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

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Program Manager

Microsystems Technology Office
Defense Advanced Research Projects Agency

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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

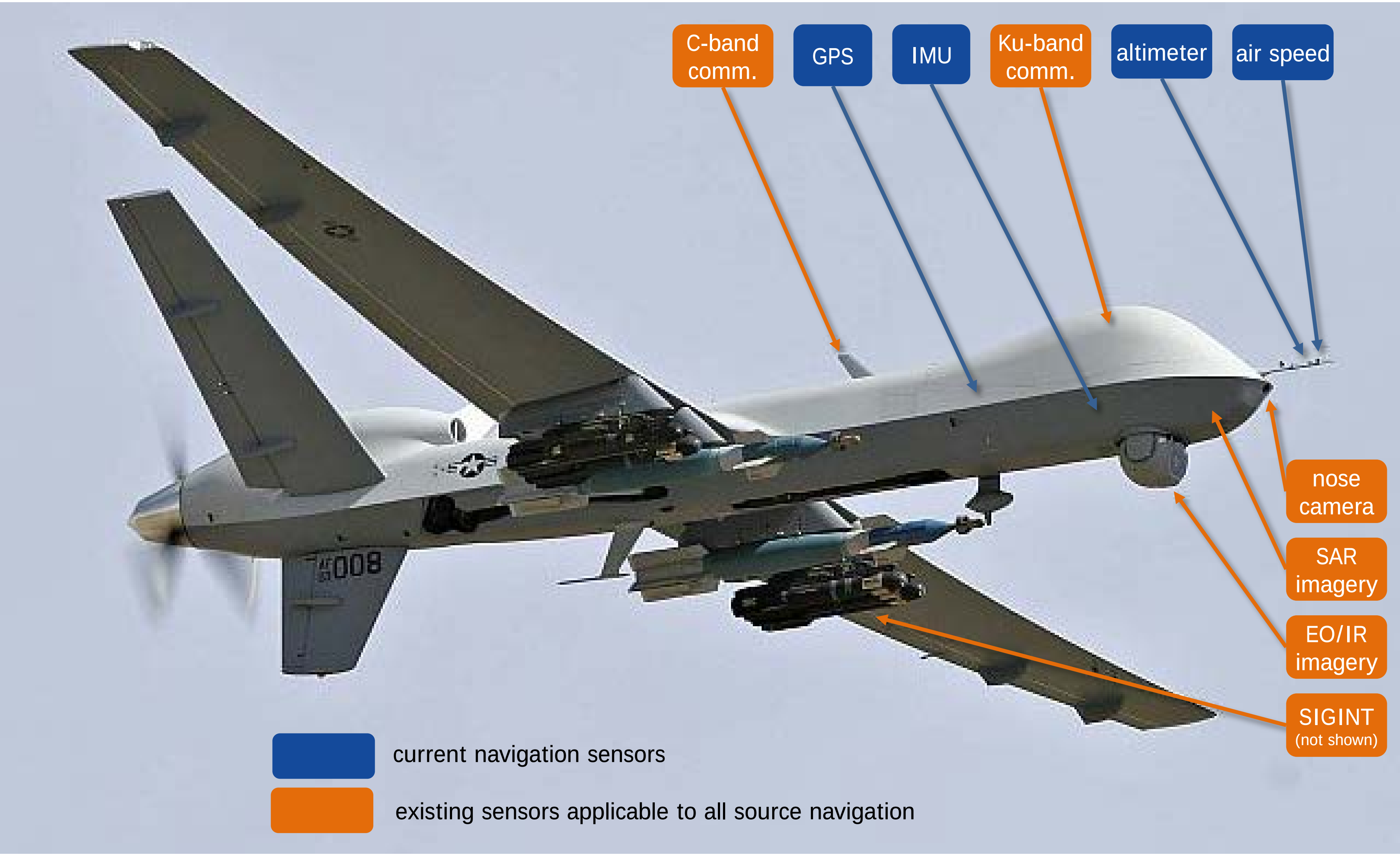
- Eliminate GPS as single point of failure
- Provide redundant capabilities and adaptable architectures
- Provide optimal PNT solution based on all available data sources

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

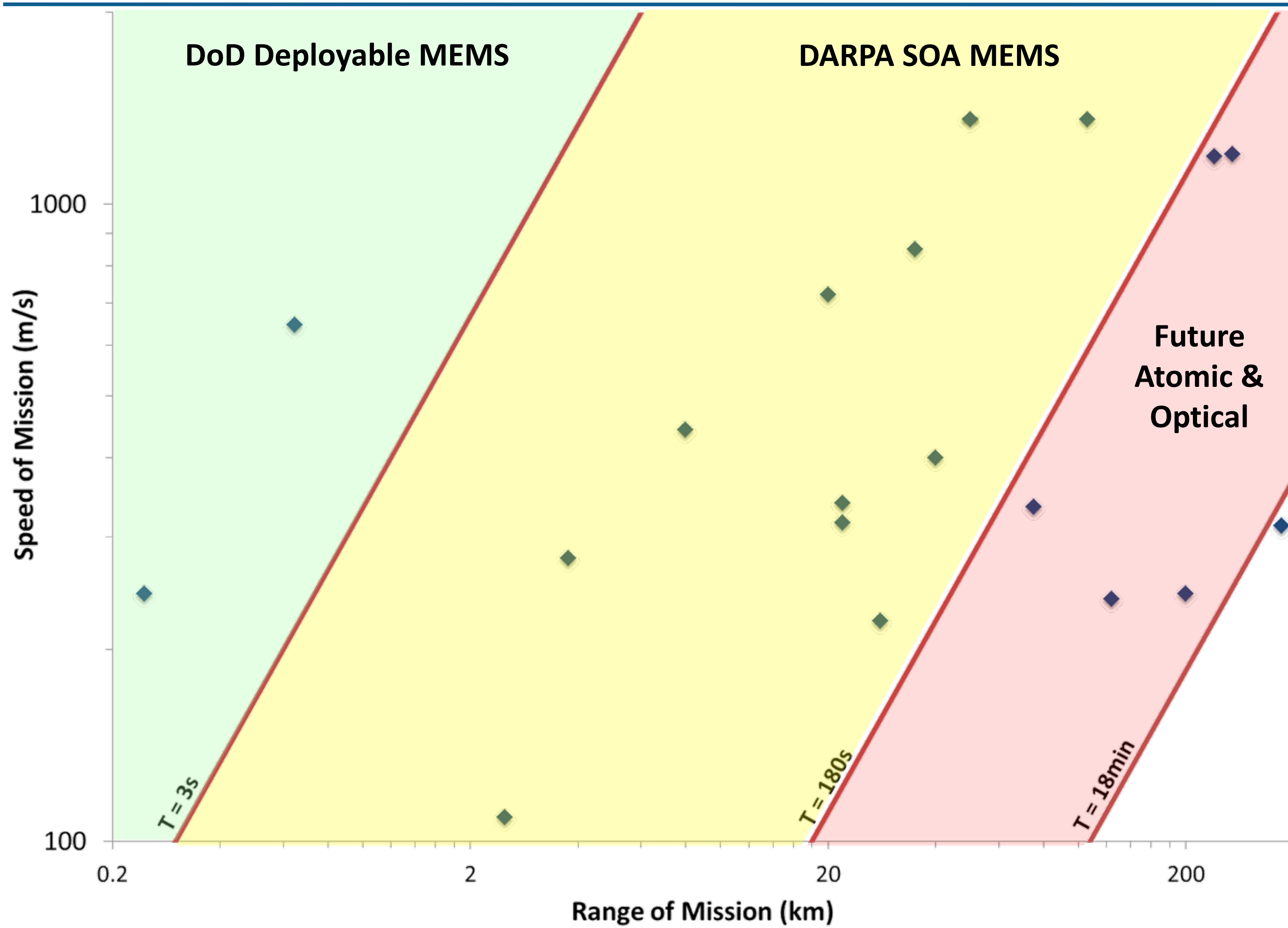
Program Objective:

