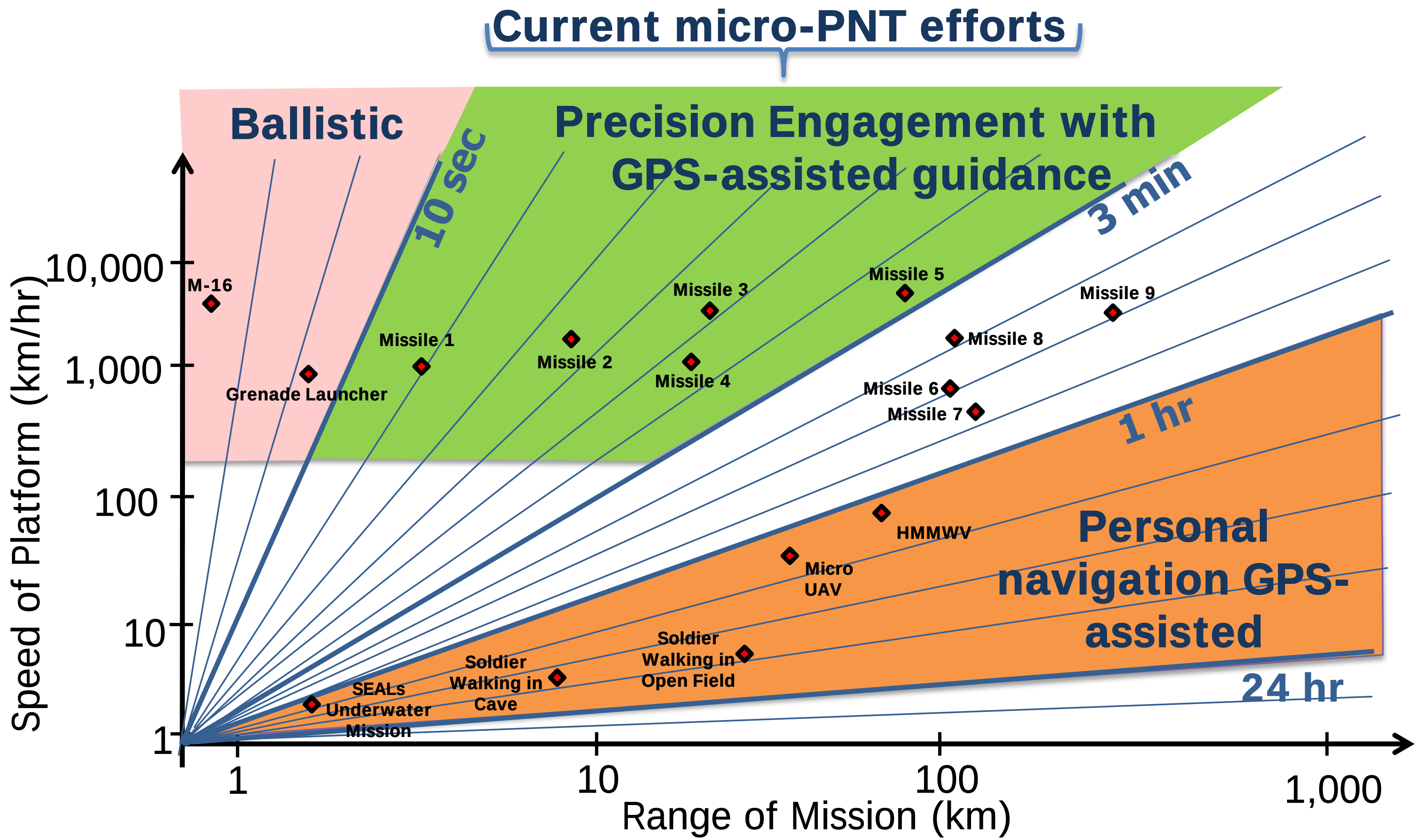
Precision Navigation, Timing, and Targeting enabled by Microtechnology: *Are We there yet ?*

Dr. Andrei Shkel
andrei.shkel@darpa.mil
Program Manager
Microsystems Technology Office
Defense Advanced Research Projects Agency

“White space” in guidance and navigation

70 % of missile missions have durations less than 3 minutes*



* Based on findings from budget documents for procurement programs (P-1) from the Office of the Under Secretary of Defense Comptroller Information System database for Army, Navy, and Air Force procurement for 2009, 2010 and 2011. Any platforms where there was no data in P-1 budgetary documents were assumed to be zero.

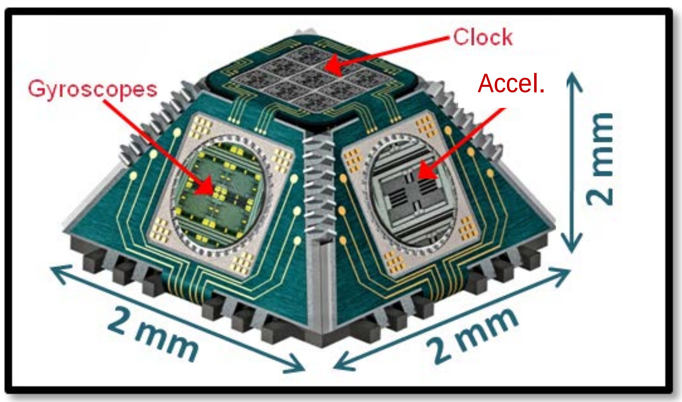
MicroPNT objective

The goal of the MicroPNT program is to achieve self-contained (GPS-independent) inertial navigation and timing, operable under severe dynamic environments through the integration of self-calibrating sensors in a micro-scale package.

