



GE AEROSPACE RESEARCH

**High Temperature Inertial Navigation Sensors, Electronics,
and Packaging for reliable 300°C Operation**

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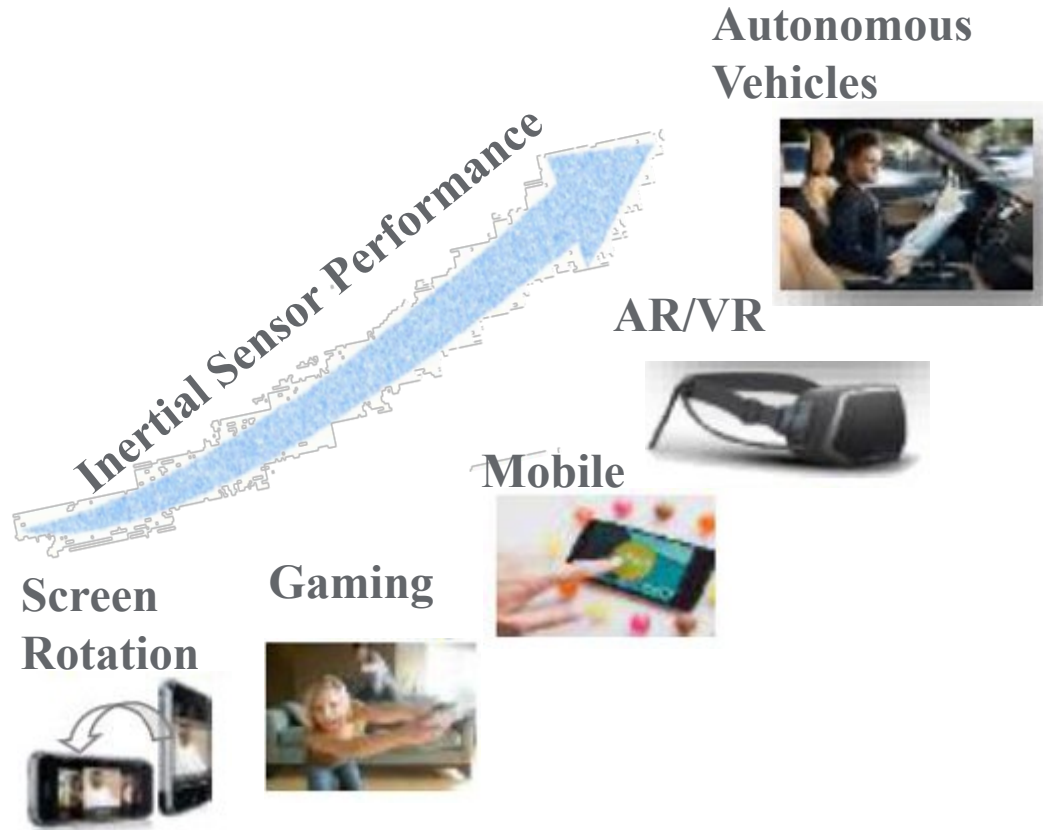
Presentation Outline

- Background and Motivation
- Polaris Process
- Component testing
- System testing
 - Packaging approach
 - Test platform design
 - Test results
- Applicability to other inertial sensors
- Conclusion and next steps



Inertial Navigation Sensor Market Drivers

Commercial applications driving inertial navigation



High-End Inertial-based Navigation

GPS denied navigation

< 1 nautical mile / hour drift (inertial-only navigation)



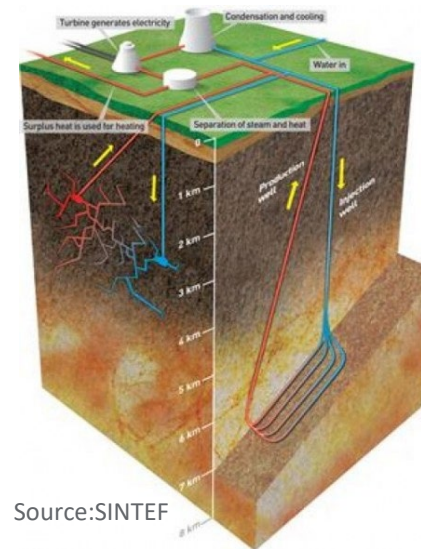
Extreme Temperature Inertial Sensor Applications

Downhole Oil & Gas Drill Navigation (150°C~200°C Ambient Operation)



Source: Safran

Geothermal Drill Navigation (200°C~300°C Ambient Operation)



Source: SINTEF

Hypersonic Vehicle Navigation (>1000°C Ambient Operation)

