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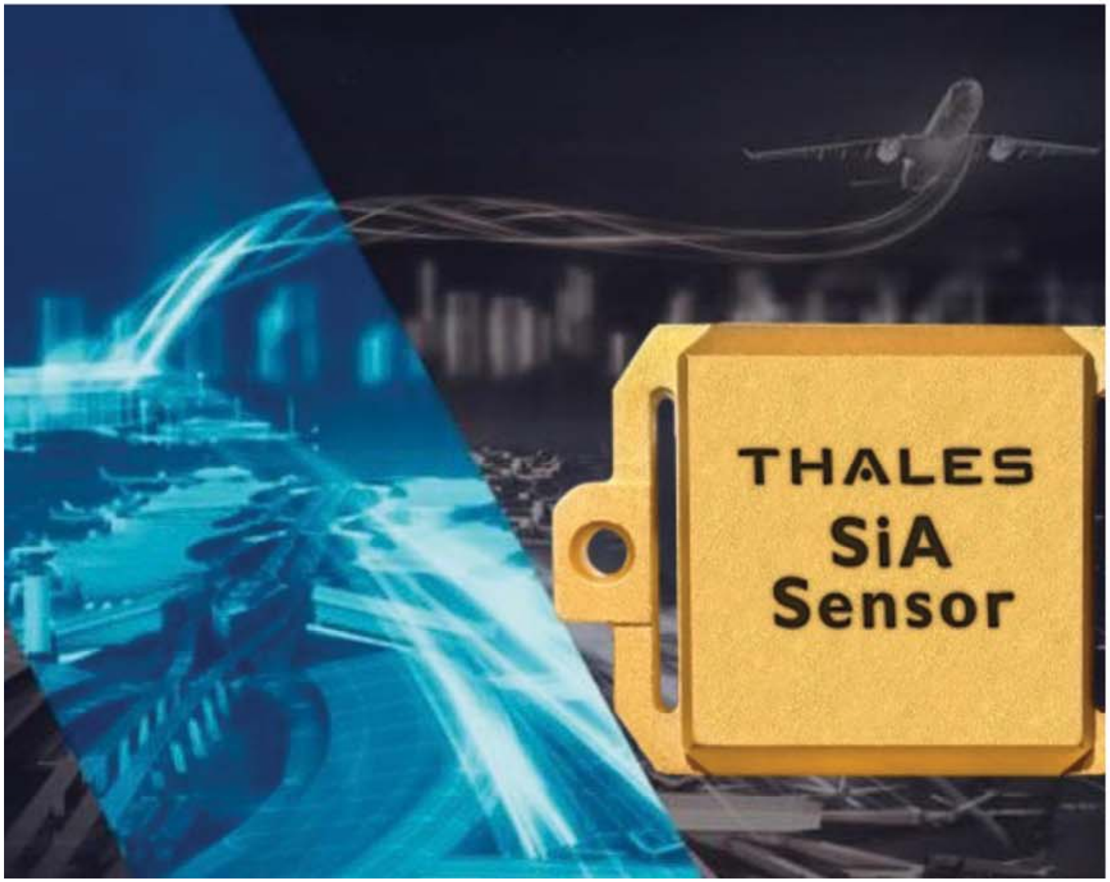
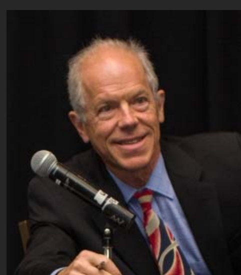


HIGH-PERFORMANCE ACCELEROMETER APPLICATION IN NAVIGATION, STABILIZATION, CONTROL AND SURVEYING

Wednesday, July 8, 2020

WELCOME TO

High-Performance Accelerometer Application in Navigation, Stabilization, Control and Surveying



Alan Cameron
Editor in Chief
Inside GNSS
Inside Unmanned Systems

Vivien Lagorce
MEMS Program Manager
Thales

Dimitrios Damianos
Technology & Market Analyst
Yole Développement

Edgar v. Hinüber
CEO and Managing Director
iMAR Navigation GmbH

Pierre-Olivier Lefort
MEMS Expert and Product Design Authority
Thales

Co-Moderator: Lori Dearman, Executive Webinar Producer

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Who's In the Audience?

A diverse audience of over 450 professionals registered from 53 countries, representing the following industries:

- **19% Military and defense**
- **15% Research**
- **11% University/Education**
- **10% Automotive**
- **6% Transportation, Logistics, Asset Tracking**
- **6% Machine Control, Mining, Construction**
- **3% Precision Agriculture**
- **30% Other**

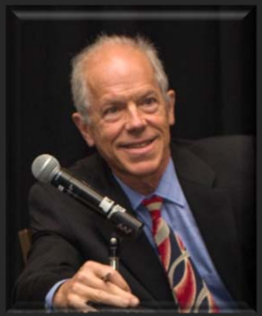
Welcome from *Inside Unmanned Systems*

Richard Fischer
Publisher
Inside GNSS
Inside Unmanned Systems

A word from the sponsor

Ariane Roller-Vantilcke
Inertial Navigation Marketing Manager
Thales

Today's Moderator



Alan Cameron
Editor in Chief
Inside GNSS
PNT Editor
Inside Unmanned Systems

QUICKPOLL

What is your status in selection of accelerometer and for which application do you plan to introduce it?

Poll Results (single answer required):

Answer	Result
In early exploration without any specific application	36%
R&D - need accelerometer for civil or military airborne apps	23%
R&D - need accelerometer for land or naval apps	10%
R&D - need accelerometer for autonomous app (UAV/auto/train)	17%
Have accelerometer solution & do not plan to change solution	15%

Silicon Accelerometer MEMS

Vivien Lagorce
MEMS Program Manager
Thales

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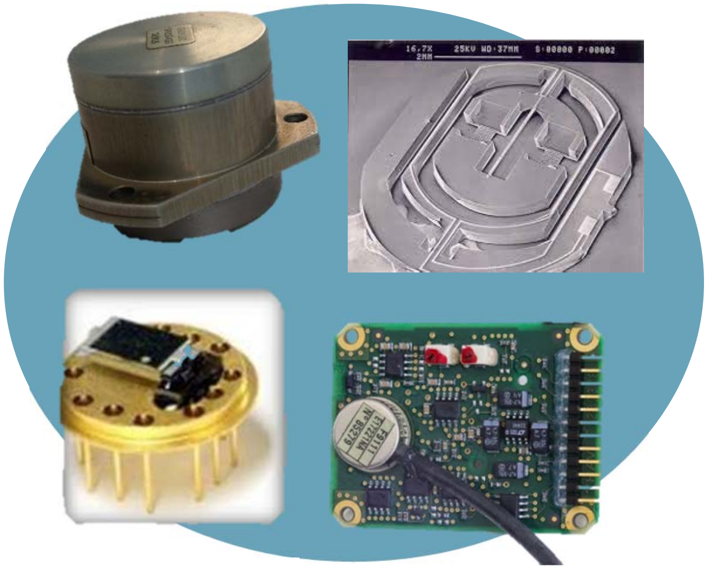
Thales recognized in high-grade inertial market since 1980

- **Embedded in major flagship civil and military programs for 40 years.**



- **High level of knowledge with more than 1,000 patents**
- **More than 10,000 navigation product/year and 300,000 MEMS sensors delivered in quartz and silicon technology**
- **More than 1,5 billions hour of using for MEMS sensors**

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New MEMS Silicon Accelerometer

The best of Thales's experience to propose a sensor alternative

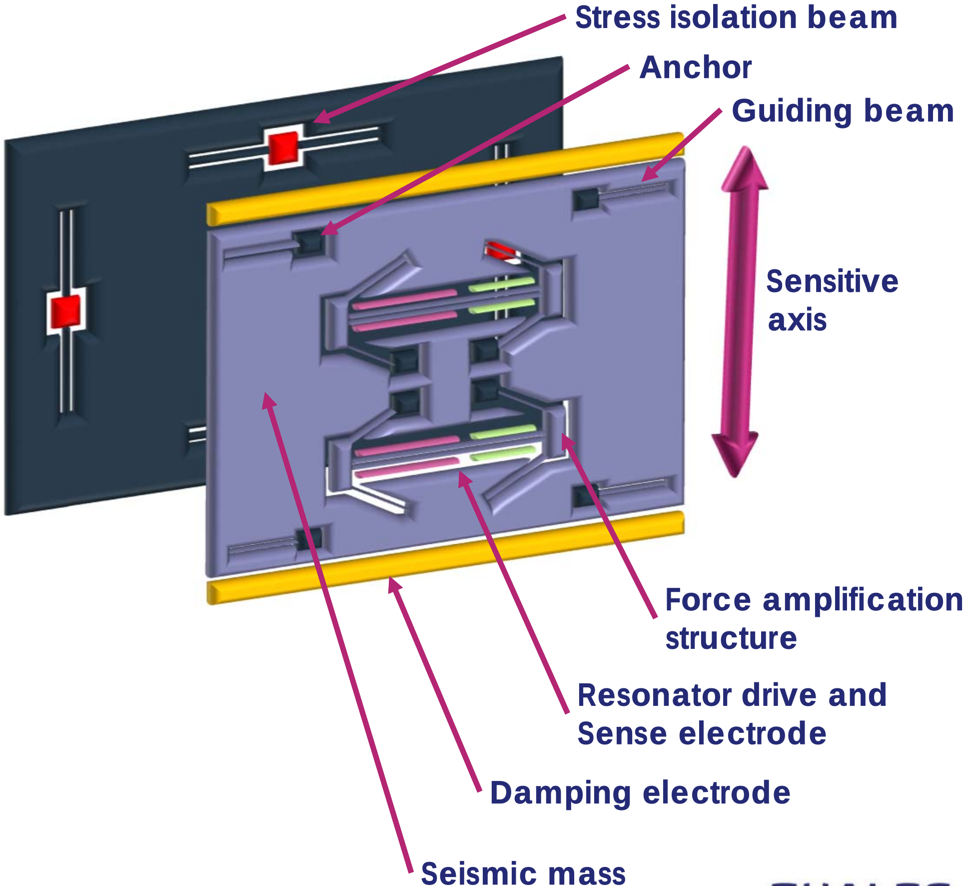
- A large portfolio with the same sensor size
  - Up to 100g range and 70µg bias
- A very small size for the best performance levels
  - 6cm^3
- Easy to integrate
  - Digital SPI interface
- 100% France design and manufacture

TopAxyz MEMS family	Ultimate input range	Extended input range				High input range				Standard input range	
	4000 UR	3000 ExR	2000 ExR	1500 ExR	500 ExR	3000 HR	2000 HR	1500 HR	650 HR	2000 SR	1500 SR
Input range	<100g	70g				40g				15g	
Bias (in run)	<40 µg	<70 µg	<500 µg	<1000 µg	<4000 µg	<70 µg	<500 µg	<1000 µg	<2000 µg	<200 µg	<1000 µg

