SSC09-XI-11

MEMS in Space – A New Technology Advancing from Flight Experiment to Proven COTS Product

Andrew Carrel
Surrey Satellite Technology Ltd
Tycho House, 20 Stephenson Road, Surrey Research Park, Guildford, GU2 7YE, United Kingdom;
+44 (0)1483 803803
A.Carrel@sstl.co.uk

Paul Alderton
Atlantic Inertial Systems
Clittaford Road, Southway, Plymouth, PL6 6DE, United Kingdom;
+44 (0)1752 695695
Paul.Alderton@atlanticinertial.com

ABSTRACT

Over the past 25 years, SSTL has shown that Small Satellites are an effective alternative to larger missions. To remain competitive, however, these spacecraft need to fit more and better functionality into the same low mass, low volume envelopes that allow them to be launched at low cost. Micro-electrical-mechanical systems (MEMS) is an advanced technology that addresses this need and an area that is presently developing rapidly.

Atlantic Inertial Systems' RRS01 MEMS rate sensor was developed for terrestrial applications but has since been found to be suitable for space flight. This compact, light-weight unit has already been shown to be very robust in military applications and has a long lifetime owing to the design of resonating silicon ring at the heart of the sensor. Silicon-wafer mass production techniques are employed, bringing all the benefits of production repeatability as well as low cost and a short lead time.

SSTL has developed an inertial sensor module, incorporating this technology that will fly on 5 missions over the next few years. This product builds on the results from 3 previous missions where SSTL has flown MEMS rate sensors, including the RRS01. NigeriaSat-2 uses this inertial sensor to supplement star tracker measurements in attitude estimation, while de-tumbling and Sun-acquisition is the application on the Kanopus platforms.

This paper describes the RRS01 MEMS rate sensor and its use in SSTL's inertial sensor module. Results will be presented from flight experimentation and environmental testing that has been undertaken by SSTL to qualify this technology for use on its customers' satellite platforms as well as its own. The application of this MEMS technology to various missions is also discussed.

INTRODUCTION

Micro Electro-Mechanical Systems (MEMS) have resulted from the evolution of microfabrication techniques, originally developed for integrated circuit manufacture, for the integration of micromechanical structures with electronic components. The technology has produced devices which are inherently small, robust and amenable to batch fabrication, creating unprecedented levels of functionality and reliability at relatively low cost.

Inertial sensors are widely used on spacecraft for a range of purposes. Unlike Sun Sensors and Star Trackers they cannot be blinded by too much or too little sunlight and they typically have good noise characteristics. Inertial sensors can only measure changes in attitude and so must be used in combination with other sensors for most applications.

MEMS inertial rate sensors have been flown as experiments and then as AOCS sensors on a number of SSTL missions. The Systron Donner QRS11 unit was first flown by SSTL in 1999 as an experiment on UoSat-12[1]. This unit is now used as an integral part of the AOCS on the successful Giove-A mission[2,3], launched in 2005. Meanwhile the RRS01 MEMS inertial rate sensor was first flown on BilSat-1[4] in 2003. Building on this experience, SSTL now has its MEMS Inertial Rate Sensor (MIRaS-01) in production, which incorporates the RRS01 rate sensor.

THE RRS01 INERTIAL RATE SENSOR

The sensing element of the RRS01 is a 6mm diameter silicon ring supported on 8 radially compliant spokes. Four pairs of conductors are deposited on the surface of the ring which is situated in a magnetic circuit driven by a samarium cobalt magnet.

In operation an alternating current, controlled to the natural frequency of the ring, is passed through a conductor pair (the primary drive circuit, Pd). The magnetomotive force produced causes the ring to resonate at its natural frequency which is perpendicular to the axis of the ring.

The motion of the ring is sensed by the electromotive force generated in the second conductor pair (primary pickoff, Pp). The drive frequency is maintained at the resonant frequency over the over the thermal environment by a phase lock loop (PLL) and a voltage controlled oscillator (VCO) and the amplitude of the ring motion is maintained an automatic gain control circuit (AGC).

Rotation of the ring at an angular rate (Ω) about its axis coupled with the linear motion (v) of the ring results in a Coriolis acceleration (a_c) about a third axis mutually perpendicular to the axis of rotation and the axis of linear motion.

