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

Space-Based Positioning Navigation & Timing National Advisory Board
Fourteenth Meeting
Washington, DC
December 10,, 2014
Forced in 1958 to **PREVENT** and **CREATE** strategic surprise.

<table>
<thead>
<tr>
<th>Capabilities, mission focused</th>
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<td>Finite duration projects</td>
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<td>Diverse performers</td>
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Multi-disciplinary approach...from basic research to system engineering

We focus on high risk, high reward R&D for national security
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<tr>
<th>BTO</th>
<th>DSO</th>
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<tbody>
<tr>
<td>Biology, Technology &amp; Complexity</td>
<td>Discover, Model, Design &amp; Build</td>
<td>Information, Innovation &amp; Cyber</td>
<td>Electronics, Photonics &amp; MEMS</td>
<td>Networks, Cost Leverage &amp; Adaptability</td>
<td>Weapons, Platforms &amp; Space</td>
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<td><strong>Restore and Maintain Warfighter Abilities</strong></td>
<td><strong>Physical Sciences</strong></td>
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<td><strong>Biological Platforms</strong></td>
<td><strong>Battle Mgmt, Command &amp; Control</strong></td>
<td><strong>Air Systems</strong></td>
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<td><strong>Harness Biological Systems</strong></td>
<td><strong>Mathematics Materials and Manufacturing</strong></td>
<td><strong>Data Analysis at Massive Scales</strong></td>
<td><strong>Computing</strong></td>
<td><strong>Comms &amp; Networks</strong></td>
<td><strong>Ground Systems</strong></td>
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<td><strong>Apply Biological Complexity at Scale</strong></td>
<td><strong>Autonomy</strong></td>
<td><strong>ISR Exploitation</strong></td>
<td><strong>Electronic Warfare</strong></td>
<td><strong>ISR</strong></td>
<td><strong>Marine Systems</strong></td>
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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)
Notional all source navigation

Current navigation sensors

Existing sensors applicable to all source navigation

C-band comm.  GPS  IMU  Ku-band comm.  altimeter  air speed  nose camera  SAR imagery  EO/IR imagery  SIGINT (not shown)
Adaptable Navigation Sensors and Systems

**Global Navigation Satellite Systems**
- **Present:** GPS, GLONASS, WAAS, EGNOS
- **Future:** Galileo, BeiDou, QZSS, IRNSS

**Inertial Sensors**
- **Present:** iFOG, RLG, MEMS
- **Future:** PINS-HiDRA, TIMU C-SCAN, MRIG, PASCAL

**Other Sensors**
- **Present:** Camera, pitot, altimeter, RADAR, magnetometer, etc.

**Signals of Opportunity**
- **Future:** Cell towers, SATCOM, Radio, TV, Lightning, etc.

**Clocks**
- **Present:** Cesium beam, Rubidium and quartz oscillators, CSAC
- **Future:** QuASAR, IMPACT, MEMs

**Adaptable Navigation Systems**
- **Optimal solution algorithms**
- **Plug-and-play architectures**

**Distributed and future-proof**
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 mm³, 2g, 1W
- Where are the off-ramps?
  - For many platforms: 30,000 cm³, 10 kg, 10 W, + $10,000
  - For most platforms: 1000 cm³, 1 kg, 1W, + $1000.
  - For EVERY platform: 1 cm³, 100 g, 100 mW, $100
DoD Munition Profiles

DoD Deployable MEMS

DARPA SOA MEMS

Future Atomic & Optical

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

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.
DARPA Timing Programs

Smaller & Better

Battery-powered atomic timing
- Next-gen GPS
- Freq. Agile Radio
- Geolocation
- ISR
- IED defeat
- Remote sensing
- Calibration

Stratum 2
Holdover

Stratum 1
TimeKeeping

Stratum 3
Communications

QuASAR (DSO)

CSWaP [$\cdot m^3\cdot kg\cdot W$]
DARPA Gyroscope Programs

Recent micro-PNT results

Smaller & Better

Time to 10 m CEP Error [s]

Navigation Grade

HiDRA (STO)

C-SCAN

Laboratory Experiment

HiDRA (STO)

NMRG (N-G)

KVH 1750

Consumer Grade

PASCAL (UCI/NG)

PASCAL (SIM)

MPU-6000

MPU-5000

ADXR3646

G-2000

HG1930

HG1700

LN100

GG1320AN

Automotive Grade

Tactical Grade

CSWaP [$\cdot m^3\cdot kg\cdot W$]

MEMS

Mechanical

Optical

Sonic

Atomic

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Gyroscope Technology Gaps

- **MEMS Gyroscopes** (current micro-PNT efforts: PASCAL, MRIG, TIMU)
  - Super-low CSWaP (< $50, < 1 cm³, < 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 cm³, 2W); MEMS-based solution?
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

