ESA Study Contract Report

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ESA Contract No:	SUBJECT:	CONTRACTOR:
4000114602	MR Angular Sensor for Space Applications	RUAG Space Germany GmbH (former HTS GmbH)
ESA CR () No:	No. of Volumes: 3 This is Volume No: 2	CONTRACTOR'S REFERENCE: MR2-RSG-RP-005

ABSTRACT:

EXECUTIVE SUMMARY

The objective of the "MR Angular Sensor for Space Applications" (ESA Contract No. 4000114602) is to develop and qualify an MR based contactless angular position sensor for at least one potential space application in order to achieve swift and efficient entry into market. To prepare this, the first objective is to consolidate and finalize the technical requirement specification of the MRS, based on a relevant reference application which will be identified, and specified in close cooperation with a potential user.

Subsequently, the second objective of this project is to develop, build and test the MRS sensor concept at breadboard level. Two breadboard (BB) models and several tests are foreseen to validate the measurement and signal conditioning concept.

Ultimately an Engineering Qualification Model (EQM) of the MRS sensor system shall be built and qualification tests shall be performed, in order to achieve TRL 6. The qualification tests to be performed include functional performance tests at ambient and thermal vacuum, vibration and shock tests, electro-magnetic compatibility and electro-static discharge tests (EMC, ESD) as well as outgassing tests.

The work described in this report was done under ESA Contract. Responsibility for the contents resides in the author or organisation that prepared it.

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DIRECTORATE: Directorate of Technology, Engineering and Quality (TEC)	

MRS Phase 2
Executive Summary

MR2-RSG-RP-005

Signatures & Approval

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1 GENERAL

1.1 Scope

This document summarizes the tasks performed and the results achieved during the ESA GSTP study "MR Angular Sensor for Space Applications", carried out under ESA contract No. 4000114602. The project was lead by RUAG Space Germany (former HTS GmbH) in cooperation with Sensitec GmbH, and lasted from October 2015 to December 2018.

This report covers the following aspects:

- Background and objectives of this activity
- Requirement Specification
- Preliminary Design and BB Activities
- Detailed Design and EQM Manufacturing
- EQM Testing
- Lessons Learned
- Conclusion and Future Development

1.2 Change record

Iss./Rev.	Date	Responsible	Description of change
1 / 0	07.12.2018	T. Schmidt	Initial Issue

1.3 Referenced Documents

RD 1	MR2-HTS-RS-002 I2R0 TN1.1 MRS System Requirements
RD 2	MR2-HTS-VCD-001 I6R0 TN1.2 Design Verification and Compliance Matrix (DVCM)
RD 3	MR2-HTS-TN-001 TN1.3 Trade off and identification of potential application
RD 4	MR2-HTS-DD-001 I2R0 TN2.1 Preliminary Design and Analyses
RD 5	MR2-HTS-AN-001 I2R0 TN2.2 FMECA
RD 6	MR2-HTS-PL-002 I4R0 TN2.3 Design Development and Test Plan

RD 7	MR2-HTS-DD-002 I1R0 TN3.1 Breadboard Selection, Design and Analyses
RD 8	MR2-HTS-PL-003 I2R0 TN3.2 Breadboard Test Plan
RD 9	MR2-HTS-RP-002 I2R0 Test Report-Component, Subsystem and Breadboard
RD 10	MR2-HTS-DD-003 I2R0 TN 4.1 Critical Design and analyses
RD 11	MR2-HTS-PR-003 I2R0 TN5.1 EQM test procedure - Physical Properties
RD 12	MR2-HTS-PR-004 I2R0 TN5.1 EQM test procedure - Functional and Performance
RD 13	MR2-HTS-PR-005 I2R0 TN5.1 EQM test procedure - Environmental
RD 14	MR2-HTS-RP-007 I1R0 TN5.2 EQM Assembly & Integration (Pre-test inspection report)
RD 15	MR2-RSG-RP-003 I1R0 Test Report-EQM (incl. TN 6.1, TN 6.2, TN 7.1)
RD 16	MR2-RSG-TN-002 I1R0 TN7.1 Roadmap

1.4 Applicable Documents

AD 1	ESA Contract 4000114602 “MR Angular Sensor for Space Applications”

1.5 Abbreviations

AD	Applicable Document
ECSS	European Cooperation for Space Standardization
EMC	Electro-Magnetic compatibility
EQM	Engineering qualification model
EUT	Equipment under test
MRS	Magneto resistive sensor
RD	Reference Document
RSG	RUAG Space Germany GmbH
SST	Sensitec GmbH
VCD	Verification control document

2 PROJECT OVERVIEW

2.1 Background of the Project

The concept which formed the baseline for the development, production and testing of the MRS EQM represents one of the concepts which have been jointly developed by HTS and SST during the TRP feasibility study performed in 2013/2014.

The MRS will use patented, magneto-resistive chips developed and built by Sensitec that have been used in a variety of system solutions. Individual system solutions are the core business of the system development at SST. In addition, hard ferrite rings are used in multiple applications as a measurement scale. Sensitec has the capability of writing magnetic tracks onto these rings.

Incremental encoders have been developed by Sensitec for customer-specific industrial applications with distinct signal conditioning options.

2.2 Objective

The ultimate objective of the performed project was to develop and qualify an MR based contactless angular position sensor for one potential space application in order to achieve swift and efficient entry into market.

To prepare this, the first objective was to consolidate and finalize the technical requirement specification of the MRS, based on a relevant reference application which will be identified, and specified in close cooperation with a potential user.

Subsequently, the second objective of this project was to develop, build and test the MRS sensor concept at breadboard level. Two breadboard (BB) models and several tests are foreseen to validate the measurement and signal conditioning concept.

Ultimately an Engineering Qualification Model (EQM) of the MRS sensor system should be built and qualification tests shall be performed, in order to achieve TRL 6. The qualification tests to be performed include functional performance tests at ambient and thermal vacuum, vibration and shock tests, electro-magnetic compatibility and electro-static discharge tests (EMC, ESD) as well as outgassing tests.

