# Micro-Technology for Positioning, Navigation, and Timing Towards PNT Everywhere and Always

**Dr. Robert Lutwak**

**Program Manager**

Microsystems Technology Office

Defense Advanced Research Projects Agency

Stanford PNT Symposium

Stanford, CA

October 29, 2014

# Formed in 1958 to **PREVENT** and **CREATE** strategic surprise.

Capabilities, mission focused

Finite duration projects

Diverse performers

Multi-disciplinary approach…from
basic research to system engineering

We focus on high risk, high reward R&D
for national security

# DARPA Technical Offices

| BTO | DSO | I2O | MTO | STO | TTO |
|---|---|---|---|---|---|
| Biology, Technology & Complexity | Discover, Model, Design & Build | Information, Innovation & Cyber | Electronics, Photonics & MEMS | Networks, Cost Leverage & Adaptability | Weapons, Platforms & Space |
| **Restore and Maintain Warfighter Abilities** | **Physical Sciences** | **Cyber** | **Biological Platforms** | **Battle Mgmt, Command & Control** | **Air Systems** |
| **Harness Biological Systems** | **Mathematics Materials and Manufacturing** | **Data Analysis at Massive Scales** | **Computing** | **Comms & Networks** | **Ground Systems** |
| **Apply Biological Complexity at Scale** | **Autonomy** | **ISR Exploitation** | **Electronic Warfare** | **ISR** | **Marine Systems** |
| | **Science of Complexity** | | **Manufacturing** | **Electronic Warfare** | **Space Systems** |
| | | | **Novel Concepts** | **Positioning, Navigation and Timing** | |
| | | | **Photonics** | | |
| | | | **Positioning, Navigation and Timing** | | |
| | | | **Thermal Management** | | |

# DARPA PNT programs focused on reducing GPS reliance

## Achieve GPS-level timing and positioning performance without GPS

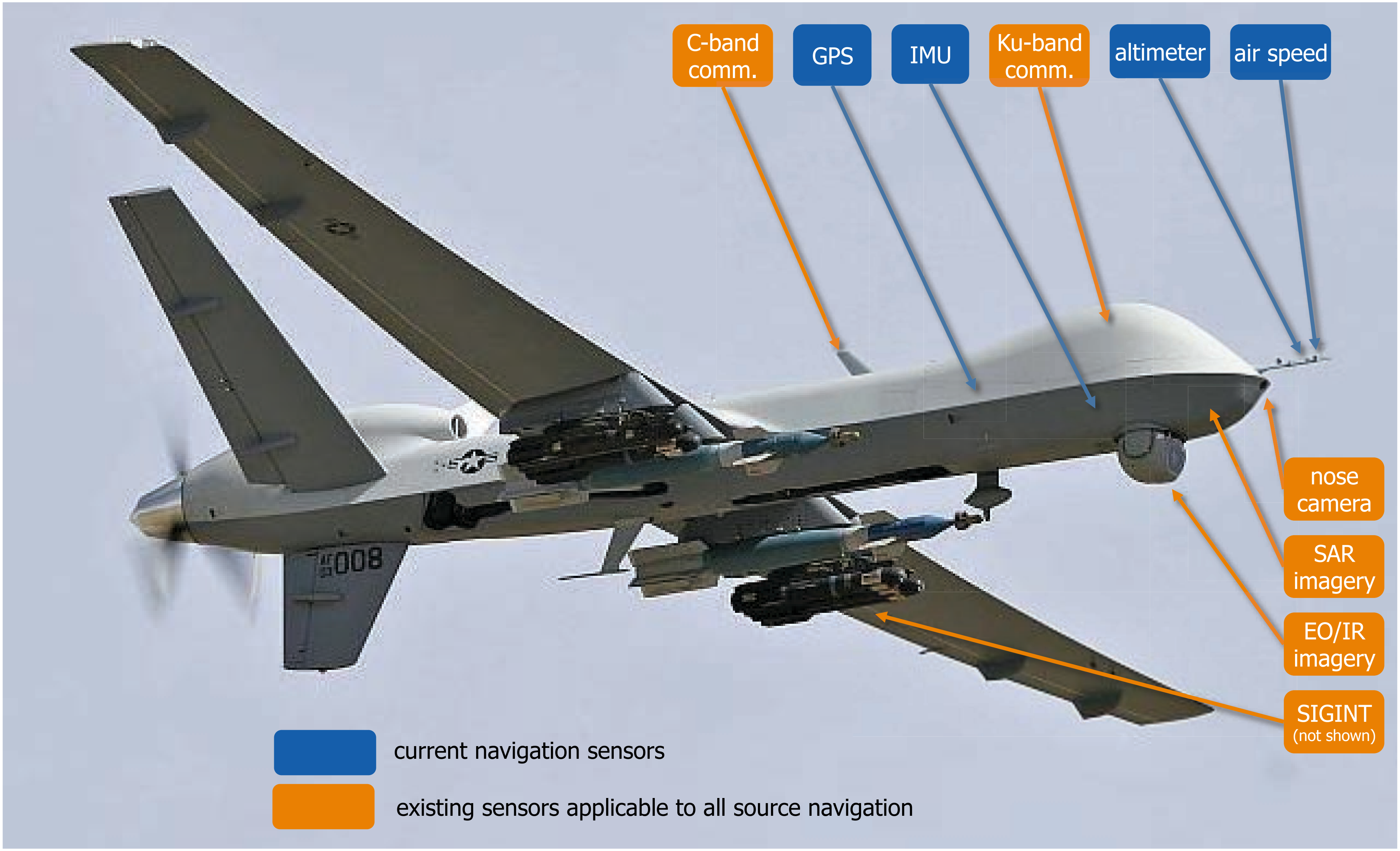
- Eliminate GPS as single point of failure
- Provide redundant capabilities and adaptable architectures
- Provide optimal PNT solution based on all available data sources

## Outperform GPS for disruptive capabilities

- Ultra-stable clocks (short and long term) for electronic warfare, ISR, and communications
- Persistent PNT in environments where GPS was never designed for use: undersea, underground, indoors
- High precision PNT for cooperative effects (distributed electronic warfare, distributed ISR, autonomous formation flying, time transfer to disadvantaged users)

