Development of High-Accuracy MEMS Gyros for Space Applications

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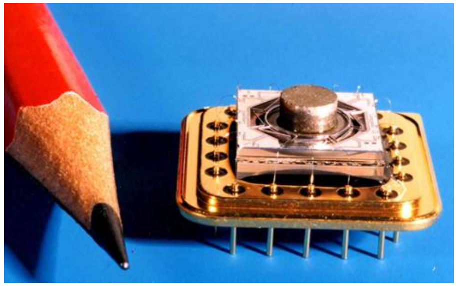
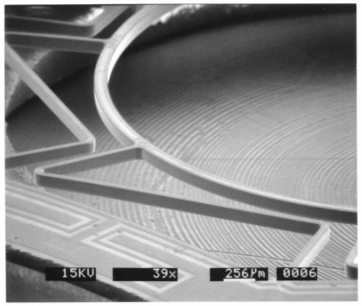
Overview

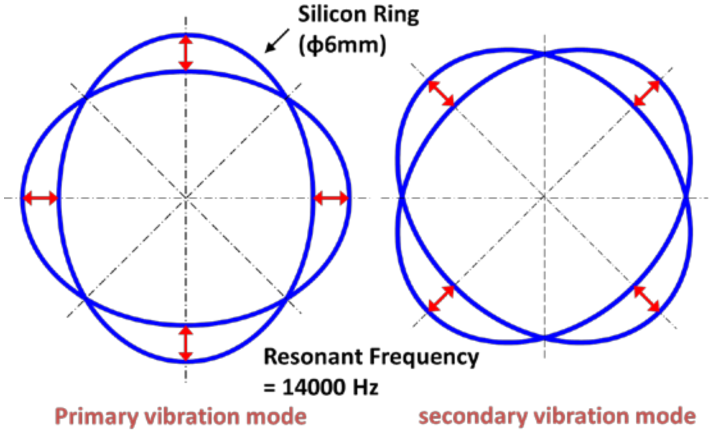
- Joint R&D of High-Accuracy Micro Electro Mechanical Systems (MEMS) gyroscope for space applications have been started since 2012, under the framework of “JAXA Open-Lab” program (total 3 years)
- Improvements of existing ring-shaped bulk silicon coriolis vibratory gyro (CVG) , to realize 10-times better than the performance of CRS09 (BI < 0.1deg/hr)
- Digital Temperature Compensation (TC) and improving MEMS packaging are mainly tried
- Our 2-year (interim) activities are presented today



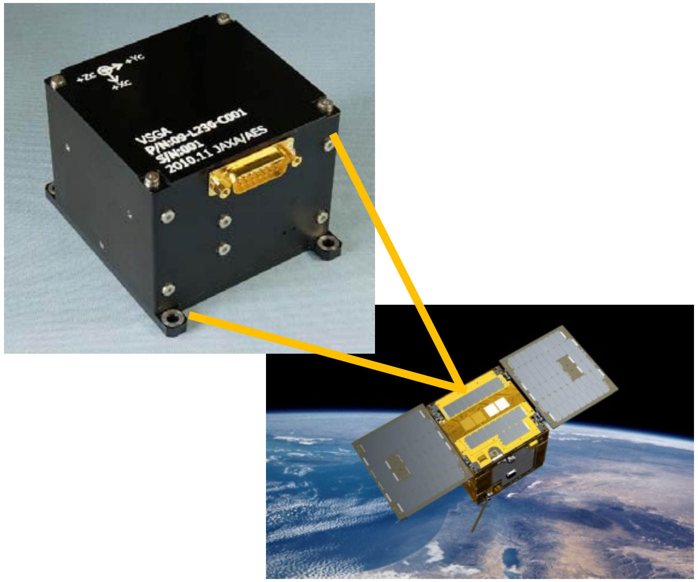


Background

- Silicon Sensing Systems (SSS), jointly ventured between SPP and UTC Aerospace & Systems (UTAS) have produced ring-shaped silicon MEMS gyro for accuracy-requiring users (automobile, train, airplane) for several years
- CRS09 was the most accurate MEMS gyro in SSS line-ups (currently, CRH01)
- As for aerospace, JAXA's small satellite (SDS-4) equipped with CRS09 as AOCS sensors was launched. The CRS09 works without failures since 2012

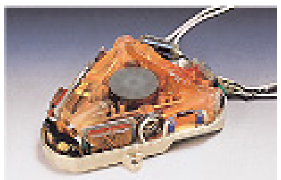


Vibration modes of resonator


SDS-4

Motivation

- Japanese main launchers (H-IIA/B and Epsilon rockets) utilize Ring Laser Gyro (RLG) in the Inertial Measurement Unit (IMU) at present
- Following points are considerable...