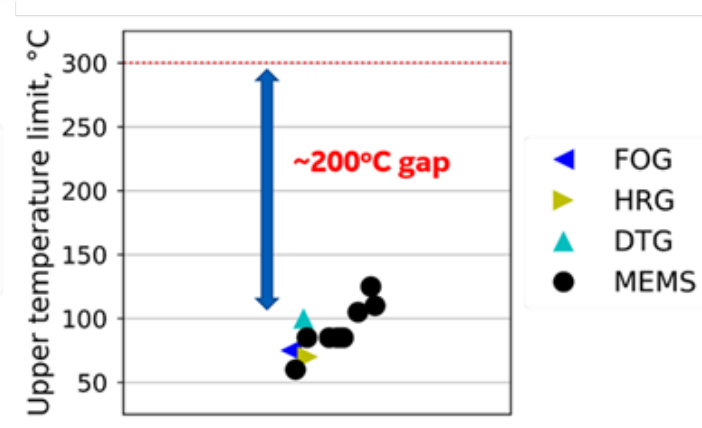
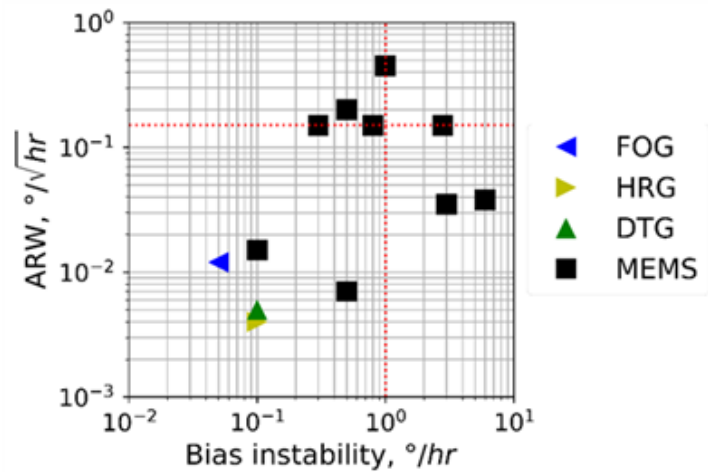


Source: DARPA

Magnetometers used in state of the art downhole directional sensing are generally limited to $\leq 200^{\circ}\text{C}$ operation

GE Survey of High Temperature Inertial Sensors

- High end MEMS gyroscopes are approaching navigation grade performance (<125°C)
- Best performing MEMS gyroscopes have room temperature noise performance necessary for navigation (<1°/hr).
- No existing commercial MEMS gyroscope reliably operate at >200C with <1°/hr performance



Vendor	Technology Referenced
Analog devices	MEMS
Gyrodata	Drilling services
Sperry Drilling	Drilling services
KVH Industries	FOG
Murata	MEMS
Northrup Grumman	DTG
Safran	MEMS, HRG
Schlumberger	Drilling services
Scientific Drilling	Drilling services
Sensoror	MEMS
Silicon Sensing	MEMS
Syston Donner	MEMS
Tronics/TDK	MEMS



GE's path to high performance high temp. MEMS Gyro

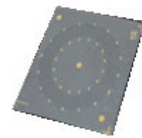
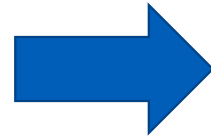
Coriolis vibratory gyroscope operation → Discovered in 1890 G.H Bryan

Source: Northrup Grumman



Hemispherical Resonator Gyro (HRG)
Quartz Macro-machining
30mm x 25mm x 25mm
Bias Stability <0.001°/hr

3D to 2D



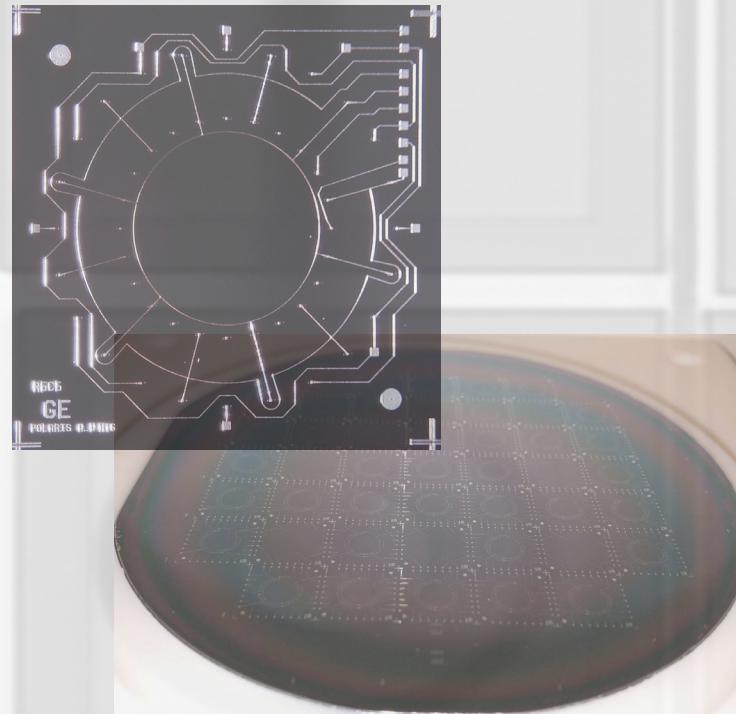
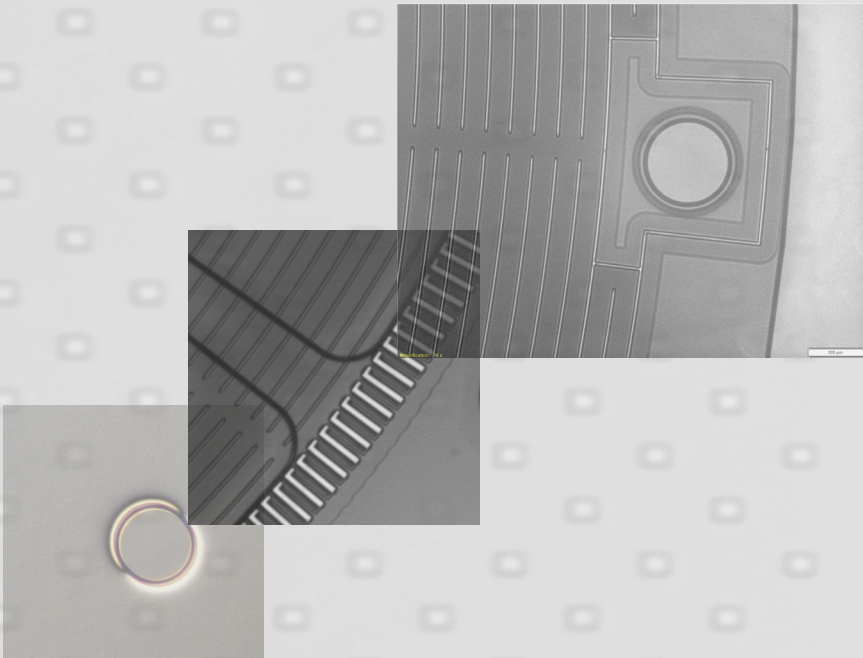
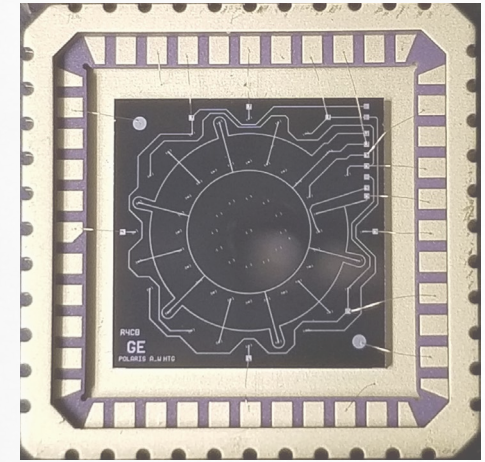
GE Multi-Ring Gyro (GE-MRG)
Silicon MEMS
10mm x 10mm x 0.7mm
Bias Stability <0.01°/hr

