Emerging Microsystem Technologies for Autonomous Positioning, Navigation, and Timing (PNT)

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National Space-Based PNT Advisory Board

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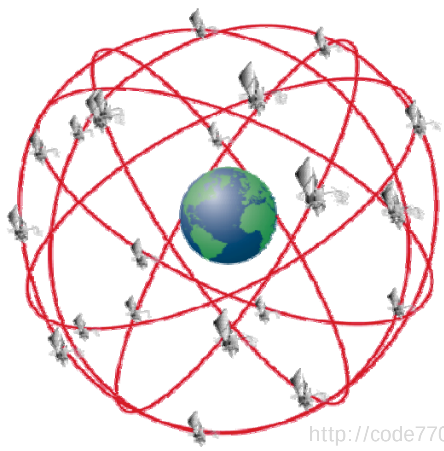
DARPA PNT Objectives

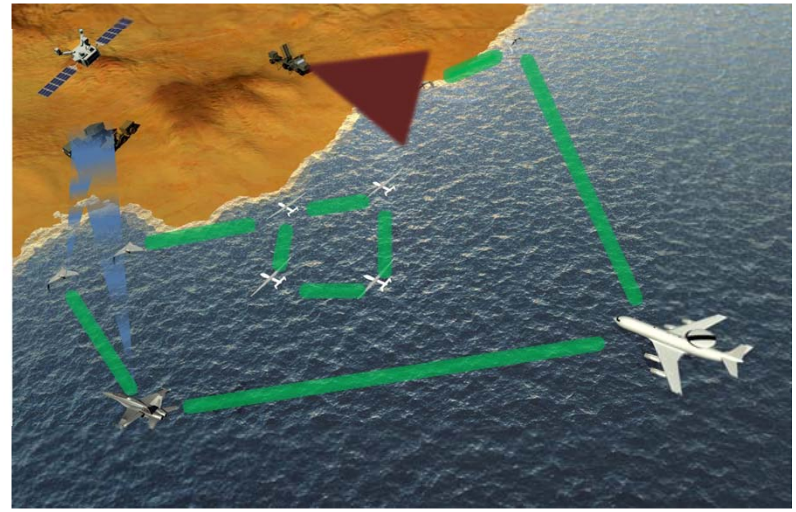
- Achieve GPS-level performance under all application scenarios
  - Eliminate GPS as single point of failure
  - Provide redundant capabilities and architectures with no single point of failure
  - Provide optimal solution based on all available data sources

- Outperform GPS for disruptive capabilities
  - Tactical time distribution, advanced communications, and EW
  - Long-term PNT in environments where GPS was never designed for use: undersea, underground, indoors
  - High-precision relative PNT for cooperative effects (multi-static radar, distributed SIGINT, autonomous formation flying, time transfer)