The program addresses emerging DOD needs to:

- Decrease reliance on GPS
- Increase system accuracy
- Reduce collateral damage
- Increase effective range
- Reduce SWAP&C

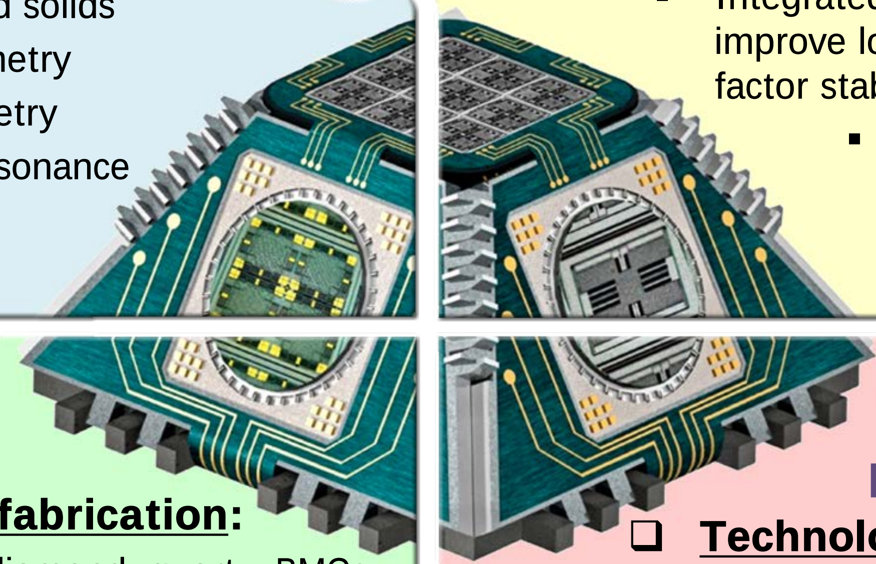
Parameters	SOA*	MicroPNT Goal
Volume	65,000 mm^3	8 mm^3
Gyro bias	4 deg/hr	0.01 deg/hr
Accelerometer bias	4 mg	0.1 mg
Short-term time loss	100 ns/min	1 ns/min
Long-term time loss	160 ns/month	32 ns/month
Power level	5 W	~1 W



* Best properties from multiple technologies:

- MEMS IMU
- Quartz Oscillators
- Magneto Optical Trap

MicroPNT scope: C-SCAN, PALADIN, PASCAL, TIMU, MRIG, IMPACT, IT-MARS, MINT, NGIMG, CSAC



IMPACT, C-SCAN, NGIMG

- **"New Physics" at micro-scale:**
  - Inertia of elastic waves
  - Atomic transitions
  - Magnetically levitated solids
  - Cold atom interferometry
  - Hot atom interferometry
  - Nuclear Magnetic Resonance

C-SCAN, PASCAL, MINT, IT-MARS

- **Algorithms for compensation of bias and scale-factor drift:**
  - Combinatorial systems of inertial sensors using dissimilar physics
  - Integrated self-calibration on-chip to improve long-term bias and scale factor stability
    - Zero-velocity updating algorithms to compensate for in-run bias and scale factor drift

MRIG, TIMU

- **Innovative microfabrication:**
  - New materials (CVD diamond, quartz, BMGs, fused silica, ULE glass)
  - 3D structures (toroids, spheres, wineglass)
  - Precision (tolerances of 10^{-4} to 10^{-6})
  - Wafer-level batch fabrication to reduce SWAP and cost

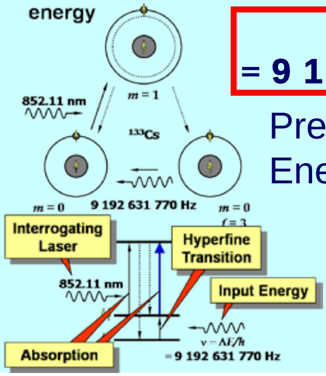
PALADIN

- **Technology transition:**
  - Early engagement of DoD branches in DARPA/MTO programs
  - Ruggedization to increase TRL
  - Independent gov't evaluation as early as Phase II to increase user buy-in

“New physics” on the micro-scale

Atomic Transitions and Laser Cooling

- Frequency determined by an atomic transition energy

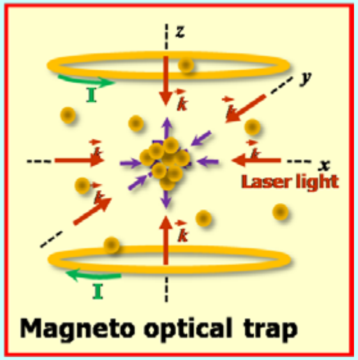


^{133}Cs

$\nu = \Delta E/\hbar$

$= 9\ 192\ 631\ 770$ Hz

Precise Number of Energy Transitions

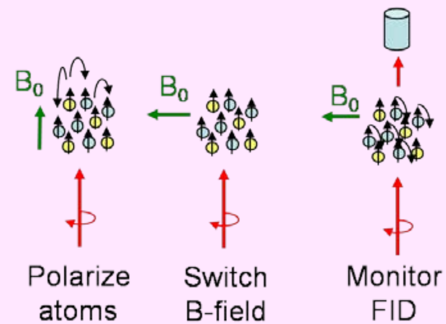


Larmor Precession

$\omega_{Al} = \gamma_{Al}\,(B_0 + B_{Xe})$

$B_0 + B_{Xe} \rightarrow$

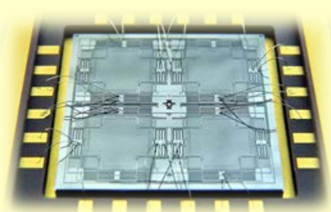
$\omega_{Xe} = \gamma_{Xe} B_0$

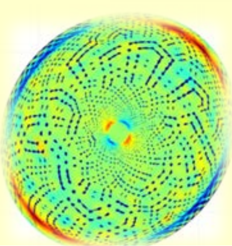


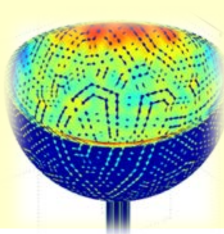
$$\frac{\partial \vec{P}_{at}}{\partial t} = \left(\vec{\Omega} + \gamma \vec{B}_0\right) \times \vec{P}_{at}$$

