3-AXIS MICRO GYROSCOPE FEASIBILITY STUDY

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Abstract / Introduction

Astrium Ltd has carried out a feasibility study for a space qualified micro gyroscope based on the commercial-of-the-shelf MEMS rate sensor SiRRS01-04 developed and manufactured by BAe Systems.

An analysis of the current/near-term space market for gyroscope equipments across a wide spectrum of missions was carried out, and from this an assessment of the application potential and realistic production rate for a MEMS-based Gyro Package has been performed.

Having identified the target application market, the study developed a preliminary set of technical requirements for a MEMS Gyro Package based on the known characteristics of the SiRRS01-04 rate sensor. Based on this specification, an equipment-level design and trade-off exercise took place, leading to the selection of a baseline design concept. This baseline was then analysed with respect to its mechanical, thermal, radiation and reliability performance. Within the design exercise, a clear policy of seeking to exploit existing COTS BAe Systems rate sensor components was followed, rather than proposing that a space-specific component should be developed.

The selected baseline concept for the MEMS Gyro Package is for a integrated equipment incorporating three standard BAe Systems SiRRS rate sensors (mounted along three mutually orthogonal axes) together with the necessary compensation and data interfacing electronics, and local power conditioning in order to ensure the new product is easily incorporated into current spacecraft electrical system architectures.

Analysis of the baseline concept shows that the proposed design can satisfy all requirements set for the MEMS Gyro Package, and that a viable basis from which a commercially attractive flight qualified product can be developed, has been found.

Rate Sensor Utilisation by Market Area

A market survey [1] aimed at investigating the application potential of MEMS gyroscopes for different types of missions was performed. This survey analysed the AOCS architectures most commonly used in a number of missions falling into the categories listed below:

- GEO Telecom
- ESA Science
- LEO Earth Observation
- Micro Satellites
- GALILEO Constellation

A particular consideration was given to the role played by on-board gyro sensors in the main mission phases. This allowed the identification of a number of typical gyro applications across a wide range of missions. These gyro application classes, considered as separated from each other, together with their estimated relative utilisation are summarized below:

Gyro Classes	Utilisation (% of all classes)
Acquisition	10%
Transfer	28%
Orbit Control	28%
Normal Mode	20%
Safe Mode	8%
Failure/anomaly Detection	6%

Table 1: Gyro classes and utilisation

A set of key gyro performance requirements was defined for every class. This, together with the knowledge of the existing gyro market, has been used to define a method of placing a market value (cost) on gyro performance and applications or classes. This is graphically represented in the chart below:

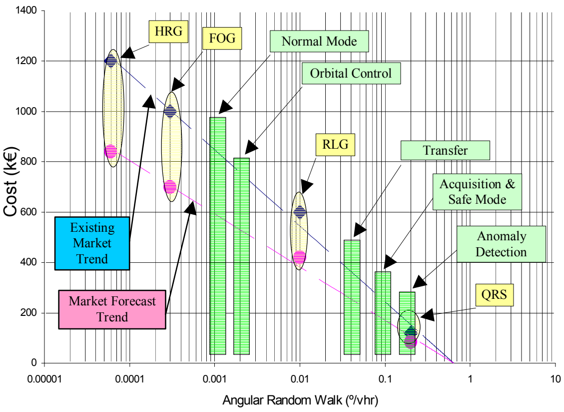

Figure 1: Cost vs. gyro performance and class

The two trends shown represent the existing gyro market and the expected market in 4 to 5 years (estimated saving of 30%).

Rate sensing element: BAe SiRRS01-04

The preselection of the BAe System SiRRS01-04 as the rate-sensing element presents a key constraint on the realistic scope of the micro gyro package requirement specification. BAe Systems (Plymouth) silicon micromachined gyroscope (developed in partnership with Sumimoto Precision Products) is based on a silicon micromachined oscillating ring and it comes as an individually packaged stand-alone unit comprising the resonator ring with integrated drive and signal conditioning electronics as shown below:

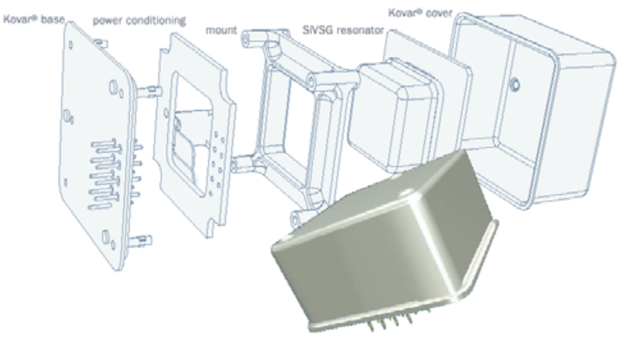

Figure 2: SiRRS01-04 packaging

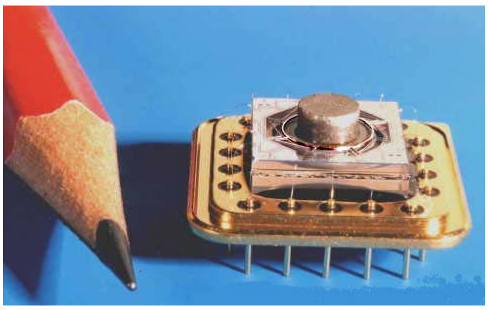

Figure 3: Sensor head ring resonator

Parameter	Performance
Rate Range (°/s)	± 25
Rate Bias (°/s), 1σ	0.3
Bias variation with temperature (°/s)	± 3.0
Bandwidth (Hz)	35
Noise in band (°/s), 1σ	0.15
Noise PSD (°/s/√Hz), 1σ	0.0025
Angular Random Walk (°/√hr), 1σ	0.15
Rate Bias Stability (°/hr), 1σ	7
Size (mm)	32 x 17 x 32
Mass (kg)	0.04
Power (W)	0.6

Table 2: SiRRS01-04 key parameters

Target Specification

In order to quickly identify the space applicability of this sensor, consistently with the previous sections, the key performance parameter Angular Random Walk has been used to locate the SiRRS performance within the space gyro classes defined previously. This is graphically represented below:

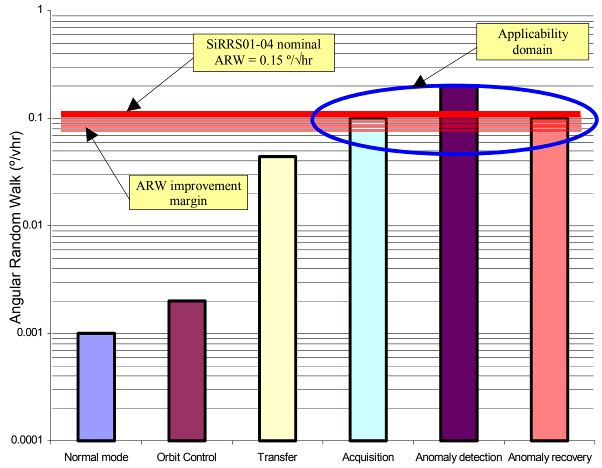

Figure 4: SiRRS01-04 performance vs. gyro classes

The performance improvement margin represented here is based on the potential rate noise reduction achievable by digital filtering.

This assessment shows therefore that the potential space market for the BAe SiRRS01-04 rate sensor appears to focus on three typical mission phases:

- Anomaly detection
- (Initial) acquisition
- Anomaly recovery / safe mode

MEMS Gyro Requirement Specification

The performance requirement analysis for each of the targeted mission phases has shown that the Acquisition phase and the Anomaly Recovery or Safe Mode can be represented by a single set of requirements while Anomaly Detection application has its own dedicated requirement set. The following table summarizes the main performance requirements for the MEMS gyro applicable to Anomaly Detection (AD) and Acquisition and Safe Mode (ASM):

Requirement	Value
Measurement Range	± 10.0 °/s
Measurement sensitivity	3-axes
Rate Null bias	< 0.5 °/s
Angular Random Walk	< 0.2 °/√hr

Table 3: Micro gyro performance requirements, AD

Requirement	Value
Measurement Range	± 20.0 °/s
Measurement sensitivity	3-axes
Rate Null bias	< 0.04 °/s
Angular Random Walk	< 0.1 °/√hr

Table 4: Micro gyro performance requirements, ASM

The main system requirements have been also identified. These are typically environmental and physical requirements that apply for both the Anomaly Detection and the Acquisition & Safe Mode classes. Key environmental elements are radiation and vibration/shock levels.