Where: $a_c = -2\Omega \times v$

The Coriolis acceleration is directly proportional to the rate of turn.

The resultant Coriolis force causes the node of oscillation of the ring to move angularly around the ring. The position of this node of oscillation is sensed by the third conductor pair (secondary pickoff, Sp). The signal from this pickoff is used to drive a secondary control loop that use the fourth conductor pair (secondary drive, Sd) to drive the node of oscillation back to the position that it would be with no rate of turn applied. The null position.

The secondary drive current is then proportional to the rate of turn.

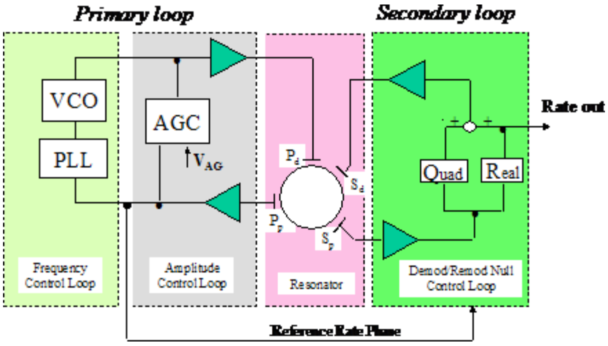

Figure 1: Schematic of the rate sensor

The silicon sensor is housed in a hermetically sealed Kovar case.

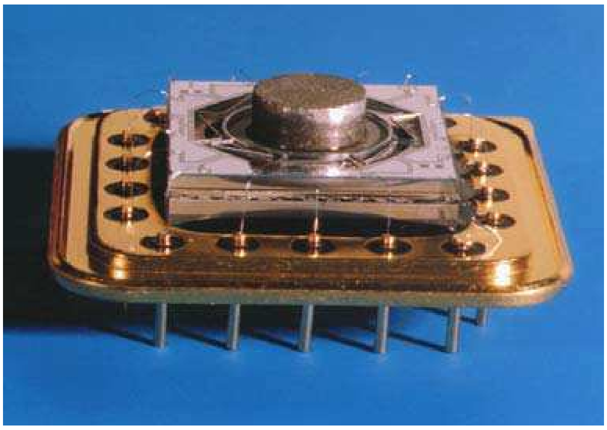

Figure 2: Silicon Resonator

This picture shows the lid of the case and the return iron of the magnetic circuit removed. The silicon ring can be seen on its 8 supporting 'dog leg' spokes which also carry the current to the conducting segments on the silicon ring. In the centre is the samarium cobalt magnet.

Figure 3: Segment of Ring Magnified

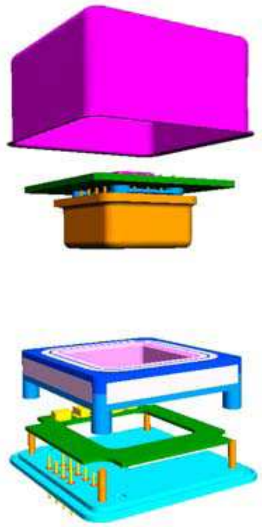

Figure 4: Rate Sensor Construction

The resonator assembled onto an isolation mount and with the power conditioning and control electronics boards are assembled into the outer case. The control loop electronics are implemented as ASIC technology.

Figure 5: Rate Sensor Control Board

The RRS01 can be configured for input angular rate ranges from 50°/s to 1500°/s. Bias performance is better than 1°/s over the full temperature range of -40°C to +75°C with scale factor linearity better than 1%. Rate output noise is less than 0.25°/s rms.

The RRS01 is used in many diverse applications including yaw control of active breaking systems in cars, control of tilting trains through to guidance and control of highly agile missile systems.

FLIGHT EXPERIMENT ON BILSAT-1

BILSAT[4] was launched on the 27th of September 2003, along with two other SSTL satellites, UK-DMC and NigeriaSat-1. Four RRS01 MEMS rate sensors were packaged together with an SSTL standard CAN interface to give rate measurements about each axis with an additional sensor for redundancy. This experimental gyro module is shown in Figure 6.