Vibratory Gyroscopes

- Vibratory mass on elastic support
- Inertia of Elastic Waves in Solids





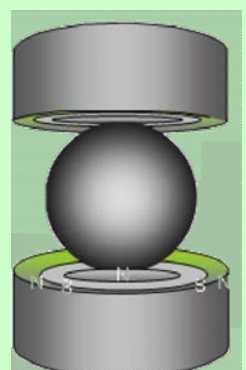


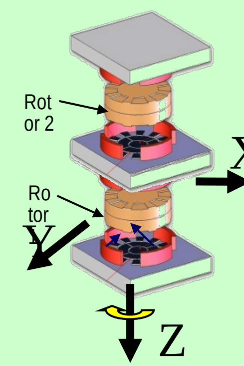
$$\left|y(t)\right| = \frac{2X_D \Omega Q}{\omega_n}$$

$$\phi \approx -2\frac{\Omega Q}{\omega_n}$$

$$\phi = -\int \Omega\, dt$$

Electrostatic Levitation



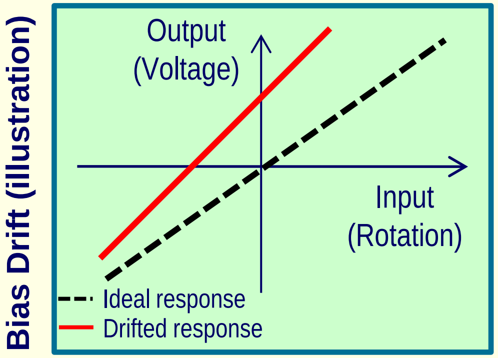


$$I_T\alpha_x - (I_T - I_P)\Omega\omega_y = \Sigma M_{X,1}$$

$$I_T\alpha_y - (I_p - I_T)\Omega\omega_x = \Sigma M_{Y,1}$$

Self-calibration on-a-chip

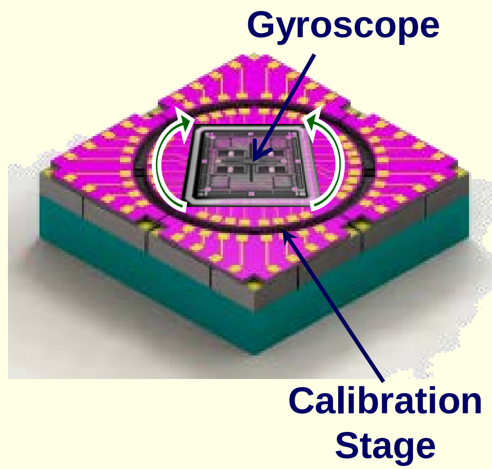
Motivation



Current options when sensor drifts:

- ❑ **Use inaccurate data**
- ❑ **Remove sensor from system**
- ❑ **re-calibrate in lab & re-insert in system**
- ❑ **discard & replace**

Approach



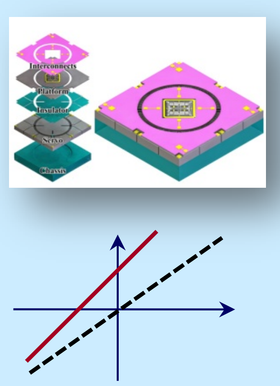
Why Now?:

- ❑ **Previously, technology pushed towards the "perfect" sensor**
  - ❑ **community now realizes the challenges of this approach**
- ❑ **Phenomenon of drift not well understood**
- ❑ **Re-calibration circumvents knowledge about the cause of drift**
- ❑ **New emerging technological advances permit the miniaturization of rate tables for on-chip calibration**

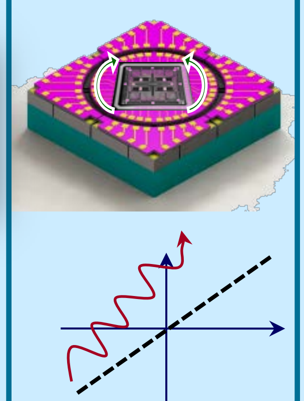
New Approach:

1.Fabricate sensor directly on calibration stage
2.Periodically apply reference stimulus (e.g. oscillatory)
3.Extract reference stimulus and sensor response
4.Recover new I/O relationship and reset bias