Typically equipment used in spacecrafts is characterised in terms of tolerance to the total (End Of Life) radiation dose without external additional shielding. The average level of expected radiation the micro gyro would experience during various types of missions ranges from 0.03 to 600 krads depending on orbit, altitude and mission lifetime (from 3 to 15 years). A trade-off has to be made between covering as many missions as possible and the level of complexity, cost and mass introduced to achieve high level of radiation tolerance.

Spacecraft equipment has to be designed to withstand sinusoidal & random vibrations and shocks whose levels are set depending on launcher type and equipment location within the spacecraft. Compared to other similar launchers the Ariane 5 introduces the highest level of vibrations and accelerations and vibration & shock analysis conducted for previous/existing missions have been used to estimate the worst level of vibrations and shocks.

The physical requirements have been driven mainly by market considerations and targeting potential competitors. The drive has been, therefore, to define a set of requirements that represented a considerable saving, in terms of mass, size and power, from existing similar products. The table summarizing the key system requirements is presented below:

Requirement	Value
Total EOL radiation dose	15 krads
Mission Lifetime	3 years
Sinusoidal vibration	±12mm, 5 to 20Hz 20 to 30g, 20 to 100Hz
Random vibration	3dB/octave, 20 to 100Hz 0.5 to 1.0 g^2/Hz, 100 to 2000Hz
Mass	< 1.2 Kg
Dimension	< 150x150x150 mm
Power	< 5.2 W

Table 5: Micro gyro system requirements

Initial Concept Development

The analysis of possible design concepts or functionalities has been performed with the objective of optimising a number of design drivers: Cost, Mass and Performance. This activity has focused mainly on the definition of the main capabilities or operational features the micro gyro should include in order to satisfy the requirements set for the Anomaly Detection (AD) and the Acquisition and Safe Mode (ASM) class gyros defined previously.
The following table summarizes all the main features considered applicable to the micro gyro:

Gyro Feature
Digital processing
Internal Temperature Compensation (Digital)
Rapid Warm-Up (< 3 sec)
Selectable (set) Dynamic Range
Selectable (set) Bandwidth
Internal drift compensation storage (Digital)
Self Test (Output validity, range check)
Interfaces: digital, RS422
Interfaces: digital, Mil Std 1553
Interfaces: digital, Spacewire
Interfaces: analogue
Power Conditioning: Primary Bus 28V
Power Conditioning: Secondary Bus 5V
Test Stimulation Port
Optical alignment cube
Internal Temperature Management
Latch-Up Free / SEU Tolerance

Table 6: Micro gyro applicable features

The adoption of different sets of features for the AD or ASM classes depends on the different performance and functional requirements imposed on them. The implementation of these features, however, can be based on either one of the following architectures:

- Analogue: this, potentially, offers lowest cost and performance solutions. It restricts the number of features that can be included but its inherent simplicity means that a high level of reliability and less susceptibility to Single Event Upset (SEU) and Latchups
- Digital: this, instead, offers highest cost and performance solutions. Its main advantage is that it can enable a high degree of integration and miniaturization of various functionalities which would be unachievable with an analogue design. The design of a digital device, however, needs to address issues related to Single Event Upsets (SEU) and other radiation-induced problems.

Considering, however, the high degree of similarity between the AD and the ASM classes it is possible to foresee a single, modularised configuration that can satisfy both applications. Furthermore at an AOCS system level the integration of a 3 (at least) analogue channels gyro package would require a higher level of complexity than a digital one. It has been envisaged, therefore, that a digital design concept is used as the baseline design with a number of optional features that can be individually integrated in order to expand gyro performances and applicability:

Baseline Gyro Features
Digital processing
Internal Temperature Compensation
Selectable (set) Dynamic Range
Selectable (set) Bandwidth
Interfaces: digital, RS422
Power Conditioning: Primary Bus 28V
Latch-Up Free / SEU Tolerance
Optical alignment cube

Optional Gyro Features
Interface: Mil Std 1553
Self Test (Output validity, range check)
Test stimulation port

Table 7: Micro gyro baseline design configuration

Baseline Design Development

The high level design of the micro gyro has been produced following the initial concept development. The micro gyro consists of four main functional parts:

- **Power Conditioning**: it converts the input power (28V) into the appropriate regulated and filtered voltage level required by rate and temperature sensing elements and the circuitry.
- **Rate and Temperature sensing**: it detects angular rates on 3 mutually orthogonal axes and temperature. These are provided by the BAe System SiRRS01-04 rate sensors.
- **Digital Conditioning**: it acquires and amplifies the analogue outputs from the SiRRS01-04 rate sensors in order to achieve the required rate range and resolution. It then digitises these signals and performs temperature bias compensation. Temperature compensated rate data are then appropriately filtered to achieved the required bandwidth.
- **Data I/F**: it formats output messages and transmits them via the digital serial interface RS422.