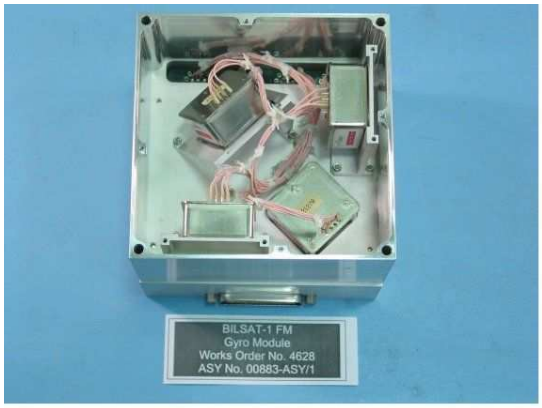

Figure 6: Bilsat-1 Gyro Module

This experiment was used to compare the attitude rates measured by the RRS01 rate sensors with those estimated from the other AOCS sensors on BilSat-1. It was found that standard approaches to gyro bias estimation were ineffective owing to the bias dependency on temperature. It was, however, found that performance is greatly improved when a Kalman filter used for bias estimation accounts for the temperature of the gyro module (see Figure 7). The effectiveness of this bias calibration against temperature was still somewhat limited because only the temperature of the whole gyro module is measured rather than the temperature of the RRS01 rate sensor themselves.

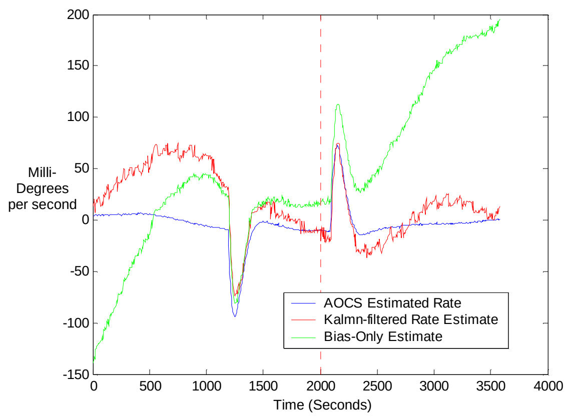

Figure 7: In-flight results from Bilsat-1

The variation of the RRS01 bias with temperature is in fact small compared to the measurement range of the sensor (for example ±50deg/sec for the RRS01-05). In space applications, however, attitude rates are typically much lower, even for agile platforms. Consequently all bias terms must be carefully accounted for. Fortunately, each RRS01 rate sensor incorporates an internal temperature sensor that allows the bias variation with temperature to be compensated for and so this channel is used in the MIRaS-01 that incorporates the RRS01 rate sensor. The BilSat-1 flight experiment showed that the behaviour of the RRS01 sensor was not affected by the space environment and provided SSTL with the necessary experience to produce a well-performing Space IS Module using this sensor.

DEVELOPMENT OF SPACE IS MODULE

After the success of the inertial sensor in use on the Giove-A mission (based on another MEMS rate sensor) SSTL decided to adopt the RRS01 sensor for its subsequent IS modules. This decision was based on the experience gained from the BilSat-1 flight experiment but also on results from extensive testing of the RRS01 at SSTL. The resulting MIRaS-01 module used on current SSTL missions is shown in Figure 8. This module performs a number of other functions as part of SSTL AOCS sub-systems, providing a CAN interface to Reaction Wheels, Star Trackers and other sensors, consequently the Inertial Sensor electronics is only a fraction of that on the processing board.

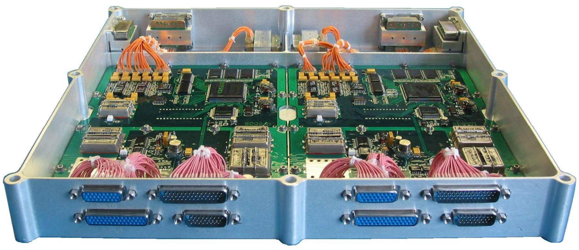

Figure 8: Cold-Redundant Pair of Flight-Ready MIRaS-01 Modules

The RRS01 rate sensor bandwidth is >50Hz, with most of the noise power concentrated at higher frequencies. The IS module processing board samples these sensors through a low-pass analogue filter with a bandwidth of 10Hz, which greatly reduces to the noise to 0.01deg/sec/rt-Hz. Samples are taken at 10Hz by an FPGA, which is able to output attitude rates at lower frequencies by time-averaging samples. This configuration gives a flat power spectral density below 10Hz. An Allan Variance plot of this output is shown in Figure 9. An alternative configuration is to use a digital filter in the FPGA to further reduce the noise where a lower bandwidth output is acceptable.

