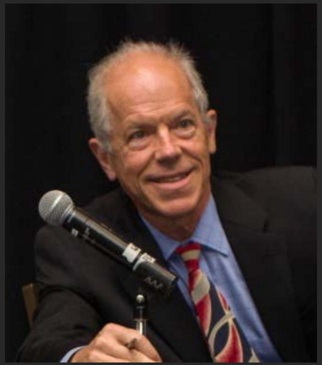
INERTIAL TECHNOLOGY FOR ROBOTICS,
UAVS AND OTHER APPLICATIONS

Wednesday, May 6, 2020

WELCOME TO

Inertial Technology for Robotics, UAVs and other Applications



Alan Cameron
Editor in Chief
Inside GNSS
Inside Unmanned Systems

Ralph Hopkins
Distinguished Member Technical Staff
Charles Stark Draper Laboratory

Reidar Holm
Manager
Product Development
Sensonor

Brian Rider
Chief Technology Officer
LeoStella

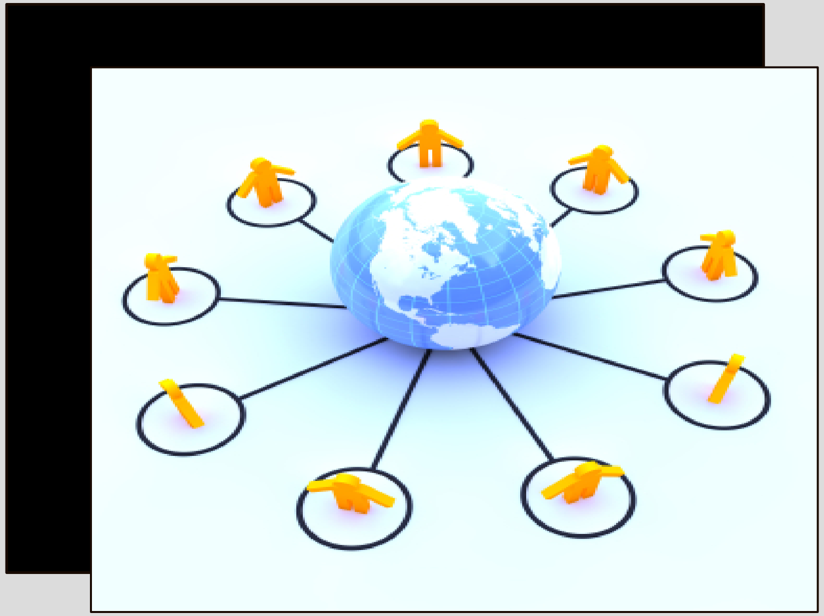
Ryan Robinson
ADCS Lead
LeoStella

Co-Moderator: Lori Dearman, Executive Webinar Producer

Who’s In the Audience?

A diverse audience of over 525 professionals registered from 50 countries, representing the following industries:

- **22%** Military
- **17%** Education/Research
- **12%** Automotive
  - **9%** Transportation, Logistics, Asset Tracking
  - **8%** Machine Control, Mining, Construction
  - **3%** Precision Agriculture
- **29%** Other



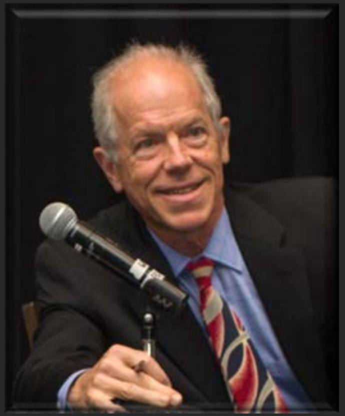
Welcome from *Inside Unmanned Systems*

Richard Fischer
Publisher
Inside GNSS
Inside Unmanned Systems

A word from the sponsor

Hans Richard Petersen
Head of Product Development & Marketing
Sensonor

Today's Moderator



Alan Cameron
Editor in Chief
Inside GNSS
Inside Unmanned Systems

QUICKPOLL

Which of the following best describes your application of inertial technology — or the one you are most interested in applying?

Poll Results (single answer required):

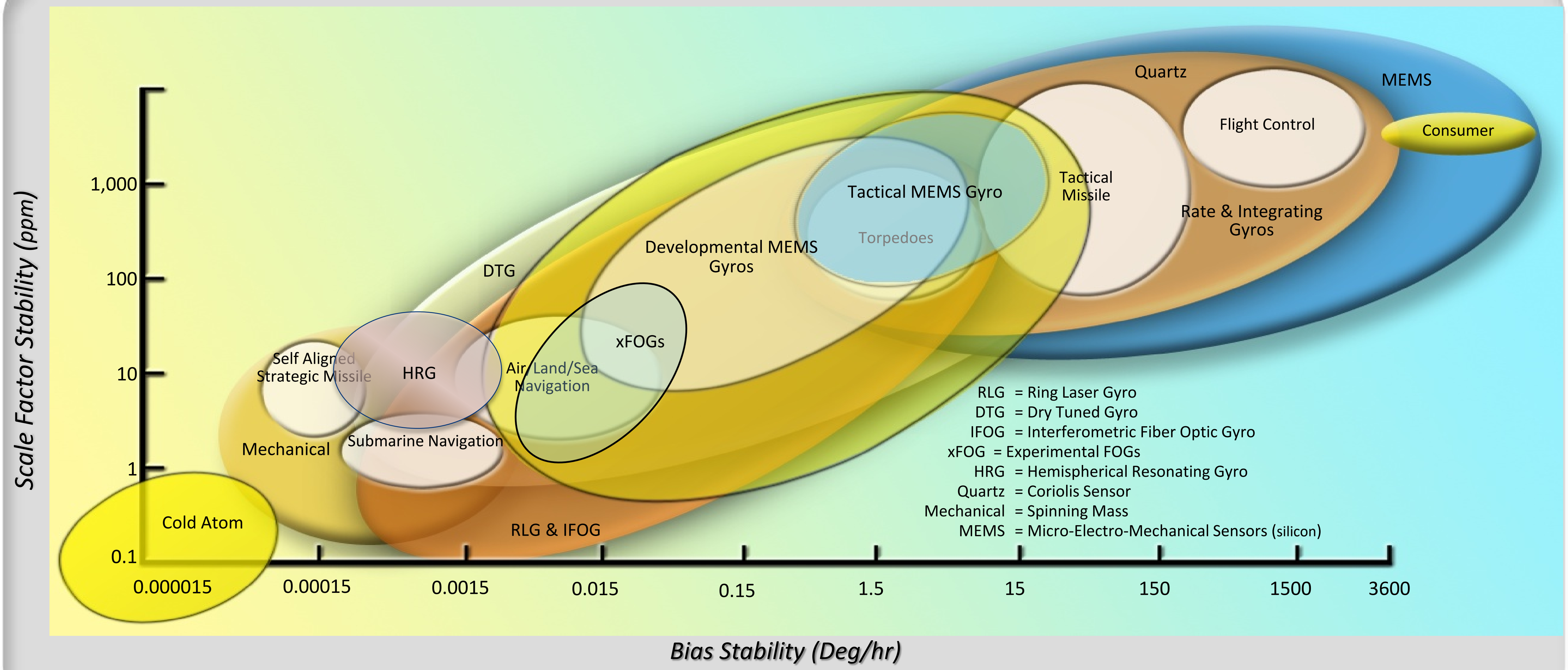
Contemporary and Emerging Inertial Sensor Technologies

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?

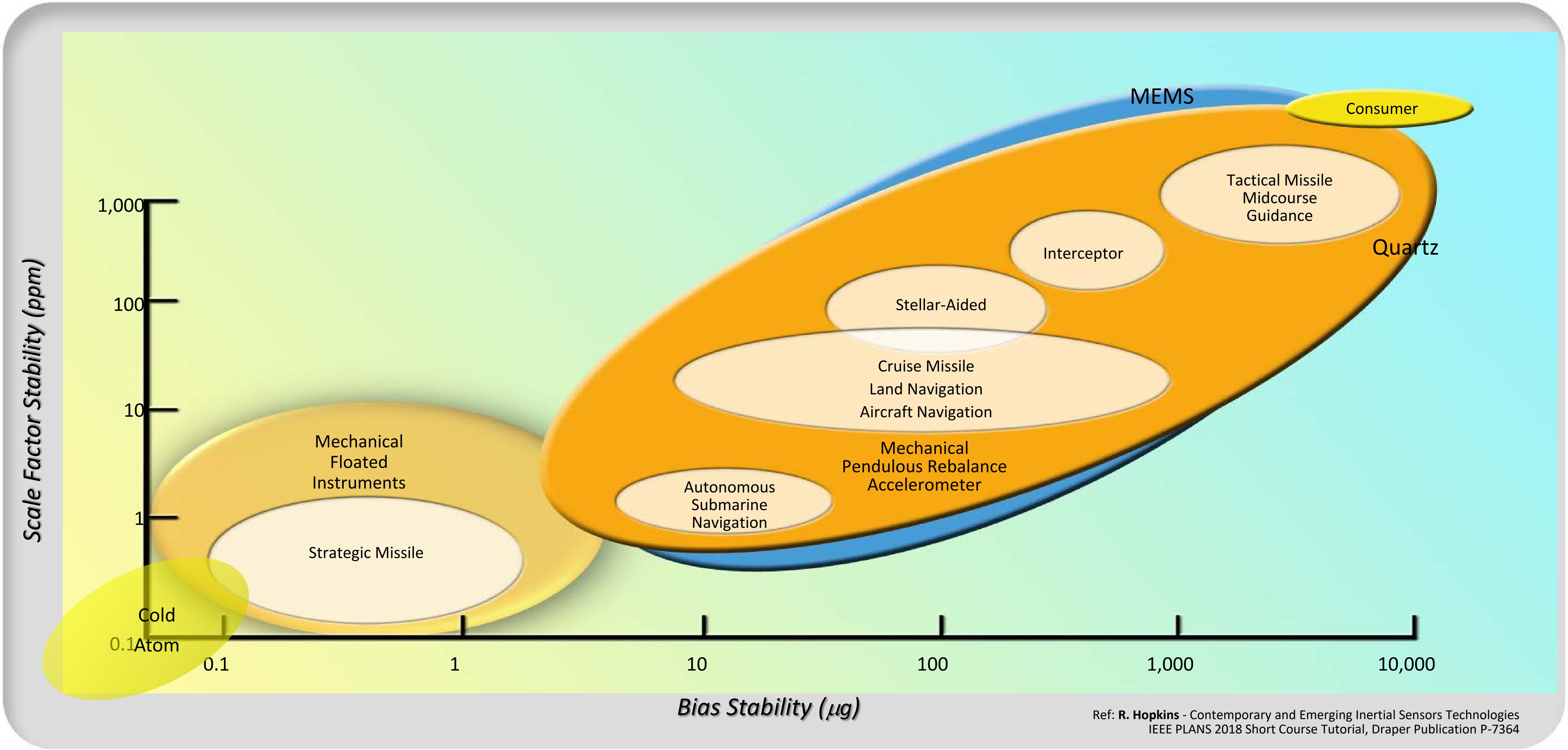
Current Gyro Technology Applications



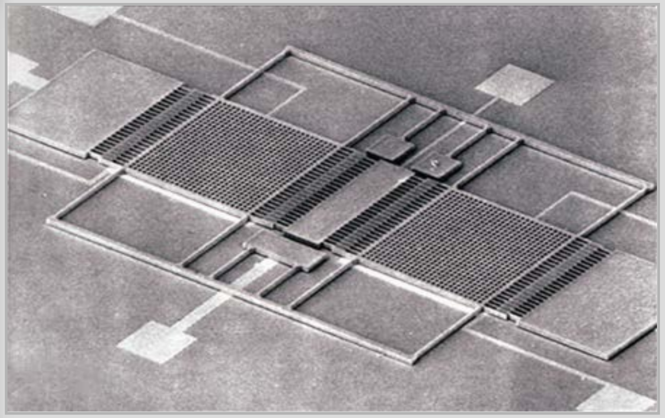
Ref: **R. Hopkins** - Contemporary and Emerging Inertial Sensors Technologies
IEEE PLANS 2018 Short Course Tutorial, Draper Publication P-7364

Current Accelerometer Technology Applications

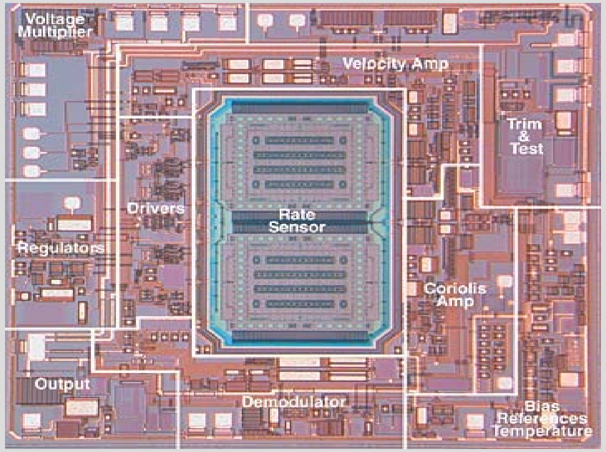
sensonor InsideGNSS inside unmanned systems



