Rate Measurement Unit for Attitude Determination and Control Subsystem

Jose Beitia[1], Steve Kowaltschek[2]

[1]InnaLabs Ltd., Snugborough Road, Blanchardstown, Ireland
[2]European Space Agency, ESTEC, Noordwijk, The Netherlands

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Abstract

Over the past 50 years, many different gyro technologies have been developed and used in space, with Fiber Optical Gyros (FOG), Ring Laser Gyros (RLG) and Hemispherical Resonator Gyros (HRG) being predominantly used from the late '90s up to today. Each technology offers a wide range of advantages and disadvantages while most of the time offering a similar performance. More recently, new applications have emerged in the commercial industry for which accuracy and precision are no longer the driving factors. Instead, reliability, mass, power budgets, and meeting performance at reduced cost and size have become paramount.

In that context, InnaLabs has developed a Coriolis Vibratory Gyroscope (CVG) sharing common features with HRG, and, with the support of the European Space Agency, a 3-axis Rad-Hard Rate Measurement Unit (RMU) named ARIETIS is now being developed by Innalabs to address Earth Observation ap-plications in Low-Earth Orbit (LEO), Navigation in Medium-Earth Orbit (MEO), and AOCS in Geostationary Orbit (GEO) with lifetime of more than 15 years. After a brief description of the InnaLabs CVG basic principles and an overview of the CVG technical strengths in comparison to competing for available technologies, this paper describes the key features and budgets of ARIETIS, it's design, construction and operating principles, with a special emphasis on the targeted end-of-life performance.

1. InnaLabs space strategy

InnaLabs is a privately held Irish limited company located in Dublin (Ireland) which has developed in the past six years, a portfolio of high-quality, innovative Coriolis Vibratory Gyroscopes (CVG) that deliver market-leading performance to cost ratios.

With thousands of units already deployed across several Commercial and Defense industries in Europe, InnaLabs CVG [1] [2] has become very attractive to the Space Industry due to its low-cost, stabilisation performance of few °/hr, high reliability, long lifetime and specific cost to performance ratio.

In perfect alignment with the Company's vision to challenge existing high-end gyros technol-ogies in all sectors, and with Enterprise Ireland's R&D support , the Company developed a team of experts and industrialists implementing with drive a Space strategy.

The achievement is clear. InnaLabs was awarded ISO 9001:2008 certification in 2014 and have been successfully audited by major EU and US Space companies. In 2016, twenty InnaLabs CVG were orbiting Earth on board of LEO satellites into sun synchronous orbits for Earth Obser-vation and more than 270,000 hours in space have passed so far without any performance devia-tion. In December 2016, InnaLabs won its first contract with the European Space Agency (ESA) to develop ARIETIS, a 3-axis Rad-Hard Rate Measurement Unit for the global commercial space market. Very recently, in December 2017, ARIETIS Preliminary Design Review (PDR) was successfully completed and passed, and the next phase of the development has now commenced with the delivery and qualification of an Engineering Qualification Model (EQM) in the next 18 months and commercial products available in the year 2020.


Figure 1. Innalabs Ltd, Dublin, Ireland.

Figure 2. Innalabs Ltd state of the art clean-room ISO Class 7 manufacturing line.


Figure 3. ARIETIS 3-axis RMU

*Chief Technology Officer, InnaLabs Ltd., Snugborough Road, Blanchardstown, Ireland.

†AOCS/GNC Sensors & Actuators Coordinator, AOCS and Pointing Systems - TEC-SAA, European Space Agency, ESTEC, Noordwijk, The Netherlands.

*www.enterprise-ireland.com

2. Technology background

Since the ‘60s, many different gyro designs have been developed and customized to address the needs of space satellites. This includes:

- DTG: Two-axis dry tuned gyroscopes (developed in the ‘60s)
- HRG: Hemispherical Resonator Gyroscope (developed in the ‘60s)
- RLG: Ring Laser Gyroscopes (developed in the ‘70s)
- FOG: Fibre Optic Gyroscopes (developed in the ‘70s)
- MEMS CVG: Microelectromechanical systems, CVG based (developed in the 2000s)

However, with the development in the late ‘70s of digital electronics with increased signal processing capabilities, in the ‘90s nearly all new applications on Land, at Sea, and in the Air, became Strapdown. FOG, HRG and RLG were then predominantly used at the expense of spinning wheel technologies (DTG), and that trend has continued to be emulated within the Space segment.