The bias instability of the RRS01 rate sensor is 3deg/hour and this is unaffected by the processing in the IS module. This is confirmed by the minimum of the Allan Variance plot in Figure 9. Allan Variance tests have also shown that the bias stability is typically <10deg/hour over one hour.

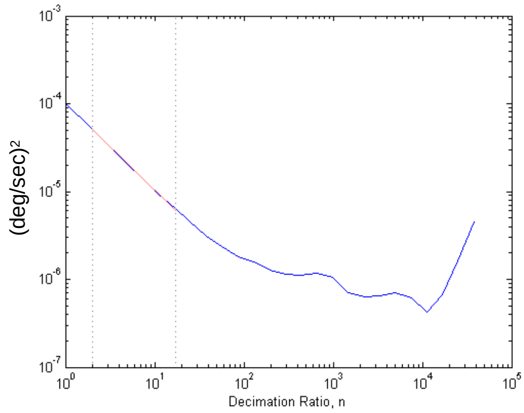

Figure 9: Allan Variance Plot of 1Hz time-averaged output (raw sampling at 10Hz)

The MIRaS-01 takes advantage of the temperature sensors inside each RRS01 rate sensor to compensate for bias variation with temperature. With this in place the RMS variation is less than 180deg/hour over the module's operating temperature range of -20degC to +50degC. Figure 10 shows the Y-axis output of the IS Module during a rotation table test at +/-3.0 deg/sec with the module operating at the upper end of its temperature range. It is clear that the bias thermal effects seen on BilSat-1 have been compensated for effectively.

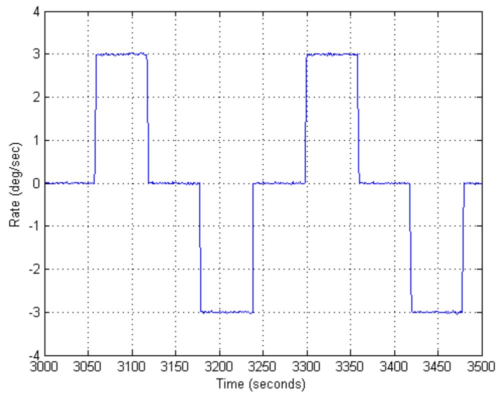

Figure 10: IS Module Rate Output at +50degC with Temperature Compensation

The MIRaS-01 incorporates an internal clock to drive the FPGA. This clock can be synchronized to either of two cold-redundant PPS inputs to support accurate timing of rate measurements. The primary data interface is via a C515C microcontroller, used to support CAN, although the module can also communicate over RS422 and RS485.

RELIABILITY OF PERFORMANCE

The 6mm diameter sensor ring is fabricated from bulk crystalline Silicon. The overall MEMS die size is 10mm by 10mm giving 56 devices on a 4 inch wafer.

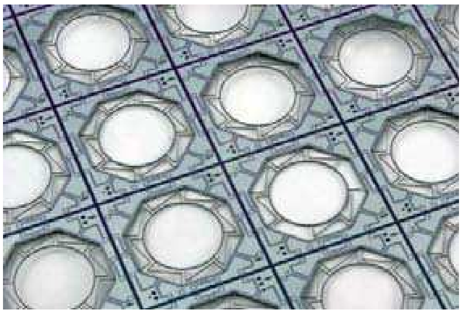

Figure 11: Silicon Wafer with Sensor Rings

The fabrication process includes oxidation and patterning followed by metal deposition of the electrodes. The ring is formed by Deep Reactive Ion Etch (DRIE). This is a critical process that determines the repeatability of the resonator dimensions. Attachment to the pedestal glass is by anodic bonding. Laser balancing of the ring ensures that the resonant frequency in the two principle axes are matched. The magnet and pole piece are bonded in place. Wire bonds to the terminals are made prior to magnetisation. The case is evacuated and the cover sealed in place by projection welding.