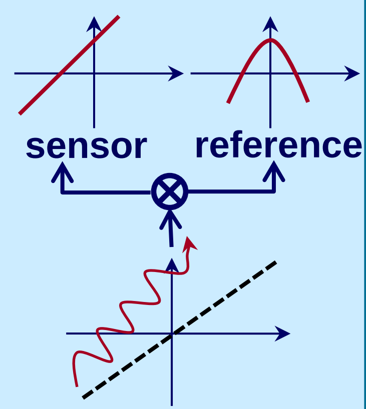
1. Co-fabricate



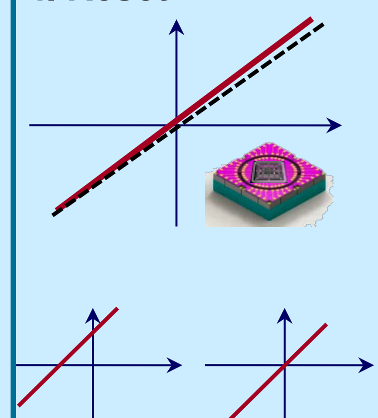
2. Excite



3. Extract

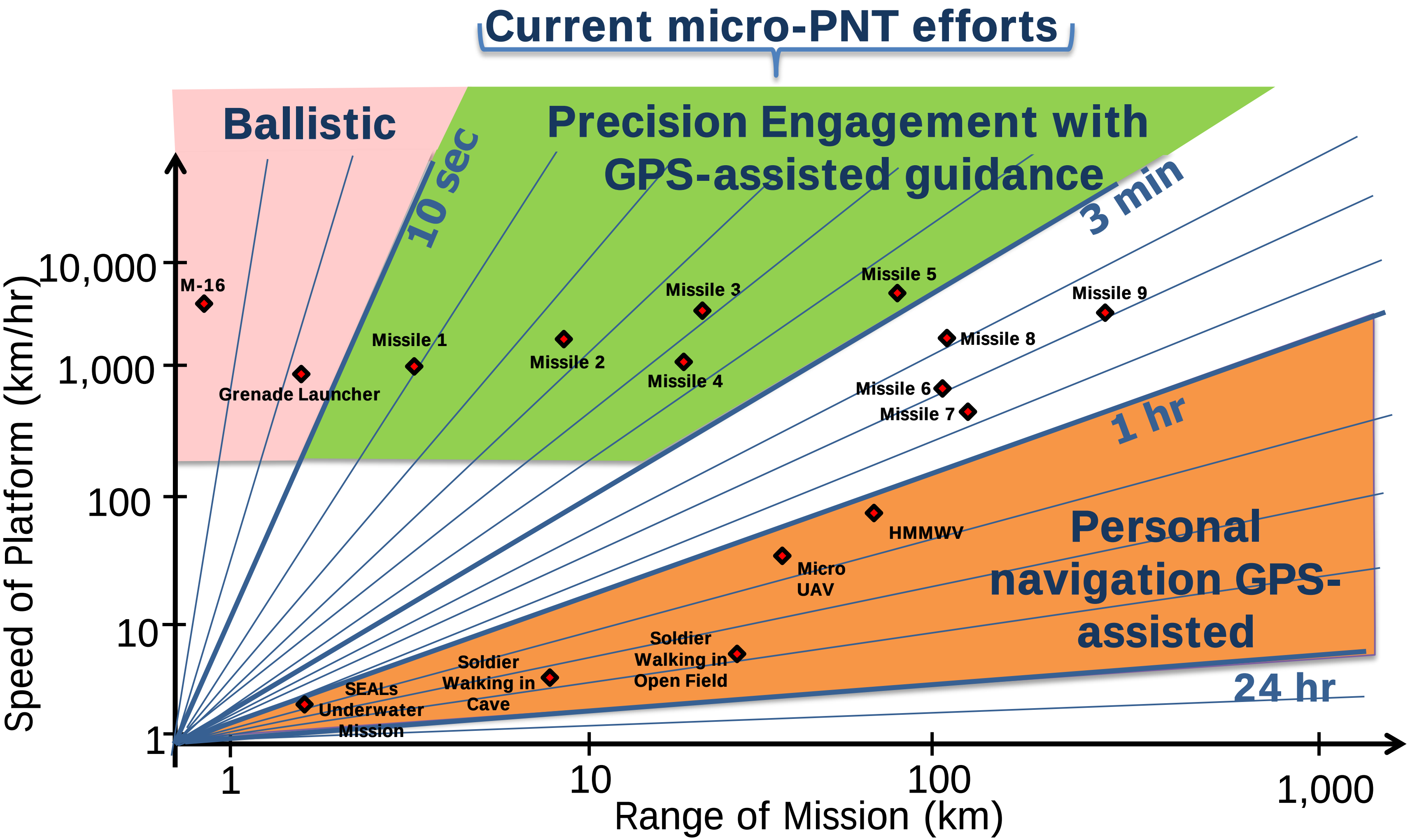


4. Reset



“White space” in guidance and navigation

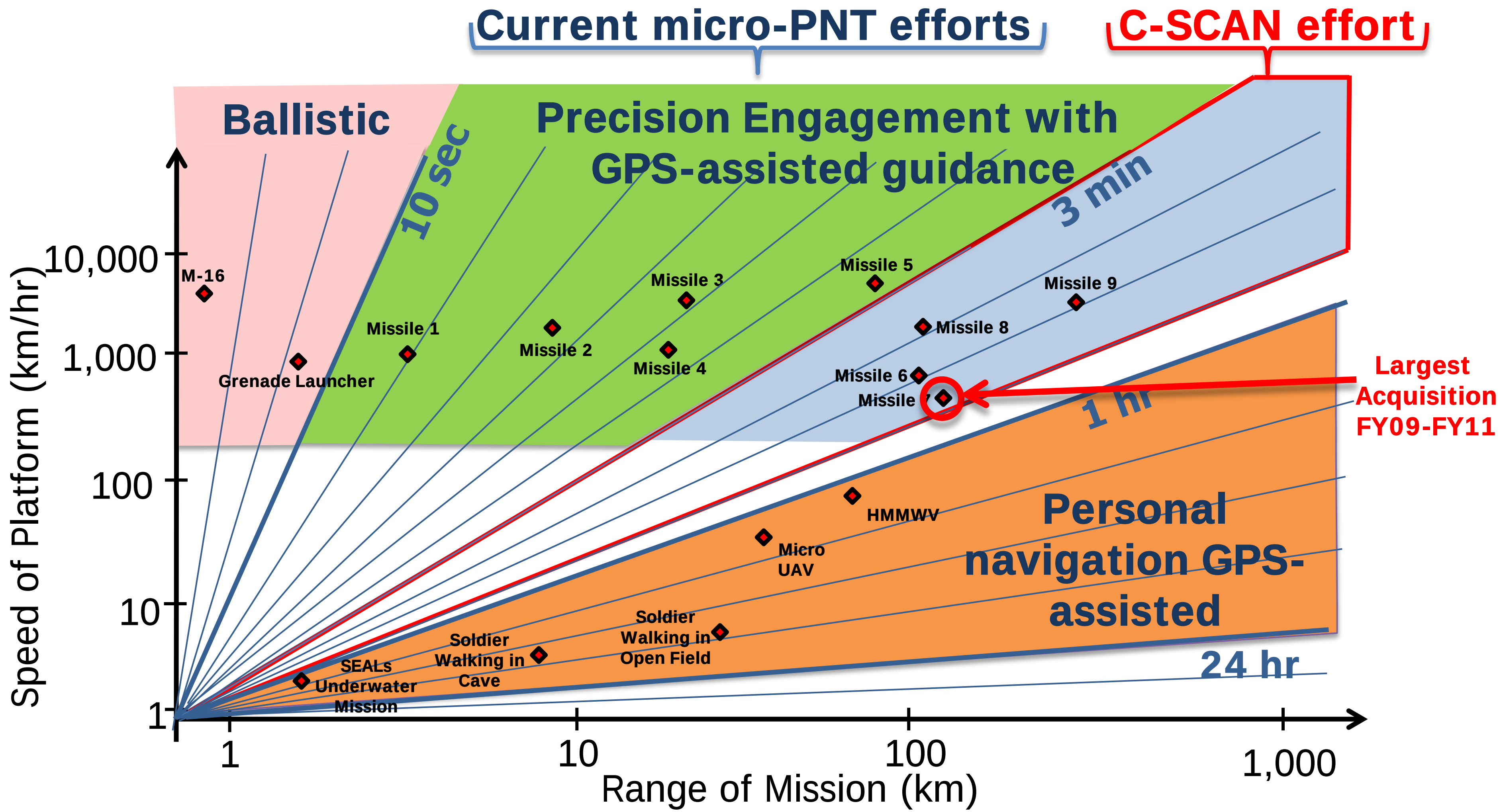
70 % of missile missions have durations less than 3 minutes*



