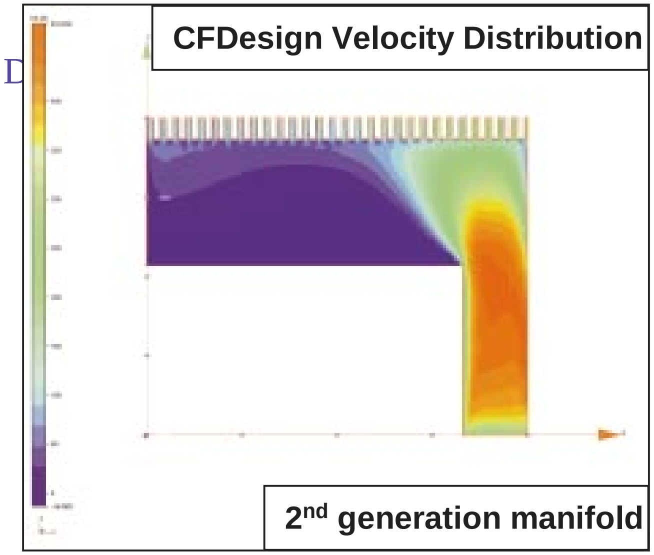
- G. Birur, T. Sur, A. Paris, P. Shakkottai, A. Green, and S. Haapanen, "Micro/nano spacecraft thermal control using a MEMS-based pumped liquid cooling system" presented at SPIE Micromachining and Microfabrication Symposium, 21–25 Oct 2001, San Francisco, CA
- A. Paris, G. Birur, T. Sur, A. Green, and S. Haapanen, "Development of Microchannel Heat Sinks for Micro/Nano Spacecraft Thermal Control," Abstract submitted to 2002 ASME International Mechanical Engineering Congress & Exposition, 17-22 Nov 2002, New Orleans, LA

## FY02:

ents to D



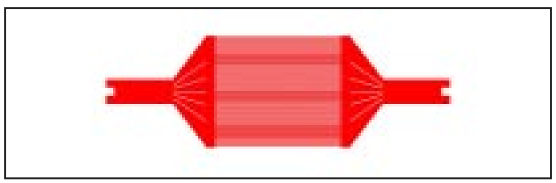

3rd generation microcoolers



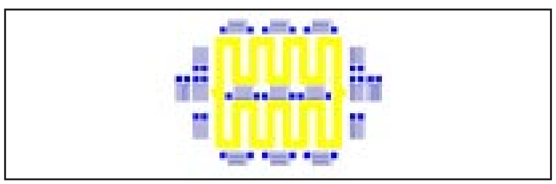
CFDesign Velocity Distribution

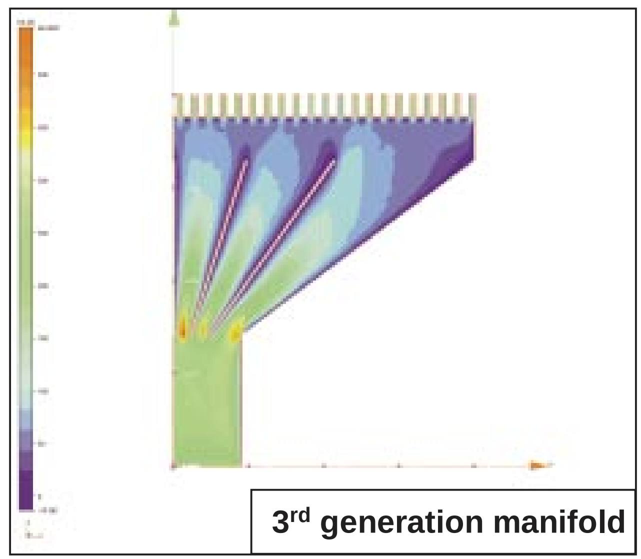
2nd generation manifold

Top side (channels)



Back side (heater and Temp sensors)

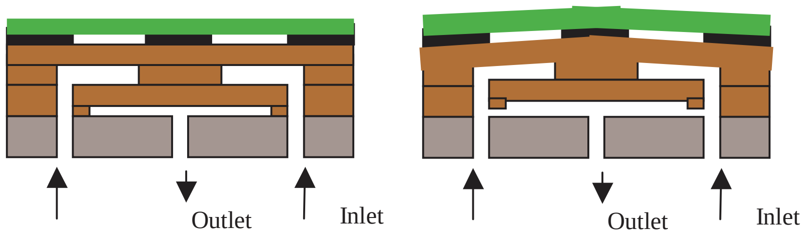




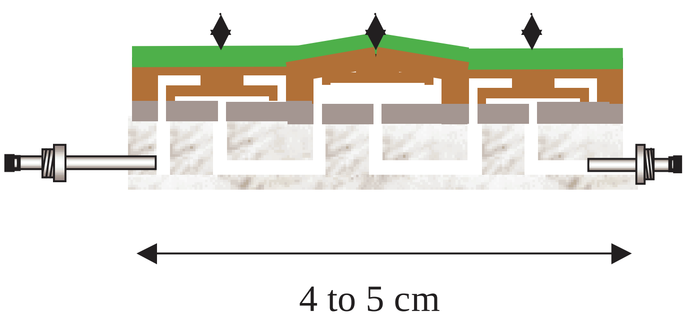
3rd generation manifold

## FY02: - Micropump*

Accomplishments to Date (cont'd)




- Multi-stack bimorph (10 mm x 10 mm x 0.3 mm)
- Pressure balanced design needed.
- 4N maximum block force @ 0 stroke
- 33 µm free stroke @ 150V
- **25 µm loaded stroke @ 1N, 150V**
- Pump volume: 30 mm x 10 mm x 2 mm
- Resonant frequency is unknown, but higher than 10kHz




| | |
|---|---|
| •Flow rate: | 25 to 50 cc/min |
| •Pressure rise: | 3 to 10 psid |
| •Size: | 5 cm X 1.5 cm X .2 cm |
| •Frequency: | 1 kHz |
| •Voltage: | 150 V |

(* Dr. E.H. Yang of Section 384 is designing and fabricating the pump)

# Resources & Interdependencies

## Team/Research Assets

- NASA GSFC (Ted Swanson): Thermal control for NASA GSFC Small-Sat program - $30K (FY00)
- Stanford Univ. (Prof. Tom Kenny): Electro-kinetic pump technology development - $45 K (FY00)

MEMS-based two-phase cooling systems

## Links to Other Programs

- Collaboration with NASA GRC (Eric Golliher) MEMS-base loop heat pipe for electronics thermal control (only other NASA supported electronics micro-cooling task)

•Code Y & M Program on FPGA (Xilink with NASA Langley funds) for spacecraft and space shuttle applications are interested in our technology and are waiting for the results of this work

# Anticipated Products & Infusion Opportunities

| Technology Product | Current TRL | Final TRL/Date | Transition Opportunities |
|---|---|---|---|
| Integrated MEMS based pumped liquid cooling System | TRL2/3 | TRL 3/02 | Code R Advanced Sensor<br>Code S microspacecraft<br>Code Y & M FPGA program |

• Investigate the thermal control need for future high-density electronics planned for Code S and Code Y missions (e.g., Avionics, sensors, for Code S; Field Programmable Gate Array [Xilinx Corp & NASA Langley] for Code Y and M etc)

• Investigate and develop MEMS based two-phase mechanically pumped cooling loop for high power density electronics for space and terrestrial applications

• Investigate the applications for MEMS based pumped liquid cooling systems for ground based high power density electronics for Defense and Commercial sectors

• Investigate MEMS based thermal control system for avionics and sensors used in extreme temperature environment (future Code S missions to Venus, Jupiter, Titan, Comets, and Asteroids)

## Summary

•A MEMS based pumped liquid cooling system is being developed for high power-density electronics thermal control for space applications for the first time. The objective is to develop a self contained integrated cooling system which can be easily installed on an existing electronic package. Both NASA and Defense sectors are eagerly following developments in this task

•An unique infrastructure (personnel, fabrication and test facilities, and evaluation tools) for investigation of MEMS-based thermal control technologies has been developed.

•Several generations of microchannel heat sinks have been designed, fabricated, and tested under this task. These microchannel devices have been optimized using the experimental data, computational models, and current micropump technologies

•At the end of the program (FY02), a MEMS based pumped liquid cooling system at TRL 3 /4 will be available for the high power density electronics and sensor community to remove heat fluxes of over 25 W/sq cm

• There are many members from the high-power density electronics and thermal control community (NASA, Defense and Civil sectors - both space and terrestrial ) following this JPL task. They are very interested in this technology to enable their advanced electronics to be used in future applications

# Next Generation, High Performance Micro-Gyro Development

Dean Wiberg

# Motivation, Challenge, and Benchmark

## Motivation

The objective of this project is to develop miniaturized, high precision, inertial grade gyroscopes for space applications. These devices will be incorporated into higher level systems such as inertial measurement units and autonomous navigation systems. Specifically it is the objective of this project to reduce volume, power and mass by one to two orders of magnitude while maintaining performance analogous to current macro scale devices.

The motivation for undertaking this endeavor is that if reduced size space craft are to be realized, proportional reductions in traditional systems such as inertial navigation must also occur. Although commercial miniature gyroscope activities are in progress, no products addressing high precision are currently available. This project addresses capabilities approximately two orders of magnitude in performance better than is available commercially.

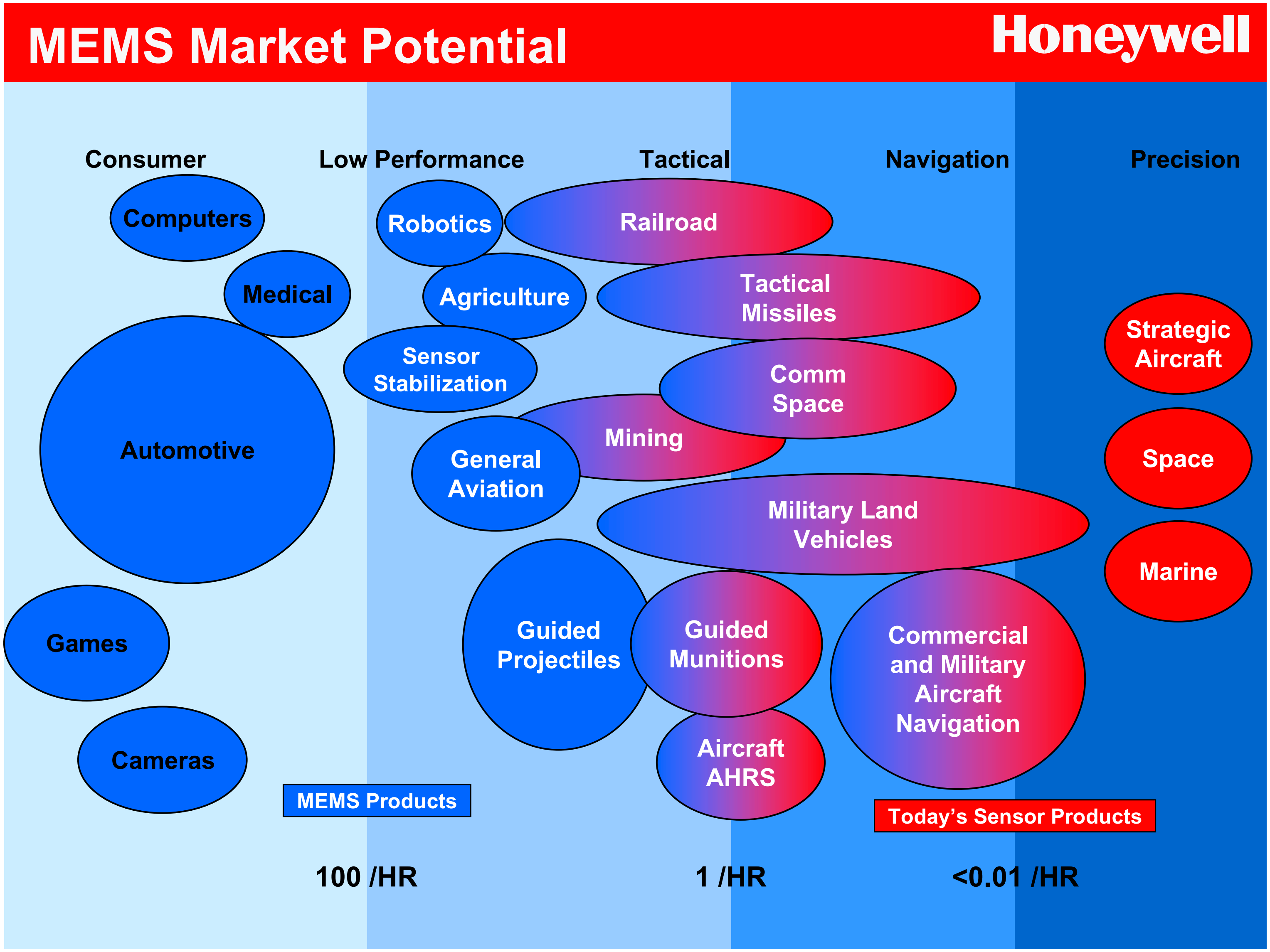
## Challenges

The principal challenges for this project are:

1. High performance at a miniature size scale.

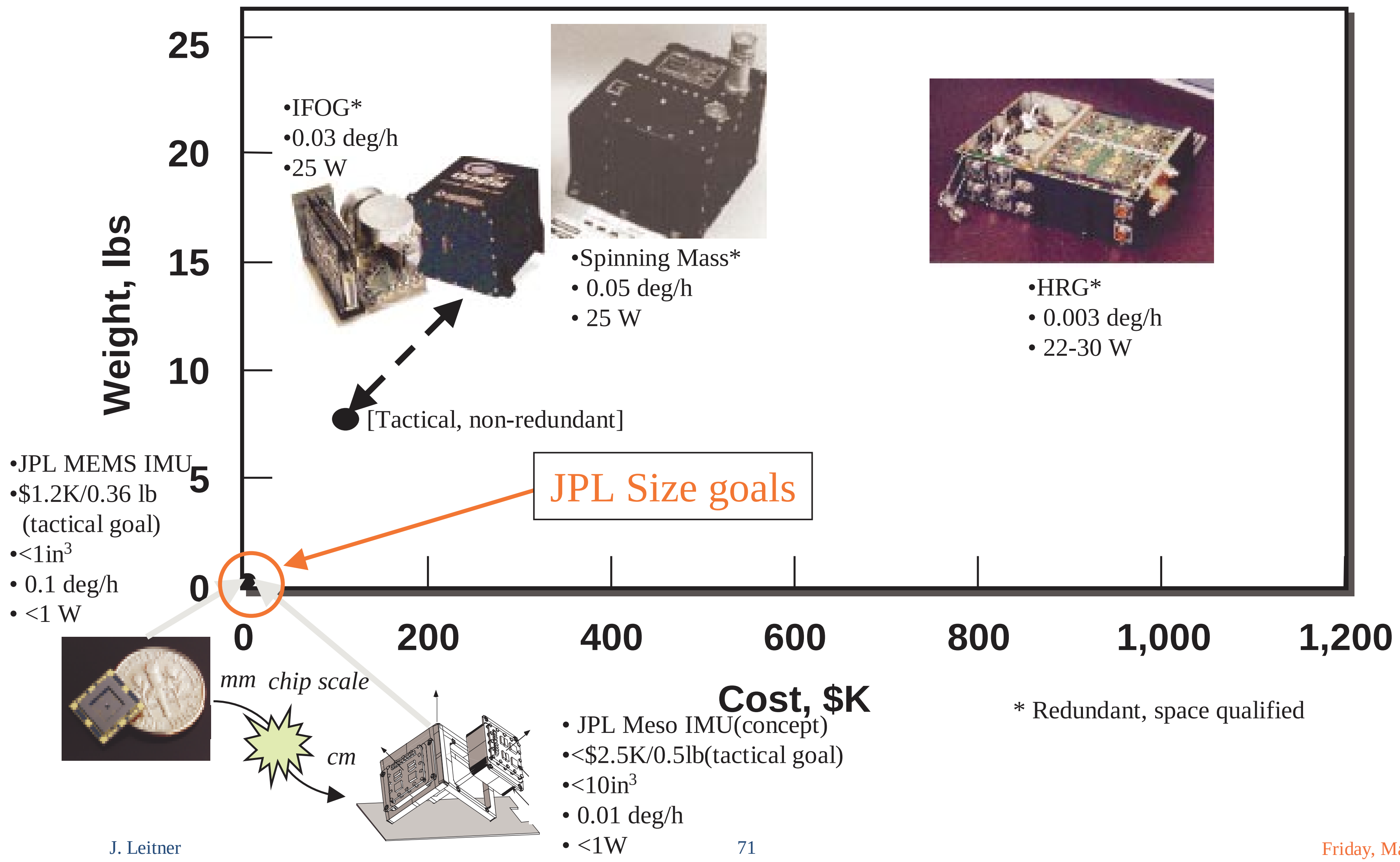
2. Packaging for high precision performance under thermal, shock and vibration environments

# Miniature Gyro Project



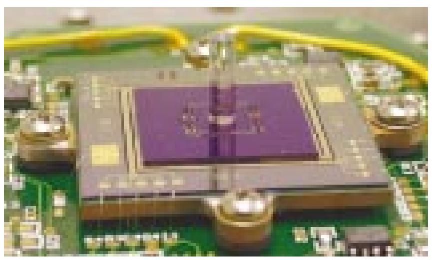
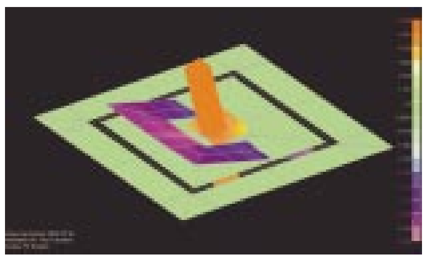

From Dr Joel Hanse, Honeywell, MEMS Inertial Products

## Current IMU's that Meet Performance Goals Do Not Meet Size Goals



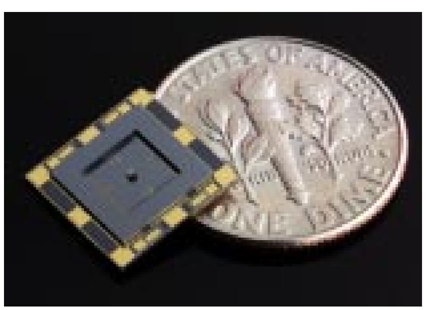
# Designed to Meet Both the Target Size and Performance Goals

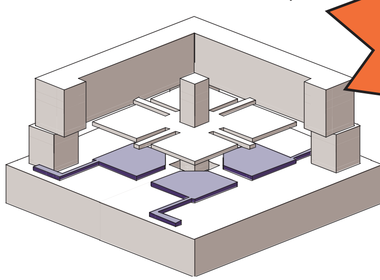
## Two key technology lines (Micro and Meso scales):

Mesogyroscope

Microgyroscope





Statistically correlated multiple microgyro units per axis

## Two performance/size targets:

**High performance Miniature IMU**

- (<10in$^3$)IMU size
- Extended time navigation grade performance (0.01deg/hr)

Four principal thrusts directed at precision performance:

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

**Ultra miniature IMU**

- (<1in$^3$) IMU size
- Navigation grade performance (0.1deg/hr) to augment micro star tracker

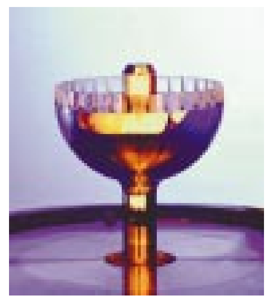
# Miniature Gyro Project

## Litton-Hemispherical Resonator Gyro (HRG)

...U **Dual String** consists of two identical 3-axis IRU's in one ...s the ideal choice for long-life spacecraft needing superior ... Redundancy is managed by the spacecraft flight computer ...tection built into the IRU. Each IRU string contains 3 HRG's, ...tronics and a power supply. The unique Hemispherical Resonator ... (HRG) technology is ideally suited to operate in the vacuum of space while providing more than 15 years of continuous attitude reference information to the spacecraft.

| | |
|---|---|
| Bias drift | $0.003^{0}$/hr |
| Size | 567 $in^3$ (13.5 X10.5 X4 inches) |
| Weight | 8.6 kg (19 pounds) |
| Power | 30W at 25C |

Hemispherical Resonator *(30mm)*



**Litton's SIRU-Core** is an internally redundant inertial reference unit (IRU) designed to provide continuous, high accuracy inertial measurement over long periods in space. The SIRU is a space-flight proven, radiation hard IRU which uses the solid-state Hemispherical Resonator Gyro (HRG) to provide high accuracy, ultrahigh reliability, and long life in a small lightweight unit. A single SIRU unit provides complete redundancy, including four HRG's, two sensor electronics modules and two power supplies. The combination of a fault tolerant design, the ultra-high reliability of the HRG and the use of high reliability electronics enables the SIRU to operate continuously over 15 years in space with an estimated reliability of 0.995.

| | |
|---|---|
| Bias drift | $0.003^{0}$/hr |
| Size | 495 $in^3$ (12.8 by 8.6 by 4.5 inches) |
| Weight | 12 pounds |
| Power | 22W |

# Miniature Gyro Project

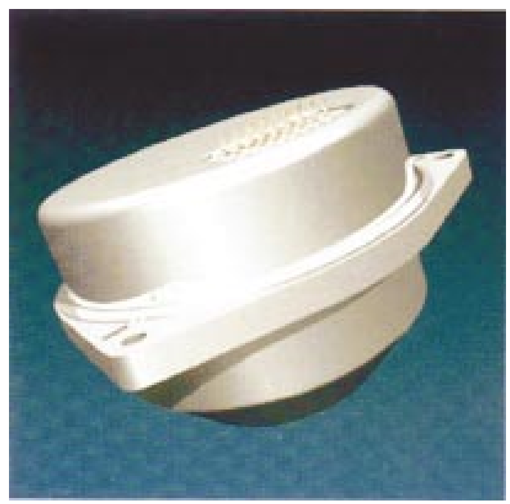
## British Aerospace (Bae)

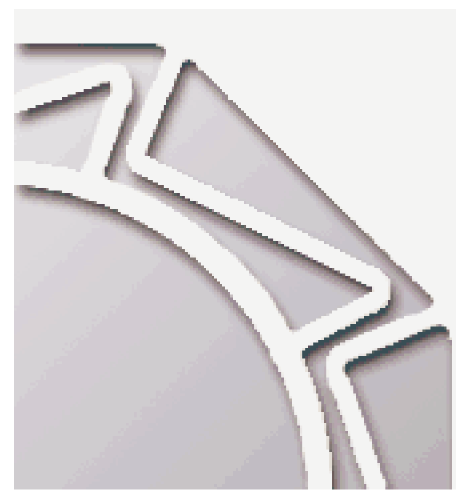
(Plymouth England)

SiIMU is an all-MEMS system which provides fully compensated 6-DOF angular rate and linear accelaration measurement suitable for vehicle navigation, guidance and stabilization. Miniature high performance silicon accelerometers and BASE's highly successful SiVSG angular rate sensors are combined in a modular design. This allows price/performance optimization of the SiIMU to meet specific customer requirements.

