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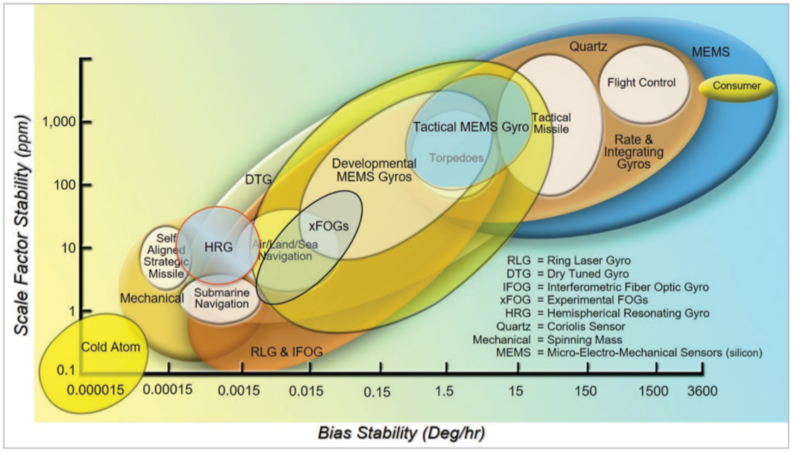
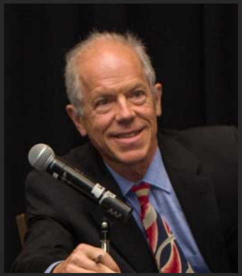


INERTIAL GOES PHOTONIC, EXPLODES GYRO TECHNOLOGY

Thursday, May 28, 2020

WELCOME TO

Inertial Goes Photonic, Explodes Gyro Technology



Alan Cameron
Editor in Chief
Inside GNSS
Inside Unmanned Systems

Ralph Hopkins
Distinguished Member Technical Staff
Charles Stark Draper Laboratory

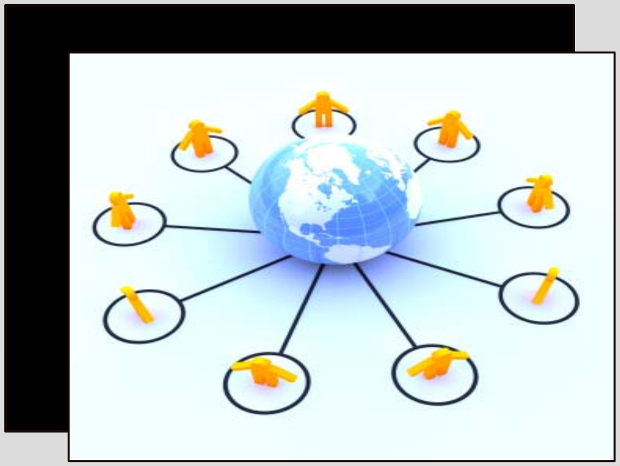
Skip Ashton
Vice President Product Development
KVH Industries, Inc.

Roger Ward
Director FOG Product Development
KVH Industries, Inc.

Co-Moderator: Lori Dearman, Executive Webinar Producer

Who’s In the Audience?

A diverse audience of over 450 professionals registered from 30 countries, representing the following industries:



- 28% Military and Defense
- 12% University/Education
- 11% Research
- 8% Automotive
- 6% Machine Control/Mining/Construction
- 4% Transportation/Logistics/Asset Tracking
- 2% Precision Agriculture
- 29% Other

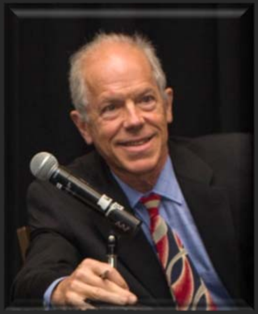
Welcome from *Inside Unmanned Systems*

Richard Fischer
Publisher
Inside GNSS
Inside Unmanned Systems

A word from the sponsor

Sean McCormack
Sr. Director Global Inertial Systems
KVH Industries, Inc

Today's Moderator



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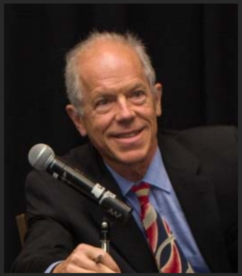

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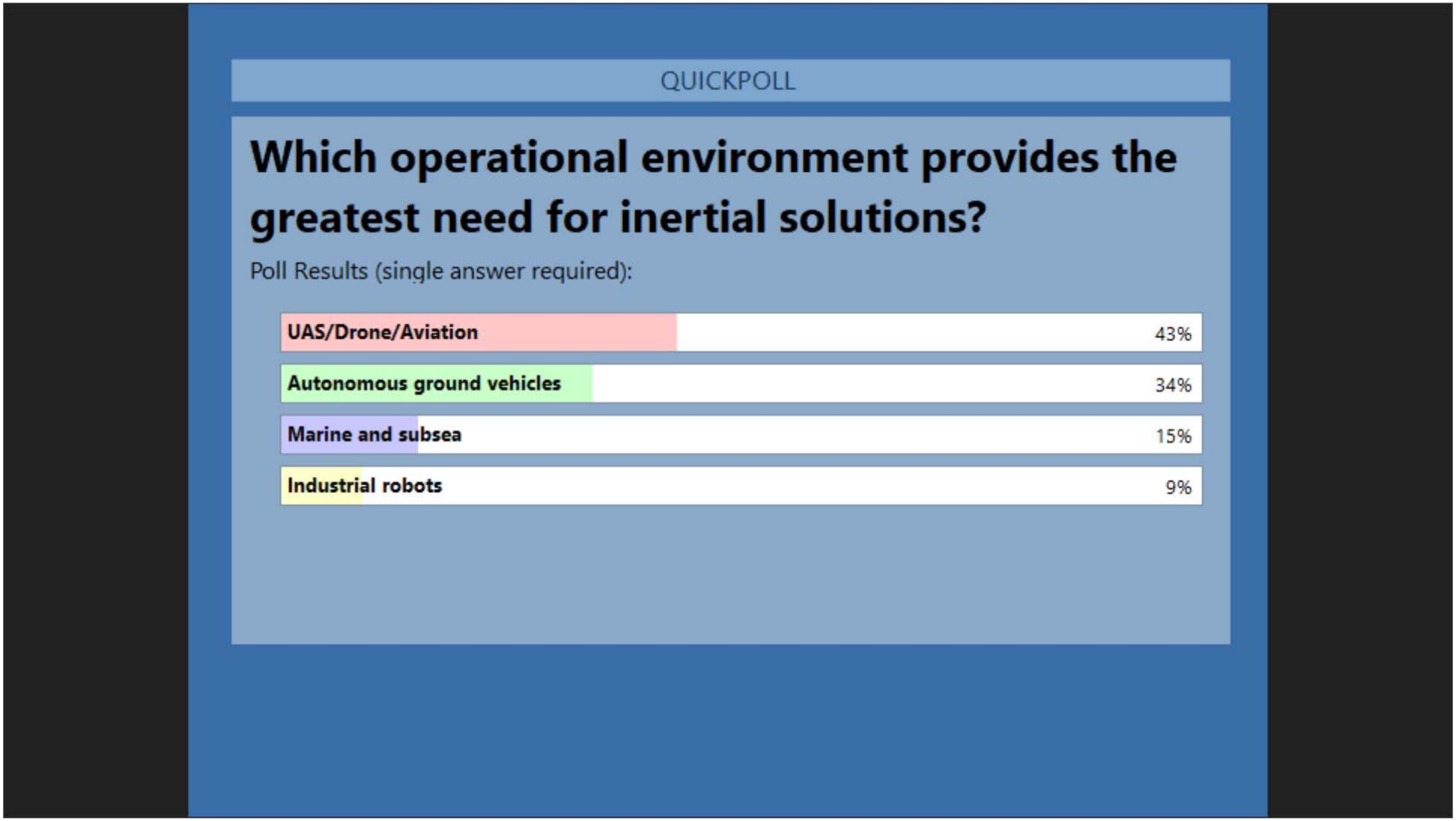


QUICKPOLL

Which operational environment provides the greatest need for inertial solutions?