2.3 Study Logic

The work logic performed activity, including the milestones, is shown in form of a flow chart in **Figure 2-1**.

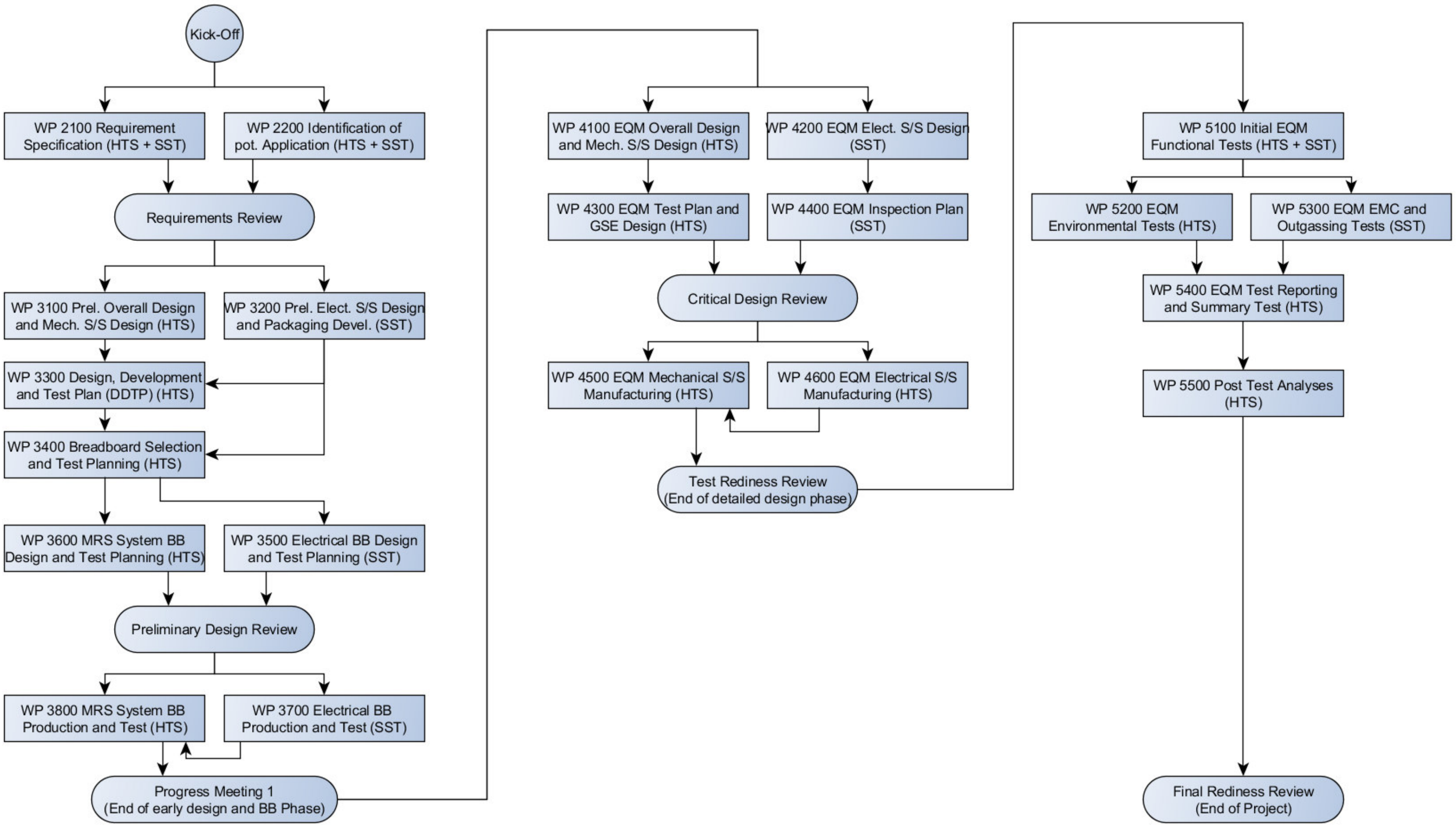

Figure 2-1: Flow chart for the activity

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3 TECHNICAL ACHIEVEMENTS

3.1 Requirements

The requirements at the project start were further developed throughout the project. This took into account the discussion with potential customers as well as the experiences gained during the BB Phase. The following table is the final version of the specification which was used for verification at EQM level. The given compliance statement indicates if the verification could be successfully performed within this activity. However NCs and PCs are often related to either deficiencies of the test or to partial compliance of either analogue or ABZ signals. For details refer to test results (RD 15)

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No.	Document Title / Requirement No.	Requirement	Requirement Justification/ Background/ Comment	R	A	T	I	compliance
1	**REQUIREMENTS**							
1.1	**MISSION REQUIREMENTS**							
1.2	**OPERATIONAL REQUIREMENTS**							
1.2.1	**Autonomy and Fault Management**							
	MRS-SY-052	For telemetried elements in redundancy, the loss or failure of one chain shall not prevent access to the telemetry of the other chain.	requirement to ensure reliability	X	X			C
1.2.2	**Operability / Command ability**							
	MRS-SY-053	The MRS shall allow for 5000 switch ON/OFF operations during on ground testing and in orbit lifetime	engineering judgement for minimum expecable performance			X		C
1.2.3	**Time Management Requirements**							
1.2.4	**Software Operational Requirements**							
1.3	**FUNCTIONAL REQUIREMENTS**							
1.3.1	**System Modes and States**							
	MRS-SY-049	The MRS System shall have the following operational modes and states: - OFF (no power required, no signal delivered) - ON (operational power demand, angular signal delivered)	general requirement allowing OFF mode with no need for continius power supply	X		X		C
1.3.2	**Specification of Functions**							
	MRS-SY-050	The MRS System shall provide a signal allowing determination of the relative angle between a rotor and a stator.	main functional intend	X		X		C
	MRS-SY-054	The MRS System shall provide a once per revolution reference pulse to allow for a position recovery of the mechanical system it is attached to (rotor/stator).	Reference with sufficient accuracy/repeatability	X		X		C
1.3.3	**Software Functional Requirements**							