The baseline electrical interface design with the main functional blocks is represented below (power conditioning is not shown):

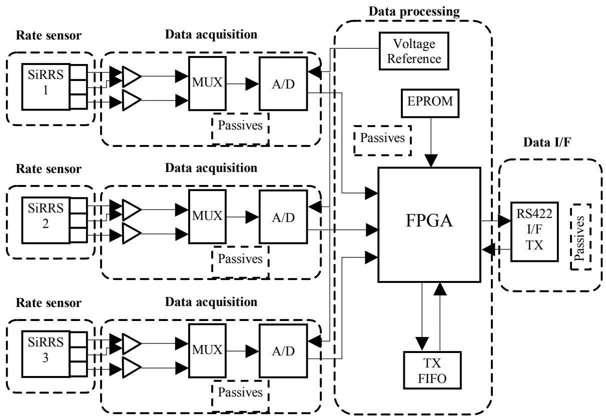

Figure 5: Micro gyro electrical circuit block diagram

The analogue rate and temperature outputs from each SiRRS sensor are acquired via operational amplifiers, and routed to a single A/D converter via an analogue multiplexer. This structure is effectively replicated for every rate sensor. The outputs from the three A/D converters are connected to the FPGA running the main processing and calibration processes necessary to achieve the performance targets set previously.

During this preliminary stage a trade-off has been made for the processing unit between a FPGA and an ASIC. The main consideration taken into account is that cost and flexibility play a critical role in the development of new equipment and preference has been given to the particular device that allows greater flexibility as provided by FPGAs at lower costs. Recent design practices, however, allow transferring VHDL designs, tested on FPGAs, to ASICs in case the latter is selected for the final implementation.

An initial design for the micro gyro packaging layout has been produced. During this process various layouts have been considered. Each of them shows different locations for the main components and different structural architectures. The location of the SiRRS rate sensors is the main identifying feature that characterises each layout. The only common approach used for all layouts is to keep the power supply sub-system separated from the other electronics. This approach should minimize signal interference with the rate sensor drive circuitry and the various digital conditioning circuits. Power dissipation can also be optimised without affecting other sub-systems. Off-the-shelf space qualified power supplies such as the Advanced Analog/M-3 L-Series DC/DC converter are included in this design.

In order then to identify the baseline package layout a trade-off between them has been made using a number of technical and feasibility related selection criteria and the selected packaging layout is presented below showing the micro gyro and its main internal components:

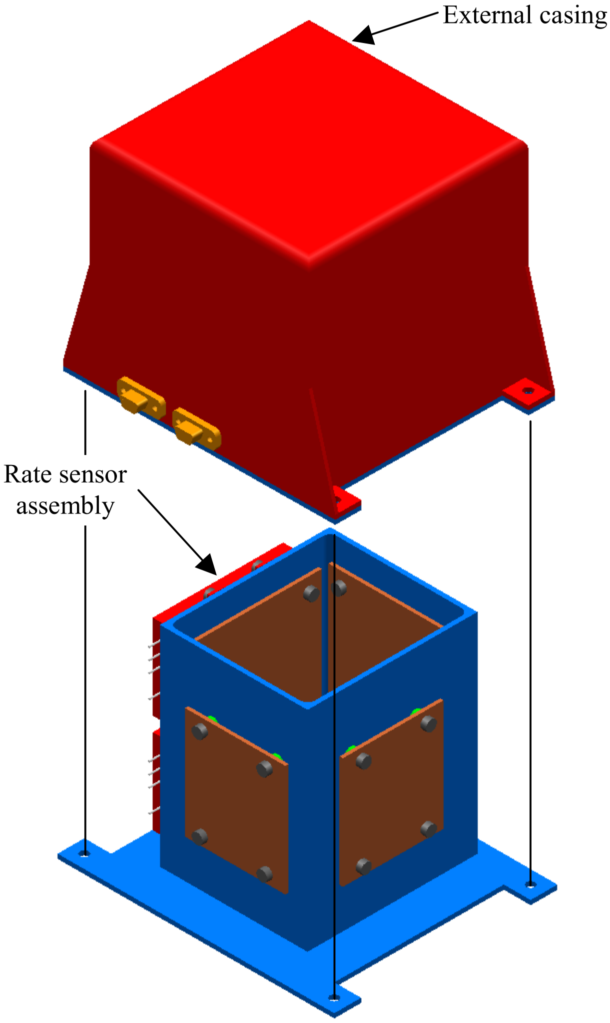

Figure 6: Micro gyro packaging layout

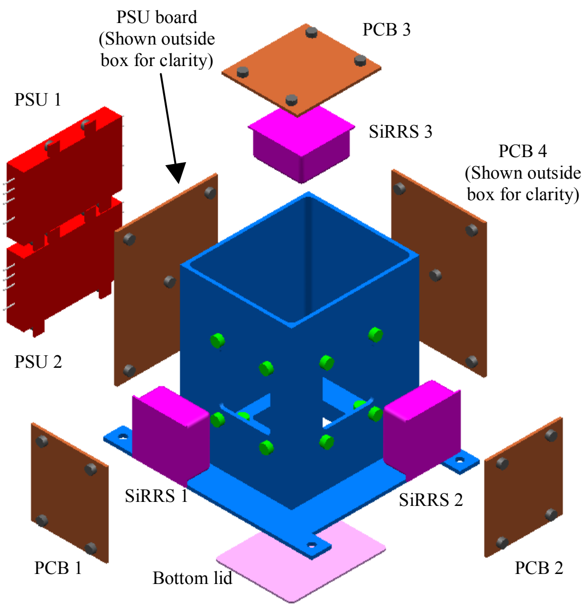

Figure 7: Exploded view of the rate sensor assembly

The baseline packaging concept has the following main components:

- **Rate sensor assembly**: main central body (in Aluminium) that holds the three rate sensors and provides support for the various PCBs. It consists of a horizontal baseplate with an integral perpendicular box section, all machined from aluminium alloy. The rate sensors are mounted inward and covered by PCBs. The power supplies are mounted on one external face of the rate sensor assembly.
- **External casing**: single machined casing made of aluminium that encloses the assembly, fitted with power and data connectors. It provides radiation shielding to the sensitive gyros and other components.
- **Five PCBs**: these support all acquisition, processing and I/F electronics.

Budgets

Based on the electrical interface design and the mechanical layout design a preliminary budget table has been drawn up and is presented below together with the baseline requirements:

Parameter		Budget	Requirement
Power	Nominal	4.78 W	< 5.2 W
	Maximum	11.46 W	
Mass	Nominal	1080 g	< 1200 g
	Maximum	1107 g	
Dimensions		10x10x10cm	< 15x15x15cm

Table 8: Micro gyro baseline design budget

Preliminary Analyses

A number of analyses have been carried out in order to verify the micro gyro proposed design compliancy with other system and performance requirements. The outcome from any analysis would be used for further design re-iterations or modify any assumption that has been made during this preliminary design process.

The **stress analysis** has performed random vibration tests and a sub-set of the shock tests whose limits were derived from the system requirements. Results have shown that the proposed design has high level of structural integrity and structural mass saving could be achieved without affecting its integrity (structural mass accounts for 66% of total mass).

The **thermal analysis** has been performed to verify that the internal temperature of the main parts was within the allowable limits when the micro gyro baseplate was subjected to the maximum operational temperature (60 ºC). Results have shown that the thermal dissipation path for the rate sensors is not optimal and can be improved by design.

The **radiation analysis** has focused on the radiation effects on the SiRRS rate sensors (non space qualified) as all the other electronics would be space qualified and radiation hardened. The aim of this analysis has been to demonstrate that the proposed design can satisfy the system requirements bearing in mind that the maximum allowable total dose on the rate sensors has been set to 3 krads.
The results have shown that passive radiation hardening via SiRRS shielding is effective for most LEO Earth Observation missions whose orbit is below 1000 km altitude and most Science missions considered in the study while it is unsuitable for more radiation demanding missions such as MEO constellations and GEO telecomm.
Radiation hardening is obviously a main design driver for this micro gyro.

The **reliability analysis** has focused on determining the micro gyro MTBF and reliability with the simple Parts Count method. The estimated MTBF is 286448 hours and system reliability by the end of the target 3 years mission is 0.912338. Main contributors to system reliability are the SiRRS sensors and the PSUs.