Increase in complexity

1. Production of glass block
2. Laser emission
3. Mirror control (actuation)

△

Need a wide variety of parts

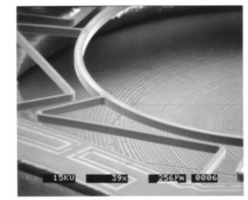
1. Weight ↑
2. Production cost ↑
3. Reliability ↓

△

Need laser emission

1. Power consumption ↑
2. Thermal radiation ↑

△



MEMS = Simple !

○

1. Light-weigh
2. Low power consumption
3. Low cost

But accuracy is not sufficient for the space applications

Targets of R&D

	CRS09	Targets
Signal Processing, Temp Compensation, Data Output	Analog	Digital
Rate range	±100～200 deg/s	±400 deg/s
Angle Random Walk (ARW)	0.1 deg/√hr	0.01 deg/√hr
Bias Instability (BI)	< 3deg/hr	< 0.1deg/hr
Bias variation with temp.	< ±1deg/s	< ±0.1deg/s
SF Bias variation with temp.	< ± 1%	←
Shock resistance	10G	20G

e.g., RLG
BI ≒ 0.01 deg/hr
ARW ≒ 0.1 deg/√hr

Approach

- **2012**
  - Prototyping (digital TC)
  - Making fitting curve (high orders) for TC
    > To shift down the “+1 slope” of allan variance
  - To reject error sources from temp. variation, identify the performance of MEMS sensor head itself
- **2013**
  - Digital circuit (digital signal processing) completed
  - Drive and Sense circuits controlled by digital signal processing
  - Design of MEMS sensor head and process

Sample in 2012

Sample in 2013

2012: dual PWB
2013: single PWB

Approach (cont.)

- **2014 (on-going)**
  - Complete and evaluation of Gyro EM
  - Flight experiment on the sounding rocket (this summer)

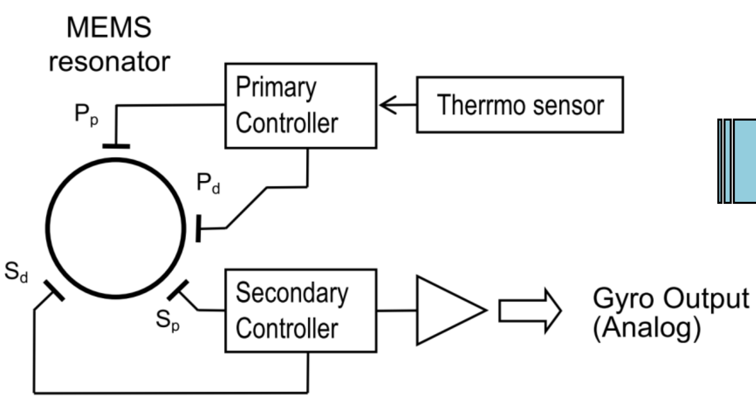
		CRS09	2012	2013
Circuit	Drive & Sense controller	Analog	←	Digital
	Gyro Output	Analog	Digital	←
TC *	Scale Factor	Analog	Digital	←
	Bias	-	Digital	←
	Phase	-	Digital	←
Package	Vacuum level	low	←	high
	Package Shape	Square	←	Round
	Bonding (Si – glass)	Anodic bonding / Adhesion	←	Lower-temp. bonding
MEMS	Resonator	Ring	←	←