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

"PNT Everywhere"

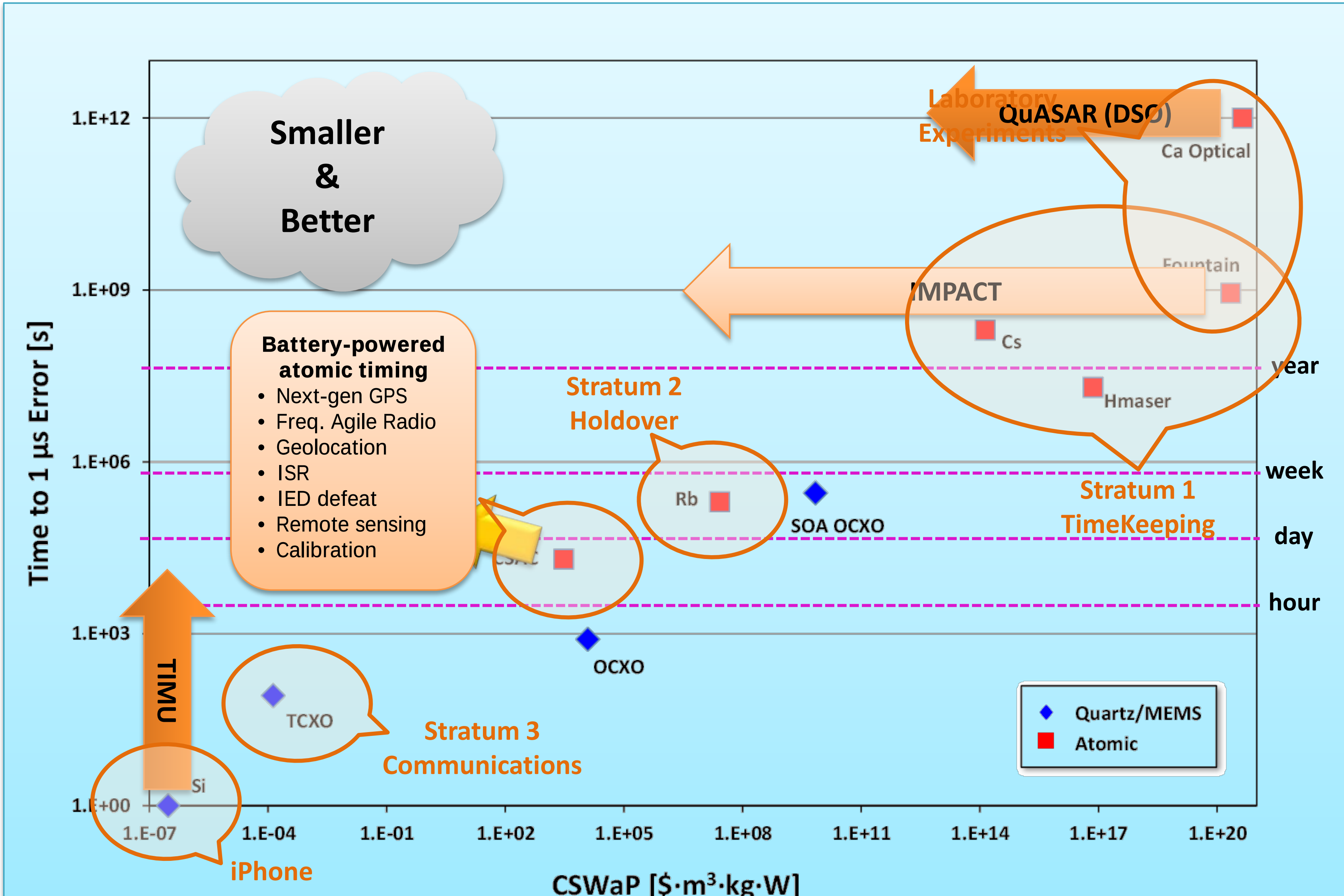
- Specifically: Unaided navigation and timing error of 20 m and 1 μs at 1 hour
- Applications have requirements on Cost, Size, Weight, and Power (CSWaP)
- At present, we can meet performance requirements in an unmoving laboratory, with unlimited power, for about $1M.
- DARPA micro-PNT goal: 10 mm^3, 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