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No.	Document Title / Requirement No.	Requirement	Requirement Justification/ Background/ Comment	R	A	T	I	compliance
1.4	**CONFIGURATION REQUIREMENTS**							
1.4.1	**Component / Equipment Breakdown**							
	MRS-SY-051	The MRS System shall be broken down into the following subsystems: - mechanical subsystem (including: housing, shaft interface, external harness and connectors) - electrical subsystem (including: sensor, signal conditioning, pole ring)	system break down	X				C
1.4.2	**Interchange ability**							
	MRS-SY-023	All parts or subassembly having the same identification number shall be functionally and dimensionally inter-changeable. They must be of the same qualification status and reliability to meet interchangeability requirements.	general design requirement	X				C
1.4.3	**Modularity**							
	MRS-SY-080	The MRS System shall be able to support the following pole ring dimensions: - outer diameter 38 … 72 mm - inner diameter ≥ 30 mm - width ≥ 6.5 mm	outer and inner diameters based on request from customer A, width is based on the required magnetic track width for 2 tracks (incremental and reference)	X				C
1.4.4	**Accessibility**							
1.5	**PERFORMANCE REQUIREMENTS**							
1.5.1	**Mechanical Performance**							
	MRS-SY-055	The MRS shall not induce any friction or magnetic resistive torque between rotor and stator.	The sensor shall not have an impact on the motorization of the mechanism it is attached to	X		X		C
	MRS-SY-056	The MRS System shall allow free rotation of the rotor without limitation.	allows mounting to systems with travel range >360°; or side	X		X		C

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No.	Document Title / Requirement No.	Requirement	Requirement Justification/ Background/ Comment	R	A	T	I	compliance
			use as rev. counter					
1.5.3	**Operational Performance**							
	MRS-SY-010	The MRS System shall have a measurement range of 360 degrees without dead zone.				X		C
	MRS-SY-012	The MRS System shall provide an incremental angular measurement with a once-per-revolution reference pulse.		X		X		C
	MRS-SY-013	The MRS System shall provide an angular resolution of: - better than 10 bits (threshold) - better than 12 bits (goal)	Customer A consultation: application requirement is 10bit			X		C
	MRS-SY-014	The MRS System shall provide an angular measurement repeatability of better than 0.1° under operational environmental conditions.	Absolute accuracy replaced by repeatability after discussion with customer A			X		PC
	MRS-SY-083	The linearity error of the MRS System shall be less the +/- 0.1°. Note: the linearity error is defined as the instantaneous difference between the MRS angular position to a ideal linear reference (e.g calibrated reference encoder with at least one magnitude higher resolution/accuracy).	Absolute accuracy requirement splitted into linearity and repeatability to fully specify the performance			X		PC
	MRS-SY-076	The MRS system shall provide a hysteresis for a ABZ signal in the range of 0.02° to 0.1°. Note: Hysteresis has to be considered when reversing the rotation direction. Hysteresis is a constant offset between angular	Hysteresis refers to the difference in the pulses when reversing the rotational direction. It shall prevent unintendet generation of signal at static posittion (e.g. caused by me-			X		NC

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No.	Document Title / Requirement No.	Requirement	Requirement Justification/ Background/ Comment	R	A	T	I	compliance
		signal in CW and CCW direction.	chanical vibrations of the concerning mechanism)					
	MRS-SY-084	The MRS system shall have a hysteresis at analogue signal less than 0.002°. Note: Hysteresis has to be considered when reversing the rotation direction.	hysteresis of analogue signal shall have no considerable influence on the position uncertainty budget			X		C
	MRS-SY-018	The MRS System shall be compatible and provide full measurement performance up to a nominal angular speed of 100 rpm (threshold); 1000rpm (goal) Note: In order to achieve sufficient accuracy when sampling the signal, at least 10 samples per 0.1° should be considered.	Customer A consultation:application requirement is 10rpm; to allow for high speed applications a goal of 1000 rpm will be considered; TS: Thresold increased to 100 rpm what seems achievable with the new measurement setup			X		C
	MRS-SY-071	The MRS System shall be compatible with and provide full measurement performance up to an angular acceleration of steady up to 120°/s^2	Customer A input.			X		C
1.5.4	**Electrical Performance**							
1.6	**CALIBRATION AND CHARACTERIZATION REQUIREMENTS**							

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	MRS-SY-024	The MRS System shall be characterized prior to delivery and the relevant certificates shall be provided for: - Offset between nominal and redundant reference puls with knowledge better than 0.1° - Hysteresis of angular signal when reversing rotation direction	Characterization process TBD. To be clarified if possible within the goal price!				X	C
	MRS-SY-057	The parameters representing the thermal and thermo-elastic behaviour of the MRS System shall be characterized and documented for each unit.	To ensure good quality and to keep track of potential error/failure sources			X		C
	MRS-SY-077	The resulting magnetic moment of the MRS shall be characterized.	from user consultation customer A			X		NC
1.7	**QUALITY AND DESIGN REQUIREMENTS**							
1.7.1	**Electrical and EMC Design**							
	MRS-SY-025	The MRS System shall contain 1N + 1R electrical subsystem, which shall be galvanically separated to provide cold redundancy.	Derived from MRS-HTS-TN-001 Results from user consultation phase 1 question 9. To be clarified if possible within the goal price!	X			X	C
	MRS-SY-026	Derating Requirements and Application Rules for Electronic Components, ESA ECSS-Q30-11A, shall be considered during design.	General requirement for space equipment.	X				C
	MRS-SY-058	Each MRS System component shall be electrical connected to ground, e.g. by provision of a grounding point or by metallic contact. NOTE: For applicable grounding	ESD requirement	X		X		C