Key SWaP-C & Performance Benefits

- >100x volume reduction
- All silicon construction → Robust temperature operation, high performance
- Batch MEMS fabrication → Low cost
- Microelectronics controller compatible → Low power, high performance

GE Research Announces Polaris

- MEMS Process for Silicon resonators with wafer level packaging & thru wafer vias
- Specifically targeting high performance navigation applications
- PDK developed & available for select customers
- Multi-project wafers in development with Industry, Academia & Gov't



GE Research, IntelliSense Software Corporation Announce Joint Activity with GE's "Polaris" Process

MEMS & Microsystems, Microelectronics, Microfabrication

- "Polaris," developed by GE scientists, is a foundry process flow for developing high precision navigation devices with Microelectromechanical Systems (MEMS)
- IntelliSense offers software package that will enable clients to customize their MEMS navigation solutions using Polaris more easily
- GE Research's Polaris process enables high precision navigation devices without GPS

NISKAYUNA, NY - March 2, 2022 – GE Research, a strategic provider of MEMS foundry services, and IntelliSense Software Corporation, a leading MEMS solution provider, today announced a joint activity to enhance the availability of GE's MEMS foundry process flow called "Polaris," for the development of MEMS inertial devices of navigation-grade at low cost.

Todd Miller, Director and Executive Mission Leader, Electronics and Sensing at GE Research says, "We built the Polaris process with Inertial Navigation Grade MEMS in mind that we are now offering a turnkey foundry process. We are excited to be working with IntelliSense, which will be applying software that enables customers to more easily design and customize their MEMS solutions."