DoD Munition Profiles

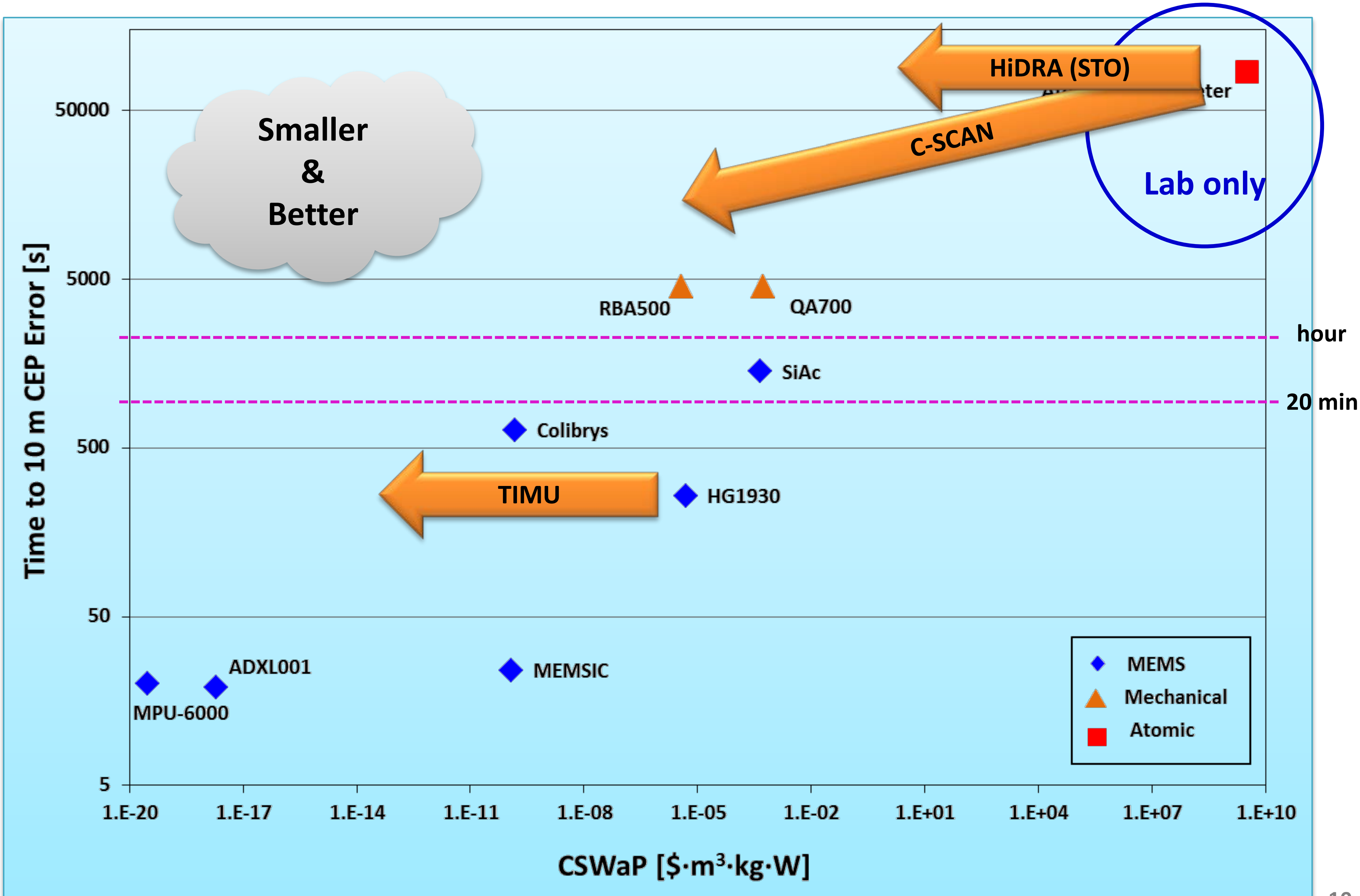


Source: http://en.wikipedia.org/wiki/List_of_active_missiles_of_the_United_States_military