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		values refer to ECSS-E-ST-33-01C Mechanisms §4.7.7.5 Grounding						
	MRS-SY-059	The design shall allow power to be switched off without previous notice and without damage.		X		X		C
	MRS-SY-060	The offset between the nominal and the redundant reference pulse shall be known and provided in order to restore the full operational performance after switching from nominal to redundant measurement system.	It shall be possbile to restore the full operational performance after switching from nominal to redundant measurement system.			X		C
	MRS-SY-061	The MRS shall be equiped with a non-transposable connector preventing polarity confusion. Note: "wrong polarity may result in severe damage" will be placed in the user manual	TBC by Sensitec	X		X		C
	MRS-SY-079	The electromagnetical compatibility shall be in conformance with requirements specified in ECSS-E-ST-20-07		X		X		C
1.7.2	**Thermal Design**							
1.7.3	**Structural Design**							
	MRS-SY-011	The first eigen-frequency of the MRS System shall be >200Hz (for modes with an effective mass or inertia > 10%)			X	X		C
1.7.4	**Mechanism design**							
	MRS-SY-063	The MRS System shall not need any internal locking	Generic design requirement to ease	X		X		C

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No.	Document Title / Requirement No.	Requirement	Requirement Justification/ Background/ Comment	R	A	T	I	compliance
		during launch.	application					
1.7.5	**Optical Design**							
1.7.6	**Software Design**							
1.7.7	**RAMS Requirements**							
	MRS-SY-020	The MRS System shall a reliability of > 0.9999 with a confidence level of 95%.			X			C
1.7.8	**Design and Development of the Product**							
	MRS-SY-021	The recurring costs of the MRS System shall be less than 10000 EUR.		X				C
	MRS-SY-029	The MRS System shall be completely ITAR free.	Derived from MRS-HTS-TN-001 Results from user consultation phase 1question 3.	X				C
1.7.9	**Marking**							
	MRS-SY-030	Each separately identifiable part or subassembly shall carry an identification consisting of at least the following information: - Identification number - Item title - Model identification - Serial number	QA requirement	X				C
1.7.10	**Radiation**							
1.7.11	**Ergonomics**							
1.7.12	**Lifetime**							
	MRS-SY-002	The MRS System shall allow for on ground storage of 15 years.	Customer A input: 15yrs is current ESA demand		X			C
	MRS-SY-003	The in orbit operational lifetime of the MRS System shall be > 15 years			X			C
1.7.13	**Manufacturing**							

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	MRS-SY-031	All external surfaces of flight hardware (including structural elements but excluding alignment references, if so) shall have a surface treatment which shall prevent corrosion of the surface.	Generic requirement for space equipment	X				C
1.7.14	**Parts, Materials, Processes**							
	MRS-SY-032	All materials used for the MRS System shall comply with the requirements of ECSS-E-ST-33-01C.	Generic requirement for space equipment	X				C
	MRS-SY-035	The MRS System shall be compliant with the ECSS outgassing values: Application TML [%] RML [%] CVCM [%] General applications < 1 n.a. < 0,1 Optical device applications n.a. < 0,1 <0,01	Generic requirement for space equipment	X				C
	MRS-SY-081	The MRS System shall be compliant to ReaCh and RoHS requirements	To be compliant with future missions	X				C
1.7.15	**Cleanliness**							
	MRS-SY-033	As a general rule, each MRS System shall be compliant to at least ISO 8 cleanliness requirements at delivery.	Generic requirement for space equipment	X				C
	MRS-SY-034	The MRS System and shall allow for cleaning to higher cleanliness levels than ISO 8, e.g. by means of manual cleaning with isopropyl alcohol or ultrasonic cleaning.	Generic requirement for space equipment	X				C
1.7.16	**Space DEBRIS Mitigation**							
	MRS-SY-067	The MRS System shall not release any lose parts when in orbit	Space debris mitigation rules	X				C
1.8	**ENVIRONMENTAL REQUIREMENTS**							

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1.8.1	**Ground Operation, Integration and Test**							
	MRS-SY-036	The MRS System shall allow testing flight conditions and levels simulated during ground tests with operational performance (i.e. thermal-vacuum, vibration testing).	generic requirement	X				C
	MRS-SY-072	The MRS system shall be able to operate in an N2 environment during on ground testing.	to be compatible to mechanism on ground tests under N2 atmosphere	X		X		C
	MRS-SY-082	The MRS system shall be designed to comply with quasi static load levels of 39 g.	Design load definition based on sine and random spectrum given by customer A		X			C
	MRS-SY-015	The MRS System shall sustain the following sine vibration qualification loads (all directions, not simultaneously) - 5-20 Hz: +/-11 mm - 20 - 100 Hz: 34.5 g (goal 39g)	Customer A suggests that loads at e.g. motor shaft ends may reach up to 100g, Specification shall consider 20g simultaneously in all directions -> ~34.5g ; HTS mechanism tests with cantileverd motor suspension resulted in 26g rms, a 50% incease will be taken for goal value; Compatible with customer B application requirements.		X	X		PC
	MRS-SY-016	The MRS System shall sustain the following random vibration qualification loads (all directions, not simultaneously) - 20 - 60 Hz: +9 db/oct. - 60 - 400 Hz: 0.5 g^2/Hz - 400 - 2000 Hz: -6 db/oct. - Global: 18.4 grms	Compatible with customer B application environment.		X	X		C