| | |
|---|---|
| ISR | Intelligence, Surveillance, and Reconnaissance |

# Notional all source navigation



# Adaptable Navigation Sensors and Systems

## Global Navigation Satellite Systems

**Present:** **GPS, GLONASS, WAAS, EGNOS**

**Future: Galileo, BeiDou, QZSS, IRNSS**

## Other Sensors

**Present:** **Camera, pitot, altimeter, RADAR, magnetometer**, etc.

## Inertial Sensors

**Present: iFOG, RLG, MEMS**

**Future:** **PINS-HiDRA, TIMU C-SCAN, MRIG, PASCAL**

## Adaptable Navigation Systems

**Optimal solution algorithms**

**Plug-and-play architectures**

## Signals of Opportunity

**Future:** **Cell towers, SATCOM, Radio, TV, Lightning**, etc.

## Clocks

**Present: Cesium beam, Rubidium and quartz oscillators, CSAC**

**Future:** **QuASAR, IMPACT, MEMs**

Distributed and future-proof

# DARPA/MTO PNT Mission

**Program Objective:**

***Every thing knows where and when it is all of the time***

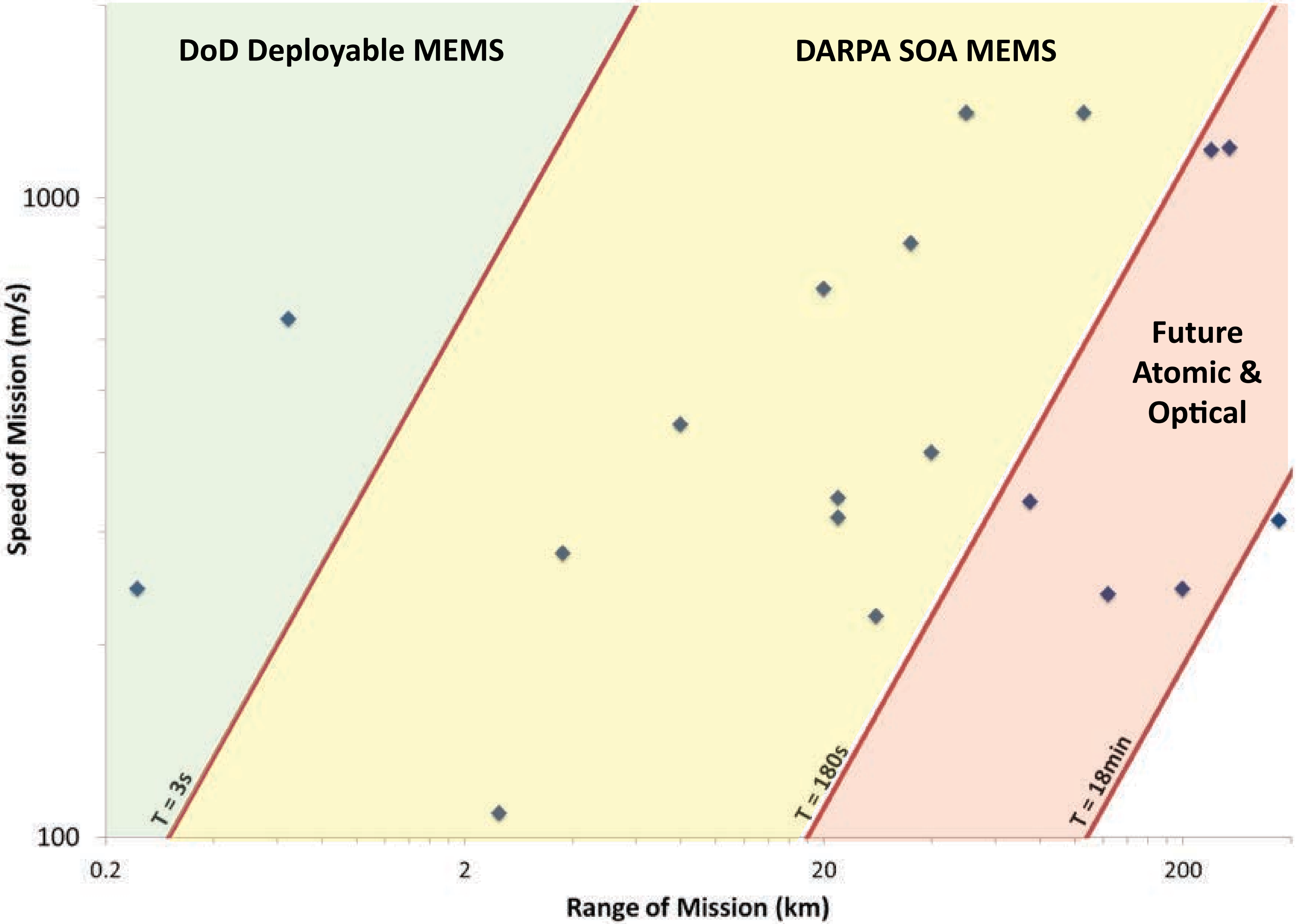
***"PNT Everywhere"***

© Wikimedia Commons
commons.wikimedia.org

- Specifically: Unaided navigation and timing error of 20 m and 1 $\mu$s at 1 hour
- Applications have requirements on Cost, Size, Weight, and Power (CSWaP)
- At present, we can meet performance requirements in an unmoving laboratory, with unlimited power, for about $1M.
- DARPA micro-PNT goal: 10 mm$^3$, 2g, 1W
- Where are the off-ramps?
  - For many platforms: 30,000 cm$^3$, 10 kg, 10 W, + $10,000
  - For most platforms: 1000 cm$^3$, 1 kg, 1W, + $1000.
  - For EVERY platform: 1 cm$^3$, 100 g, 100 mW, $100

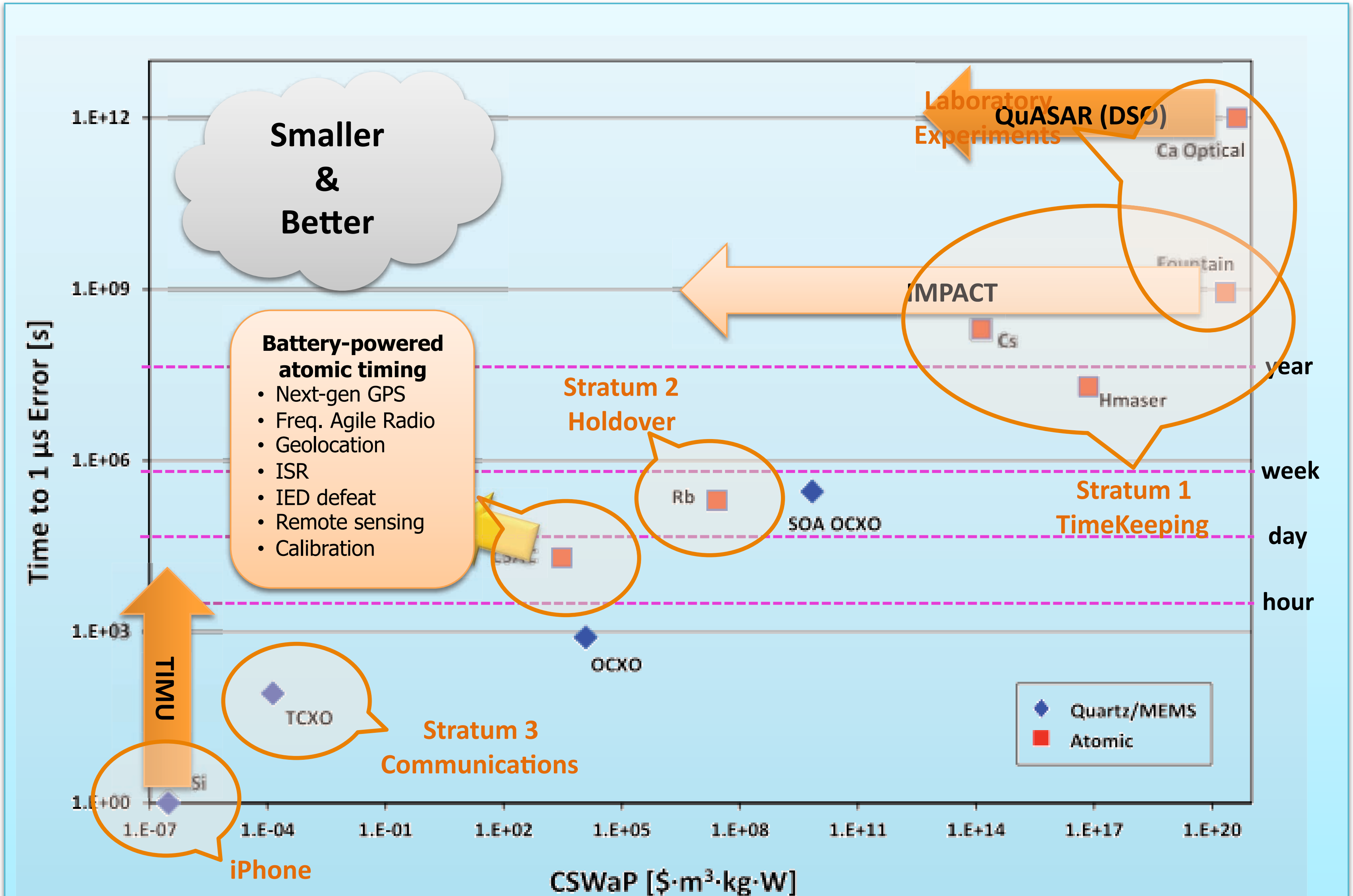
© Wikimedia Commons
commons.wikimedia.org