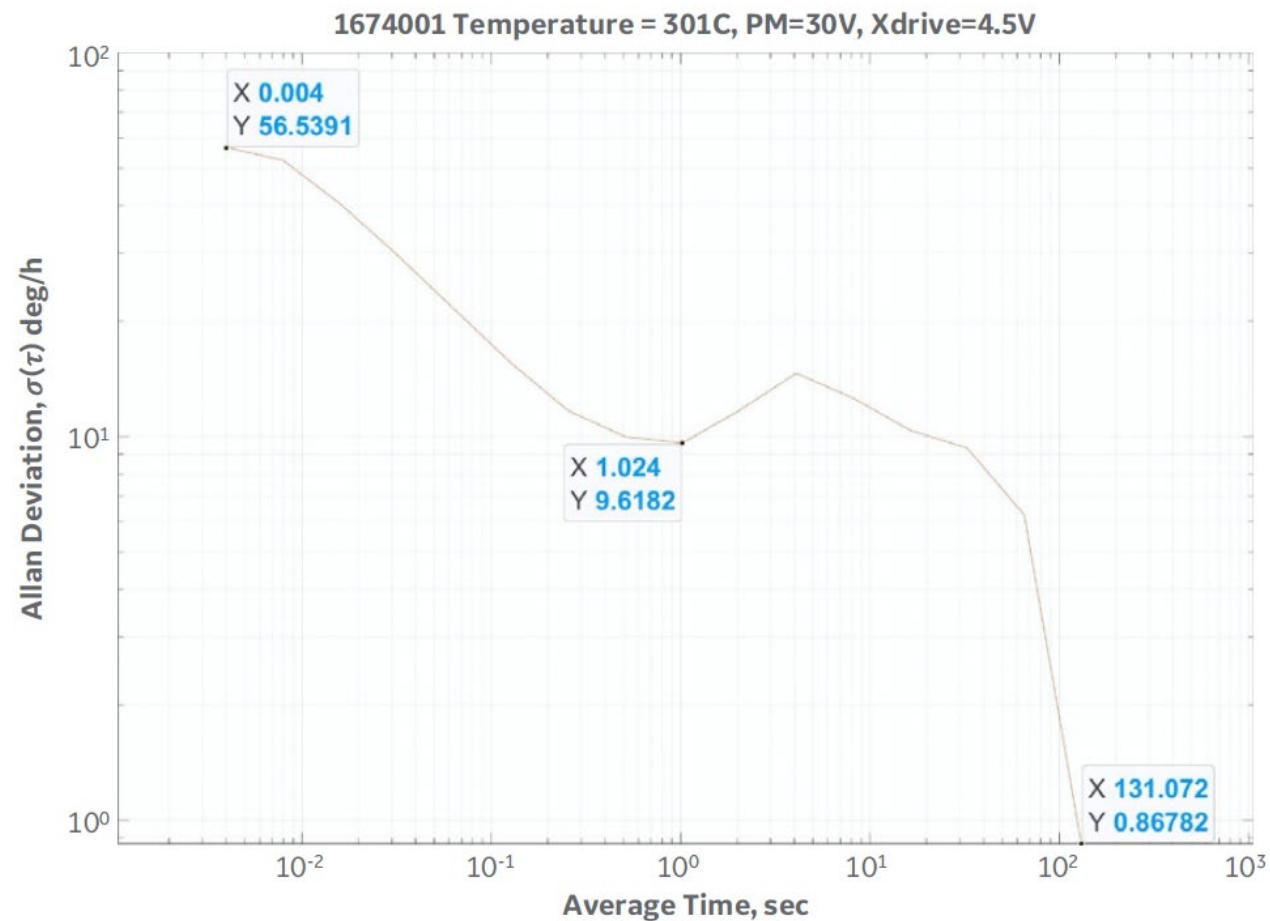
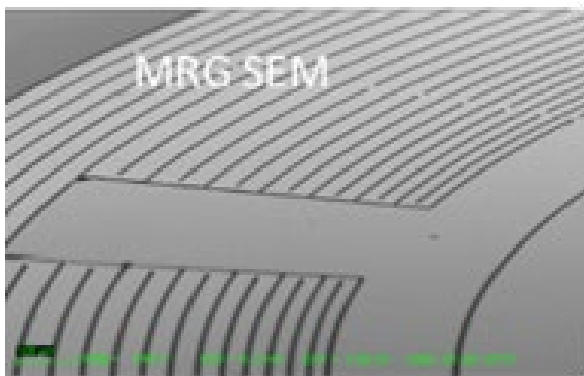
<https://www.ge.com/research/newsroom/ge-research-intellisense-software-corporation-announce-joint-activity-ges-polaris-process>