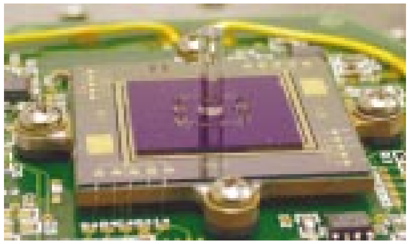
The Silicon resonator is fabricated by Sumitomo Electric in Japan and transported to British Aerospace in Plymouth, England for integration.

| | |
|---|---|
| Bias stability | $2^0$/hr |
| Operating Temperature | -46$^0$C to +85$^0$C |
| Mass | 0.25 kg (0.56 lb) |
| Volume | 8.3 in$^3$ |
| Price | $16,000 |

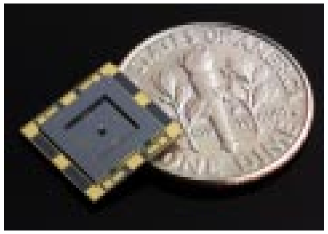




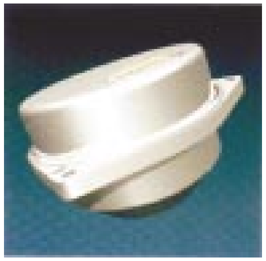
**Litton LN 200 IMU**



**JPL Meso Scale Gyro**



JPL Micro Scale Gyro



British Aerospace (BAE) SiMU

| **IMU** | **LN 200** | **Meso Scale** | **Micro Scale** | **BAE SiMU** |
|---|---|---|---|---|
| **Physical** | | | | |
| Weight | 1.54 lbs | (0.5 lbs)* | (0.4 lbs)* | 0.25 kg (0.56 lb) |
| Size | 32.2 $in^2$ | (<10 $in^2$)* | (<1 $in^2$)* | 8.3 $in^3$ |
| Power | 10 watts | (<1 Watt)* | (<1 Watt)* | |
| **Performance - Gyro** | | | | |
| Bias Repeatability | 1deg./hr to 10deg./hr | 2 deg/hr (0.01 deg/hr)* | 1 deg/hr (0.1 deg/hr)* | 2-5 deg/hr |
| Angle Random Walk | 0.04 to 0.1 deg/rt-hr | 0.03 deg/rt-hr | 0.095 deg/rt-hr | 1 deg/rt-hr |

*(JPL objectives indicated in red). Black values are actual data

# Schedule and Budget

## Schedule and Milestones:

**From FY00 Technology Development Agreement:**

1) A meso scale cloverleaf resonant gyroscope will be fabricated, characterized and packaged incorporating vibration isolation and demonstrating 0.1 degree/hour bias stability.
2) A micro scale cloverleaf gyroscope will be fabricated, characterized and packaged incorporating vibration isolation and 1 degree/hour bias stability.
3) An advanced concepts study identifying the next generation of high performance, extremely miniaturized, environmentally tolerant gyroscopes will be conducted incorporating a recommendation for future work on concepts beyond the current cloverleaf resonator gyro.

## Budget:

| FY | Funding Allocation |
|---|---|
| 2000 | $334k |
| 2001 | $380k |
| 2002 | $300k |

## Accomplishments to Date

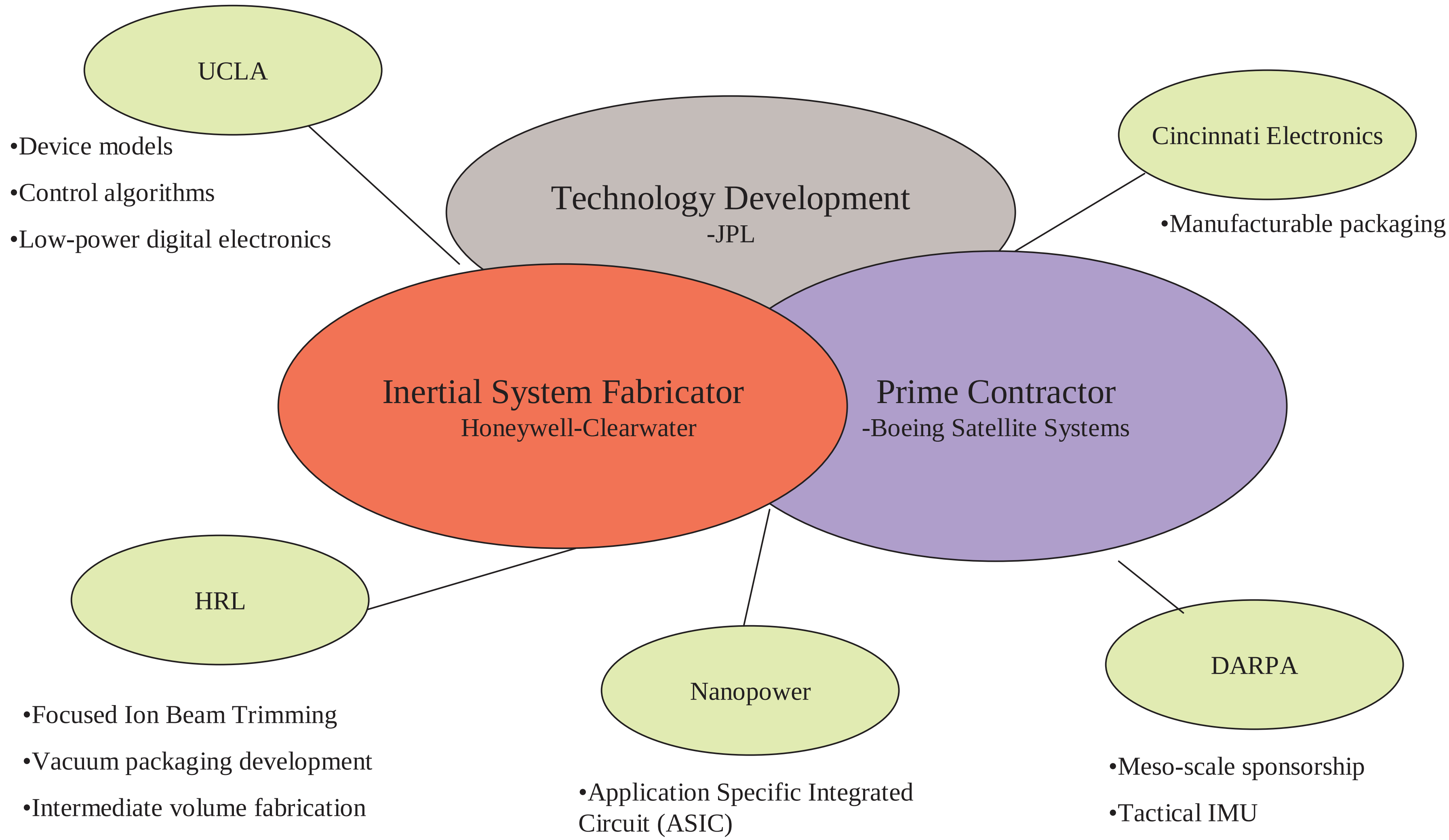
- Demonstrated capability to fabricate both micro and meso scale devices at wafer level.
- Developed meso scale gyros from concept to 0.4 deg/hour bias drift performance.
- Demonstrated wafer scale microgyro fabrication to 2 deg/hour bias drift performance.
- Developed comprehensive team including Boeing, HRL, Honeywell. UCLA, Nanopower, Cincinnati Electronics
- Captured outside agency funding support (DARPA/SPO and DARPA/DSO)
- Contributed to pool of over thirty patents surrounding this technology.
- Supported in licensing and commercialization of JPL based miniature gyro.

# Resources & Interdependencies

## Synergy

| Sponsor Name | Start & End Dates | FY'02 $ | $ to Date | Competed |
|---|---|---|---|---|
| DARPA/SPO | [FY01 - FY04] | 1000 K$ | 550 K$ | yes |
| JPL/CISM | FY02 | 100 K$ | 910K$ (FY01) | no |
| GSFC | FY02 | 25K$ | 0$K | yes |

# Team/Research Assets



# Anticipated Products & Infusion Opportunities

| Technology Product | Current TRL | Final TRL/Date | Transition Opportunities |
|---|---|---|---|
| Miniature (Meso and Micro Gyro) | TRL 3 | 5/FY05 | ●Pico and Nano missions<br>●Rovers<br>●Deep space, low power missions<br>●Commercial (Cell phone, Automotive, etc)<br>●DOD (Personnel Locator, GPS augmentation, Guided munitions) |

The future plans for the miniature gyro development task include:

•Continued technology enhancement in precision performance and environmental tolerance.

•Integration with accelerometers, electronics and software to form an Inertial Measurement Unit.

•Further integration into an autonomous navigation system incorporating star trackers, sun sensors, GPS or other interim reference capability together with sufficient intelligence to provide autonomous navigation.

•Continue to support commercialization effort to realize reduced or low cost inertial navigation components.

•Demonstrate miniature gyro on pico sat opportunity in FY04

# Summary

•Commercial manufacturers are not addressing the highly miniaturized market for inertial grade gyroscopes and inertial measurement units (IMU's) necessary for space flight requirements. The JPL miniature gyro project is specifically intended to address this void and provide enabling devices at orders of magnitude reductions in power, mass and cost with minimal impact on performance.

•The JPL effort to develop miniature gyroscopes and IMU's has approached the critical mass necessary to realize flight quality devices through strategic relationships with Boeing Satellite Systems, Honeywell, Cincinnati Electronics, Defense Advanced Research Projects Agency (DARPA), University of California at Los Angeles (UCLA) and Hughes Research Laboratory.

•The JPL miniature gyroscope project has successfully addressed designs at both the micro and meso scale to allow the benefits for each size scale to be exploited.

•Commercialization of the miniature gyro appears imminent and will facilitate insertion into future requirements at a cost and schedule reflecting the economies of scale inherent with large scale commercial fabrication.

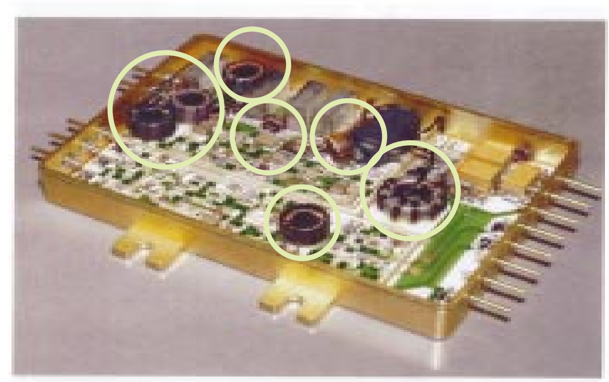
# Microinductors for Integrated Power Electronics

**Erik Brandon**

**erik.j.brandon@jpl.nasa.gov**

# Motivation, Challenge, and Benchmark

**Motivation** Power electronics are occupying an increasing percentage of spacecraft avionics and are difficult to miniaturize due to a reliance on passive components, particularly magnetics. Innovations are required to bring the mass and volume down. One approach is to develop new integrated magnetic components, capable of operating at frequencies >1 MHz, combined with distributed power architectures and matrixing.



**Space-rated converter with discrete magnetics highlighted**

## Challenges

-Develop magnetic films to operate at 1 MHz

-Design for adequate Q and power in small area

## Benchmark

Other approaches/drawbacks:

*Air core inductor, monolithic converter*—inductor Q too low, efficiency too low

*Capacitive charge pump converter*—insufficient power handling and regulation

*Magnetic composite sheets, micro-machined inductor cores*—not batch fabricated

# Schedule and Budget

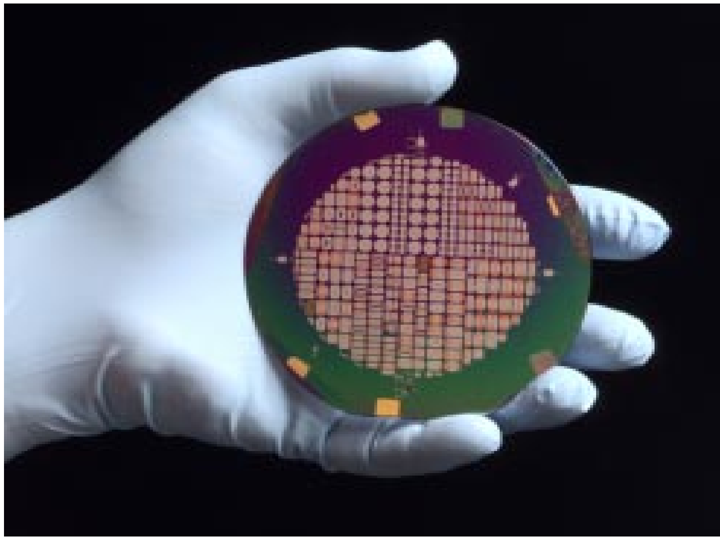
<u>Schedule and Milestones:</u>

| Schedule from FY00 proposal | Year 1 | Year 2 | Year 3 |
|---|---|---|---|
| **Products** | Prototype inductors and selection of initial magnetic materials | Inductors integrated with high voltage transistors and optimized performance at 1 MHz | Integrated dc-dc converter |

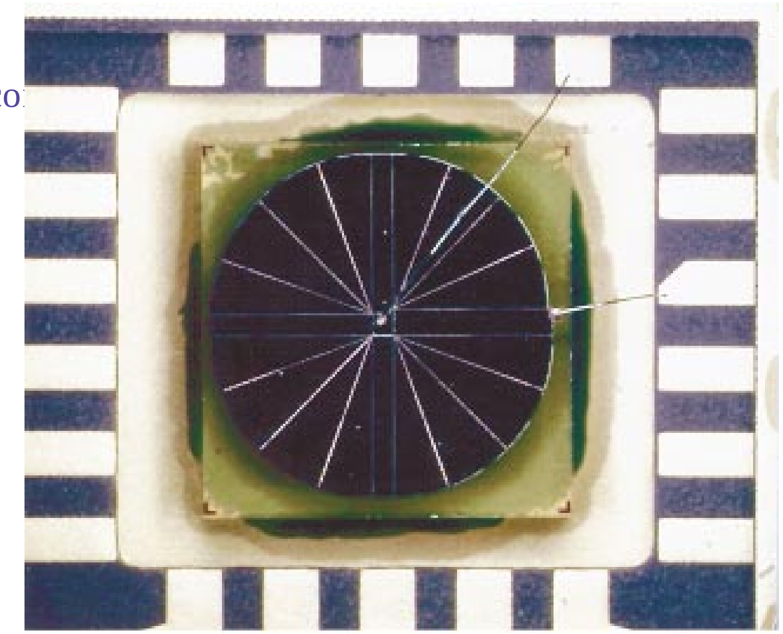
To date: -Fabricated several types of prototype microinductors
-Tested microinductors with HV transistors at *board level*
-*Trying a new process to boost sub-optimal Q at 1 MHz*

<u>Budget:</u> FY00 Budget: 200 K
FY01 Budget: 150 K
FY02 Budget: 265 K

Acco



Batch fabricated microinductors on wafer



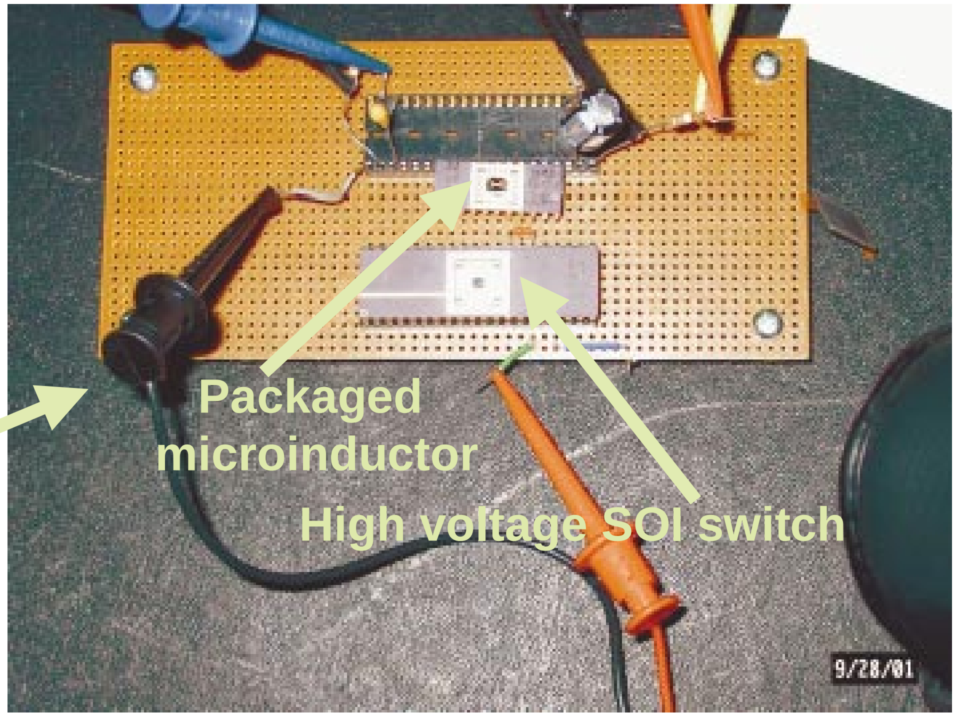
Diced microinductor packaged for board level testing