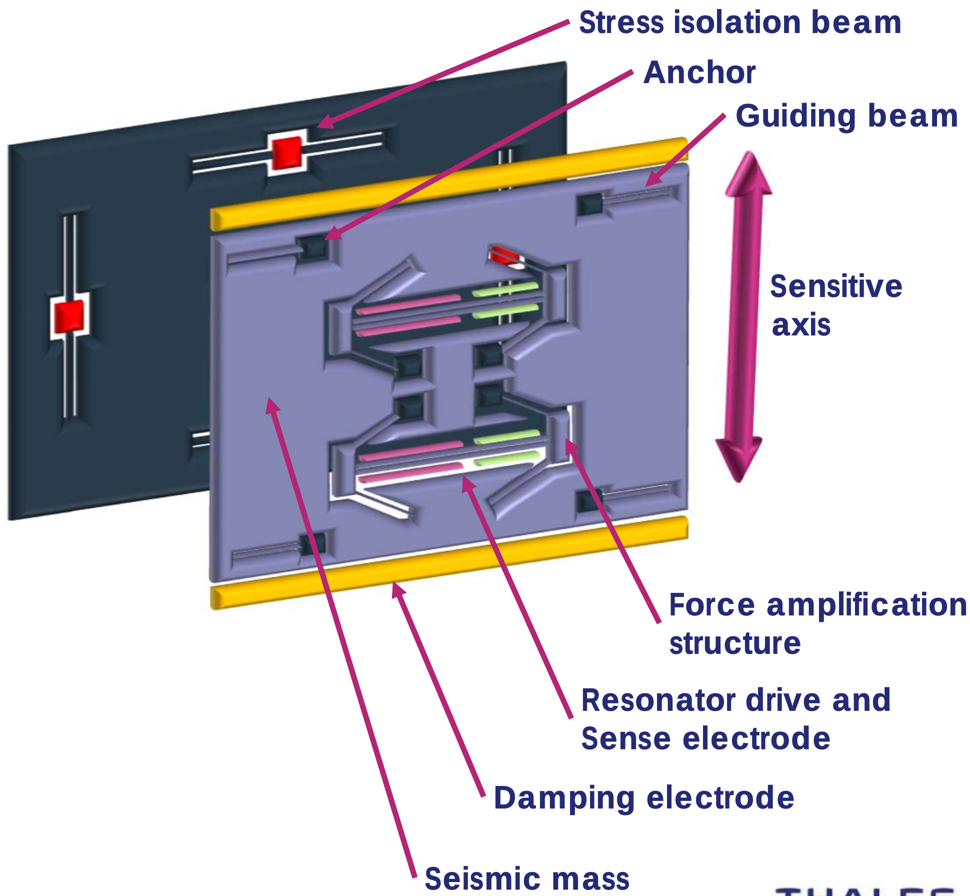
UR and ExR: under French exportation control
HR: under European dual use exportation control
SR: free of exportation control

Thales design choices

- High-sensitivity vibrating beam principle, with differential design for 10^3 common mode errors rejection
- Manufacturing with only highly stable silicon and silicon oxide materials (no metals), including THALES patent stress isolation features for die assembly
- Custom damping system to improve performance under vibration

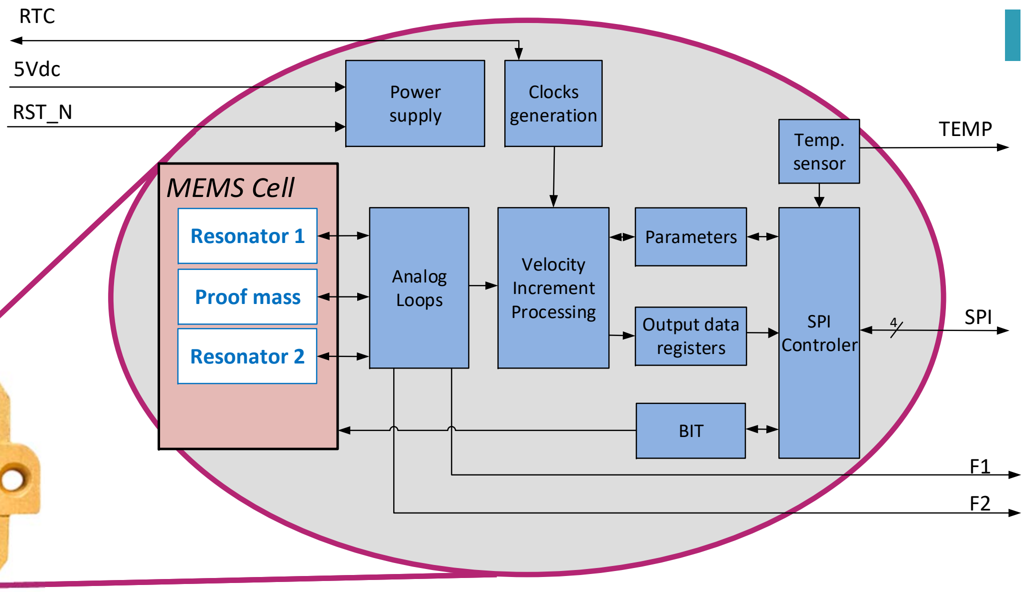


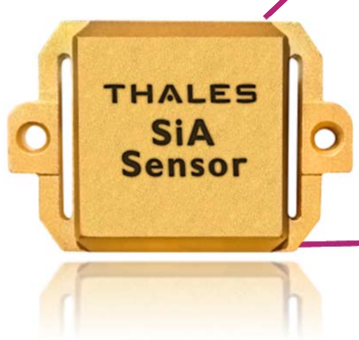
Thales design choices



Designed to be simple to use

- Programmable sample rate up to 6400 Hz
- Single Supply Voltage
- Compensation parameters stored in memory for fast plug and play
- Analog and digital temperature information for compensation
- Calibrated digital speed increment output
- Sinusoidal analog output to be compatible with existing system
- Built-in test for safety critical system and maintainability





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A robust French supply chain

- More than 10 years strong collaboration with Tronics Microsystems
- SiA integration, calibration and acceptance tests performed in Thales facilities
- Product availability and support is guaranteed throughout program lifetime, however long
- Production capacity higher than 30,000/year, with a smart logistic like Vendor Managed Inventory (VMI)
- A robust production line applying APQP international standard

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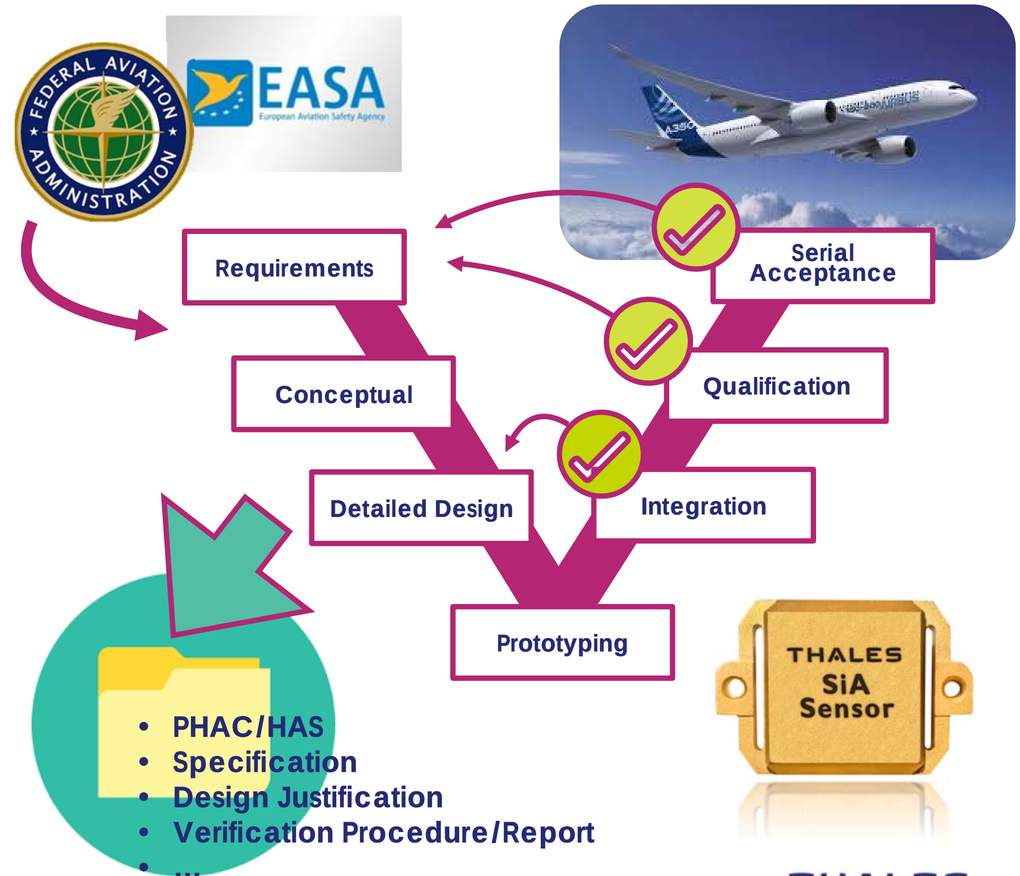
Our expertise in safety and critical applications for your system

- Applying **DO254 DAL A** aeronautics development methodology to prevent any potential failure

- Thales expertise to **support customer during certification** process with airworthiness authorities

- Safety and reliability justification to offer **lifetime over 25 years** and operational **failure rate lower than 160.10^{-9}/h**(*)

(*) Under predefined life profile



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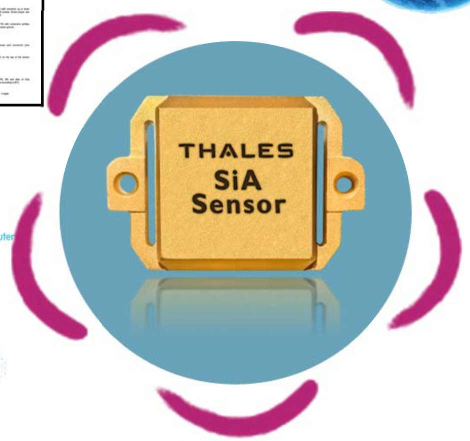
What choosing Thales means...

THALES InsideGNSS inside unmanned systems

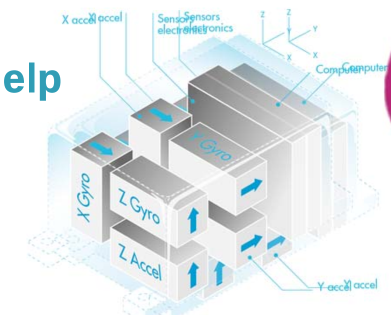
Our support from your product development to serial production

- Complete user guide to integrate SiA in your system

- An enhance logicistic and a worldwide support



- Integration support to help you in your choices



- A calibrated sensor associated to a Certificate of Conformity (CoC) for each sensor.