# DoD Munition Profiles

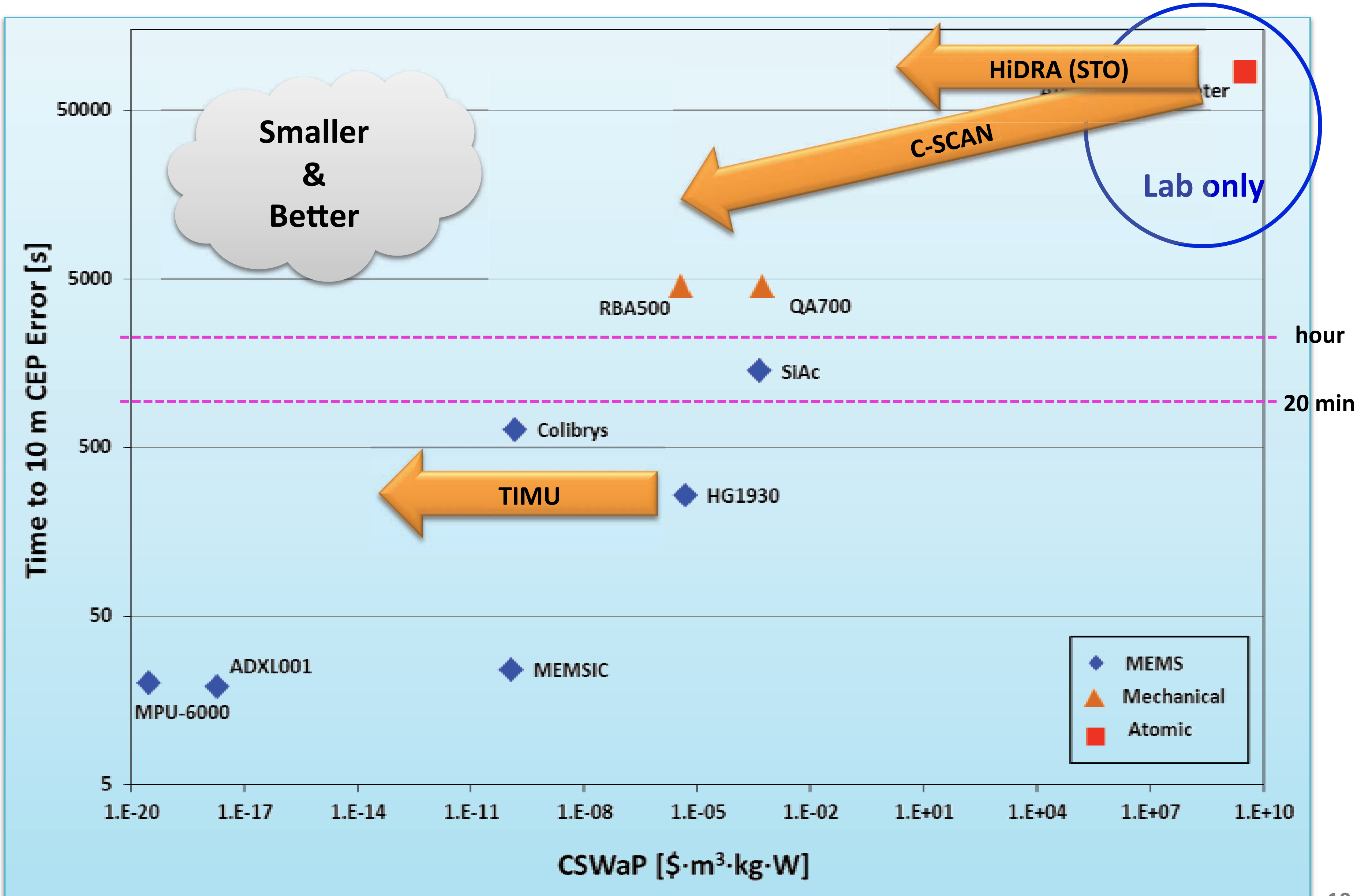



Source: http://en.wikipedia.org/wiki/List_of_active_missiles_of_the_United_States_military