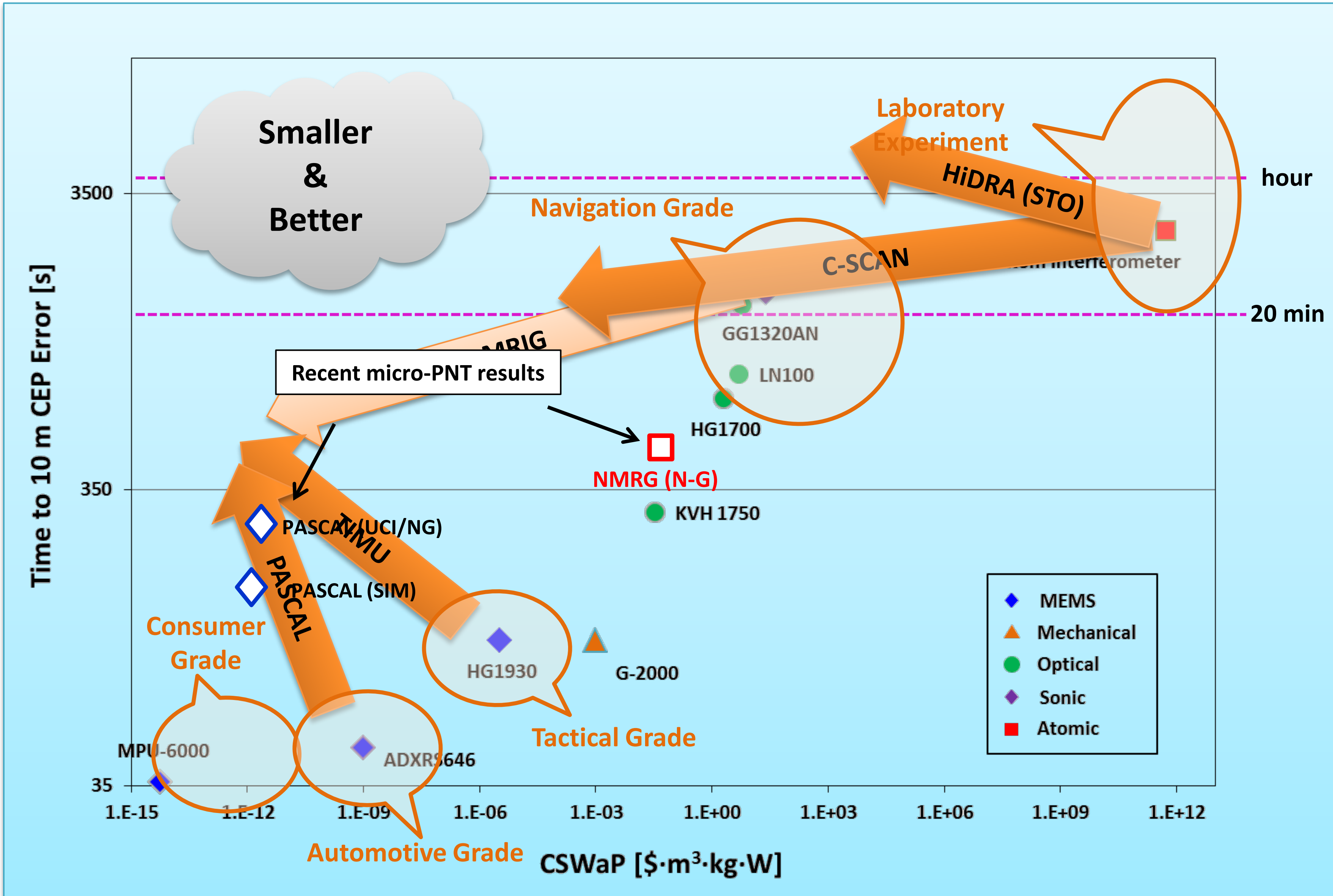
DARPA Timing Programs



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

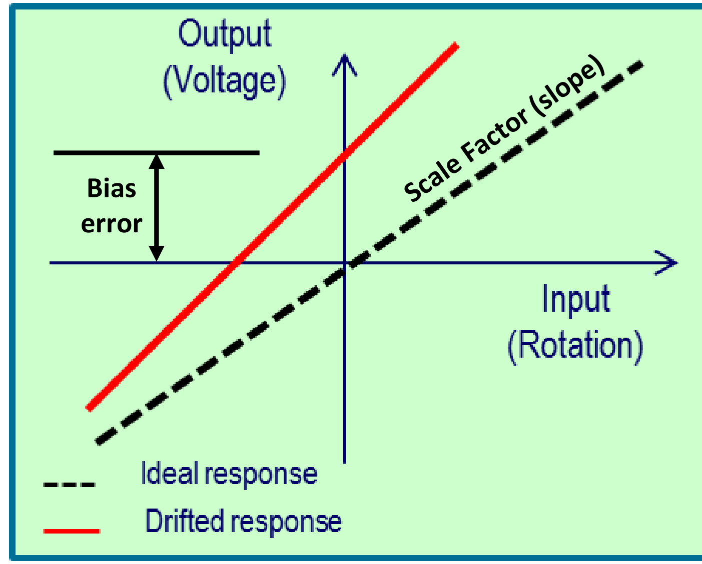
- Atomic Gyroscopes (current micro-PNT efforts: C-SCAN)
  - Superb stability and accuracy
  - Viable candidate for navigation in FY2030
  - **Gap:** Only lab demonstrations to date; enabling atomic physics components needed

- 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

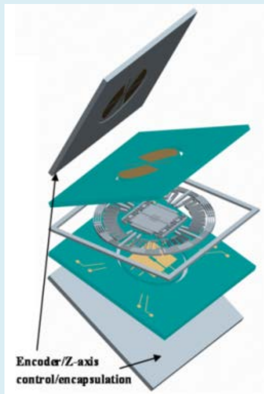
Key challenges:
- Co-fabrication of high-performance MEMS devices and calibration stages
- Calibrator calibration, numerous (tiny) moving parts
- “True” reversibility



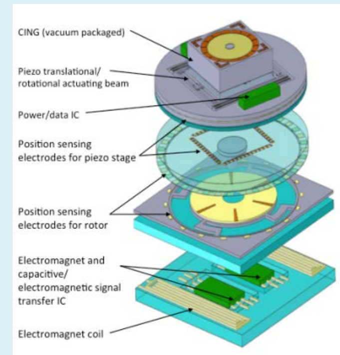
PASCAL Metrics	Ph I	Ph II	End Goal
Volume [mm^3]	**30**	**30**	**30**
Bias stability (1 month) [ppm]	**100**	**10**	**1**
Scale factor stability (1 month) [ppm]	**100**	**10**	**1**

Approaches: Active Layer Stage (TA1)

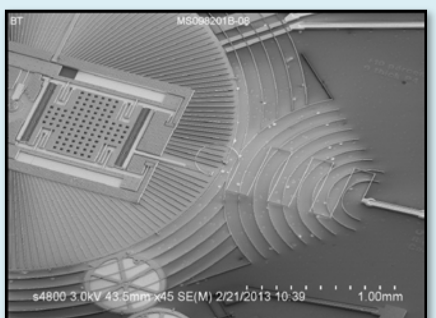
External physical reference stimulus (dithering, maytagging, etc.)