- Engineering support and accessible DO254 data package for certification process

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MEMS History and Market

Dimitrios Damianos, PhD
Technology & Market Analyst
Yole Développement

HIGH PERFORMANCE INERTIAL SYSTEM APPLICATIONS

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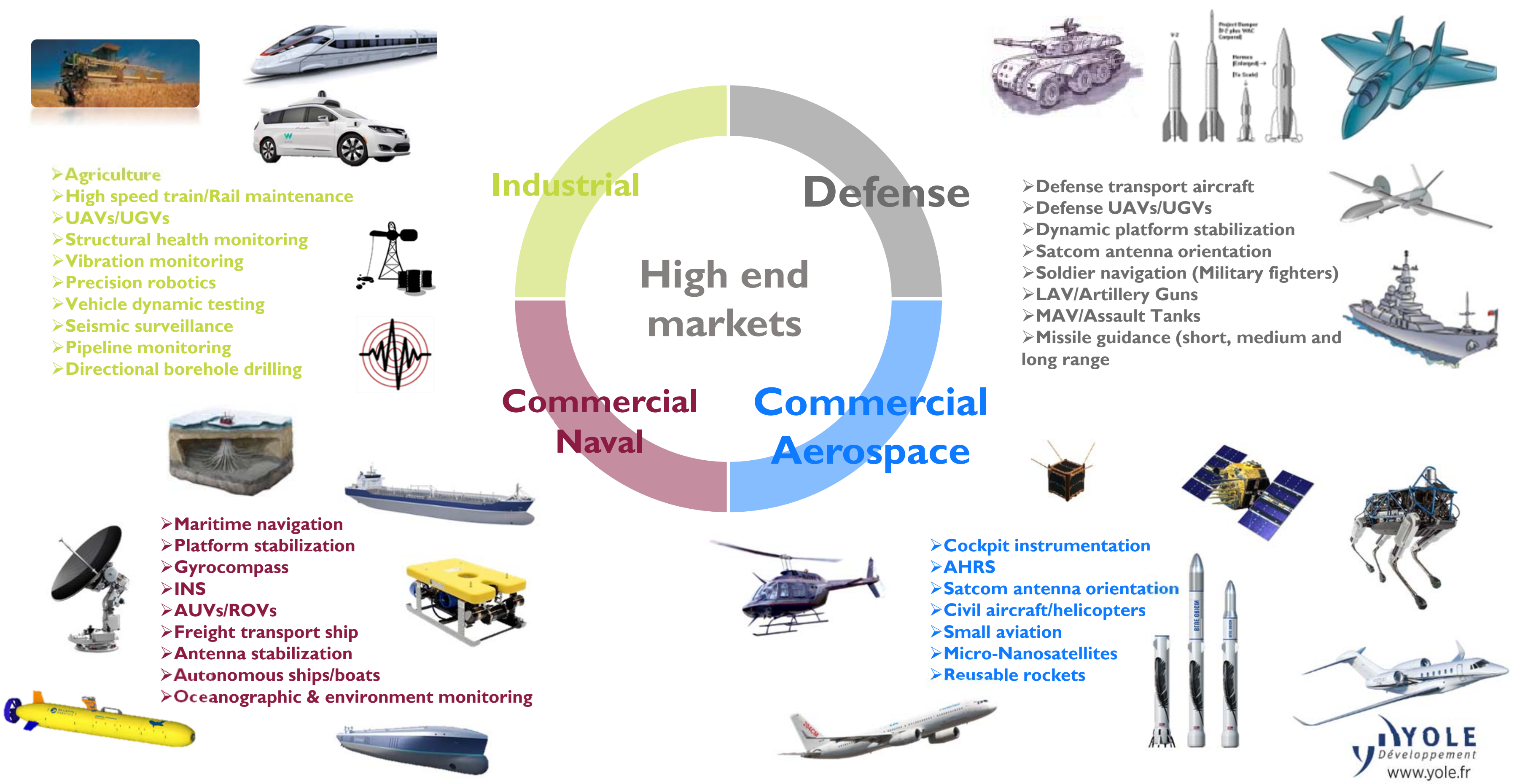
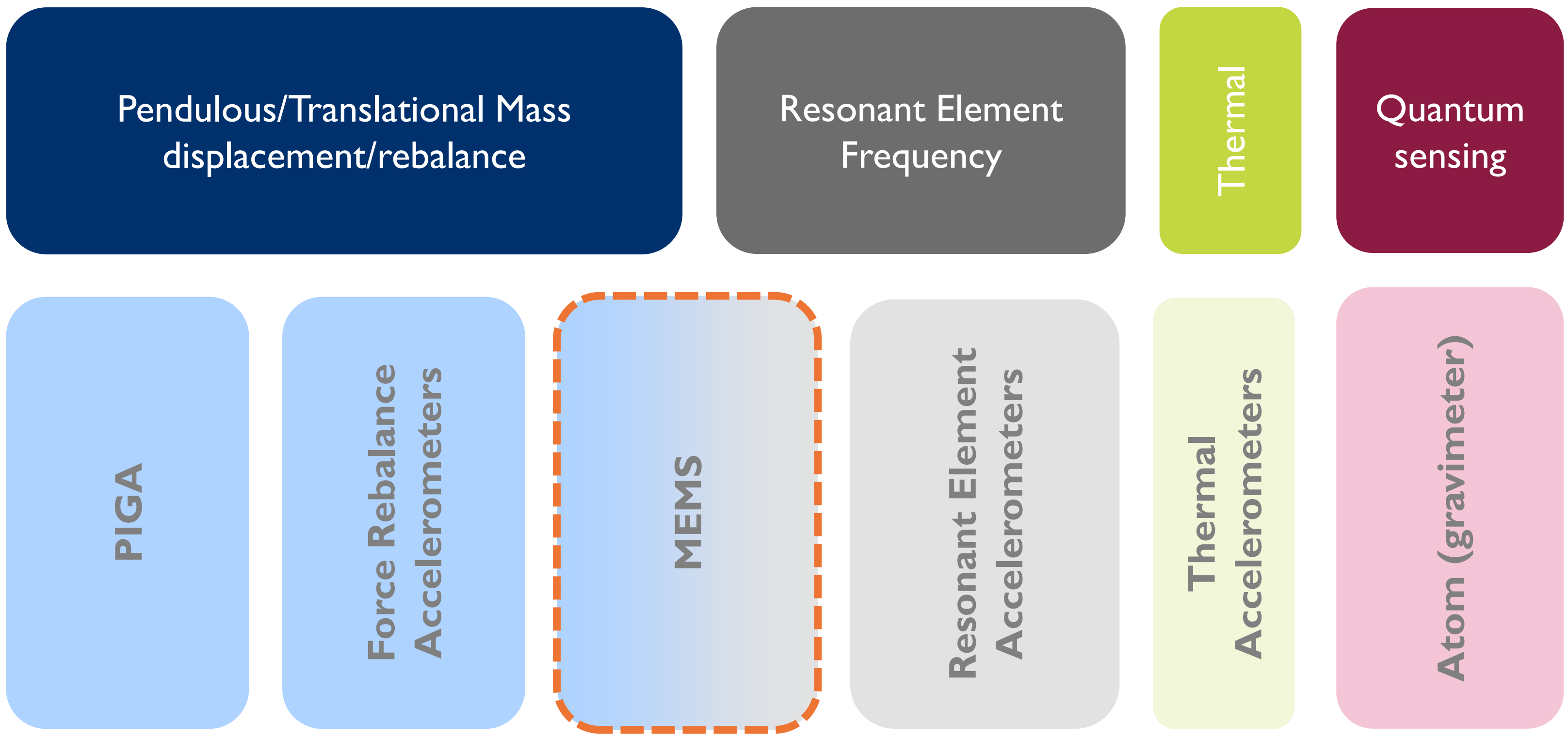
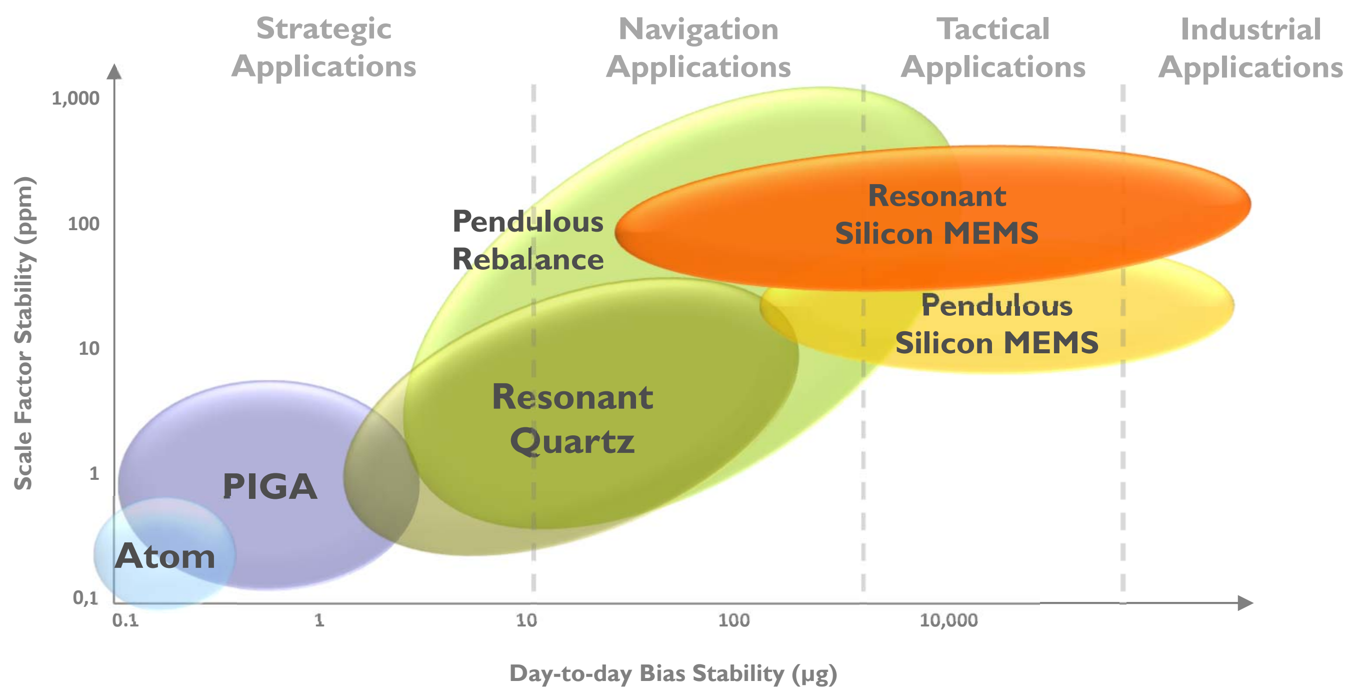