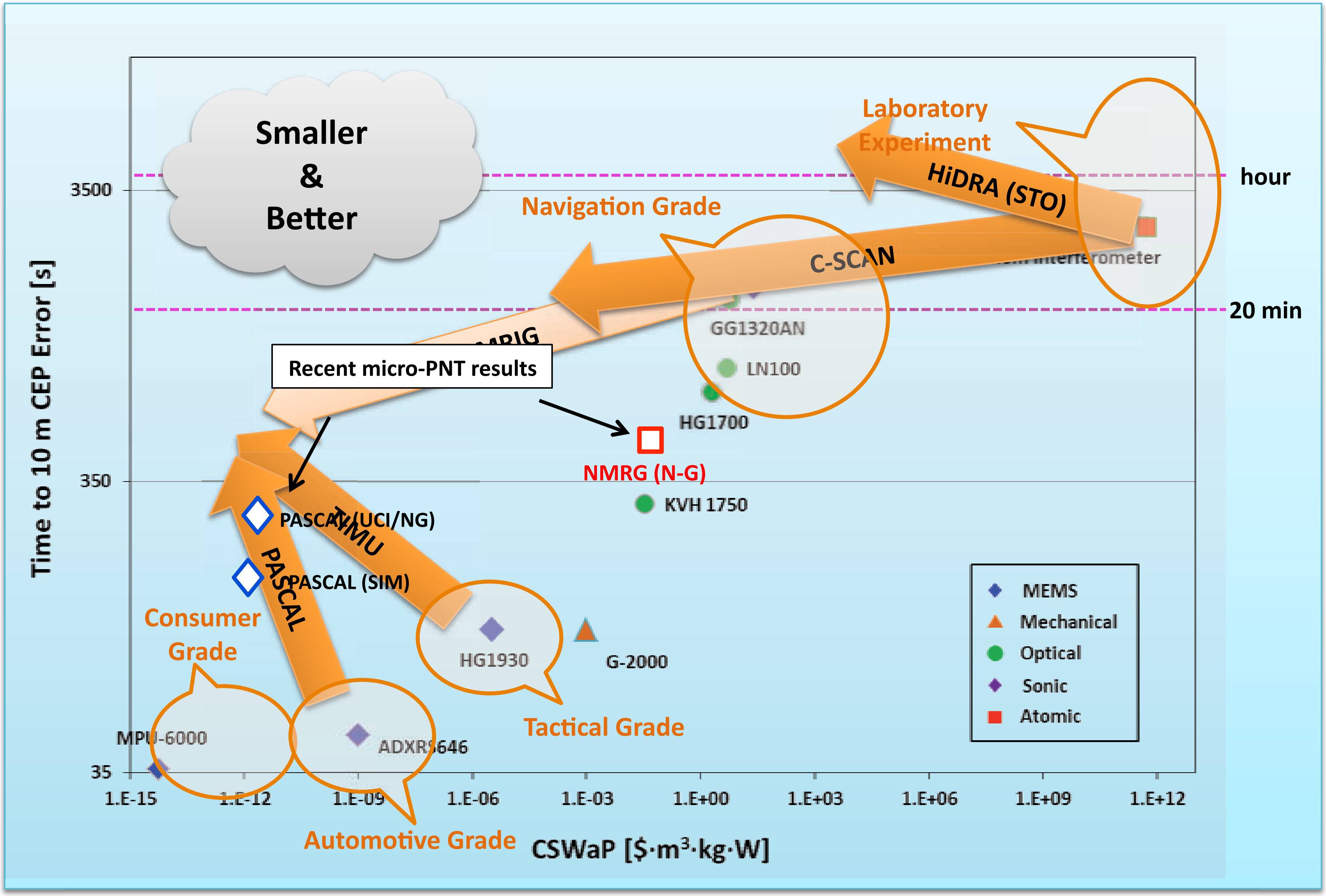
# DARPA Timing Programs



# SOA Accelerometers



# DARPA Gyroscope Programs



# Gyroscope Technology Gaps

- MEMS Gyroscopes (current micro-PNT efforts: PASCAL, MRIG, TIMU)
  - Super-low CSWaP (< \$50, < 1 $cm^3$, < 100 mW)
  - **Gap:** Performance, mostly bandwidth, calibration drift and temperature sensitivity

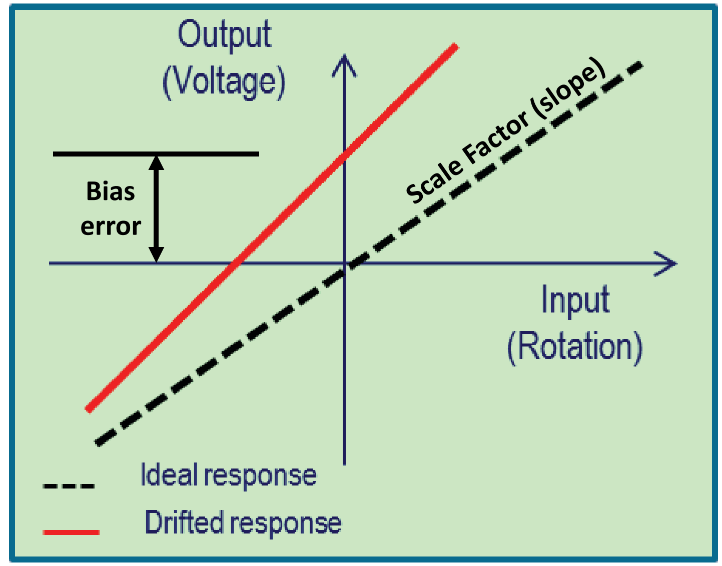
- Atomic Gyroscopes (current micro-PNT efforts: C-SCAN)
  - Superb stability and accuracy
  - Viable candidate for navigation in FY2030
  - **Gap:** Only lab demonstrations to date; enabling atomic physics components needed

- Optical Gyroscopes (e.g. RLG and iFOG)
  - Good stability and accuracy
  - Candidate technology for gyrocompassing
  - **Gap:** Cost and SWaP (\$25K, 500 $cm^3$, 2W); MEMS-based solution?

# Primary and Secondary Calibration on Active Layer

**PASCAL Objective:**
Realize MEMS inertial sensors with on-chip calibration to address long-term drift of bias and scale factor

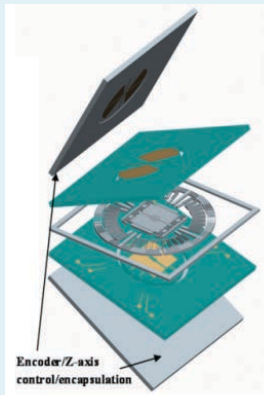
**Key challenges:**
- Co-fabrication of high-performance MEMS devices and calibration stages
- Calibrator calibration, numerous (tiny) moving parts
- “True” reversibility



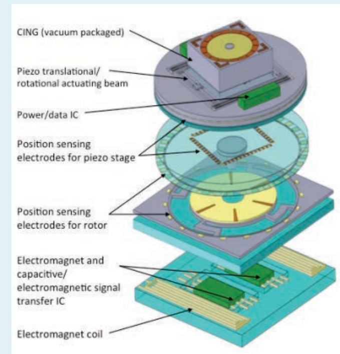

| PASCAL Metrics | Ph I | Ph II | End Goal |
|---|---|---|---|
| Volume [$mm^3$] | **30** | **30** | **30** |
| Bias stability (1 month) [ppm] | **100** | **10** | **1** |
| Scale factor stability (1 month) [ppm] | **100** | **10** | **1** |

# Approaches: Active Layer Stage (TA1)

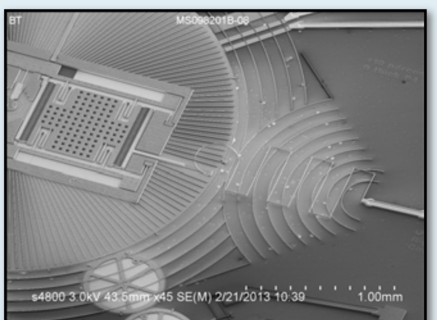
## External physical reference stimulus (dithering, maytagging, etc.)