Today, about 1,000 operational satellites are in orbit, and with the development of the telecom market and the requirements for global Internet broadband service to individual consumers, thousands of satellites will have to be launched in the next few years in LEO and GEO. This requires a step-change in the manufacture of satellites at a prime level to component suppliers to achieve low-cost, less mass, less power consumption, and ultimately to scale up production.

In that context, Coriolis gyros (HRG and MEMS CVG) are particularly interesting as their mass and size are significantly reduced, and, because the number of parts for these solid-state sensors is much less than for other technologies, their MTBF is advantageously high and their production cost is obviously low. For Land and Space applications, a broad categorization of gyro types and associated MTBF levels is provided in the following Table:

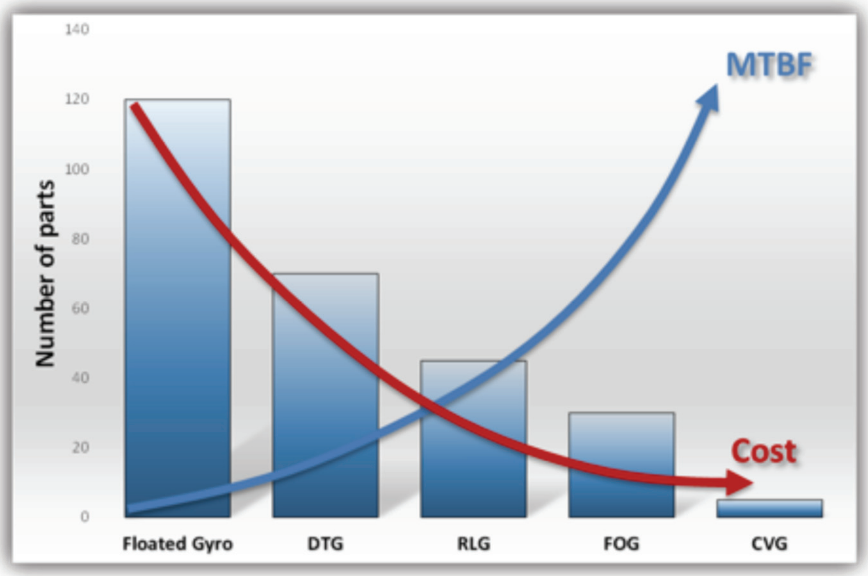

Table 1. Broad categorisation of gyro types based on MTBF levels

Presently, HRG Coriolis gyros [3] have become “sensors of choice” for high value satellites and long space missions, as demonstrated in Europe with REGYS20 now qualified to Alphabus and Spacebus 4000 geostationary communications platforms, and by the figures achieved by the Northrop Grumman SIRUTM with Angle Random Walk (ARW) parameters well below 0.0002°/√hr, more than 35 million on-orbit hours and 100% mission success.

However, these HRG solutions remain significantly expensive and therefore do not address well the medium accuracy segment in LEO up to GEO which requires sensors delivering 1°/hr bias stability over long observation periods and ARW of less than 0.01°/√hr. High-performance MEMS Coriolis gyros could be suggested as alternatives for that specific segment, but no competitive solution (price versus performance) has yet been successfully commercialised.

This middle point that was missing between HRG and MEMS Coriolis gyros thus laid the foundation for building up InnaLabs CVG technology.

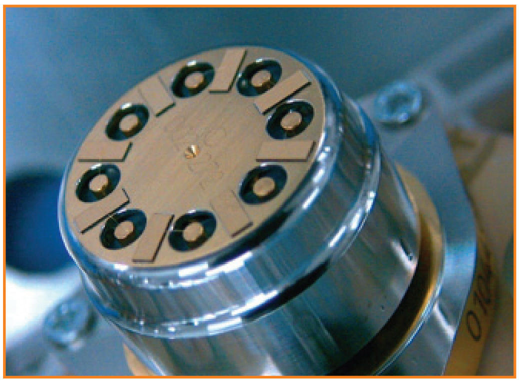

Figure 4. InnaLabs CVG resonator

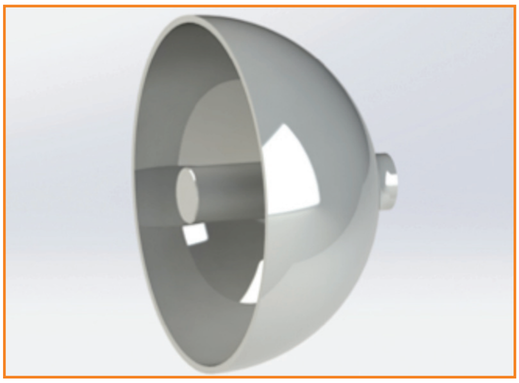

Figure 5. HRG resonator

Figure 3. InnaLabs CVG resonator (left) – HRG resonator (right)