The **performance analysis** has provided a preliminary assessment of the benefits of the thermal bias compensation and the noise filtering. This has been done by simulating the post-acquisition digital processing block functionality with a mathematical model.

The model of the digital processing block is represented below:

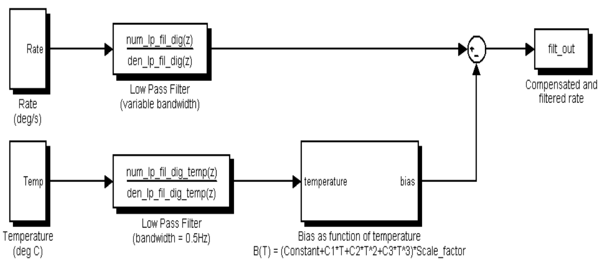

Figure 8: Micro gyro post-acquisition processing

The results have shown that by reducing the bandwidth of the SiRRS rate sensor, the rate output noise decreases as expected and to a lesser extent angular random walk as summarized in the following table:

Bandwidth (Hz)	Output noise reduction	ARW reduction
35	18%	2%
20	42%	6%
10	65%	9%
5	80%	11%
2	90%	17%

Table 9: Digital filtering performance

In practical terms a simple digital low pass filter with bandwidth between 2 and 5Hz (typical for space applications) would reduce ARW to a 0.10 - 0.13º/√hr range which would meet the 0.1 - 0.2º/√hr noise requirement identified previously.

The analysis has also assessed the effects of the thermal bias compensation. The results have shown that the residual bias after thermal compensation ranges from 0.001º/s to 0.03º/s over the full temperature range. The performance requirement for this parameter is between 0.07º/s (or less) and 0.5º/s.
This analysis, however, has not addressed issues related to bias repeatability (with potentially hysteresis effects) and bias thermal stability. The latter one is related to the more general issue of sensor characteristics degradation. These issues would be fully analysed in any further micro gyro development.

Conclusions

The market assessment has indicated a MEMS based rate sensor device can meet the Anomaly Detection and Acquisition/Safe Mode mission needs.
A viable product design has been identified and developed featuring the BAe SiRRS01-04 gyros as the rate sensing elements.
The micro gyroscope main baseline design characteristics are summarized below:

Characteristics	Value
Number of axes	3
Residual Null Bias	< 0.03º/s
Angular Random Walk	< 0.13º/√hr
Bias Stability	< 0.7º/hr
Mass	1.080kg
Dimensions	100x100x100mm
Power Interface	28V
Power Consumption	4.78W
Data Interface	RS422
Total EOL radiation dose	3 Years on LEO (≤ 1000km) and Science

Table 10: Micro gyro baseline design characteristics

Analysis of the baseline design shows that the proposed design can satisfy all requirements set for the Anomaly Detection (AD) and Acquisition/Safe Mode (ASM) gyro classes. Two main observations can be made at this stage:

- The stress analysis has shown that micro gyro is a very solid structure and structural mass optimisation could be achieved without affecting its stiffness.
- The radiation analysis has identified the limits of this design in terms of mission applicability. Passive radiation of the current BAe SiRRS rate sensors allows the micro gyro to be safely employed on a considerable number of missions but precludes its application on potentially high volume GEO telecom and MEO constellation missions. Moreover radiation hardening drives the mass of the system. In the case the radiation hardened SiRRS rate sensor becomes available then it can be easily included in the current micro gyro design with minimal re-design activity.

In view of some of the analysis results, some key investigations are suggested before any further design and development of the micro gyro equipment:

- Radiation effects on BAe SiRRS rate sensors to be accurately investigated and documented. Batch testing would be preferred.
- Detailed radiation analysis to be performed on the designed micro gyro and structure layout and mass to be optimised.
- Performance analysis to be expanded in order to investigate various digital filters and thermal compensation techniques.
- Batch full thermal screening (repeated cycles) of BAE SiRRS rate sensors to investigate bias repeatability and bias thermal stability.

Finally a development plan has been produced with the following milestones:

- Sensing element characterisation & qualification in 6 months
- Product prototyping (breadboard) in 16 months (duration 10 months)
- EQM manufacture and qualification in 31 months (duration 15 months)
- FM production duration 12 months (including LLI procurement)

Acknowledgement:

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References

1. Prezzavento, A M., *Micro Gyroscope Feasibility Study*, Final Report, GNC/TNO/2056, Issue 1, December 2002