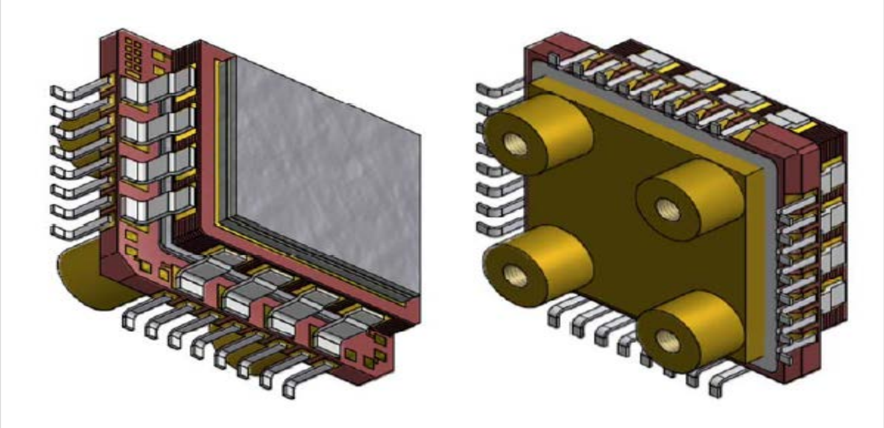
Examples: Miniature Gyroscopes



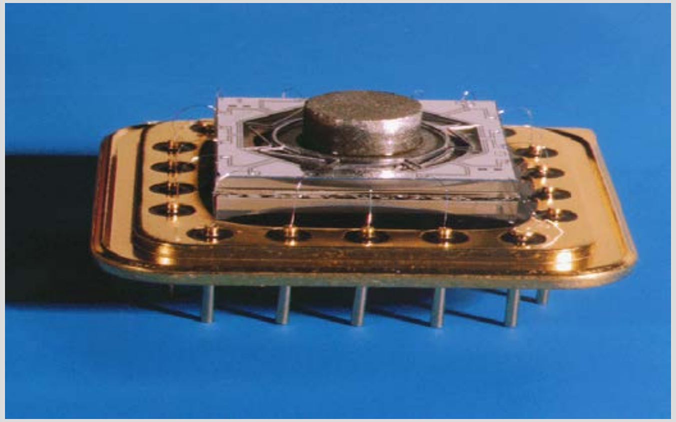
Draper/Honeywell TFG



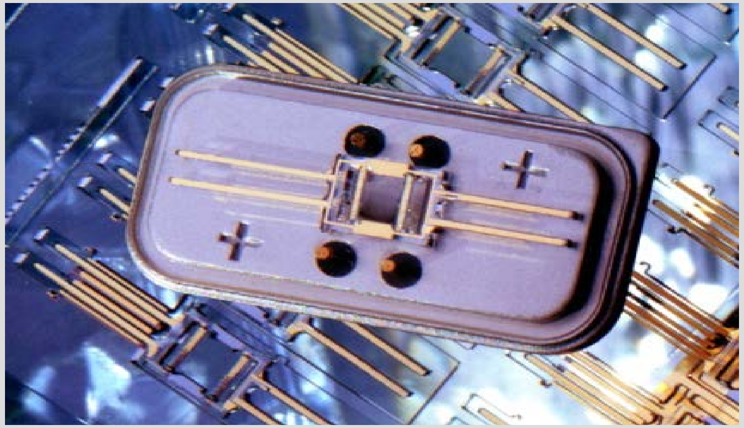
Analog Devices ADXRS



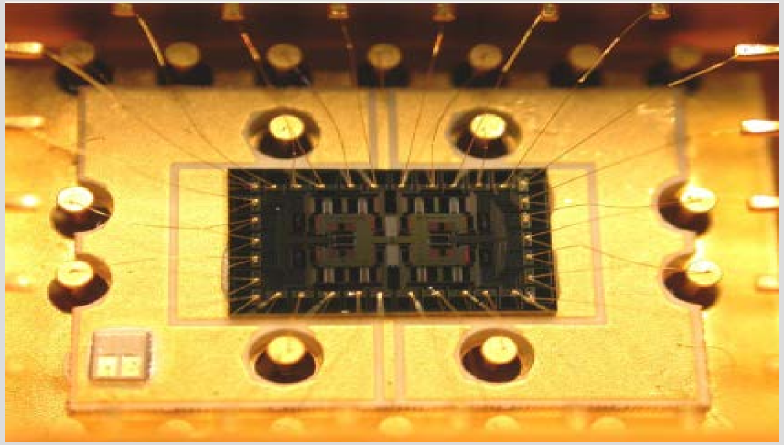
Sensonor SAR500 gyro



UTC SiVSG



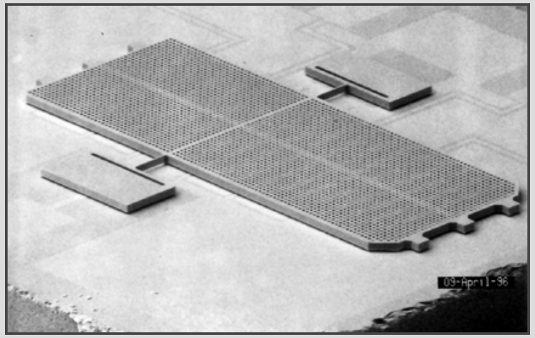
Systron Donner QRS11



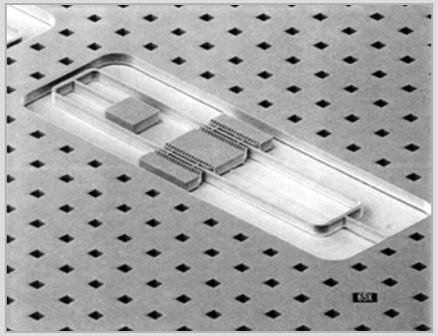
LITEF μCORS gyro

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

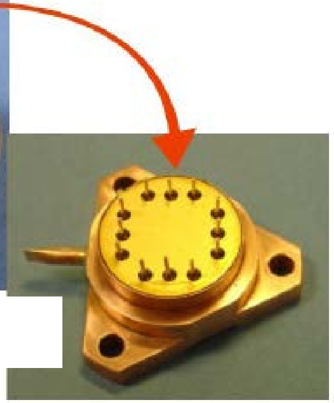
Examples: Miniature Accelerometers



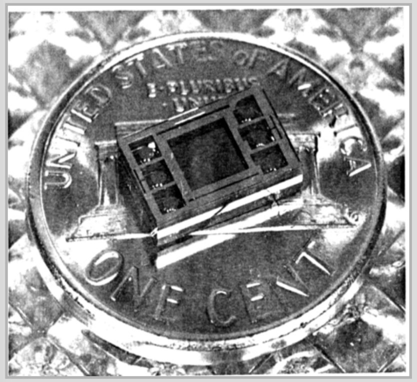
Draper/Honeywell



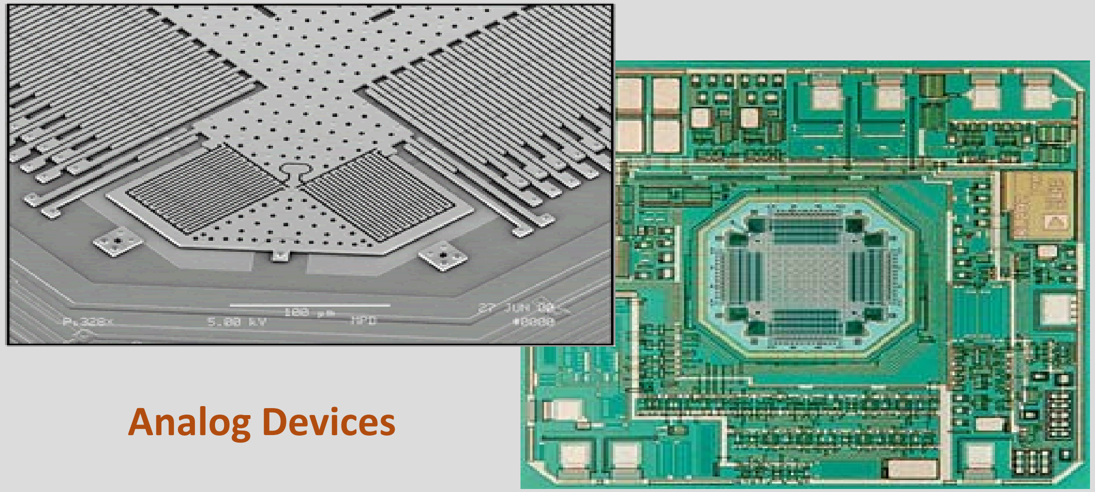
Draper SOA

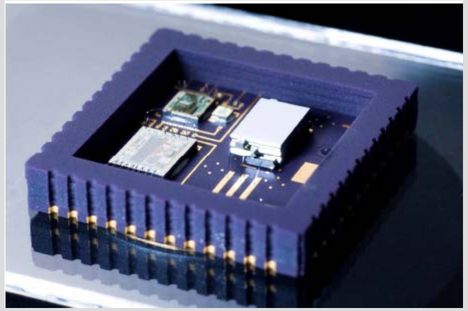
Onera DIVA



Northrop Grumman SiAC



Analog Devices



Colibrys Accelerometer

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

Solid State MEMS IMUs

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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

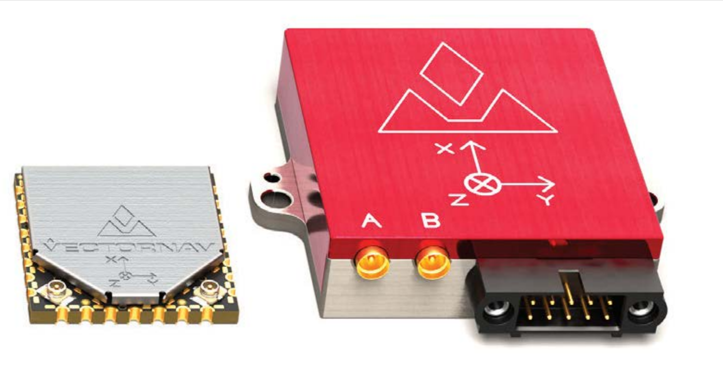
2 in^3
< 55 gm
2 W

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

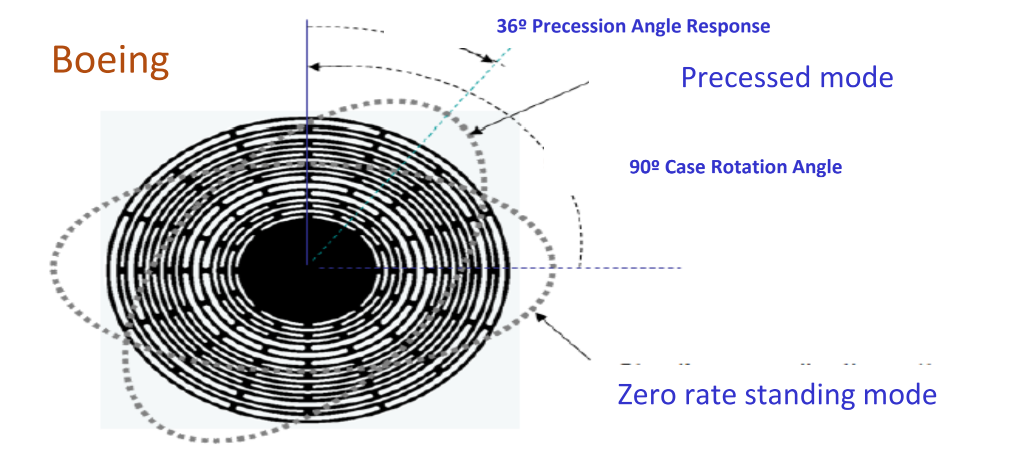
Analog Devices – ADIS1649X

1.8 in^3
42 gm
0.3 W

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

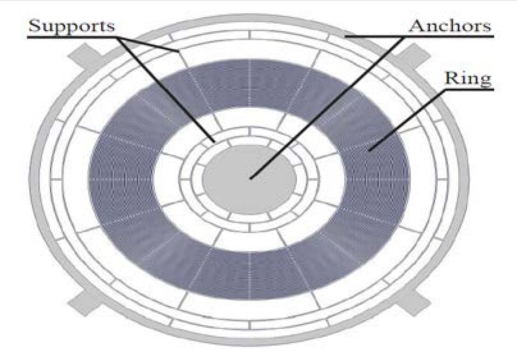
Ref: **R. Hopkins** - Contemporary and Emerging Inertial Sensors Technologies
IEEE PLANS 2018 Short Course Tutorial, Draper Publication P-7364

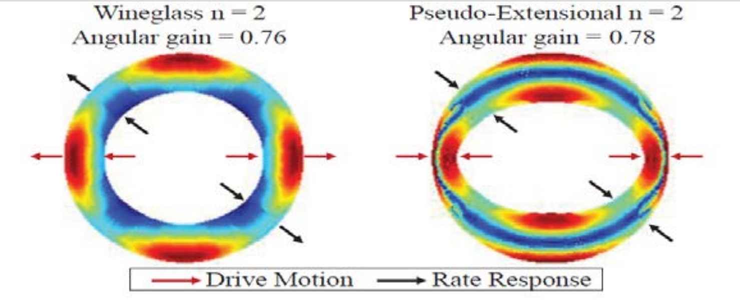
Boeing



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

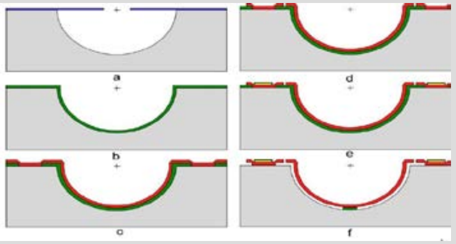
Analog Devices

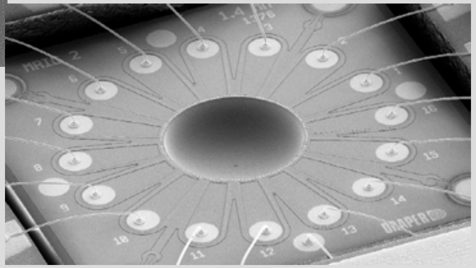




Prikhodko, I.P, D. Shin, et al. Analog Devices and Stanford University, *Pseudo-Extensional Mode MEMS Ring Gyroscope*: Proceedings 2019 IEEE International Symposium on Inertial Sensors and Systems, Naples, FL

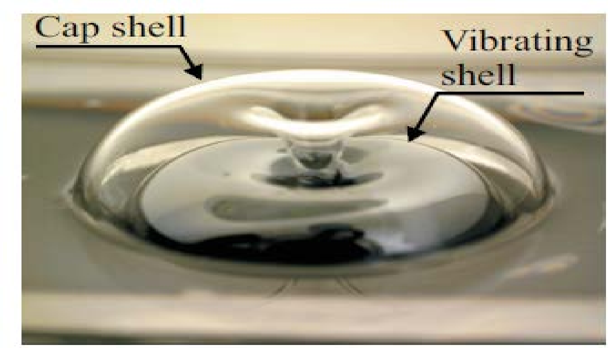
Draper

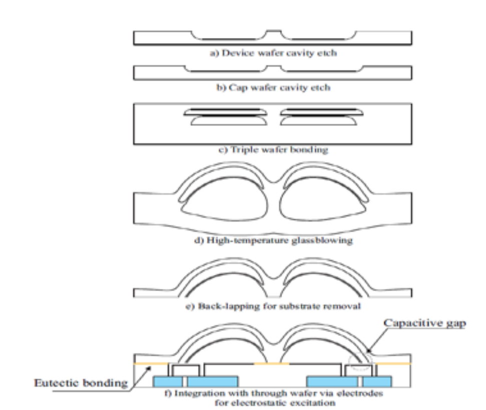




REF: **Bernstein, J**. et al, *High Q diamond hemispherical resonators: fabrication and energy loss mechanisms* , J. Micromech. Microeng. 25 (2015) 085006
REF: Bernstein et al, *A MEMS diamond hemispherical resonator*, J. Micromech. Microeng. 23 (2013) 125007