-Batch fabrication of >200 microinductors on a single wafer

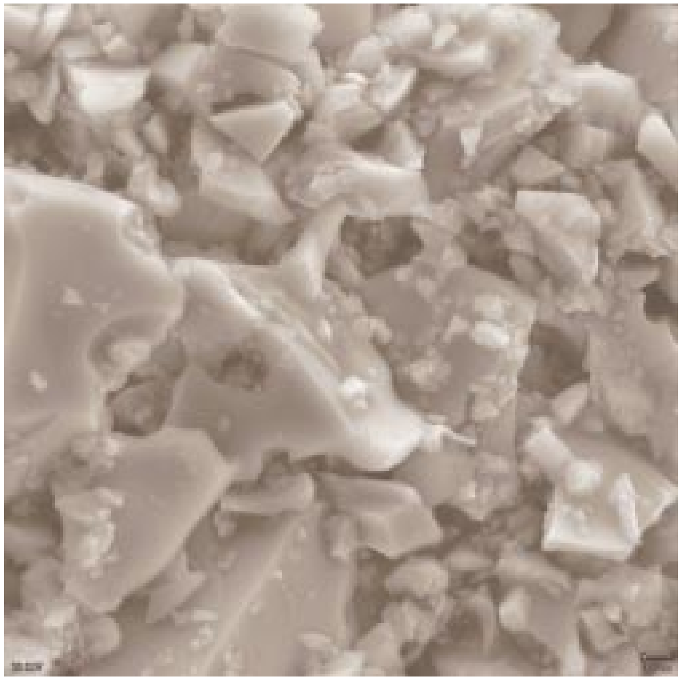
-Achieved a 13 $mm^2$ microinductor exhibiting L=3.2 µH and Q=1.3 at 1 MHz
(to our knowledge, the best balance of inductor area, L and Q at 1 MHz achieved to date)

-Still lower than desired—*we need thicker, better performing magnetic materials and higher operating frequencies to increase Q and relax L requirements (higher frequency inductors require less L and achieve higher Q)*

Accomplishments to Date

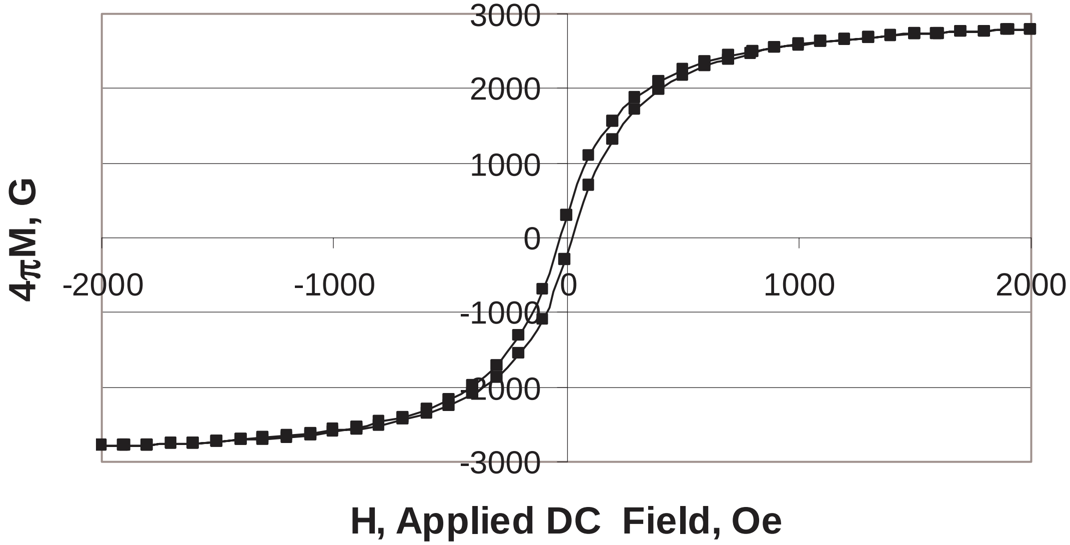



-Testing in board level boost converter at the University of Idaho
-Although boost in voltage observed, efficiencies are too low
-Need superior low loss, high frequency magnetic materials



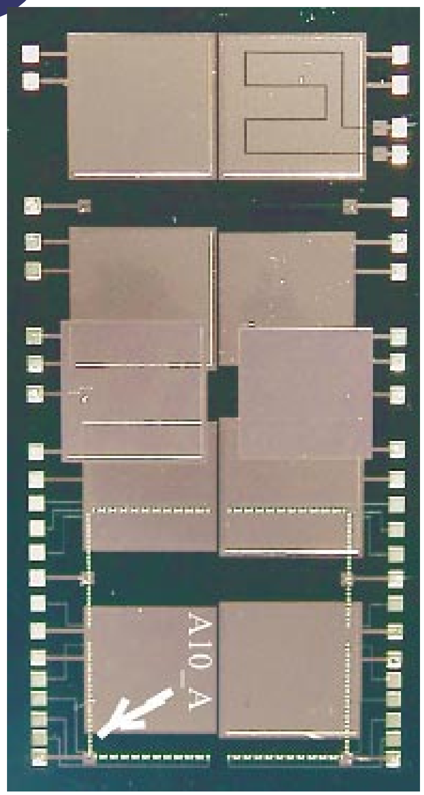
SEM of stencil printed
Ferrite-polymer composite film

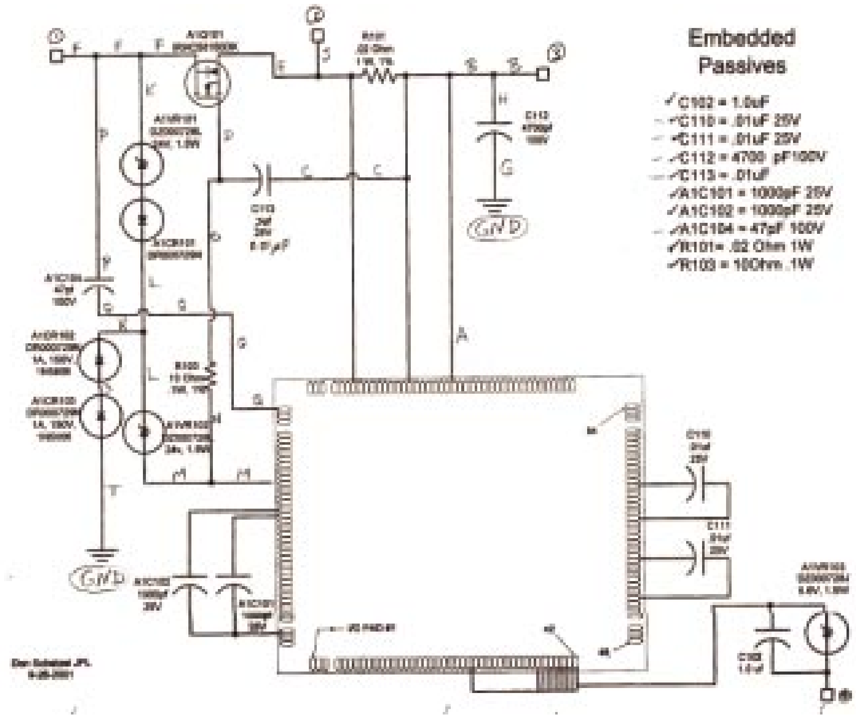
Accomplishments to Date

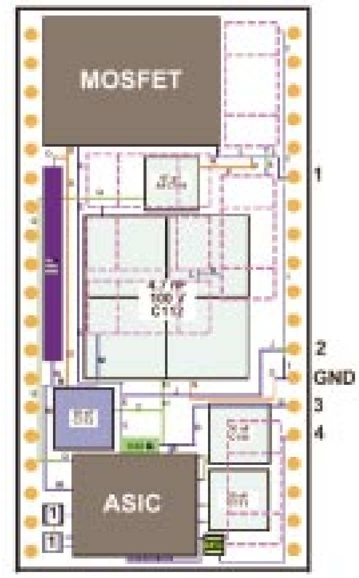



Magnetization curve for printed magnetic film

-Developing novel stencil printed ferrite-polymer composite films
-Deposited at low temperatures
-Provide higher frequency operation, thicker films and higher power handling




Layout

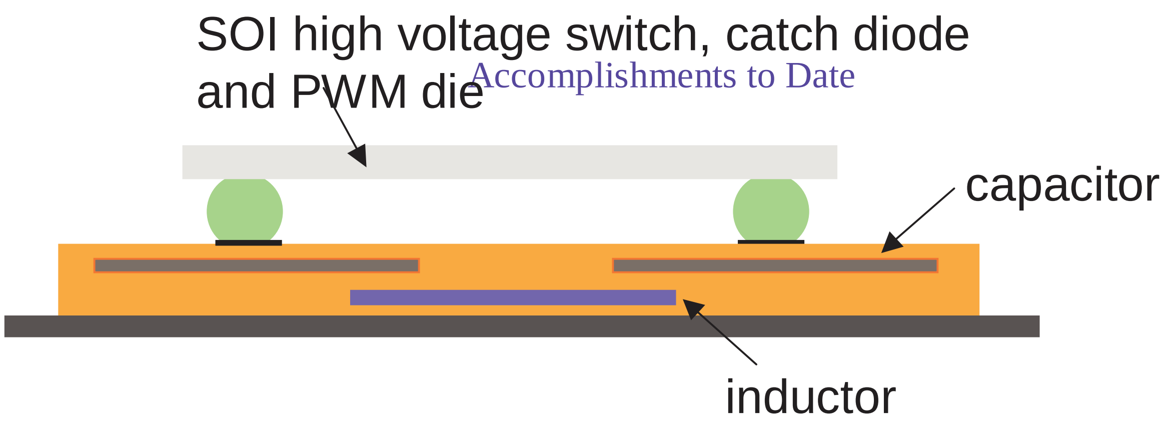
**Passives test substrate**

**-BCB, tantalum oxide capacitors**
**-Cr-Si resistors**
**-Flip-chip test die**
**-Three layer substrate**

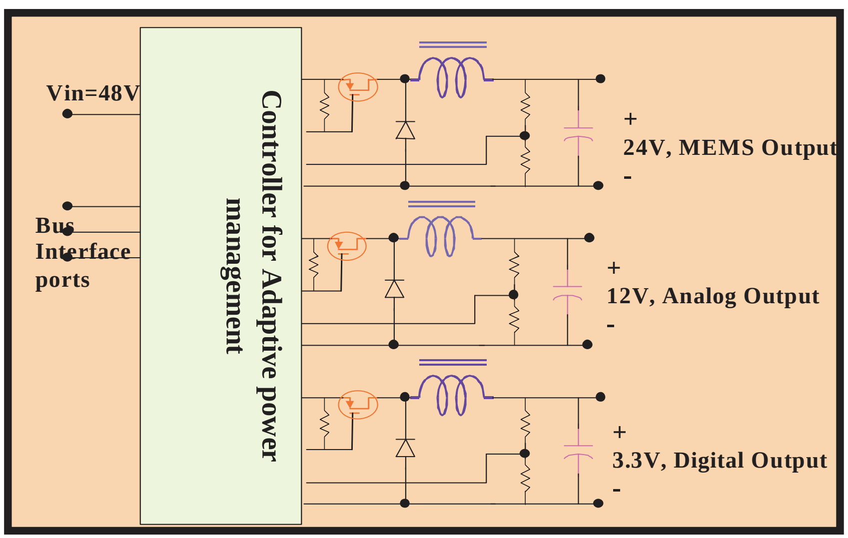
**Integrated passives power switching test circuit**

**-integrated capacitors and resistors**
**-multilayer substrate on silicon**
**-Flip chip die attach of ASIC**

-Finishing integrated power module through NEPP (was supported through System-on-a-chip)
-Provides an approach for integrated capacitors, resistors and integration of power switches




**Developing concepts for integrated power converters**




**Developing concepts for distributed power architectures**

## Publications and presentations

Accomplishments to Date

E. Brandon, E. Wesseling, V. White, C. Ramsey, L. Del Castillo, U. Lieneweg, "Fabrication and characterization of microinductors for distributed power converter applications" *IEEE Trans. Magn*., *submitted,* 2001.

E. Brandon, E. Wesseling, V. White, U. Lieneweg, H. Cherry and J. Podosek, "Microinductors for spacecraft power electronics," in *Proc. of the Electrochemical Society: Magnetic Materials, Processes and Devices VI*, vol. 2000-29, pp. 559-567, 2000.

E. Wesseling, E. Brandon, U. Lieneweg, R. Rub, S. Gupta, T.C. Nam and C.H. Ahn, "AC and DC current dependence of on-chip inductors," in *Proc. of the Electrochemical Society: Magnetic Materials, Processes and Devices VI*, vol. 2000-29, pp. 547-558, 2000.

"Microinductors for Integrated Power Conversion," at the IEEE sponsored 16th Annual Battery Conference on Applications and Advances, Long Beach, CA., Jan. 2001.

"Microinductors for Spacecraft Power Electronics" at the 198th Mtg. of the Electrochemical Soc., Phoenix, AZ, Oct. 2000.

"Electrodeposition of high-permeability magnetic films," at the Spring 2000 American Chemical Society Conference, San Francisco, CA, Mar. 2000.

# Resources & Interdependencies

## Synergy

No other NASA funding at this time

Proposal to Department of Energy

## Team/Research Assets

**WF-Erik Brandon 1 FTE (Other WF, Emily Wesseling, recently left JPL)**

Goddard Space Flight Center-board level buck converter design and testing

University of Arkansas-fabrication and testing of passive components

Auburn University-packaging

University of Idaho-board level boost converter design and testing

Kansas State University-high frequency (>1 MHz) inductor testing

## Links to Other Programs

Formerly linked to the System-on-a-chip program

Overlap with NEPP program in packaging and integration

Work closely with Power Electronics Group and their efforts in power integration

# Anticipated Products & Infusion Opportunities

| **Technology Product** | **Current TRL** | **Final TRL/Date** | **Transition Opportunities** |
|---|---|---|---|
| Microinductor components | 1 to 2 | 2 to 3 (9/02) | Earth orbiting missions (Goddard) |
| *(for 3.3 to 12 V boost converters* | | | Mars Scout-type missions |
| *and 25 V to 12 V buck converters)* | | | Offspring of X-2000 |

-Finishing new inductors using new design and materials

*aim for board level testing this summer*

-Submitting proposal to the Department of Energy

*continue investigation of magnetic materials*

-Investigating opportunities with Navy SPAWAR Program

*targeting 500 $W/in^3$ converters*

-Continue working with power electronics group

*identify new power architectures*

-Inductors are one of the fundamental circuit elements in electrical engineering—*microinductors are challenging*

-Have established a path toward microinductors with sufficient Q

-Will keep trying to bring together all of our work over the last few years in integrated passives, high voltage transistors and packaging to develop an integrated power converter

# Highly Miniaturized, Long-Life, Alpha Particle Power Source for Electronics Operating at Extreme Temperatures in Deep-Space Missions

**Jagdish Patel and Jean-Pierre Fleurial**

**JPL**

# Motivation, Challenge, and Benchmark

Motivation : To develop miniaturized, high-efficiency, discrete power source for distributed applications in extremes space environments i.e.:

1. **Interplanetary exploration missions looking for life using multiple micro explorers and distributed smart sensors under sun obscuring conditions and extreme temperatures.**
2. **Micro/nano spacecraft with discretely powered distributed electronics.**
3. **Long transit/life missions such as the interstellar travel in a persistent low temperature and radiation environment**
4. **Electronics and MEMS used in robotics for a long duration robotic colonization of planets.**

Challenges: Lattice damage from alpha particles dictates device lifetime. Rapid degradation of various generations of devices upon irradiation by the alpha particle beams requires optimum device design and materials selection.

Benchmark: RTGs performing at 5 W/kg is the existing SOA technology. Our approaches is aiming at a factor of 20 to 100 improvement in specific power. Efficiency improvisation over existing beta-voltaic(1~2%) approach by a factor of 5 to 10 is targeted.

# Schedule and Budget

## Schedule and Milestones:

**Year 1: Feasibility study will be completed, a proof of the principle device will be fabricated based upon the existing design, and will be tested.**

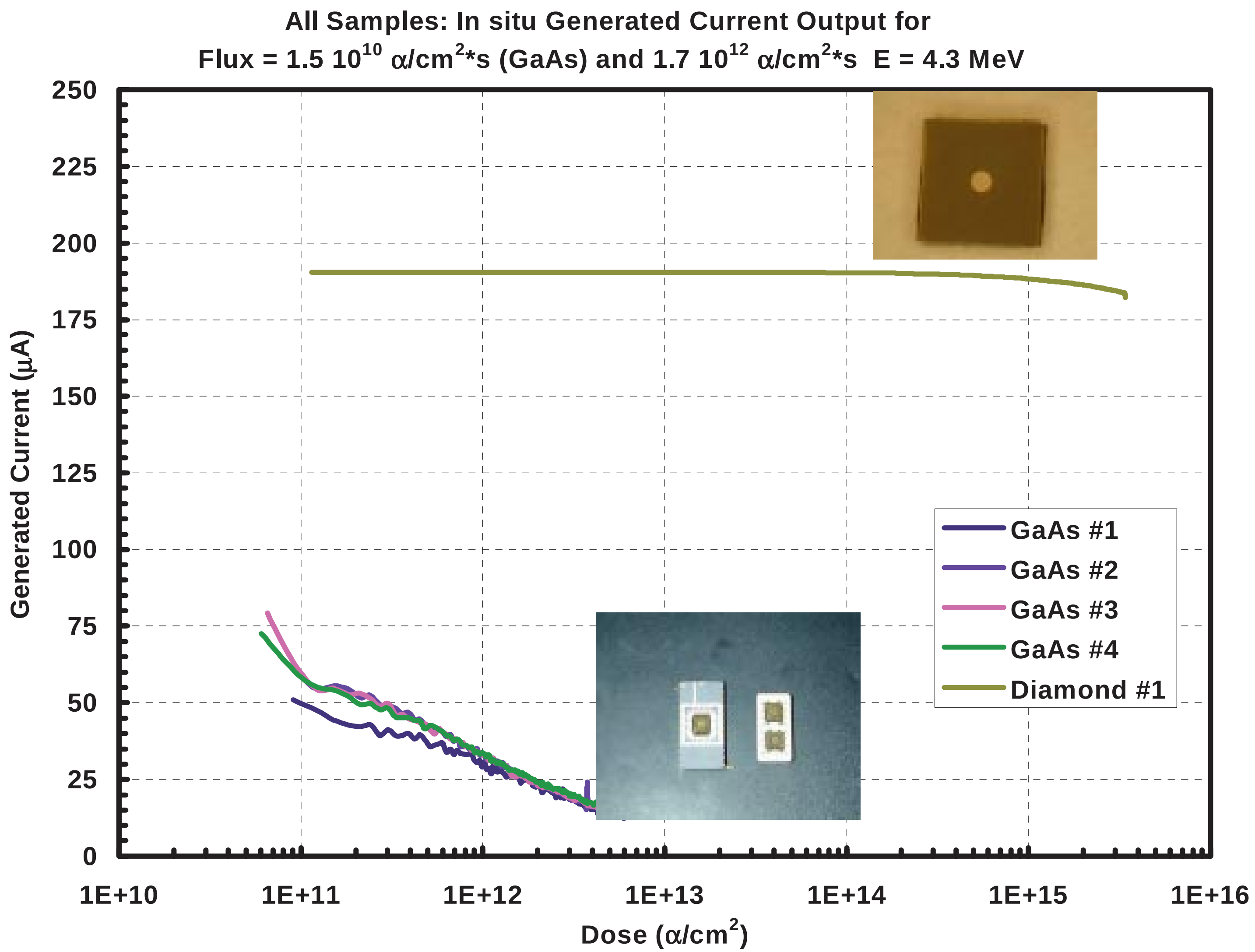
**Year 2: Optimum device design will be done in the second year and device fabrication and testing will be done.**

**Year 3: Integration of devices in high current and high voltage configurations will be done such configured power sources on a chip will be attempted.**

## Budget:

| Year | FY 2000 | FY 2001 | FY 2002 |
|---|---|---|---|
| Planned | $150K | $180K | $200K |
| Actual | $143K | $173K | $140K |

# Accomplishments to Date



# Resources & Interdependencies

## Synergy

| Sponsor Name | Start & End Dates | FY’02 $ | $ to Date | Competed |
|---|---|---|---|---|
| JPL/CISM | 2000-2001 | 0 K$ | 60 K$ | no |