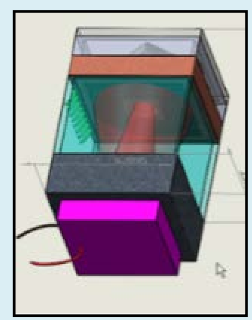
Honeywell
Dr. Grant Lodden



University of Michigan
Prof. Khalil Najafi

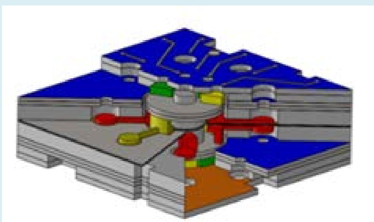
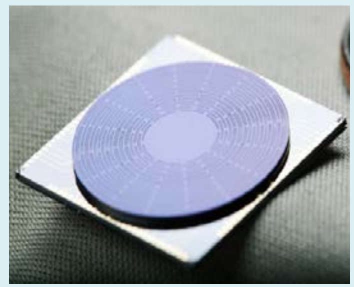
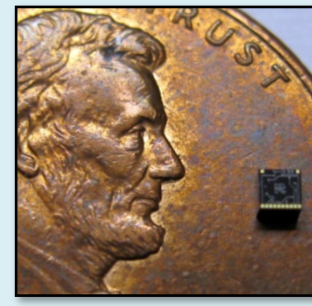
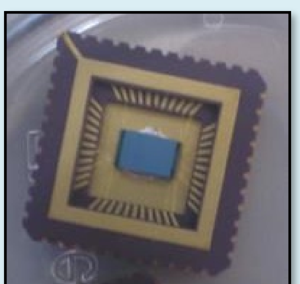
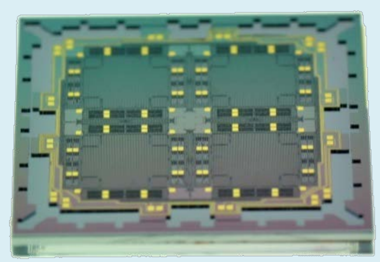
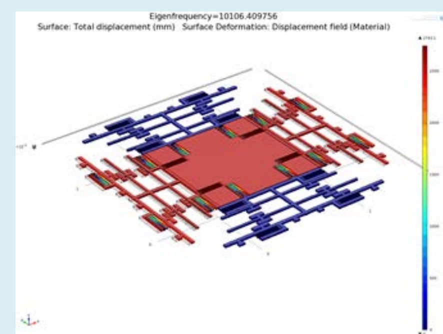


Sandia National Labs/Draper Laboratory
Dr. Murat Okandan

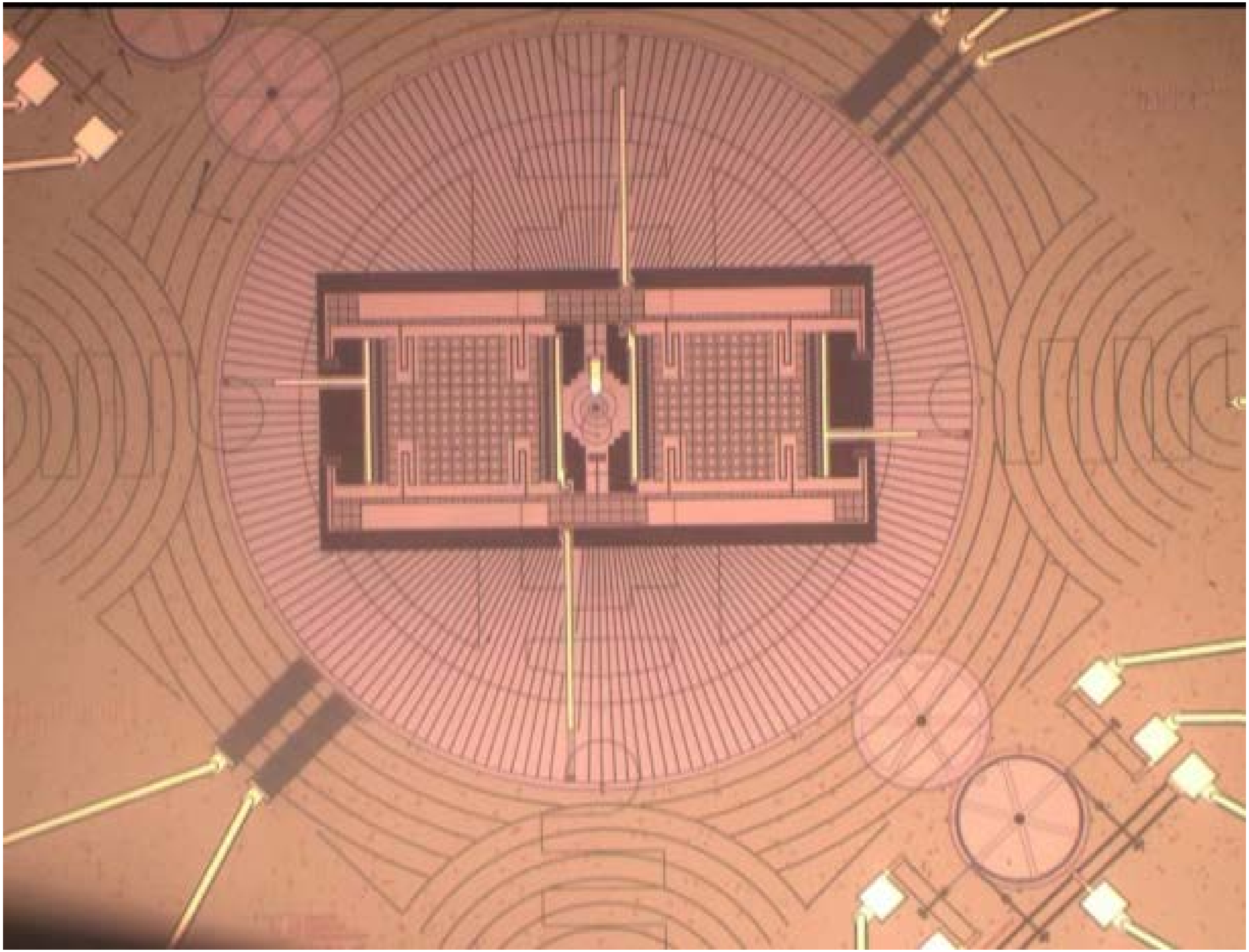


Cornell University
Prof. Amit Lal

Approaches: Electronic Self-Calibration (TA2)

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

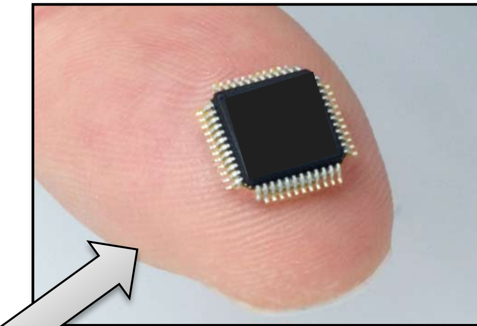
Sandia/Draper MEMS Gyro + Active Layer Gimbal Rotation