Poll Results (single answer required):

UAS/Drone/Aviation	43%
Autonomous ground vehicles	34%
Marine and subsea	15%
Industrial robots	9%

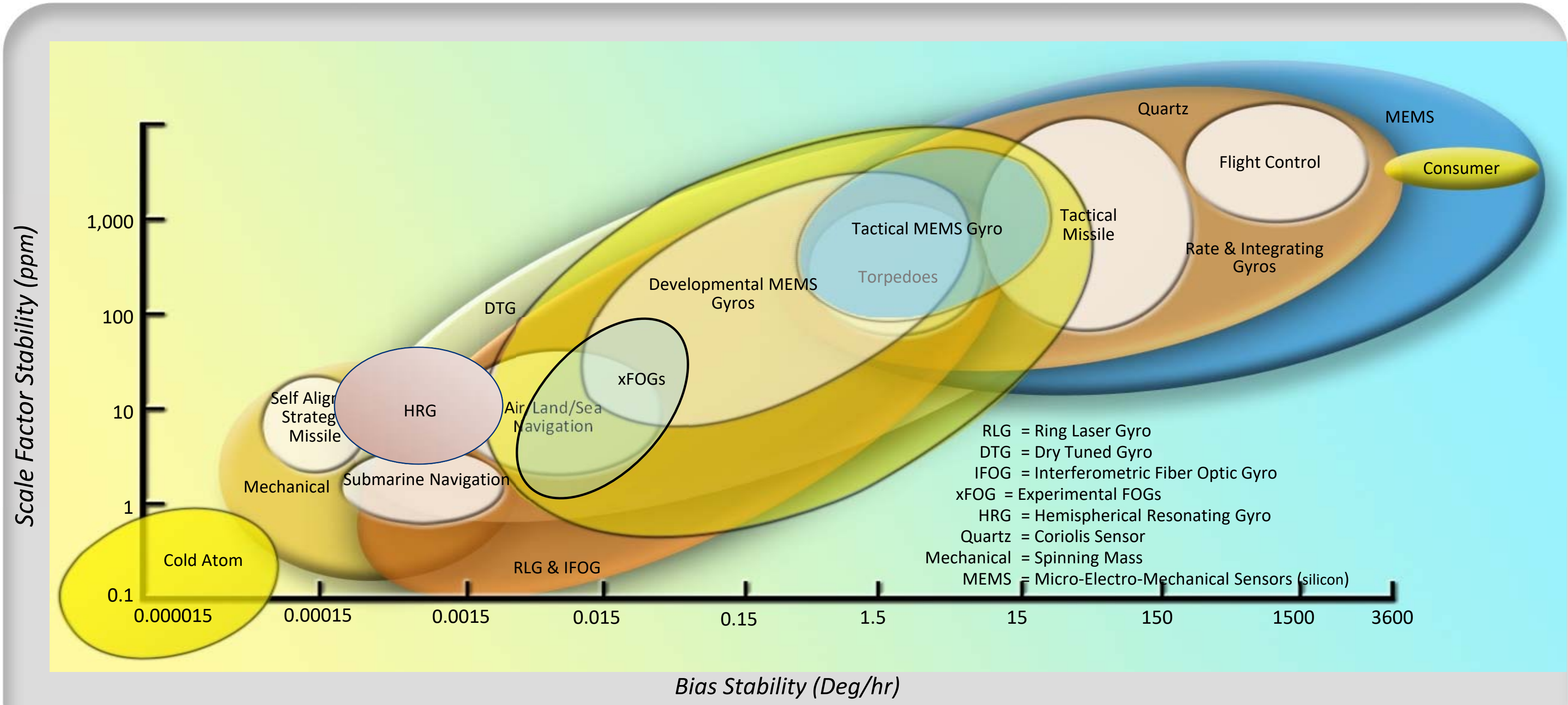
Contemporary and Emerging Inertial Sensor Technologies

Ralph Hopkins
Distinguished Member
Technical Staff
Charles Stark Draper
Laboratory

Overview

- Current Inertial Sensor Landscape
- MEMS and Low SWaP Inertial Sensors
- Emerging Technology Trends
- Inertial System Augmentation
- Inertial Sensors: Where do we go from here?

Current Gyro Technology Applications

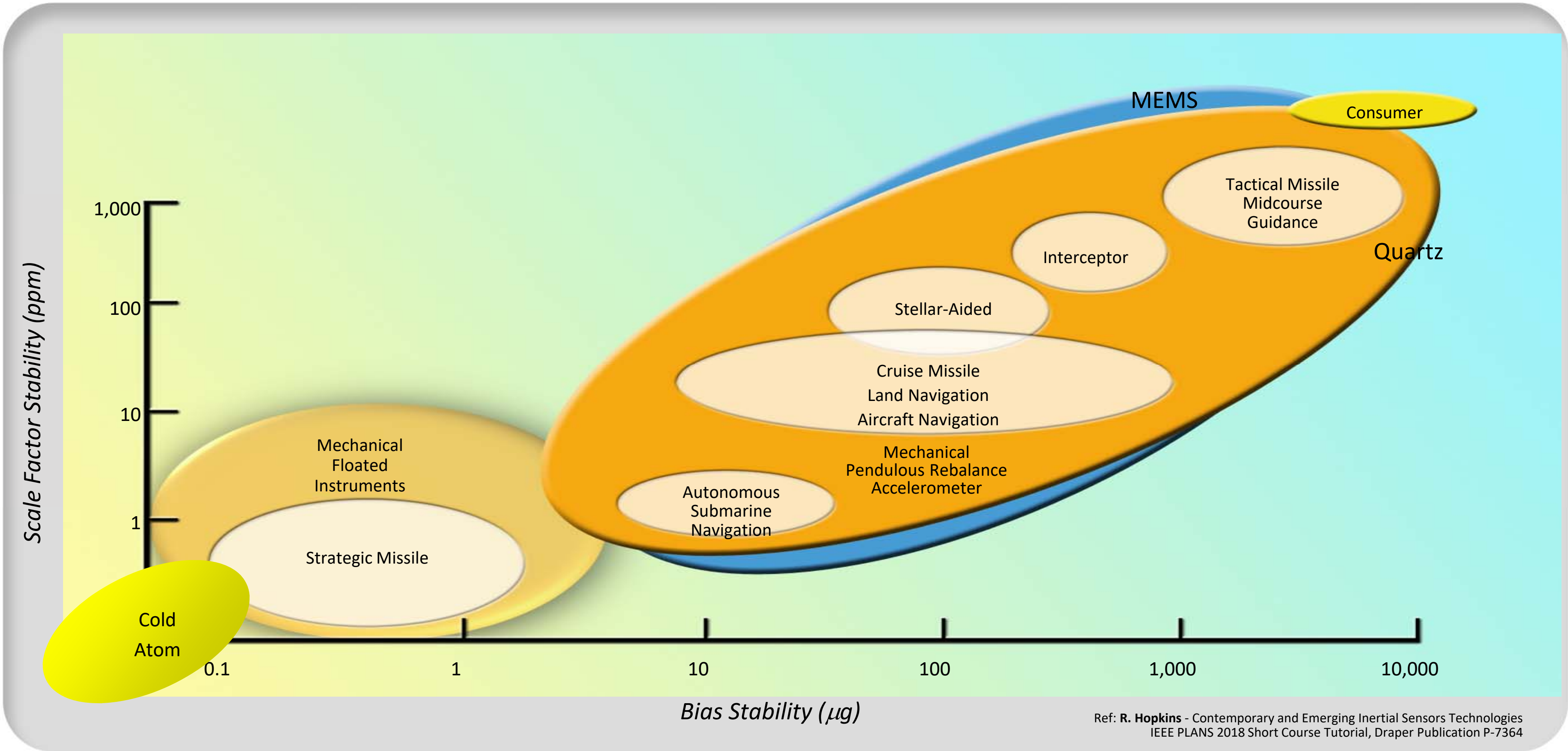


RLG = Ring Laser Gyro
DTG = Dry Tuned Gyro
IFOG = Interferometric Fiber Optic Gyro
xFOG = Experimental FOGs
HRG = Hemispherical Resonating Gyro
Quartz = Coriolis Sensor
Mechanical = Spinning Mass
MEMS = Micro-Electro-Mechanical Sensors (silicon)

Ref: **R. Hopkins** - Contemporary and Emerging Inertial Sensors Technologies
IEEE PLANS 2018 Short Course Tutorial, Draper Publication P-7364

Contemporary and Emerging Inertial Sensor Technologies – *Inside GNSS*
Ralph Hopkins – May 2020

Current Accelerometer Technology Applications



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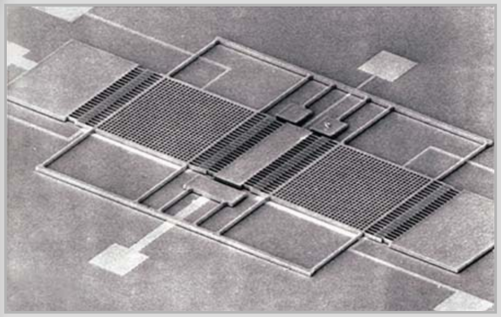
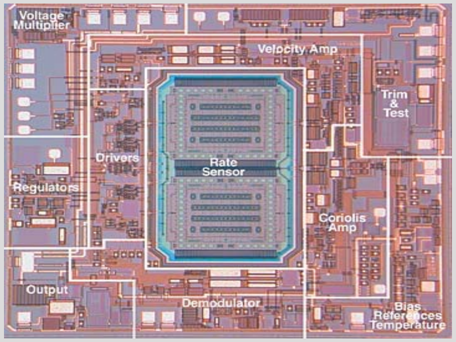
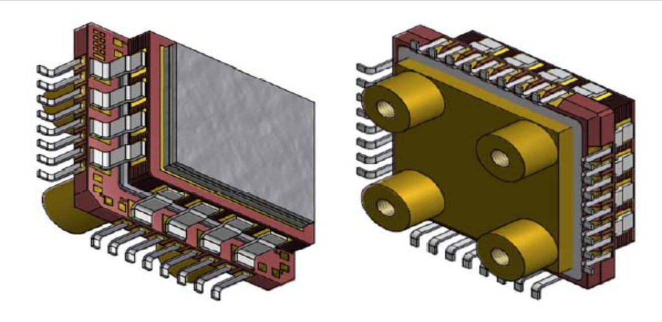
Examples: Miniature Gyroscopes