* Based on findings from budget documents for procurement programs (P-1) from the Office of the Under Secretary of Defense Comptroller Information System database for Army, Navy, and Air Force procurement for 2009, 2010 and 2011. Any platforms where there was no data in P-1 budgetary documents were assumed to be zero.

“White space” in guidance and navigation

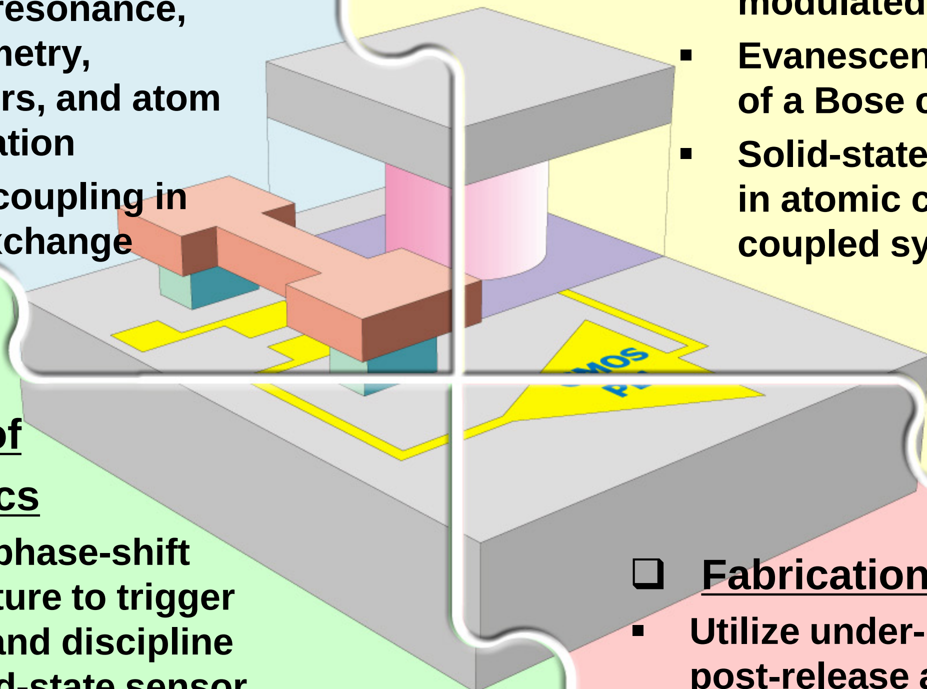
98 % of missile missions have durations less than 18 minutes*



* Based on findings from budget documents for procurement programs (P-1) from the Office of the Under Secretary of Defense Comptroller Information System database for Army, Navy, and Air Force procurement for 2009, 2010 and 2011. Any platforms where there was no data in P-1 budgetary documents were assumed to be zero.

Chip-Scale Combinatorial Atomic Navigator (C-SCAN)

Utilize ensemble of technologies to increase precision and sample rate



❑ Ultra-miniaturization of atomic inertial sensors

- Harness energy transitions in nuclei magnetic resonance, atomic interferometry, hyperfine transfers, and atom number amplification
- Exploit inherent coupling in polarized spin-exchange

❑ Multi-functional microsystem

- Atomic clocks as a frequency reference for frequency modulated sensors.
- Evanescent wave confinement of a Bose condensate
- Solid-state devices integrated in atomic cells, feed-back coupled systems

❑ Combinatorics of dissimilar physics

- Develop zero net phase-shift coupling architecture to trigger atomic emission and discipline less accurate solid-state sensor
- Adapt optimal estimators for bias adjustment and compensation