Resonators are produced by the million for the commercial market. Performance of the RRS01 is guaranteed by selecting from the upper percentile.

To ensure reliability units are subjected to highly accelerated stress screening prior to calibration and final test.

QUALIFICATION OF SPACE IS MODULE

The RRS01 resonator has been qualified for a number of military applications including guided munitions. The silicon ring is inherently strong and its low mass enables it to survive launch shocks in excess of 20,000g.

Several flight builds of the MIRaS-01 module have successfully undergone mechanical load testing, with overall random vibration levels in excess of 15gRMS. In addition this module is currently being qualified to 25gRMS. The module is mechanically very rugged and there are no concerns over the RRS01 rate sensor thanks to its extensive qualification for extremely demanding loads.

The MIRaS-01 operates with full performance over all of its operating temperature range of -20degC to +50degC. This has been demonstrated over many cycles of the full range on several units. There is no active thermal control, with heat dissipation of high-power components and the RRS01 rate sensors being managed passively. The passive thermal control has been validated in Thermal-vacuum testing.

The RRS01 sensor is hermetically sealed in its Kovar case and so does not out-gas in vacuum conditions such that there is no effect on performance in a vacuum. The MIRaS-01 processing board has a very low Total Mass Loss in a vacuum. Thermal-vacuum testing of previously delivered modules has confirmed that there is no degradation when operating in a vacuum.

Radiation testing of the RRS01 sensor has demonstrated that it is tolerant to Total Ionizing Dose (TID) levels typically seen in Low Earth Orbit without any shielding. Figure 12 shows the change in the noise output of a MIRaS unit with its three RRS01 sensors exposed to varying doses. It can be seen that for doses of up to 20Krad the change is marginal. All the components on the processor board have good flight heritage from previous SSTL missions. All the units built for the LEO missions described below are packaged in 2mm thick aluminium, which provides further shielding. Additional tolerance to TID can be provided by thickening these walls for use in more harsh environments.

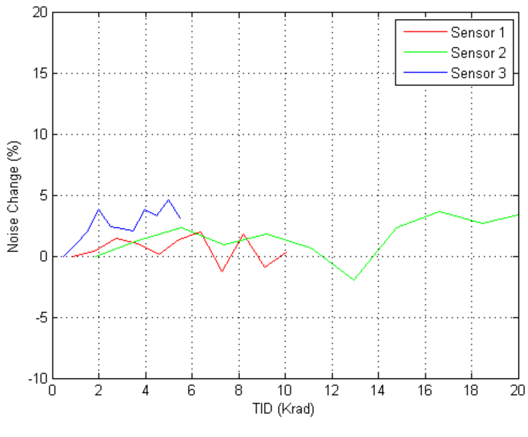

Figure 12: Affect of TID on rate noise

Several MIRaS-01 modules have undergone EMC testing as part of system-level tests and there have been no signs of interference effects. Furthermore, there is an ongoing activity to undertake full EMC characterization of the module according to MIL-STD-461E.

APPLICATION OF IS MODULE TO MISSIONS

The MIRaS-01, incorporating the RRS01 rate sensor, is being flown on a number of missions where it is being used in different ways. Cold-redundant pairs have already been delivered for two Kanopus platforms (Figure 13) with a third currently undergoing test. This Earth observation platform uses the MIRaS-01 for its Sun acquisition mode.

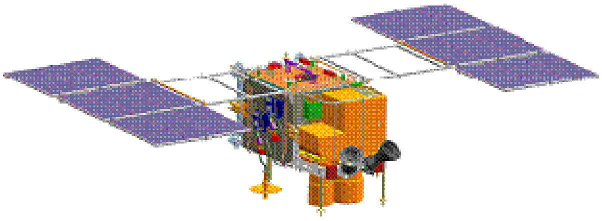

Figure 13: Kanopus

The SSTL-300 platform incorporates a pair of MIRaS-01 modules, which it uses for supplementing star tracker measurements during high-rate slews for agile imaging operations. NigeriaSat-2[5,6], the first SSTL-300 mission, is undergoing its final stages of test and will be flight-ready later this year.