* Temperature compensation

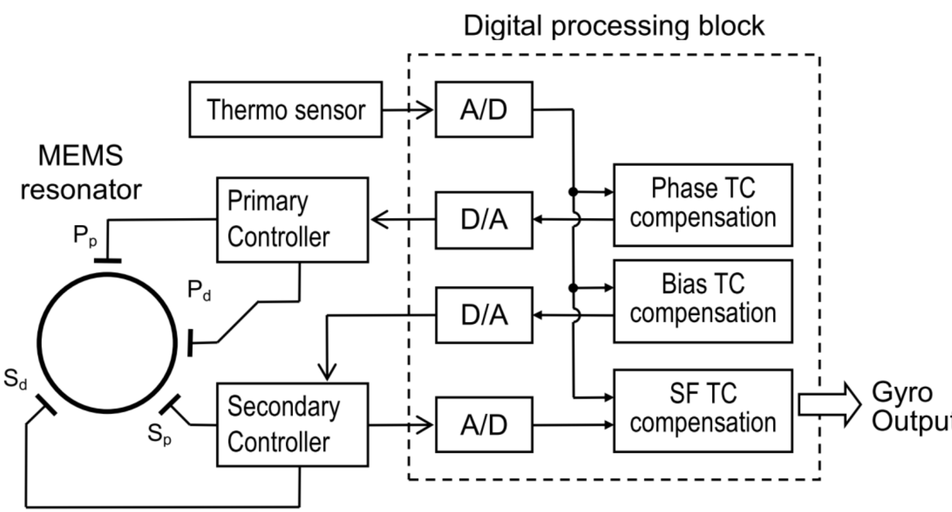
Digital Temperature Compensation (Design)

- CRS09
- Only SF TC was compensated using thermo sensor in the primary controller

- Trial (Sample in 2012/2013)
- SF TC is calculated in the output
- SF, Bias and Phase are compensated with calculation.