Position is Time is Position

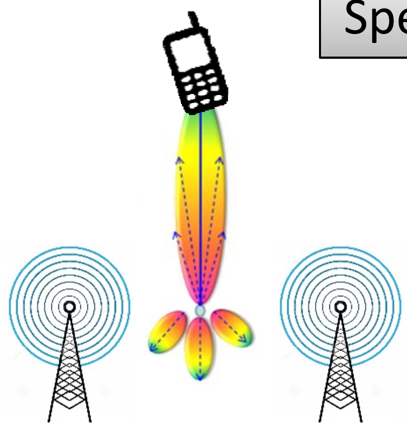


GNSS



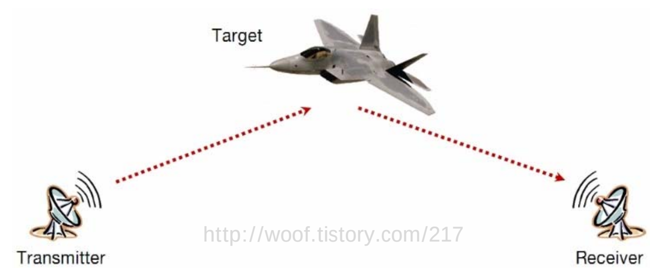
Coordinated engagement

Speed of Light = 1 foot / 1 nanosecond

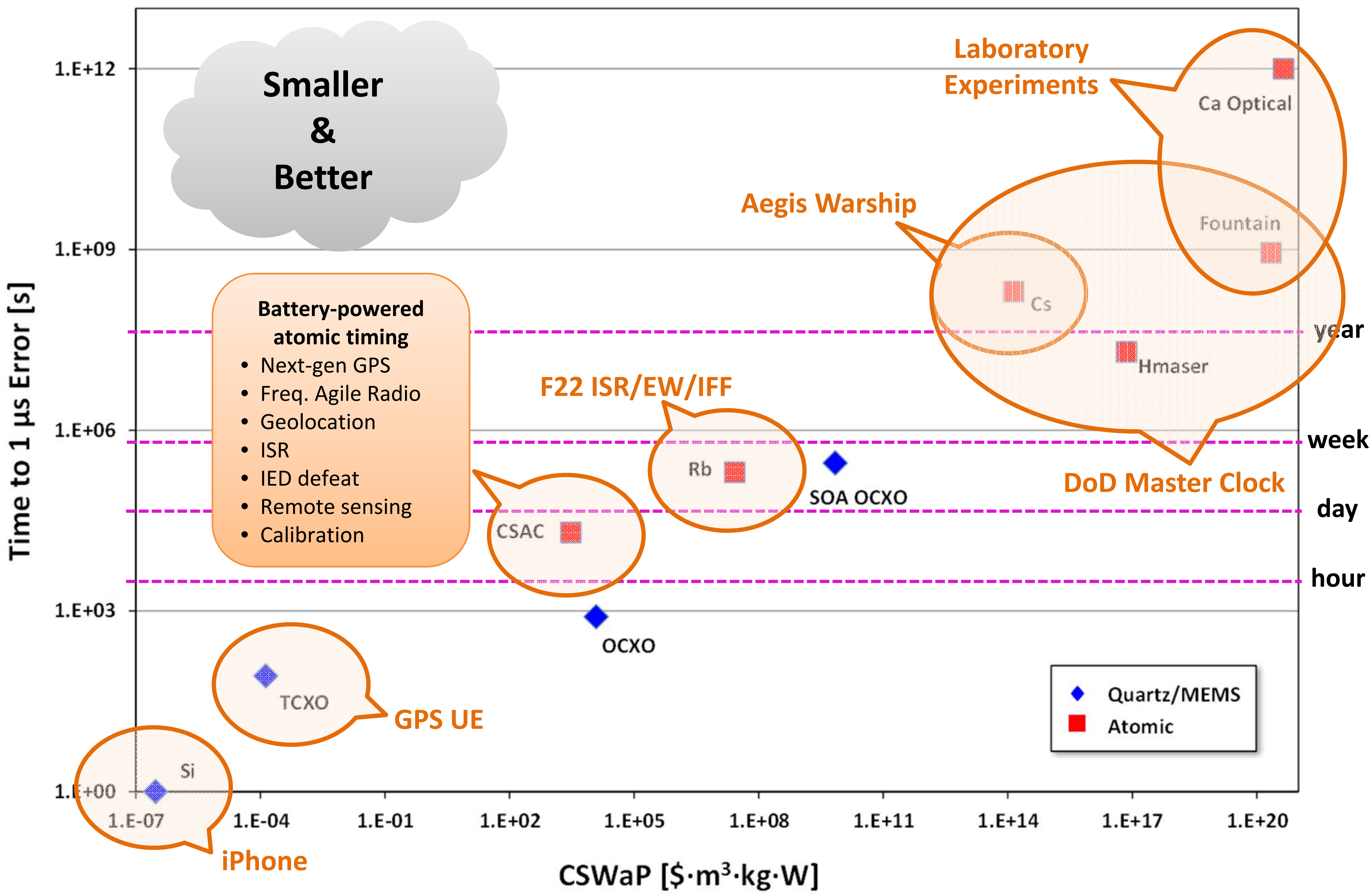


Coherent EW

Bistatic RADAR



State-of-the-Art Clocks



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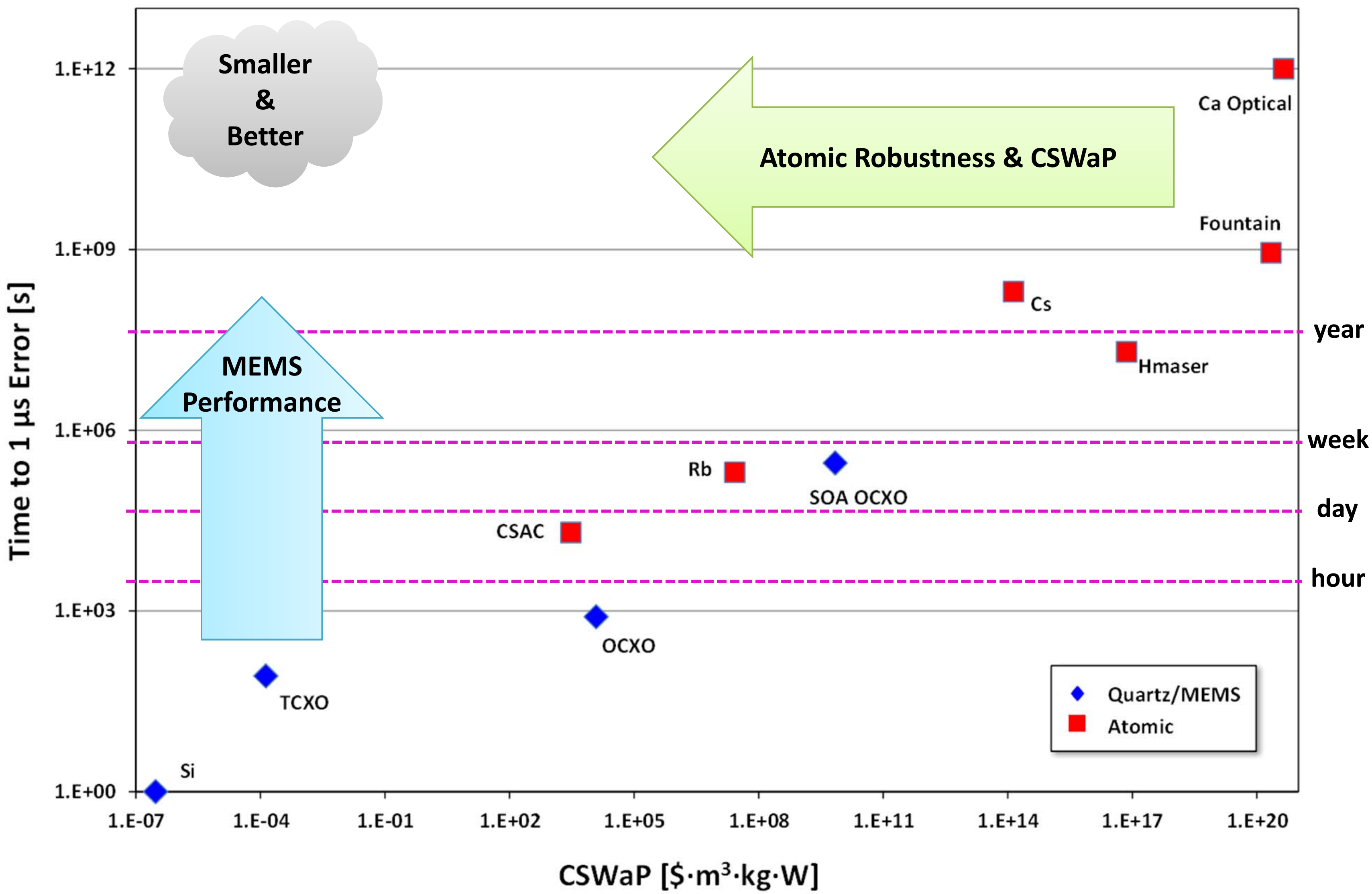
DARPA Clock Investment Strategy



Timing Error

$$\Phi(\tau) = \Phi_0 + f_0 \times \tau + \frac{1}{2} f_0' \times \tau^2 + \frac{\sigma_y(\tau)}{\sqrt{3}} \times \tau + \int_0^\tau f[T(t)]dt + \int_0^\tau f[B(t)]dt + \cdots$$

- Total accumulated time error: $\Phi(\tau)$
- Initial time error (sync): Φ_0
- Initial freq. error (cal): f_0
- Freq. Aging: f_0'
- Noise-driven wander (Instability): $\sigma_y(\tau)$
- Frequency Sensitivity to Temperature (TempCo): $\int_0^\tau f[T(t)]dt$
- Frequency Sensitivity to Magnetic Field: $\int_0^\tau f[B(t)]dt$
- Other Environmental Sensitivities: $\cdots$

CSAC Typical application model (ΔT=10°C)

Error Source		Timing error, Φ, after 6-hour calibration			
		τ= 1 hour	1 day	1 week	1 month
Initial Sync	Φ_0	10 ns	10 ns	10 ns	10 ns
Initial Cal	f_0	11 ns	259 ns	1.8 μs	7.3 μs
Frequency Aging	f'_0	107 ps	62 ns	3 μs	363 μs
Instability	σ_y	10 ns	51 ns	135 ns	269 ns
TempCo	f[T]	360 ns	8.6 μs	60.5 μs	242 μs
Total:		**360 ns**	**8.7 μs**	**65 μs**	**436 μs**

Miniature Atomic Clocks

- Chip-Scale Atomic Clock (CSAC) program:
  - 100 mW, 15 cm^3, 1 μs/1 day
  - Fully transitioned to industrial production (> 30,000 units shipped)
  - Second-source development underway by U.S. Army ManTech program

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~4 x 3.5 x 1 cm

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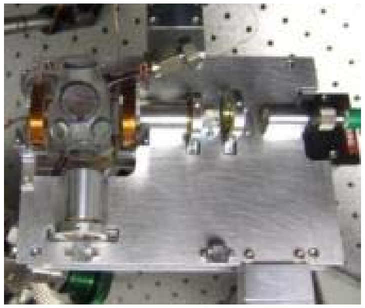
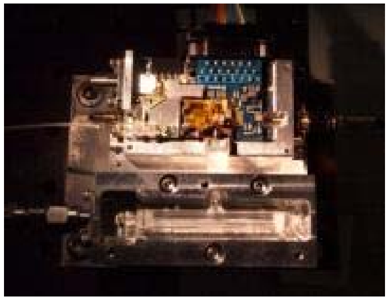
- Integrated Micro-Primary Atomic Clock Technology (IMPACT) program:
  - Objective: CSAC size with rackmount cesium-beam performance (32 ns/1 month)



Honeywell CAMPS (cold atoms)



OEwaves AOIMPAC (optical clock)

Symmetricom MCAFS (cold atoms)

Sandia MIFS (ion clock)

Limitations of Gas Cell Atomic Oscillators

TempCo and Drift have the same root causes:

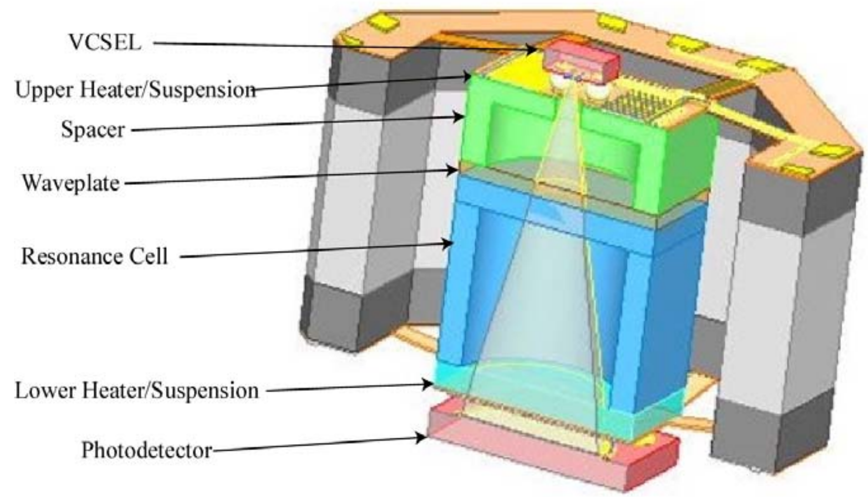
- Pressure and composition of cell contents ("buffer gas shift")
- Laser spectrum ("light shift")

Superior performance requires:

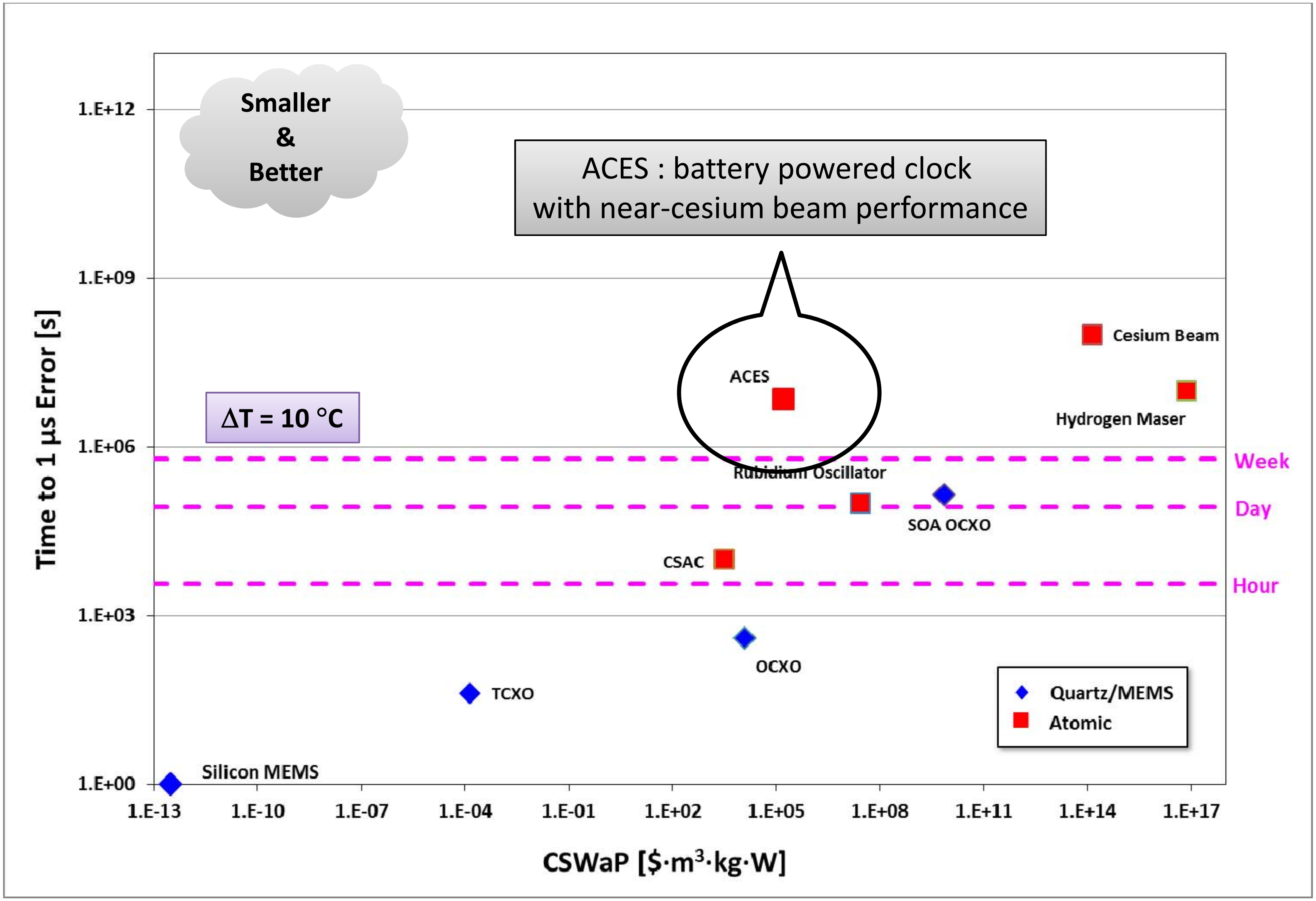
- Atoms in vacuum
- Light off during interrogation

Possible ACES interrogation architectures:

- Laser-cooled/trapped neutral atoms
- Trapped ions
- Interrogation of optical transitions
- Other?