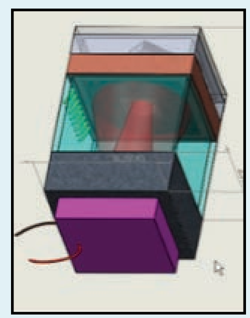

**Honeywell**
Dr. Grant Lodden




**University of Michigan**
Prof. Khalil Najafi

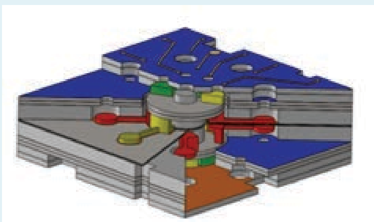
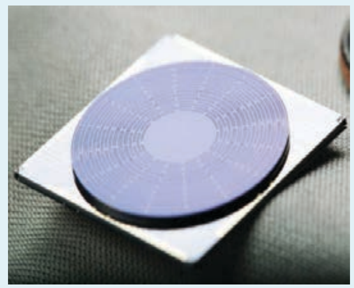
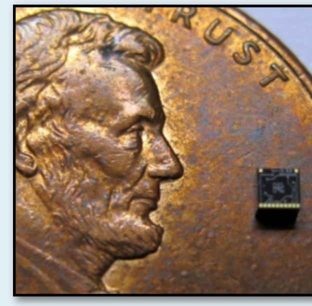
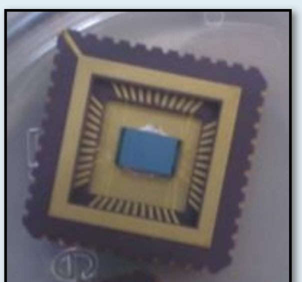
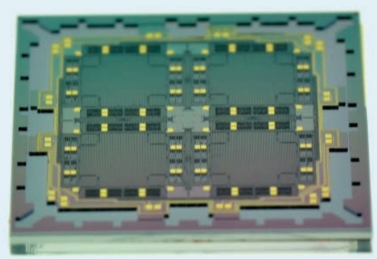
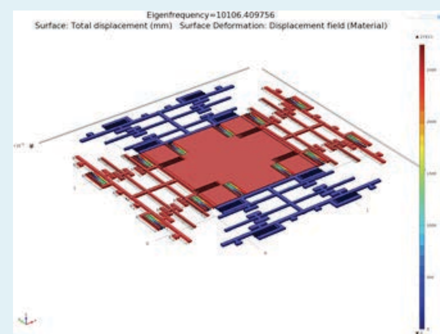


**Sandia National Labs/Draper Laboratory**
Dr. Murat Okandan

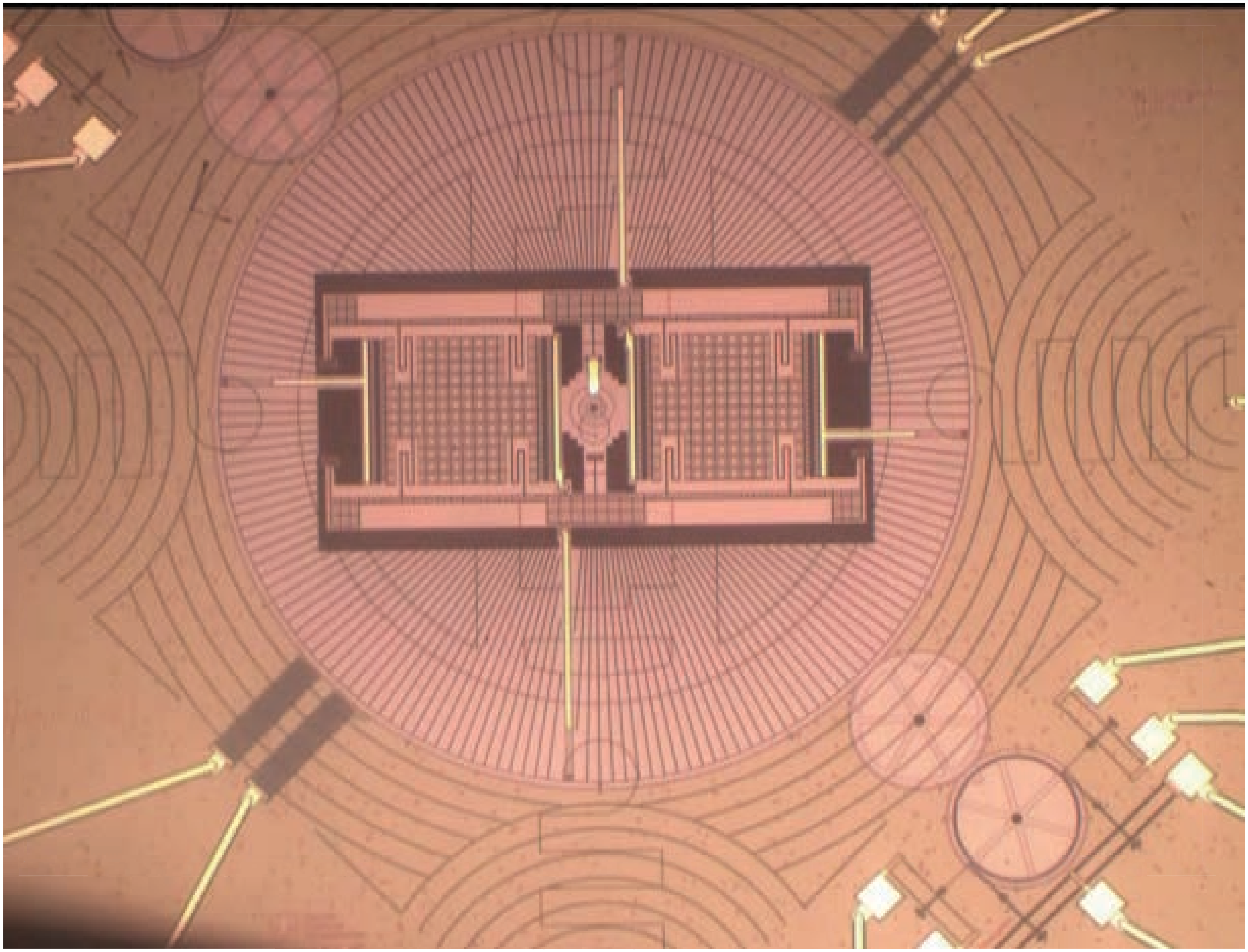


**Cornell University**
Prof. Amit Lal

# Approaches: Electronic Self-Calibration (TA2)

| Electronic interchange of drive/sense (detect and correct for mechanical change) | | |
|---|---|---|
|  |  |  |
| **PSU-ARL**<br>Mr. Terry Roszhart | **Sensors In Motion**<br>Dr. Kirill Shcheglov | **Georgia Tech**<br>Prof. Farrokh Ayazi |
|  |  |  |
| **UC Berkeley**<br>Prof. Bernhard Boser | **UC Irvine**<br>Prof. Andrei Shkel | **Carnegie Mellon**<br>Prof. Gary Fedder |