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No.	Document Title / Requirement No.	Requirement	Requirement Justification/ Background/ Comment	R	A	T	I	compliance
	MRS-SY-017	The MRS System shall sustain the following shock levels qualification loads (all directions, not simultaneously, Q =10) - 100 Hz: 50 g (goal 80g) - 1000 Hz: 1500 g (goal 2000g) - 10000 Hz: 1500 g (goal 4000g)	Goal values from user consultation customer A and B; feasibility to be checked			X		C
1.8.2	**Launch**							
	MRS-SY-038	The MRS System shall sustain the environmental condititions during launch without permanent performance degradation.	Thermal conditions, depressurisation, launch vibrations (covered by qualification loads?)		X	X		C
	MRS-SY-078	The MRS System shall sustain pressure change rates up to 2kPa/s.	User consultation: Custumer B requirement		X			C
1.8.3	**In Flight**							
	MRS-SY-037	The MRS System shall be fully operational in vacuum.				X		C
	MRS-SY-005	The MRS System shall be fully operational and perform without any performance degradation within a temperature range from -50°C to +100°C.			X	X		C
	MRS-SY-006	The MRS System shall sustain a non-operational temperature range from -60 to + 110°C				X		C
	MRS-SY-007	The MRS System shall sustain a total ionizing dose (TID) of 250 krad during in orbit life.				X		C
	MRS-SY-008	The MRS System shall sustain a proton flux of 2e11 protons/cm2 at 50 MeV.	Derived from MetOp SG radiation hardness assurance plan			X		C
	MRS-SY-009	The MRS System shall be robust against SEE effects.		X				C

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	MRS-SY-073	The MRS System shall sustain a maximum homogeneous magnetic field of 1kA/m during operation	Based on SST simulation		X	X		C
	MRS-SY-074	The MRS System shall sustain a maximum inhomogeneous magnetic field of 0.1(kA/m)/mm during operation	Based on SST best practise and experience		X	X		C
1.9	**VERIFICATION REQUIREMENTS**							
1.10	**PA REQUIREMENTS**							
	MRS-SY-040	At delivery of an MRS System, the following documentation shall be provided - Serial number - Certificate of Conformance - DCL, DML, DPL - Interface Control Drawing - Verification report - Installation Guide, including electrical schematic for connector wires	Required documentation to be discussed with JOP, ESA, etc.	X				C
1.11	**GROUND SUPPORT EQUIPMENT REQUIREMENTS**							
2	**INTERFACE REQUIREMENTS**							
2.1.1	**Physical Requirements**							
	MRS-SY-001	The mass of the MRS System shall be below: 200g threshold; 150g goal.	based on preliminary mass breakdown 150g seems demanding; customer B requirement 200g	X		X		NC
2.1.2	**Mechanical Interfaces**							

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	MRS-SY-045	The mechanical S/S shall fit within the following envelope: Baseline is hollow shaft configuration: -inner diameter: 30mm -outer diameter: 120mm -height: 25mm Alternative end of shaft configuration: -shaft diameter:5mm -outer diameter: 50mm -height: 40mm	Application custumer A requirement: diameter 50mm / height 40mm; Application custumer B requirement: diameter 75mm / height 25mm; feasibility to be confirmed	X		X		PC
	MRS-SY-046	The MRS System shall provide the following mechanical I/F to an external rotor shaft: - clamp ring	To be defined by JOP application	X				C
	MRS-SY-047	The MRS System shall provide the following mechanical I/F to the mechanism: - 3 point screwed connection	To be defined by JOP application	X				C
	MRS-SY-066	The interface to the mechanism shall allow for radial, and axial adjustment in the range +/- 0.5mm each.	the adjustment range will be adapted close to the range for operational allowable airgap	X		X		C
	MRS-SY-068	The MRS System shall provide full performance considering mechanical tolerances of the system it is mounted to up to: - shaft radial runout 0,05mm (goal 0.1mm) - shaft axial runout 0,05mm (goal 0.1mm)	preliminary assessment of sensor performance			X		C
2.1.3	**Thermal Interfaces**							
2.1.4	**Optical Interfaces**							
2.1.5	**Electrical Interfaces**							
	MRS-SY-019	The MRS System shall have a power consumption lower than 150 mW	Based on preliminary power consumption analysis, Compatible		X	X		C

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No.	Document Title / Requirement No.	Requirement	Requirement Justification/ Background/ Comment	R	A	T	I	compliance
		during operation.	with customer A application.					
	MRS-SY-041	The MRS System shall be compliant with the following input voltages: - 5 V DC (bipolar)	Derived from MRS-HTS-TN-001 Results from User Consultation question 23. 3.3 V limits the possible OpAmps, therefore limit I/F to 5 V (TBC) Compatible with customer A application.	X		X		C
	MRS-SY-042	The MRS System shall be compliant to all performance requirements with a limited maximum current of 0.15 A.	Derived from MRS-HTS-TN-001 Results from User Consultation question 23.	X	X	X		C
	MRS-SY-043	The MRS System shall be compatible to one of the following external interface types - Differential TTL with 0-5V signal level (Baseline) - Analogue pre-amplified sine-cosine 1V peak to peak signal (+/-0.5V) (alternative output depending on application)	Derived from MRS-HTS-TN-001 Results from User Consultation question 21. Compatible with customer A application.	X		X		C
	MRS-SY-070	The MRS system shall sustain and shall provide full performance with an input voltage deviating by up to 2% voltage (peak to peak).	feasibility to be checked			X		C

3.2 Design and Testing Activities

The design and development was split into two phases. In the first phase the design of the sensor unit was elaborated up to a Breadboard status. This was intended to allow for gathering comprehensive technical knowledge and experience in the following testing phase. Mechanical parts were manufactured using advanced manufacturing methods.

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Along with the MRS hardware the design of the testing equipment was performed. A specifically suited test stand comprising a small thermal vacuum chamber with motorised mechanical feedthrough was developed and built (Figure 3-1).