Experienced provider of PDKs & building components from outside entities



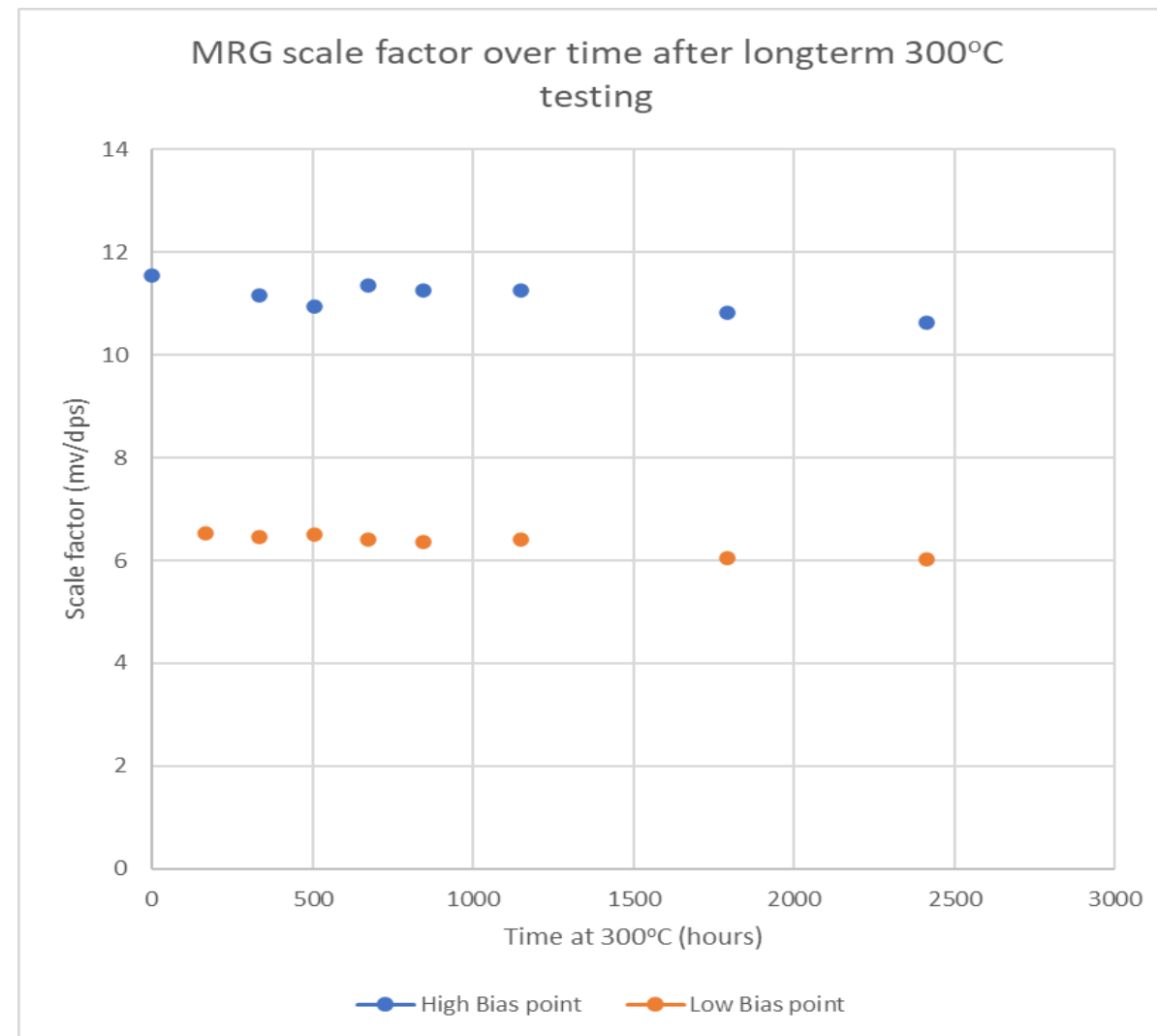
GE MEMS MRG – Performance Testing 300C

- Demonstrated MRG $<1^\circ/\text{hr}$ performance short term bias instability
- Noise levels enable 300°C gyro-compassing (inertial northfinding)
- Working on further improvements in performance with electronic thermal compensation



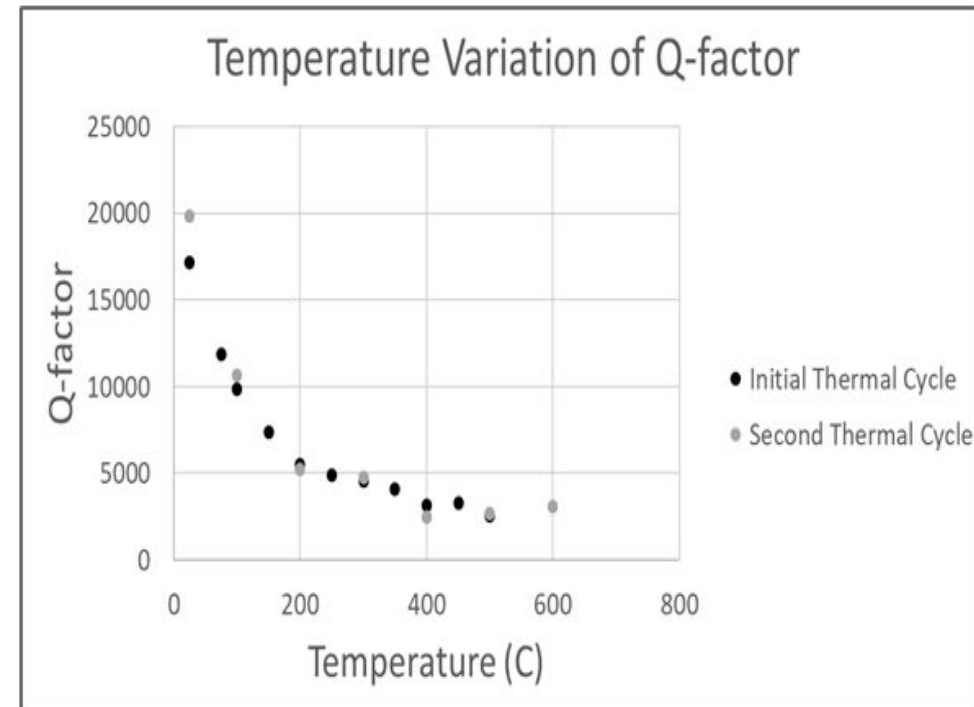
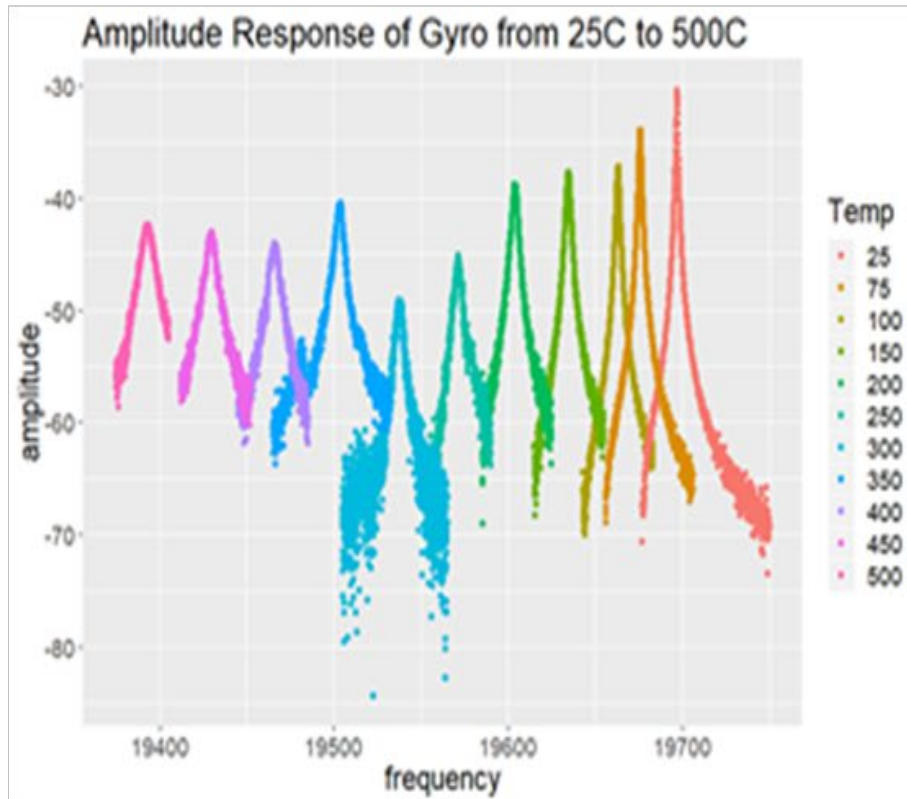
GE MEMS MRG – Long term 300°C testing