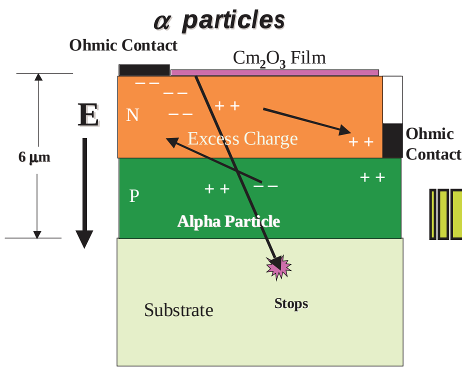
## Team/Research Assets

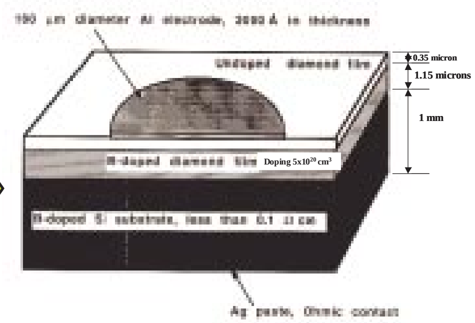
- •Jagdish Patel and Jean-Pierre Fleurial, Jet Propulsion Laboratory (JPL)
- •Prof. Robert Averback, University of Illinois at Urbana-Champaign
- •Takeshi Tachibana, Kobe Steel Ltd., Japan
- •Oak Ridge National Laboratory (ORNL)
- •Primary Enterprise Customer: *HEDS, Mars Exploration Program*
- •Secondary Enterprise Customer: *Solar System Exploration Program*

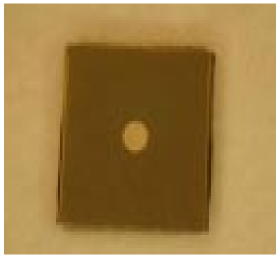
Links to Other Programs DARPA-sponsored Thermoelectric Microdevices for power generation and thermal management at JPL

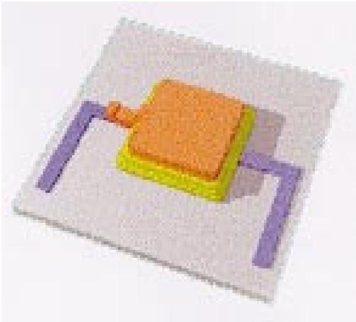
# Anticipated Products & Infusion Opportunities

| Technology Product | Current TRL | Final TRL/Date | Transition Opportunities |
|---|---|---|---|
| [Diamond/Alpha-voltaic Power source] | [2] | [3 / September 2002] | [NASA/R & DARPA] |





On-Chip Power Source

# Future Plans: Near-term

**•Newer device designs will be fabricated at Kobe Steel Japan, till targeted performance and device life are achieved.**

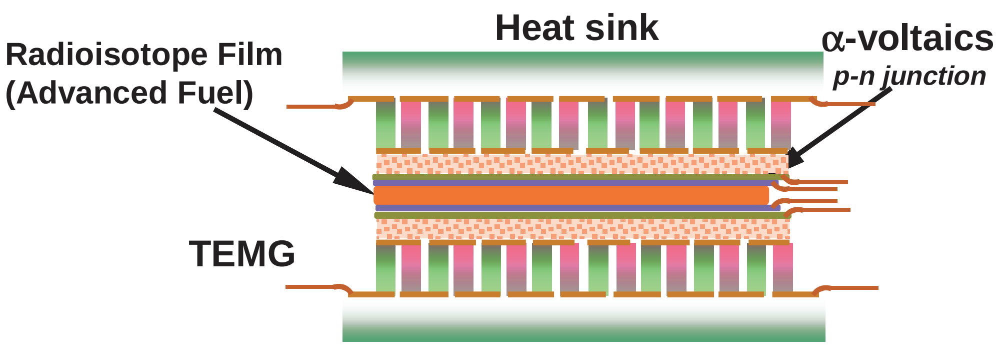
**•Alpha particle irradiations of diamond devices will be carried out at elevated temperatures to characterize the annealing effects for application at high temperatures.**

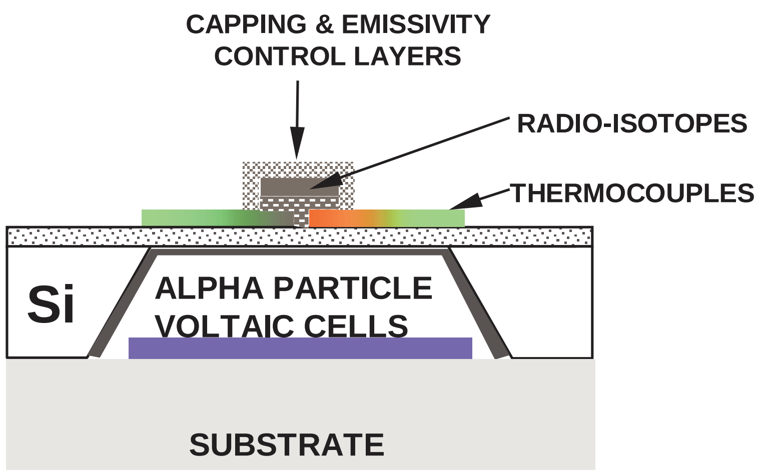
**• Possibility of the application of new materials similar to diamond will be investigated**

**•Analytical modeling of the conduction properties of diamond films and the alpha particle damage will be done for optimizing the device design.**

# Future Plans: Long -term

## Creating a Hybrid α-Voltaics/TE Device




- Possible combined α-V/TE device
  - **High efficiency, long life, ultra compact power sources - About 14% conversion efficiency calculated from a "long-life" device design (minimization of lattice damage)**
- Alpha-particles are then trapped in thin film or supporting substrate microelectronics
  - **Use transferred heat to convert electricity - Potential for using 86% of leftover energy from α emitter - Could add another 3 to 10% to conversion efficiency**
  - **Depending on α-converter operating temperature, device design**

# Summary

•Fabricated proof-of-principle devices using GaAs and diamond devices

–Still a lot of work needed

•GaAs-devices produced lower power during irradiation compared to diamond devices

•Now working on re-designed diamond-based devices

–Better life time and efficiency

–Better understanding of device performance and damage mechanisms

# Motivation, Challenge, and Benchmark

<u>Motivation</u> *Develop fully integrated micropropulsion systems that combine MEMS-based propulsion components with integrated microelectronics control circuits for future microspacecraft:*

- *Ultra-compact propulsion (~1 $cm^3$, ~10 g) modules containing feed system and driver electronics*
- *Ease of integration*
- *High-precision impulse bit performances, as required for microspacecraft, possible with MEMS-fabricated nozzles.*

<u>Challenges</u>

- *Demonstrate feasibility of microfabrciation and operation of individual micropropulsion components (well underway at this point, key feasibility demos have been achieved).*
- *Integration of components and drivers into modular units, addressing 3-D packaging concerns, thermal control. Functional demo planned for summer FY'02.*

# Motivation, Challenge, and Benchmark - cont'd

Benchmark *Several MEMS propulsion development efforts exist, or have emerged since the JPL activity. Among them:*

- *MEMS Cold Gas Thruster (Angstroem Institute, U. of Uppsalla, Sweden): Uses cold gas, needs large and heavy tankage*
- *Free Molecular Resistojet - FMMR (USC/AFRL): No thrust data yet. Requires about 11 W.*
- *MEMS Bi-Propellant Thruster (MIT): Operated on gaseous propellants only (include. oxygen). Operation on liquid propellants requires vaporization and atomization on MEMS scales. Cooling issues.*
- *Digital Thruster Arrays (Aerospace Corp/TRW/Caltech, CNRS/France, Honeywell, DERA/UK): Consists of multiple single-shot thrusters arranged into a wafer based array. So far only 10s of thrusters placed onto array (limiting total impulse and number of impulse bits). Competing with other S/C subsystems for S/C surface area.*

*The JPL Integrated Micropropulsion approach provides:*

- *A thruster system using liquid propellant (water, ammonia, other), saving system mass (lighter tankage than cold gas).*
- *Low power operation: demonstrated 32 µN thrust for 0.8 W (!) of power.*
- *Addresses integration issues between propulsion components and with driver circuits, needed for all MEMS propulsion approaches.*

## Schedule and Milestones:

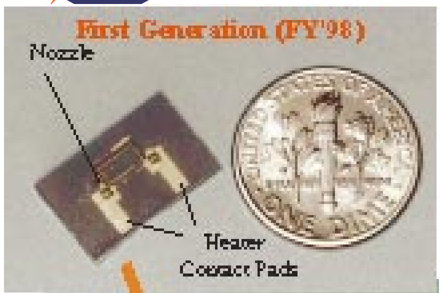
# Schedule and Budget

| Highly Integrated Micropropulsion Systems | | | |
|---|---|---|---|
| | **Year 1** | **Year 2** | **Year 3** |
| Electronics | • Electrical Requirement Spec.<br>• Design and fabricate a library of cells in 0.8µm SOICMOS | • Characterization of the 1st iteration of the cell library<br>• 2nd iteration and design optimization of the cell library | • Initial design iteration of a propulsion control system on a chip.<br>• Map the cell library to Honeywell 0.35µm SOI CMOS |
| Propulsion | • Micro Propulsion Req. Study<br>• VLM, MIV Performance Testing and Verification.<br>• MMV Fab (co-funded) | • VLM, MIV design optimization<br>• MMV Testing, Optimization | |
| Micro-Propulsion System Integration | | Heterogeneous Integration of VLM, MIV, MMV with driver | Demonstrate system integration of propulsion module (VLM + MMV + MIV + Drivers) |
| Funds Sought from CETDP ($K) | 500 | 500 | 500 |
| Anticipated Co-Funding ($K) [1] | 300 | TBD | TBD |
| Workforce (FTE) Sci/Eng. Tech. | Sci/Eng: 2<br>Tech: 1 | Sci/Eng: 2<br>Tech: 1 | Sci/Eng: 2<br>Tech: 1 |

DRDF ($150K - Development of Micro Electromagnetic Valve), and Moog Space Products IRAD Funding

## Budget:

| FY ‘00 | FY’01 | FY’02 |
|---|---|---|
| $450K | $470K | $450K |

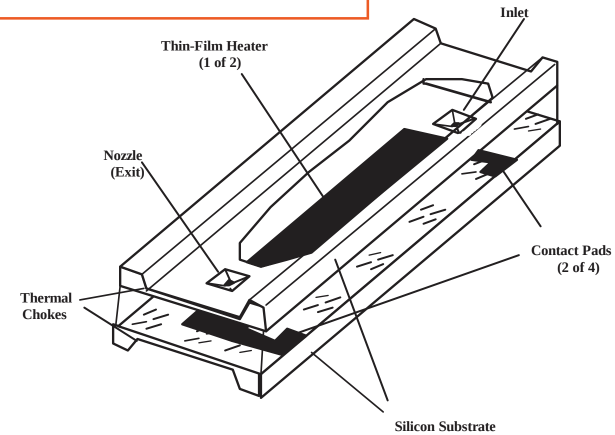




**Third Generation (FY'00/01)**

Vaporizing Liquid Microthruster (VLM):

- Vaporize liquid propellant on demand in a microfabrciated heat exchanger to produce thrust.
- Thin-film deposited heater elements.
- Use of liquid propellant will reduce system weight and volume.



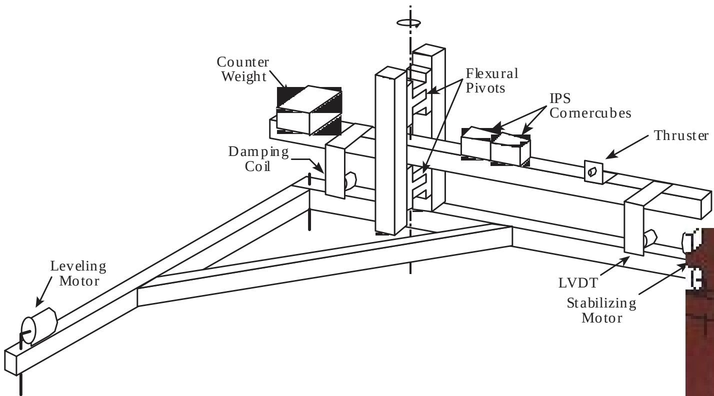

**VLM Concept**

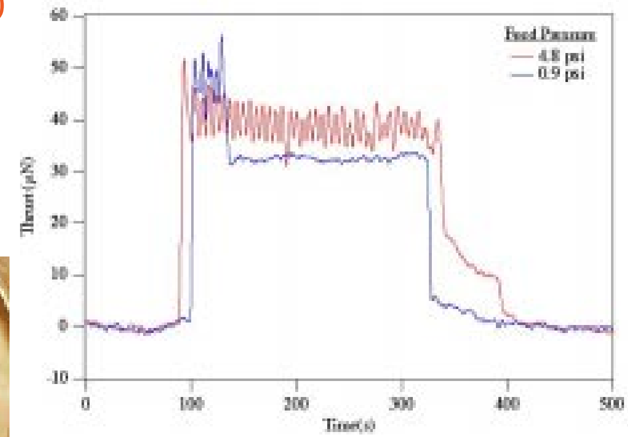
## Significant Accomplishments:

- **Proof-of-concept: complete vaporization of propellant possible on chip-scales.**
- **Measured 32 µN thrust at 0.8 W input power**
- **Operation at power levels as low as 0.5 W**
- **Operational characteristics appear to overlap with microspacecraft thrust requirements.**
- **However, emerging picosat designs may require even lower power levels (total 1 W per spacecraft)**

# Significant Facilities Development

• 0.5 µN resolution thrust stand based on Princeton U. design (John Ziemer, 353)

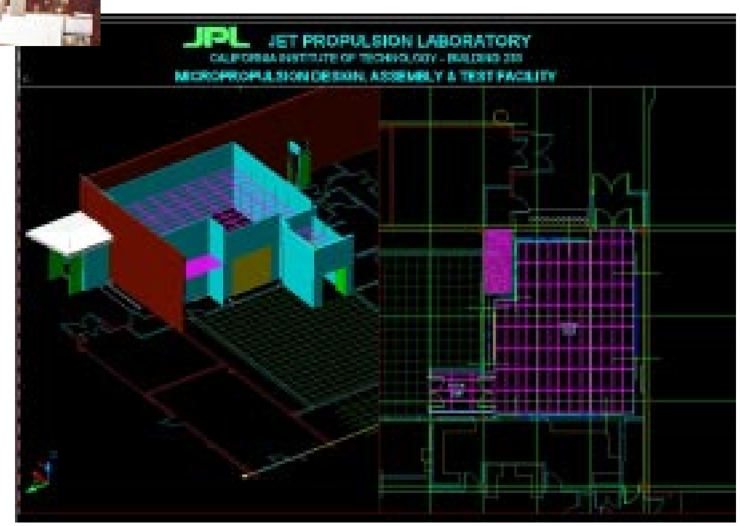



**VLM Thrust Trace (32 µN)**
**(J. Ziemer)**

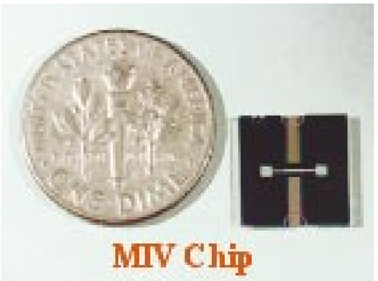
• Micropropulsion Design, Assembly and Test Facility (MDAT) (Dave Bame, 353):

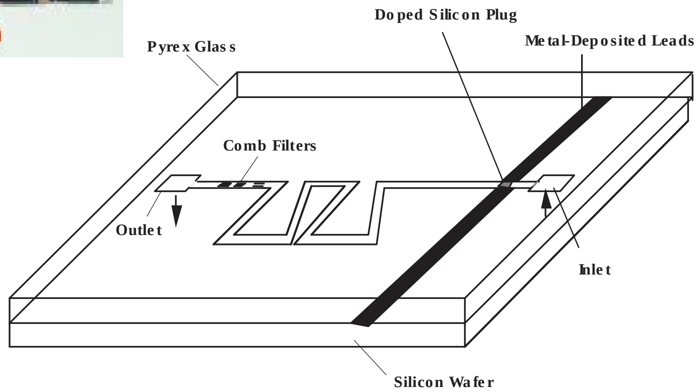
- Current facility to be replaced by 1000 sq-ft, Class 10 cleanroom facility
- To be established in FY'02/03 under $1.2M capital facilities grant (Dave Bame)




**New MDAT Facility**

# Accomplishments to Date - MIV



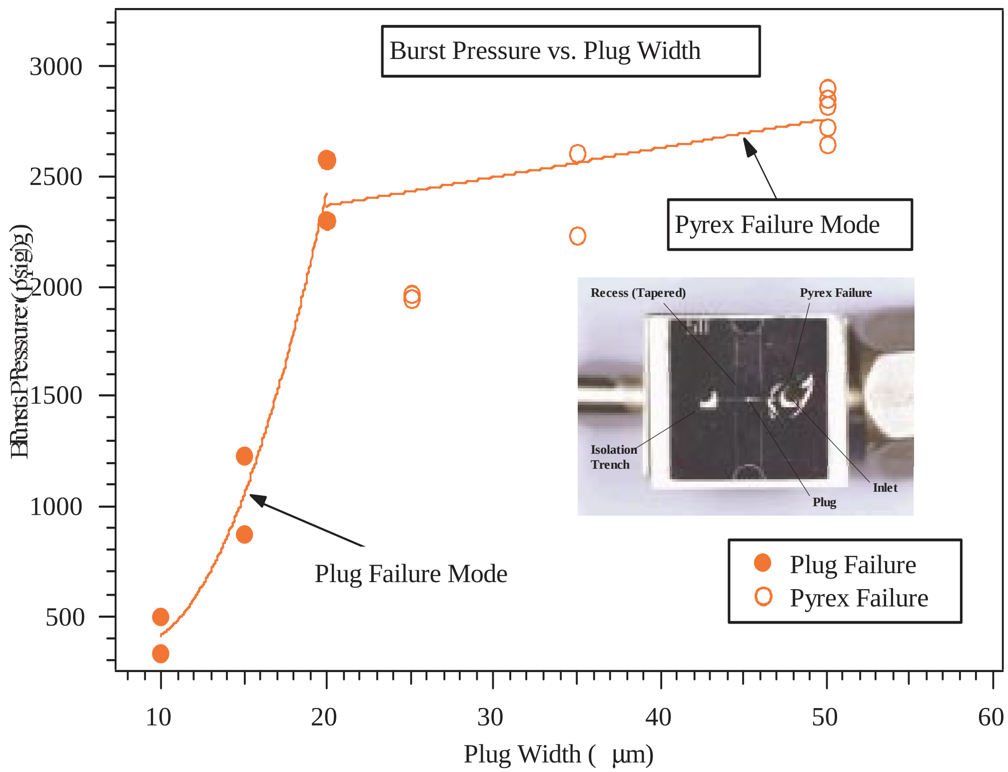

Micro-Isolation Valve:

- Two-laminate chip construction:
  - Silicon (contains all flow passages)
  - Pyrex (cover to seal chip)
- Si barrier etched into place, blocking flow path.
  - No seams and seal - zero-leakage
  - One time actuation only (normally-closed)
- Pass current through conductive barrier and melt/crack barrier to open, actuating flow system
- System advantage: zero leak rates for microprobes prior to actuation. Conserves propellant, which is limited on microspacecraft.