ACES Program Goals

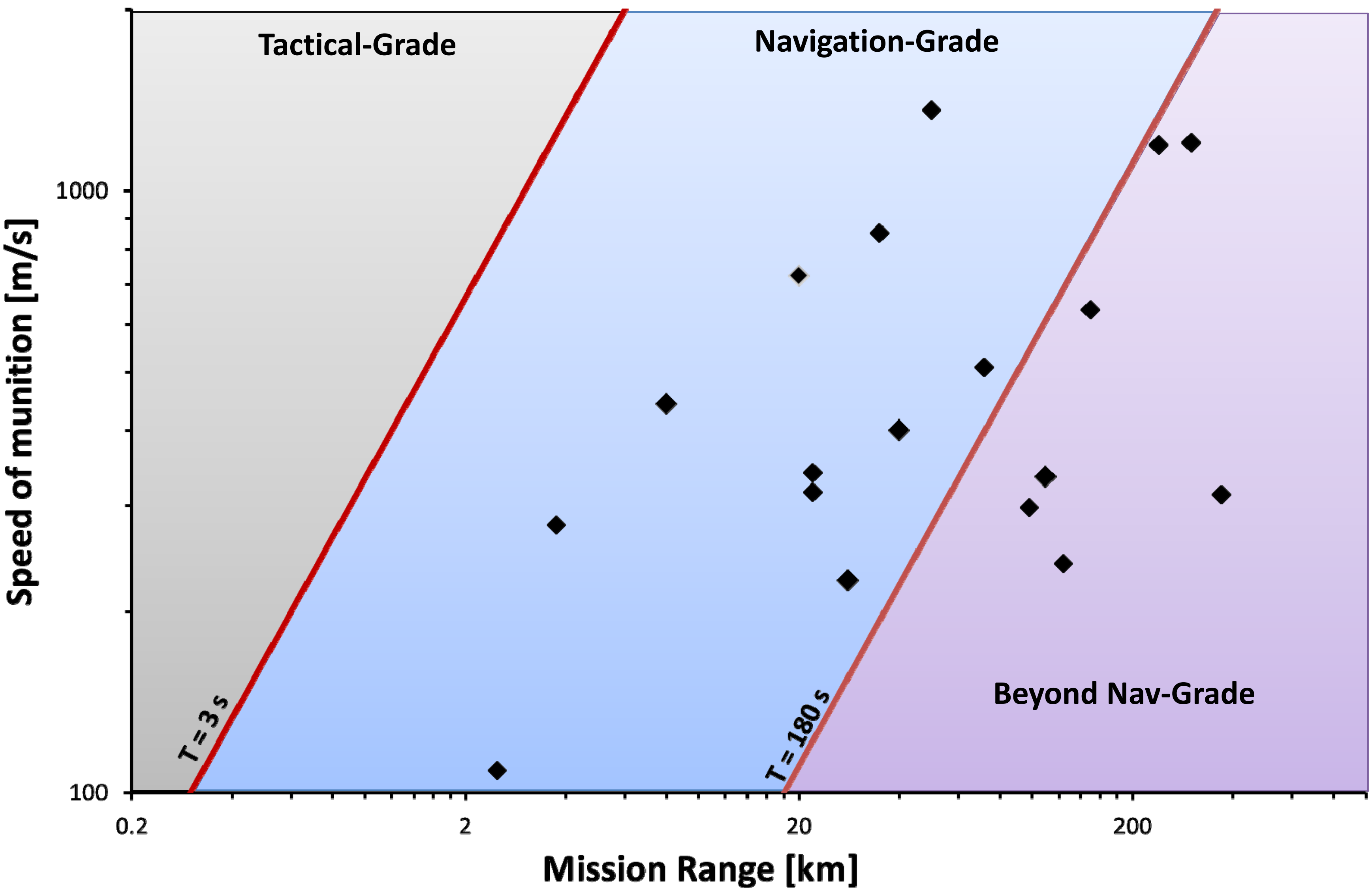


ACES TA-1 Program Milestones

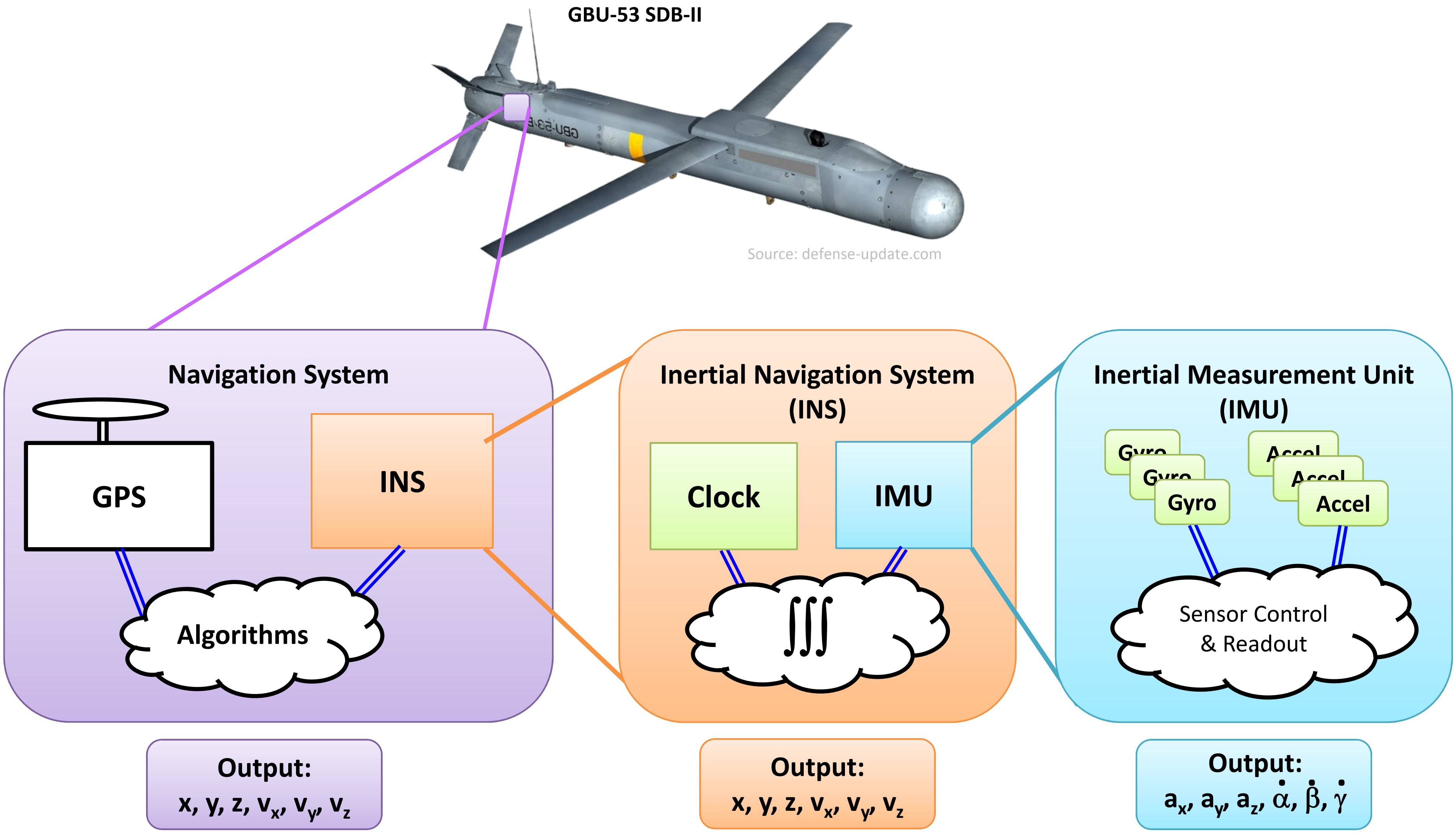
TA-1 over three Phases:

	Proof-of-concept	Integrated Physics	Deliverable Clock
	Phase 1	**Phase 2**	**Phase 3**
Aging	N/A	$< 10^{-12}$/month	$< 10^{-13}$/month
TempCo (-40°C to +85°C)	N/A	$< 10^{-14}/°C$	$< 10^{-15}/°C$
ReTrace (on/off/on, 4/24/4 hours)	$\Delta y < 10^{-11}$	$\Delta y < 10^{-12}$	$\Delta y < 10^{-13}$
Volume	N/A	30 cm^3	50 cm^3
Power	250 mW	250 mW	250 mW
Instability	$\sigma_y(\tau) < 1x10^{-11} / \tau^{1/2}$	$\sigma_y(\tau) < 1x10^{-11} / \tau^{1/2}$	$\sigma_y(\tau) < 1x10^{-11} / \tau^{1/2}$
Notes	Power applies to physics package, which includes all vacuum, optical, and thermal control components	Size and power apply to physics package only, which includes all vacuum, optical, and thermal control components	Size and power apply to fully packaged device, which includes all physics and electronic components