ACCELEROMETER DETECTION CLASSIFICATION



ACCELEROMETER PERFORMANCE



Source: Neil Barbour & Yole

MEMS IMU PERFORMANCES IN TIME

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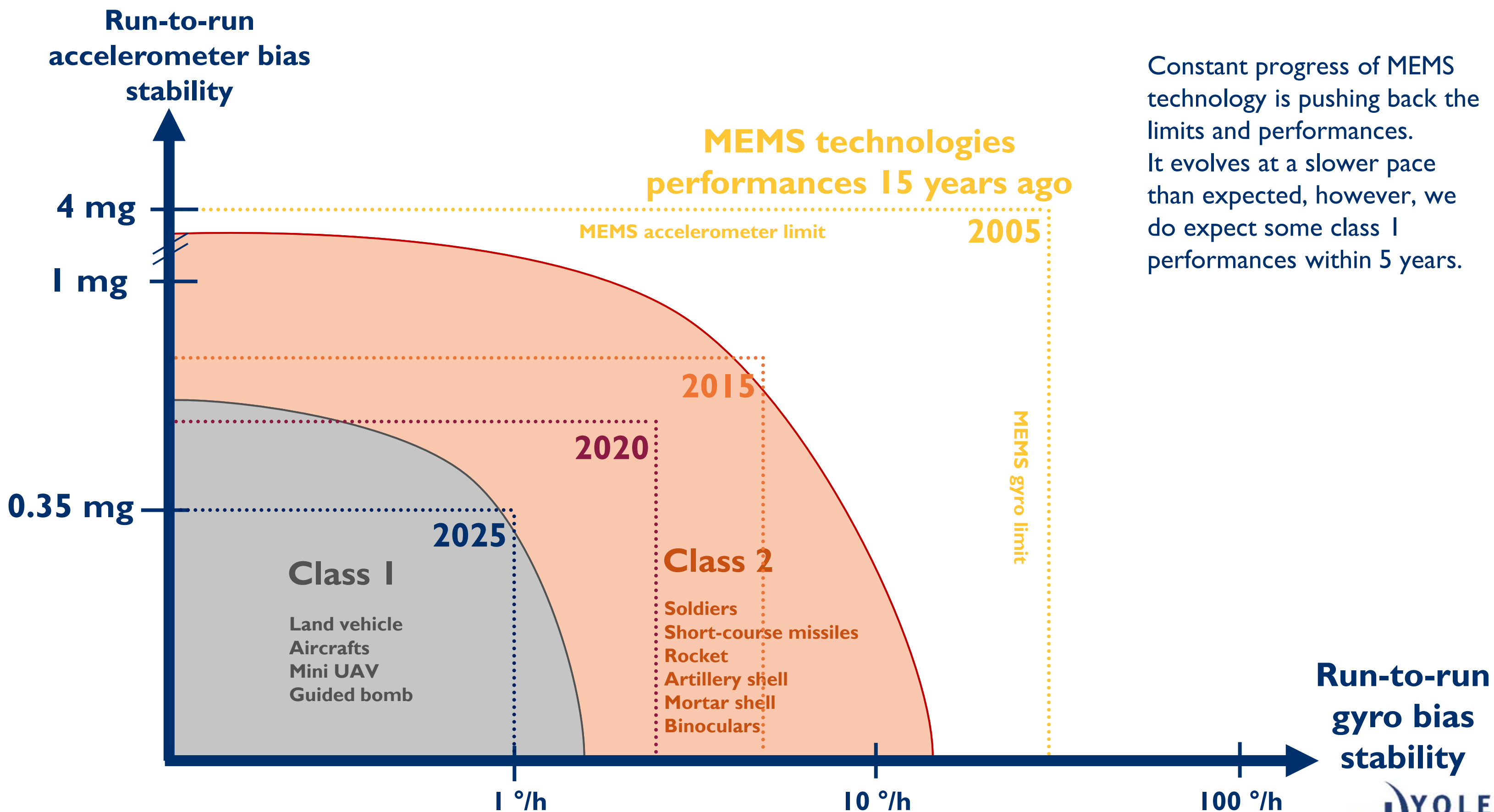
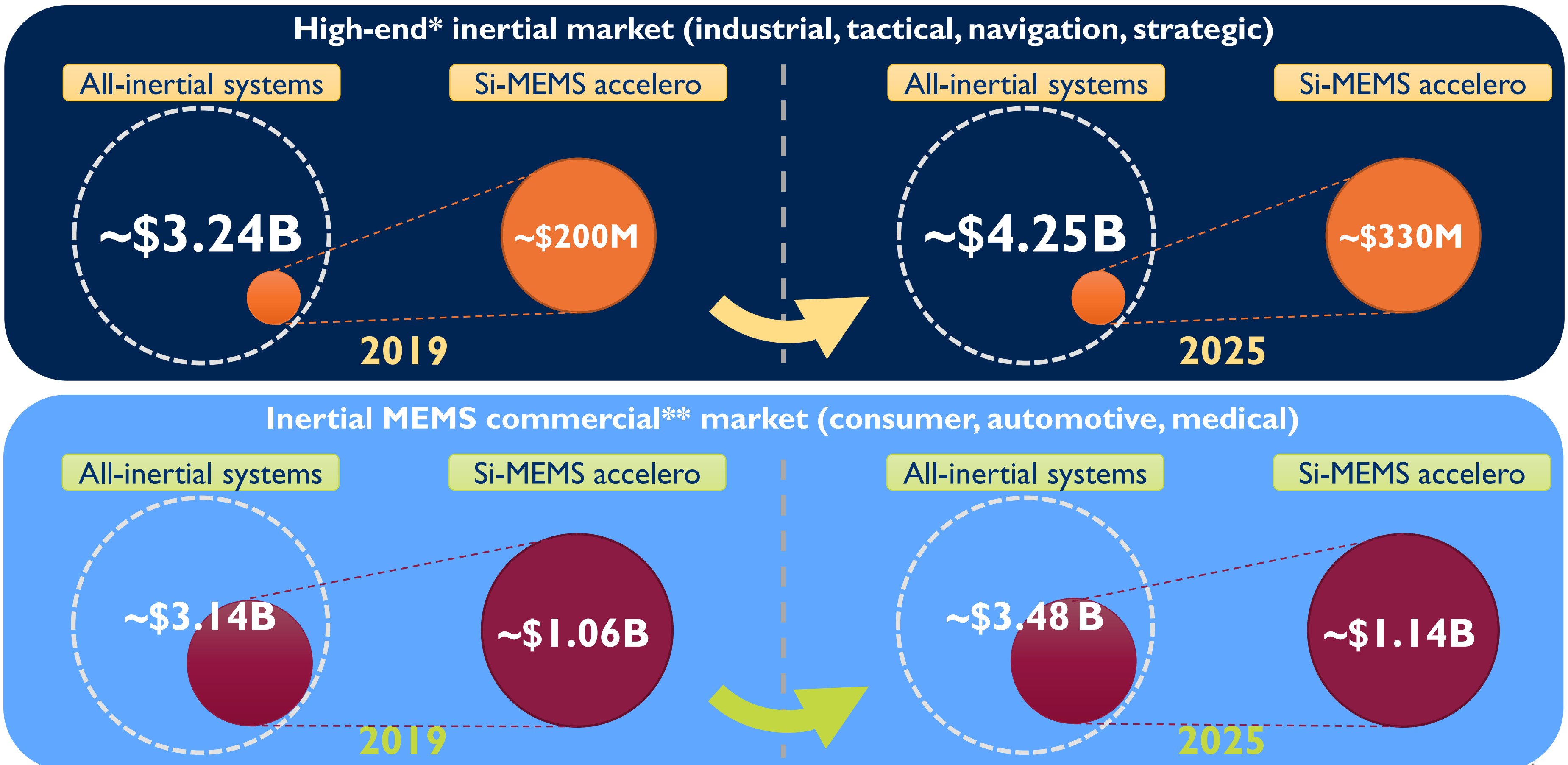


15 years ago, MEMS performances were far from High end applications specifications…

Constant progress of MEMS technology is pushing back the limits and performances.
It evolves at a slower pace than expected, however, we do expect some class 1 performances within 5 years.

YOLE Développement
www.yole.fr

FOCUS ON SI-MEMS ACCELEROMETER MARKET



*High-end: stand-alone acceleros/gyros, combos IMU/INS etc. All technologies included (Si-MEMS, Q-MEMS, rebalance, FOG, RLG, HRG, DTG etc)

**Commercial: stand-alone acceleros/gyros/magnetometers, combos (IMUs). Only Si-MEMS technology included.

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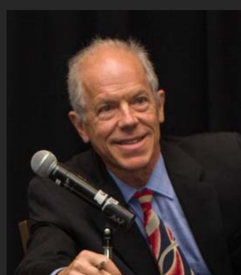
Ask the Experts Part I

High-Performance Accelerometer Application in Navigation, Stabilization, Control and Surveying



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Co-Moderator: Lori Dearman, Executive Webinar Producer

QUICKPOLL

Which class of performance would you be interested in for your applications?

Poll Results (single answer required):

Answer	Result
Bias composite less than 70µg	41%
Bias composite between 70µg and 200µg	31%
Bias composite between 200µg and 1000µg	17%
Bias composite greater than 1000µg	11%

Usage of High Performance MEMS Accelerometers in Navigation, Stabilization, Surveying and Control

Edgar v. Hinüber
CEO and Managing Director
iMAR Navigation GmbH

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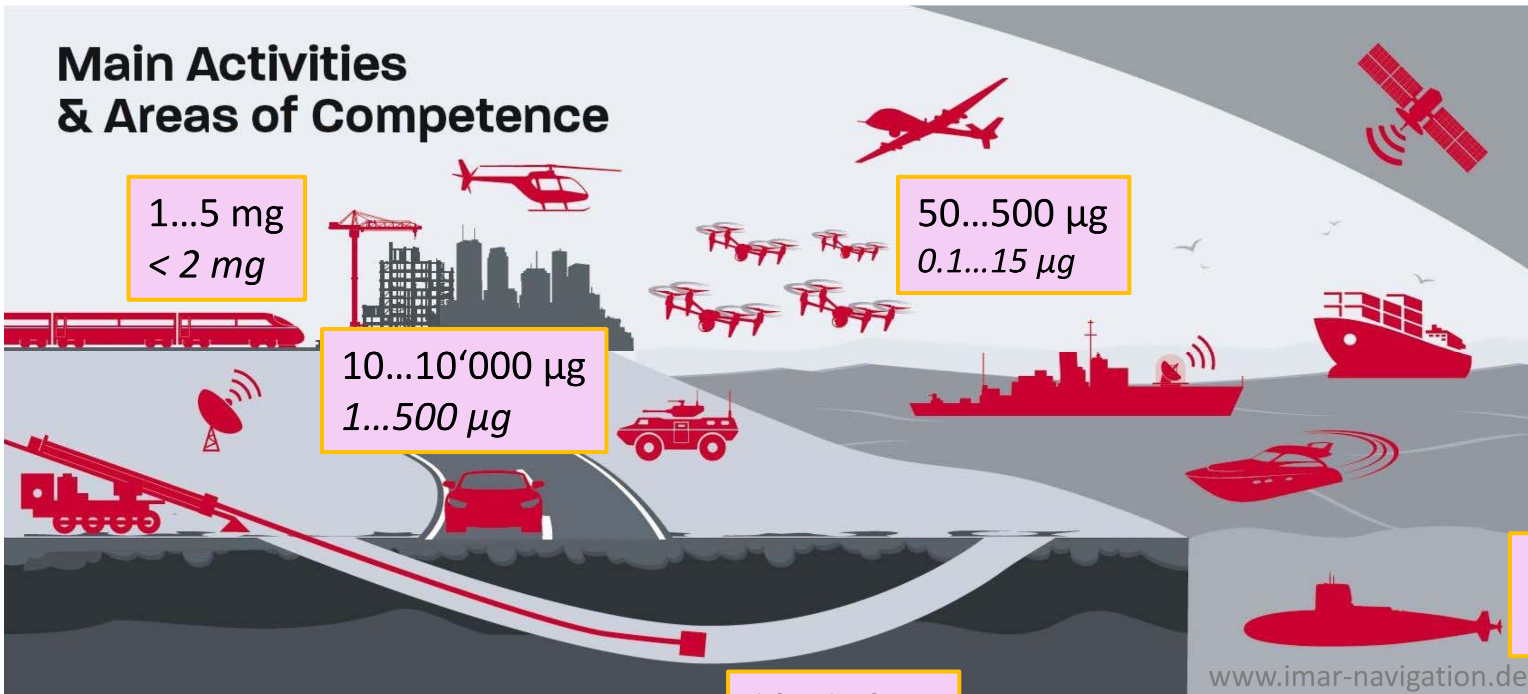
Serving our customers for more than 25 years – worldwide