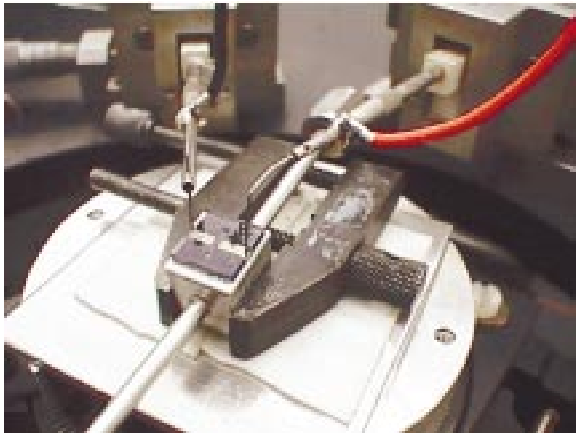
**Significant Results: All key feasibility issues successfully addressed.**

- **Actuation energies of 10-60 mJ (suitable for microspacecraft)**
- **Burst pressures of 3000 psi (high for Si/Pyrex chip).**
- **So far no evidence of barrier debris leaving chip (contamination contained).**
- **Response times of 0.1 - 0.3 ms**
- **0.6 - 7 μF firing capacitances**

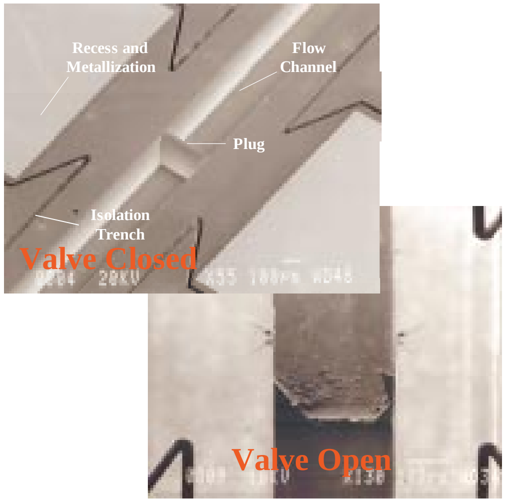
- **Isolation valves may see full tank pressure.**
- **Burst pressures of MIV as high as 3000 psi.**
  - **Below 20 µm barrier breakage possible.**
  - **Above 20 µm Pyrex breakage occurred first.**
  - **Thicker Pyrex (currently 0.5 mm) or Si material could improve burst pressure further**

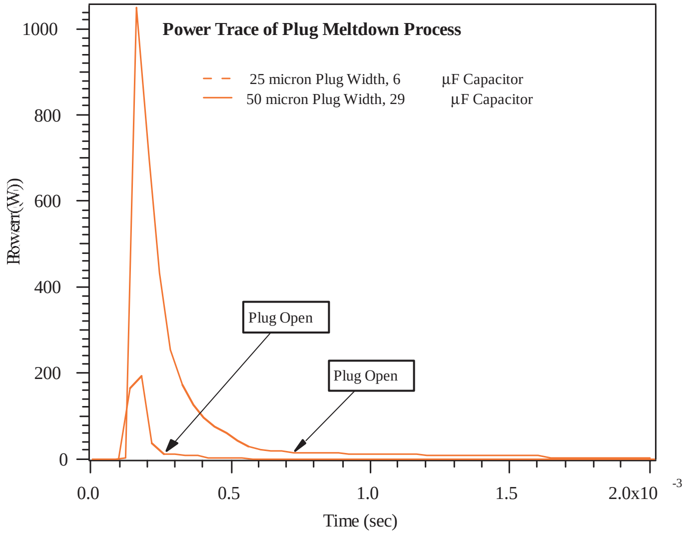


# Valve actuation experiments showed actuation possible within 10-60 mJ

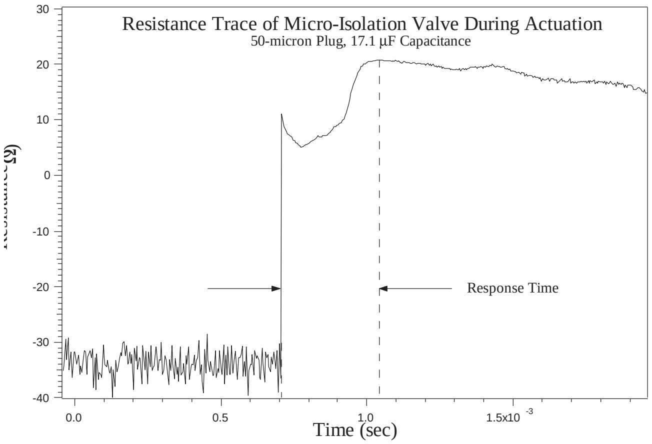


Experimental Set Up

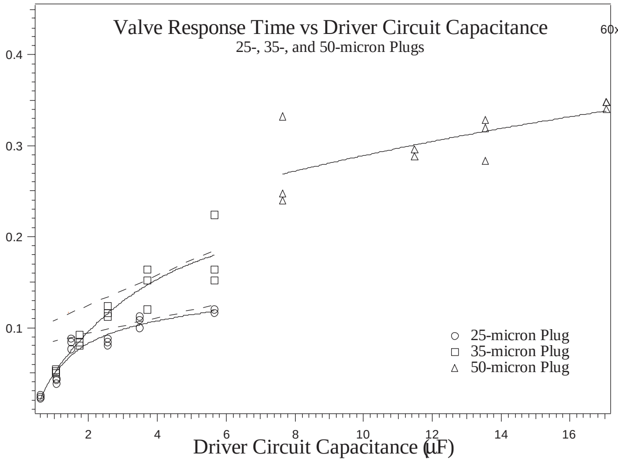


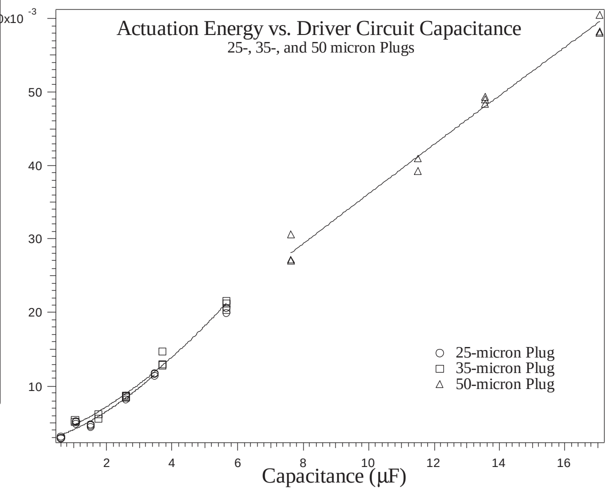

Typical Power Trace




Resistance Trace during Opening of Valve

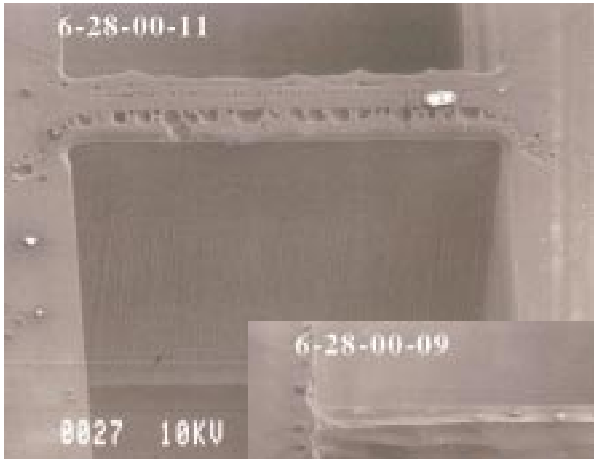



Valve Response (Opening) Times

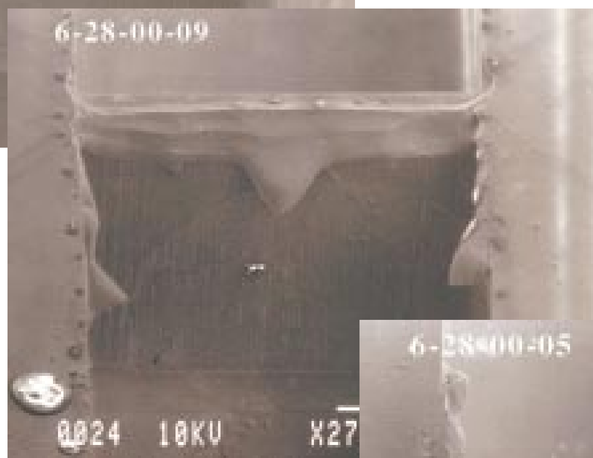



Actuation Energies

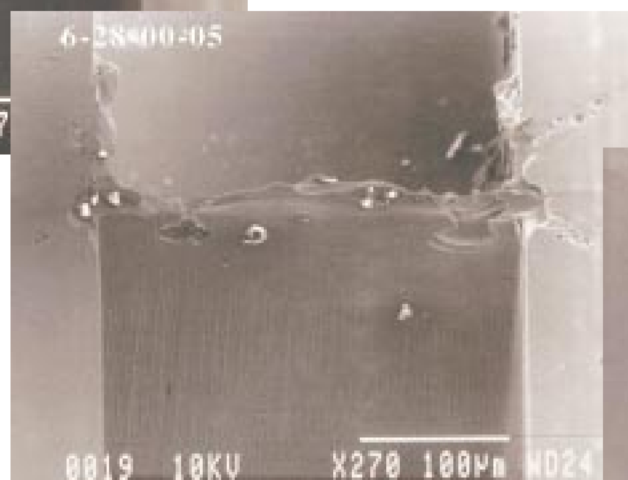
**Both plug melting and cracking occur depending on actuation energies (driver capacitances).**




3.5 uF

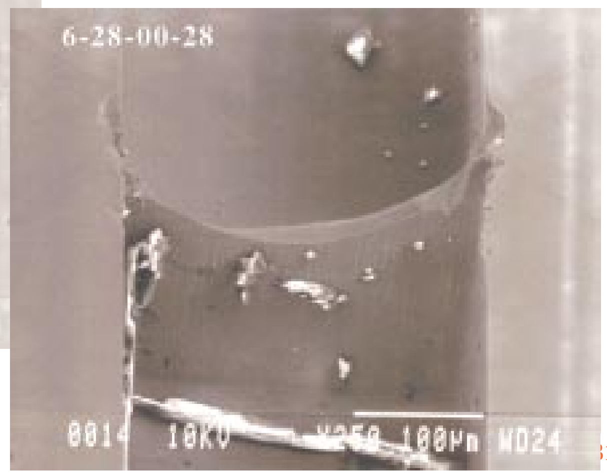



7.6 uF

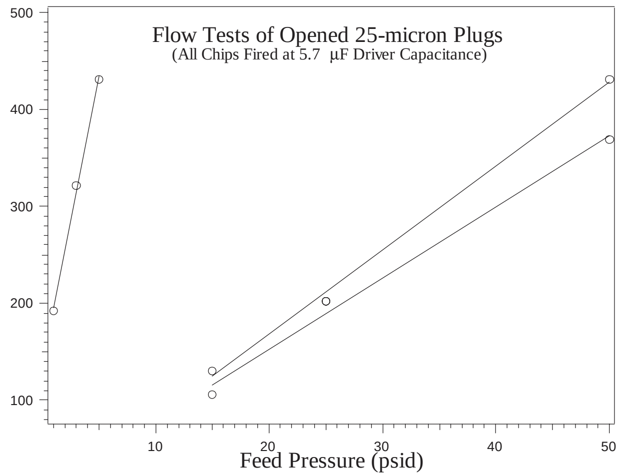



11.5 uF

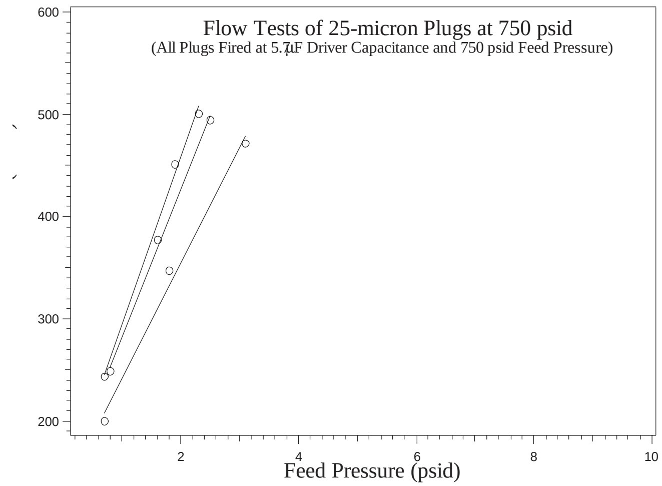
13.5 uF



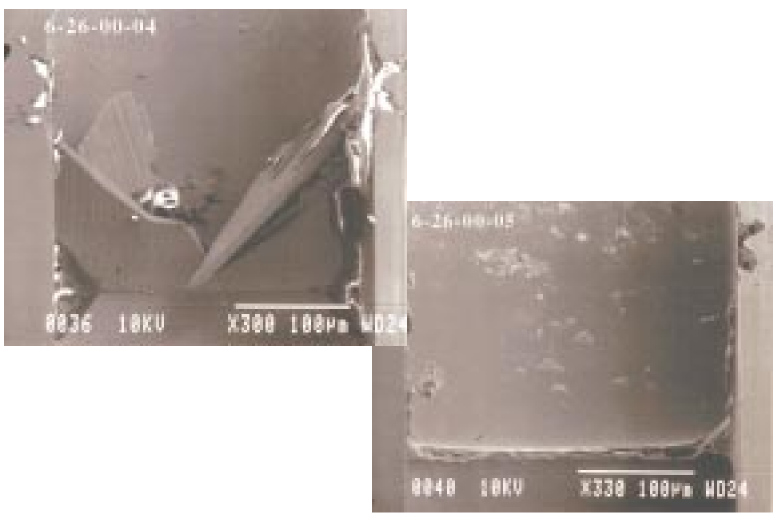
**When operating plug at higher pressure, valve repeatability increases**

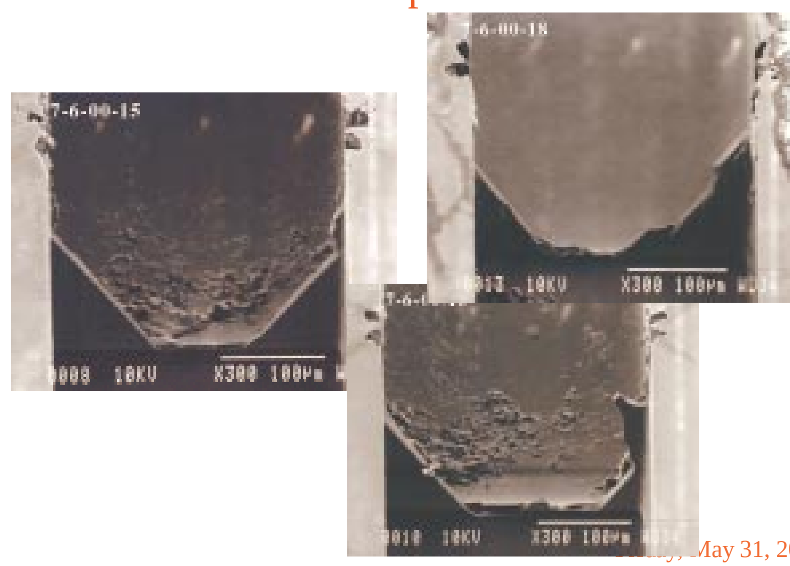



Fired @ 300 psi inlet

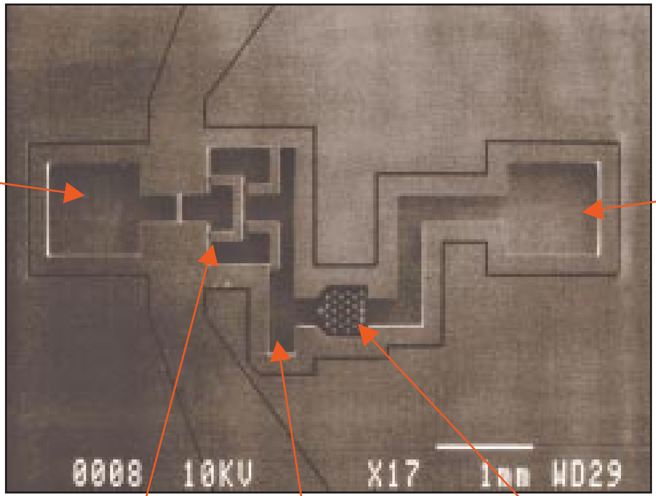



Fired at 750 psi inlet

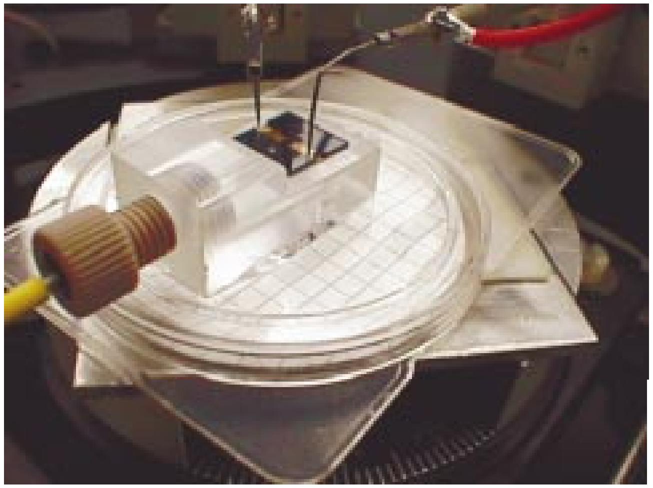


**New MIV chip design with debris trap and filter**

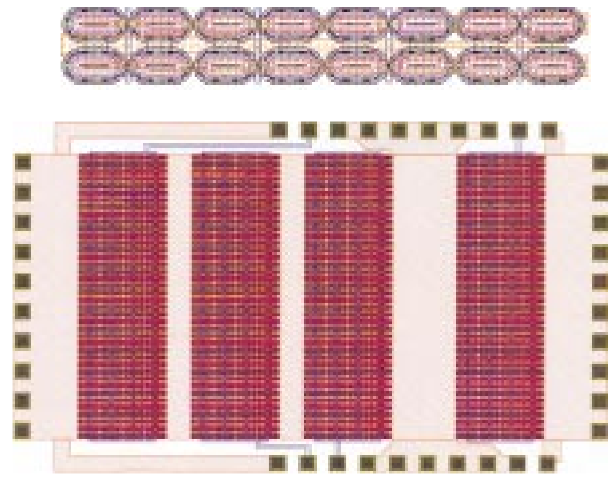



**Filtration tests so far show no debris exciting the valve. Further studies required under varying operating conditions (driver cap., inlet pressure).**

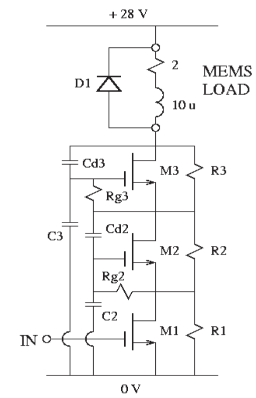


**Experimental Set-Up**

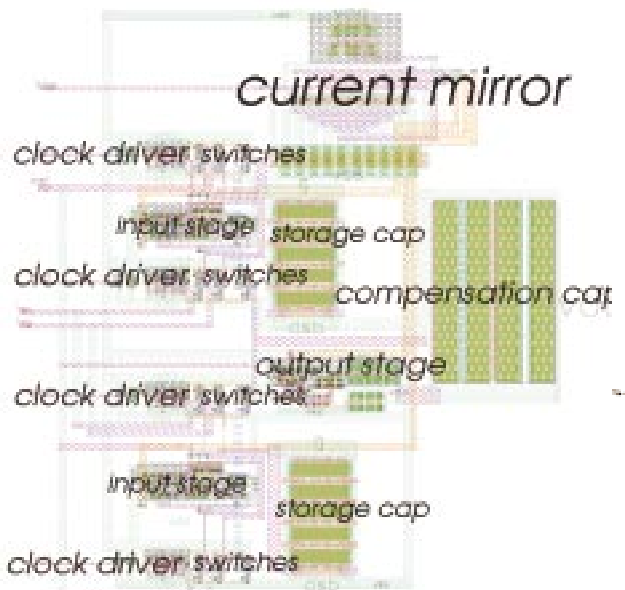
- Basic electronic building blocks have been fabricated and are under evaluation
  - ⇒ High voltage valve driver
  - ⇒ Single poly floating gate EEPROM for analog trimming
  - ⇒ Offset cancelled op amp for sensors
- Architecture of the first Micro propulsion system has been defined
- Simulation and layout are underway