Simplified Missile/Munition Profiles



Munitions Navigation



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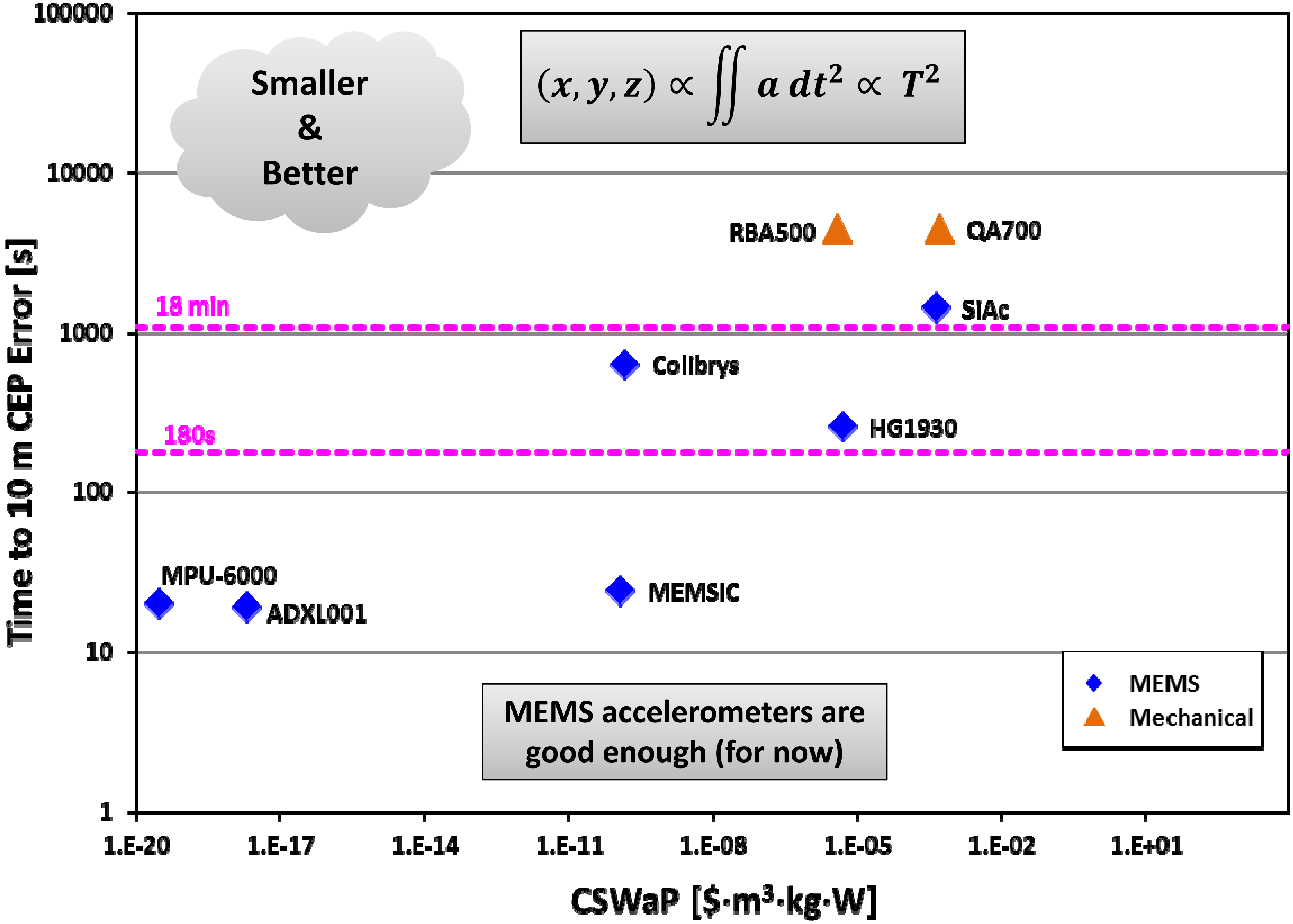
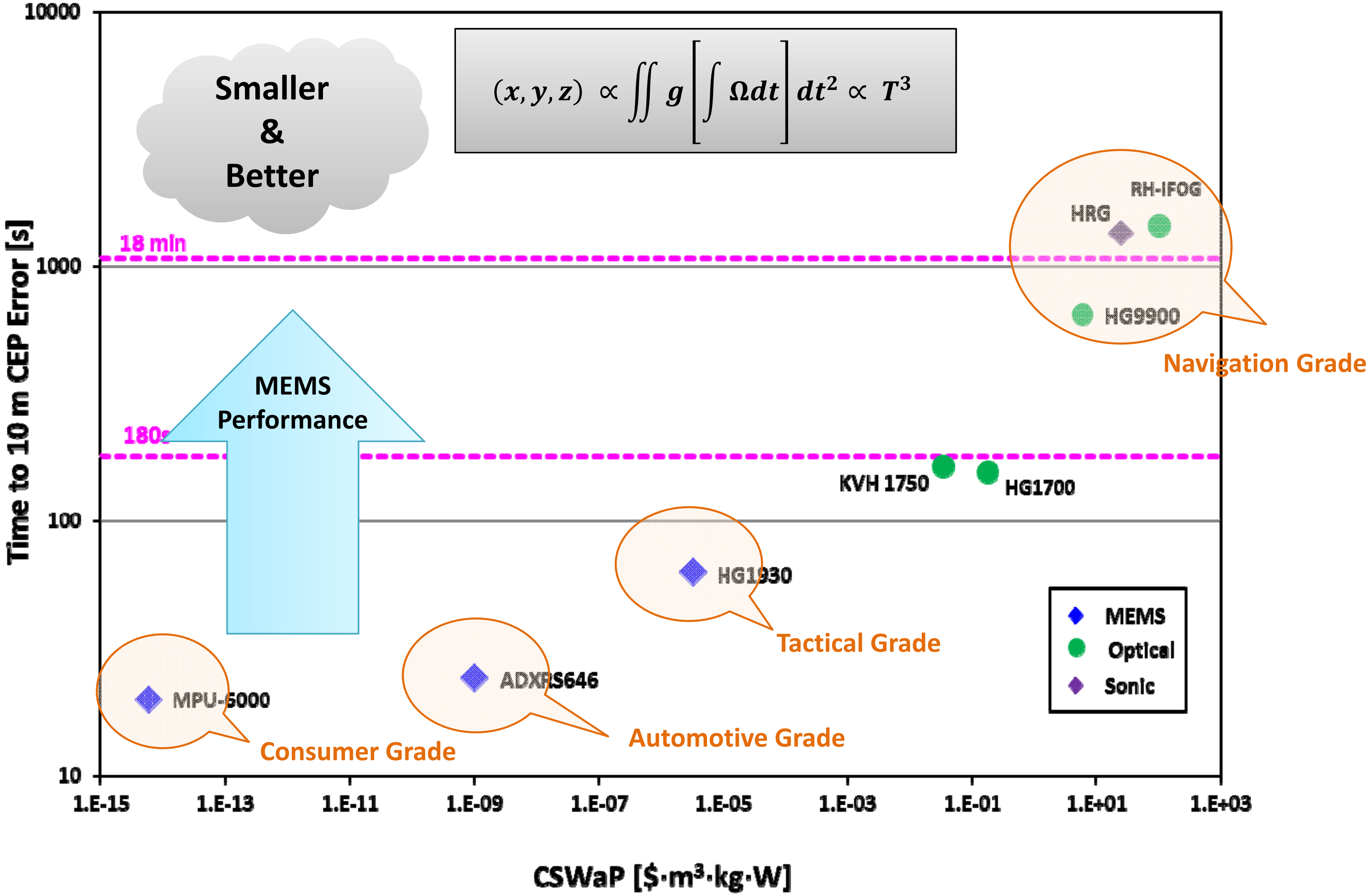
State-of-the-Art Accelerometers



State-of-the-Art Gyroscopes



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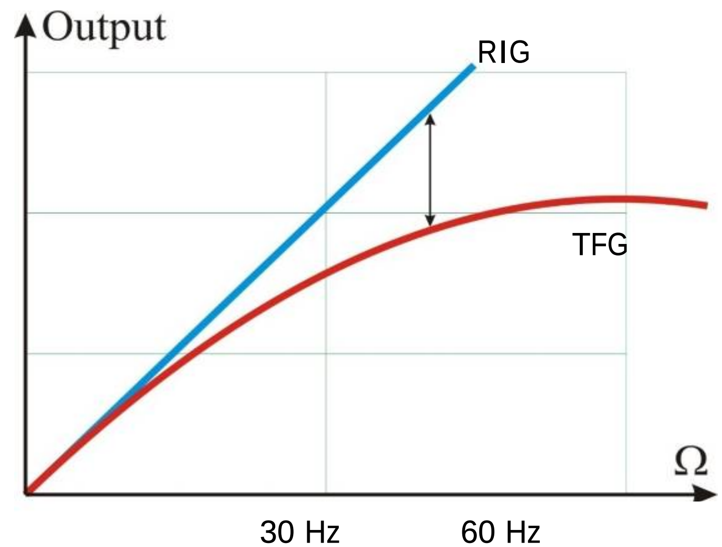
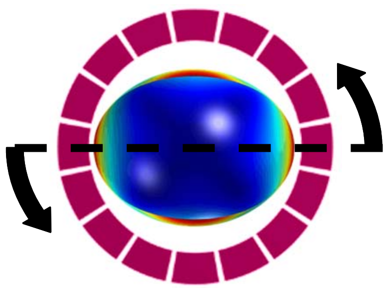
Micro-Scale Rate-Integrating Gyroscope (MRIG)

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

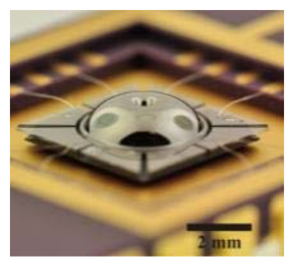


Northrop Grumman
Hemispherical Resonator Gyroscope (HRG)
4W, 250 cm^3, $100K



Courtesy L. Sorenson, HRL

Novel 3-D MEMS



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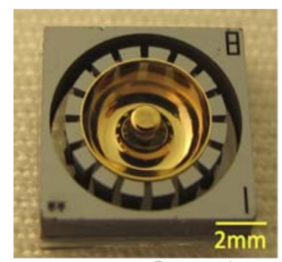