The basic principles of the Coriolis gyroscope technology are well known, as the first reported practical demonstration was used in the Foucault pendulum to measure the earth’s rotation in 1851. However, the conversion of the initial idea into practicality started in 1965 with the development of the Hemispherical Resonator Gyros (HRG) by Delco (today Northrop Grumman). For those familiar with HRG design, InnaLabs CVG and HRGs [3] [4] belong precisely to the same family and have numerous features in common. The two designs host a 3D-axisymmetric resonator with a central stem holding the resonator, and both have similar outline dimensions of few cubic centimetres in volume. Both operate with one mode being excited to provide the linear momentum (primary mode), and that mode is then coupled to a second mode (secondary mode) by Coriolis forces induced by rotation of the structure around its axis of symmetry, referred to as the sensitive axis.

Still, from a cost perspective, considering overall materials involved, machining and assembly processes, the InnaLabs CVG design exhibits key advantages leading to categorising that gyroscope as a “Low-Cost HRG” design.

InnaLabs CVG	HRG
Metal resonator	Silica resonator
Cylindrical resonator	Hemispherical resonator
Piezo-electric pick-off and drive system directly attached to the bottom flat surface of the resonator (Figure 4)	Electrostatic pick-off and drive system requiring high drive voltage and micrometric gap between electrodes
Medium vacuum required in the cavity hosting the resonator	High vacuum assisted by getter material in the cavity hosting the resonator
⇒ **Low Cost**	⇒ **High Cost**

Table 2. Key design features of InnaLabs CVG

As a result, after having experienced in recent years a significant growth and successes in high-end land stabilisation applications, InnaLabs CVG is now being considered by ESA in a custom rad-hard 3-axis package named ARIETIS for LEO, MEO, and AOCS in Geostationary Orbits and Science missions. That development started on January 30th, 2017 and, although the land qualified InnaLabs CVG resonator is reused, it includes the development of a fully digital control loop system and new assembly processes improving cost and performance. A PDR has been passed in December 2017, and the project is now heading to an EQM delivery in 2019 to demonstrate performance in PLATO ESA mission environment and lifetime. PLATO (Planetary Transits and Oscillations of stars) is the third medium-class mission in ESA's Cosmic Vision programme and is considered well representative of future ESA science missions.

3. ARIETIS key features

Regarding specifications, ARIETIS is a high-performance, high-reliability, ITAR-free non-redundant 3-axis Gyros Unit providing inertial angle increments measurement of rotations about three orthogonal axes. The output is provided on a non-redundant RS-422 data bus with RS-485 compatibility. ARIETIS also comes with in-orbit calibration functionalities, displays a non-redundant RS-422 stimuli interface and its power interface is compatible with Spacecraft Primary power of 28 VDC nominal up to 100 VDC.

The mass of the equipment is targeting 2kg and its power consumption is below 7W. Its measurement range is settable up to ±96°/s, with noise and ARW parameters optimised for ±3°/s. The estimated reliability figure of ARIETIS is less than 500 FIT at 30°C (MTBF of 2,000,000 hours) and the equipment is being designed for long life-time GEO missions of more than 15 years with a solid sphere dose depth curve exhibiting TID of few hundreds of kRad over the mission duration. The equipment will be qualified to a temperature range of -40°C (-40°F) to +70°C (+158°F) and shall withstand random vibration profiles during launch phase of 31.7 grms.