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

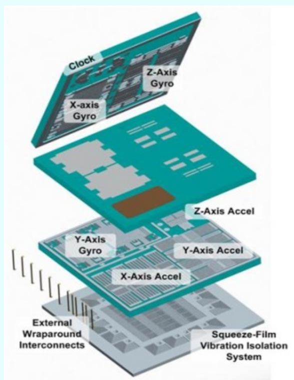


TIMU Metrics	Phase I	Phase II	Phase III
Volume [mm^3]	**10**	**10**	**10**
IMU accuracy [CEP, nmi/hour]	**Oper.**	**10**	**1**
Timing accuracy [ns/min]	**Oper.**	**10**	**1**
Power [mW] ($-55^{o}C$ to $+85^{o}C$)	**-**	**500**	**200**

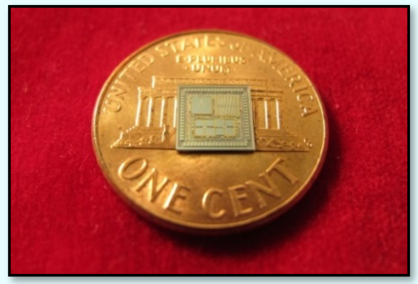
Approaches

Multi-layer (stacked die)

Honeywell
Dr. Bob Horning

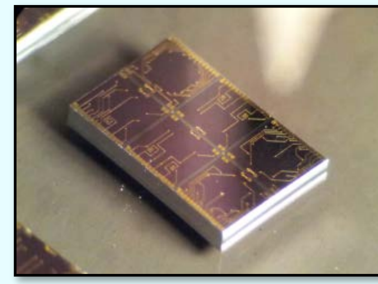


University of Michigan
Prof. Khalil Najafi



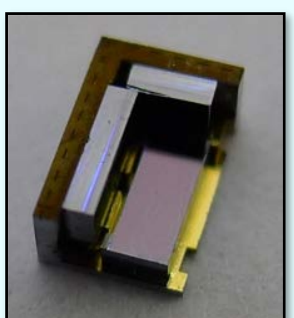
Monolithic (single die)

Georgia Tech
Prof. Farrokh Ayazi

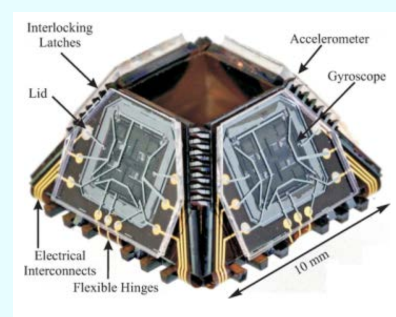


Three-Dimensional (folded, co-integrated)

Evigia
Dr. Navid Yazdi



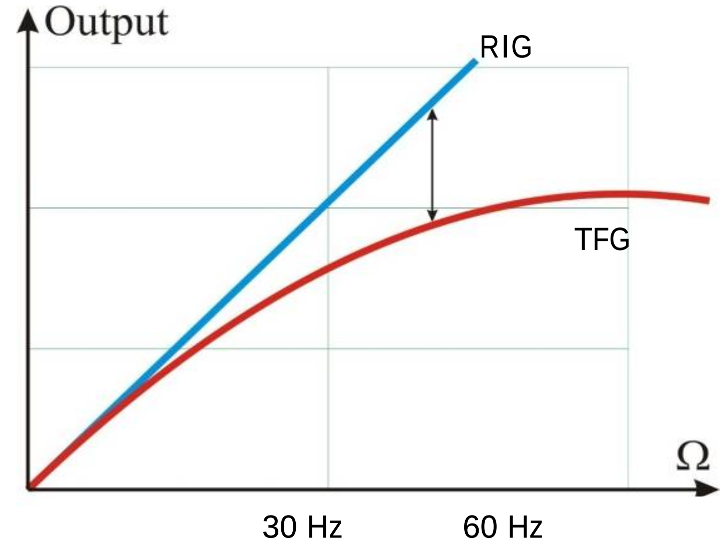
UC Irvine
Prof. Andrei Shkel



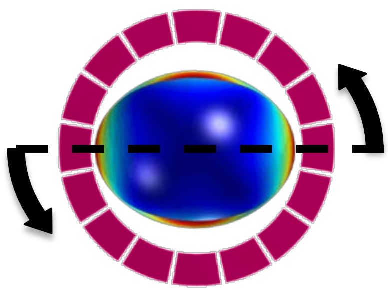
Micro-Scale Rate-Integrating Gyroscope (MRIG)