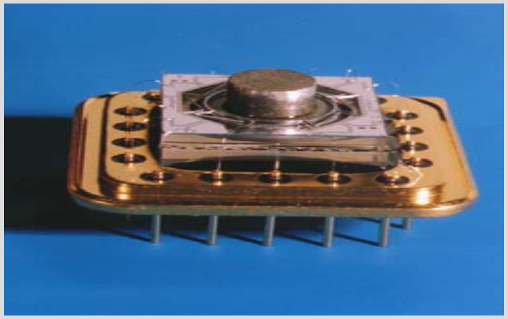
Draper/Honeywell TFG



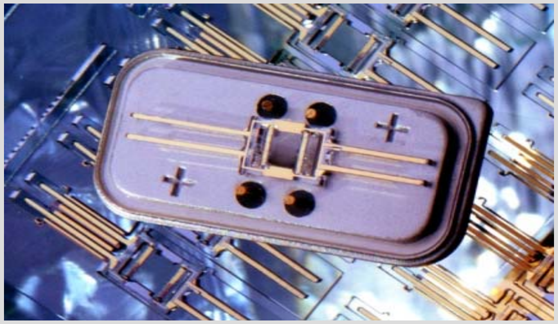
Analog Devices ADXRS



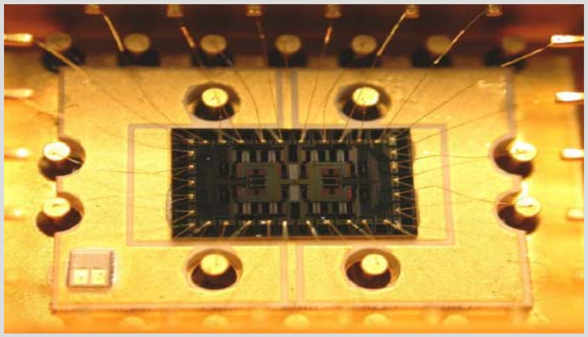
Sensonor SAR500 gyro



UTC SiVSG



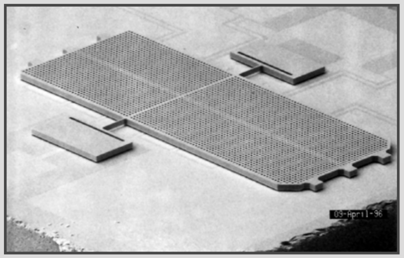
Systron Donner QRS11



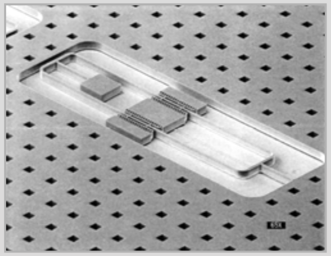
LITEF µCORS gyro

Ref: **R. Hopkins** - Contemporary and Emerging Inertial Sensors Technologies
IEEE PLANS 2018 Short Course Tutorial, Draper Publication P-7364

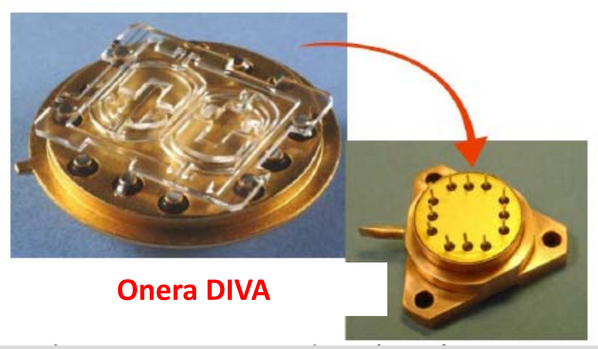
Examples: Miniature Accelerometers



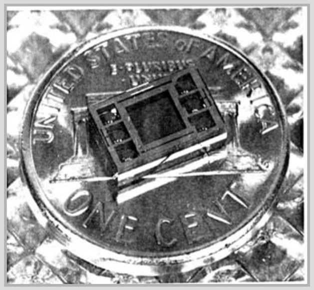
Draper/Honeywell



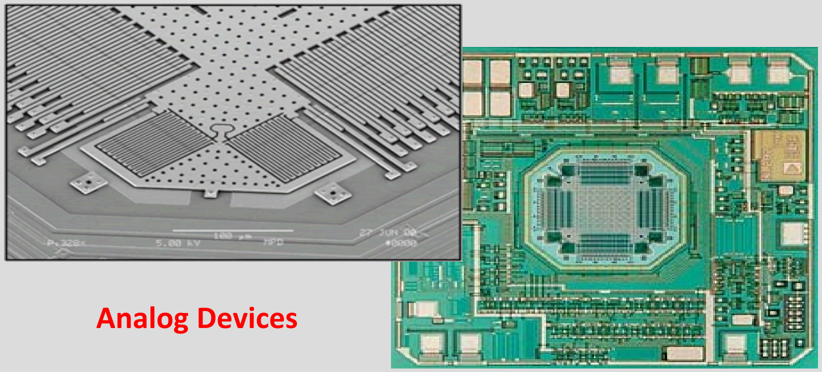
Draper SOA



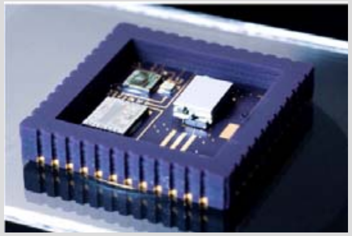
Onera DIVA



Northrop Grumman SiAC



Analog Devices



Colibrys Accelerometer

Solid State MEMS IMUs

UTC - SiIMU02

4 in^3
< 210 gm
< 3.75 W

HI- HG1930

< 5 in^3
< 160 gm
< 3 W

Litef- µIMU-1

< 21 in^3
680 gm
< 8 W

Sensonor – STIM 300

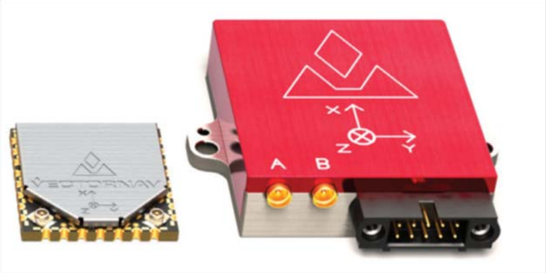
2 in^3
< 55 gm
2 W

SBG – Apogee-D and Ellipse µIMU

60 in^3
< 900 gm
< 7 W

0.3 in^3
10 gm
0.4 W

VectorNav – VN200



0.1 in^3
5 gm
1.2 W

1.3 in^3
30 gm
1.5 W

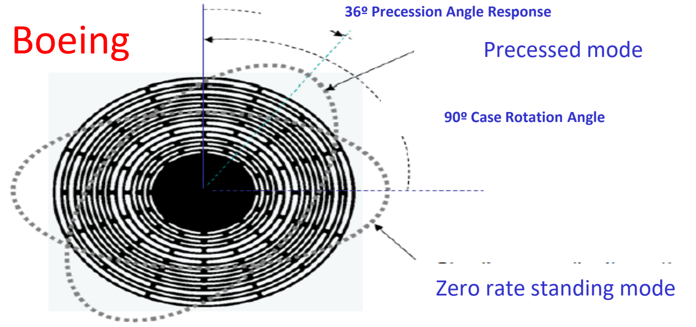
Analog Devices – ADIS1649X

1.8 in^3
42 gm
0.3 W

Contemporary and Emerging Inertial Sensor Technologies – *Inside GNSS*
Ralph Hopkins – May 2020

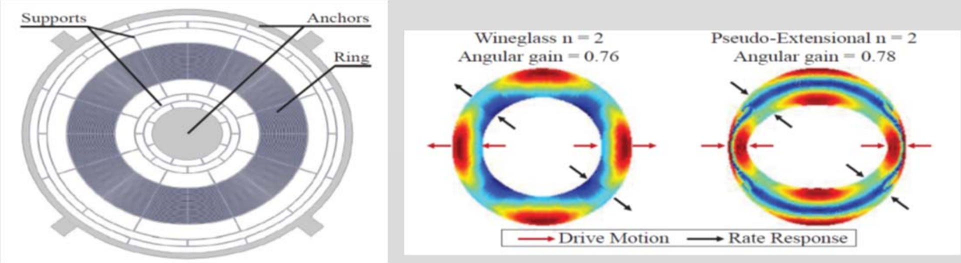
Emerging MEMS Gyro Technology Trends

Boeing



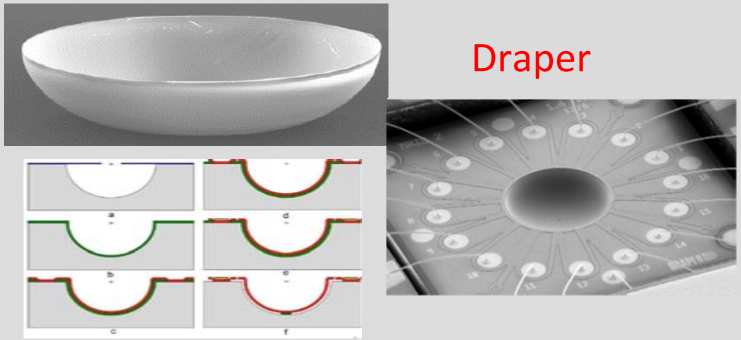
Boeing Disc Resonator Gyroscope: *A.D. Challoner et. al, Boeing Co* ., Proceedings IEEE PLANS 2014, Monterey, CA, May 5-8, 2014