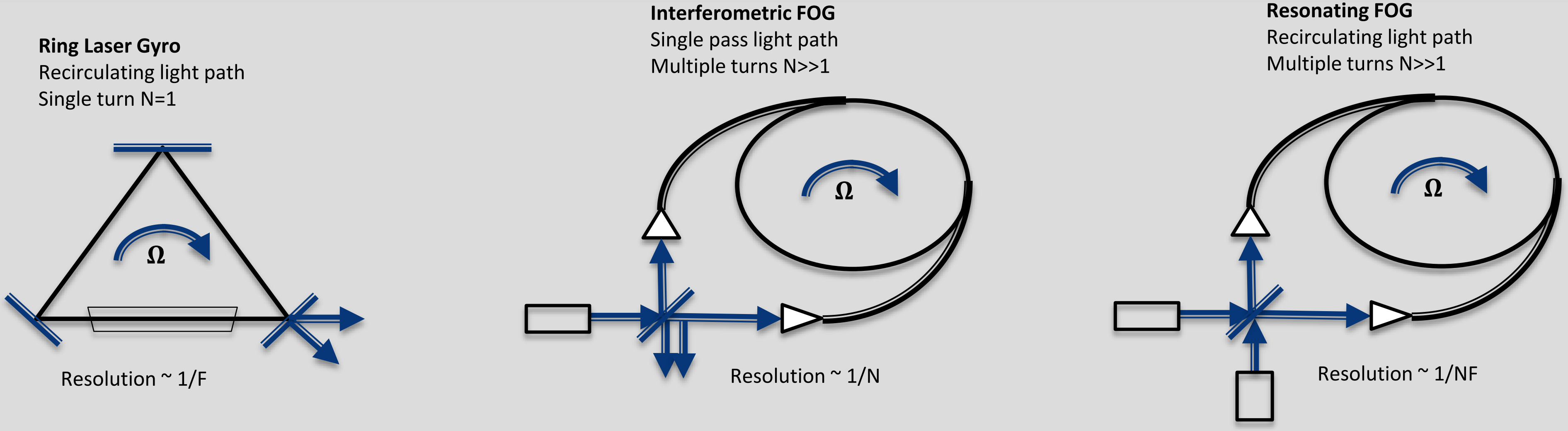
UC Irvine



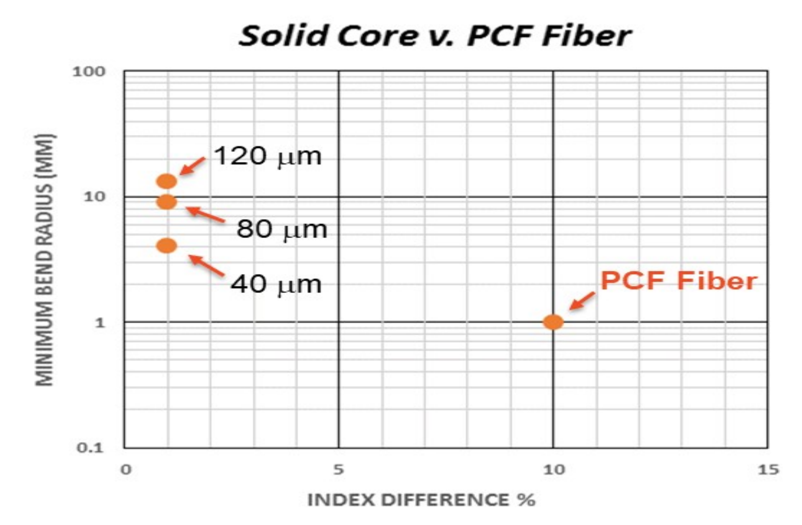


Asadian, M., Shkel, A., MicroSystems Laboratory, University of California, Irvine, CA, *Fused Quartz Dual Shell Resonator*; Proceedings 2019 IEEE International Symposium on Inertial Sensors and Systems, Naples, FL

Optical Gyro Size Reduction: Resonating FOG

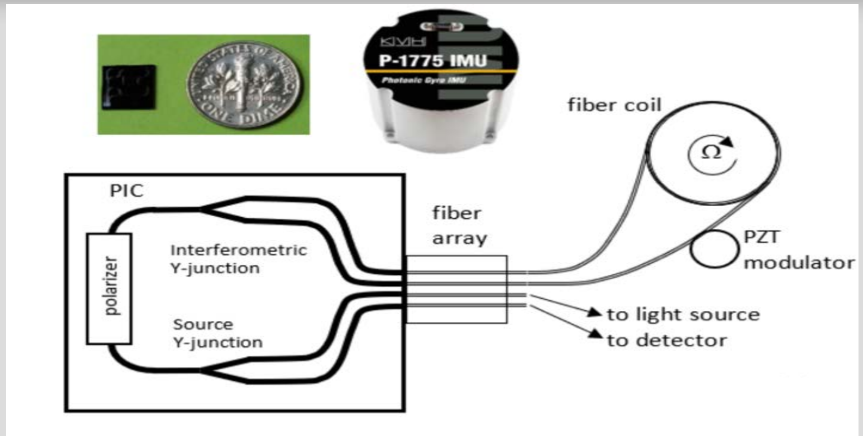


- RFOG performance driven by resonator quality:
  - *Previous RFOGs limited by errors due to high intensity in glass core & backscatter*
- New developments:
  - *Hollow core PC fiber- bulk of light (99%) travels in AIR not Glass*
  - *Modulation scheme to separately probe CW and CCW resonances*



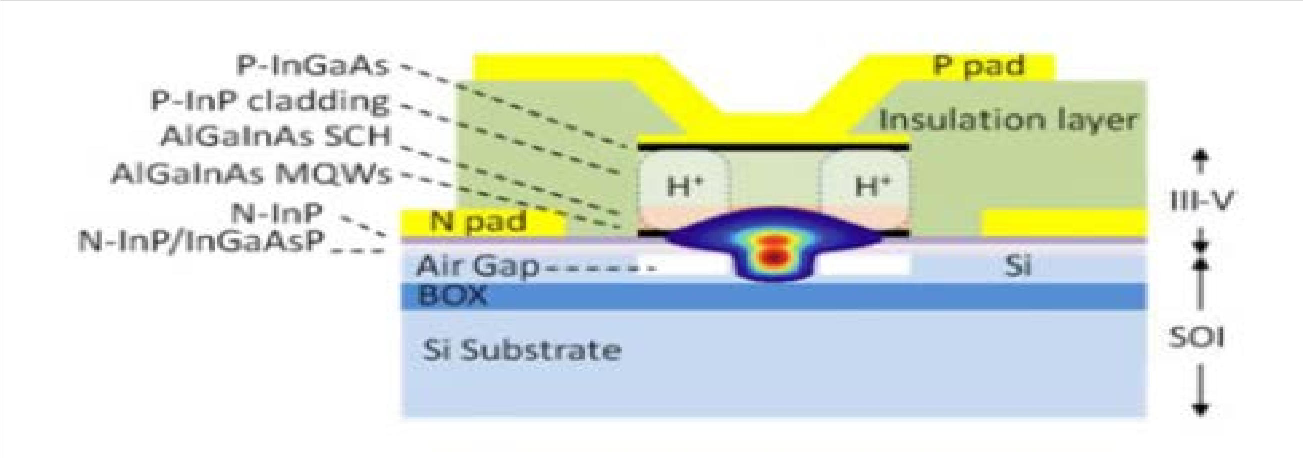
FOG Size Reduction: Integrated Photonics

- 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.*

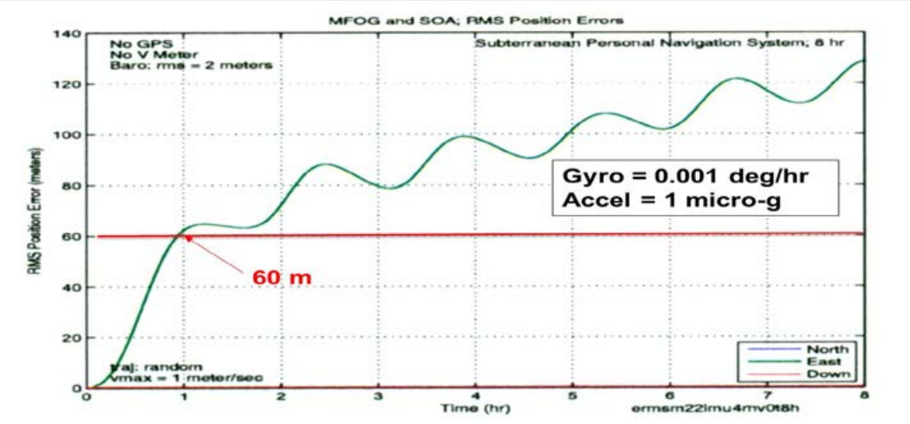


Ref: Spector, et.al, *Mode Engineering for Hybrid SOI/III-V Optical Devices,* SOI Conference (SOI), 2012 IEEE International

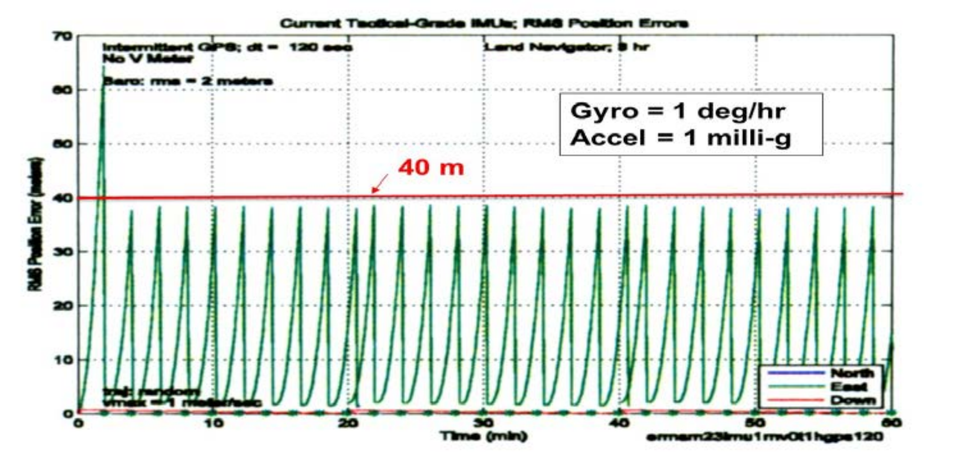
Goals	Mission: Urban Personal Navigation System	Subterranean Personal Navigation System		Search & Rescue Robot	Autonomous Land Vehicle	Autonomous Undersea Vehicle
Size (in^3)	10	12		4	25	25
Weight (lb)	0.5	3		1	2	2
Power (w)	5	5		1	20	20
GPS Availability	Intermittent	Denied		Denied	Intermittent	Denied
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

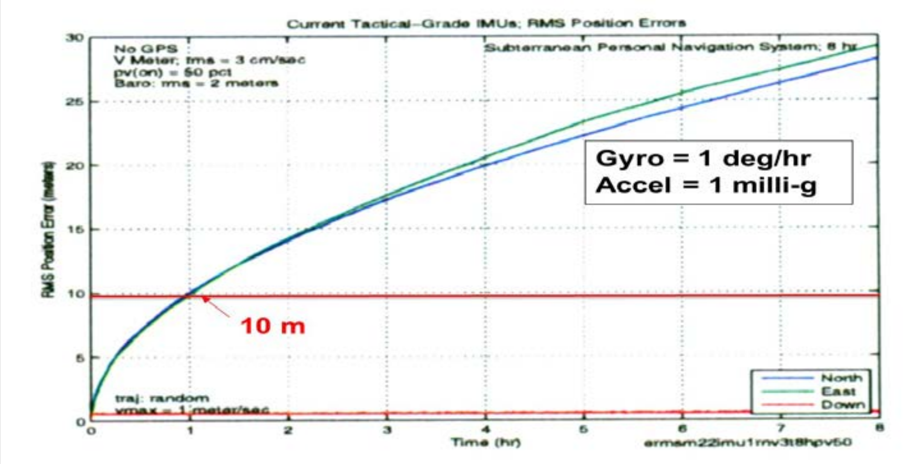


Inertial w/GPS Updates



- **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/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: Reliability by Design

Reidar Holm
Manager
Product Development
Sensonor

Overview:

- Introduction to Sensonor
- Application areas
- Gyro and IMU overview and key-features
- Approach to the field of tactical grade products
    - diagnostic function
    - standard qualification programs
    - vibrations
    - radiation
- Developments in progress

Brief history of Sensonor

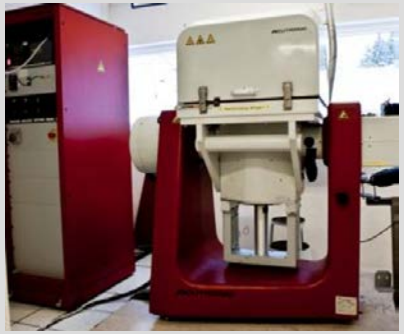
	Defense Aerospace Industrial	10k/year 35k	Tactical grade IMUs and gyro modules
2009	Automotive safety	35M 250M 2M	Airbag accelerometers Tire pressure sensors Roll-over gyros
1992	Medical Defense Aerospace Automotive	100k	Pressure sensors Accelerometers
1985	Medical Defense		Pressure sensors Accelerometers
	Silicon MEMS pioneer work in Horten, Norway		
1965			

Sensonor
Location: Horten, Norway

MEMS Fabrication

Gyro Module and IMU Production



MEMS Wafer Fab

- State of the art 150mm MEMS line
- Line upgraded 2016
- Production / clean room area: 2600m^2

Capacity

- 700 triple stack wafer starts per week
- Foundry services available

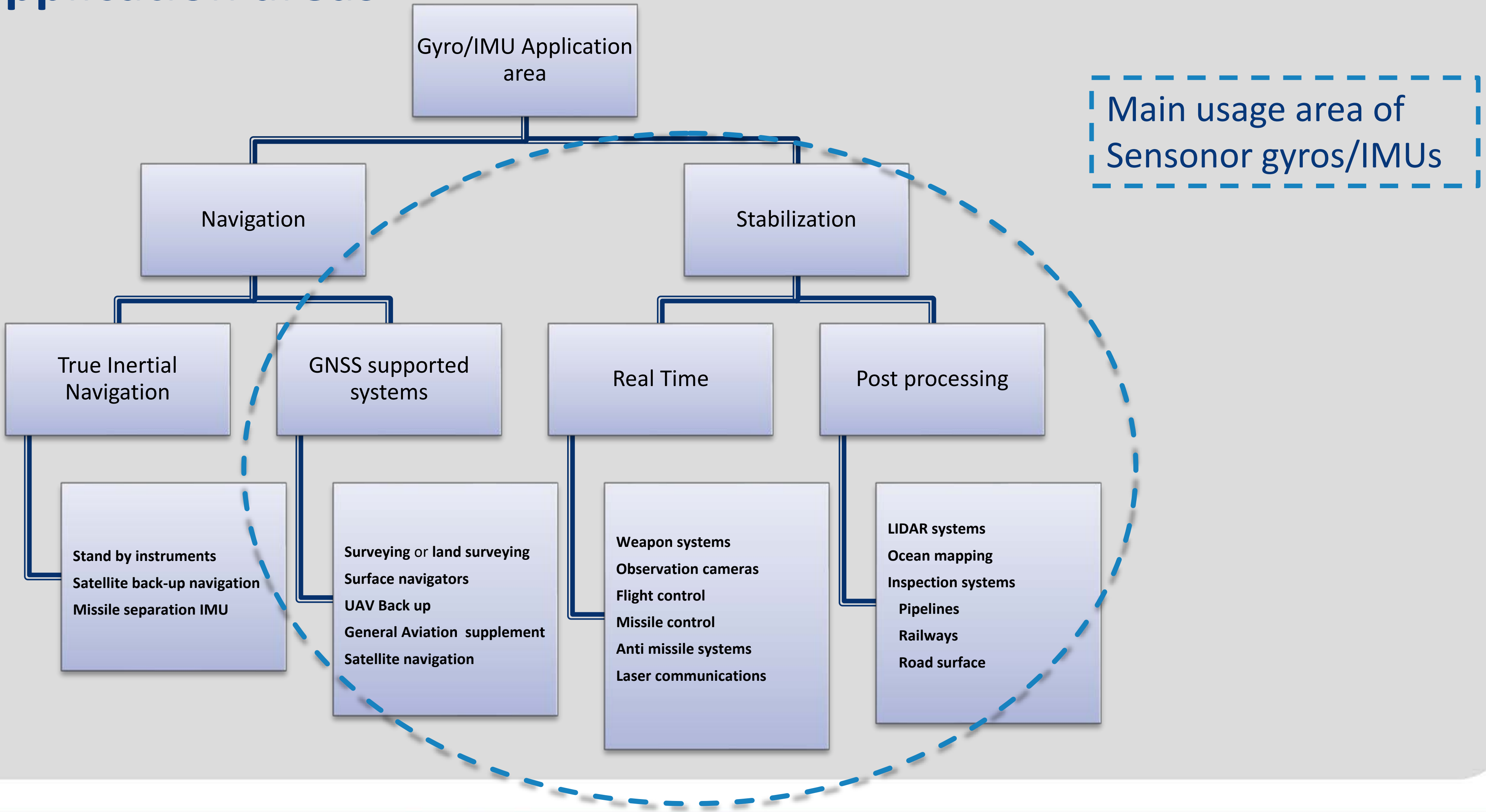
Assembly, Calibration and Test

- Fully automated flexible assembly line
- Development and qualification lab
- Production / clean room area: 4000m^2