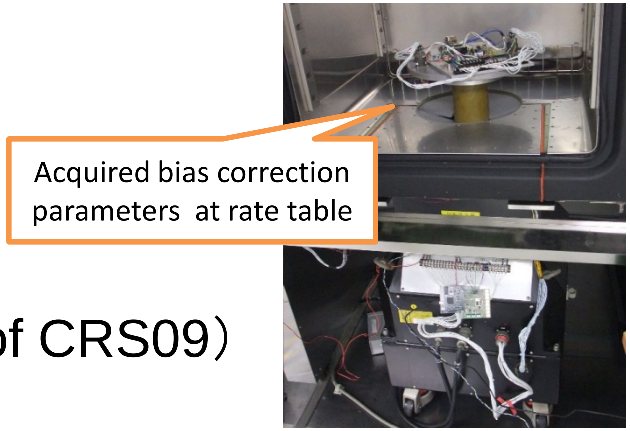


Before

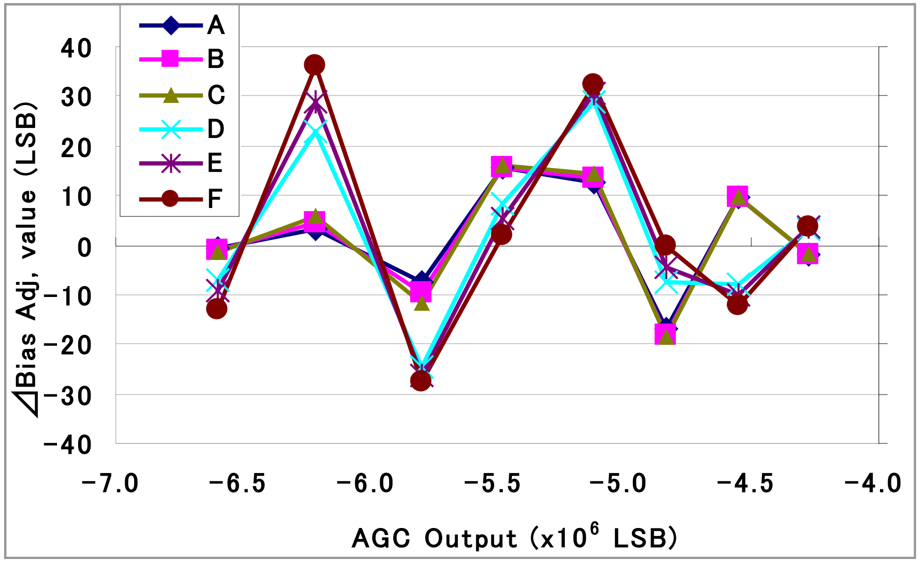


After

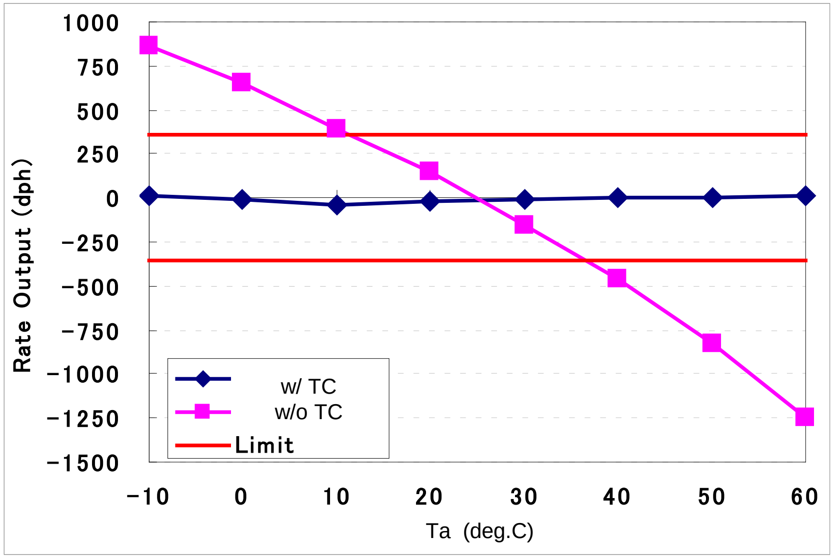
Reducing Bias Variation with Temp.



- Bias variation (pk-pk) of -10～60 deg.C
  - w/o TC: 2,000 deg/hr
  - TC (target): 360 deg/hr（1/10 of CRS09）
  - TC (results): 50 deg/hr
- Bias variation with digital TC is 40 times smaller than that without TC



Evaluation of correction function
（Max. 5th-order function）

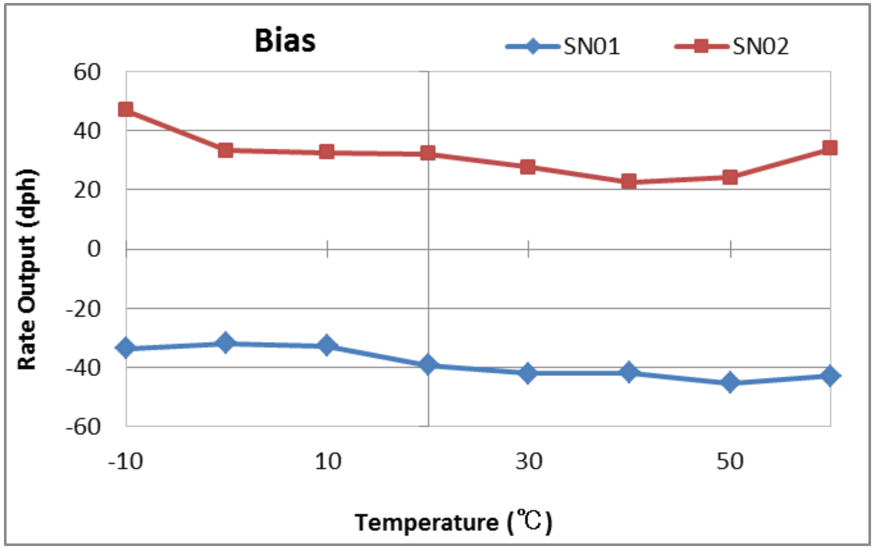


Bias variation with temp.
(w/o TC and w/ TC)

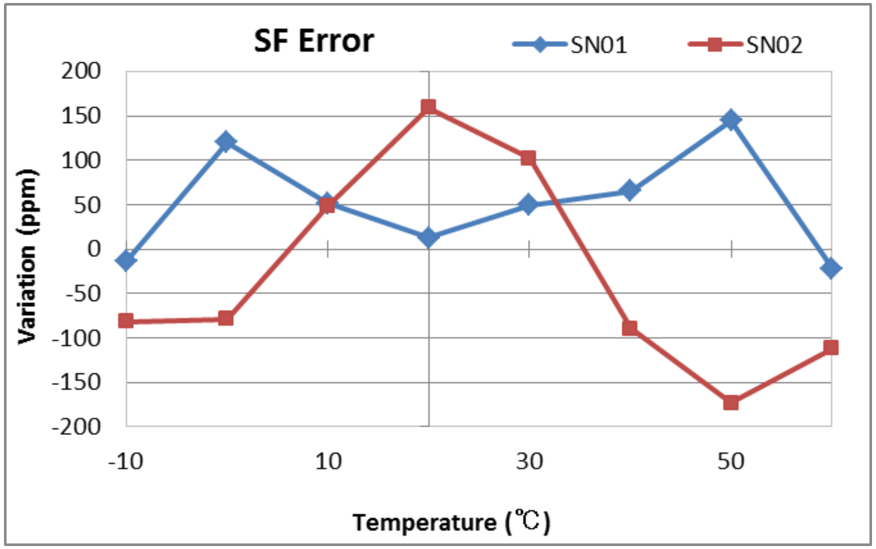
Digital Temperature Compensation Results