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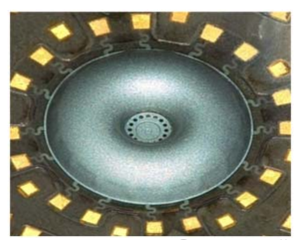

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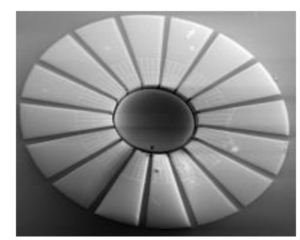

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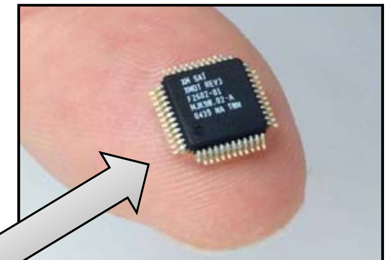
Single-Chip Timing and Inertial Measurement Unit (TIMU)

TIMU Objective:
Fully-integrated co-fabricated 6-DOF IMU with extremely low CSWaP

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



http://tinyurl.com/po7lqgz

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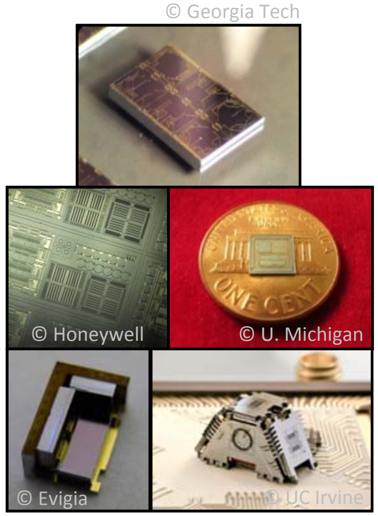
TIMU Approaches

Monolithic (single die)

Multi-layer (stacked die)

Three-dimensional (folded/co-integrated)



Goal	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**

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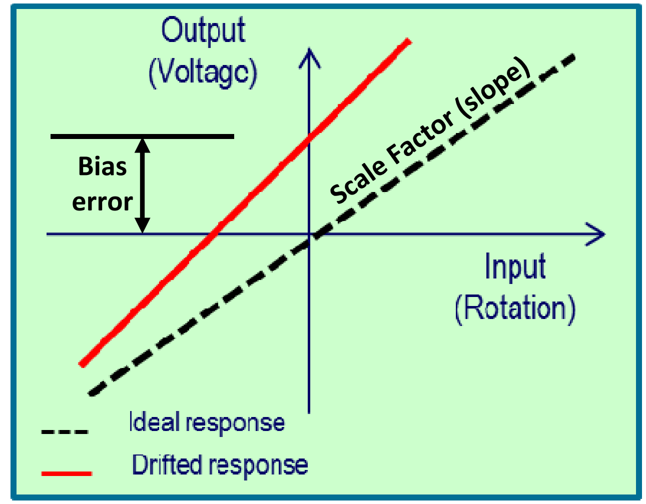
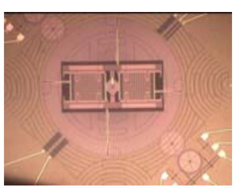
Primary and Secondary Calibration on Active Layer

PASCAL Objective:
Realize MEMS inertial sensors with on-chip calibration
Absolute calibration is essential for north-finding

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



Technical Area 1 (TA1): Mechanical self-calibration	**Technical Area 2 (TA2):** Electronic self-calibration
• Co-integrated gyroscope + rotary stage • External physical stimulus • Maytagging, dithering	• Electronic stimulus mimics rotation • Mode-reversal, virtual carouseling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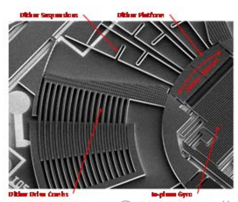
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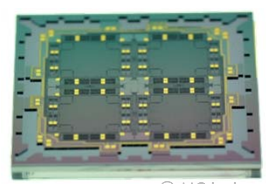
- Fabrication challenges delayed TA1 performer transition to Phase 3; results anticipated in Spring 2016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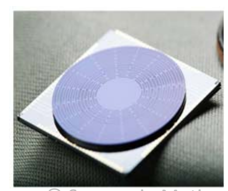
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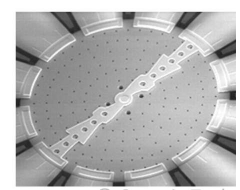
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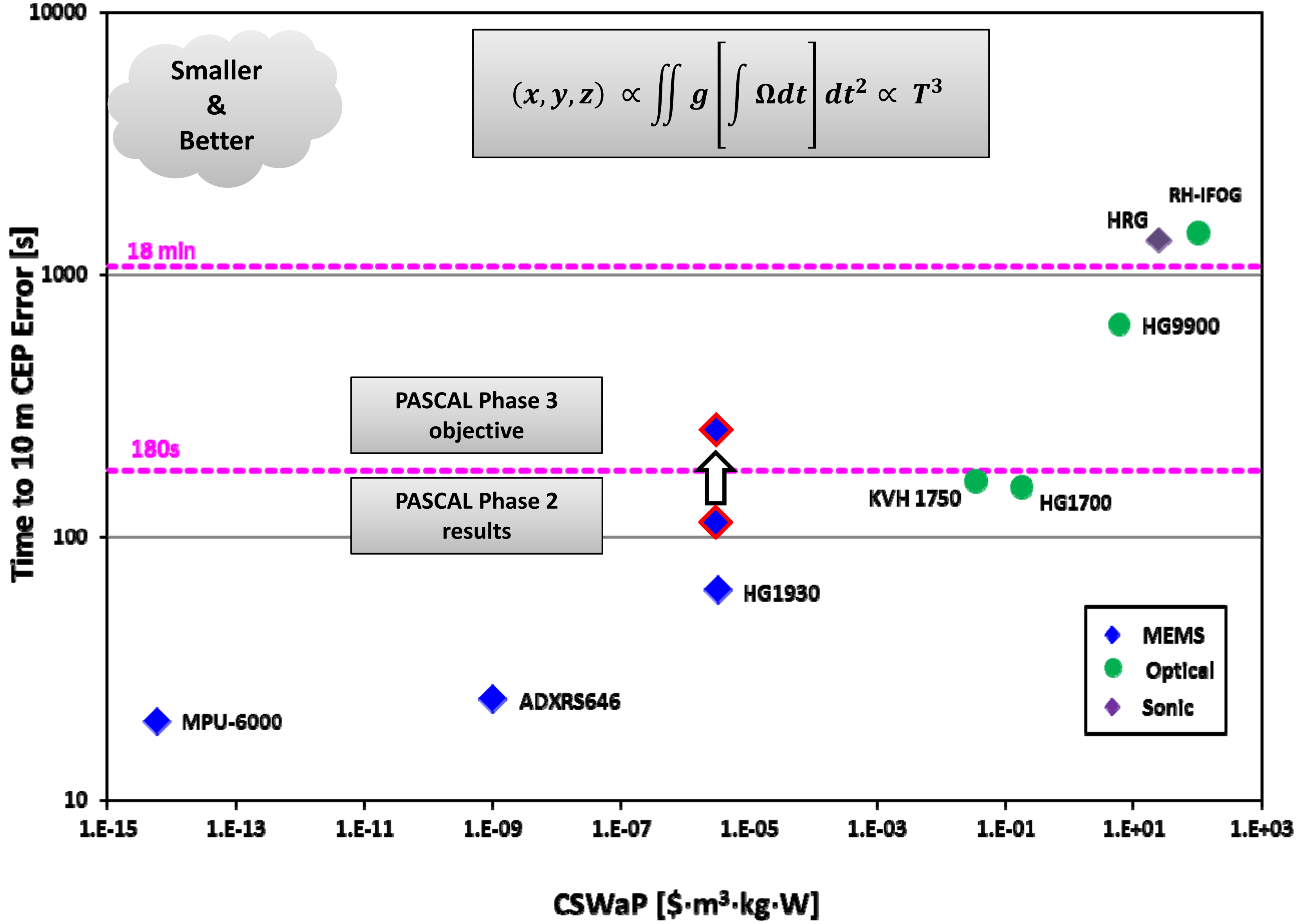
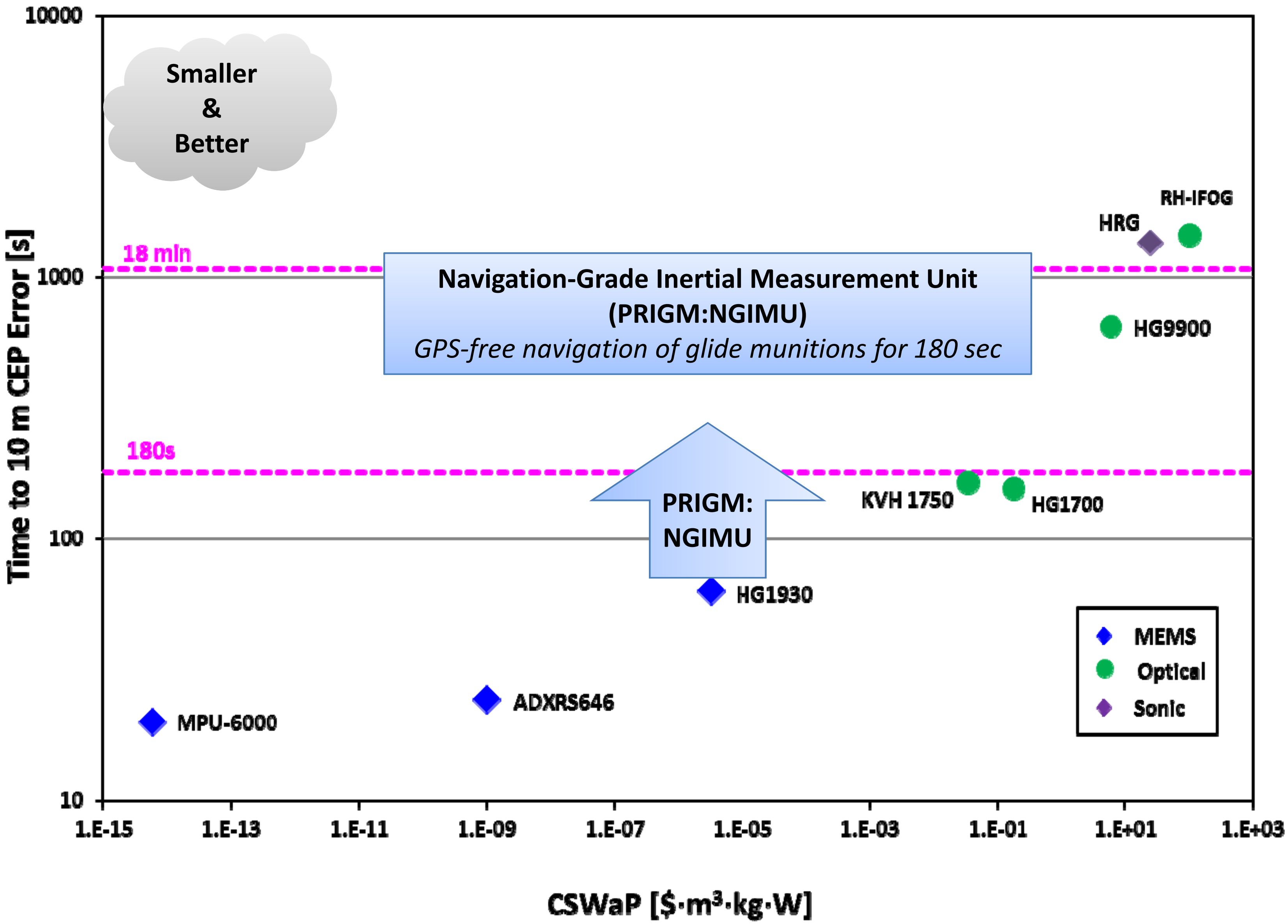
- Four performers (TA2) have submitted devices for Phase 2 government evaluation