- GE MEMS MRG 300°C testing
 - High drive & low drive testing
 - Demonstrates linear operation
 - Robust MRG device performance
 - No appreciable change in device characteristics (2400+ hrs)



GE MEMS MRG – Functional Testing > 500°C

Demonstrated MRG gyroscope functionality at 25°C to 500°C+ with temperature cycling.



GE MRG Integrated Circuit (IC) Controller

- Silicon-on-Insulator (SOI) CMOS Application Specific Integrated Circuit (ASIC)
 - Designed for $-55^{\circ}\text{C} \rightarrow 300^{\circ}\text{C}$ operation
 - Gyroscope controller (Amplitude controller, frequency tracking, Rate sensing w/ digitally controllable settings)
- Low power & area
 - $<20\text{mW}$ power consumption / gyroscope
 - $\sim 3\text{mm} \times 3\text{mm}$
- Noise performance
 - Noise increased $\sim 2\times$ from room temperature to 300°C
 - Below mechanical noise of MRG



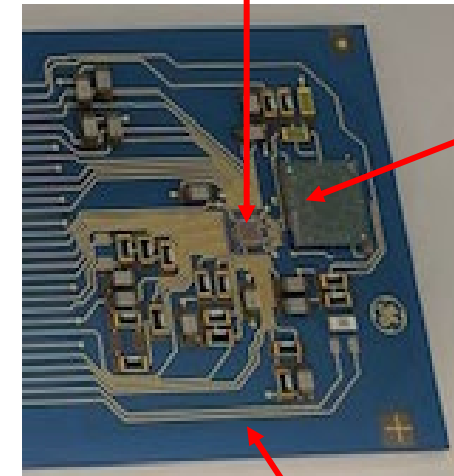
ASIC setup in 300°C chamber, probe connections to test system (outside chamber), and test equipment

Temperature	Sense Channel (10X Gain)	Drive Channel (1X - Gain)
25°C	1.3uV/VHz	2.8uV/VHz
100°C	1.5uV/VHz	3.1uV/VHz
200°C	1.8uV/VHz	4.3uV/VHz
300°C	2.2uV/VHz	5.2uV/VHz

Integrated MRG and ASIC testboard

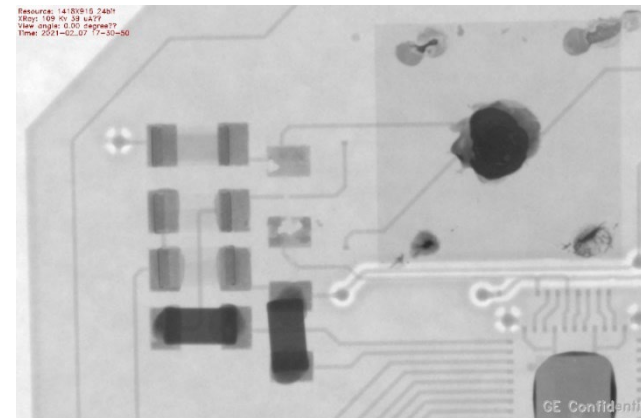
- Highly integrated MRG/IC packaging
 - AlN ceramic substrate
 - High reliability die attach & wirebonding
 - Printed conductors and dielectric
 - Two printed Au thick film interconnect layers with dielectric layer in between
 - Interconnect
 - Au sintering paste for ASIC and MRG attach
 - CuSn TLP passive attach
 - X-ray inspection after board assembly

GE IC Controller chip (3mm x 3mm)



GE MRG MEMS chip (10mm x 10mm)