- Bias & Scale Factor variation with temperature

	Results	Target
Bias variation	< +/- 50 dph	< +/- 0.1dps (= 360 dph)
SF variation	< +/- 200 ppm	< +/- 1% (= 10,000 ppm)



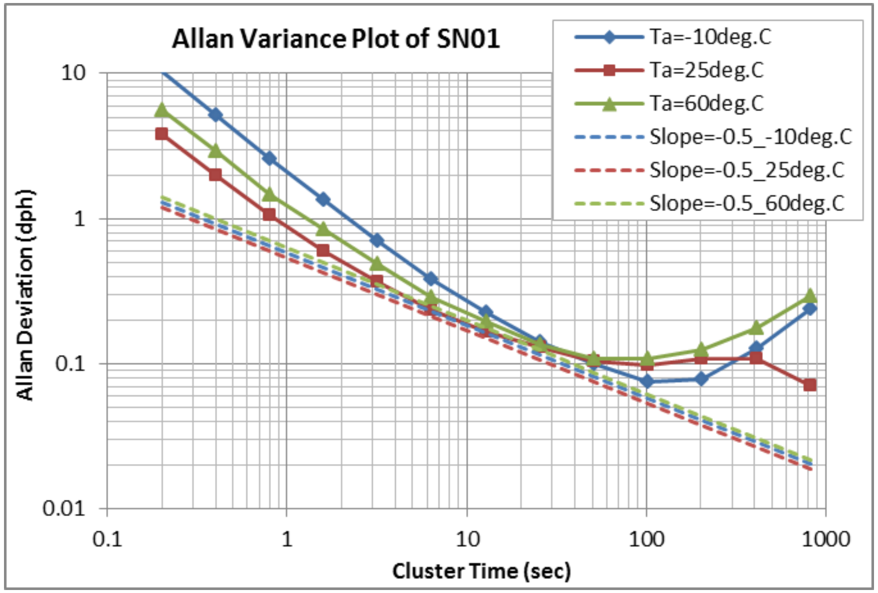
Bias variation w/ temp.



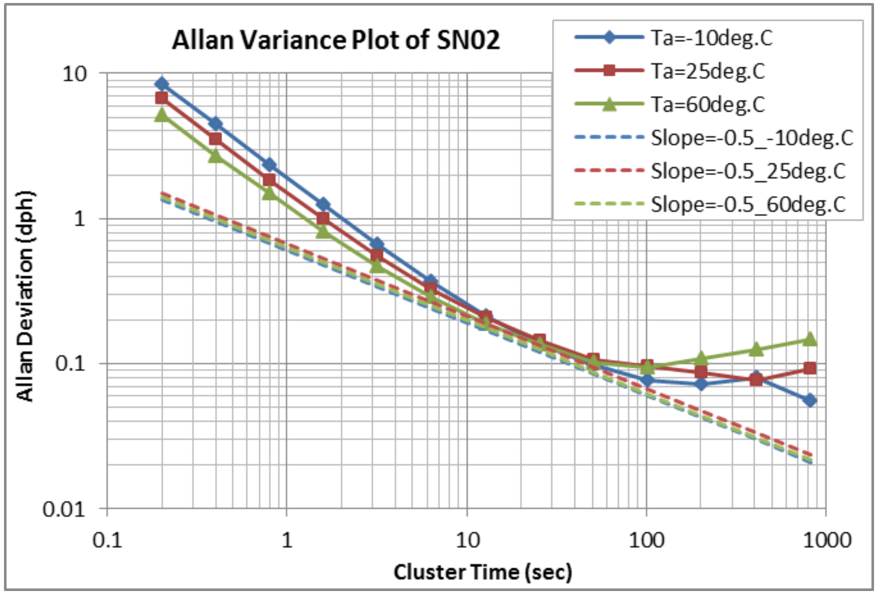
Scale factor variation w/ temp.

Digital Temp. Compensation Results (cont.)