SOA Gyroscopes



Precise Robust Inertial Guidance for Munitions (PRIGM)



PRIGM:NGIMU Program Overview

Motivation

- Enable guided munitions in GPS-contested theaters by 2020

Objective

- Eliminate compromise between **low-CSWaP, tactical-grade MEMS** and **high-CSWaP, navigation-grade RLG/iFOG-based IMUs**
- 6.3 program will deliver 10 prototype drop-in replacement **navigation-grade MEMS IMUs** in 2019
- Engage Service Labs to perform flight demos in 2020

Navigation-grade performance with MEMS CSWaP

Current IMU Technology		PRIGM:NGIMU Enabled Technology
 © Honeywell **Nav-Grade IMU** **Ring laser gyros, quartz accels**	vs.  © Honeywell **Tactical-Grade IMU** **MEMS gyros & accels**	 © Honeywell **Navigation-Grade IMU** **SOA MEMS gyros & accels**

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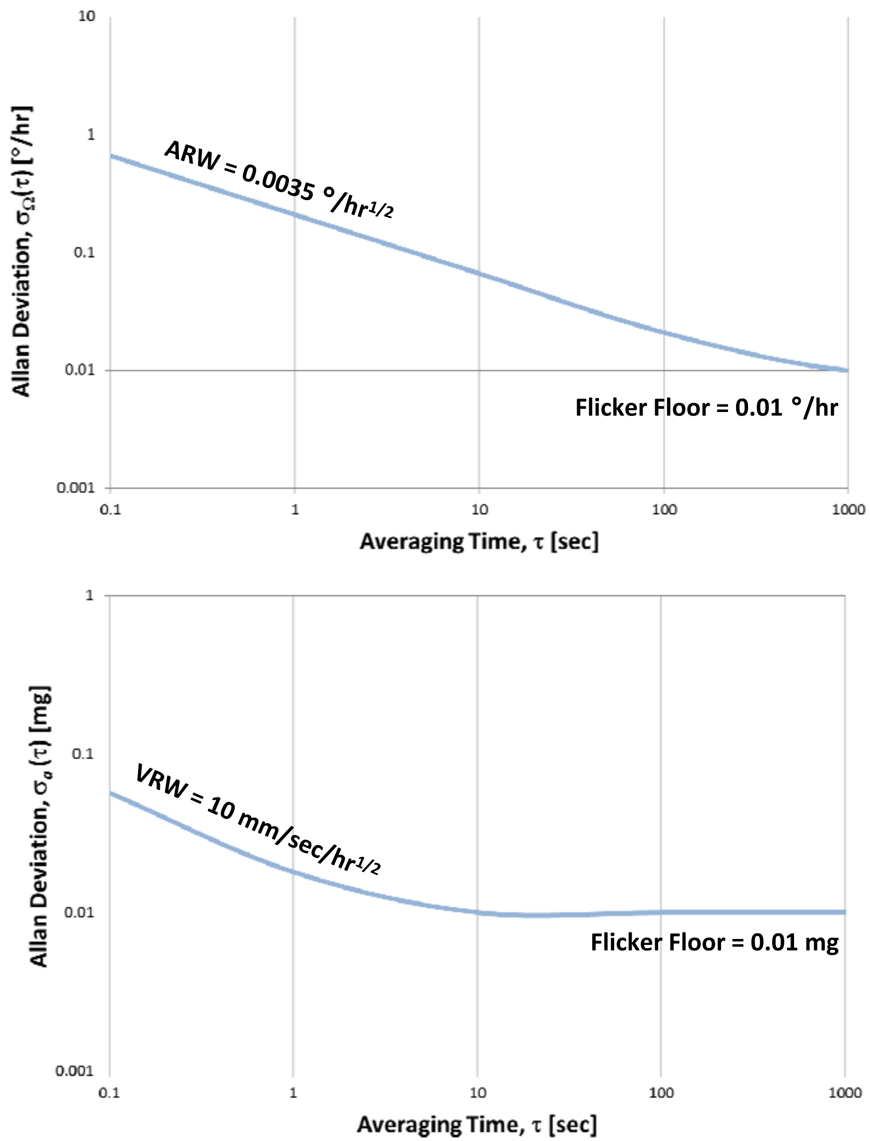
PRIGM:NGIMU Program Objectives

Program Deliverables: 10 MEMS-based IMUs at TRL 6 that are DoD-standard, tactical-grade drop-in replacements with navigation-grade performance

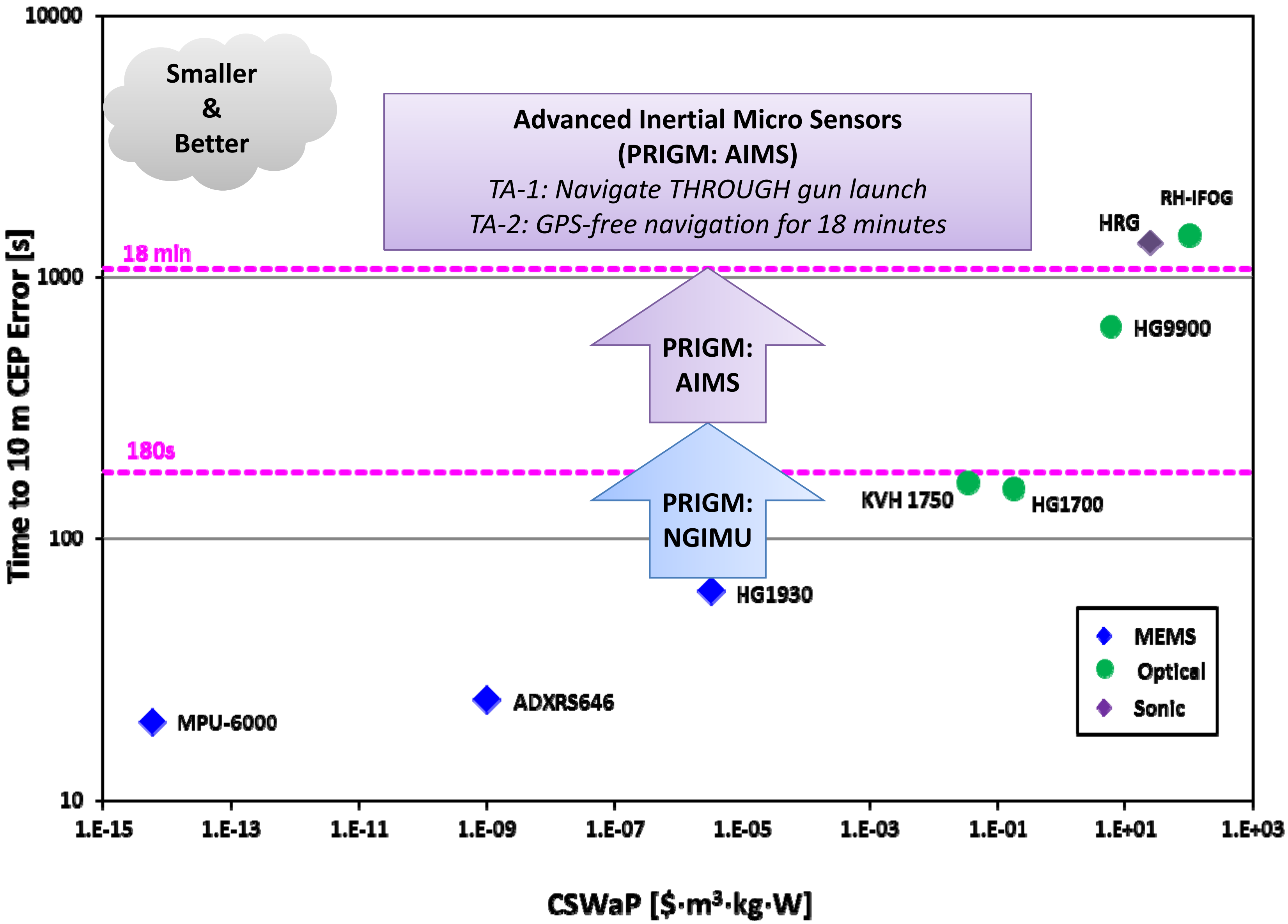
Performance Metric	Objective	Units
Volume	82	**cm^3**
Weight	160	**g**
Power	< 3	**W**
Operating temperature range	-54 to +85	**°C**
Vibration DC to 2 kHz	7.7	**g_{RMS}**
Shock survivability	20,000	**g**
Bandwidth (min. @ -90° phase lag)	70	**Hz**
Gyroscope		
Operating range	± 900	**°/sec**
Turn-on to turn-on bias repeatability	0.01	**°/hr, 1σ**
Scale factor repeatability	5	**ppm**
Accelerometer		
Operating range	± 60	**g**
Turn-on to turn-on bias repeatability	25	**µg, 1σ**
Scale factor repeatability	25	**ppm**