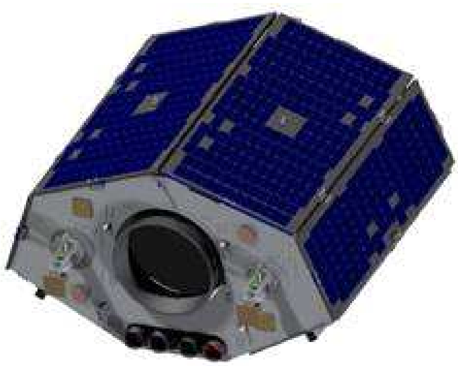

Figure 14: NigeriaSat-2

The MIRaS-01 is also being flown on GökTürk-2, although in this case the mechanical housing has been made more compact (Figure 15) with two cold-redudant modules stacked rather than placed side-by-side.

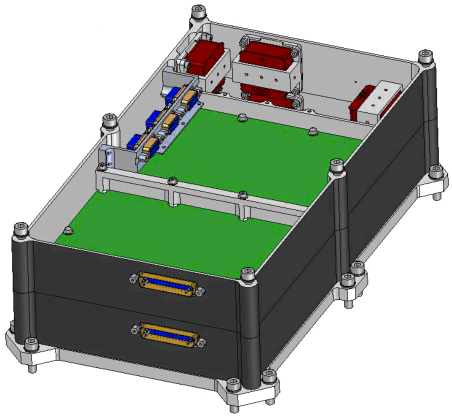

Figure 15: GokTurk-2 IS Module

EVOLVING TECHNOLOGY

Recently the RRS01 resonator design has been improved by the addition of a second conductor track which doubles the signal to noise ratio of the sensor. This together with an improved calibration process over temperature has resulted in the new higher performance RRS02.

The RRS02 has the same mechanical and electrical interfaces as the RRS01, and so can be incorporated directly into the current MIRaS design to improve noise performance. Furthermore, a more compact version of the processor board is being developed with the CAN interface for other sensors and actuators removed. This will create a far more compact, lightweight unit that makes the most of the miniaturized MEMS technology.

CONCLUSIONS

MEMS is an area of rapid development at the present time, with obvious application to small satellites owing to the miniaturization that this technology allows. Some MEMS technologies such as the RRS01 rate sensor are now mature, production technologies that are in widespread use in terrestrial applications. Until recently the use of MEMS technology in the space context was predominantly experimental. Now, however, the MIRaS-01 is a proven, production Space Inertial Sensor, with several modules delivered for flight, and more in build. Furthermore, due to the continuing advances in MEMS sensor performance this module will soon be succeeded by a higher performance successor, building on the success of the MIRaS-01.

REFERENCES

1. Fouquet, M and Sweeting, M.N. "UoSAT-12 MiniSatellite for High Performance Earth Observation at Low Cost," Proceedings of the 47th International Astronautical Congress, Beijing, China, 1996.
2. Cropp, A., Collingwood, C. and Dussy, S. "The Characterization and Testing of MEMS Gyros for GIOVE-A," Proceedings of the AIAA GNC, Keystone Colorado, 2006.
3. Johnston, G., Holt, A. and Jackson, C. "An Experience from Verification to Flight," Proceeding of the 7th ESA GNC, Ireland, 2008.
4. Gomes, L.M., da Silva Curiel, A., Bradford, A., Lappas, V., Oosthuizen, P., Cropp, A. Sweeting, M.N., Yuksel, G. "BILSAT: Advancing Smallsat Capabilities," Proceedings of the 17th AIAA/USU Conference on Small Satellites, Logan, Utah, Aug. 11-14, 2003.
5. Cawthorne, A.D., Lawal, A., Carrel, A.R., Beard, M., Richardson, G. "Launching 2009: The NigeriaSat-2 mission – High-performance Earth observation with a small satellite," Proceedings of the 22nd AIAA/USU Conference on Small Satellites, Logan, Utah, 2008.
6. Cawthorne, A.D., Lawal, A., Carrel, A.R., Sweeting, M.N. "NigeriaSat-2 – The High-performance small satellite programme at the service of Nigeria," Proceedings of the 59th International Astronautical Congress, Glasgow, UK, 2008.