- Bias Stability in the temp. range between -10 and +60 deg.C
  - Bias Instability (Bottom of plot) ≃ 0.1 dph
  - Angler Random Walk ≃ 0.01 deg/h$^{0.5}$ (= 0.6 dph at 1 sec)
- These data are not optimized



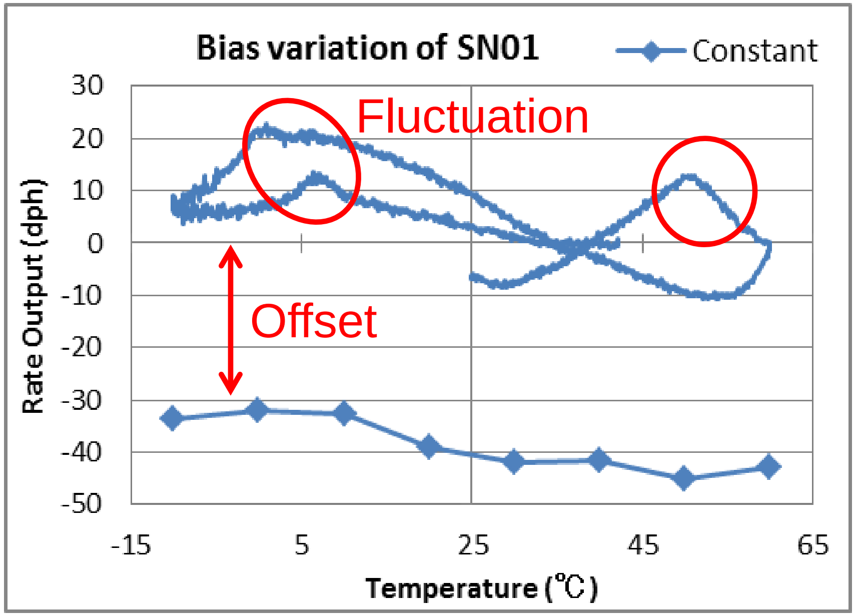
Allan variance (SN01)



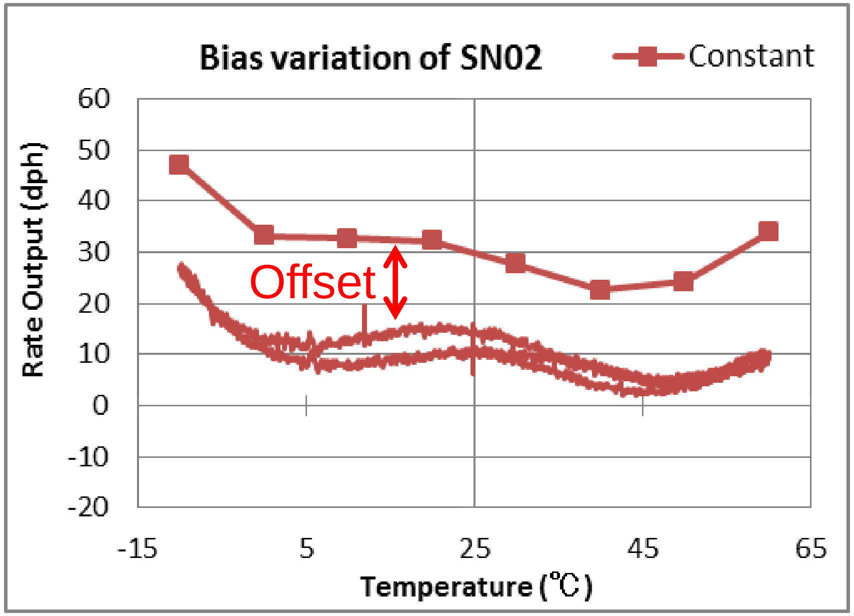
Allan variance (SN02)

Digital Temperature Compensation Results (cont.)

- Bias variation under temp. gradient
  - Gradient condition = 0.58 deg.C / min.
  - Large offset between under constant temp. and gradient temp.
  - Output fluctuations in SN01



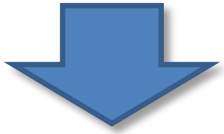
SN01



SN02

Concern about the MEMS sensor head

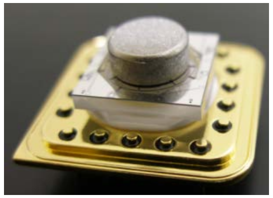
- **Bias offsets**
  - Change of mechanical or material characteristics with passage of time
  - Change of some kind of error components with time
    Mechanical stress, Electrical offset, etc…
- **Output fluctuation under temp. gradient**
  - Variation of mechanical stress with temp.