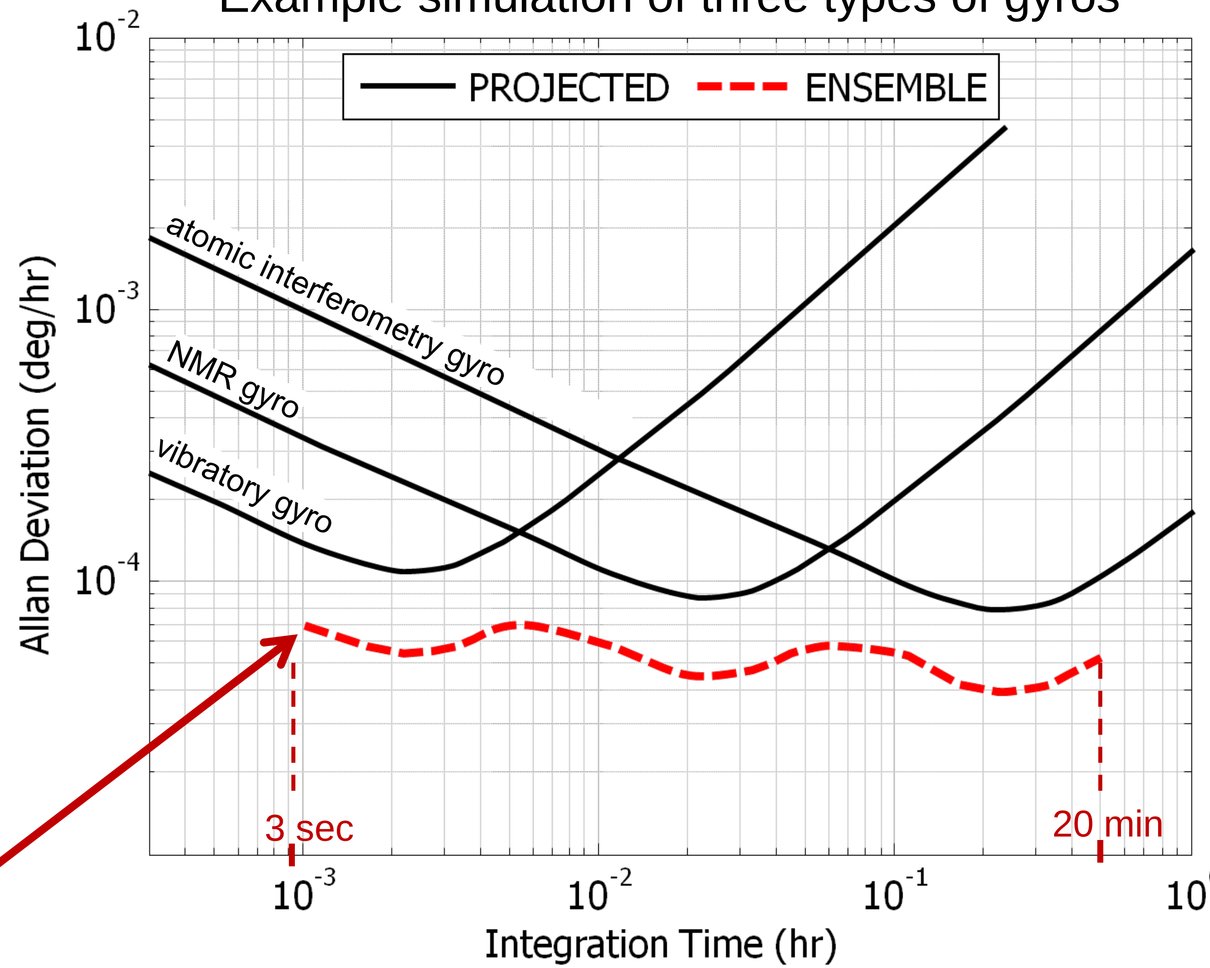
❑ Fabrication processes

- Utilize under-explored processes: post-release assembly, chip-level welding
- 3D fabrication and assembly processes: blow, stretch, stamp, roll

C-SCAN Benefits

- Utilize ensemble of gyros to widen the range of averaging intervals
- Combinatorics anticipate simultaneous improvement in start-up time, bias/scale-factor stability, dynamic range, sensitivity, and angle random walk

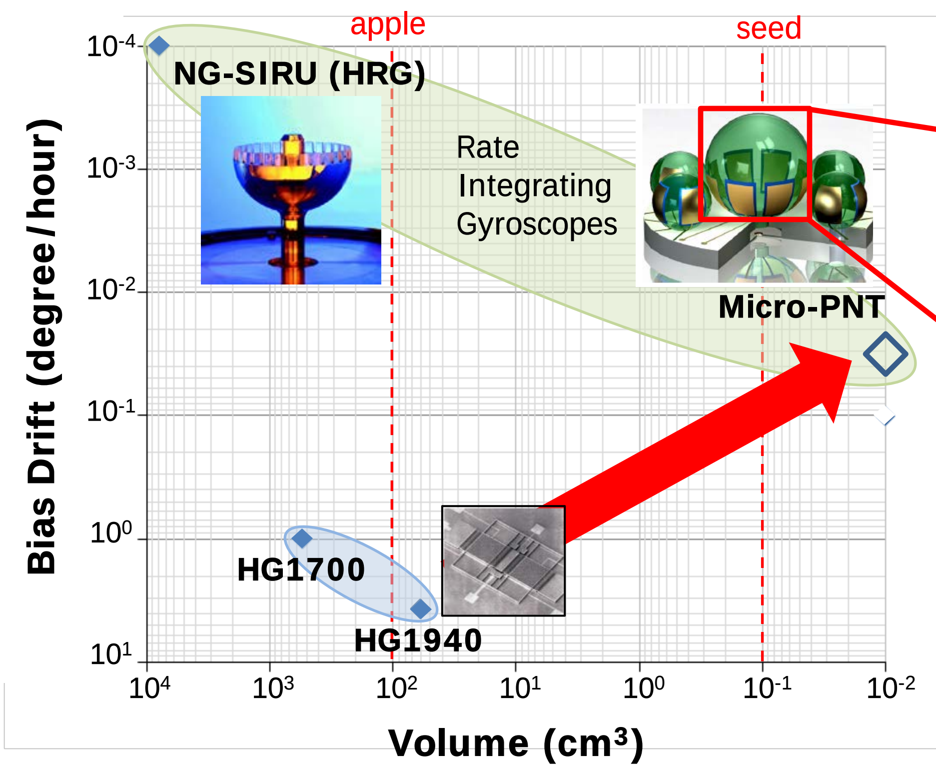
Example simulation of three types of gyros