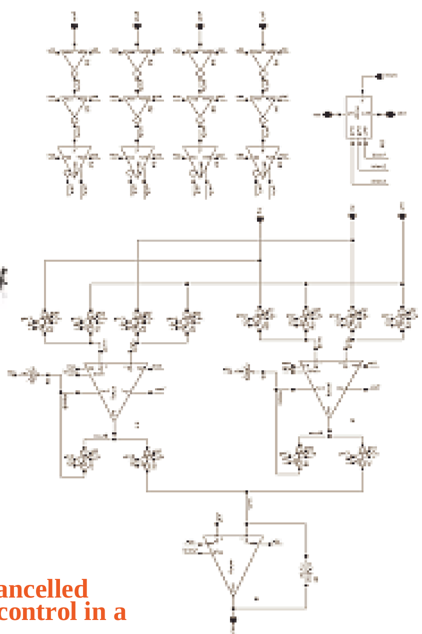


Layout of the high voltage MEMS actuator driver

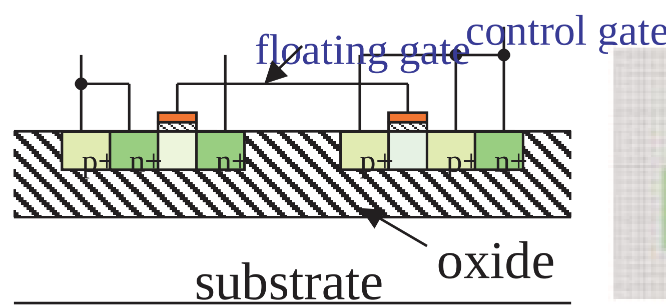


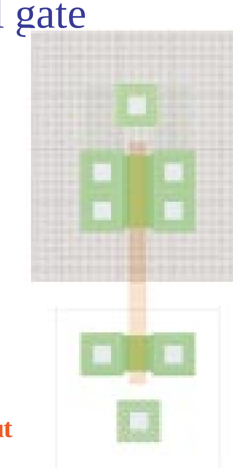

Circuit diagram for high voltage MEMS actuator driver



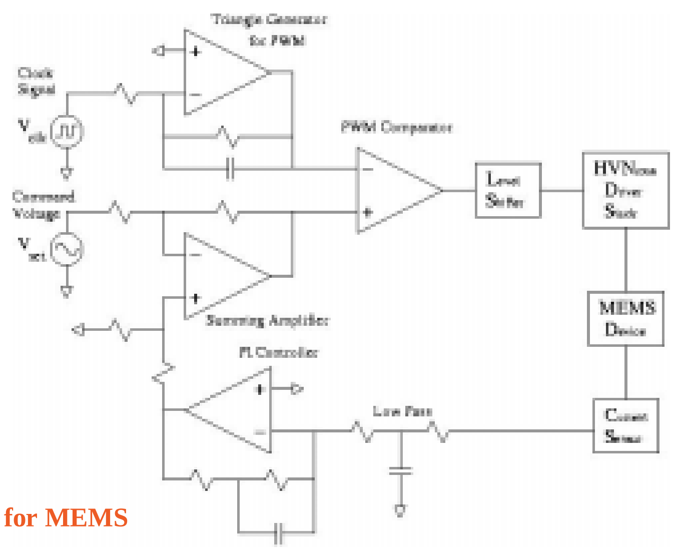
Layout and circuit diagram for an offset cancelled operational amplifier for sensors and analog control in a smart propulsion system



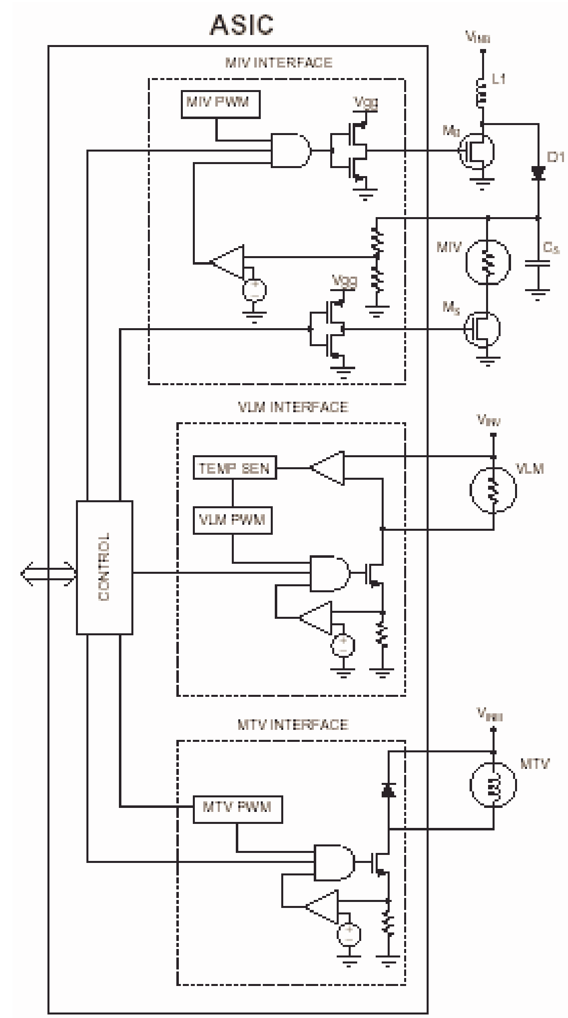



Single Poly EEPROM cross section and layout

- Provide control for three elements of a micro propulsion system
- Independent interface for MIV, VLM, and MTV
- Minimize external components
- Low power
- High efficiency




Smart Controller ASIC for MEMS




Integrated Micro Propulsion ASIC

# References/NT□Rs

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Mueller, J., “Thruster Options for Microspacecraft: A Review and Evaluation of State-of-the-Art and Emerging Technologies”, *Micropropulsion for Small Spacecraft*, Progress in Astronautics and Aeronautics, Vol. 187, edited by Micci, M. and Ketsdever, A., AIAA , Reston, VA, 2000, Chap. 3.

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Mueller, J., Vargo, S., Bame, D., Chakraborty, I., and Tang, W., “The Micro-Isolation Valve Concept: Initial Results of a Feasibility Study”, *Micropropulsion for Small Spacecraft*, Progress in Astronautics and Aeronautics, Vol. 187, edited by Micci, M. and Ketsdever, A., AIAA , Reston, VA, 2000, Chap. 17.

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Vargo, S., Green, A., Mueller, J., Bame, D., and Reinicke, R., “Characterization of Kovar-Pyrex anodically bonded samples – a new packaging approach for MEMS devices”, SPIE 2000 Symposium on Micromachining and Microfabrication, Santa Clara, CA, Sept. 18-19, 2000.

Mueller, J., Vargo, S., Green, A., Bame, D., Orens, R., and Roe, L., “Development of a Micro-Isolation Valve: Minimum Energy Requirements, Repeatability of Valve Actuation, and Preliminary Studies of Debris Generation”, AIAA Paper 2000-3675, 36th Joint Propulsion Conference, Huntsville, AL, July 16-19, 2000.

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**NTRs:**

"Micromachined Vaporizing Liquid Microthruster (VLM) with Superior Thrust Vector Control and Increased Thermal Efficiency", Chakraborty, I., Mueller, J., and Bame, D., NPO-21100, 8/14/00.

"Vaporizing Liquid Thruster for Microspacecraft", Mueller, J., Leifer, S., Muller, L, George, T., NPO-19928, 4/24/96.

"Micro-Isolation Valve for Microspacecraft Applications", Chakraborty, I., Mueller, J., Wallace, A., NPO-20473, 9/9/98.

"Normally Closed Micro-Isolation Valve for Microspacecraft Applications", Mueller, J., Muller, L., and George, T., NPO-19927, 4/18/96.

# Resources & Interdependencies

## Synergy

*No synergistic efforts are taking place in FY'02. However, in FY'00, a joint Moog Inc./JPL activity funded under Moog IRAD and JPL DRDF took place to develop a micro-solenoid valve:*

| Sponsor Name | Start & End Dates | FY'00 $ | $ to Date | Competed |
|---|---|---|---|---|
| Moog IRAD, JPL DRDF | FY'00 | 350 K$ | 350 K$ | No |

## Team/Research Assets

*JPL has assembled a highly capable team of experts in microfabrication, valve design, electronic circuitry, and propulsion to address the unique aspects of highly integrated micropropulsion module design:*

| | |
|---|---|
| Amanda Green | Microfabrication |
| David Bame | Test Support |
| Dr. John Ziemer | Micro-Thrust Stand |
| Dr. EH Yang | Piezovalve Development |
| Dr. Victor White | Solenoid Development |
| Robert Reinicke | Moog/Solenoid Valve Development |
| Prof. Ben Blalock | U. Tennessee/ Driver Fabrication |
| Prof. Harry Li | U. Idaho/Driver Fabrication |

We are utilizing JPL's state of the art Micro Device Laboratory (MDL), a 0.5 µN resolution thrust stand in its dedicated vacuum facility, and are in the process of design and construction of a $1.2 M novel 1000 sq-ft, Class 10 cleanroom-based Micropropulsion Design, Assembly, and Test (MDAT) facility, featuring a novel 2m-dia./2-m length UHV chamber. This facility will be shared with LISA and ST-7 projects.

# Anticipated Products & Infusion Opportunities

| Technology Product | Current TRL | Final TRL/Date | Transition Opportunities |
|---|---|---|---|
| VLM Thruster | 2-3 | 3/Sept. 02 | Micro/Picosats (Cube Sat, DARPA Picosat, New Millennium)<br>Picosat-based Constellation Missions (Sun-Earth Connection) |
| Micro-Isolation Valve | 3 | 3/Sept.02 | Micro/Picosats (Cube Sat, DARPA Picosat, New Millennium)<br>Picosat-based Constellation Missions (Sun-Earth Connection)<br>Advanced Electric Propulsion Feed Systems (New Millennium, Discovery Missions, …) |
| Driver Electronics | 2 | 3/Sept.02 | Micro/Picosats (Cube Sat, DARPA Picosat, New Millennium)<br>Picosat-based Constellation Missions (Sun-Earth Connection)<br>Any microvalve application (space& commercial) |
| Integrated Propulsion System | 1 | 2/Sept.02 | Micro/Picosats (Cube Sat, DARPA Picosat, New Millennium)<br>Picosat-based Constellation Missions (Sun-Earth Connection) |

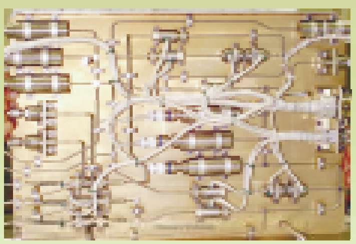
## Future Plans

- *A functional test of integrate driver electronics and propulsion components (MIV, VLM, and Moog solenoid valve) will be performed this summer. However, additional design integration is required under close involvement of commercial valve manufacturers to arrive at vision below (packaging approaches, thermal control, etc. - see image below)*
- *The VLM operates at very low power levels (< 1 W). However, picosat designs have emerged that have total S/C power levels of only 1 W or less. An even lower-power thruster option may be required:*

  *- Study monopropellant (catalytic) thruster options based on VLM design*

  *- To be initiated with $25K Lew-Allen Grant this CY.*

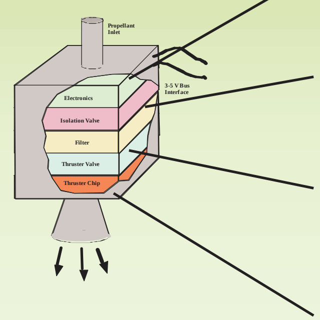
### Vision of Future Highly Integrated Propulsion Systems:

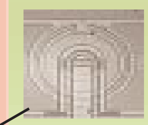


**Past:**
- **Conventional Components**
- **Conventionally Integrated**

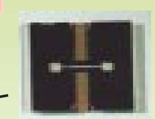

**State-of-the-Art:**
- **Miniature Components**
- **Conventionally Integrated**

**Goal:**
- **Micromachined Components**
- **Highly Integrated Modules**
- **Minimal External Interfaces**



Integrated High Voltage Interface



Micro-Isolation Valve

Micro-Thruster Valve

Vaporizing Liquid Micro-Thruster

## Summary

- *The Integrated Micropropulsion task not only seeks to develop new microfabricated propulsion components and drivers, but explores a paradigm shift in the design, integration, and assembly of propulsion hardware for very small spacecraft.*
- *Key feasibility issues have been successfully addressed:*

*MIV:*
- *High pressure (3000 psi) operation*
- *Low energy initiation (10-60 mJ) suitable for microspacecraft use.*
- *Successful debris filtration within the chip (prelim. results). Additional experiments required in FY'02.*

*VLM:*
- *Complete vaporization of propellant*
- *Acceptable low power operation (0.8 W and 32 μN). Operated as low as 0.5 W.*
- *Thrust levels appear to match microspacecraft attitude control requirements (μN-level and less)*

- *Further work is required:*
  - *Integrated propulsion module designs (in addition to functional tests this FY) involving close cooperation of commercial valve designer.*
  - *Even lower power operation (catalytic chemical monopropellant version of VLM)*

# Sun Sensor on a Chip

Sohrab Mobasser

# Motivation

## Motivation

To develop a low mass (<8 grams) and low power (<25 mW) sun sensor (12x17 mm) with larger than 128° field of view and better than 0.02° accuracy for next generation nanorovers and nanospacecraft navigation applications

State of the Art:

Accuracy: 0.3°
Size: 130 x 61 x 48 mm
Field-of-view: 128°
Mass: 500 grams
Power: 300 mW

Current Micro Sun Sensor:

Accuracy: 0.04°
Size: 25 x 25 x 8 mm
Field-of-view: 128°
Mass: 11.5 grams
Power: 20 mW

# Challenge and Benchmark

## Challenges

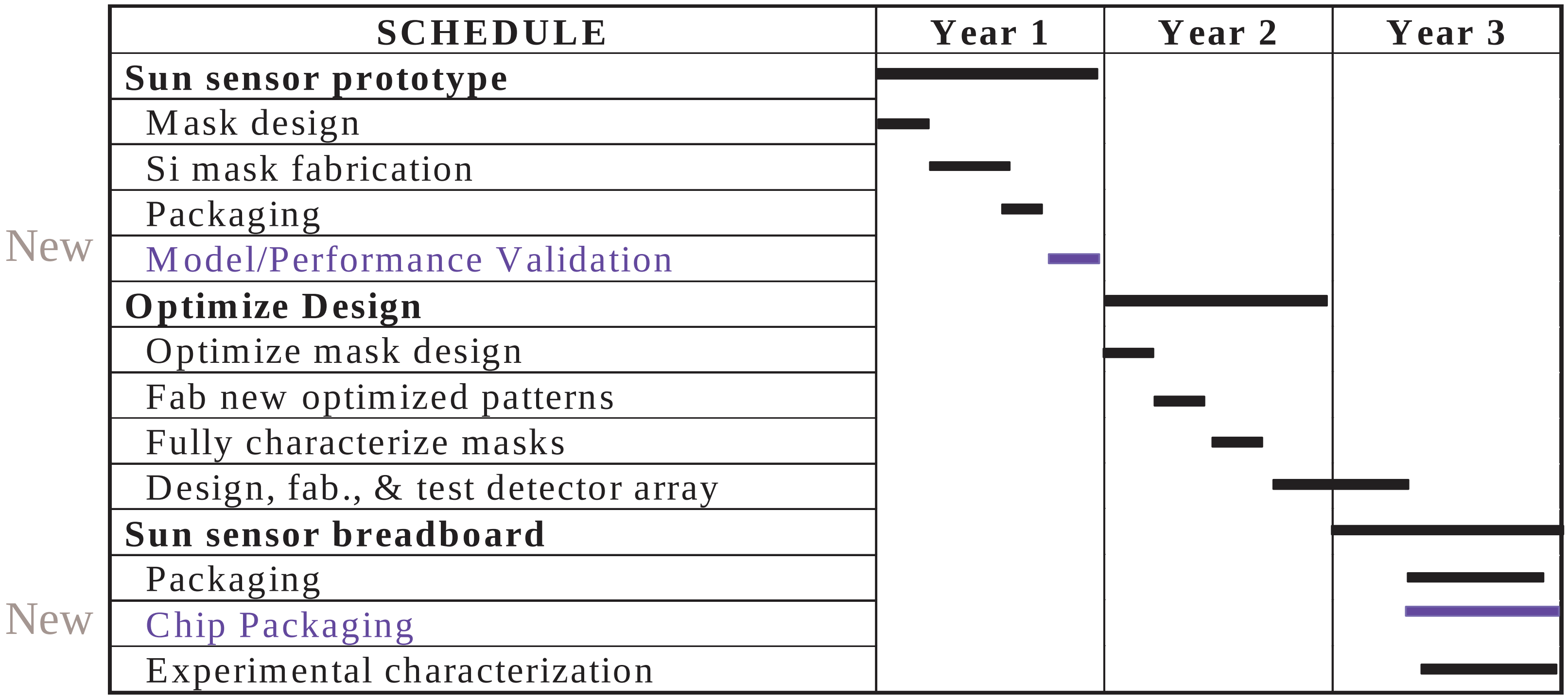
- Imaging optical sensor miniaturization difficulties
  - At small dimensions light begins to behaves as waves and the geometric optics assumptions do not apply
  - Packaging the Mask and APS detector into a very small package
  - Internal instrument alignment
- Designing an instrument which can potentially cover a very wide AU dynamic range(0.3-30 AU) and be insensitive to the sun’s angular subtends at different AUs

## Benchmark

- JHU/APL has also been active in the area of miniaturized sun sensors
- JHU/APL work has been focused on detector development and not on mask/packaging issues
- JHU/APL has developed an APS chip that capable of autonomous centroiding of a single centroid on the APS chip itself (similar capability was demonstrated at JPL in 99)
- JPL design is an order of magnitude lower mass

# Schedule and Budget

## Schedule and Milestones:



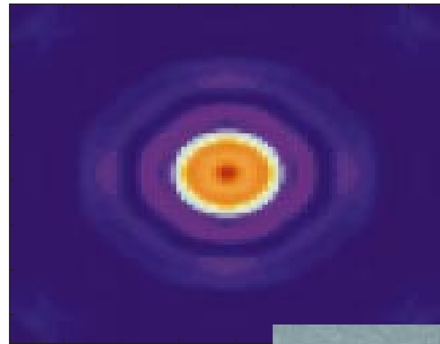

## Budget ($K):

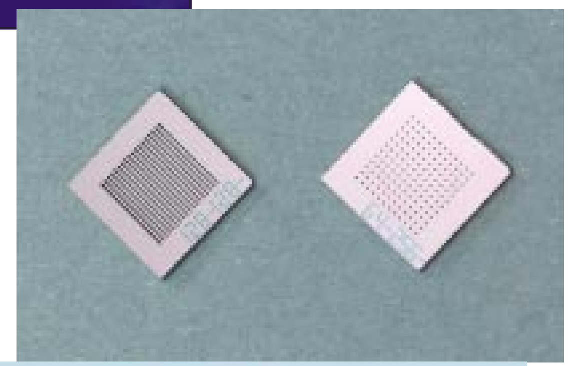
FY00: 200

FY01: 170

FY02: 150

- FY 00 Accomplishments Ac
  - Developed a concept for micro sun sensor utilizing MEMS process
  - Matlab simulations of near field intensity patterns





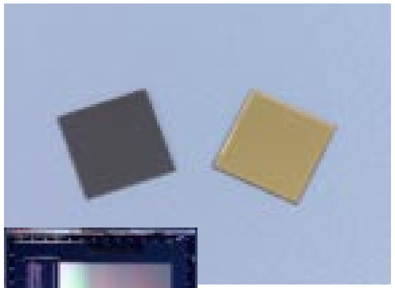
  - Designed, fabricated and tested MEMS masks made out of 500 microns thick silicon wafer

  - Developed acquisition system to characterize the MEMS masks utilizing commercial CCD camera
  - Developed camera model/centroiding program

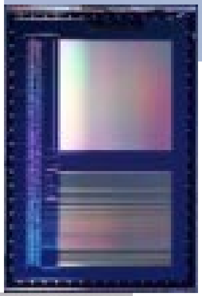
- # FY 01 Accomplishments

## Accomplishments to Date (Cont'd)

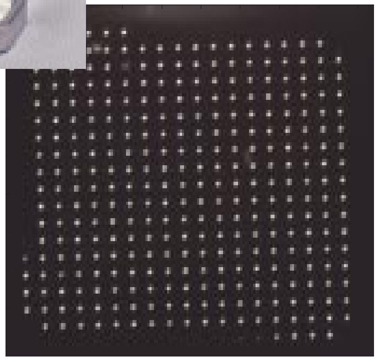
  - Fabricated MEMS masks out of a 500 micron silicon wafer with a layer of 590 A$^{o}$ chrome coating (to attenuate sunlight) and another layer of 3000 A$^{o}$ gold grid of pinholes



  - Built new CMOS based image detector setup using VIDI Active Pixel Sensor (APS) chip with all camera functions on the chip