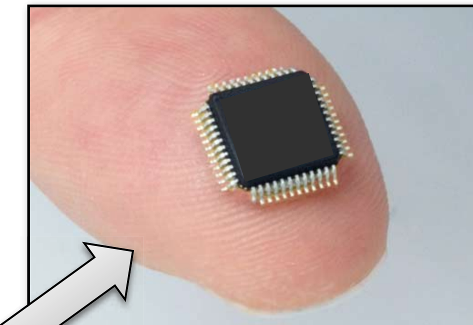
# Sandia/Draper MEMS Gyro + Active Layer Gimbal Rotation



# Single-chip Timing and Inertial Measurement Unit (TIMU)

**TIMU Objective:**
Fully-integrated co-fabricated 6-axis IMU for extraordinarily low CSWaP

**Key challenges:**
- Co-fabrication of high-performance MEMS inertial sensors
- Encapsulation requirements for gyros vs. accels
- Top-level yield

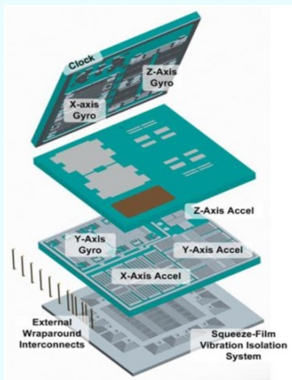


| TIMU Metrics | Phase I | Phase II | Phase III |
|---|---|---|---|
| Volume [$mm^3$] | **10** | **10** | **10** |
| IMU accuracy [CEP, nmi/hour] | **Oper.** | **10** | **1** |
| Timing accuracy [ns/min] | **Oper.** | **10** | **1** |
| Power [mW] (-55°C to +85°C) | **-** | **500** | **200** |

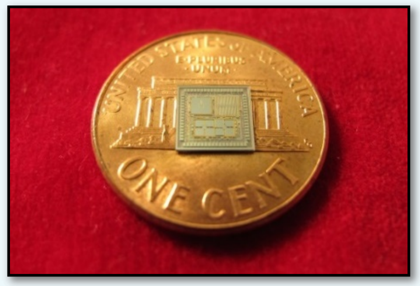
# Approaches

## Multi-layer (stacked die)

Honeywell
Dr. Bob Horning




University of Michigan
Prof. Khalil Najafi

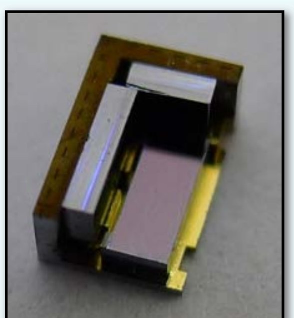



## Monolithic (single die)

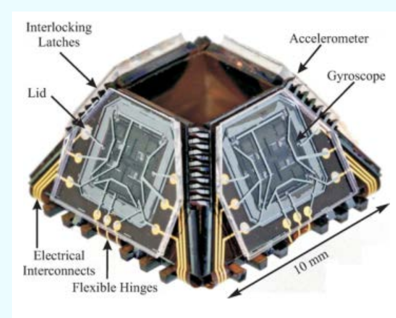
Georgia Tech
Prof. Farrokh Ayazi

## Three-Dimensional (folded, co-integrated)

Evigia
Dr. Navid Yazdi



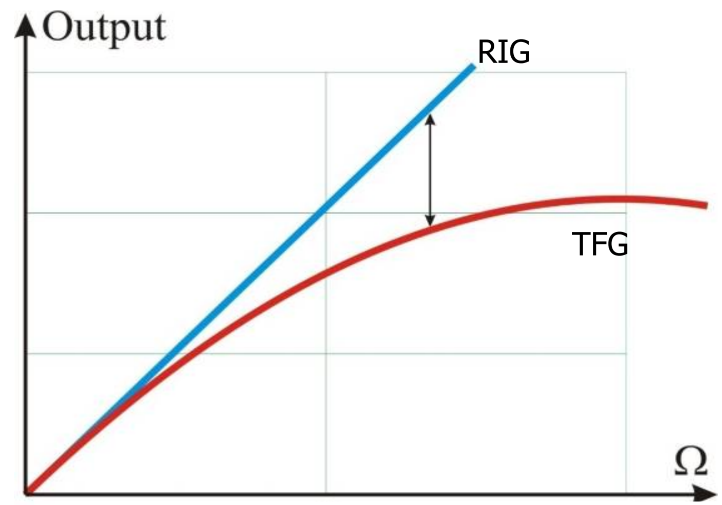
UC Irvine
Prof. Andrei Shkel



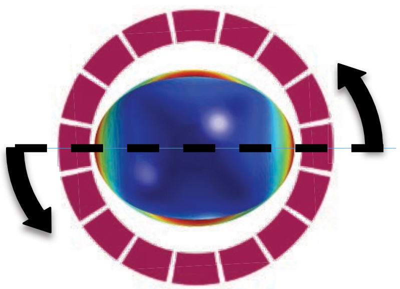
# Micro-Scale Rate-Integrating Gyroscope (MRIG)

**MRIG Objective:**
Micro-scale, high-performance, rate-integrating gyroscope for high-bandwidth high-accuracy inertial navigation