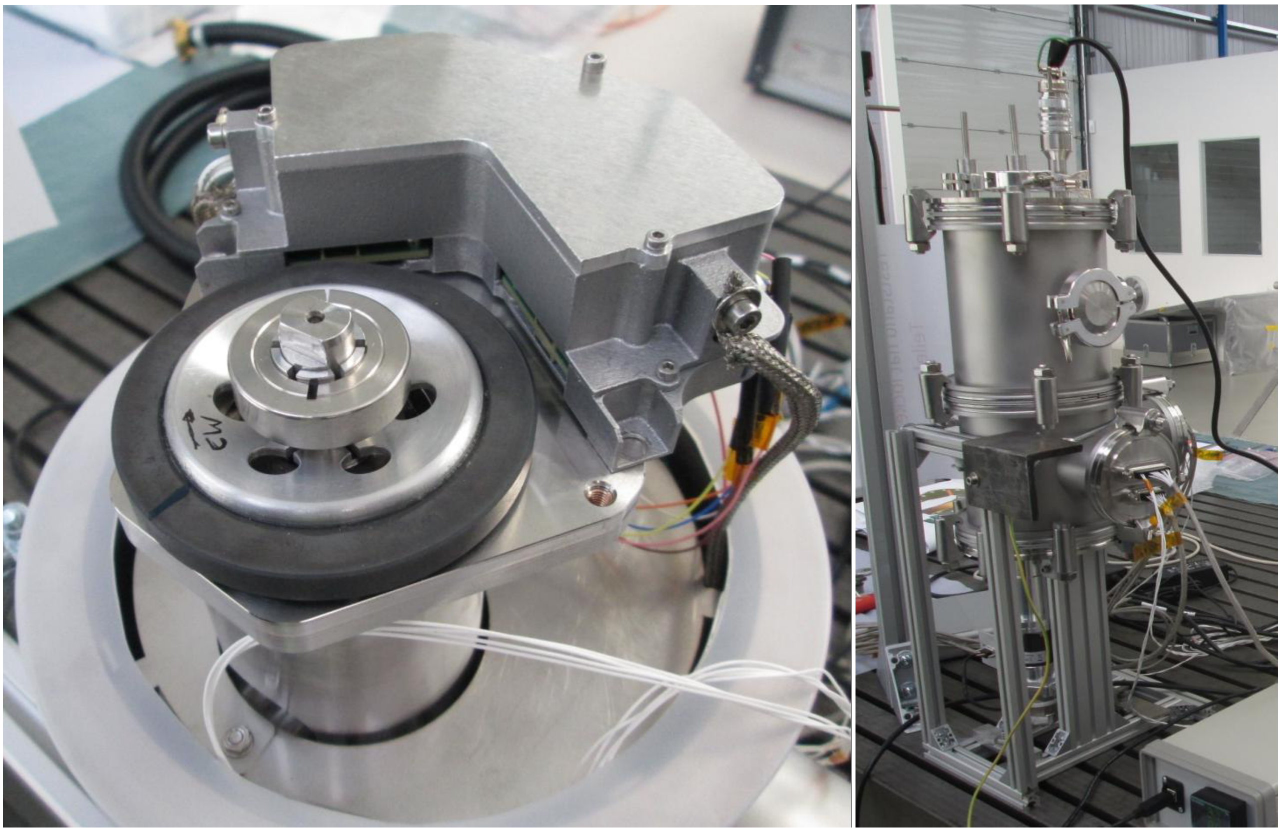

Figure 3-1 MRS BB and test stand

Based on BB lessons learned and discussions with potential customers the EQM design was developed in a more modular approach. The development of a hermetic ceramic package (LTCC) was started in parallel. The design was following the goal to apply space qualified processes and used space qualified components as far as possible. This resulted for instance in the high radiation hardness of the sensor module of 300krad. The EQM Design comprises three main components: A rotor assembly which is providing the magnetic measure scale, a sensor assembly which is generating a differential sin/cos signal from varying magnetic field direction and a signal assembly which converts the analogue to a TTL output, respectively an ABZ signal interface.

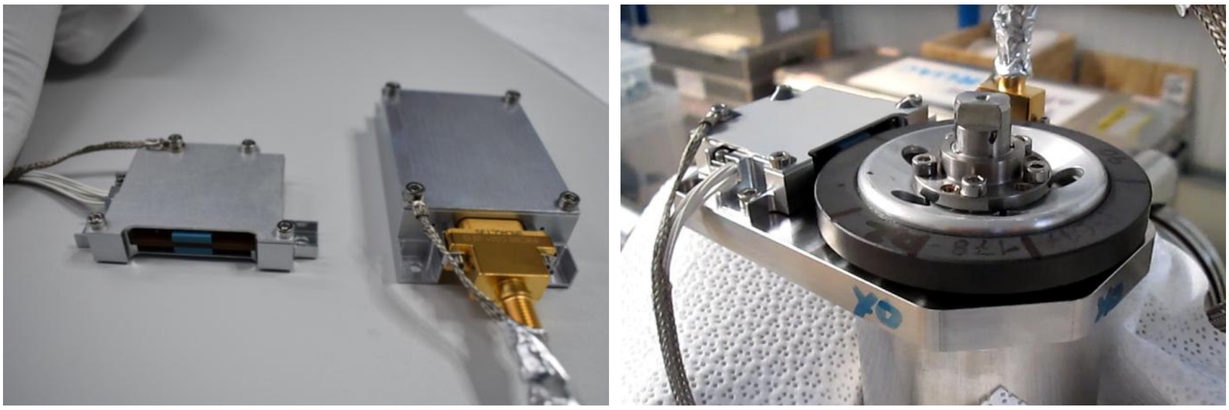

Figure 3-2 Sensor ASM and Signal ASM / MRS during performance test

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In the frame of this activity extensive development and testing was performed. This resulted in a comprehensive knowledge and insight in the MR technology capabilities. The use for space application was especially explored by specific testing of environmental compatibility such as radiation, vibration, shock, thermal vacuum.

Also the tests of characteristics of the Sensor unit, such as air gap to the magnetic measure different angular speeds, etc., completed the picture of this measurement principle. A test flow is given in Figure 3-3 and Figure 3-4.