Analog Devices



Prikhodko, I.P, D. Shin, et al. Analog Devices and Stanford University, *Pseudo-Extensional Mode MEMS Ring Gyroscope*: Proceedings 2019 IEEE International Symposium on Inertial Sensors and Systems, Naples, FL

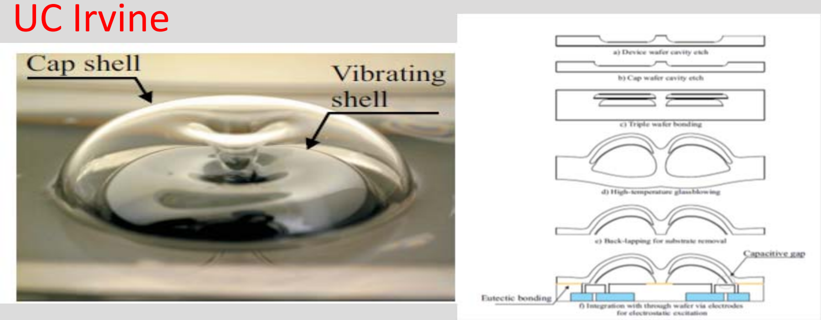
Draper



REF: **Bernstein, J.** et al, *High Q diamond hemispherical resonators: fabrication and energy loss mechanisms* , J. Micromech. Microeng. 25 (2015) 085006

REF: Bernstein et al, *A MEMS diamond hemispherical resonator*, J. Micromech. Microeng. 23 (2013) 125007

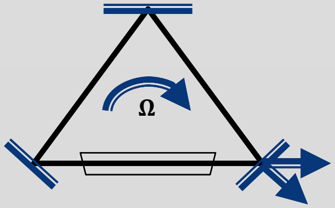
UC Irvine



Asadian, M., Shkel, A., MicroSystems Laboratory, University of California, Irvine, CA, *Fused Quartz Dual Shell Resonator*; Proceedings 2019 IEEE International Symposium on Inertial Sensors and Systems, Naples, FL

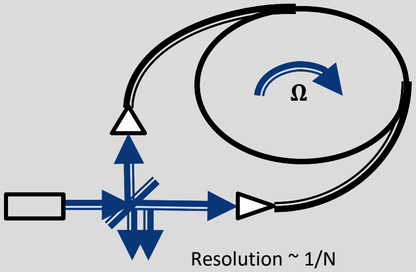
Optical Gyro Size Reduction: Resonating FOG

Ring Laser Gyro
Recirculating light path
Single turn N=1



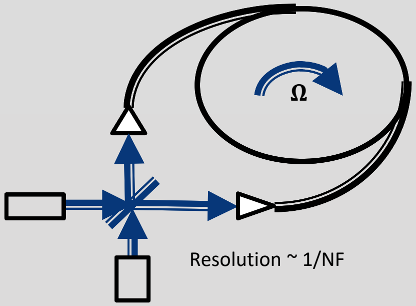
Resolution ~ 1/F

Interferometric FOG
Single pass light path
Multiple turns N>>1



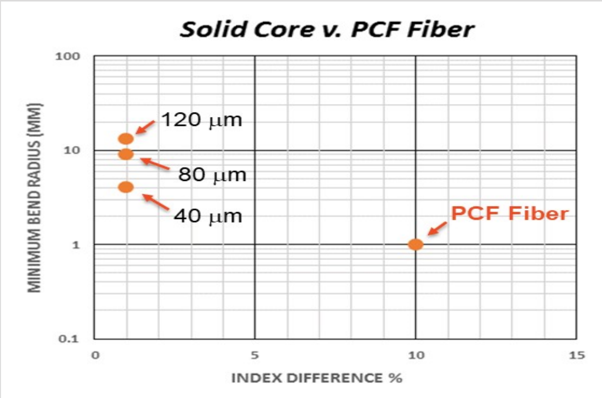
Resolution ~ 1/N

Resonating FOG
Recirculating light path
Multiple turns N>>1



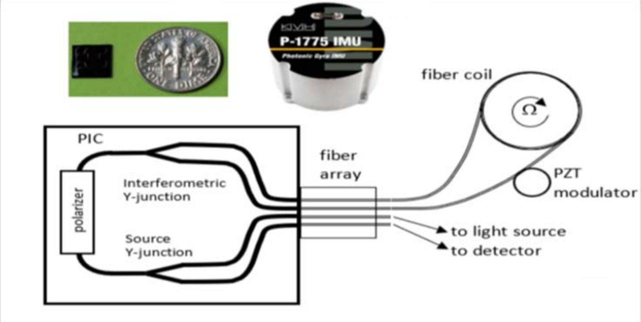
Resolution ~ 1/NF

- RFOG performance driven by resonator quality:
  - *Previous RFOGs limited by errors due to high intensity in glass core & backscatter*
- New developments:
  - *Hollow core PC fiber- bulk of light (99%) travels in AIR not Glass*
  - *Modulation scheme to separately probe CW and CCW resonances*



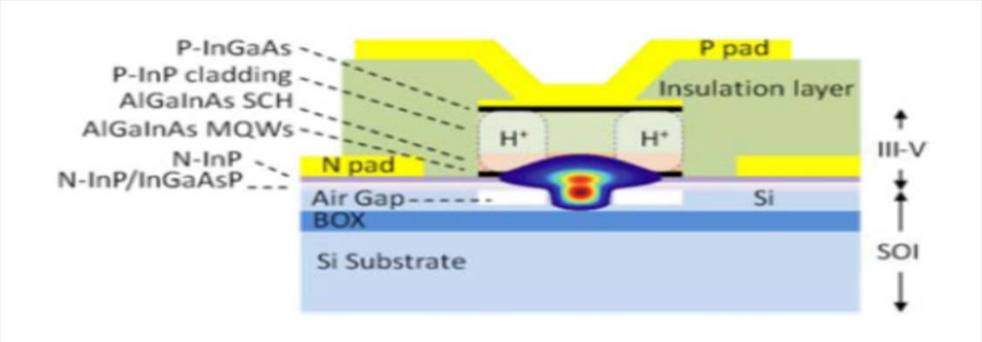
FOG Size Reduction: Integrated Photonics

- Photonic Integrated Circuit (PIC):
    - Si_3N_4/SiO_2 polarization maintaining (PM) waveguides
    - Low-loss waveguide couplers
    - High Polarization Extinction Ratio



Wang L., et al.KVH Industries, *Low-cost, High-end Tactical-grade Fiber Optic Gyroscope Based on Photonic Integrated Circuit*: Proceedings 2019 IEEE International Symposium on Inertial Sensors and Systems, Naples, FL

- Hybrid silicon photonics: CMOS on SOI
    - SOI: Substrate for optical waveguides
        - *Silicon waveguides*
        - *Ultra Low Loss silicon waveguides*
    - CMOS: III/V Semi-conductor Photonic components
        - *Photodetectors, Modulators, etc.*



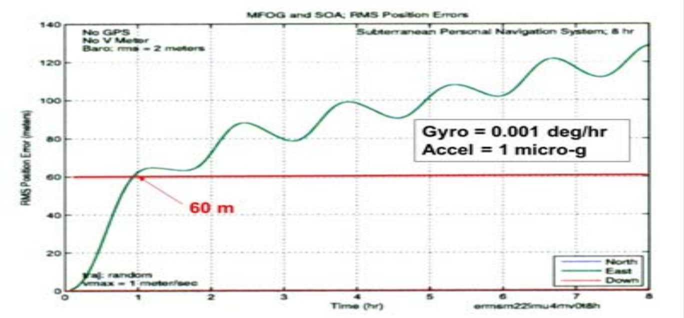
Ref: Spector, et.al, *Mode Engineering for Hybrid SOI/III-V Optical Devices,* SOI Conference (SOI), 2012 IEEE International

Emerging Mission Applications for Miniature INS

	Mission					
Goals	**Urban Personal Navigation System**	**Subterranean Personal Navigation System**		**Search & Rescue Robot**	**Autonomous Land Vehicle**	**Autonomous Undersea Vehicle**
Size (in^3)	10	12		4	25	25
Weight (lb)	0.5	3		1	2	2
Power (w)	5	5		1	20	20
GPS Availability	Intermittent	Denied		Denied	Intermittent	Denied
Mission Time (h)	No Limit	0.5	8	1	1	8
Position Knowledge (meters)	3	3	3	1	3	10
Velocity Meter	Yes	No	Yes	Yes	Yes	Yes
Max Speed (m/s)	1	1	1	1	10	10