**Key Challenges:**
Fabrication of high-Q, high-symmetry MEMS devices

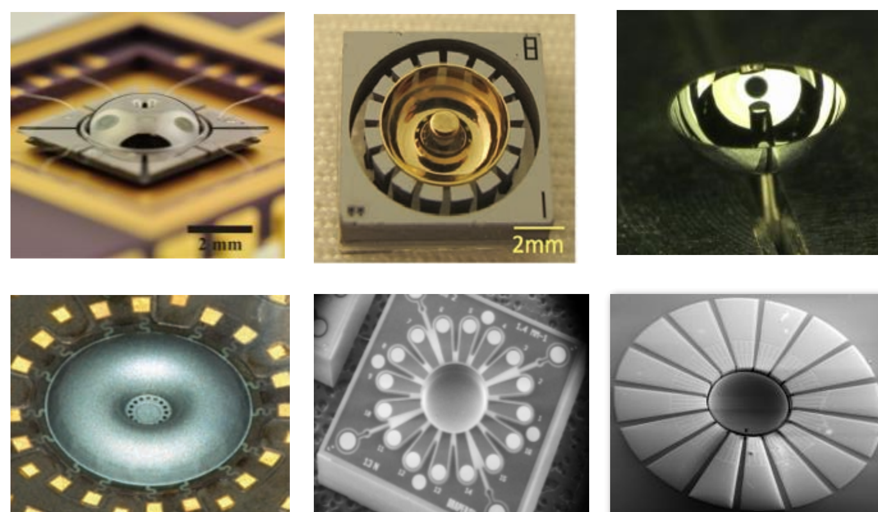



Northrop-Grumman
Hemispherical Resonator Gyroscope (HRG)
4W, 250 cm³, $100K



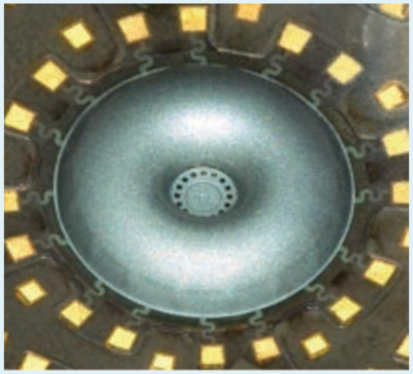
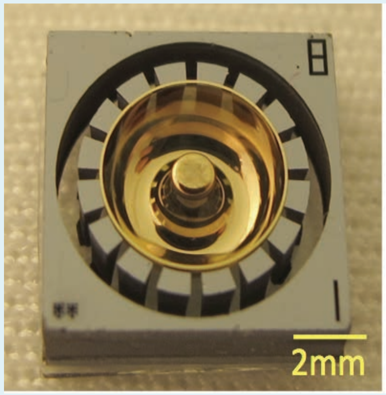
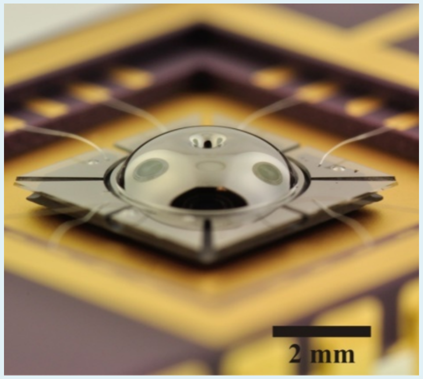
*Courtesy L. Sorenson, HRL*

**Novel 3-D MEMS**

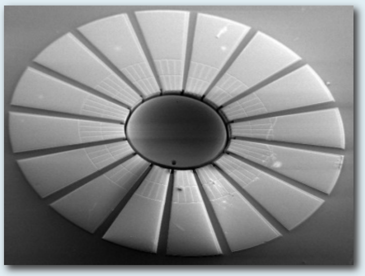
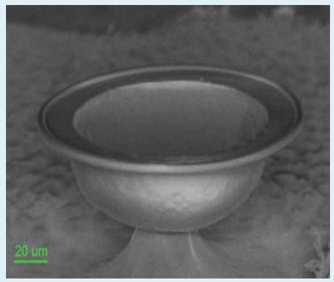
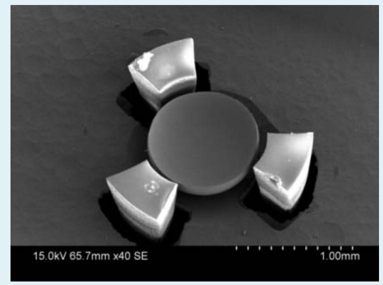
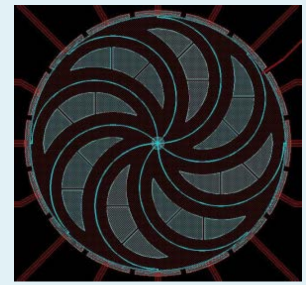
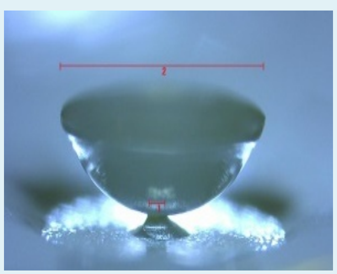
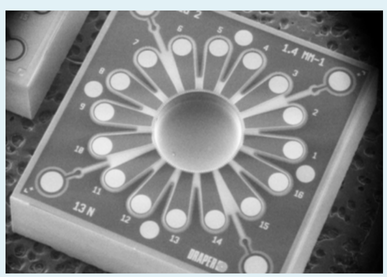
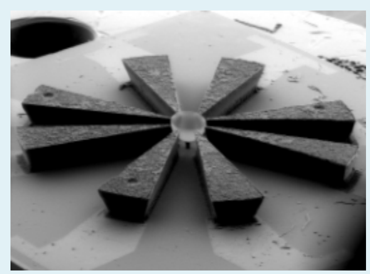
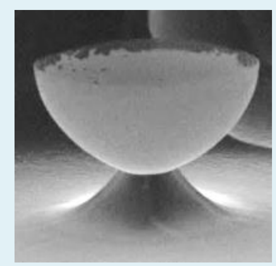



**MRIG Goals**
**100 mW, 1 cm³, $50**

# Approach: Surface Tension Processes

| CVD Diamond | Fused Silica |
|---|---|
| Honeywell (Dr. Burgess Johnson) | Univ. of Michigan (Prof. Khalil Najafi) |
|  |  |
| **Bulk Metallic Glass** | **ULE Glass** |
| Yale University (Prof. Jan Schroers) | UC Irvine (Prof. Andrei Shkel) |
|  |  |

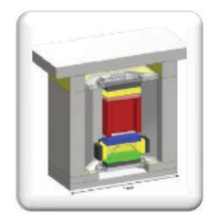
# Approach: Deposition on a Mold

| Silicon-Based | | Nickel Alloy | |
|---|---|---|---|
| Northrop / Ga Tech<br>D. Rozelle, Prof. F. Ayazi | Cornell University<br>Prof. Sunil Bhave | Northrop / Georgia Tech<br>D. Rozelle, Prof. F. Ayazi | GE Global Research<br>Christopher Keimel |
|  |  |  |  |
| **CVD Diamond** | | **ULE Glass** | **ALD $Al_2O_3$** |
| UC Davis<br>Prof. David Horsley | Draper Laboratory<br>Dr. Jon Bernstein | University of Utah<br>Prof. Carlos Mastrangelo | CU Boulder<br>Prof. Victor Bright |
|  |  |  |  |

# Atomic Gyroscopes

- **Similar to clocks, atoms make fabulous gyroscopes**
  - All atoms are the same
  - No manufacturing variance, minimal calibration drift
- **Chip-Scale Combinatorial Atomic Navigator (C-SCAN) Program**
  - Parallel pursuit of two physics architectures
    - Nuclear Magnetic Resonance Gyroscopes (NMRG)
      - Each atom is a tiny spinning-top gyroscope (but no bearing friction)
      - Under development since 1940's
      - New opportunity for practicality leveraging CSAC technology
    - Atom-Interferometric (AI) Gyroscopes
      - Similar to fiber-optic gyroscope (FOG) and ring-laser gyroscope (RLG)
      - Use *atom* waves rather than *light* waves
      - Provides both gyroscopy and accelerometry
      - STO PINS/HiDRA program targeting extra-super performance
      - MTO C-SCAN targeting great performance in low C-SWaP
  - **Technology gap:** Enabling atomic physics components
    - Nearly identical requirements as high-performance clocks, magnetometers, gravimeters, etc.