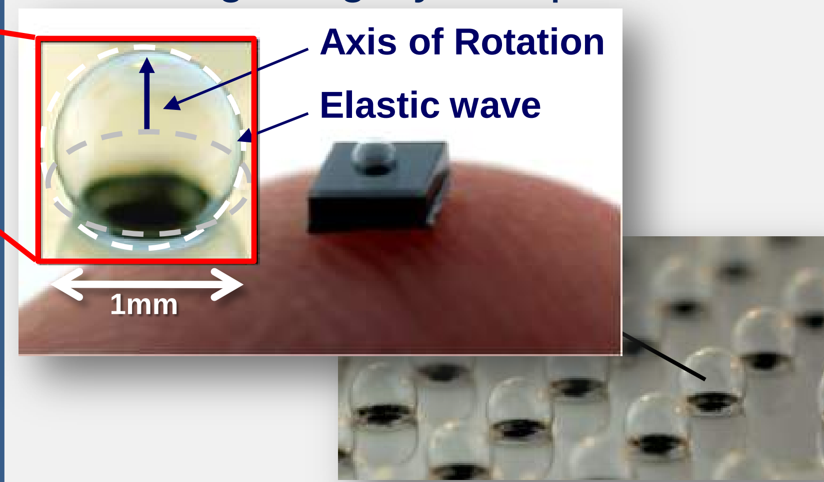
Ensemble of gyros are predicted to produce a system with noise characteristic 10^2 lower than any single consistent inertial sensor

Micro Rate Integrating Gyroscopes (MRIG)

High Dynamic Range, High Linearity



Micro-fabricated Rate Integrating Gyroscope

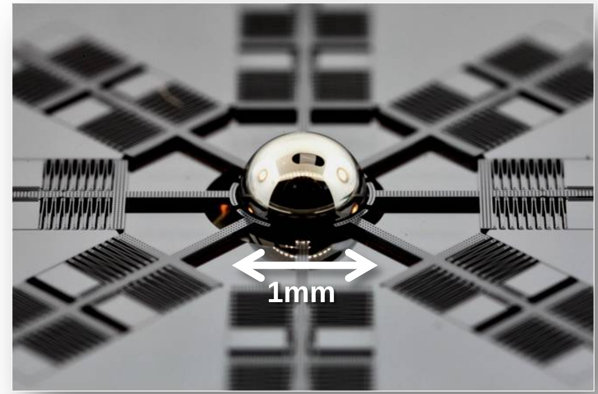


To eliminate wear-out, exploit inertial properties of elastic standing waves in solids. This leverages inherent isotropic behavior in exotic materials.

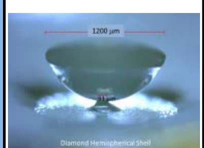
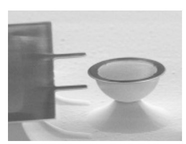
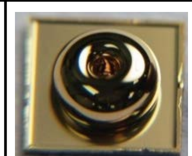
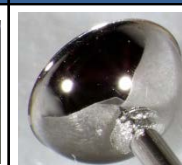
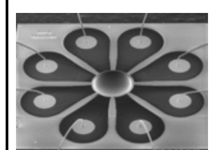
- **Potential for decrease in cost from $1,000 to $100 per gyro axis.**
- **Near navigation-grade gyro performance in form factor smaller than today's tactical grade gyros.**

Recent Results (MRIG)

- The microPNT program seeks to develop high dynamic range sensors to directly measure the angle of rotation
- The program explores new processes and high-Q materials for fabricating micro-scale 3D structures
- This effort is currently in Phase II of a three phase development



Phase I prototype of Micro Rate Integrating Gyroscope (fused quartz shell, Si electrodes)

	UC, Berkeley	Honeywell	Cornell	Univ. of Michigan	Northrop Grumman	Yale	Draper	UC, Irvine
Structures								
Material	CVD Diamond	ULE Glass / CVD Diamond	Silicon Nitride	Fused Silica	SiO_2	Bulk Metallic Glass	CVD Diamond	Pyrex, ULE Glass, Quartz
Frequency mismatch (Hz)	5	13	8	8	6	20	240	0.15
Ring down time (sec)	0.11	0.8	0.16	8.3	0.28	1.5	0.23	0.7

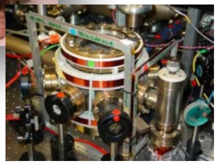
Program objective is 1 Hz frequency mismatch and 100 sec ring down time

Micro-PNT objective

The program addresses the emerging DOD need to:

- Decrease reliance on GPS
- Increase system accuracy
- Reduce co-lateral damage
- Increase effective range
- Reduce SWAP&C

HG9900 Nav grade IMU

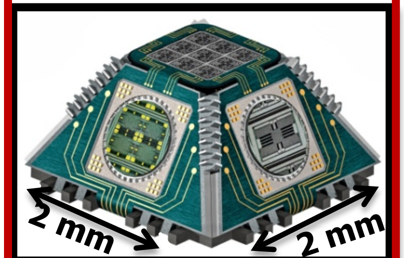


Magneto Optical trap

HG1930 MEMS IMU

Quartz Oscillator

This program



Parameters	Units	SOA	SOA MEMS	micro-PNT
Size	mm^3	$1.6x10^7$	$6.5x10^4$	8
Weight	gram	$4.5x10^3$	$2x10^2$	~2
Power	Watt	25	5	~1
Gyro Range	deg/sec (Hz)	1,000 (3)	3,600 (10)	15,000 (40)
Gyro Bias	deg/hr	0.02	4	0.01 (0.001)
Gyro ARW	deg/√hr	0.01	0.12	0.001 (0.0001)
Gyro Drift	ppm, 3σ	1	400	1
Accel. Range	g	25	70	1,000
Accel. Bias	mg	0.1	4	0.1 (0.001)
Misalignment	μ-radians, 3σ	200	1,000	100
Short-term Time Loss	ns/min	0.001	100	1
Long-term Time Loss	ns/month	10	N/A	32

Maturity of MicroPNT technologies

Maturity

Commercialized Product

CSAC

CSAC
- ~$1500, 20 mW ,6 cm^3, 35 gram
- <1 μs time loss after 1 week while exposed to MIL-STD