PRIGM:NGIMU Program Objectives



Stability Specification (Allan Deviation)		
τ [sec]	Gyroscope $\sigma_\Omega(\tau)$ [°/hr]	Accelerometer $\sigma_a(\tau)$ [mg]
0.1	0.66	0.19
1	0.21	0.06
10	0.066	0.01
100	0.021	0.01
1000	0.01	0.01

SOA Gyros: Path to Advanced Inertial Micro Sensors



AIMS Approaches: Rate Integrating Gyroscopes

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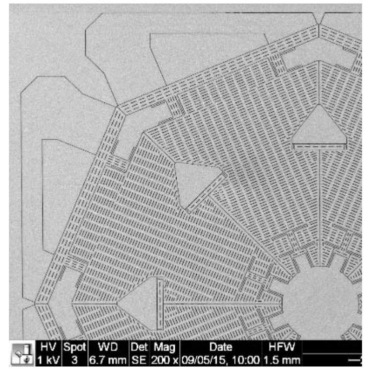
Conventional
Hemispherical Resonator Gyro (HRG)

AIMS



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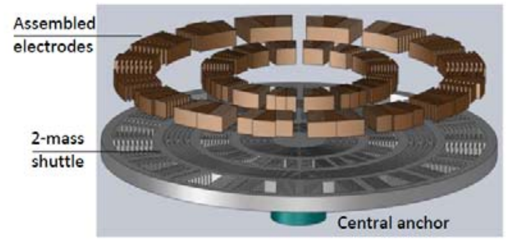

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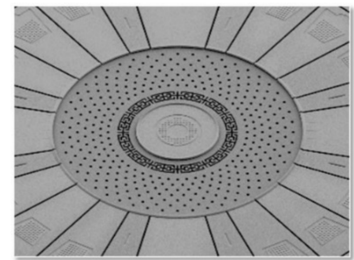

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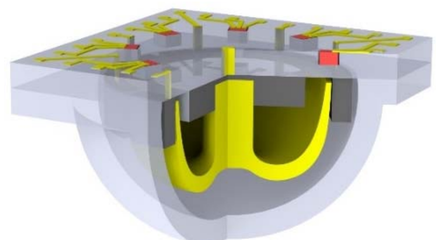

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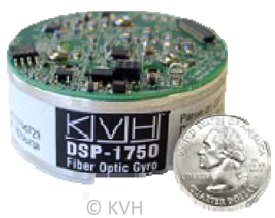
MEMS Rate Integrating Gyroscopes

Advantages:
- No mechanical bandwidth limit
- No integration error
- Certain candidate geometries (disks, shells) are shock and vibration tolerant
- Silicon carbide (SiC) provides environmental robustness

Challenges:
- High symmetry required to achieve high-performance
- Poor SNR due to circumferential sensing

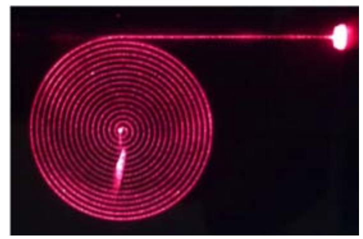
AIMS Approaches: Photonic Gyroscopes

Waveguide Optical Gyroscopes: Integrated FOG/RLG on a chip



Conventional Fiber Optic Gyro

AIMS



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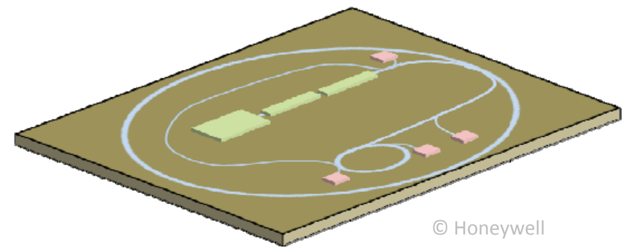


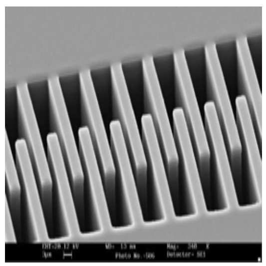
Photonic waveguide gyro

Advantages:
- No moving parts
- Tight integration reduces CSWaP and key environmental sensitivities of conventional FOG/RLG

Challenges:
- Low-loss waveguides
- Vertical integration of multiple waveguides for higher sensitivity
- High SNR needed to overcome smaller enclosed area than fiber spool
- Photonic integration

AIMS Approaches: Optically Interrogated MEMS

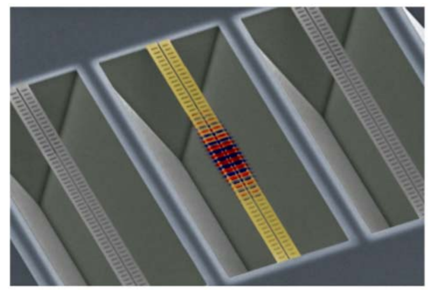
Optically Sensed MEMS Accelerometers



http://www.tbp.org/pubs/Features/Su06Brown.pdf

Conventional capacitive sensing

AIMS



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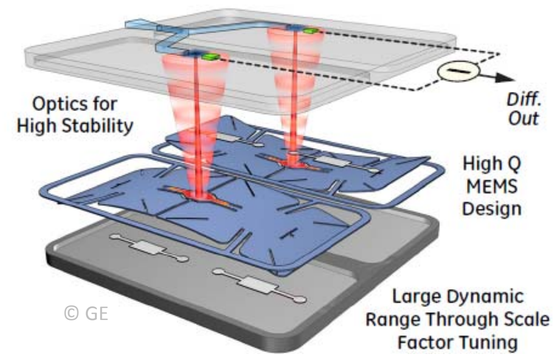


Optically interrogated accelerometers

Optical rather than capacitive sensing of MEMS position for high SNR

Advantages:

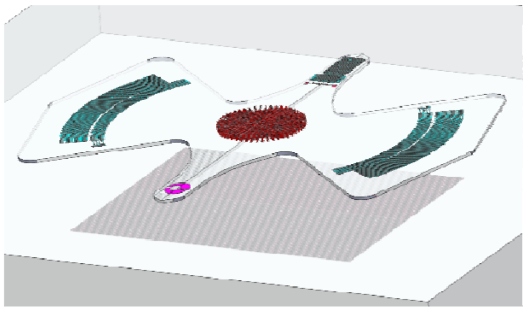
- High displacement sensitivity allows for stiffer structures (gun-hardened)
- Stiffer structures → higher bandwidth
- Potential for self-calibration in units of laser wavelength (“light as a ruler”)

Challenges:

- Opto-electronic-MEMS co-fabrication/integration
- Laser wavelength stability

AIMS Approaches: Acoustic Gyros, Accelerometers

Surface Acoustic Wave (SAW) Gyroscopes



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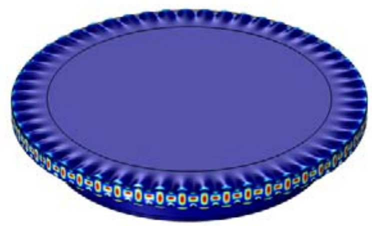

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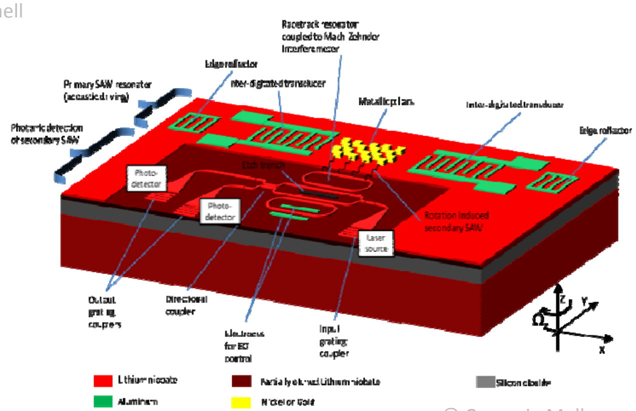

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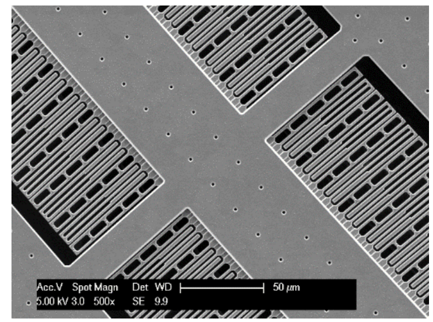
Resonant and Thermal Accelerometers