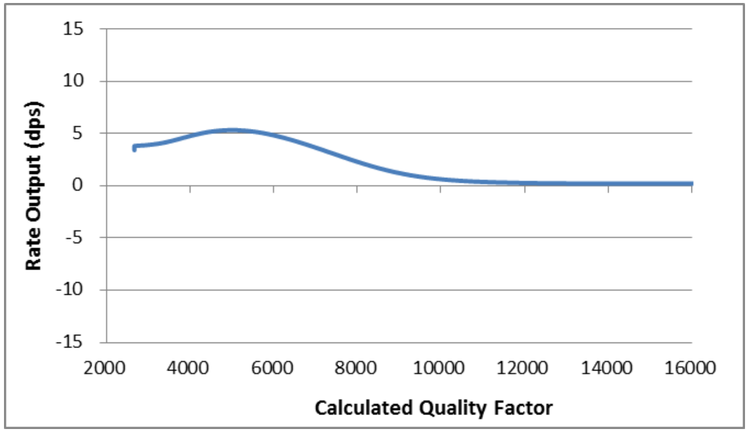
- **Focused on the mechanical stress around MEMS sensor head**
  - Packaging → Done in 2013 (next page)
  - Bonding structure of MEMS → on-going

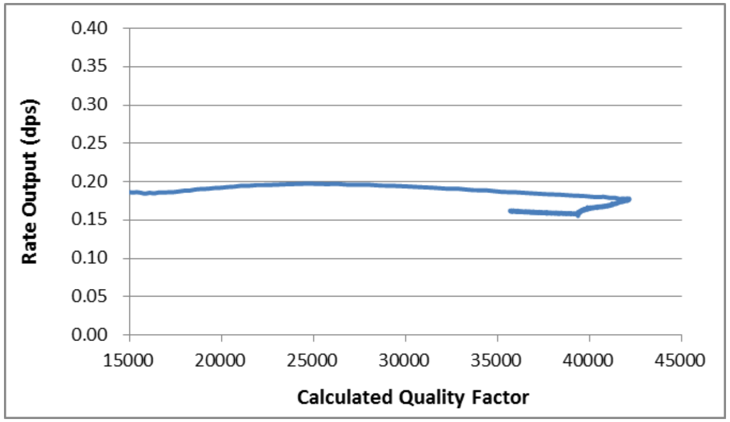
Study to Improve MEMS sensor head

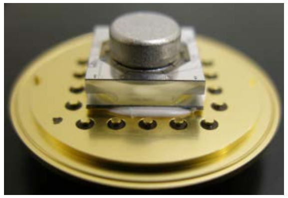
- **Investigating the influence of mechanical stress from packaging**
  - Package base types: Square (Present) / Round (Trial)
  - Monitoring the output with vacuuming in the chamber
    Quality factor is calculated by the output of AGC loop



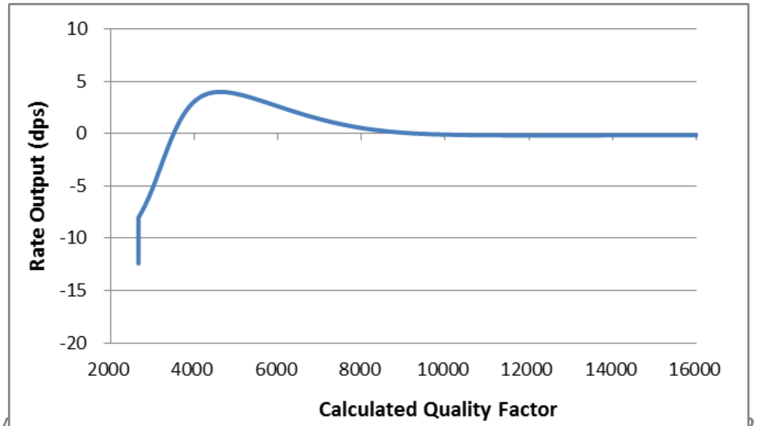
Square

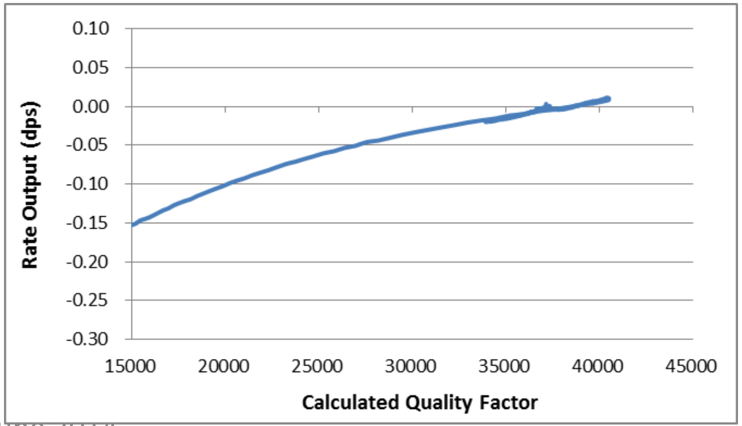






Round





Study to Improve MEMS sensor head (cont.)