Capacity

- 10,000 Gyro Modules per year
- 5,000 IMUs per year

Gyro/IMU application areas



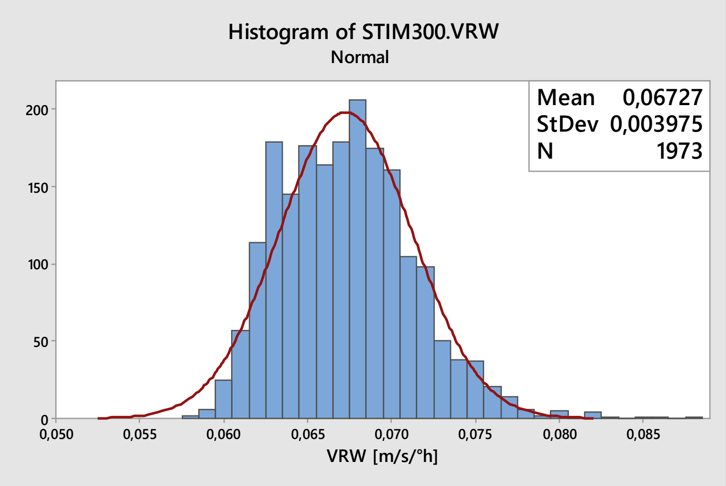
Sensonor portfolio

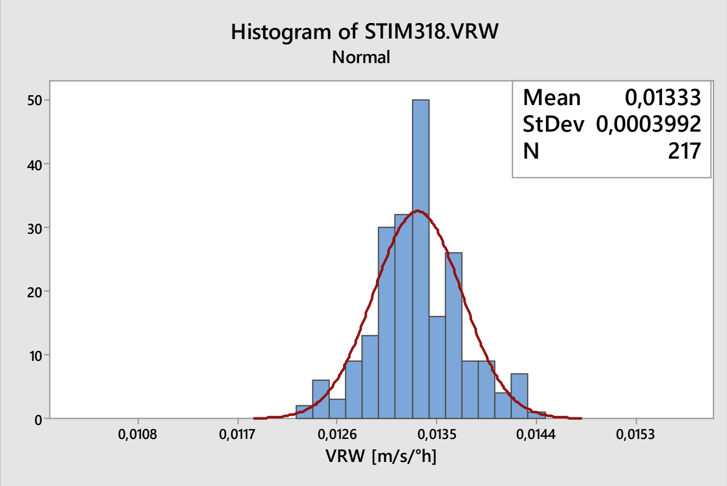
Parameter	STIM202	STIM210	STIM300	STIM318
Configuration	3 axis gyro	3 axis gyro	3 axis gyro 3 axis acc 3 axis inc	3 axis gyro 3 axis acc 3 axis inc
Gyro ARW (±400 - ±1200°/s)	0.15°/√h	0.15°/√h	0.15°/√h	0.15°/√h
Gyro Bias Instability (±400 - ±1200°/s)	0.4°/h	0.3°/h	0.3°/h	0.3°/h
Gyro Bias 1-year stability (400 - ±1200°/s)	35°/h	35°/h	35°/h	35°/h
Accelerometer VRW (±10g*)	-	-	0.07m/s/√h	0.015m/s/√h
Accelerometer Bias Instability (±10g*)	-	-	0.05mg	0.003mg
Accelerometer Bias 1-year stability (±10g*)	-	-	1.5mg (nom)	1.2mg (nom)
Inclinometer VRW (±1.7g)	-	-	0.08m/s/√h	0.08m/s/√h
Inclinometer Bias Instability (±1.7g)	-	-	0.05mg	0.05mg
Inclinometer Bias 1-year stability (±1.7g)	-	-	1.0mg (nom)	1.0mg (nom)
Start-up time	5s	1s	1s	1s
AUX input (±2.5V)	No	No	Yes	No
Bias Trim Offset functionality	No	Coming	Coming	Yes

*) Other accelerometer ranges available: ±5g, ±30g and

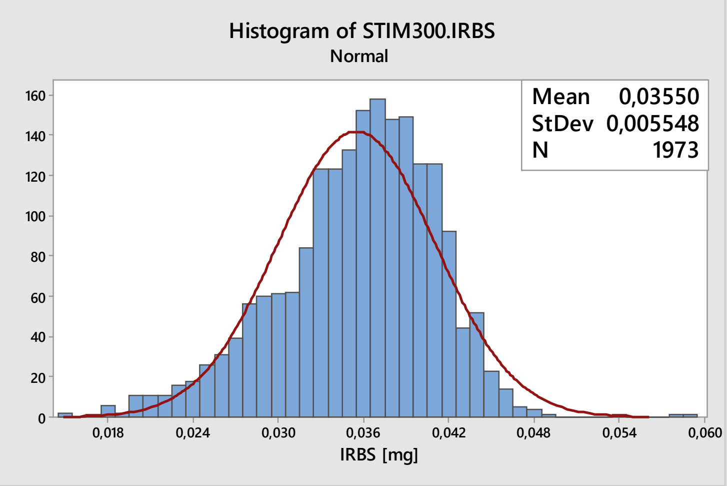
For complete datasheets, see: www.sensonor.com

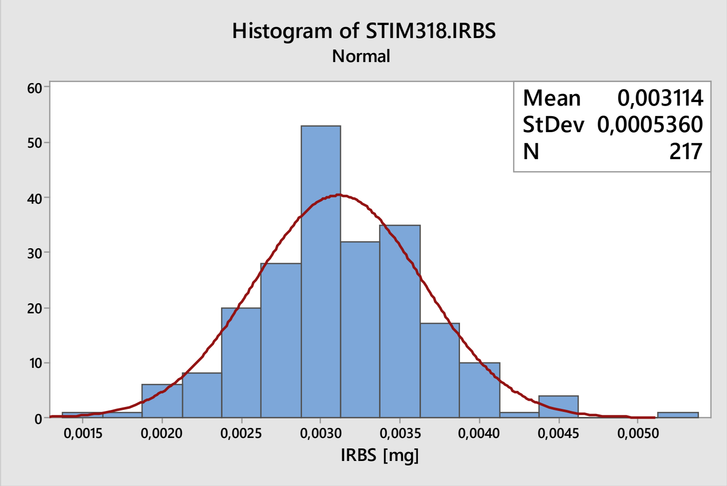
Comparing accelerometer performance STIM300 –> STIM318