- Systems for inertial navigation, guidance, surveying and control
- Gyro stabilized platforms – target observation & tracking
- Manufacturing and Development – R&D of ALG, SW/FW, HW, ME
- 75 employees, including 38 engineers ● 18.3 m. € turnover (2019)
- Markets: Surveying, naval / marine, airborne, automotive testing, mining, industrial, defense – manned & unmanned

iMAR NAVIGATION & CONTROL
www.imar-navigation.de

iMAR's Markets & Applications



accelerometer requirements:
day-to-day bias
bias instability

1…5 mg
< 2 mg

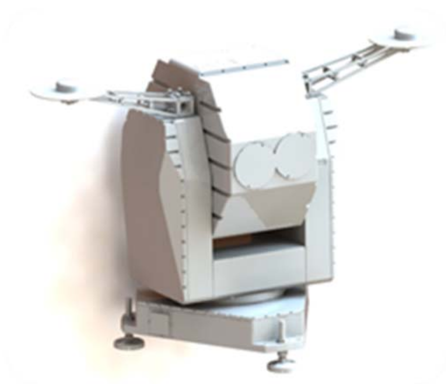
10…10'000 µg
1…500 µg

50…500 µg
0.1…15 µg

10…70 µg
0.1… 5 µg

10…150 µg
1…20 µg

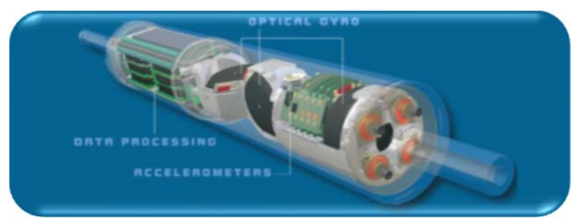
Systems using high performance accelerometers



iIPSC
Stabilized Gimbals for customized Payloads

iCORUS
High accurate Airborne & Shipborne Gravimeters

iNAT, iTraceRT, iPRENA…
INS/GNSS Solutions for Navigation, Stabilization, Surveying & Control



iGST / iPST
Pipeline Surveying and Drillhead Control

High Performance Accelerometer Requirements

Precise Navigation and Precise Tilt Sensing

- Very low **accelerometer bias** and also good **long time stability** of absolute bias
  (to achieve best system performance and to avoid an unacceptable short recalibration period)
- Very low **scale factor error** and non-linearity as well as good long time stability
- Very low noise resp. **velocity random walk** (VRW) to support fast converging of data fusion
- High **shock and vibration** resistance and immunity (e.g. operation together with RLGs)
- High **bandwidth**; low and well determined **data latency and jitter** regarding data sampling
- High stability of mechanical sensor axes (**long time misalignment stability**)
- Extensive self testing capability / **BITE**, high **MTBF / FIT** (reliability)
- **Synchronization** capability between several sensors, easy **interface** (SPI) with multiplex capability

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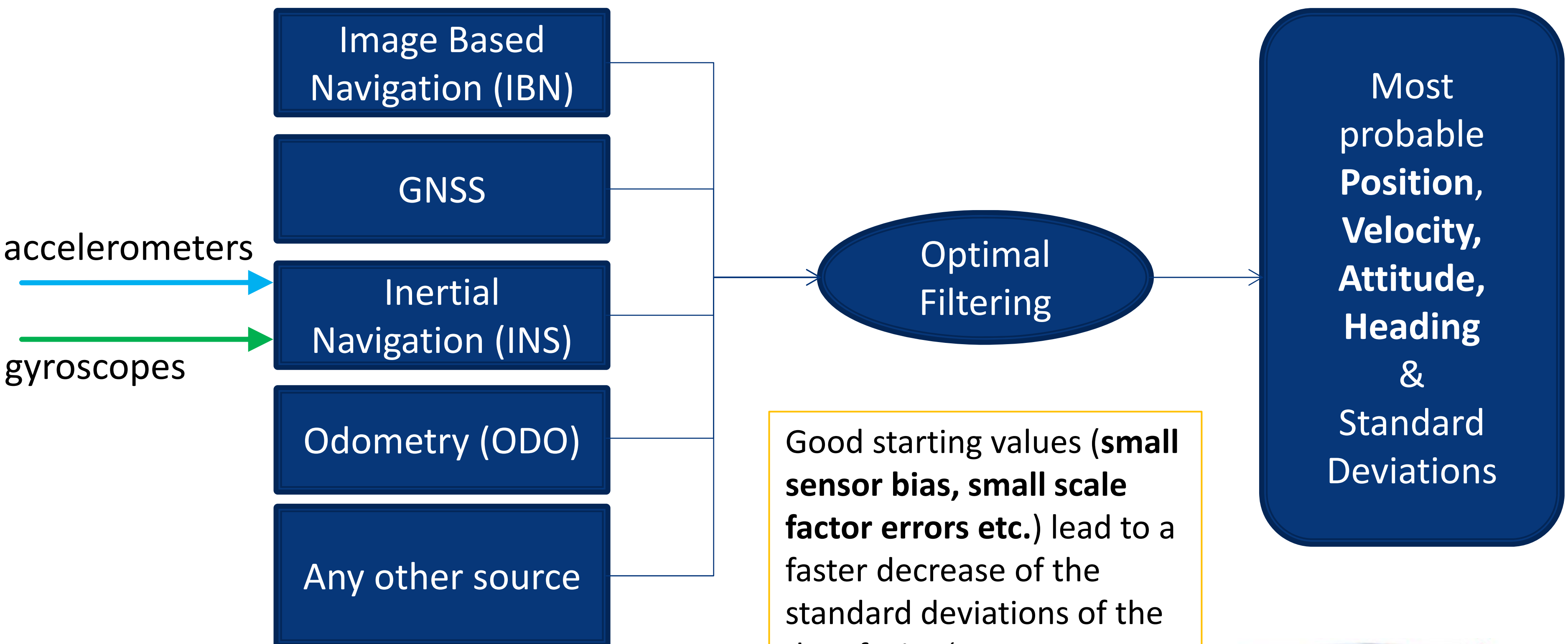
Data Fusion („Kalman Filter“): Fusion of Complementary Data to improve the overall accuracy



Good starting values (**small sensor bias, small scale factor errors etc.**) lead to a faster decrease of the standard deviations of the data fusion‘s output

Accelerometers: Why low bias is important?

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lower bias → better performance even in **free-inertial** mode
lower bias instability → gives the INS/GNSS data fusion **more time / reliability for parameter estimation**

- Flat earth: Position error increases **quadratically over time** with accelerometer bias → $\Delta s = \frac{1}{2} \Delta a\, t^2$ → Δa = 1 mg → **Δs (10 s) = 0.5 m**
  Δs (1'000 s) = 5 km

- Schuler Oscillation: The free inertial navigation error is damped by the geometry (sphere) of the earth.
  → The gravity is the reason, that the position error does not increase quadratically but only **linear over time**!

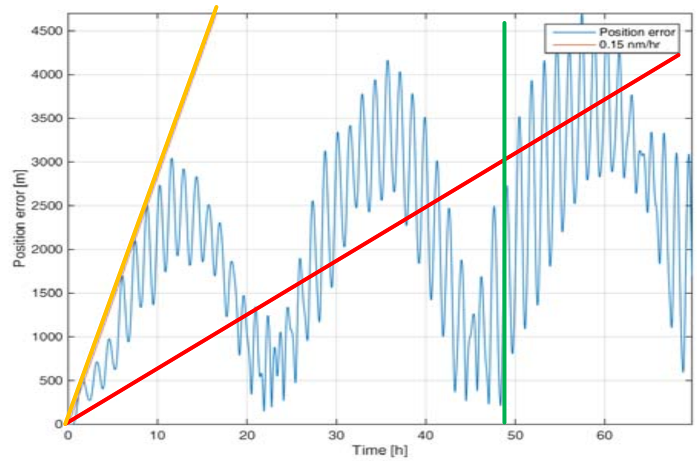
- The Schuler amplitude is proportional to the accelerometer offset.

- **The Schuler position error amplitude is about 13 m per 1 µg accelerometer offset.**

- The Schuler period is about 84.4 minutes on the Earth.

$$s_{Schuler} = 2\,\Delta a\,\frac{r_E}{g}$$ Position amplitude of Schuler oscillation

Schuler Oscillation (84 min)
here: 0.15 nm/hr



24 hrs Oscillation
here: 0.8 nm/day

- Furthermore a gyro bias leads to a Schuler **position drift of about 60 nm/hr per 1 °/hr gyro bias**.
  (simplified explanation)

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Accelerometers: Why low noise is important?

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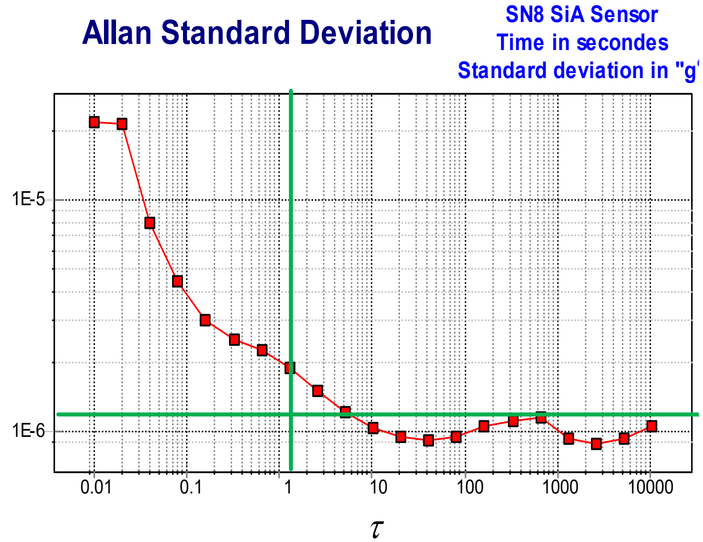
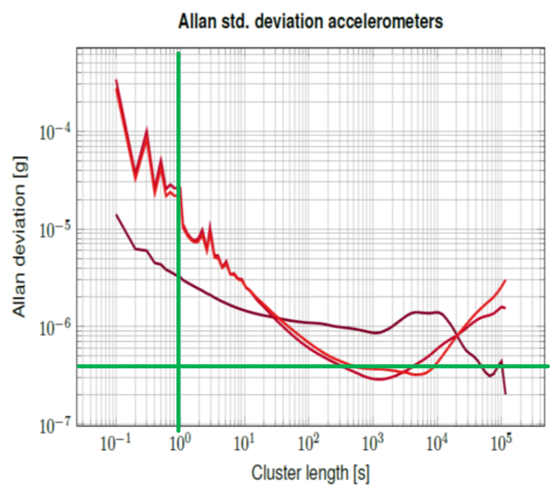
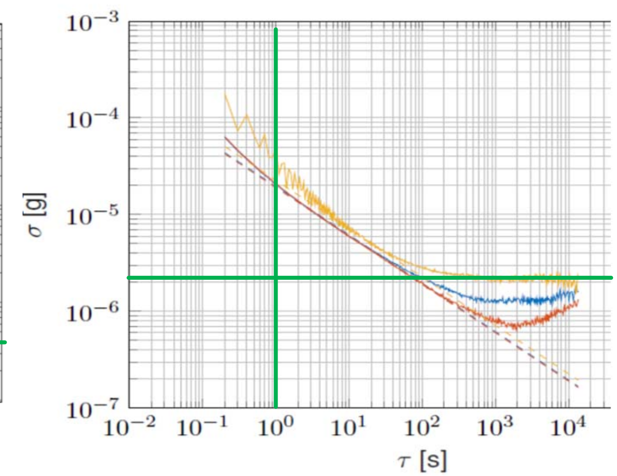
lower noise (VRW) → allows **faster parameter estimation** within the data fusion