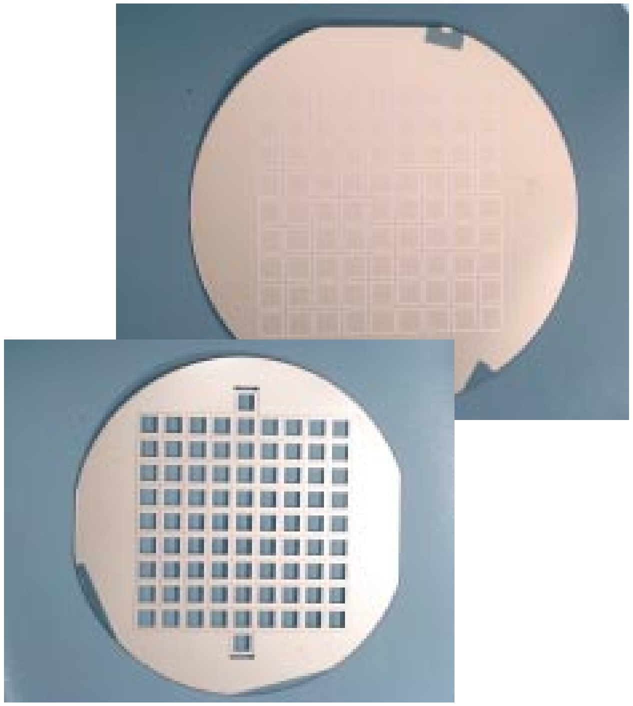
  - Designed and fabricated a small (25x25x8 mm) package with a nano connector
  - Integrated Mask and APS into the package (11.5 gm total weight)



- Acquired and analyzed images of sun using JPL's Heliostat facility

- Initiated research on the use of Fuzzy logic for processing the images from the image detector

- FY 02 Accomplishments
  - Designed a unique mask pattern which allows determination of sun angles with no apriori knowledge
  - Designed and fabricated silicon MEMS spacer to mount the MEMS mask directly on the APS chip



  - Bonded MEMS mask and spacer directly on the APS chip – Sun sensor on a chip
  - Participated in the Technology Insertion Maturity Assessment (TIMA) workshop for the micro sun sensor
  - Investigating the integration of the processing electronics into the sun sensor package

## List of Publication:

C.C.Liebe, S. Mobasser, "**MEMS based sun sensor**", proceedings of the 2001 IEEE Aerospace Conference, Big Sky, Montana, 10-17 March 2001

S. Mobasser, C.C.Liebe, A. Howard, "**Application of Fuzzy Logic in Sun Sensor Data Interpretation**", to appear in the proceedings of The Second International Conference on Intelligent Technologies (InTech'2001), Bangkok,Thailand, 27-29 November 2001

S.Mobasser, C.C.Liebe, A.Howard, "**Fuzzy Image Processing in Sun Sensor**", to appear in proceedings of 10th IEEE International Conference on Fuzzy Systems, Melbourne, Australia, 2-5 December 2001

Carl Christian Liebe, Sohrab Mobasser, Youngsam Bae, Chris J. Wrigley, Jeffrey R. Schroeder, Ayanna M. Howard, "**Micro Sun Sensor**", proceedings of the 2002 IEEE Aerospace Conference, Big Sky, Montana, 9-16 March 2002

# Resources & Interdependencies

## Synergy

| Sponsor Name | Start & End Dates | FY'02 $ | $ to Date | Competed |
|---|---|---|---|---|
| None | | | | |

## Team/Research Assets

None

## Links to Other Programs

- VIDI Active Pixel Sensor (JPL) developed under Code R and DoD
- Wireless camera board design (JPL)funded by DoD sponsor
- Formation flying thrust area funded by Codes R and Y

# Anticipated Products & Infusion Opportunities

| Technology Product | Current TRL | Final TRL/Date | Transition Opportunities |
|---|---|---|---|
| Micro Sun Sensor:<br>Accuracy: 0.02°<br>Size: 12 x 17 x 4 mm<br>Field-of-view: 128°<br>Mass: <8 grams<br>Power: 25 mW | 3-4 | 4/Sept 02 | Mars Safe Landing |

- Initial flight qualification study
- Include micro processor in the package to calculate and output sun angles autonomously
- Explore other applications (e.g. Formation flying)
- Getting baselined for a flight mission (e.g. Mars Safe Lander)

## Summary

- A micro sun sensor based on MEMS technology has been developed
- MEMS mask consist of 500 micron thick silicon wafer coated with 570 A$^{o}$ chrome and 3000 Angstrom gold
- Image detector consists of APS camera on a chip
- Accuracy potential of 0.02 degrees
- Micro sun sensor is more than an order of magnitude miniaturized compared to state of the art sun sensors

# Piezoelectric MEMS Microvalve

EH Yang

# Motivation

**Micropropulsion will play a major role in many future, high-visibility space missions, such as**

– Interferometry/Constellation Missions (LISA, TPF, Planet Imager, Life Finder, MagCon, MAXIM Pathfinder, Stellar Imager, MAXIM)

– Space Inflatables, Microspacecraft

– Advanced Miniature Components for Conventional Spacecraft

Thrust levels and impulse bits of a micropropulsion system require the control of very small propellant flow rates. Microvalves will be required to control those flows.

Nominal Microvalve Requirements for Micropropulsion

- Leak Rate - 0.3 scc/hr He
- Differential Pressure - < 300 psia
- Actuation Speed - < 10 ms
- Power - < 1 W
- Package Weight - < 10 gms
- Temperature - -120 to +200 °C

# Motivation

- Current SOA Technologies:

  - COTS miniaturized valves ❍ mass/volume restriction, power consumption
  - MEMS valves ❍ leakage, pressure handling limitation
  - We need new microvalves to meet the micropropulsion requirements.

- Benefits and Applications:

  **JPL's piezoelectric microvalve technology is to provide small mass/volume, low leak, low power consumption, fast response, liquid compatibility**

  - Micropropulsion, Microcooler
  - Micro Fuel Cell/Bio Reactor, Micro HPLC, LIGA GC/MS
  - Inflatable Reflector for Picosat
  - Fluidic MEMS in general

# Challenge and Benchmark

## Challenges

• Key technical challenges: Bonding/assembly of *actuators and micro-components*; Microvalve housing ; Leak test at high pressures.

## Benchmark

• Other Competitive approaches

- Moog, Inc.: The valves consume 4W to open and 0.7 W to hold.
- VACCO: The valves consume 3 - 8W.
- Redwoods MEMS valve ❍ The valves are too slow (> 400 ms), consume 2 W.
- Typical MEMS valves: The valves are leaky or cannot operate at high pressure.

• Uniqueness

- For the first time, JPL's piezoelectric MEMS valve will provide small volume (< 0.5 $cm^2$), low leak (< 0.001 sccm @ 300 psi), low power consumption (< 1 W @ 10ms) , fast response (< 10ms), liquid compatibility.

# Schedule and Budget

Planned Deliverables (MEMS-Valve)

- **Year 1 (FY00)**
  - Actuated Micro Valve Structure (TRL - 2)
- **Year 2 (FY01)**
  - Low Pressure ( < 300 psi) Micro Valve (TRL - 3)
- **Year 3 (FY02)**
  - High Pressure (< 3000 psi) Micro Valve (TRL - 3)
  - High Pressure Mass Flow Controller (TRL - 3)

Major changes: **In Jan. 2001, the valve structure was redesigned to comply with the leak-tight, high pressure handling requirements for micropropulsions. A leak tight valve operation was successfully demonstrated!**

Deliverables

- FY01: **Actuated MEMS valve structure**
- FY02: **Leak tight MEMS valve**

Planned Deliverables (MEMS-Materials)

- **Year 1 (FY00)**
  - Deposit PZT film on substrates (TRL - 1)
- **Year 2 (FY01)**
  - Deposit PZT film on membrane substrates (TRL - 2)
- **Year 3 (FY02)**
  - Establish robust recipes (TRL - 3)

Major changes: **In Feb. 02, the objective was redirected to support the microvalve task. Thin film PZT was not beneficial for the high force actuation. Miniaturized, robust PZT actuators were custom-designed to achieve low power consumption.**

Deliverables

- FY01: **Actuator materials**
- FY02: **PZT actuators for microvalve**

# Schedule and Milestones for FY 02

| MILESTONE DELIVERY/PLANNED ACTIVITIES: | | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Re-evaluation of the task | | | | | | | | | | |
| 2 | Feasibility study for piezoelectric actuators and other actuation mechanism | | | | | | | | | | |
| 3 | The 2nd generation design (pressure balanced) for liquid valve | | | | | | | | | | |
| 4 | Modification of the 1st generation valve | | | | | | | | | | |
| 5 | Acquisition of actuation materials for the 2nd generation valves | | | | | | | | | | |
| 6 | Leak and actuation test of a 1st generation valve | | | | | | | | | | |
| 7 | Fabrication of the 2nd generation valves | | | | | | | | | | |
| 8 | New valve seat approach | | | | | | | | | | |
| 9 | Assembly and test - flow test with 2nd generation structures | | | | | | | | | | |

Planned Start
Planned Completion
Planned Activity
Actual Start
Actual Completion
Actual Activity

# Budget

## MEMS Valve

- Actual Budget for last 2 years:
  FY00: $250k, FY01: $250k.
- Plans vs. **Actual** for this year: $46K vs. **$66K**

## MEMS Actuator Materials

- Actual Budget for last 2 years:
  FY00: $89k, FY01: $150k.
- Plans vs. **Actual** for this year: $3.3K vs. **$18K**

## Accomplishments to Date

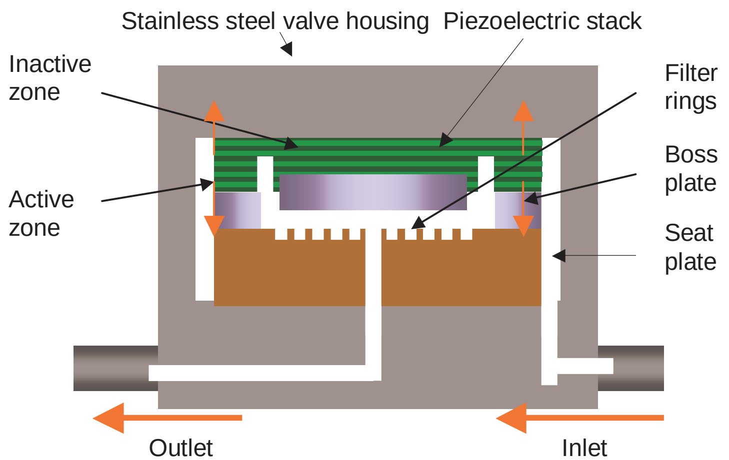
1. The fabricated 1st generation valve components have been assembled and tested. The leak testing of a zero powered valve showed a promising result with an extremely low leak rate (undetectable @ 0 ~ 500 psig). Successful piezoelectric actuations were also demonstrated. The tested valve was piezoelectrically opened and closed at 500 psig before and after the leak tests without observable degradation.

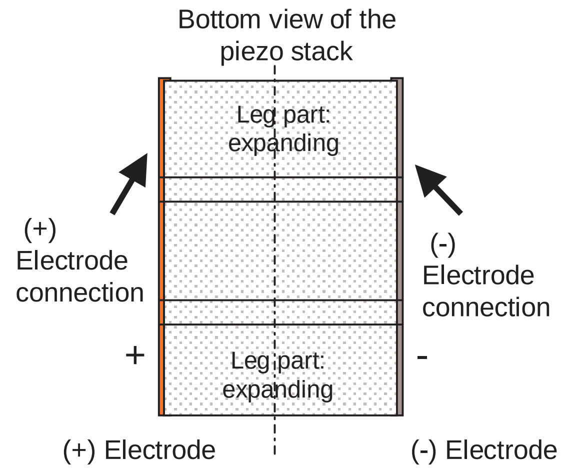
2. Link with COTS technologies: VACCO Inc; NDA is in place, we are working on generating TCA this week. VACCO is interested in producing piezo-type valve, so current JPL's piezo-valve concept is a good starting point to work with. It appears that we may initiate a joint effort to develop piezoelectric microvalves for commercial applications.

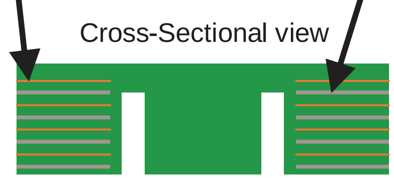
3. Custom-designed PZT actuators are small enough for MEMS valve: These PZT actuators are incorporated into the $2^{nd}$ generation valve designs.

4. PbZr1–*x*Ti*x*O3 films vs. Ir etching experiments resulted in the selectivity of 11:1 with BCl3:Cl2 = 10%:50%: Currently initiating collaboration with Penn State Univ. (Thick film PZT) for microvalve toward micro/nano fluidics.

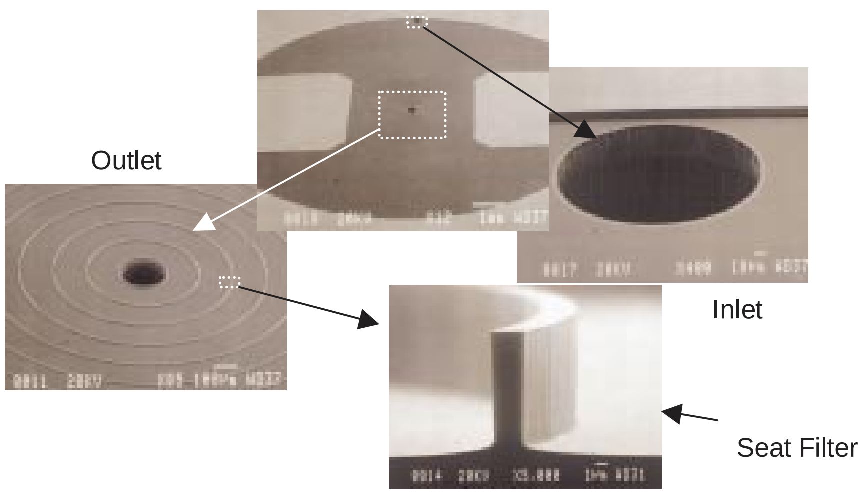
5. Four provisional patent applications were filed.

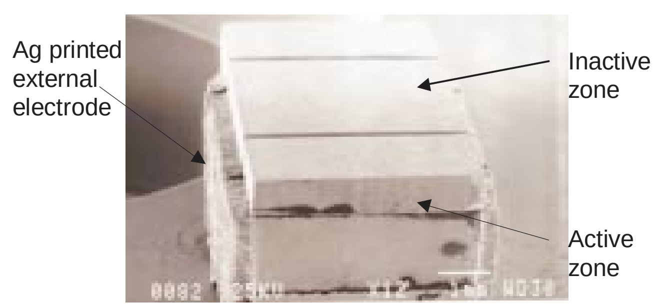


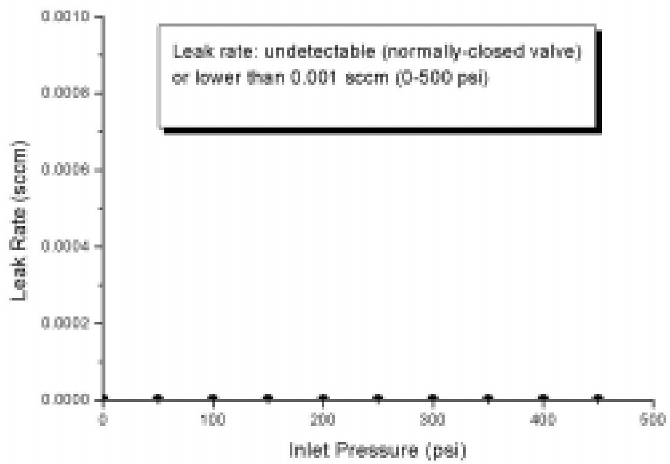



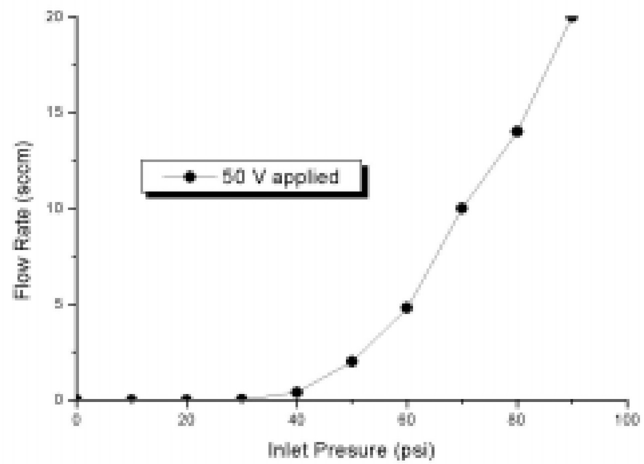

**Key features:**
- Seating
- Actuation
- Flow channel



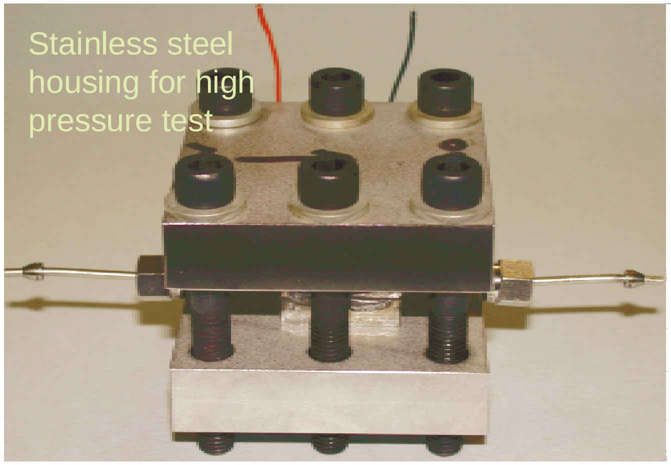
# Undetectable Leak




Leak < 0.001 sccm @ 0 ~ 500 psig: Normally Closed

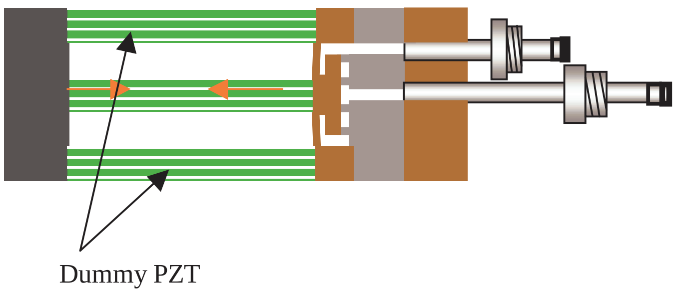
Piezoelectric valve operation was successfully demonstrated.

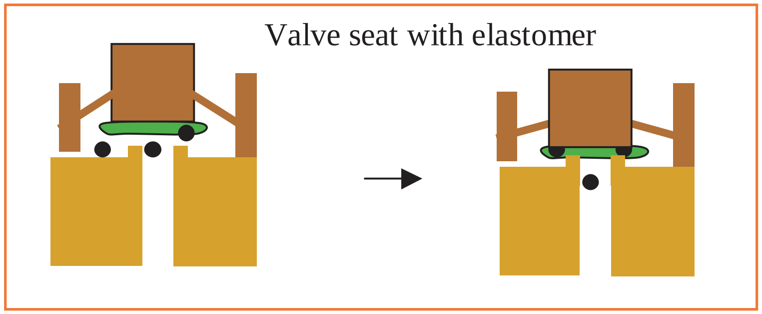


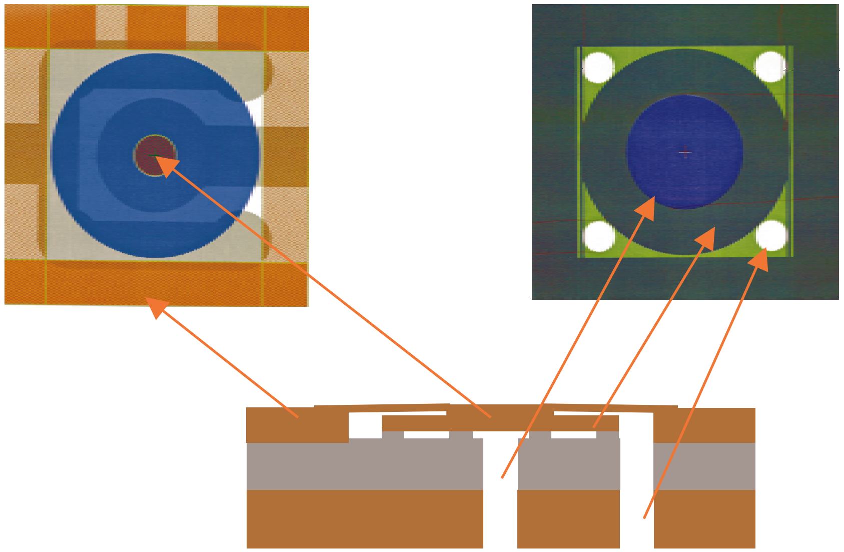

**What's new?**

- Incorporation of miniaturized custom-designed piezoelectric stack for lower power consumption.
- Pressure balanced design with elastomer seats for liquid effluents.