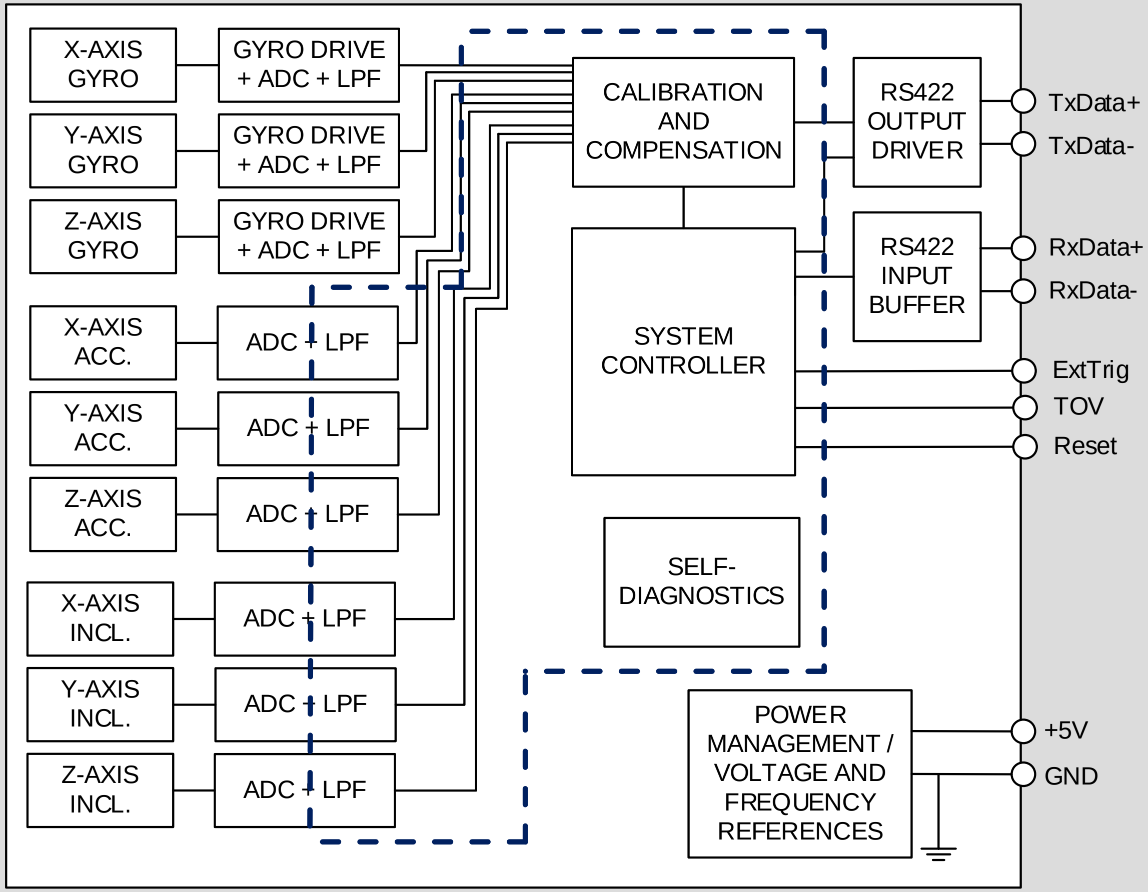
5x reduction in VRW





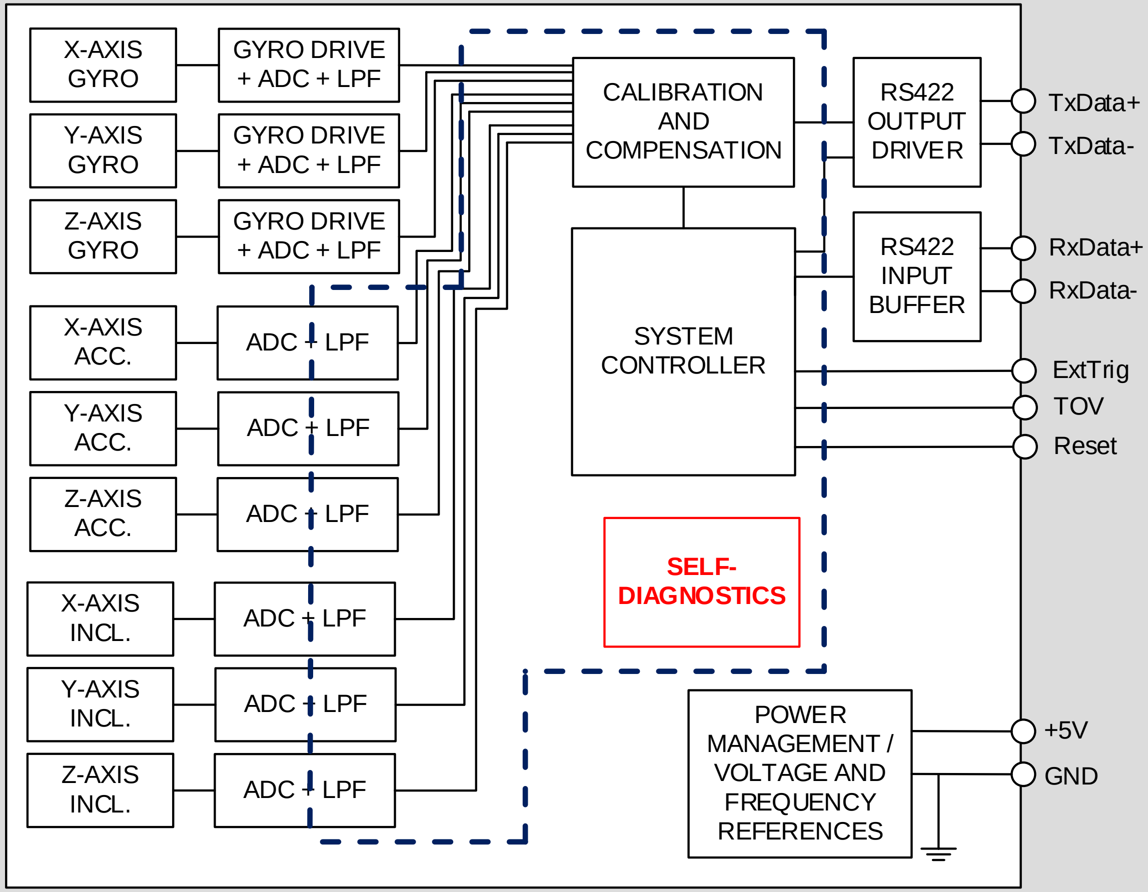
10x reduction in IRBS

STIM functional block diagram



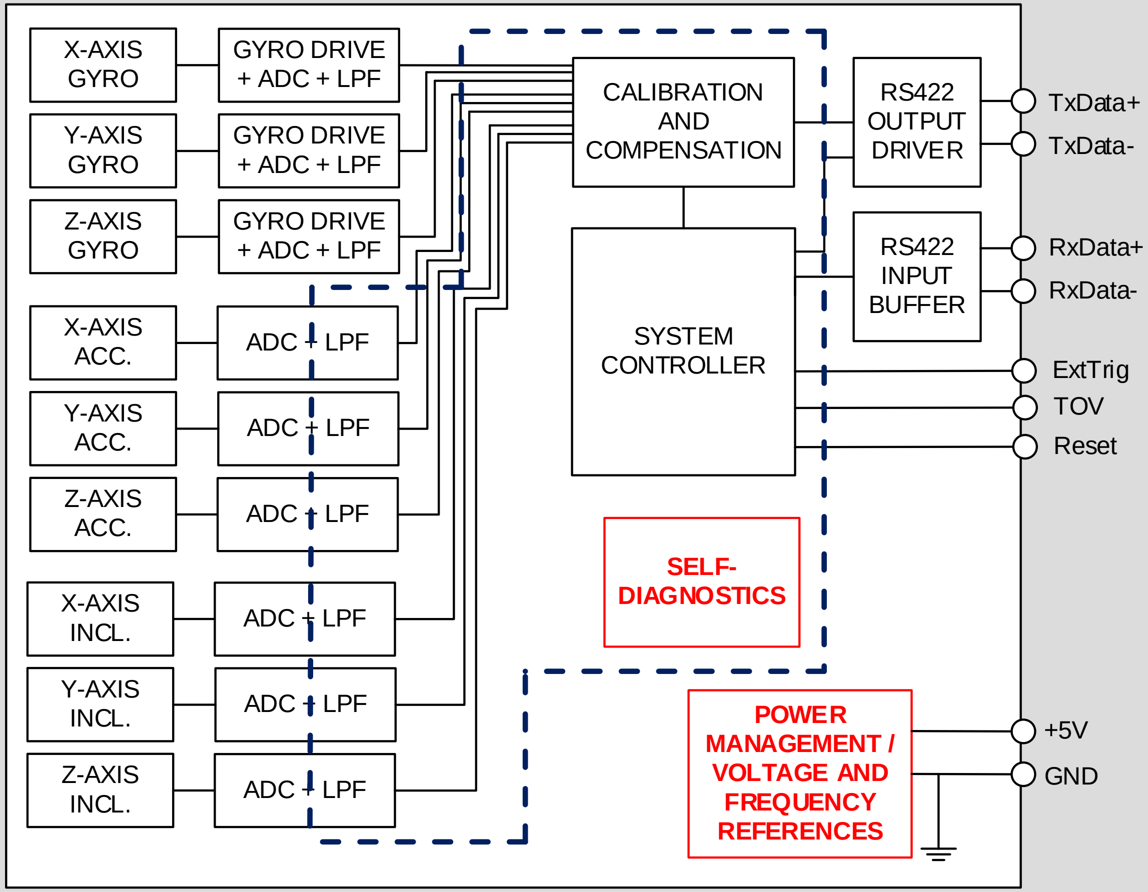
Functionality covered by 32 bit RISC ARM µC

STIM – self-diagnostic

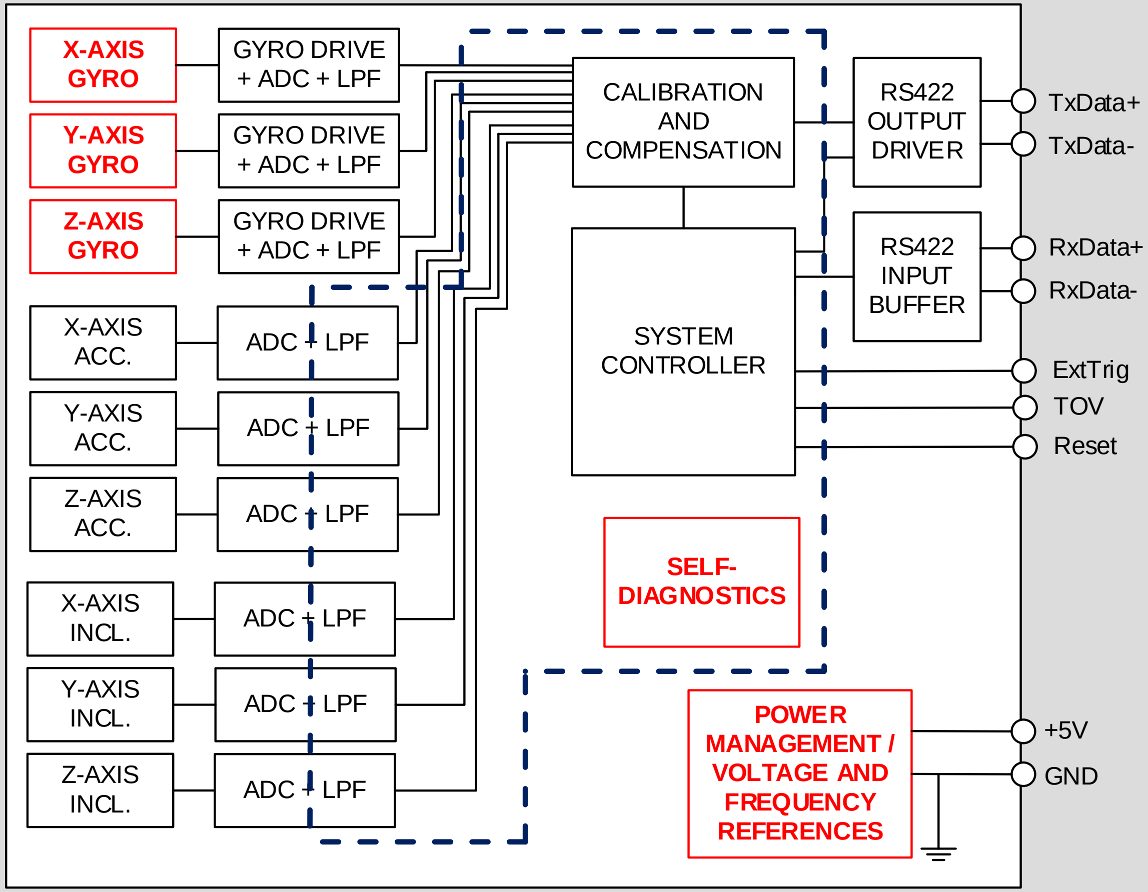


STIM – self-diagnostic

Use internal ADC of µC to monitor internal voltages



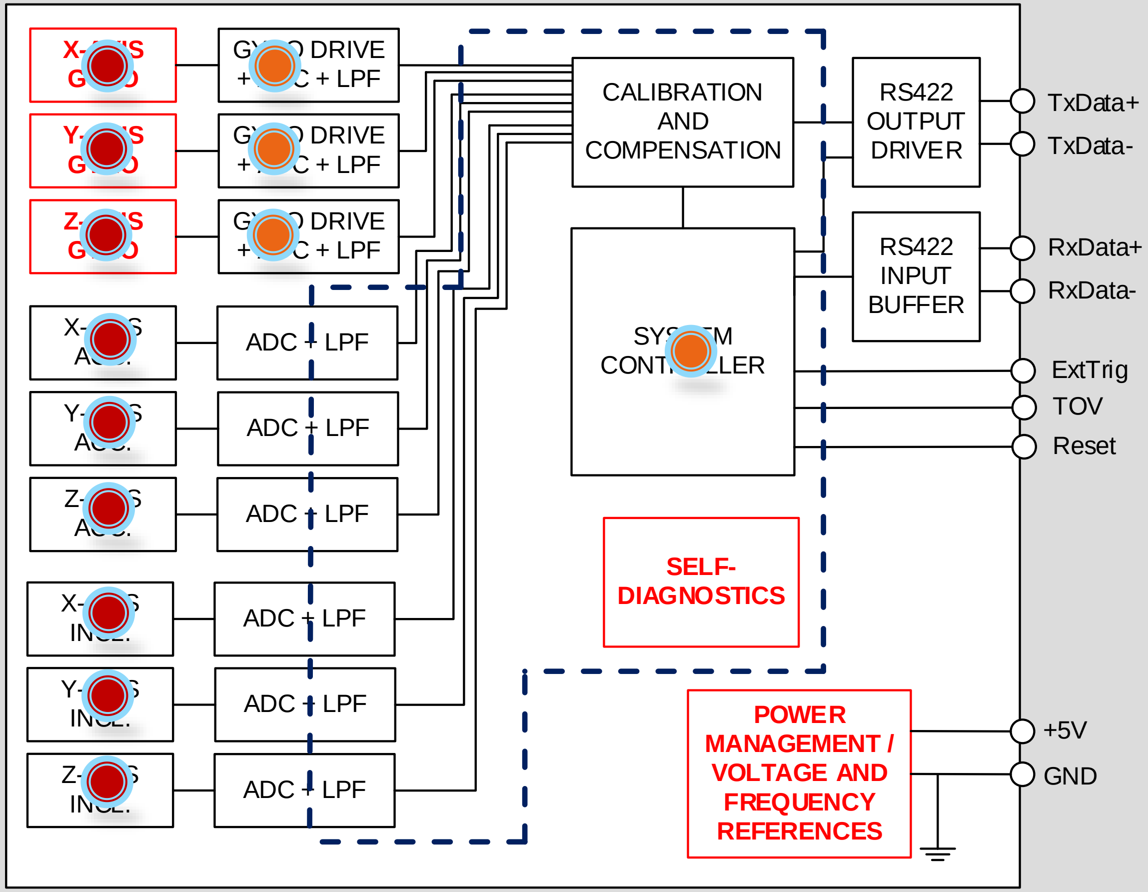
STIM– self-diagnostic



Use internal ADC of µC to monitor internal voltages

Monitor resonance frequencies of MEMS gyros
-> continuous self-test of the complete gyro proof mass
-> test-coverage of system clock

STIM – self-diagnostic



Use internal ADC of µC to monitor internal voltages

Monitor resonance frequencies of MEMS gyros
-> continuous self-test of the complete gyro proof mass
-> test-coverage of system clock

Monitor all available temperatures
Monitor deviation between temperatures

- (red dot) Temperatures used for temperature compensation of signals
- (orange dot) Additional available temperatures

Parameters monitored

Bit#	Specification	Bit#	Specification	Bit#	Specification	Bit#	Specification
E_{127}	For future use (=0)	E_{126}	For future use (=0)	E_{125}	For future use (=0)	E_{124}	For future use (=0)
E_{123}	For future use (=0)	E_{122}	For future use (=0)	E_{121}	For future use (=0)	E_{120}	For future use (=0)
E_{119}	For future use (=0)	E_{118}	For future use (=0)	E_{117}	For future use (=0)	E_{116}	For future use (=0)
E_{115}	For future use (=0)	E_{114}	For future use (=0)	E_{113}	For future use (=0)	E_{112}	For future use (=0)
E_{111}	Reference voltage#4 error	E_{110}	For future use (=0)	E_{109}	INC Z: Overload	E_{108}	INC Y: Overload
E_{107}	INC X: Overload	E_{106}	ACC Z: Overload	E_{105}	ACC Y: Overload	E_{104}	ACC X: Overload
E_{103}	GYRO Z: Overload	E_{102}	GYRO Y: Overload	E_{101}	GYRO X: Overload	E_{100}	GYRO Z: Config,error
E_{99}	GYRO Y: Config,error	E_{98}	GYRO X: Config.error	E_{97}	µC temperature failure	E_{96}	GYRO Z: ASIC temp.dev.
E_{95}	GYRO Y: ASIC temp.dev	E_{94}	GYRO X: ASIC temp.dev	E_{93}	INC Y: Temp.deviation	E_{92}	INC X/Z: Temp.deviation
E_{91}	ACC Z: Temp.deviation	E_{90}	ACC Y: Temp.deviation	E_{89}	ACC X: Temp.deviation	E_{88}	GYRO Z: Temp.deviation
E_{87}	GYRO Y: Temp.deviation	E_{86}	GYRO X: Temp.deviation	E_{85}	Self-test not running	E_{84}	TEMP INC Y: ADC error
E_{83}	TEMP INC X/Z: ADC error	E_{82}	TEMP ACC Z: ADC error	E_{81}	TEMP ACC Y: ADC error	E_{80}	TEMP ACC X: ADC error
E_{79}	TEMP GYRO Z: Clipped	E_{78}	TEMP GYRO Y: Clipped	E_{77}	TEMP GYRO X: Clipped	E_{76}	For future use (=0)
E_{75}	INC Z: ADC error	E_{74}	INC Y: ADC error	E_{73}	INC X: ADC error	E_{72}	ACC Z: ADC error
E_{71}	ACC Y: ADC error	E_{70}	ACC X: ADC error	E_{69}	For future use (=0)	E_{68}	UART unable to transmit
E_{67}	GYRO Z: data missing	E_{66}	GYRO Y: Data missing	E_{65}	GYRO X: Data missing	E_{64}	Transmit stack warning
E_{63}	Flash stack warning	E_{62}	Sample stack warning	E_{61}	Command stack warning	E_{60}	Monitor stack warning
E_{59}	Supply overvoltage	E_{58}	Internal DAC error	E_{57}	Flash check error	E_{56}	RAM check error
E_{55}	TEMP INC Y: Error	E_{54}	TEMP INC X/Z: Error	E_{53}	INC Z: Clipped	E_{52}	INC Y: Clipped
E_{51}	INC X: Clipped	E_{50}	TEMP ACC Z: Error	E_{49}	TEMP ACC Y: Error	E_{48}	TEMP ACC X: Error
E_{47}	ACC Z: Clipped	E_{46}	ACC Y: Clipped	E_{45}	ACC X: Clipped	E_{44}	GYRO Z: Data lost
E_{43}	GYRO Z: Exc.ampl.error	E_{42}	GYRO Z: Int.comm.error	E_{41}	For future use (=0)	E_{40}	For future use (=0)
E_{39}	GYRO Z: ASIC overflow, I	E_{38}	GYRO Z: ASIC overflow, Q	E_{37}	GYRO Y: Data lost	E_{36}	GYRO Y: Exc.ampl.error
E_{35}	GYRO Y: Int.comm.error	E_{34}	For future use (=0)	E_{33}	For future use (=0)	E_{32}	GYRO Y: ASIC overflow, I
E_{31}	GYRO Y: ASIC overflow, Q	E_{30}	GYRO X: Data lost	E_{29}	GYRO X: Exc.ampl.error	E_{28}	GYRO X: Int.comm.error
E_{27}	For future use (=0)	E_{26}	For future use (=0)	E_{25}	GYRO X: ASIC overflow, I	E_{24}	GYRO X: ASIC overflow, Q
E_{23}	Regulated voltage#3 error	E_{22}	Regulated voltage#2 error	E_{21}	Regulated voltage#1 error	E_{20}	Supply voltage error
E_{19}	Reference voltage#3 error	E_{18}	Reference voltage#2 error	E_{17}	Reference voltage#1 error	E_{16}	Start-up phase active
E_{15}	GYRO Z: Int.comm.error	E_{14}	GYRO Y: Int.comm.error	E_{13}	GYRO X: Int.comm.error	E_{12}	GYRO Z: Clipped
E_{11}	GYRO Y: Clipped	E_{10}	GYRO X: Clipped	E_{9}	TEMP GYRO Z: Error	E_{8}	TEMP GYRO Y: Error
E_{7}	TEMP GYRO X: Error	E_{6}	GYRO Z: ASIC temp.error	E_{5}	GYRO Y: ASIC temp.error	E_{4}	GYRO X: ASIC temp.error
E_{3}	µC temperature error	E_{2}	GYRO Z: Exc.freq.error	E_{1}	GYRO Y: Exc.freq.error	E_{0}	GYRO X: Exc.freq.error

> 100 different parameters

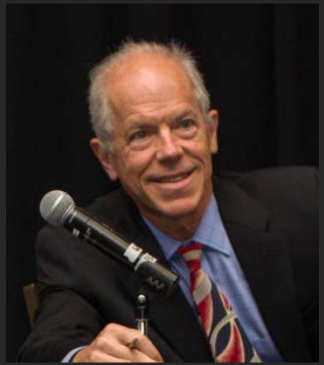
Self-test running

Each transmitted data package will include status-byte(s)

Result from all tests are available to user

Ask the Experts Part I

Inertial Technology for Robotics, UAVs and other Applications



Alan Cameron
Editor in Chief
Inside GNSS
Inside Unmanned Systems

Ralph Hopkins
Distinguished Member Technical Staff
Charles Stark Draper Laboratory

Reidar Holm
Manager
Product Development
Sensonor

Brian Rider
Chief Technology Officer
LeoStella

Ryan Robinson
ADCS Lead
LeoStella

QUICKPOLL

What level of gyroscope bias instability performance does your application require?