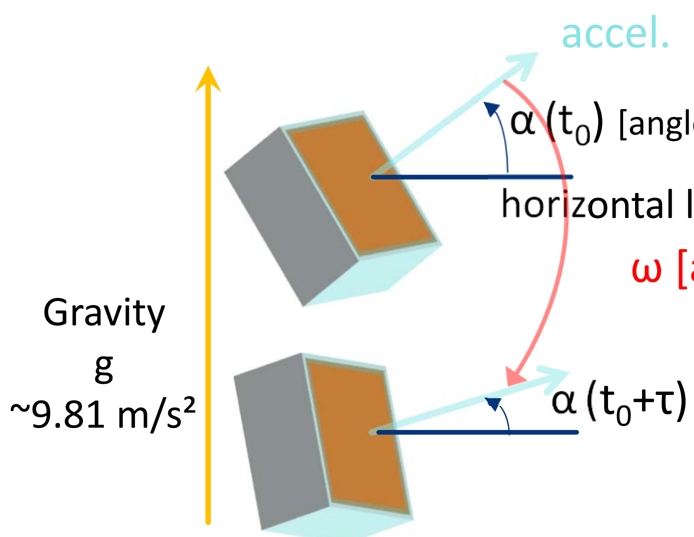
New **Thales SiA MEMS accelerometer** (lab samples):
- VRW: 2 µg/√Hz (< 8 µg/√Hz)
- bias instability: 1.1 µg @ > 10'000 sec
- bias (day-to-day): < 70 µg

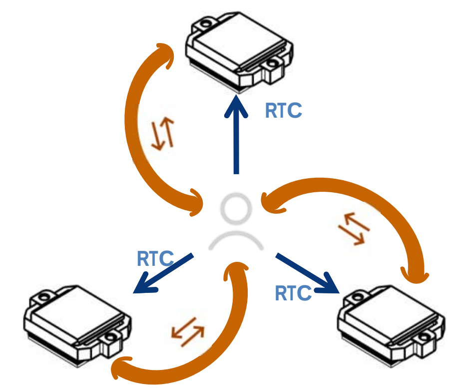
QA2000-030 accelerometer:
- VRW: 7 µg/√Hz
- bias instability: 0.3 µg
- bias (day-to-day): < 70 µg

State-of-the-Art standard nav./AHRS grade **MEMS** accel.:
- VRW: 20 µg/√Hz (< 50 µg/√Hz)
- bias instability: 2 µg
- bias (day-to-day): < 300 µg

Accelerometer: Why low latency and jitter required?

- All implemented accelerometers within the INS shall acquire its acceleration **at the same time**
- Justification: accurate **gravity compensation required** during vehicle rotation





- Accelerometer mounted on rotating object
- **Assume: rotation rate ω = 200 °/s, pitch = α(t_0) = 5 °; unknown delay τ = 1 ms,**
- At time t_0 the gravity **g** has to be compensated on the accelerometer with
  g ● sin α(t_0)
- If accelerometer **data acquisition delay is τ**, the resulting gravity compensation error is
  Δa = g ● sin α(t_0) - g ● sin [α(t_0) + ω ● τ)]
  Example: Δa (τ = 1 ms) = 3 mg (e.g. 50 x larger than desired sensor bias!)
- **Delay τ :** (deterministic) latency can be corrected if known, but stochastical jitter not!
  → jitter has critical impact on navigation performance – same as fast changing bias!
  → to achieve < 60 µg accel. accuracy, **jitter shall be < 20 µs (Thales SiA:** ✓ **)**

Silicon Accelerometer MEMS

Pierre-Olivier Lefort
MEMS Expert and Product Design Authority
Thales

Sensor characteristics

KEY PERFORMANCES (MEDIAN VALUES)

• Acceleration range	Up to 100g
• Bias temperature sensitivity	12 µg/°C
• Bias (temperature compensated)	0.1 mg
• Scale factor (before/after compensation)	2 ppm/°C - 5ppm
• Vibration rectification	6 µg/g²
• Noise	[0.01 – 10 Hz] 8 µg/√Hz

ELECTRICAL INTERFACE

• Power	5 Vdc / < 150 mW
• Communication	3.3 V SPI Full Duplex / Up to 6400Hz sample rate(configurable)

ENVIRONMENTAL

• Operating temperature	[-46 ; +90] °C / [-50 ; +195] °F
• Vibration	15 grms [20 – 2000 Hz]
• Shocks	< 250 g without recalibation

MEMS vibrating beam implementation → navigation grade performances with high input range and robustness

Thermal behavior : better than 50 µg / 10 ppm accuracy

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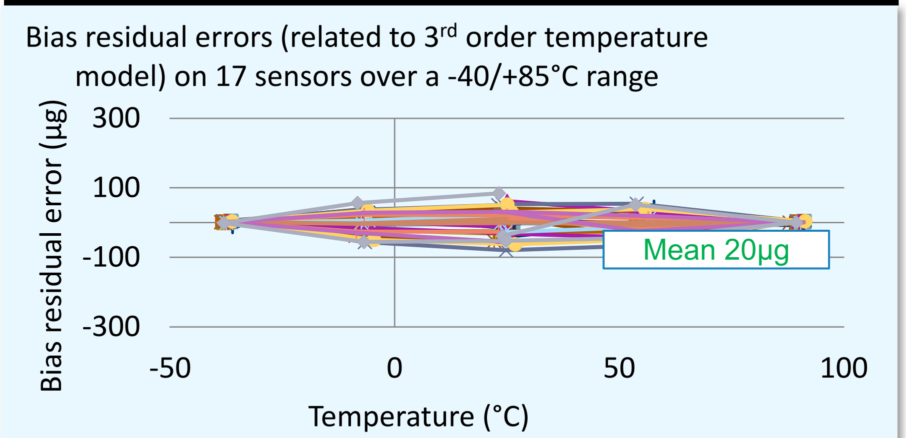
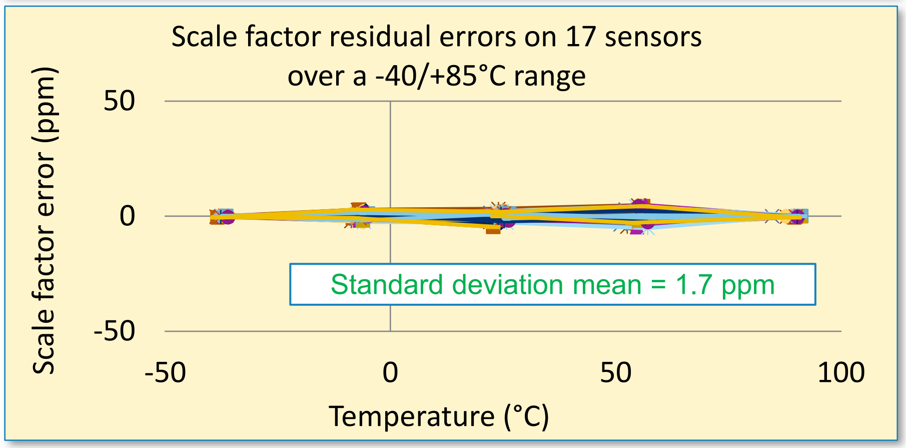
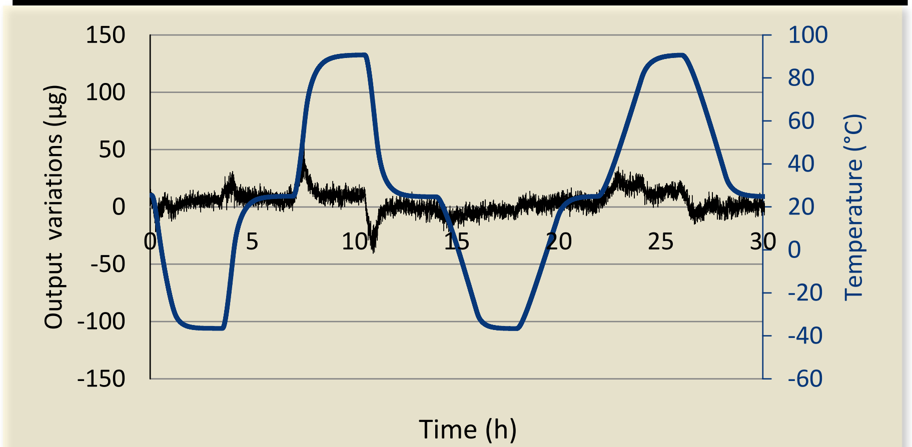
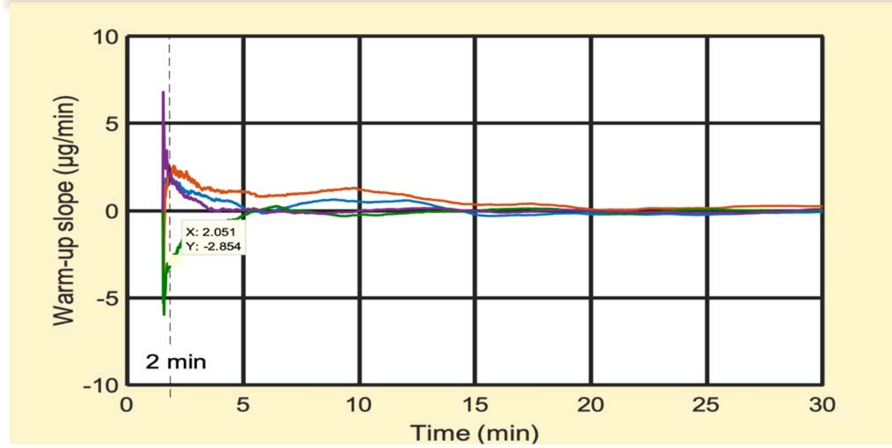
Stabilized temperature