The following Table 3 provides an overview of the key functional performance of ARIETIS:

Performance Parameters	Value
Switch-on response time	≤ 1s
Time to full performance after switch-on	≤ 6s
ARW	≤ 0.005°/√hr (up to ±3°/s) ≤ 0.16°/√hr (from 3 to ±96°/s)
Bias stability over 24hr (steady temperature)	≤ 1.5°/hr (1σ)
Bias stability over 1hr (steady temperature)	≤ 0.3°/hr (1σ)
Bias errors (all effects, EOL)	≤ 5°/hr (max)
Scale Factor repeatability errors (all effects, EOL)	≤ 700ppm (1σ)

Table 3. ARIETIS key features

[2] End Of Life

4. ARIETIS architecture

The current embodiment of ARIETIS is composed of four main modules, a housing, a 3-axis cluster hosting three InnaLabs CVG sensing elements (SE/X, SE/Y, SE/Z) and proximity boards (PB), and a set of two electronics used to operate and perform all functions required by the equipment: CLDB (gyro Digital Control Loops) and IFB (Interface Board). CLDB hosts a European new generation rad-hard FPGA (65nm technology) which manages the gyro control loops and the communication to the user. IFB includes a DC/DC converter and digital means to interface with the User on a RS-422 serial output. Each CVG sensing element is attached to a vibration isolator to isolate them from high-vibrations levels during the launch phase.

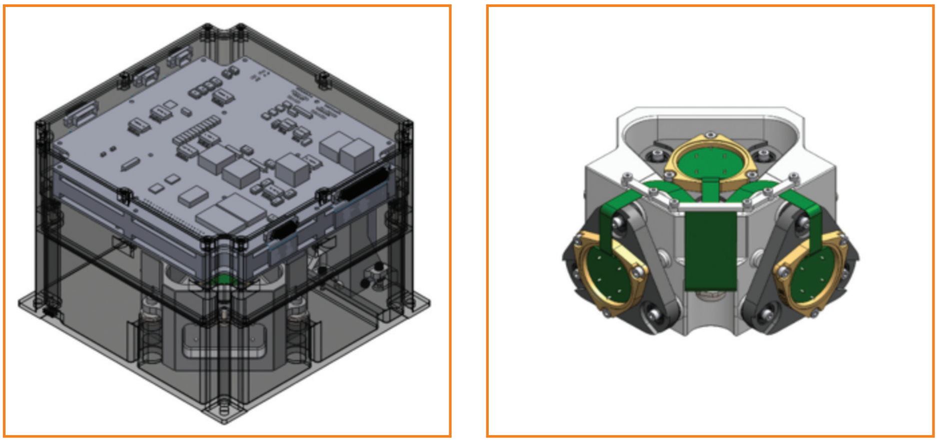

Figure 4. ARIETIS equipment (left), 3-axis CVG cluster (right)

The following block diagram provides more details on the architecture:

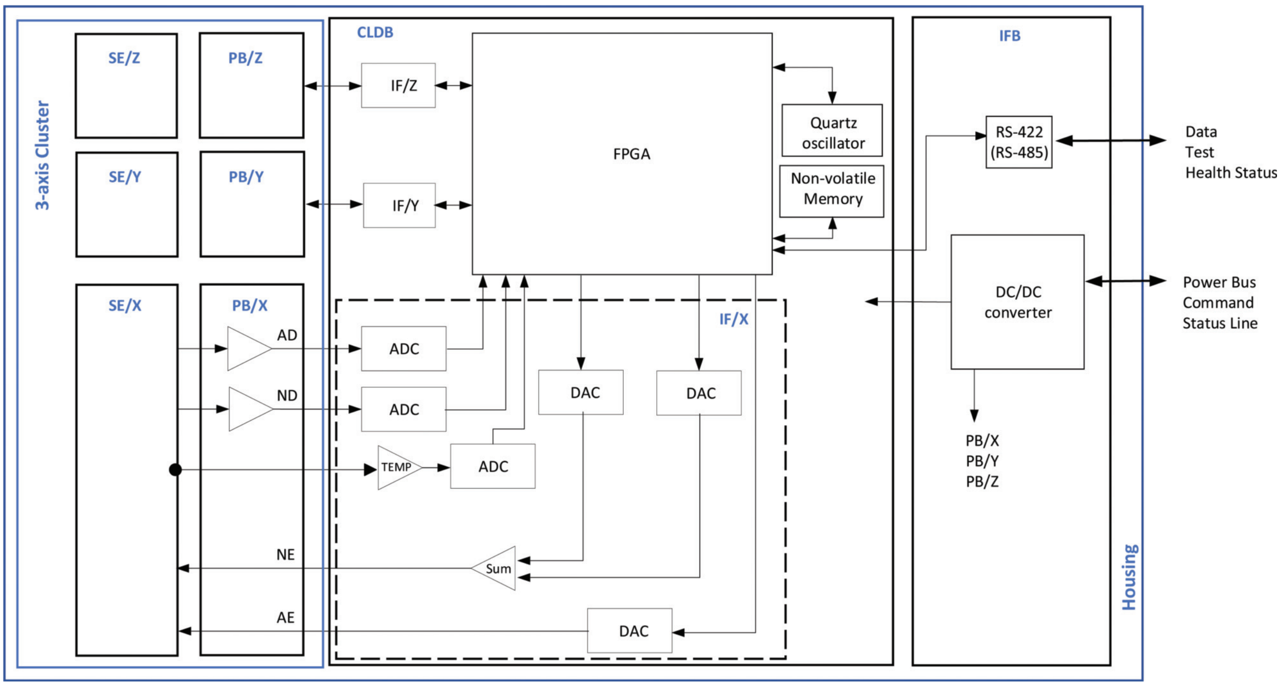

Figure 5. Block diagram

For each CVG sensing element (SE), 12-bits/1MHz ADC functions are used to digitise the primary mode detection signals (AD), the secondary mode detection signals (ND) and each SE temperature sensor signal (TEMP). The ADC functions include low-pass filtering and scaling functions.

As InnaLabs CVGs are operating closed loop in a Force Rebalance (FR) control system [5], once digitised, AD, ND and TEMP are processed in the FPGA which implements the following functions: a PLL, amplitude control of the primary mode, In-phase and In-quadrature control of the secondary mode, compensation of errors, and health status monitoring. 12-bits/1MHz DACs are used to feedback appropriately each control signal to each resonator, and an external non-volatile memory is used to store the compensation parameters for correction of Bias, Scale Factor and misalignment errors.

IFB hosts a DC/DC converter function interfacing the power bus of the satellite and providing to ARIETIS sub-functions regulated DC secondary voltages. That DC/DC function is not a redundant system but works as a dual power bus connector providing some of the redundancy benefits of a dual DC/DC converter.

5. Preliminary results

Bias errors of InnaLabs CVG are mainly temperature dependent as temperature is a factor that influences the physical properties of any mechanisms involved in energy loss. This leads to a change of the damping level of the primary resonant mode, upsets the stability of the controlled oscillation and leads to bias errors. As early as 2014 [2], few improvements have been imple-mented to InnaLabs CVG control system to cope with that and achieve excellent performance parameters and reduced ARW.

A typical bias temperature stability result on an InnaLabs' 1-axis gyro is shown in Figure 6 below. The analysis is based on the bias residuals calculated by subtracting a third order least squares model from the raw data over the full temperature range. Pending completion of ARIETIS digital development in the next 18 months, the test is carried out at breadboard level with InnaLabs' current qualified analogue control electronics using MIL grade components. The temperature range is -45°C to +90°C, and the ramp rate is ±1°C/min:

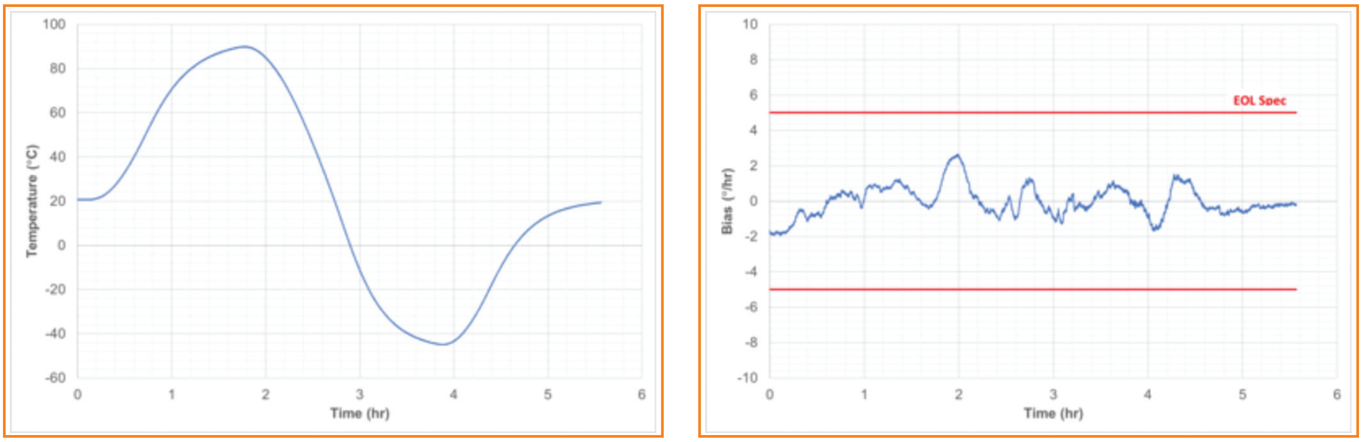

Figure 6. Temperature profile at SE level (left) - Bias errors over time (right)

From this, between -40°C and +70°C, the bias peak value is ~1.94°/hr with a standard devia-tion of 0.7°/hr. These bias thermal stability figures are significantly below the EOL specification of ±5°/hr set in Table 3. When considering the gyro output noise and the gyro bias short-term sta-bility, the Allan Variance method [6] can advantageously be used to highlight the different types of random processes generating bias instabilities.

The figure below shows the results obtained. The minimum root Allan Variance is 0.015/hr at 30 seconds which is consistent with an estimated ARW of less than 0.0016/√hr. The straight red line with slope -1/2 indicates the specification limit sets in Table 3. The origin of the slope -1 which can be seen on left side of the data plots is described in [2] and is related to the electrical-thermal noise generated by the op-amps scaling Node detection signals:

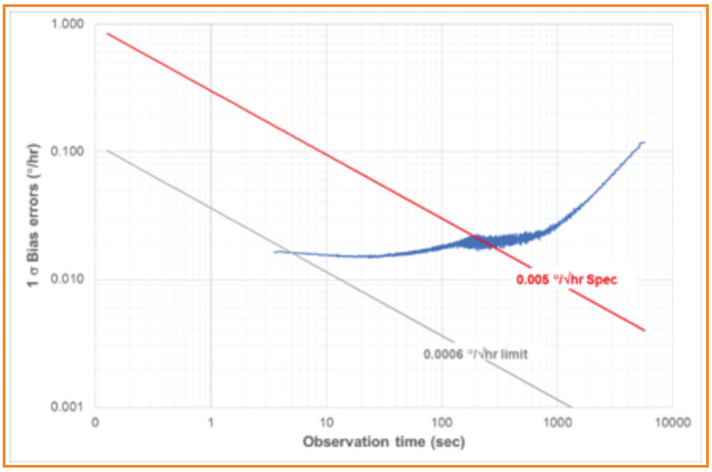

Figure 7. Allan deviation of InnaLabs CVG

Finally, to conclude this section on what is important to the survival of space equipment, radiation levels of 170kRad (TID) over one month have been investigated at CVG Sensing Element (SE) level. Gamma irradiations were performed with a panoramic Cobalt 60 source of 14.8 TBq providing a dose rate of 210rad/hr. As expected, no significant bias radiation sensitivity has been observed indicating that the InnaLabs CVG technology used in ARIETIS is inherently and naturally radiation hardened.

6. Conclusion

The design, construction and operating principles of InnaLabs ARIETIS 3-axis Rad-Hard Rate Measurement Unit (RMU) have thus been described. This ITAR-free product is being developed under a European Space Agency contract with an EQM fully qualified to long-life GEO and Science missions in the next 18 months. Commercial products will be ready to fly from the year 2020.

ARIETIS is based on InnaLabs patented CVG technology which delivers already market-leading performance to cost ratios for the past six years on land and marine stabilisation platforms. That technology is a middle point, in some way, between HRG and high-performance MEMS Coriolis gyros with bias in-run stability parameters of less than 0.02/hr and ARW better than 0.002/√hr.

Although InnaLabs is relatively new as a space company when compared to the overall industry, our combination of rare inertial sensor experts, operational excellence, and world-class engineering have positioned us as a vital source in an industry where space sensors are a scarce resource. We are comfortable with the challenges posed by our clients and industry partners and are in the process of delivering exciting space grade sensor technology that will be a key milestone in the development of inertial sensors for space.

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