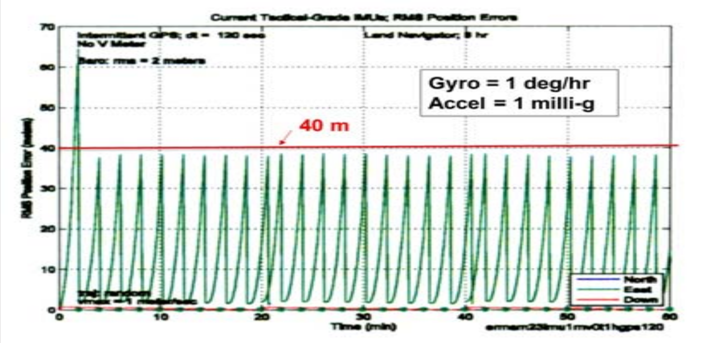
Sensor Augmentation and Integration

Inertial Only

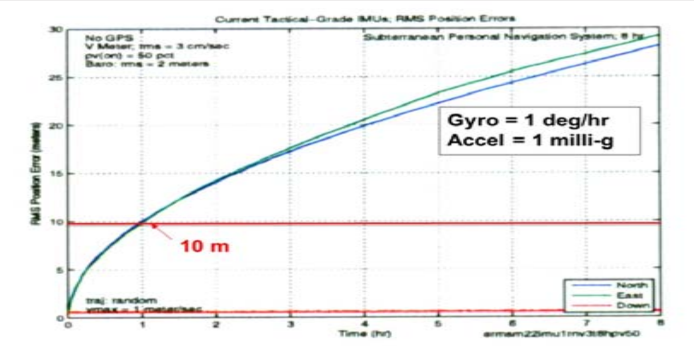


- **Smartphone Personal Navigator**
  - Example Technology Elements:
    - COTS Inertial (10°/hr, 1 mg)*
    - GPS
    - Optimal Navigation Filter
    - ZUPT/ZARU
    - Altimeter/Magnetometer
    - Doppler Radar
    - Map Matching

Inertial w/GPS Updates



Inertial w/Velocity Meter



Inertial Sensor technology: Where do we go from here?

- **MEMS technology originated ~1985 and has rapidly developed into global multi-billion dollar a year business**
  - Inertial products span mid-level tactical grade to consumer mass market performance range
  - New fabrication processes and design architectures are pushing inertial performance into the navigation grade regime
- **Advances in photonic technology being adapted in FOG designs ("Tech pull")**
  - Optical fibers and waveguides (small diameter PM, photonic crystal, IOC, ULLW)
  - Silicon Hybrid photonic platform
- **Emerging and future PN&T solutions will be based on integrated inertial and augmentation sensor architectures implemented in a variety of platforms**
  - Inertial sensors as chip-scale commodity item

- Inertial technology will remain a critical and evolving enabling feature, but PN&T product value will lie in the integrated system, not individual components

PN&T System > Sum of parts

Part I: Requirements for PIC Reliability Testing and Release to Manufacturing

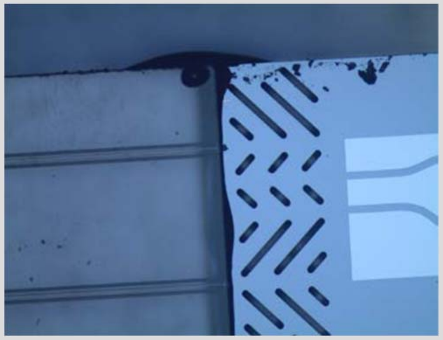
Skip Ashton
Vice President Product Development
KVH Industries, Inc.

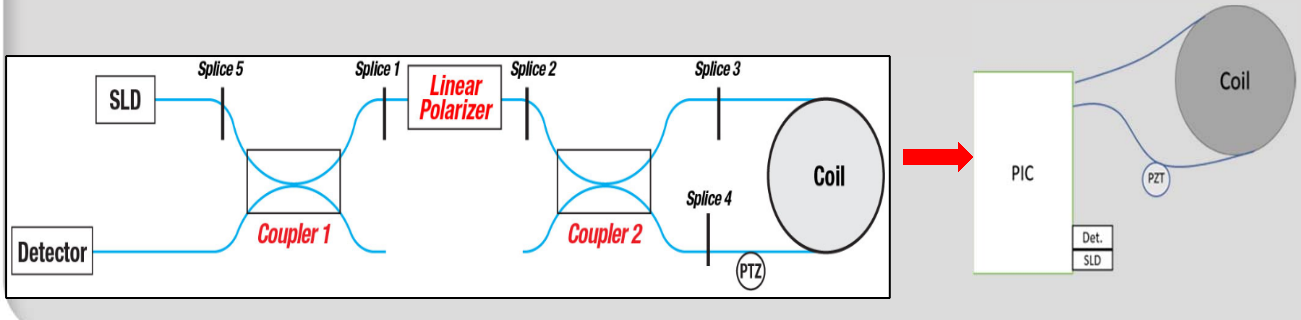
Topics

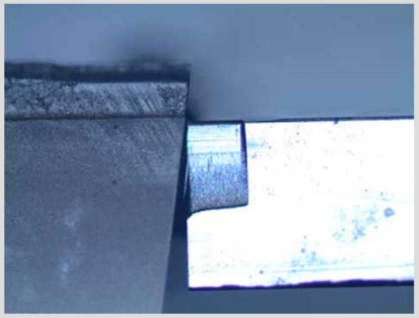
- What is the PIC (Photonics Integrated Chip)
- Criteria for PIC Testing
- Manufacturing Ramp and Tooling
- Testing and Lessons

PIC Overview and Benefits

- Update Optical Assembly with PIC
  - Reduce variability
  - Improve performance
  - Improve reliability and yield







DEFINING PIC TESTING

- Semiconductor testing is well defined in various standards
  - JEDEC, Automotive,
- Optics Testing defined in Telecordia standards
- PIC is a combination of semiconductor and optical testing and reflects the design and expected failure mechanism
  - Testing also reflects product standards and requirements
- DVT (Design, Validation Test) validates the design, but also defines process limits and acceptance

JEDEC Testing for Semiconductors

- Accelerated Environmental Screening
- Accelerated Life Testing
- Package and Electrical Testing
- Parts Characterization
- Mechanical Testing

Telecordia Specifications

- Temperature Cycling
- Temp-Humidity
- Thermal Shock
- High and Low Temp Storage

KVH PIC DVT Testing Conducted

OVERVIEW OF TESTING CONDUCTED

- Risk reduction testing
  - Early design units put into temperature cycling to allow evaluation while design and manufacturing flow were being finalized
- PIC and Fiber Array testing efforts
  - Temperature cycling (-55 to +95 degrees C – 1000 hours, 536 cycles)
  - Temperature and Humidity (55 degrees C 95% relative humidity for 264 hours)
  - Shock (MIL-STD-810G shock – all axis, 18 shock total)
  - Vibration (2 hours each axis @ 18 G RMS from 10-2000 Hz)
  - Gyro build and characterization
  - Shear testing (PIC/FA) – strength of joint

DVT Testing

DVT TESTING

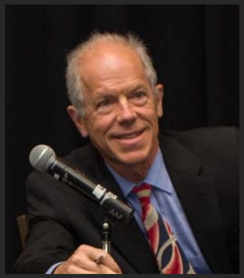
- Done on finalized design at the part and product level and using the final manufacturing flow
  - DVT parts used to help refine manufacturing processes
- Included other parts of optical assembly to provide confidence in total design
- Testing of sufficient quantity of material to provide confidence in results and manufacturing process
  - Using 3 Lots of semiconductor build to allow evaluation of wafer to wafer and lot to lot variations in performance and yield
  - 2 PIC designs with different suppliers and process technology were used to minimize risk, diversify supply chain

Incoming Parts Validation

- Parts used in testing must be validated before assembly to ensure they meet design intent and optical budget
  - PIC parts evaluated using wafer test structures, PIC test structures and free launch into parts
  - Fiber arrays individually measured for acceptance
- All parts tracked from:
  - Supplier testing results
  - Incoming inspection results
  - Manufacturing process validation measurements
  - Final test of individual assembly
- Key parameters for optical budget
  - Power loss, insertion loss, extinction ratio, split ratios, repeatability over temperature