- Linear stack (**0.9 mm x 0.9 mm x 10 mm**)
- Free stroke of 8 µm @ 100 V
- Block force of 100N
- Power consumption < 0.9 W @ 100 Hz
- Valve volume: 2 mm x 4 mm x 12 mm



# Publications and Patents

- Relevant publications

(POC: EH Yang)

**- E. H. Yang, "Piezoelectric microvalves for micropropulsions,"** ***ASME International Mechanical Engineering Congress and Exposition,*** **Orlando, FL, November 2002 to be presented.**

**- E. H. Yang, Nishant Rohatgi and Larry Wild, "A piezoelectric microvalve for micropropulsions,"** ***AIAA Conference on Nanotech 2002 - "At the Edge of Revolution"*** **Houston, Texas, 9 - 12 Sep 2002 to be presented.**

**- E.H.Yang and Larry Wild and Nishant Rohatgi, "Improvements in a piezoelectrically actuated microvalve" NASA Tech Briefs, vol. 26, No. 1, p. 29.**

**- E.H.Yang and D. Bame, "Improved Piezoelectrically Actuated Microvalve" NASA Tech Briefs, vol. 26, No. 3, p. 75.**

**- E. H. Yang, "Variable Control MEMS Valve for Gas/Liquid Systems,"** ***EXPLORER WORKSHOP,*** **Washington, DC, March 12, 2002.**

(POC: Indrani Chakraborty)

**- Indrani Chakraborty** ***et al.,*** **"MEMS Micro Valve for Space Applications",** ***Transducers '99,*** **Sendai, Japan, June 7-10, 1999,**

**- Indrani Chakraborty** ***et al.,*** **"MEMS Micro Valve for Space Applications",** ***AIAA Space Technology Conference,*** **Albuquerque, New Mexico, September 28-30, 1999,**

**- Indrani Chakraborty** ***et al.,*** **"MEMS Micro Valve for Space Applications",** ***45th American Vacuum Society Meeting,*** **Seattle, Washington, October 25-29, 1999**

# Publications and Patents

- Provisional patent applications (POC: EH Yang)

  **- E.H. Yang, "A high stroke micro valve actuated by miniaturized piezoelectric bender actuator for miniaturized liquid systems with particulates" CIT-3632, filed for a provisional patent application by Caltech on 4/9/02**

  **- E.H. Yang, "An improved design of micro valve actuated by miniaturized piezoelectric stack for high pressure liquid system applications" CIT-3631, filed for a provisional patent application by Caltech on 4/9/02**

  **- E-H Yang and Larry Wild, "A reactive ion etch process for the high selective patterning of PZT capacitor films" CIT-3545, filed for a provisional patent application by Caltech on10/05/01**

  **- E.H. Yang, Larry Wild, Nishant Rohatgi and David Bame, "A micro valve for high pressure applications", CIT-3521, filed for a provisional patent application by Caltech on 8/16/01**

- Relevant NTRs (POC: EH Yang)

  **- E.H. Yang, "A high stroke micro valve actuated by miniaturized piezoelectric bender actuator for miniaturized liquid systems with particulates" (NPO-30563)**

  **- E.H. Yang, "An improved design of micro valve actuated by miniaturized piezoelectric stack for high pressure liquid system applications " (NPO-30562)**

  **- E-H Yang and Larry Wild, "A reactive ion etch process for the high selective patterning of PZT capacitor films" (NPO-30349)**

  **- E.H.Yang and Larry Wild and Nishant Rohatgi, "Improvements in a piezoelectrically actuated microvalve" (NPO-30338)**

  **- E.H.Yang and D. Bame, "Improved Piezoelectrically Actuated Microvalve" (NPO-30158)**

# Resources & Interdependencies

## Synergy

• VACCO (POC: Joe Cardin) is interested in producing piezo-type valve, so current JPL's piezoelectric valve concept is a good starting point to work with. It appears that we may initiate a joint effort to develop piezoelectric microvalves for commercial applications.

• Many other research groups have expressed interests in JPL's micro valve technology. The interested parties include Mark Crockett at Applied Materials, Bob Reinke at Moog Inc., Konstantine Penanen at UC Berkeley Physics lab, Daniel Schenck at Caltech, Giulio Manzoni at Mechatronic GmbH, Austria, Luke Lee at UC Berkeley, and Susan Troiler-Mckinstry at Penn. State University. In the near future, we will work on joint proposals for NIH, DARPA, NRA and STTR, which may need the incorporation of micro-valves and pumps.

• Currently available synergistic projects include the micro edge actuator development (Gossamer NRA) and the PZT membrane development (CfAO).

| **Sponsor Name** | **Start & End Dates** | **FY'02 $** | **$ to Date** | **Competed** |
|---|---|---|---|---|
| [CfAO] | [5/1/02 – 4/30/03] | [24] K$ | [0] K$ | [Yes] |
| [Gossamer NRA] | [2/4/02 – 9/30/02] | [113] K$ | [113] K$ | [ no] |

## Research Assets

[List of collaborators]

[Information on expertise/facilities that justify this work and strengths of collaborators]

- Dr. Juergen Mueller (JPL, 3534), Micropropulsion
- Dr. Daniel Choi (JPL, 3848), Nano fluidics valve survey, 0.01 FTE
- Mr. Joe Cardin at VACCO Industries Inc., Director, COTS valve (TCA being in place.)
- Dr. Gajanana C. Birur (JPL, 3530), Advanced thermal control system
- Dr. Mohammad Mojarradi (JPL, 3465), Voltage converter
- Prof. Susan Troiler-Mckinstry at Penn State Univ., Thick film PZT development (NDA being in place.)

## Links to Other Programs

This activity is independent with any other programs.

[Program or mission name and relevant information] None.

# Anticipated Products & Infusion Opportunities

| Technology Product | Current TRL | Final TRL/Date | Transition Opportunities |
|---|---|---|---|
| [Product/capability description] | [TRL] | [TRL/Date] | [Program or mission that might pick it up] |
| Low leak (< 0.001 sccm), fast response (< 10ms), low power consumption (< 1W) microvalve | 2 | 3 / 9/30/02 | - Micropropulsion (10 Kg Craft)<br>- Picosat<br>- NMP<br>***In the future…..*** |

## Future Plans

- Functional tests of valve devices with driver circuits (1 Yr)
- High-pressure (< 300 psi) liquid mass flow controller (2 Yr)
- Low-power chemical, catalytic monopropellant test for micropropulsions (2 Yrs)
- Ultra-low leak (Helium leak detector level) micro valve development (3 Yrs)
- Fully integrated MEMS-valve modules (3 Yrs)

## Benefits

- Miniaturized, leak tight, low power consumption, fast response valve
    - There are several customers in the micropropulsions and microfluidics area.

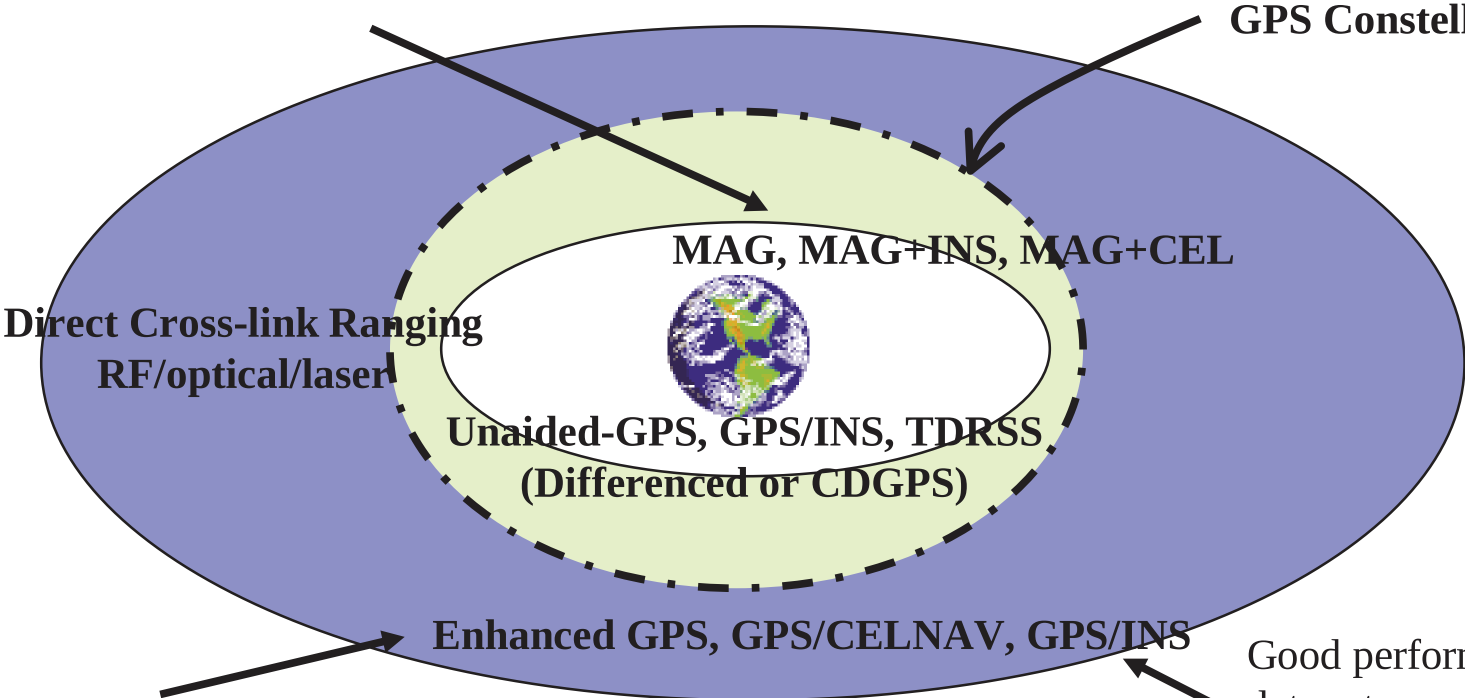
# Summary

- Small volume (< 0.5 $cm^2$), low leak (< 0.001 sccm @ 300 psi), low power consumption/fast response (< 1 W @ 10ms) valves are being developed.
- Leak rate of the fabricated valve was 0.001 sccm or undetectable at the nitrogen pressures of 0 ~ 500 psig. This valve was successfully actuated (opened and closed) during the operations from 0 to 500 psi without observable degradation.
- VACCO is interested in commercializing piezo-type valve. We are generating the TCA to work together based on JPL's piezoelectric microvalve concept.
- The success of this project will open several doors to future micropropulsions and other microfluidics applications for NASA.

# Relative Navigation

Low-cost approaches

GPS Constellation




Good performance at high data rates

Enhanced receivers with integrated filter and tracking loops, weak signal acquisition and tracking capability.

CELNAV, WFE sensing

Use sensors already on-board for attitude, safe-hold, etc.

Perhaps the only means of achieving “optical quality” figure errors of formations

# Wide dynamic range and fine resolution: formation modes

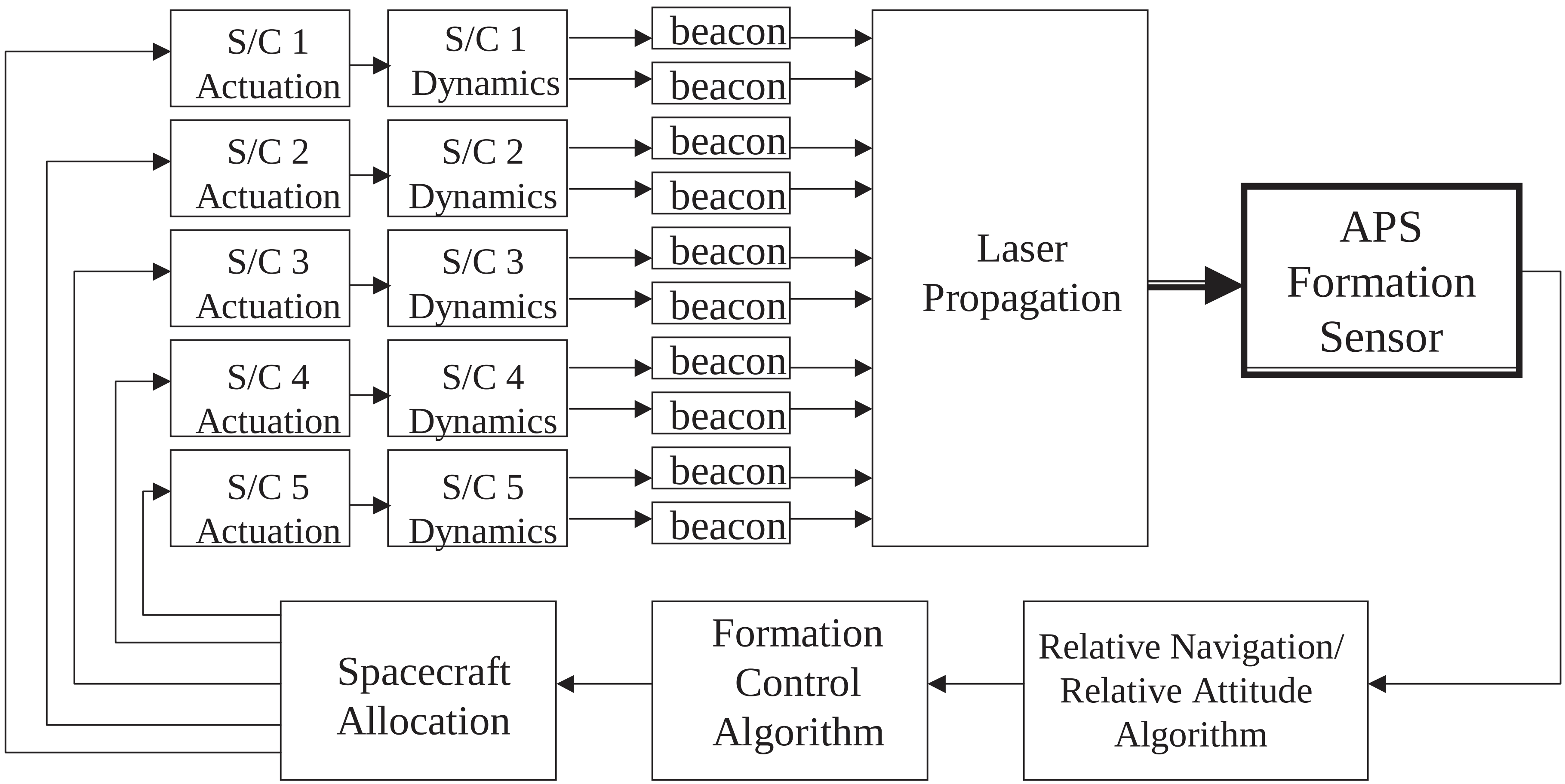
- **Lost-in-space/initial insertion**
- **Coarse vehicle placement**
- **Coarse vehicle orientation**

} GN&C

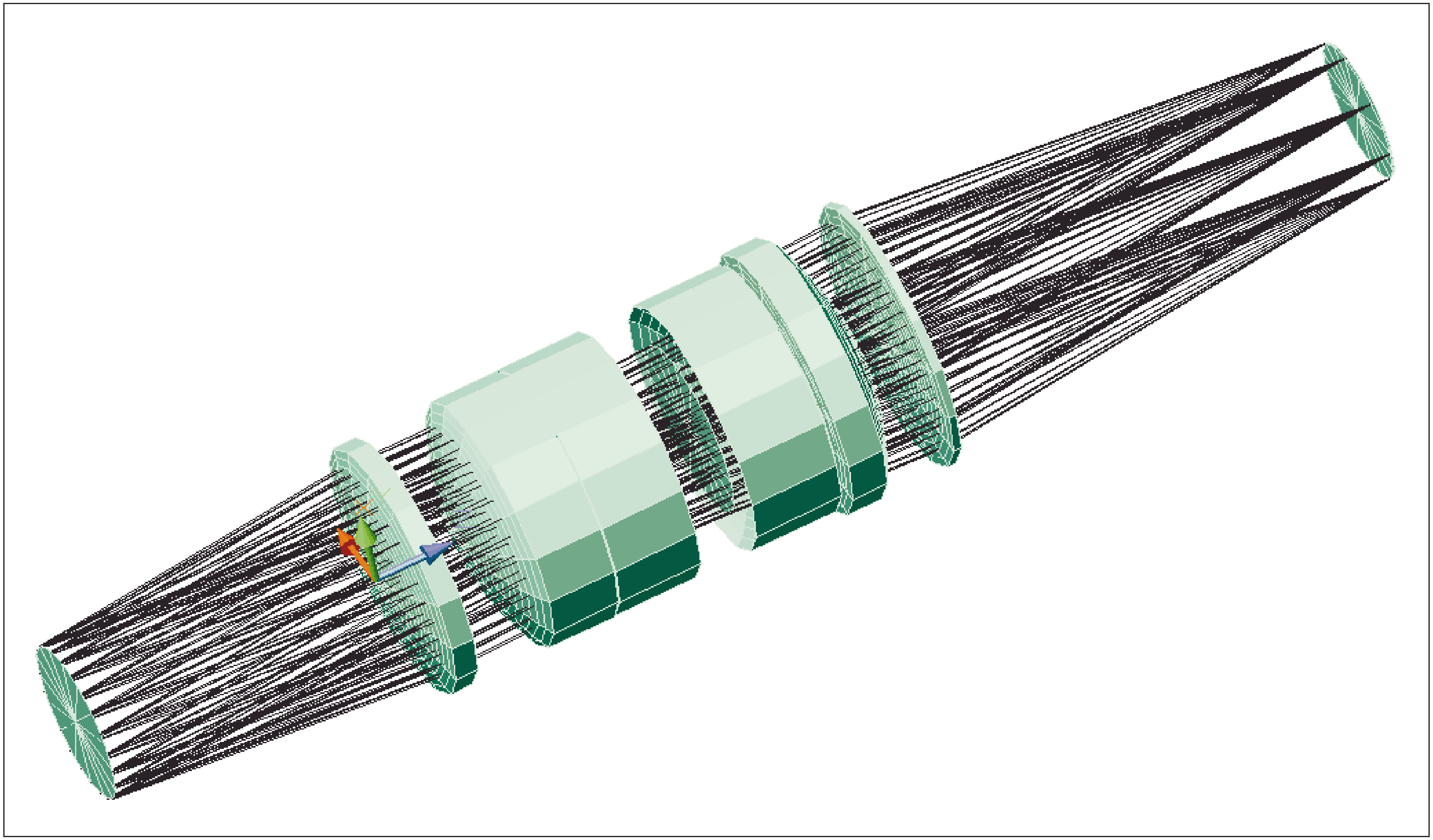
- **Formation initialization**
  - VISNAV/CCD/modified star tracker (25 mm lateral motions)
  - 3 color laser interferometer (10 nm distance from hub)
  - Star trackers on mirror-craft all tracking same guide star (as)
- **Capture**
  - mirrorcraft-to-mirrorcraft laser ranging required to get from 25 mm to 50 micron measurement accuracy
  - Other handoff values must be determined by ISAL analysis based partially on dynamic range of wavefront error sensing approach.
- **Calibration (backing out system parameters)**
- **Maintenance**
  - Real-time wavefront error sensing (e.g., phase diversity)
  - Mirror motion control
  - Continuous feep counterbalance on spacecraft

# Coarse Formation Alignment Block Diagram

## (5 S/C example)



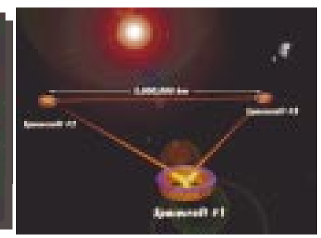
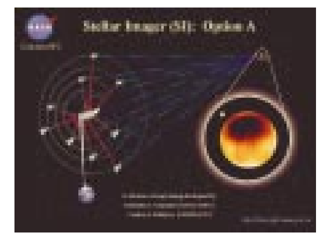
# APS AutoCAD 3D Model



# The Large Aperture Sensing Spectrum

## *What's best, connected or freeflying?*

**Extremely Challenging Dynamics!**

| Hubble | NGST | UltraLITE | SPECS | LISA | Stellar Imager |
|---|---|---|---|---|---|
|  |  |  |  |  |  |
| Monolithic | Deployable Filled | Deployable Sparse | Tethered Formations | Hybrid Formations | Freeflyer Formations |

**Rigidity**
**Large and heavy**
**Absolute Resolution Constraint**
**Near perfect large-scale manufacturing required**

**Controllability**
**Sensing extremely challenging**
**"Unconstrained Resolution"**
**Manufacturing requirements on smaller optics**