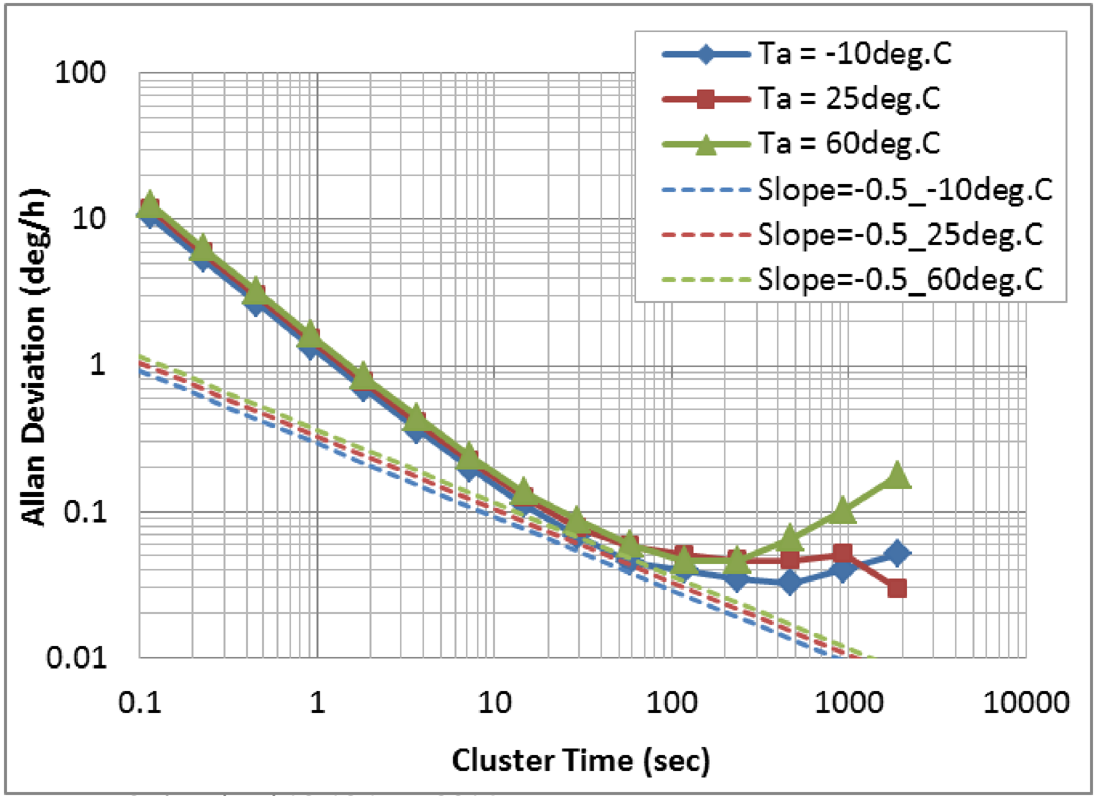
- Changing the shape of package did not show the desired results. It had difference but square shape was better than round.
  The main reasons we consider;
  - Effect of the internal mechanical stress occurring around bond parts of MEMS chips

- We are on the process of;
  - the bonding between package and MEMS chips
  - Internal mechanical stress around bond parts of MEMS chips

Study to Improve Gyro Controller

- Optimizing the motion of resonator in response to increased Q-factor (vacuum level changed)
- Optimizing the gain of each circuit block
- Bias Instability (Bottom of plots) ≃ 0.03 ~ 0.05 deg/hr
- Angle Random Walk ≃ 0.005 deg/h$^{0.5}$ (= 0.3 deg/hr at 1 sec)

After optimization of electronics
but
MEMS package is not changed



Summary / Future Plans

- Our 2-year activities are introduced
- Effectiveness of digital temperature compensation is confirmed
- After some tuning, Samples in 2013 can reach:
  - Bias Instability: 0.03 ~ 0.05 deg/hr
  - Angle Random Walk: 0.005 deg/h$^{0.5}$
- Complete and evaluation of Gyro EM in 2014
- Sample in 2013 (full digital circuit type) will be demonstrated by high roll rate (1Hz) sounding rocket (JAXA S-520) in the summer of 2014

S-520
sounding rocket