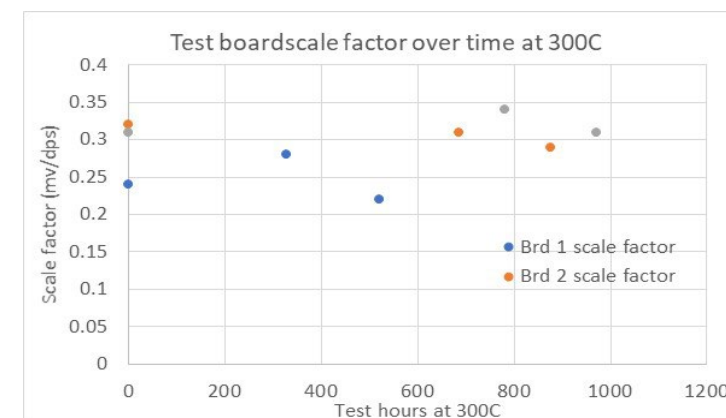
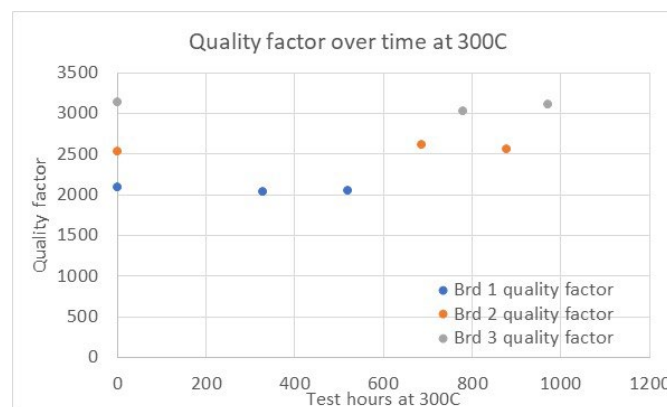
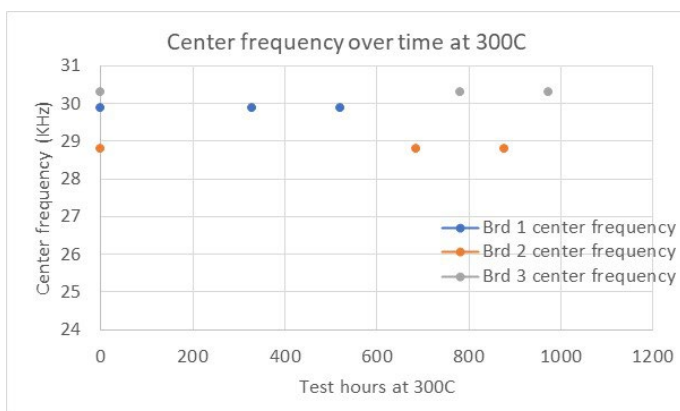
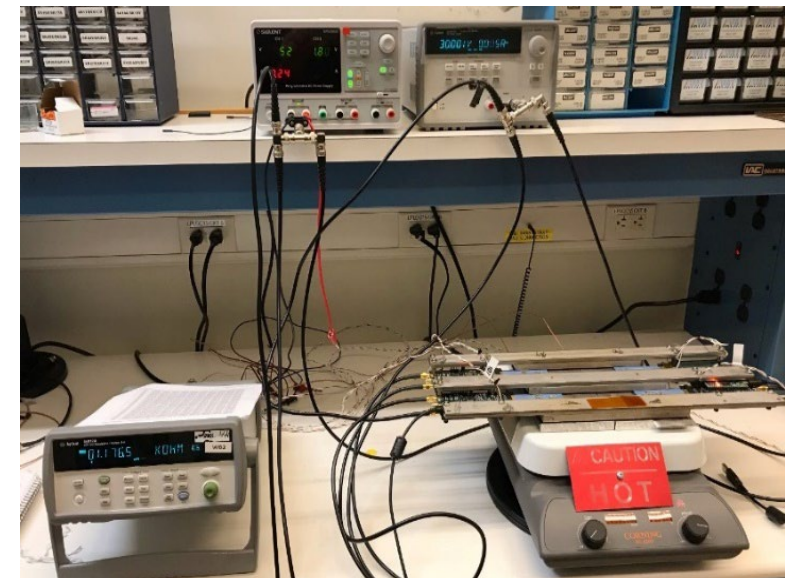
GE 300°C ceramic substrate PWB



Xray inspection post assembly

GE MRG with IC Controller Testing at 300°C

- Demonstrated >900hrs operational performance
 - 3 units tested
 - Constant 300°C temperature while MRG and IC operating
- Demonstrated long term 300°C reliability
 - IC Controller operating gyroscope
 - MRG under constant operation



What is a 'geophone'?



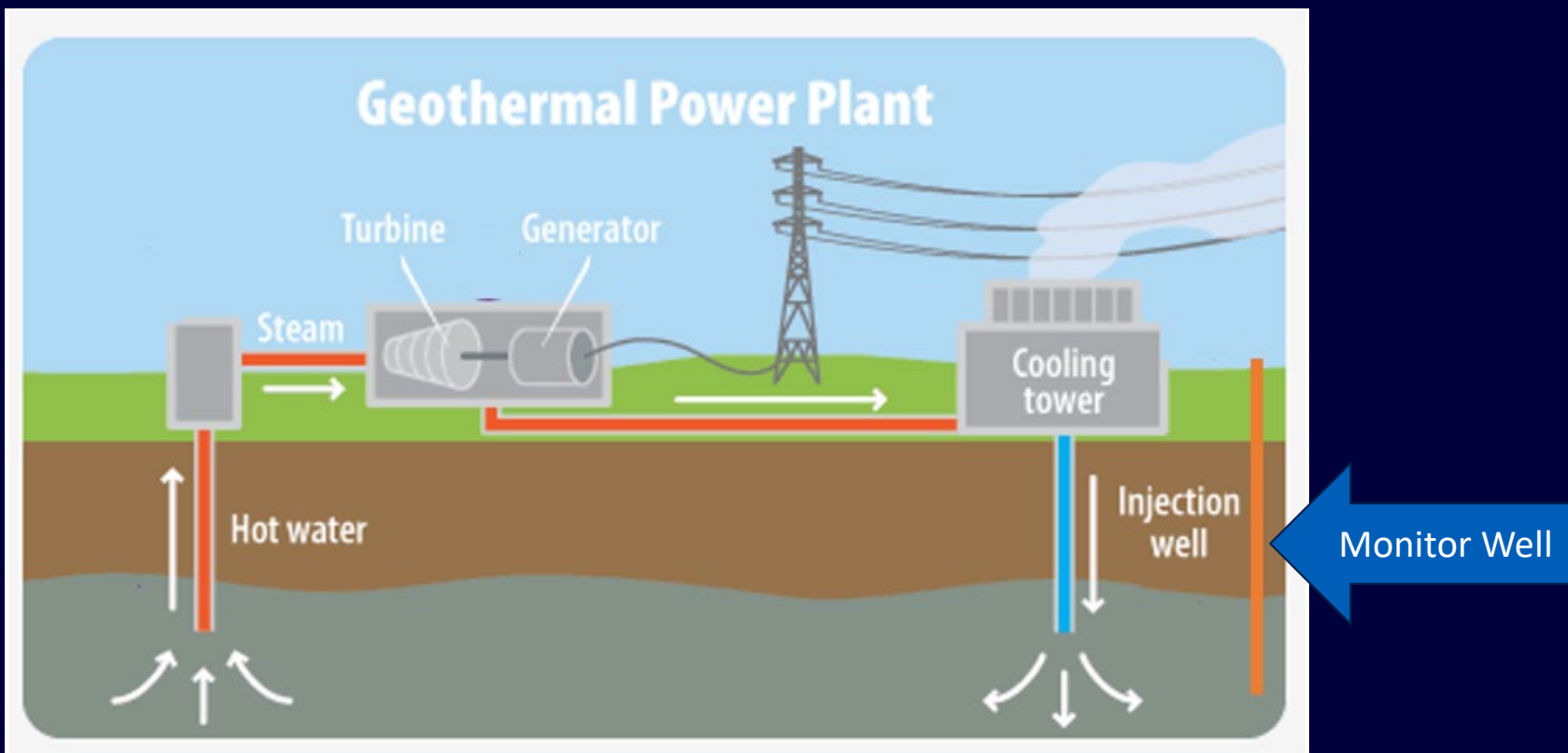
<https://en.wikipedia.org/wiki/Geophone>