Ask the Experts Part I

Inertial Goes Photonic, Explodes Gyro Technology



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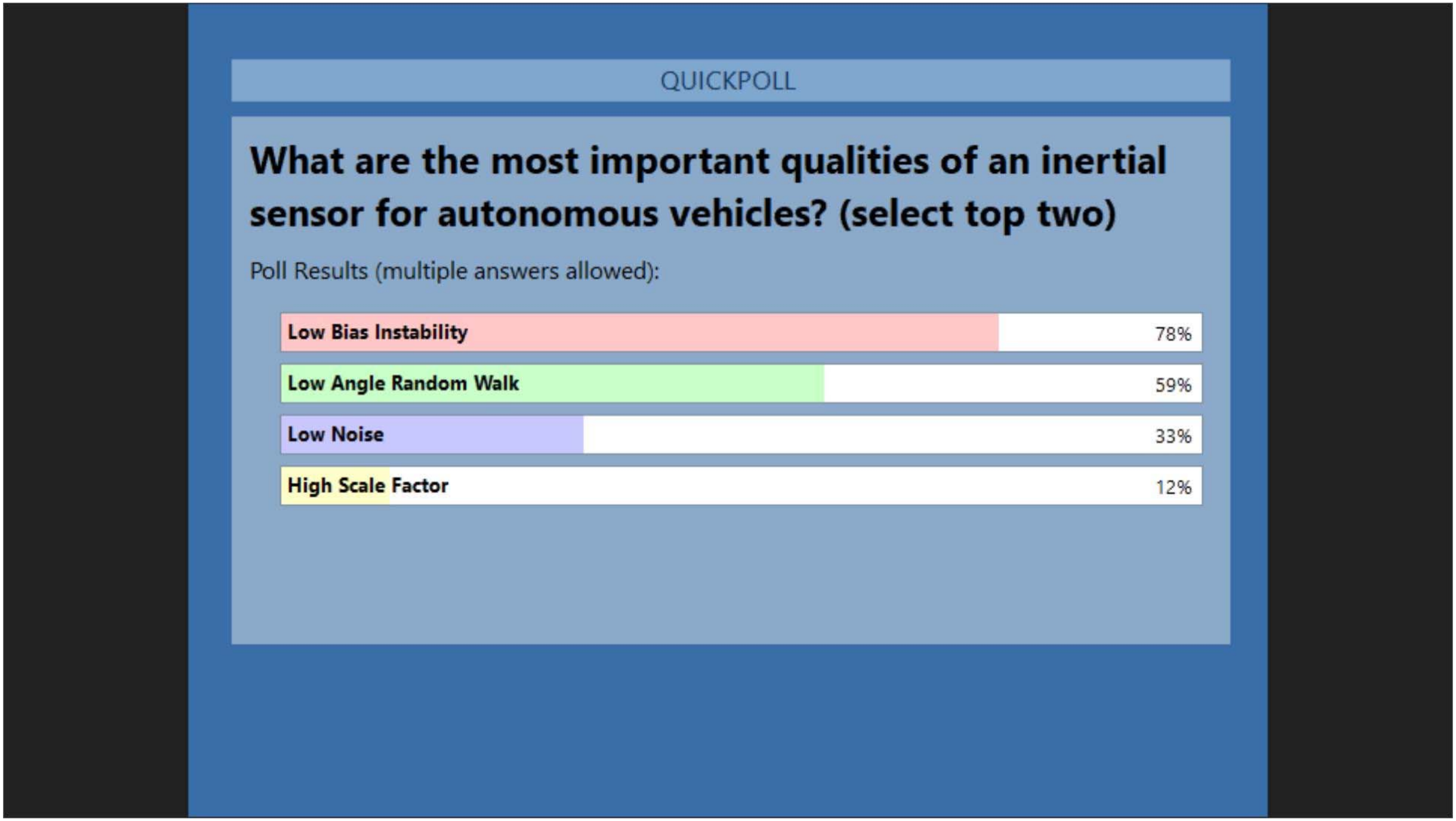


QUICKPOLL

What are the most important qualities of an inertial sensor for autonomous vehicles? (select top two)

Poll Results (multiple answers allowed):

Low Bias Instability	78%
Low Angle Random Walk	59%
Low Noise	33%
High Scale Factor	12%

Part II: Requirements for PIC Reliability Testing and Release to Manufacturing

Skip Ashton
Vice President Product
Development
KVH Industries, Inc.

Typical DVT Test Matrix

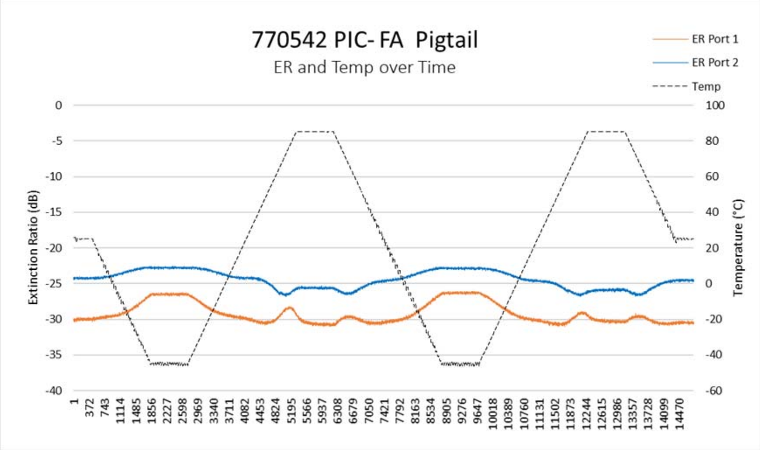
	Parts Set 1	Parts Set 2		
	Accel temp cycling	Temp/humid	Shock	Vibration
Parts Configuration #1	20	20	reuse temp/humid	reuse shock
Parts Configuration #2	20	20	reuse temp/humid	reuse shock

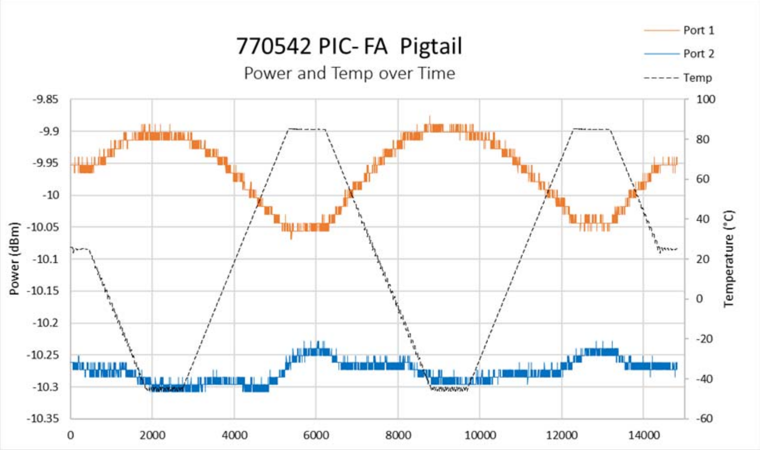
Test Sequence:

- 2 sets of 20 parts built
- Parts measured and validated
- 1 set goes into temperature testing
- 1 set goes into temp/humidity
- Parts measured and validated
- Set from temp/humidity used for shock
- Parts measured and validated
- Set from shock used for vibration
- Parts measured and validated
- All parts evaluated for change in pretest to post test measurements

Typical Test Results

TYPICAL MEASUREMENTS ON EACH DEVICE

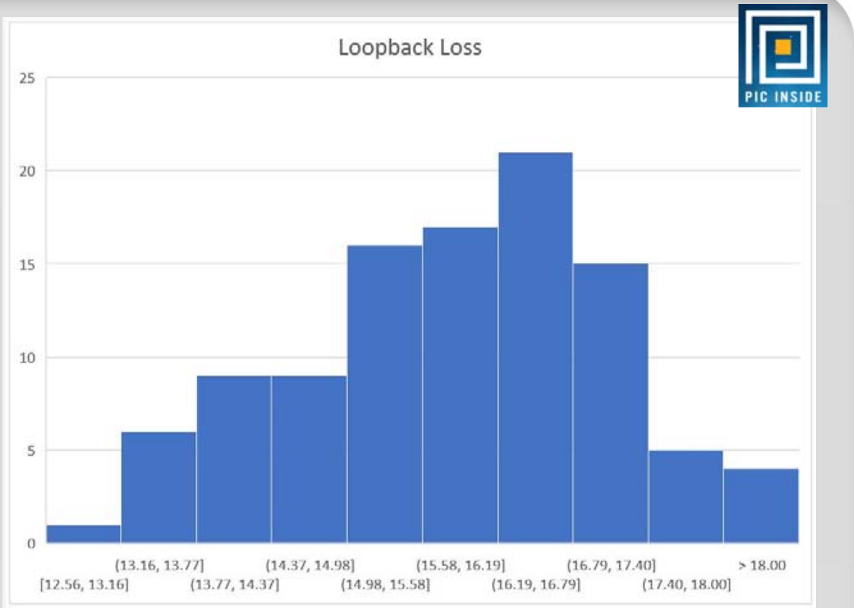




Actively measuring extinction ratio and power out of each fiber port over multiple temperature cycles from -45 to 80 Celsius

Overall Results Analysis

Wafer ID	Average of Loss	Average of ER Min	Average of Insertion Loss Repeatability over Temp	Average of (25°C) Ending Power Balance
V3.2L1W4	17.48	25.12	0.05	1.03%
V3.2L1W5	16.92	23.93	0.08	1.05%
V3.2L1W6	16.69	25.19	0.05	2.76%
V3.2L2W2	13.79	23.74	0.05	8.02%
V3.2L3W10	18.07	24.05	0.10	0.83%
V3.2L3W7	14.97	26.25	0.04	5.41%
Total	16.82	24.70	0.06	2.46%



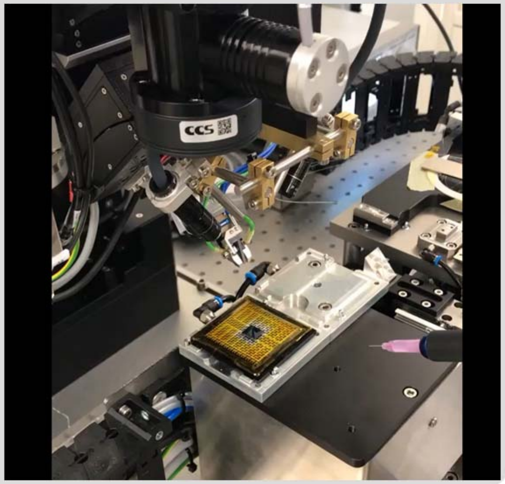
Data must be analyzed different ways – wafer to wafer variations

Repeatability over temperature cycles

Overall loopback loss of PIC and FA

Manufacturing Process Development

- DVT must validate the design, but also the ability to produce reliably in volume
- DVT team was joint effort of engineering and manufacturing
- Started with manual assembly and validation
- Completed installation of automated alignment and assembly machine for PIC and Fiber array assembly



Parts Testing Results and Lessons

- Early engineering testing and design validation reduced risk with DVT but did not uncover all issues found
- Humidity testing revealed weakness in PIC/FA joint not seen in other testing or validation
  - Required changing adhesive and assembly processing to increase robustness of joint
- Building larger batches of parts provides better visibility into manufacturing yields and process improvements
  - Required for DVT but assisted in critical development steps
- Close cooperation needed between optical, mechanical, reliability and manufacturing engineers

FOG Gyro DVT

- Individual parts testing critical but only part of the testing – final proof is in operational gyro's and normal production results
  - Gyros built with different configurations and of sufficient quantity to allow comparison of results with existing manufacturing data
  - Key parameters – bias, scale factor over temperature, linearity
- Longer term reliability at the gyro level built up from parts reliability and overall assembly (optics, mechanical, electronics, software)

Current Status

- Completing initial DVT efforts and releasing PIC into products
  - Done and finalizing results and paperwork!
- Ongoing testing will continue to monitor design through early manufacturing
- Ongoing manufacturing monitoring done to:
  - Improve yields and process controls
  - Further improve performance
  - Adjust acceptance criteria as sample size and lots increase
  - Ongoing joint effort with engineering and manufacturing

The Future of FOGs

Roger H. Ward
Director of FOG Product Development
KVH Industries, Inc.