Graduating from DARPA

MINT **NGIMG** **PALADIN**

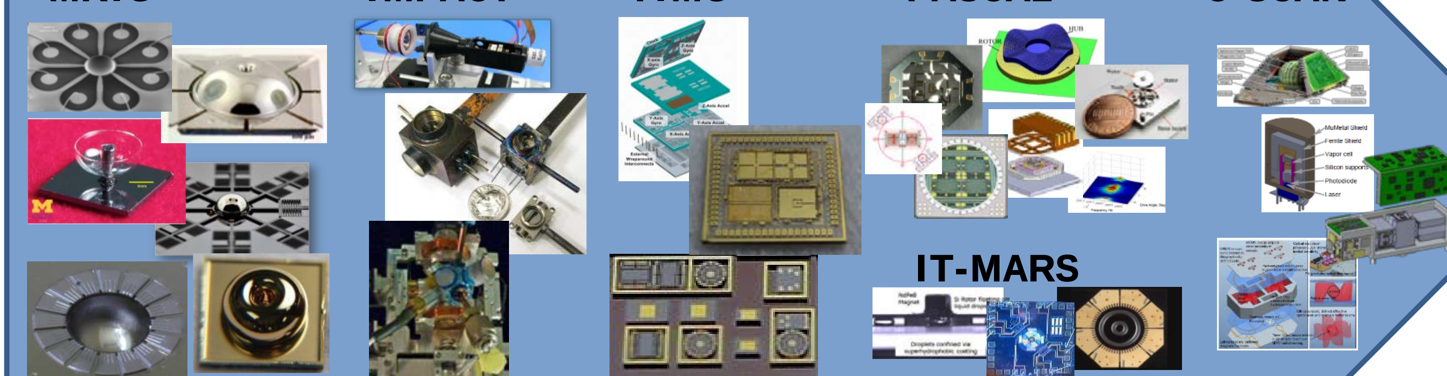
NGIMG NMR Gyro
- 20 mW ,5 cm^3, near Nav-grade

MINT Velocity assisted micro-IMU
- 16m accuracy after 4hr GPS-denied environment (gov't tested)

PALADIN Common PNT test platform

Infancy

MRIG **IMPACT** **TIMU** **PASCAL** **C-SCAN** **IT-MARS**

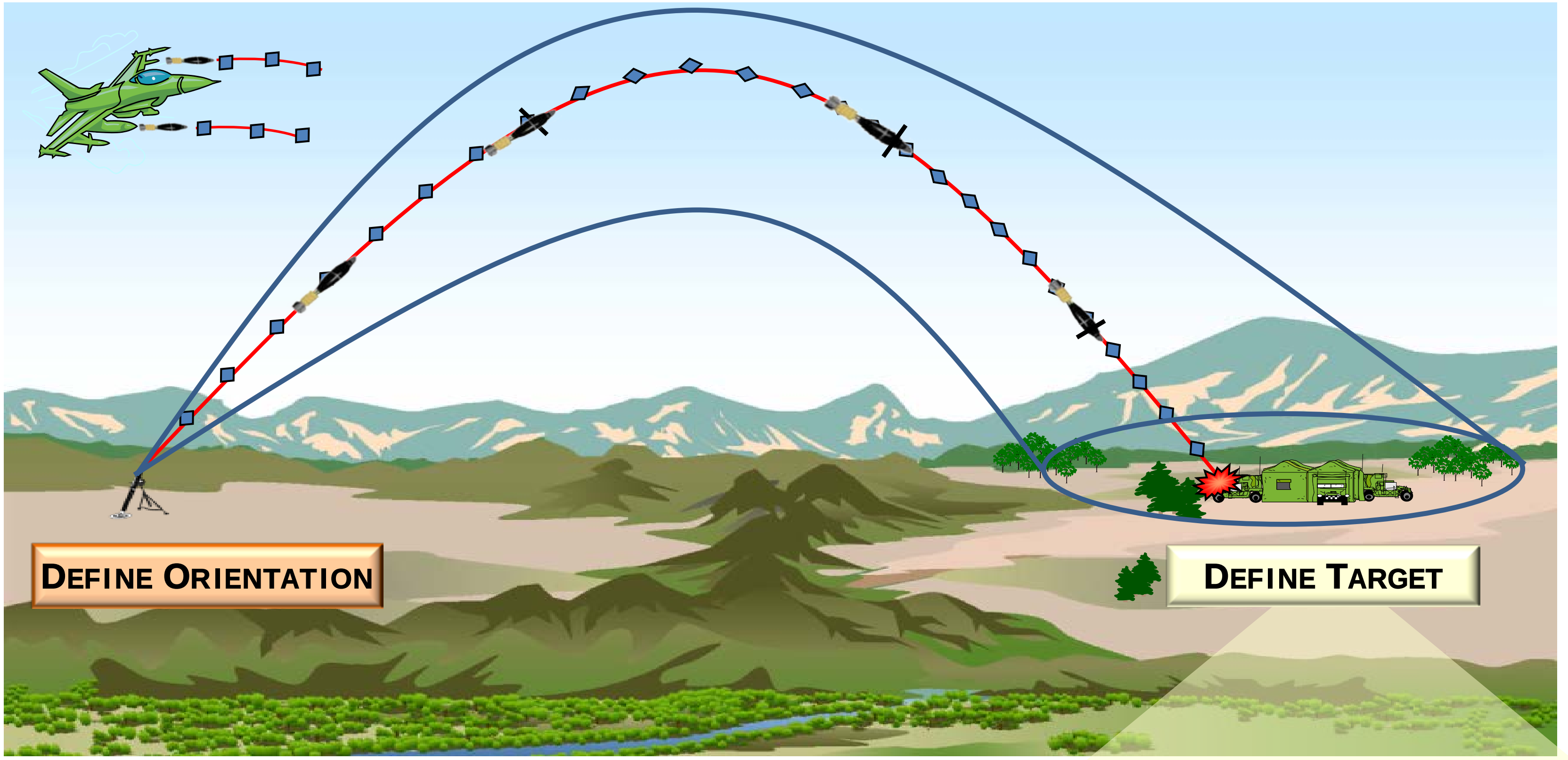


- New Physics
- Algorithms

- Microfab
- Technology integration

Precision engagement

10 m (or better) CEP from hundreds of miles



- Define fast the intended target (in seconds)
- Know your initial conditions
- GN&C without external signals

All need to be done in the same coordinate system