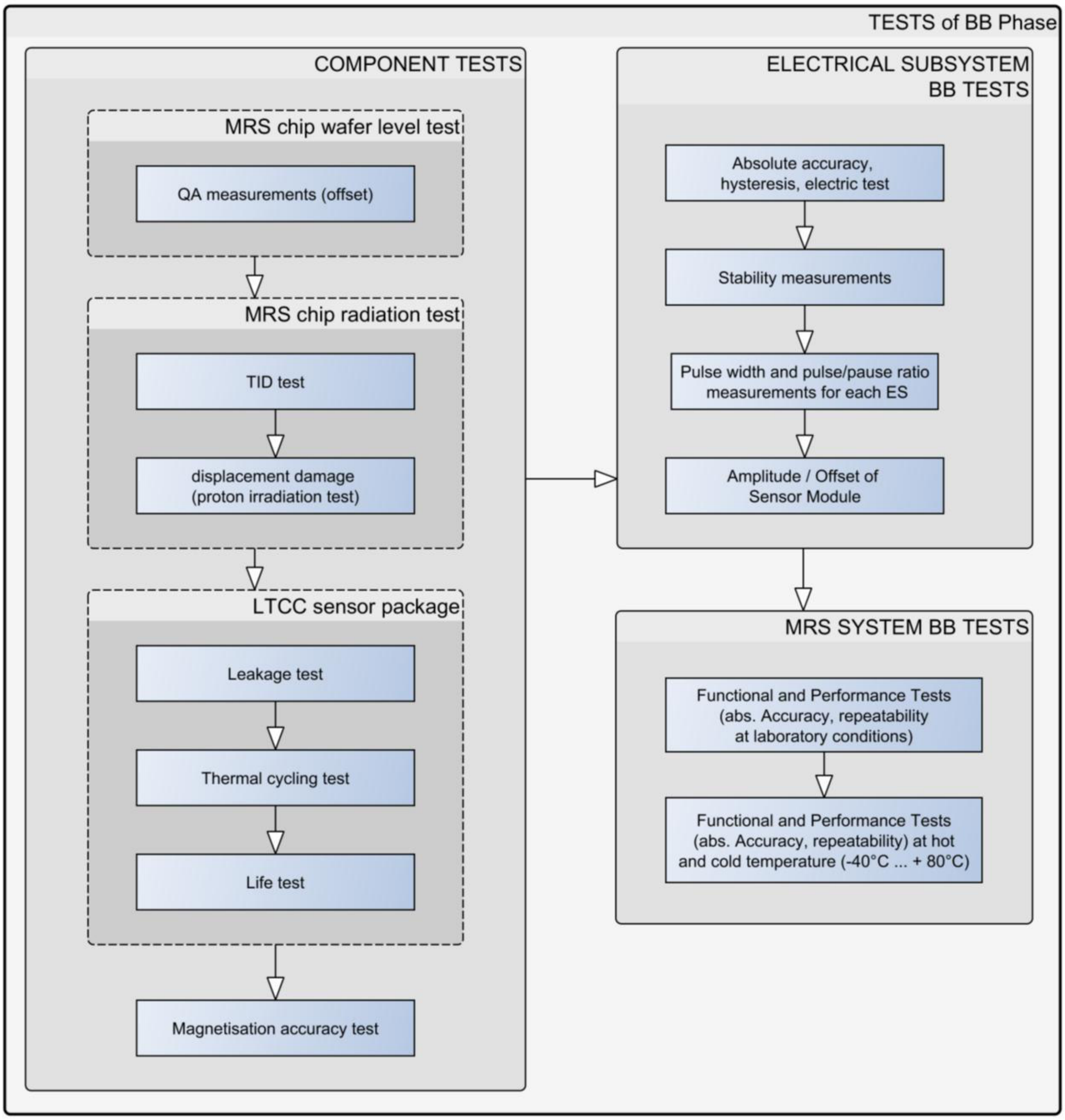

Figure 3-3 BB testing phase

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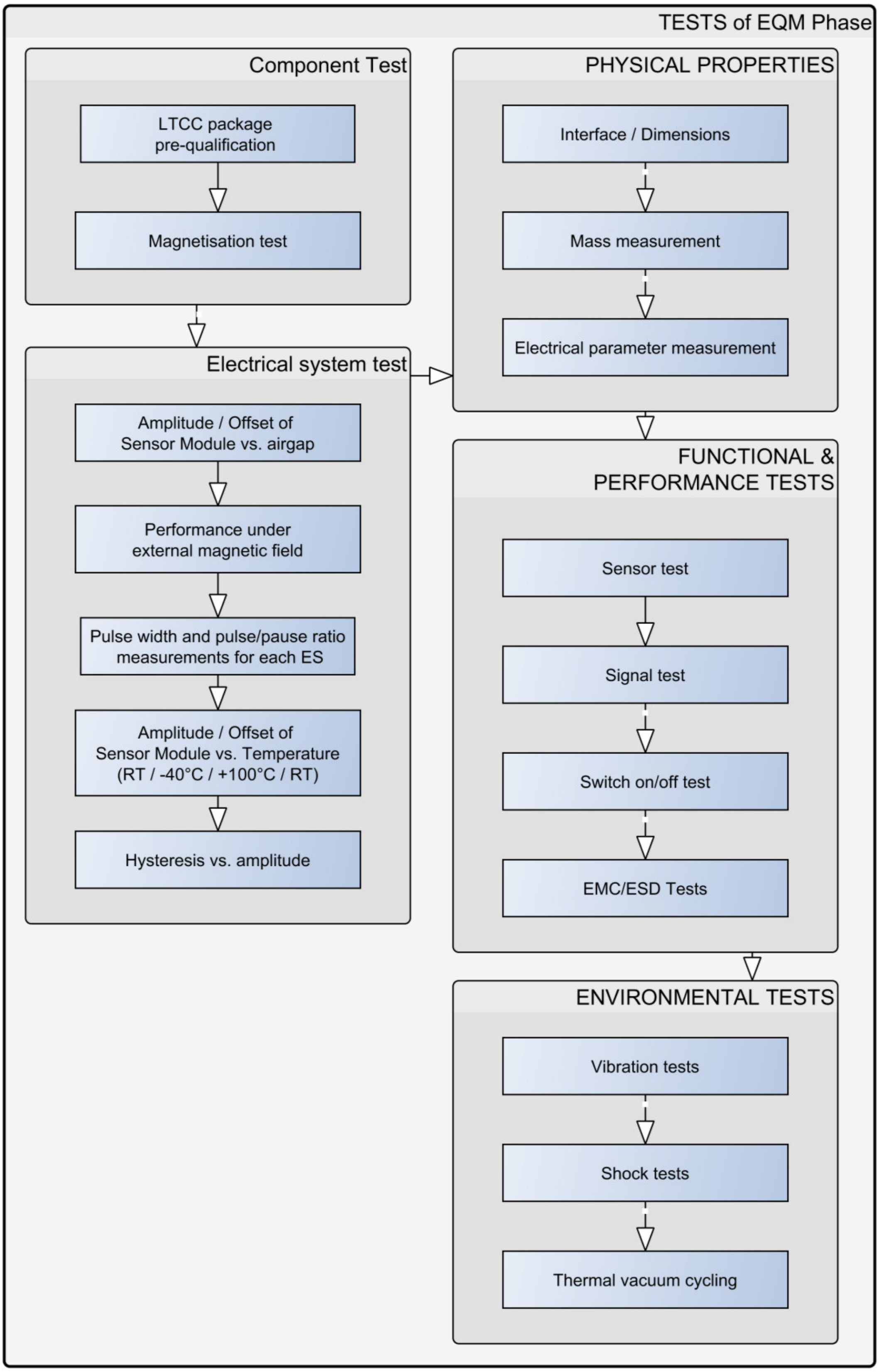