- A Geophone is a seismic sensor that measures small accelerations.
- It 'listens' to the earth.
- Geophones are well understood technology, very sensitive, but geophones that can withstand 250C are not available.
- The goal of this project to make one that can operate at very high temperatures indefinitely without loss of fidelity.

Why are Geophones needed in Geothermal energy Production?

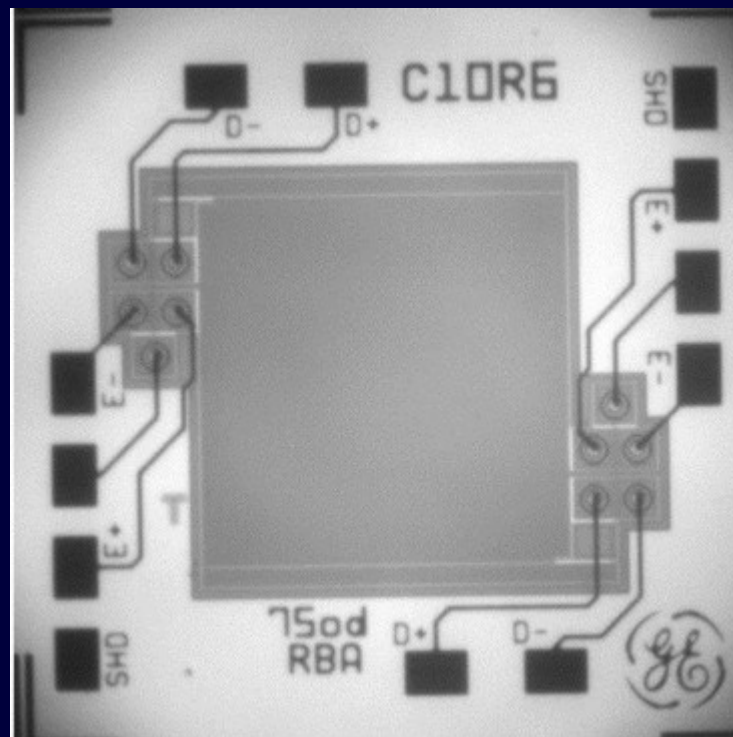
- Henfling, et. Al: Geothermal requires stimulation via hydraulic fracture. **Microseismic monitoring** provides real-time mapping of this process. Monitoring to assess stimulation effectiveness.
- **Induced Seismicity:** Geothermal plants tend to be located in areas of high seismic activity. Plant operators want to ensure they are not inducing seismicity during stimulation and production.
- Ideally the geophone is closer to the seismic energy source. This is accomplished with **Monitor Wells**. These wells are hot. Putting sensors in them is expensive.



Project Goals and our Solution

Geophone Project Goals
Survive 300C, Operate 225C indefinitely, 250C up to 6 months.
3 Axis Sonde/Sensitive
50nG/rtHz
0.1 to 1000 Hz bandwidth
10kpsi pressure

- Our geophone is a silicon high temp MEMS based transducer
- Integral high temp ASIC buffer/driver
- Sensor provides frequency-based output



The mass is held in place by two strings.
The strings are vibrating.
As the mass is accelerated the frequency of vibration changes.
The difference in frequencies between X and Y is proportional to the acceleration.

Summary and Future Work

- Prior work
 - Demonstrated 300°C capable high performance MEMS Gyroscopes
 - Performance enables inertial navigation functionality ($<1^\circ/\text{hr}$)
 - Highly reliable MEMS ($>2400\text{hr}$)
 - 300C System including Gyro, IC controller and associated packaging
 - Extremely compact ($>100\text{x}$ reduction over macro-scale gyroscopes)
- Current Work
 - MEMS based geophone with HT SOI ASIC for long term operation

MEMS inertial sensors offer low SWaP-C with high temperature capability



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And

The Geothermal Geophone Prize

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Thank You.



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