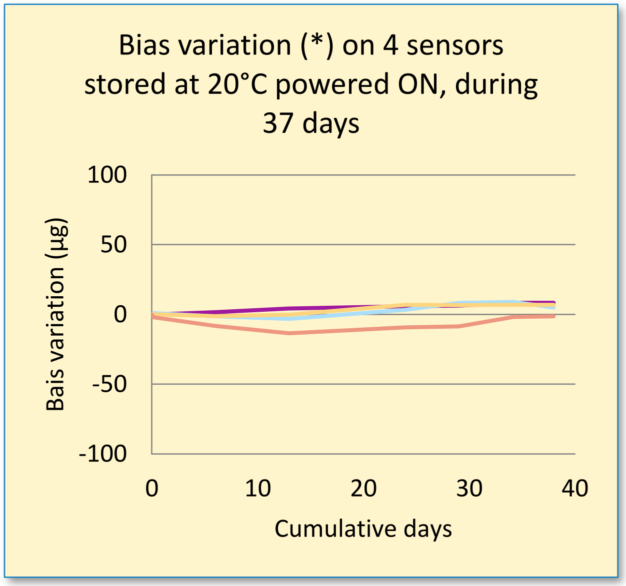
Variable temperature

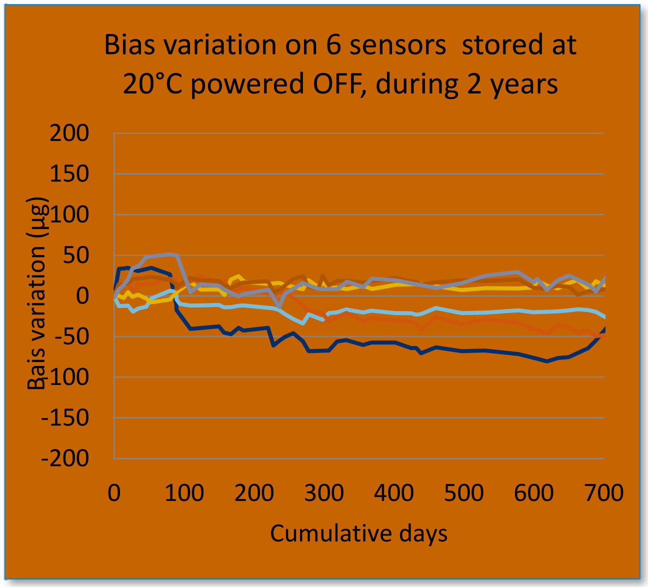


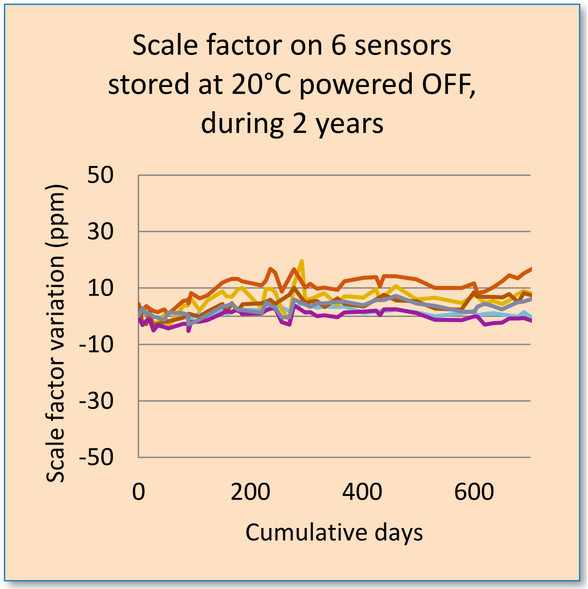


Repeatability

- Sensors stored on shelf at 20°C, powered on or off.
- Measurements performed on a regular basis to follow bias and scale factor variations over time.





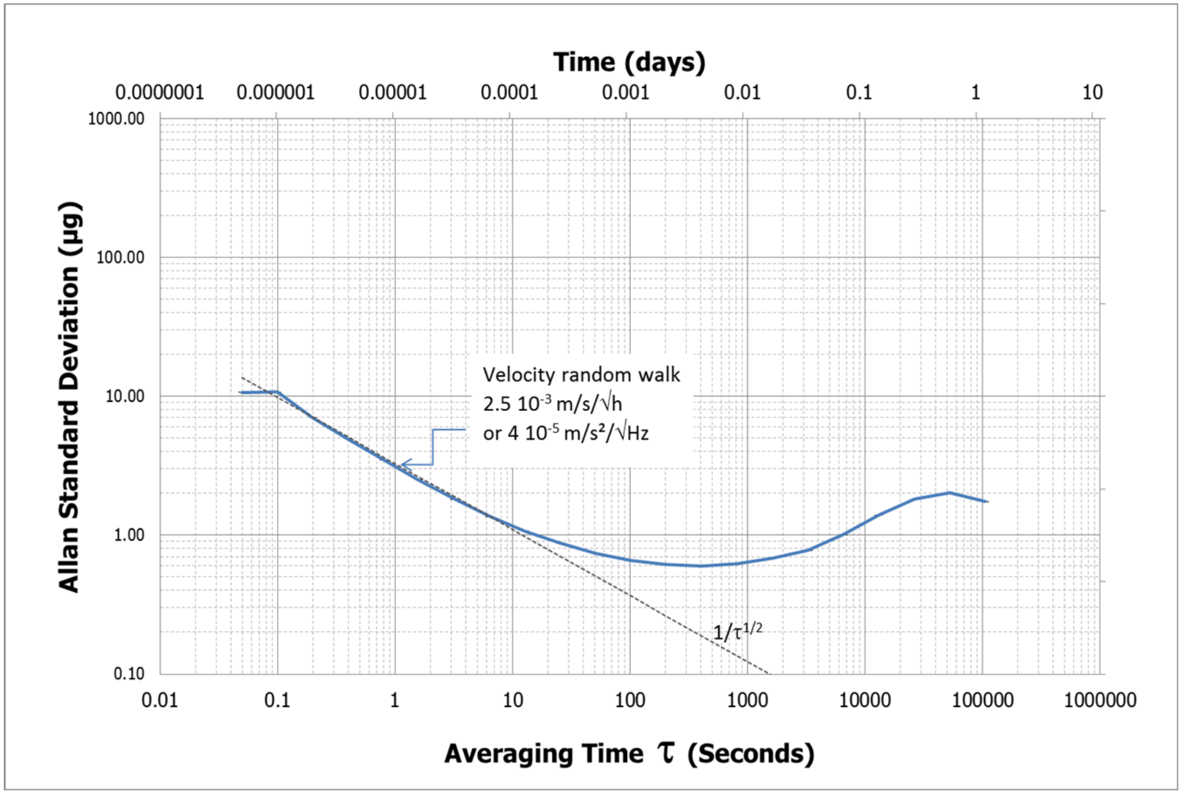


Bias stability fully compatible with high grade inertial system requirements

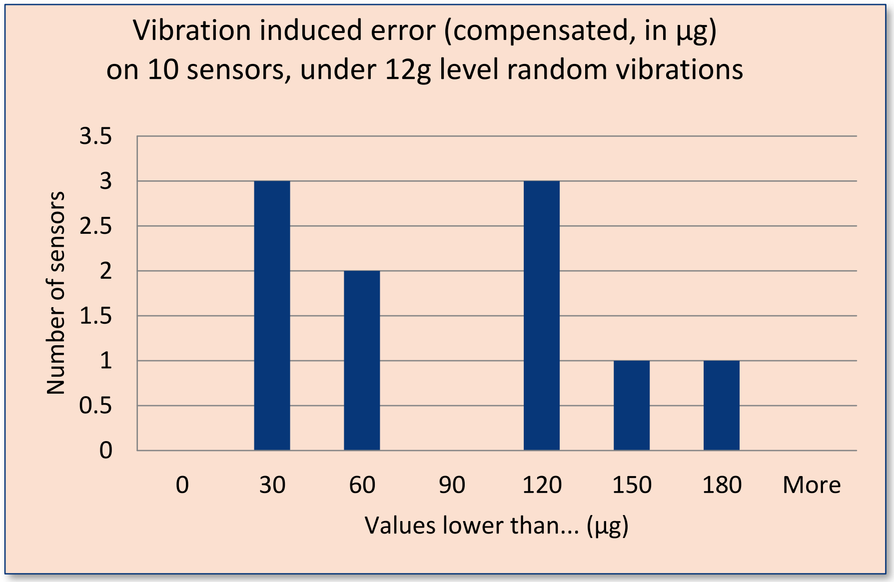
Allan Standard Deviation

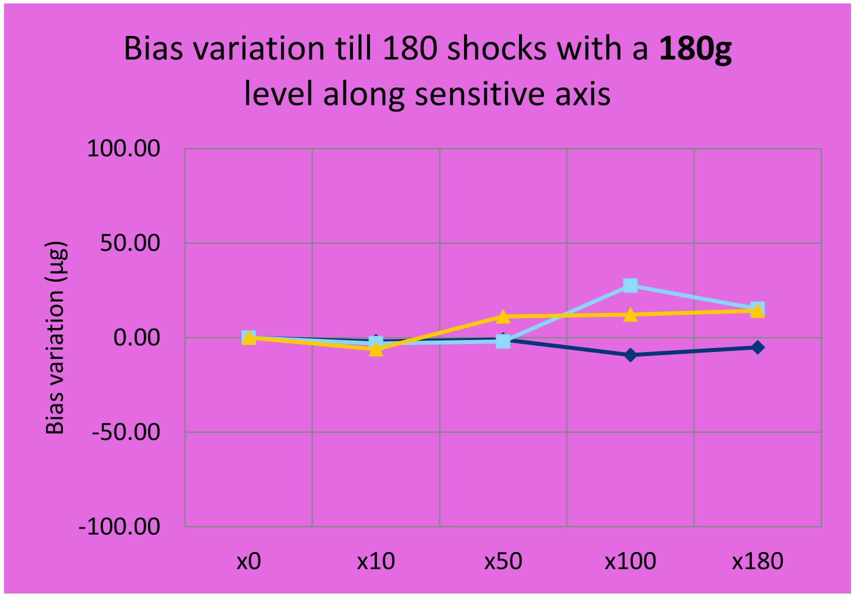
Allan Standard Deviation for SiA Sensor SN318

- from 4 days recording, 20 Hz sample rate
- lab conditions - 1g static acceleration
- after temperature compensation

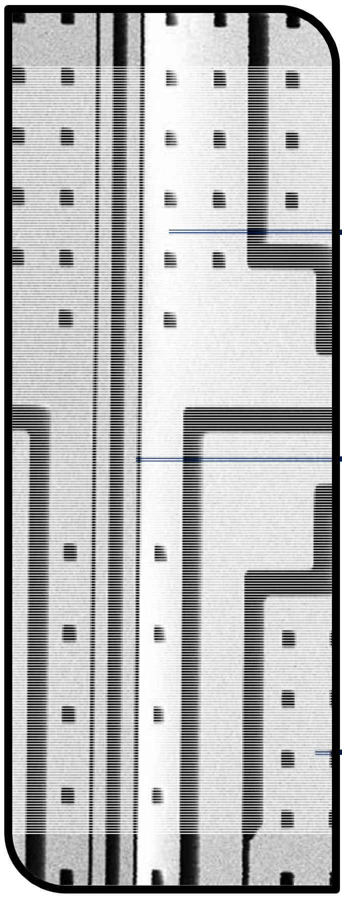


Shock and vibration behavior

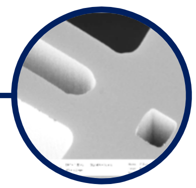




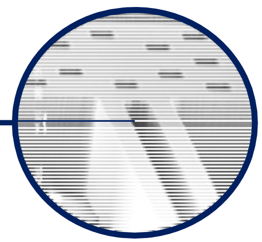
Our silicon technology



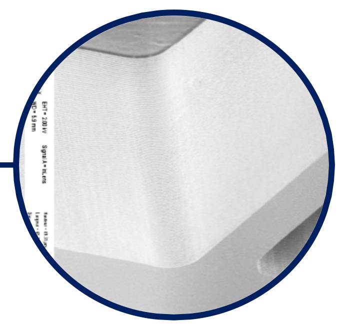
From wafer to chip using high-end processes