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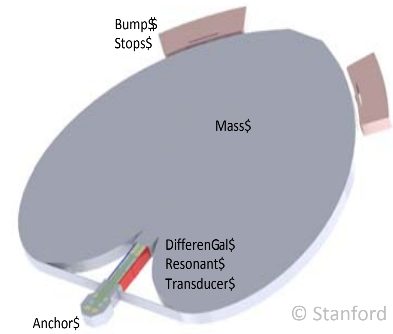

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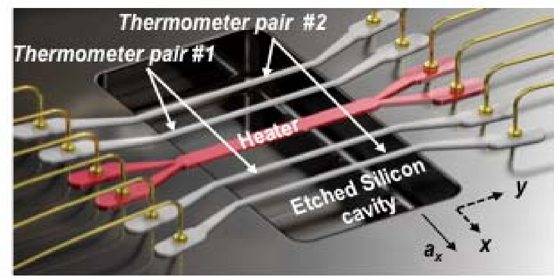

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Advantages:

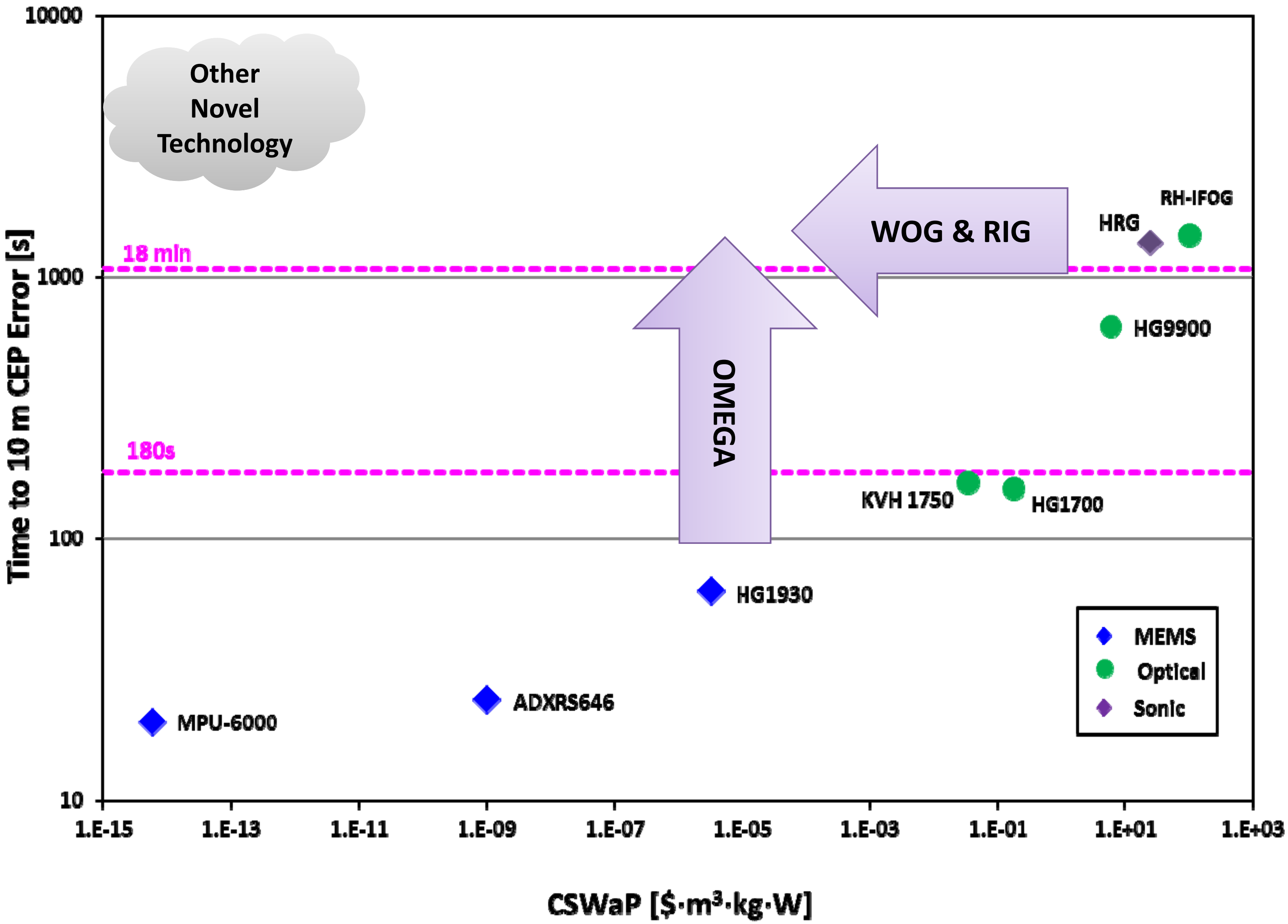
No moving parts (environmental robustness, gun-hardened)

Increased gyro sensitivity due to optical readout

Challenges:

Thermal stability

SOA Gyros: Path to Advanced Inertial Micro Sensors



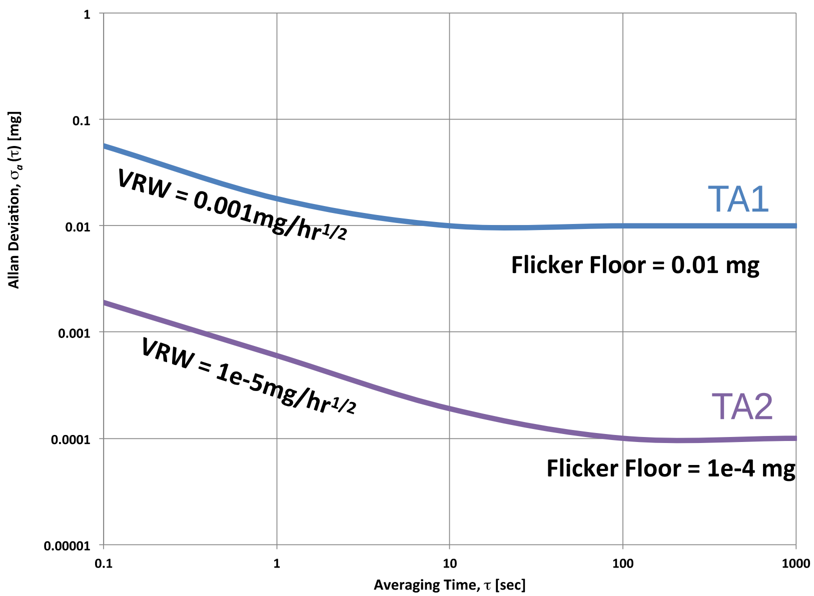
DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

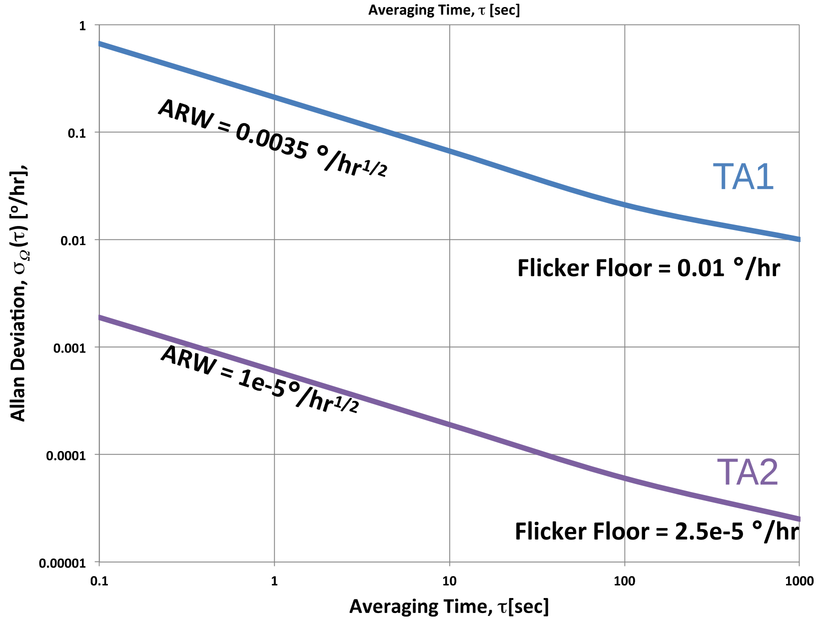
PRIGM: AIMS Program Objectives

SWaP & Survival Metric	TA1	TA2
Volume	1 cm^3	1 cm^3
Weight	1 g	1 g
Power	250 mW	250 mW
Operating temperature range	-54 to +85 ^oC	-54 to +85 ^oC
Vibration (5Hz to 5kHz)	50 g_{RMS}	7.7 g_{RMS}
Shock survivability	50,000 g	20,000 g

Operating Conditions				
	Gyroscope		Accelerometer	
	TA1	TA2	TA1	TA2
Full-Scale Range	±100,000 ^{o}/s	±900 ^{o}/s	±50,000g	±60g
Bias Repeatability	0.01 ^{o}/hr	0.001 ^{o}/hr	10 μg	1 μg
Bias Environmental Sensitivity	0.01 ^{o}/hr	2e-5 ^{o}/hr	10 μg	0.5 μg
Scale Factor Repeatability	1 ppm	0.01 ppm	1ppm	1ppm
Scale Factor Environmental Sensitivity	1 ppm	1 ppm	1 ppm	1 ppm

PRIGM: AIMS Program Objectives





Stability Specification (Allan Deviation)				
τ [sec]	Gyroscope $\sigma_\Omega(\tau)$ [°/hr]		Accelerometer $\sigma_a(\tau)$ [mg]	
	TA1	TA2	TA1	TA2
0.1	0.66	2e-3	0.19	1.9e-2
1	0.21	6e-4	0.06	6e-3
10	0.066	2e-4	0.01	1.9e-4
100	0.021	6e-5	0.01	1e-4
1000	0.01	2.5e-5	0.01	1e-4

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