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

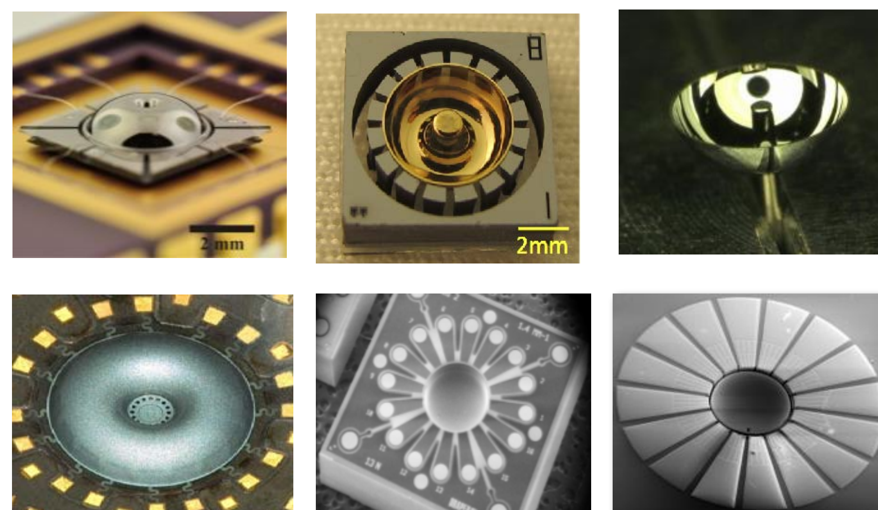


Northrop-Grumman
Hemispherical Resonator Gyroscope (HRG)
4W, 250 cm³, $100K



Courtesy L. Sorenson, HRL

Novel 3-D MEMS

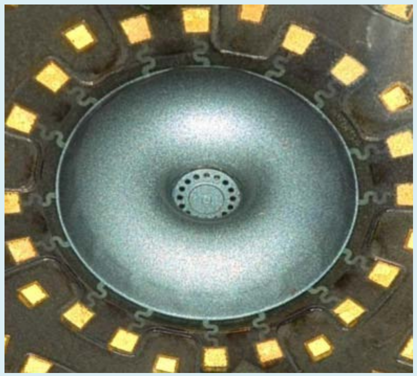


MRIG Goals
100 mW, 1 cm³, $50

Approach: Surface Tension Processes

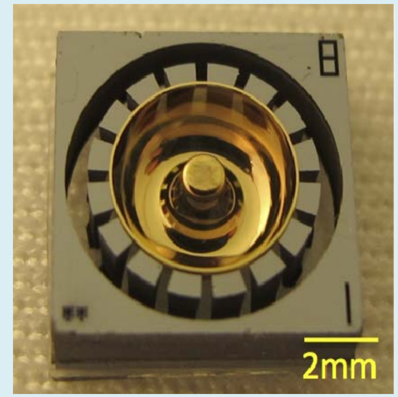
CVD Diamond

Honeywell (Dr. Burgess Johnson)



Fused Silica

Univ. of Michigan (Prof. Khalil Najafi)

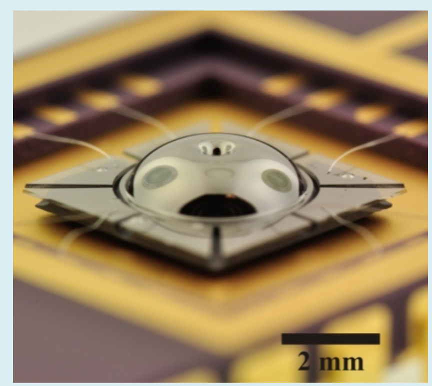


Bulk Metallic Glass

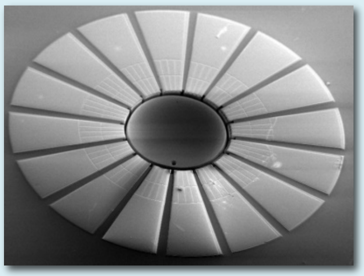
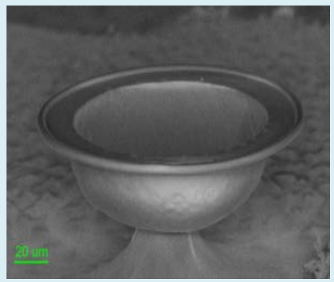
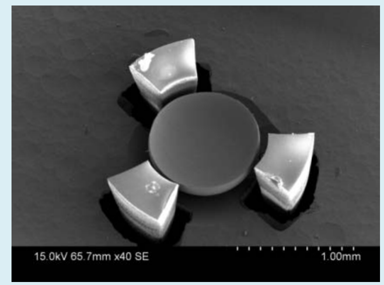
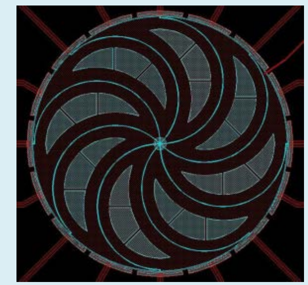
Yale University (Prof. Jan Schroers)

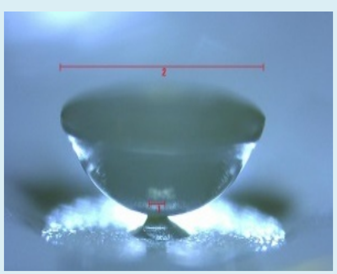
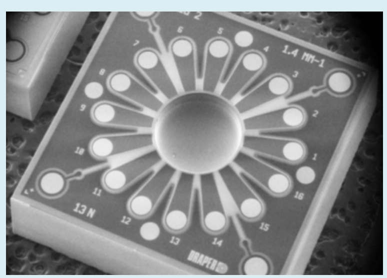
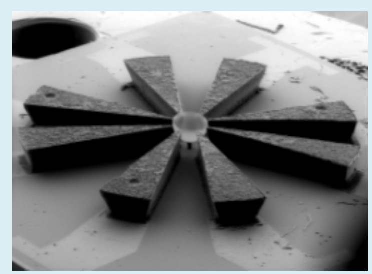
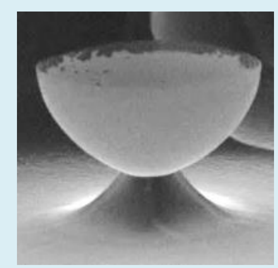
ULE Glass

UC Irvine (Prof. Andrei Shkel)



Approach: Deposition on a Mold

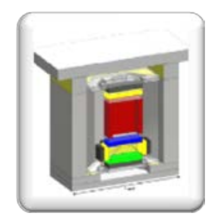
Silicon-Based		Nickel Alloy	
Northrop / Ga Tech D. Rozelle, Prof. F. Ayazi	Cornell University Prof. Sunil Bhave	Northrop / Georgia Tech D. Rozelle, Prof. F. Ayazi	GE Global Research Christopher Keimel
			

CVD Diamond		ULE Glass	ALD Al_2O_3
UC Davis Prof. David Horsley	Draper Laboratory Dr. Jon Bernstein	University of Utah Prof. Carlos Mastrangelo	CU Boulder 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.