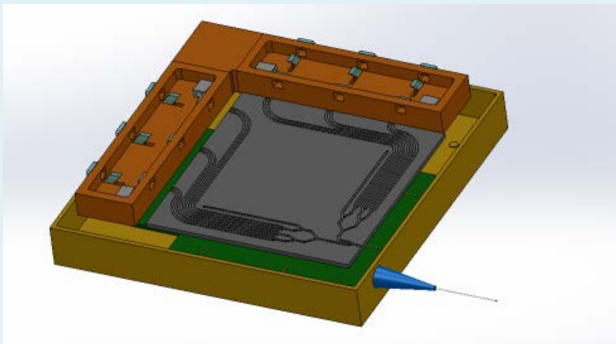
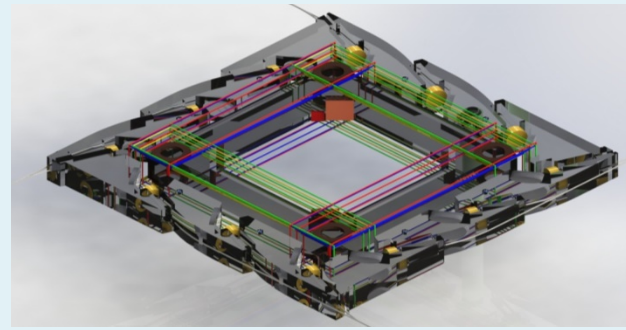
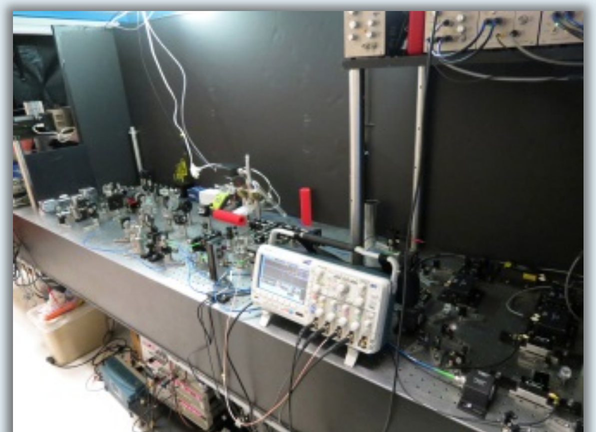
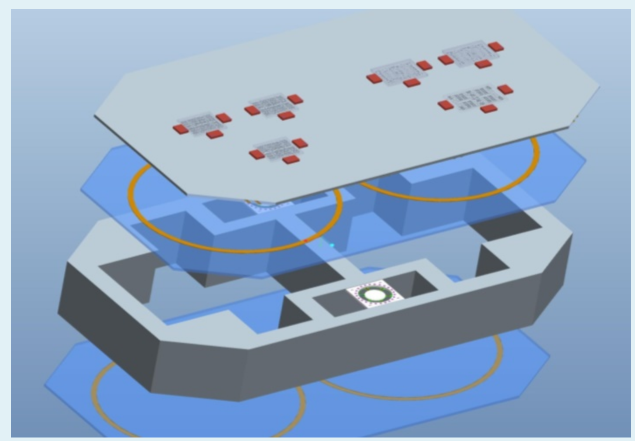
Northrop NMRG



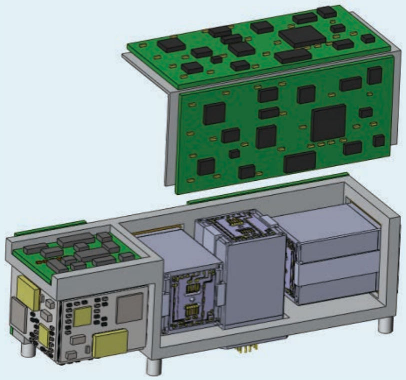
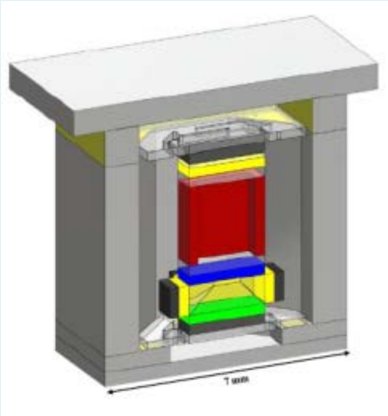
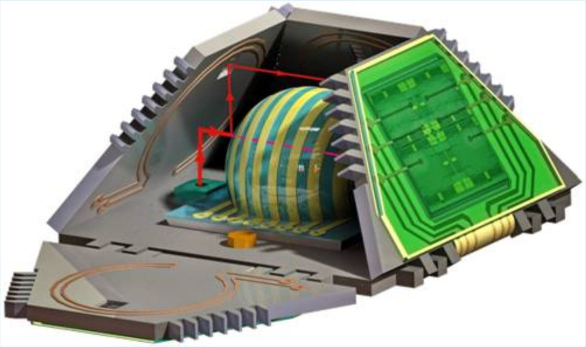
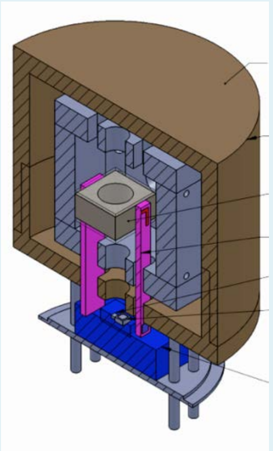
Microsemi NMRG (concept)


Draper AI (concept)

# Approach: Light Pulsed Atomic Interferometry

| AOsense<br>Dr. Matt Cashen | Draper Laboratory<br>Dr. David M. Johnson |
|---|---|
|  |  |
| Sandia National Labs<br>Dr. Grant Biedermann | Honeywell<br>Dr. Robert Compton |
|  |  |

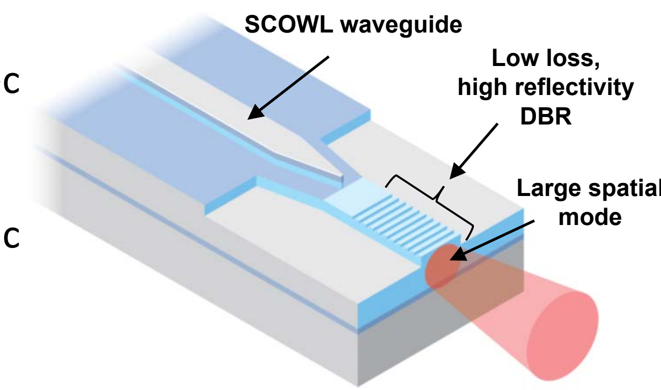
# Approach: Nuclear Magnetic Resonance

| Northrop Grumman<br>Dr. Mike Larsen | Microsemi<br>Dr. Richard Overstreet |
|---|---|
|  |  |
| UC Irvine<br>Prof. Andrei Shkel | Princeton University<br>Prof. Mike Romalis |
|  |  |

# Enabling Technology for Cold Atom Microsystems (CAMS)

**CAMS Objective:**
Laboratory experiments have demonstrated that laser-cooled atomic clocks and inertial sensors are capable of extraordinary performance.
Practical deployment of cold-atom sensors requires the development of enabling components.
CAMS is a collection of seedlings developing low-CSWaP atomic wavelength lasers, optical isolators, shutters, vacuum cells, alkali vapor pressure control, and frequency control techniques.

**Key Challenges:**
- Maintain lifetime vacuum levels of 1nT without magnets
- Stabilization of alkali vapor pressure across mil-spec temperature range
- Fast, large aperture, shutters with extinction ratio >70dB
- Stable, single-mode, narrow-linewidth lasers at atomic transition wavelengths
- *All at low-CSWaP*



# Thank you

*Robert.Lutwak@darpa.mil*