Poll Results (single answer required):

1 deg / hr	10%
.1 deg / hr	23%
.01 deg / hr	43%
.001 deg / hr	17%
.0001 deg / hr	6%

Part II: Reliability by Design

Reidar Holm
Manager
Product Development
Sensonor

Standard qualification programs

1-year stability program:

Stability test
50hrs @+20°C (powered)

Low Temperature Storage
72hrs @-55°C (non-powered)

High Temperature Storage
240hrs @+85°C (non-powered)

TurnOn (powerswitching)
100x switch on/off @+20°C

Temperature Cycling
132 cycles, -40°C/+85°C (non-powered)

High Temperature Operating Life
240hrs @+85°C (powered)

Vibration
20min per axis, 10-2000Hz/20grms (non-powered)

Mechanical Shock
5x 500g, 0.5ms/ 6 dir (non-powered)

10-year qualification program:

Environmental tests

Operating Temperature:

HTOL 1000hrs, 85°C:

MIL-STD-810G/501.4-II

LTOL 1000hrs, -40°C:

MIL-STD-810G/501.4-II

Non Operating Temperature:

HTSL 1000hrs, 90°C:

MIL-STD-810G/501.4-I

LTSL 1000hrs, -55°C:

MIL-STD-810G/501.4-I

Powered and Non-Powered Temperature Cycling:

250 cycles,-40/+85°C
MIL-STD-810GMethod 503.5 Procedure 1-C

Humidity:

THB 1000hrs 85°C/85%RH:

JEDEC JESD 22-A101

Low Pressure test:

MIL-STD-810G method 500.5 procedure 3

Mechanical Tests

Vibration:

MIL-STD-810E 514.4-8 "High Performance Aircraft“, 15 min/axis

Mechanical Shock:

MIL-STD-883: 1500g/0.5ms, 5 shocks/6 directions

EMC

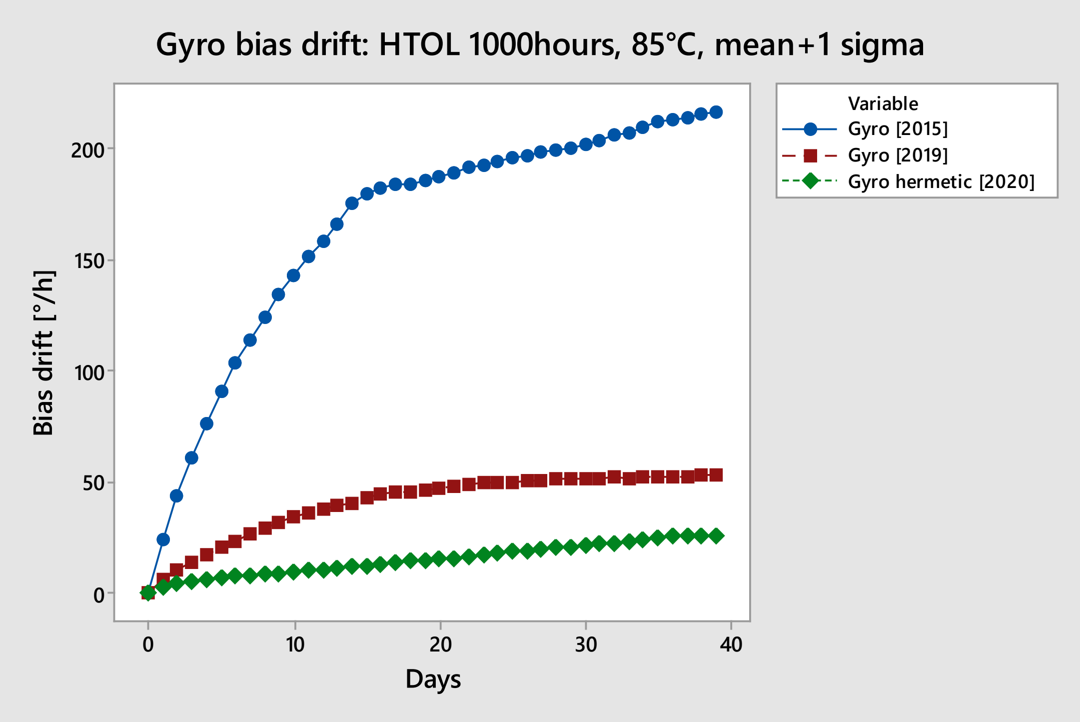
Emission

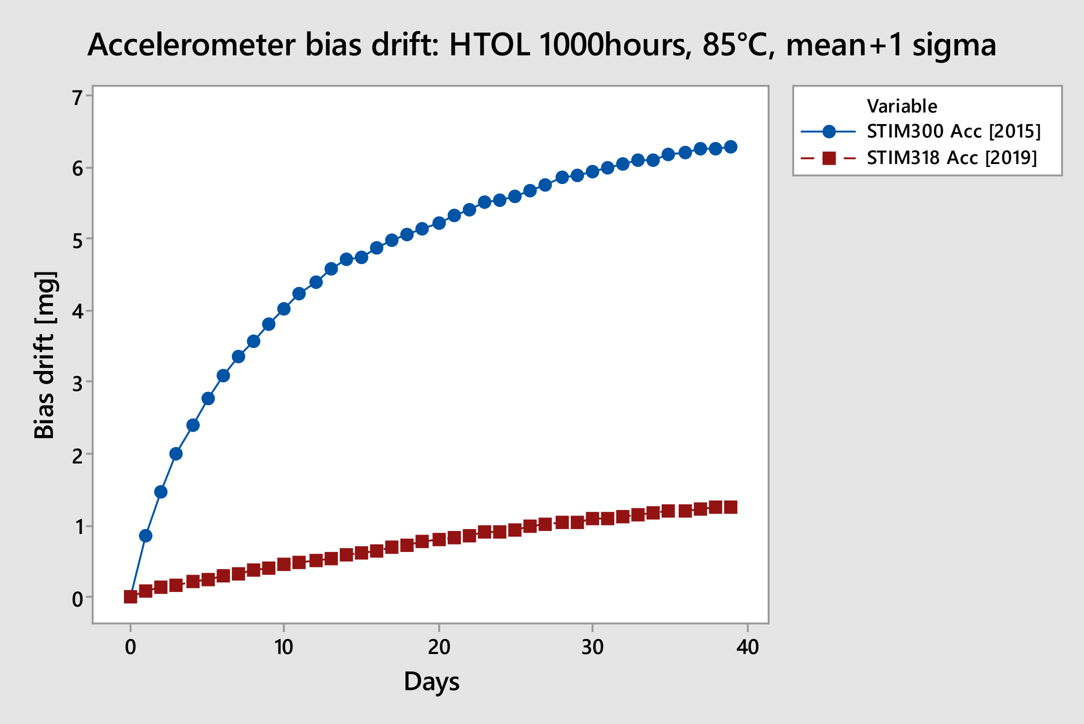
Immunity

MIL-STD-461G CS114
MIL-STD-461G RE102
MIL-STD-461G RS103

sensonor InsideGNSS inside unmanned systems

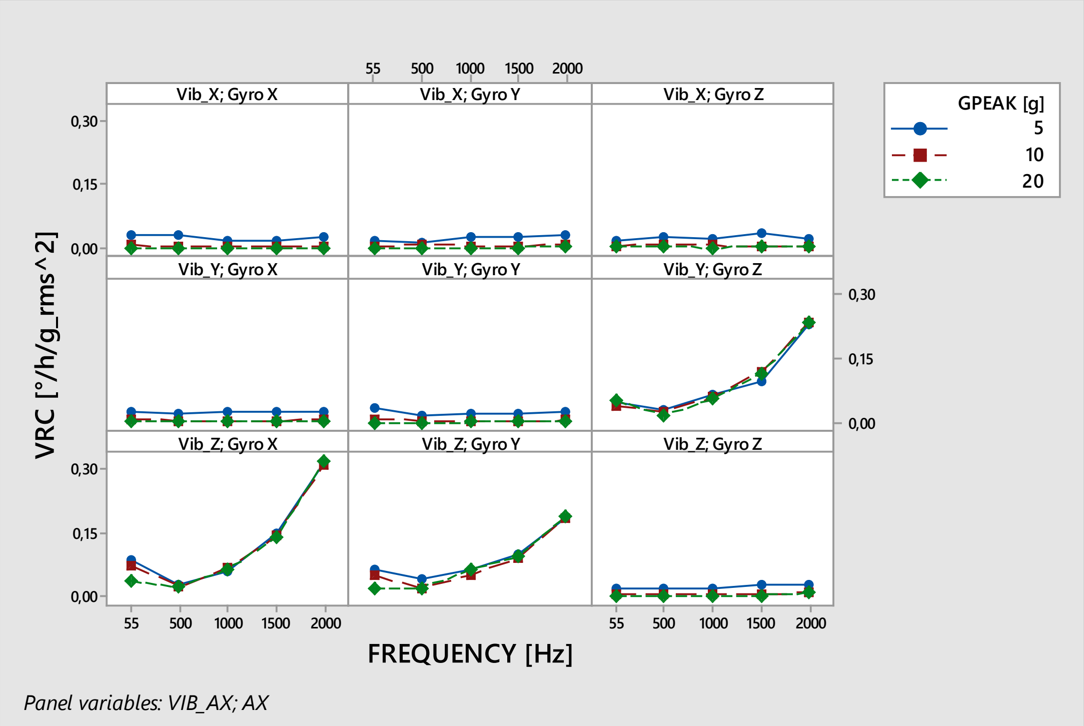
High Temperature Operating Life: 1000 hours powered at +85°C



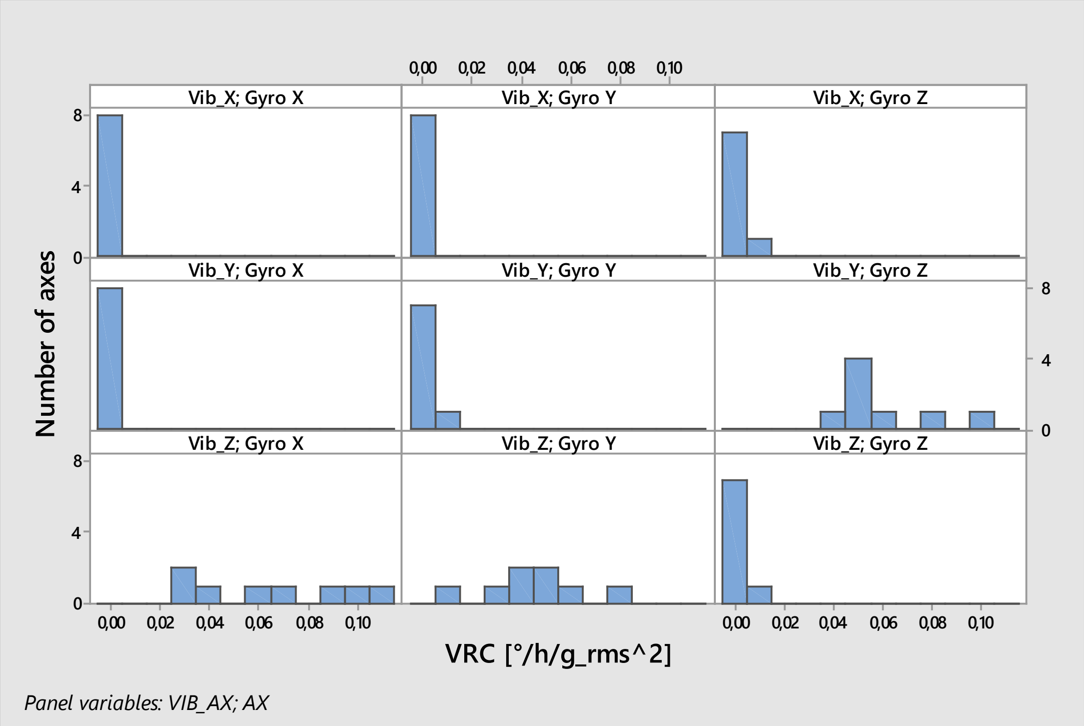


Extensive vibration testing

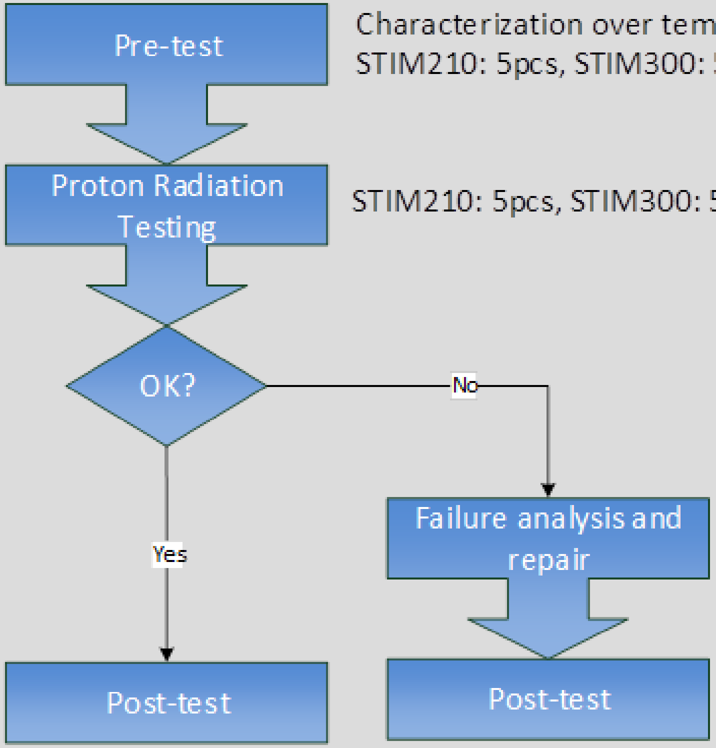
Sinusoidal vibrations (5 – 20g, 50 – 2000Hz):