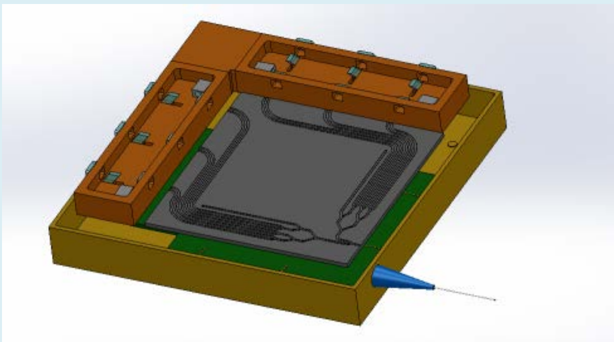
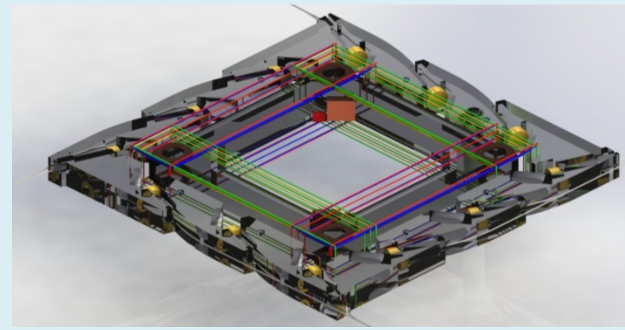
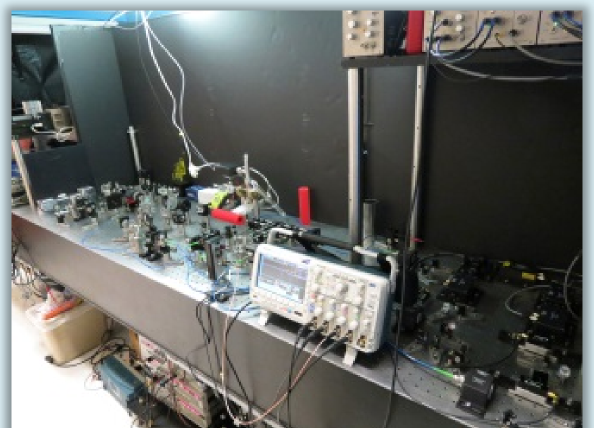
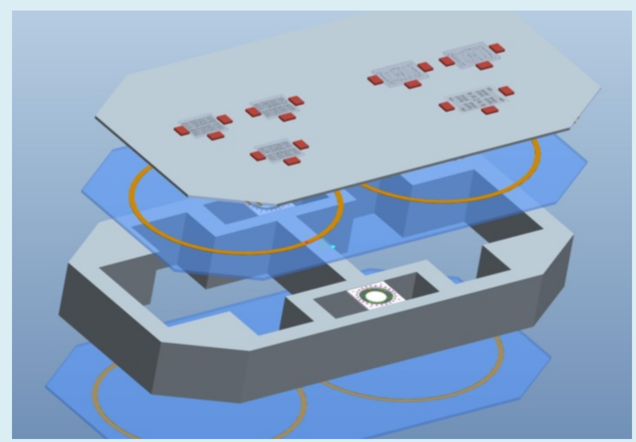
Northrop NMRG



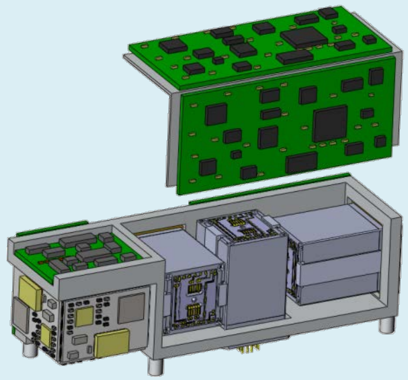
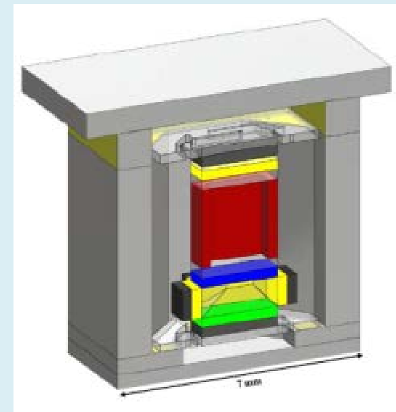
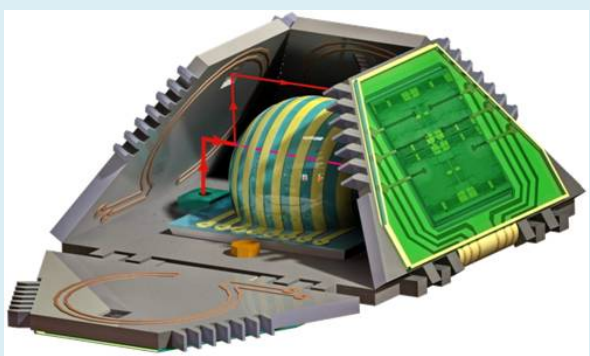
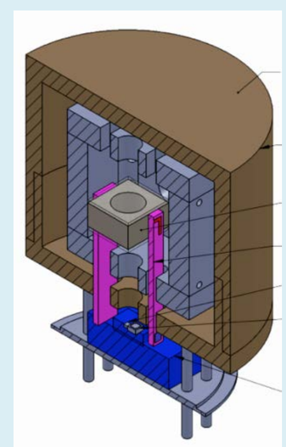
Microsemi NMRG (concept)

Draper AI (concept)

Approach: Light Pulsed Atomic Interferometry

AOsense Dr. Matt Cashen	Draper Laboratory Dr. David M. Johnson
	
Sandia National Labs Dr. Grant Biedermann	Honeywell Dr. Robert Compton
	

Approach: Nuclear Magnetic Resonance

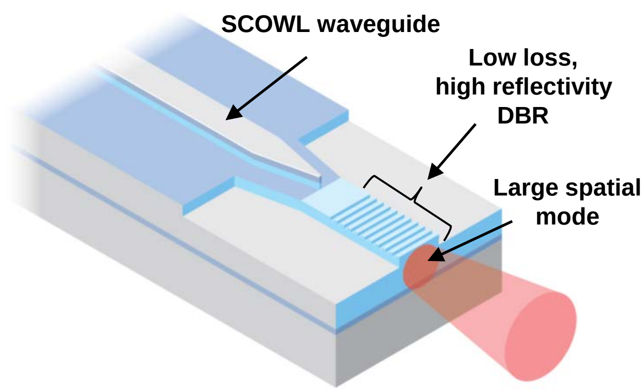
Northrop Grumman Dr. Mike Larsen	Microsemi Dr. Richard Overstreet
	
UC Irvine Prof. Andrei Shkel	**Princeton University Prof. Mike Romalis**
	

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*



MIT Lincoln Laboratory HELP Laser

Thank you

Robert.Lutwak@darpa.mil