<table>
<thead>
<tr>
<th>PASCAL Metrics</th>
<th>Ph I</th>
<th>Ph II</th>
<th>End Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume [mm³]</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Bias stability (1 month) [ppm]</td>
<td>100</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Scale factor stability (1 month) [ppm]</td>
<td>100</td>
<td>10</td>
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</table>
### Approaches: Active Layer Stage (TA1)

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

<table>
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<tr>
<th>Honeywell</th>
<th>University of Michigan</th>
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<tr>
<td>Dr. Grant Lodden</td>
<td>Prof. Khalil Najafi</td>
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<tr>
<th>Sandia National Labs/Draper Laboratory</th>
<th>Cornell University</th>
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<tbody>
<tr>
<td>Dr. Murat Okandan</td>
<td>Prof. Amit Lal</td>
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**Approaches: Electronic Self-Calibration (TA2)**

Electronic interchange of drive/sense (detect and correct for mechanical change)

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<thead>
<tr>
<th>PSU-ARL</th>
<th>Sensors In Motion</th>
<th>Georgia Tech</th>
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<tbody>
<tr>
<td>Mr. Terry Roszhart</td>
<td>Dr. Kirill Shcheglov</td>
<td>Prof. Farrokh Ayazi</td>
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<tr>
<td>UC Berkeley</td>
<td>UC Irvine</td>
<td>Carnegie Mellon</td>
</tr>
<tr>
<td>Prof. Bernhard Boser</td>
<td>Prof. Andrei Shkel</td>
<td>Prof. Gary Fedder</td>
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**Disk Resonant Gyroscope (DRG):**
- **Design** (2004-present)
- Degenerate modes
- Mounted at a true common node
- Tuning
- Wafer-scale manufacturable
- Differential driving and sensing with CMR of unwanted modes

**Bias:** 0.1 to 0.05 º/hr on average
**ARW:** 0.003 º/√hr best result observed

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**Original Cloverleaf design (1997):**
- Degenerate modes
- NOT mounted at a node (no common node)

**PRG design (1999-2002):**
- Degenerate modes
- Mounted at a quasi-node (post and plate counter-rock cancelling the forces, vibration isolation)
- Tuning
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

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<thead>
<tr>
<th>TIMU Metrics</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
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<tbody>
<tr>
<td>Volume [mm³]</td>
<td>10</td>
<td>10</td>
<td>10</td>
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<tr>
<td>IMU accuracy [CEP, nmi/hour]</td>
<td>Oper.</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Timing accuracy [ns/min]</td>
<td>Oper.</td>
<td>10</td>
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<tr>
<td>Power [mW] (-55°C to +85°C)</td>
<td>-</td>
<td>500</td>
<td>200</td>
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## Approaches

<table>
<thead>
<tr>
<th>Multi-layer (stacked die)</th>
<th>Monolithic (single die)</th>
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<tr>
<td>Honeywell</td>
<td>University of Michigan</td>
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<td>Dr. Bob Horning</td>
<td>Prof. Khalil Najafi</td>
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<td>Georgia Tech</td>
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<td></td>
<td>Prof. Farrokh Ayazi</td>
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### Three-Dimensional (folded, co-integrated)

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<tr>
<th>Evigia</th>
<th>UC Irvine</th>
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<tbody>
<tr>
<td>Dr. Navid Yazdi</td>
<td>Prof. Andrei Shkel</td>
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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

Novel 3-D MEMS

MRIG Goals
100 mW, 1 cm³, $50

Courtesy L. Sorenson, HRL
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<thead>
<tr>
<th></th>
<th>CVD Diamond</th>
<th>Fused Silica</th>
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<td>Univ. of Michigan (Prof. Khalil Najafi)</td>
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<td><img src="image2.png" alt="" /></td>
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<tr>
<td></td>
<td>Bulk Metallic Glass</td>
<td>ULE Glass</td>
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<td>Yale University (Prof. Jan Schroers)</td>
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<td>UC Irvine (Prof. Andrei Shkel)</td>
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## Approach: Deposition on a Mold

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<th>Silicon-Based</th>
<th>Nickel Alloy</th>
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<tr>
<td>Northrop / Ga Tech</td>
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<tr>
<td>D. Rozelle, Prof. F. Ayazi</td>
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<td>Prof. Sunil Bhave</td>
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<tr>
<td><strong>CVD Diamond</strong></td>
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<td>Prof. David Horsley</td>
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<td>Draper Laboratory</td>
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<td>Dr. Jon Bernstein</td>
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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.
## Approach: Light Pulsed Atomic Interferometry

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### Approach: Nuclear Magnetic Resonance

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<th>Microsemi</th>
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<td>Dr. Richard Overstreet</td>
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<td>Prof. Mike Romalis</td>
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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