Random vibrations (MIL STD 810E 514.4 "High Performance Aircraft", g_{rms}=14.83):



Radiation
Test plan: Proton test



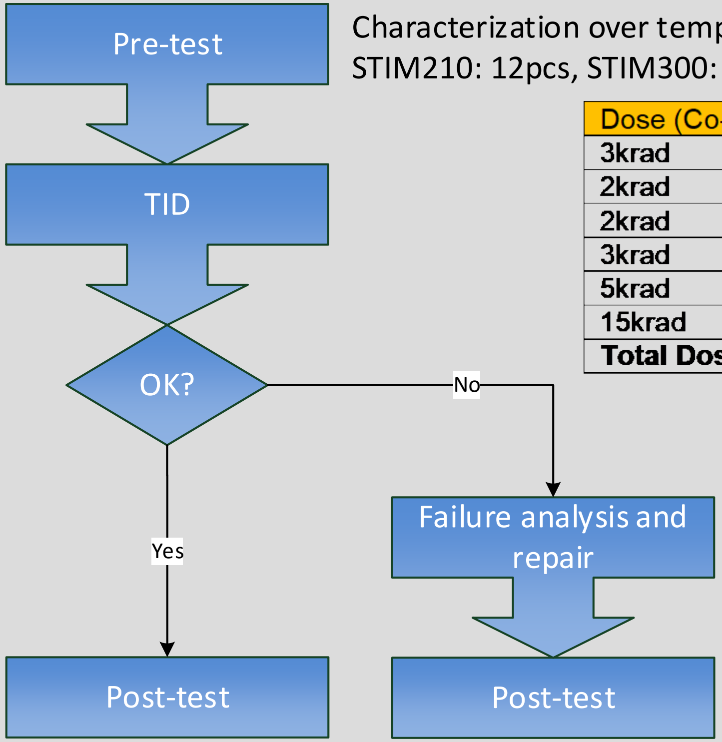
Characterization over temperature, rate and g (g for STIM300only)
STIM210: 5pcs, STIM300: 5pcs

STIM210: 5pcs, STIM300: 5pcs

Energy level [MeV]	STIM210					STIM300				
	#1	#2	#3	#4	#5	#1	#2	#3	#4	#5
200			X	X		X				
120	X	X					X			
60		X						X		
30			X						X	
20					X					X
Fluence	$>=10^{11} p/cm^2$									

Characterization over temperature, rate and g (g for STIM300 only)
STIM210: 5pcs, STIM300: 5pcs

Radiation
Test plan: Total Ion Doze (TID)

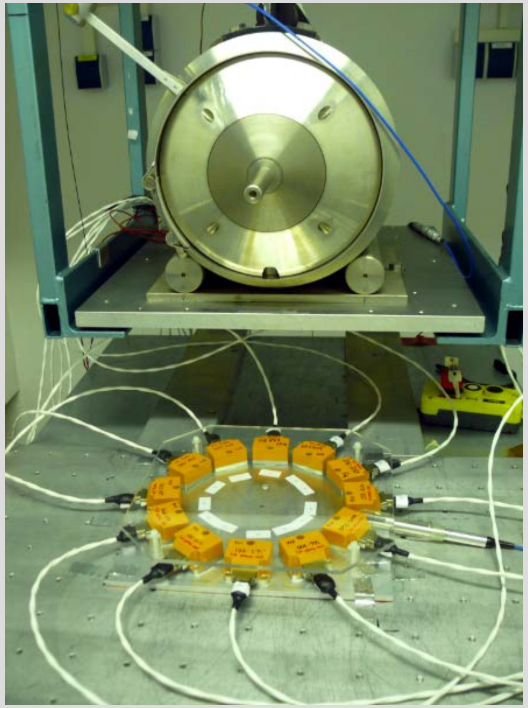


Characterization over temperature, rate and g (g for STIM300 only)
STIM210: 12pcs, STIM300: 12pcs

Dose (Co-60)	Dose#1	Dose#2	Dose#3	Dose#4	Dose#5	Dose#6
3krad	2 pcs	2 pcs	2 pcs	2 pcs	2 pcs	2 pcs
2krad						
2krad						
3krad						
5krad						
15krad						
Total Dose:	**3krad**	**5krad**	**7krad**	**10krad**	**15krad**	**30krad**

Number of pieces in table above is for each IMU:
STIM210: 12pcs, STIM300: 12pcs

Characterization over temperature, rate and g (g for STIM300 only)
STIM210: 12pcs, STIM300: 12pcs



Radiation

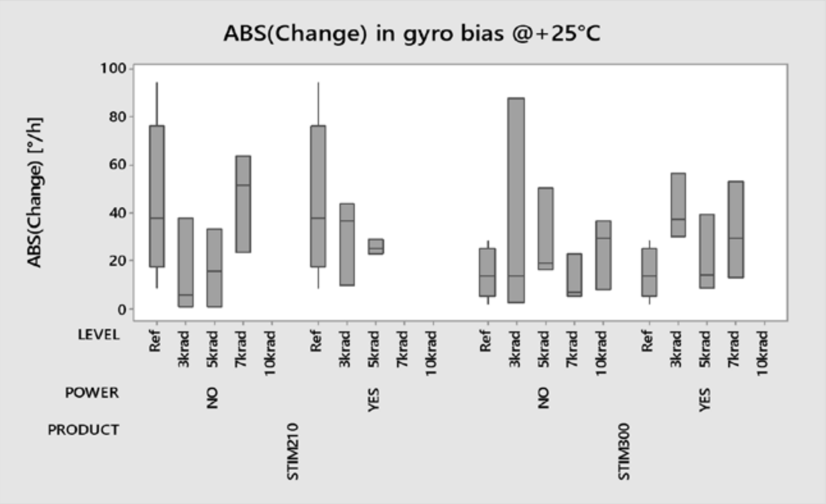
Test result: TID

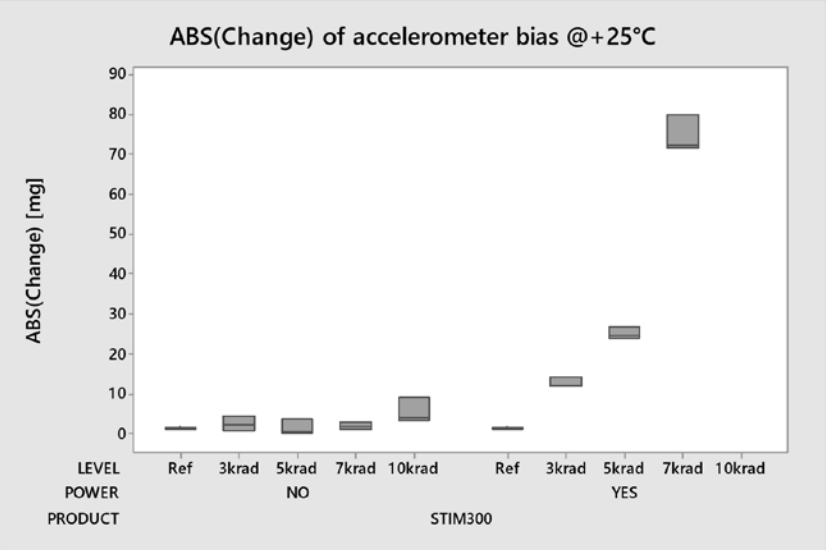
#	Dose step	STIM210											
		Powered						Unpowered					
		#1	#2	#3	#4	#5	#6	#1	#2	#3	#4	#5	#6
0	Pre-irradiation												
1	0 -> 3 krad												
2	3 -> 5 krad												
3	5 -> 7 krad												
4	7 -> 10 krad												
5	10 -> 15 krad												
6	15 -> 30 krad												

- Not included at dose step
- Passed at post-irradiation tes
- Failed at post-irradiation test
- No communication at post-irradiation test

#	Dose step	STIM300											
		Powered						Unpowered					
		#1	#2	#3	#4	#5	#6	#1	#2	#3	#4	#5	#6
0	Pre-irradiation												
1	0 -> 3 krad												
2	3 -> 5 krad												
3	5 -> 7 krad												
4	7 -> 10 krad												
5	10 -> 15 krad												
6	15 -> 30 krad												

- Not included at dose step
- Passed at post-irradiation tes
- Failed at post-irradiation test
- No communication at post-irradiation test





Developments in progress

- Introduce new IMU based on STIM318 with improved gyro ARW and PPS input
- Introduce products with hermetic package
  - STIM277H (form-fit-function as STIM210)
  - STIM377H (form-fit-function as STIM300)
- Radiation testing on new prototype IMU with expected improved robustness towards radiation. Testing completed Q1/202

LeoStella Satellite Use Case

Brian Rider
Chief Technology Officer
LeoStella

Ryan Robinson
ADCS Lead
LeoStella

Emerging Space Market Drives Paradigm Shift for Satellite Technology

- **New Wave of Products and Services Offered by Commercial Companies**
  - Economic Forecasting, Resource Management, Change Detection, Conflict Monitoring, Affordable Science, Data Transport/Security, Reserve Defense
- **Engineering Decisions Strongly Coupled with Business Case**
  - Satellite technology must enable profitable business
  - Intelligent volume manufacturing required to lower overhead
- **Competition Drives Advanced Performance**
  - Emphasis on data quality, availability, system throughput
  - Requires constant capability advancement to stay ahead
- **Ruggedized Tactical Hardware Critical to Balance Cost/Capability**
  - Leveraging rapid advancements in terrestrial, marine, air tactical products
  - Unique opportunity to benefit from growing tactical market and industry funded R&D

Example Use Cases in the News

BlackSky Offering Geospatial Intelligence Tools for Analysts who Telework
https://spacenews.com/blacksky-offering-geospatial-intelligence-tools-for-analysts-who-telework/

Global-1 satellite shot of Iron Ore Transhipment Facility, Port Hedland, Western Australia. Credit: BlackSky

Satellite Data Reveals the Pandemic's Effects From Above
https://www.wired.com/story/satellite-data-reveals-the-pandemics-effects-from-above/

COURTESY OF MAXAR

COURTESY OF MAXAR

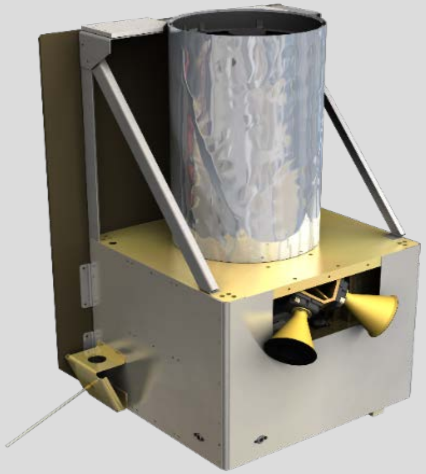
Use Case: Commercial Earth Observation Constellation

Satellites Comprised of Many Systems Working Together

- ADCS System Maneuvers, Stabilizes, and Points Satellite
- Propulsion System Maintains Orbit Altitude & Phasing
- Power System Manages Power Generation, Storage, Usage
- Comms System Transfers Commands, Telemetry & Data
- Payloads Collect and Process Mission Data
- Structures and Thermal Manage Environmental Loads

High Agility/Stability Satellites Rely Heavily on the ADCS system for Launch Detumble, Power Generation, Communications, & Mission Data Collection. ADCS is a Complex System of Numerous Sensors, Actuators and Control Systems that all Must Work in Unison to Meet Performance

Example 50kg class satellite with 1m resolution imaging and high agility to capture multiple snap-shots per pass with ground speed of ~7500 m/s



*Satellites Built in **High Volume Production Lines***

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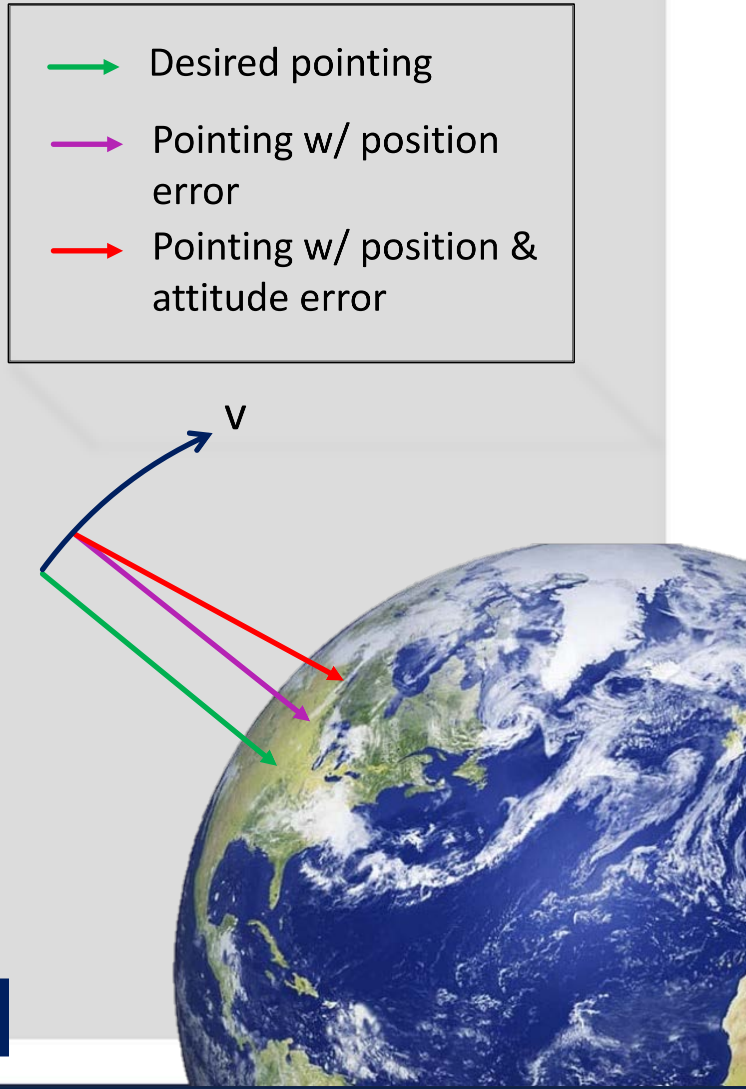
Satellite & ADCS Driving Requirements

- Earth observation satellites in Low Earth Orbit (LEO) require precise position, attitude, and rate knowledge/control to meet ground pointing requirements
  - Example Reqt: Tens of arcsec of pointing error, tens of meters of position error
  - In LEO, satellite may need to precisely rotate over target at >1 deg/s to maintain pointing
- Image quality depends on minimizing “smear”
  - Smear: Motion over exposure time, driven by angular rate error
  - Ideally << 1 pixel smear
- Low-cost components for constellation-level production
- Reliability in LEO environment (vs. thermal variation, vibration/shock, vacuum, radiation)