Manufactured from a 150mm silicon wafer with high accuracy DRIE etching

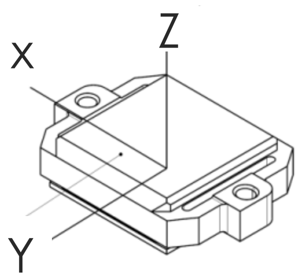


A 60 µm thick active layer with low resistivity, within a 3 layers assembly

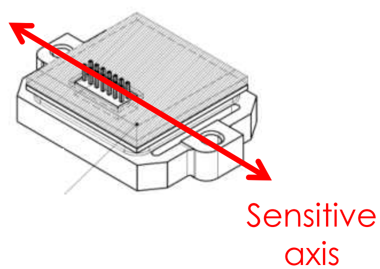


Layers assembly with silicon oxide obtained by high temperature silicon bonding

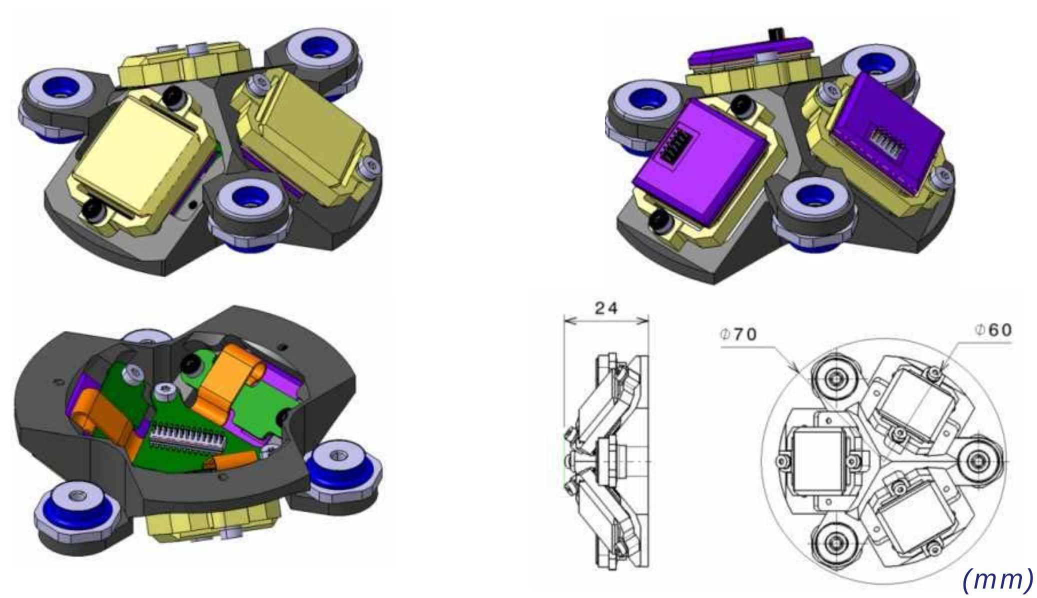
Mechanical interface and integration example



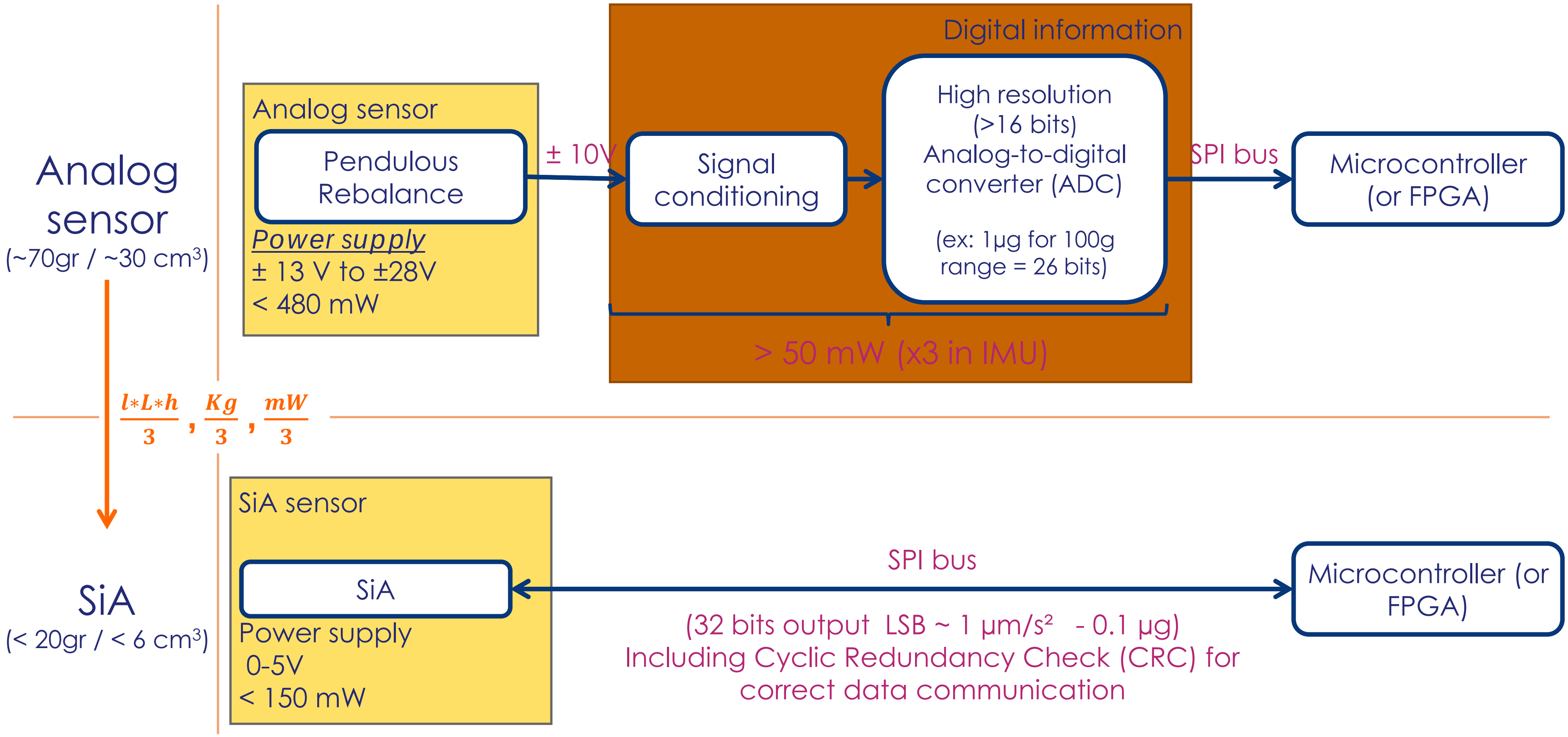
SiA sensor **can be mounted with connector up or down** relative to the mounting plane chosen using 2 M2 screws.



28,6 x 19,4 x 8,8 mm



Electronic integration – Analog sensor vs. SiA



Synchronisation

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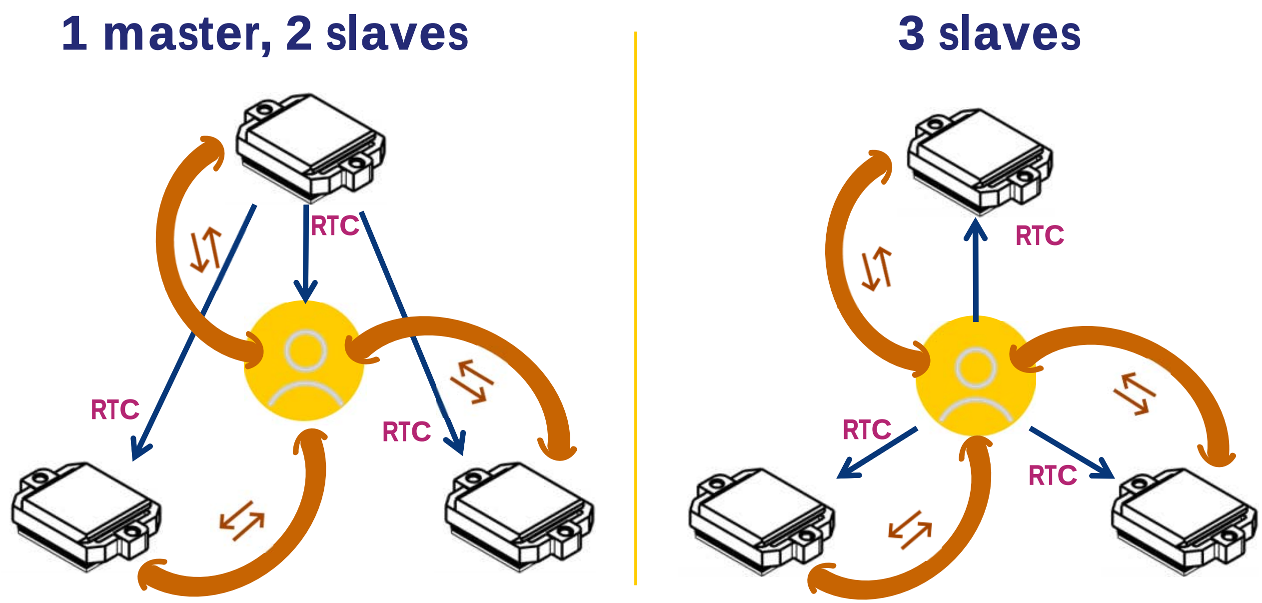
RTC (Real Time Clock) configurable by the user

Speed increment delivered at RTC rising edge frequency



- RTC sampling frequency can be defined by the user or generated inside the SiA sensor
- **Latency 400 µs +/- 30 µs** (for 6400 Hz RTC including 50µs SPI transmission duration)

Reliability assessment

Functional & design analysis : from device functions, failure modes identification & classification through criticality analysis.

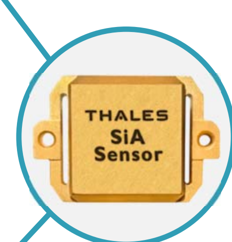
- Reliability assessment plan for each sub-assembly and SiA product
- Reliability quantitative evaluation for different mission profiles

Packaging

- 2 years 85°C storage (x4)
- 500 thermal cycles -40/95°C (x3)

MEMS Cell

- 1 year 85°C storage (x24)
- 1 year 150°C storage (x8)
- 1000 thermal cycles -40/95°C (x8)



Electronics

Failure rate estimated to $30\ 10^{-9}$/h using FIDES approach (*)

(*) for long range aircraft mission profile

- IBIT : Initial Built-In Test

Available upon user's request (checking of the sensors functionality : seismic mass check and MEMS resonators behavior check).

- CBIT : Continuous Built-In Test

Covering out of range acceleration input, out of range resonators frequencies, CRC errors, Internal bias voltages control, oscillator loop parameter check.

QUICKPOLL

Except for performance, what is the other key requirement your accelerometer should have?

Poll Results (single answer required):

Small size	39%
Easy to communicate (SPI)	23%
Without exportation constraint	24%
Civil Certification data package (DO254)	7%
Large portfolio for a same size of sensor	6%

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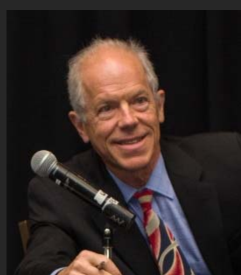
Ask the Experts Part II

High-Performance Accelerometer Application in Navigation, Stabilization, Control and Surveying



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