Figure 3-4 EQM testing phase

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3.3 Lessons Learned

- The Sensor performance (analogue signal) is higher than expected. It provides highly accurate measurement of the existing magnetic field direction and high repeatability. During testing it was shown that it can survive and operate under harsh environmental conditions. It therefore seems well suited for space applications and may serve also for other measurement applications.
- There are two dominant sources of errors identified: First these are mechanical errors of the pole ring such as eccentricity and roundness. Second the magnetisation of the incremental track, specifically at the start stop overlap. By decreasing these detrimental factors the performance may be increased significantly. It is also not investigated how these error sources influence each other (e.g. eccentricity during magnetisation) Mechanical errors could be decreased by precision grinding the pole rings prior to magnetization. This shall be considered also for further work.
- In general, ABZ signal is much less performing than analogue signal. Here not the discretization by a comparator circuit is meant, but hysteresis and the corresponding relationship to signal amplitude, respectively temperature.
- The reference track in combination with the GMR sensor provides a precise, repeatable signal with steep flanks. This might be well suited for other applications too (e.g. switches).
- The supply chain in project was too long and should be limited to less companies.
- Lead tines for electronics and the procurement of HiRel ICs in small quantity is putting a schedule risk on the development, especially in case of occurring NCs. Lead time of EEE components are typically around 14-26 weeks compared to in-stock items of most industrial parts. Long lead times are especially true for European EEE parts. Lead times for PCBs are around 4-6 weeks compared to 2 weeks or even 2 days express for industrial grade PCBs
- The package technology rather soon focused on LTCC although later, aluminium packages as used on a qualified line by Thales Alenia Space could prove to be more suitable in terms of costs , also it was found that hermeticity as a requirement is not actually needed; Alternatively COTS packages might be suitable as well
- For the specific case of the MR sensor inside the LTCC package, no ECSS / ESCC standard as such was found applicable
- For a market suitable product a non-hermetic package/assembly with a tailored lot acceptance test seems to be more fitting than a strict ECSS approach
- The simulaneous measurment of all channels including a reference system (Renishaw) with high resolution was needed. This generated a huge amount of data to be evaluated. Evaluation scripts were running partly more than 24 hours per data file. Here a improvement of data analytics, and / or consider proper digital pre-processing directly while measuring is indicated.
- The preparation of adequate evaluation routines / scripts shall always include a programming flow chart.
- Thermal cycles took extremely long and are extremely energy consuming (potentially due to poor thermal energy exchange with test specimen. Therefore the cold case temperature not reached during all test cycles. Establishing a hot/cold table with conductive heat transfer seems more efficient.
- In general the Renishaw reference sensor is well suited, but at higher speeds with given sampling rate the performance is not sufficient to verify the repeatability requirement of the test article
- Eccentricity measurement has to be improved, because of high influence on over all performance. The mechanical failure is supposed to be a combination of eccentricity and roundness tolerances, because the failure cannot be fully removed by a sinus curve fitting.

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4 CONCLUSION AND FUTURE DEVELOPMENT

The MRS2 activity has shown that this technology is fit to provide a medium accuracy angular measurement system for space applications. There is even potential for higher accuracy identified in case some of the main failure contributors (eccentricity, magnetization) can be eliminated or reduced. Extensive testing on component, subsystem and unit level has been successfully sustained.

However the market readiness is impaired by the costly production approach with fully space grade processes and components. Especially the development of the LTCC hermetic package revealed that a COTS approach for the MR sensor implantation is reasonable in terms of cost. The BB which was tested at extreme temperatures and in vacuum used a COTS SIL package and showed no signs of degradation. This is a promising basis for next development steps to increase marketability.

The plan for further development of the MRS includes the following tasks:

1. Identification and selection of a suitable off-the-shelf package for the MRS (also assess if an off-the-shelf MR sensor from Sensitec would already be suitable)
2. Consolidate and upgrade the MRS sensor board layout and select the required COTS EEE parts for the MRS
3. Consolidate and upgrade the MRS Rotor design and magnetization
4. Select suppliers for EEE parts and PCB
5. Select supplier for PCB assembly
6. With PCB assembly supplier, define and develop the manufacturing processes
7. Perform evaluation testing and lot acceptance testing of an initial „pilot“ production lot (10 – 50 units, TBC)
8. Perform performance verification testing and environmental testing at sensor system level

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