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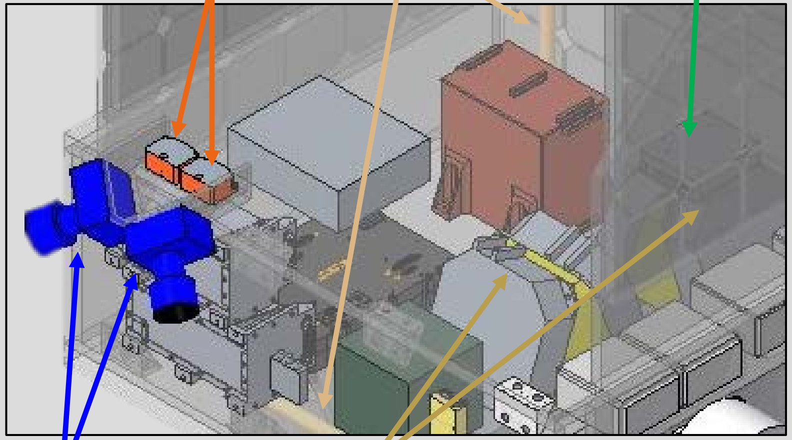
Attitude Determination & Control System (ADCS) Architecture

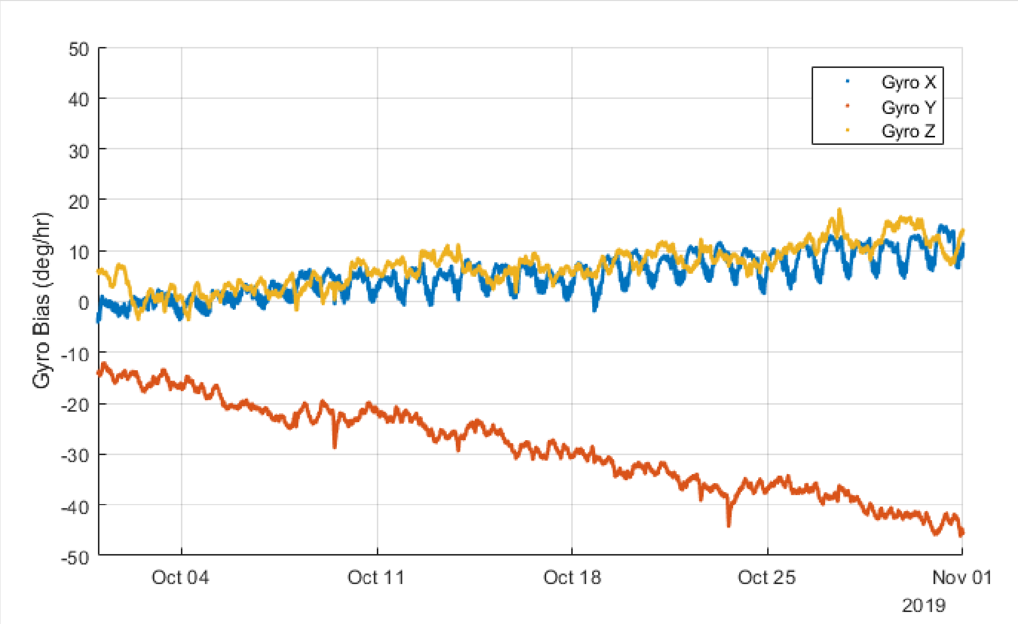
- **Control feedback loop includes sensors, estimation & control algorithms, and actuators**
- **Rate Gyros (IMUs) + Star Trackers are critical for fine pointing**
  - Star Tracker: Measures attitude (orientation) at low frequency (e.g. 2 Hz)
  - Rate Gyro: Provides body rate data at high frequency (e.g. 20 Hz)
  - Kalman Filter: Combines attitude + body rate measurements with dynamic model to estimate attitude at high frequency; also used to estimate and correct gyro bias
- **Calibration performed on-orbit corrects misalignment between ST(s) and IMU(s), as well as scale factor and bias (note: bias drifts over time)**



IMU Driving Requirements

- Low gyro noise / angle random walk (ARW)
- Low bias drift
- High measurement rate
- Minimize size, weight, and power

Kalman Filter Estimated Gyro Bias, 1 month



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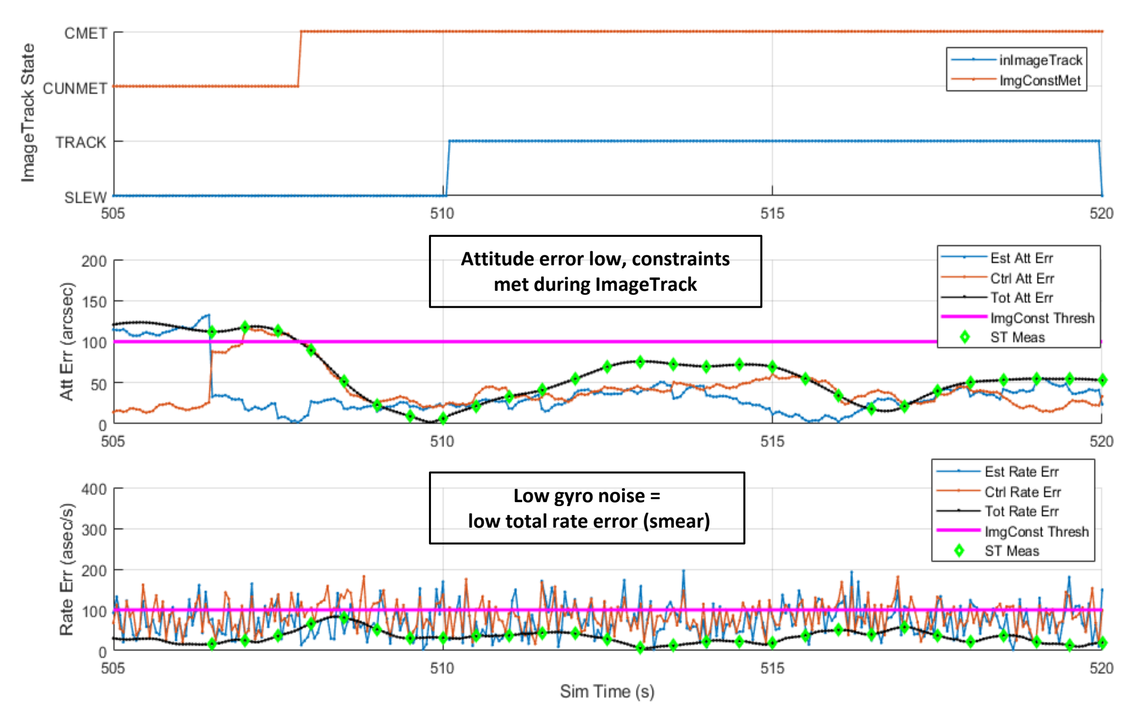
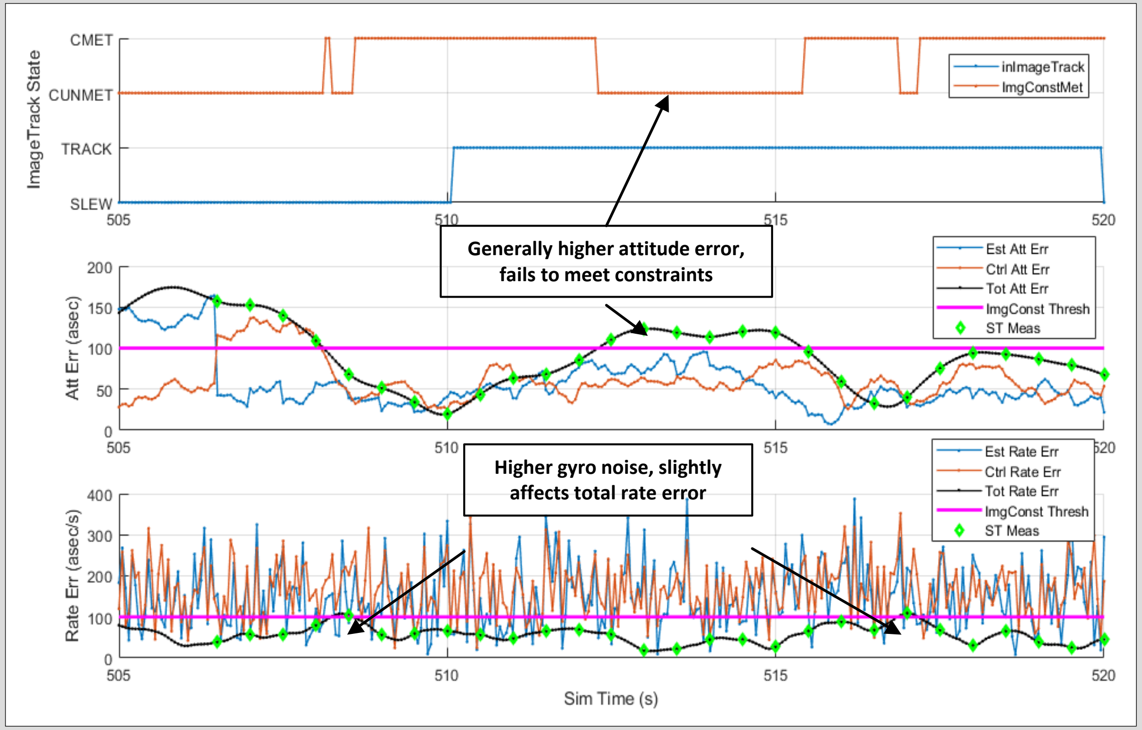
ADCS Performance Simulation

- “High” accuracy IMU produces low attitude and rate error, meeting pointing and smear performance criteria



- Noisy IMU (2x noise stdev) increases avg rate error and results in worse attitude estimation/control



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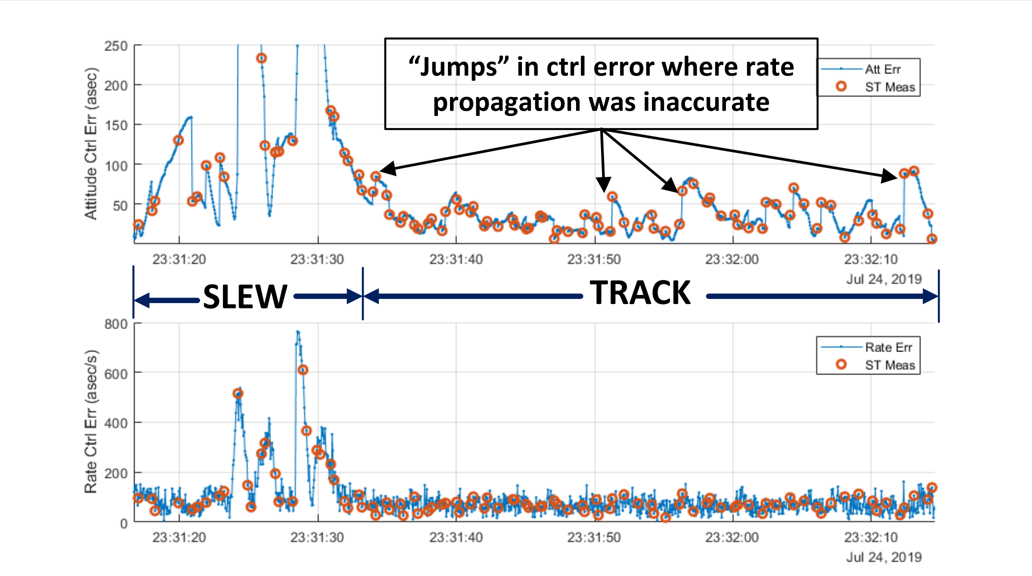
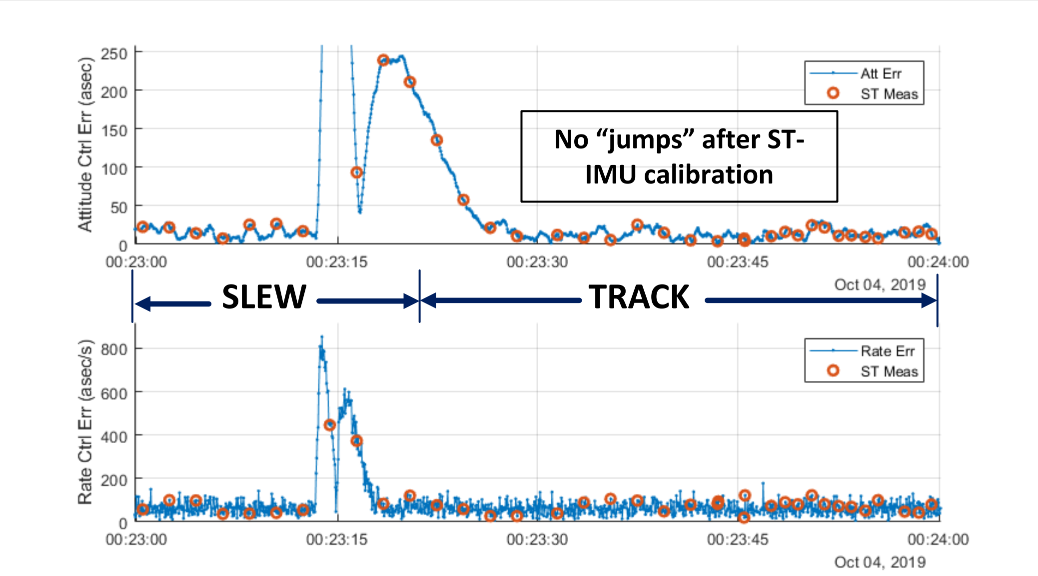
On-Orbit Data

- Pre-Calibration: ST-IMU misalignment propagates rate in slightly wrong direction, creating "jumps" when STs "correct" the attitude estimate
- Post-Calibration: Aligned ST & IMU minimize attitude control error

Control Error, Pre-Calibration (2 Hz STs, 20 Hz Gyro)



Control Error, Post-Calibration (1 Hz STs, 20 Hz Gyro)



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Future Technology Developments

- Continue to push limits of performance, robustness, size/weight/power, and cost efficiency
- Fully hermetic IMUs: helium on launch vehicles may interfere w/ MEMS gyros
- Radiation tolerance: redundant memory, latchup protection, self-diagnostics, etc
- Accelerometers: Sensitive enough to measure thrust from electronic propulsion (i.e. ion thrusters, ~10 micro-g)

QUICKPOLL

How critical is the need for fully hermetic IMUs in your solutions?

Poll Results (single answer required):

A necessity	16%
Important, but not critical	25%
Becoming increasingly important	24%
Not important	20%
Not sure	16%

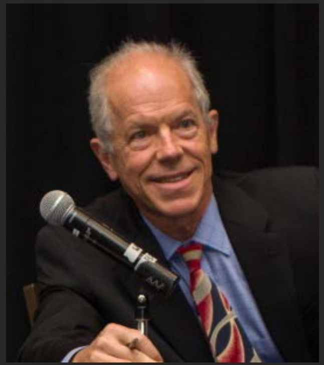
QUICKPOLL

Which is the leading requirement for inertial in your application?

Poll Results (single answer required):

Low gyro noise / angle random walk (ARW)	25%
Low bias drift	38%
High measurement rate	8%
Minimize size, weight, and power	28%

Ask the Experts



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