KVH Industries, Inc.

KVH Industries, founded in 1982

- Employees ~650 worldwide
- Annual revenue ~$155M
- Two state-of-the-art design and manufacturing facilities in the United States

Inertial navigation segment

- Fiber optic gyro-based inertial navigation
- 120,000+ FOGs produced

Market leader in precision FOGs

- Strong intellectual property position
- The first and only company to develop and commercialize a photonic FOG

Product Line of High Precision Systems

Fiber Optic Gyros (FOGs)

- Compact, rugged, solid-state, with ultra-high bandwidth

Photonic FOGs

- Unparalleled SWAP-C in todays inertial trade space

Inertial Measurement Units (IMUs)

- Six-degrees of freedom, combining three axes of FOGs and three axes of accelerometers

Military Inertial Navigation Systems (INS)

- Key military technology for Assured Position, Navigation, & Timing (A-PNT)
- Inertial and digital compass-based navigation not dependent on GPS

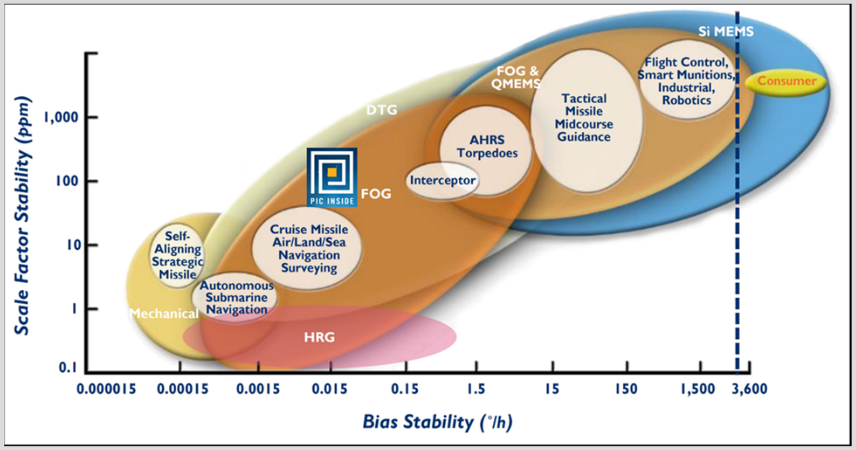
FOG-level Performance Critical for Dead Reckoning

FOG-level performance is critical in dead reckoning applications

Leveraging Si-photonics to enable development:

- Reliable
- High Performance
- Scalable
- Smaller

KVH has developed a high-performing FOG for autonomous applications while simultaneously reducing variability in performance and temperature performance.



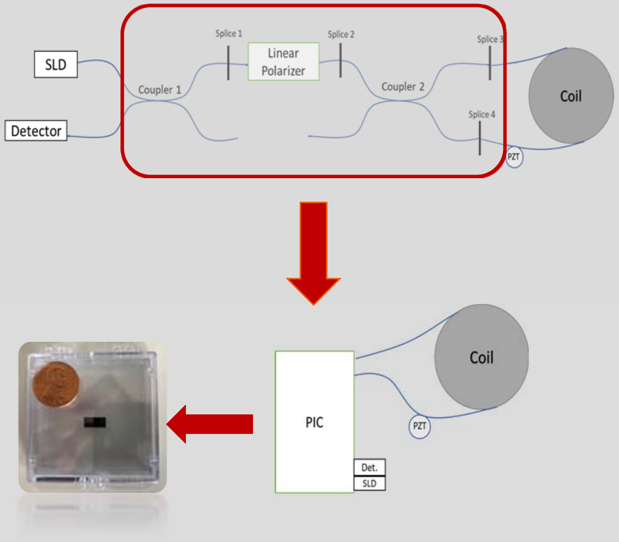
Disruption of Inertial Navigation is Happening

KVH's PIC Integrates Components with Highly Scalable Manufacturing Technologies

Solution: Photonics Integrated Circuit (PIC)

- **Increased repeatability when compared to fiber based components**
  - Environmentally insensitivity when compared to fiber components
  - Bend loss, split ratio, Wavelength dependent loss
- **Monolithic integration creates a splice-less gyro**
  - Eliminating failure modes and reducing assembly labor
- **Lower loss propagation ~3.4dB and tunability allows for higher performance**
- **Scalable design via wafer level fabrication processes**
  - Wafer scale fabrication allows for orders of magnitude increase in production runs
- **Semiconductor based quality structure**
  - Providing lot, wafer and PIC level verification, test and control structures
- **Mature integration and packaging methods enables high repeatability in manufacturing**

Optical Circuit Development



Transportation Trend

Mobility as a Service (MaaS) has begun

- Three components: autonomous cars, autonomous shuttles, autonomous aircraft

By 2035, autonomous vehicle will be common

- Accelerated transition to autonomous trucks and unmanned aerial vehicles now through 2050

Factors affecting delays in autonomous vehicle rollout

- Accidents *(May 2016 Tesla, March 2018 Uber)*
- ADAS-based autonomy taking longer than expected
- SAE definition of levels of autonomy nearly useless; intermediate levels 2+ and 2++ are being introduced

Source: Yole, Sensors for Robotic Mobility 2020

Autonomous Mobility: Vehicles

- **Autonomous vehicles/taxis = 4,000+ on the road now, led by:**
  - **Waymo:** 600 cars, 20M miles driven
  - **Lyft:** 200 cars, 50,000 rides
  - **Baidu:** 300 cars, 2M miles driven
- By 2032, autonomous vehicle technologies and markets will *"disrupt the traditional automotive market; yearly capital expenditure in excess of $50B per year will be spent on the vehicles and associated autonomy hardware"*

Source: Yole, Sensors for Robotic Mobility 2020

Autonomous Mobility: Shuttles

- **Autonomous shuttles = 440 on road now, led by:**
  - **Baidu:** 100+ shuttles, 10,000 passengers
  - **Navya:** 60+ shuttles
  - **Easy Mile:** 30 shuttles
  - **Others** *(including May Mobility, Local Motors)*

- **Rollout pattern**
  - **Large cities first, 2020-2028**
    - 75 cities with 80 shuttles each = 6,000 shuttles
  - **Small cities next, 2032**
    - 1,250 cities with 80 shuttles each = 100,000 shuttles

Source: Yole, Sensors for Robotic Mobility 2020

Autonomous Mobility: Aircraft

- **Autonomous aircraft = early stages now until 2024**
  - **2024:** 1,000 aircraft needed for airport to city and sightseeing
  - **2028:** 5,000 aircraft for city-to-city transport
  - **2032:** 76,000 aircraft for start of urban air mobility (UAM) commuting

- **Uber Elevate**
  - Partnerships with aircraft leaders including Boeing, Embraer, Bell, Jaunt, Hyundai, Karem, Joby, Pipistrel
  - *“It is highly probably that the full benefit of autonomous cars will necessitate the cooperation of urban air mobility (UAM)”*

Source: Yole, Sensors for Robotic Mobility 2020

Potential Applications for PIC-inside FOGs

Market values for applications mentioned as desirable during our PIC research

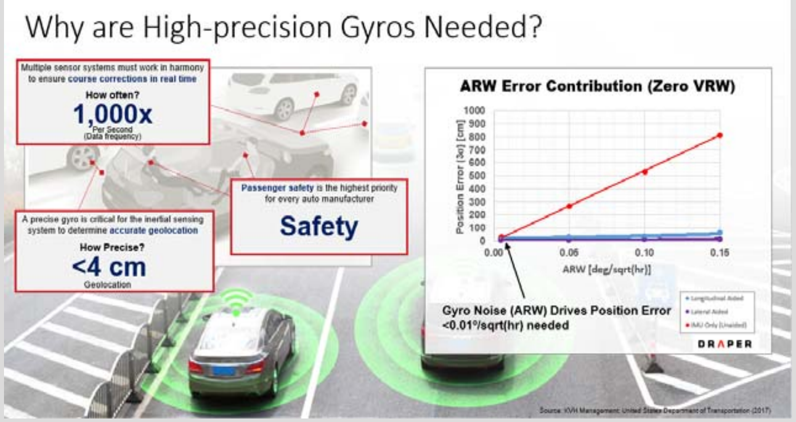
- **Robotics: 6% revenue CAGR, 8% unit CAGR 2019-2025**
  - From $27 million to $38 million; from 18,896 units to 29,985 units
- **Construction (mining, truck): 23% revenue CAGR, 25% unit CAGR 2019-2025**
  - From $3 million to $10 million; from 391 units to 1,490 units
- **Pipeline: -1% revenue CAGR, 1% unit CAGR 2019-2025**
  - From $2 million to $2 million; from 3,091 units to 3,281 units
- **Agriculture: 5% revenue CAGR, 7% unit CAGR 2019-2025**
  - From $38 million to $50 million; from 4,900 units to 7,354 units

Source: Yole, High-end Inertial Sensors 2020 Report

Key Metrics for Success in Autonomy

- Low Bias Instability
- Low Angle Random Walk or Noise
- High Scale factor
- High Reliability

87.5% of autonomous vehicle developers indicated a FOG is used in systems as navigational input & to constrain drift



Why are High-precision Gyros Needed?

Multiple sensor systems must work in harmony to ensure course corrections in real time

How often?

1,000x

Per Second (Data frequency)

A precise gyro is critical for the inertial sensing system to determine accurate geolocation

How Precise?

<4 cm

Geolocation

Passenger safety is the highest priority for every auto manufacturer

Safety

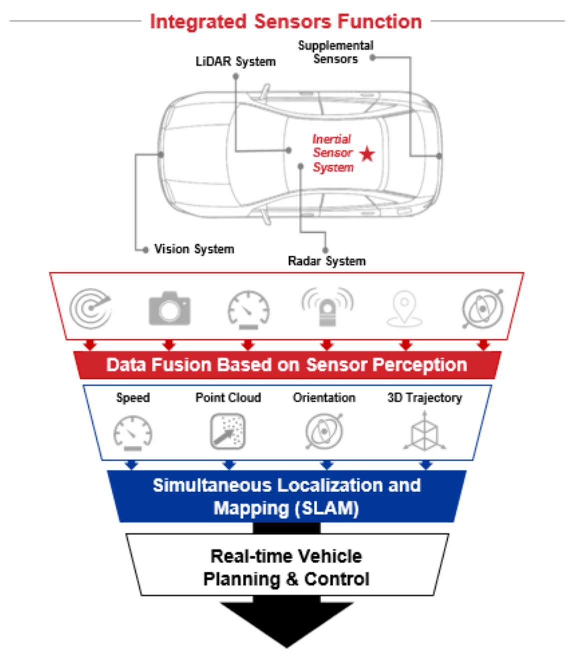
Gyro Noise (ARW) Drives Position Error <0.01°/sqrt(hr) needed

Source: KVH Management; United States Department of Transportation (2017)

Why KVH

Dead reckoning is vital in autonomous navigation to continuously know your true position, precisely

- **Safety is of huge importance to autonomous vehicles**
  - MEMs currently do not have low noise and low bias instability needed
  - Some companies have looked at lower performance sensors but navigation errors accumulate over time and varying conditions
- **Higher reliability and affordability are key to autonomous vehicles, with size and power consumption being less important**
- **There are different levels of autonomous navigation processing**
  - Inertial sensors like FOGs are easily integrated into sensor fusion solutions and KVH offers tools to facilitate integration
  - FOGs are complementary sensors to LiDAR, radar and other sensors
- **KVH offers a wide variety of performance in its sensors: gyros, IMUs, INS**
- **PIC expanding portfolio to offer performance and reliability autonomous vehicles demand**


Integrated Sensors Function

Data Fusion Based on Sensor Perception

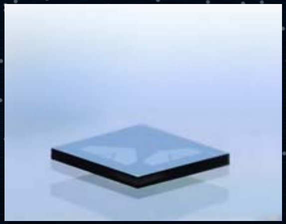
Simultaneous Localization and Mapping (SLAM)

Real-time Vehicle Planning & Control

Sensor fusion enables precise positioning and orientation performance in all environments

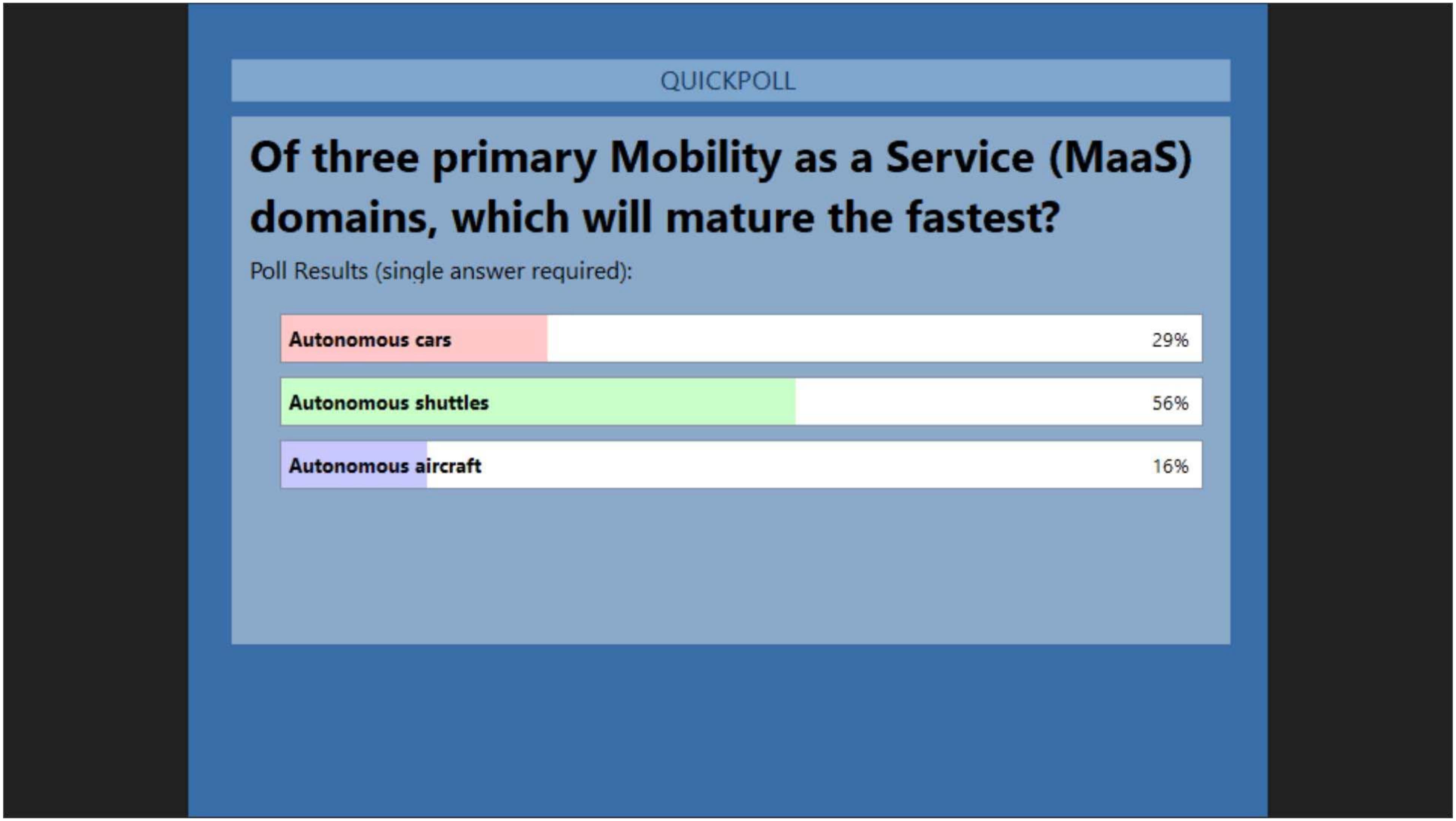
Photonic Integrated Chip (PIC) Technology

- Price and performance targets met
- Shipped end of Q1
- Integration into current products on track



Resources from KVH

- **Photonic Chip Technology-based Inertial Systems: Disruptive Technology for Safe Autonomous Navigation**
  - https://landing.kvh.com/photonicEbook
- **Positioning, Navigation & Timing Assurance: Meeting the Growing Threat of GPS/GNSS Disruption**
  - https://landing.kvh.com/tacnavpnt
- **Desert WAVE Enjoys Victory in RoboSub 2019 with KVH Precision Sensors Onboard**
  - https://landing.kvh.com/desertwave
- **May Mobility Solves Autonomous Vehicle Positioning Challenges with Accurate & Affordable KVH Inertial Sensors**
  - https://landing.kvh.com/maymobility



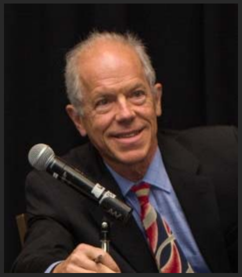
QUICKPOLL

Of three primary Mobility as a Service (MaaS) domains, which will mature the fastest?

Poll Results (single answer required):

Autonomous cars	29%
Autonomous shuttles	56%
Autonomous aircraft	16%

Ask the Experts



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