AQUILA and 3AA: design and test results of high-accuracy accelerometer sensor and equipment

Alberto Torasso[(1)], Rabin Francis[(1)], Jeroen Vandersteen[(2)]

[(1)] InnaLabs Ltd, Snugborough Rd, Blanchardstown, Dublin 15, Ireland.
Phone: +353 1 809 6200, email: alberto.torasso@innalabs.com.
[(2)] ESA-ESTEC, Noordwijk, The Netherlands.
Phone: +31 71 565 8737, email: jeroen.vandersteen@esa.int.

ABSTRACT

InnaLabs Ltd, a privately held limited company incorporated in Ireland in 2011, is producing European ITAR-free Quartz Pendulous accelerometers since 2013, achieving top-end navigation performance with its AI-Q-2000 series of accelerometers. Thousands of those accelerometers have been since integrated into a wide range of land, marine, and aerospace platforms. These accelerometers have recently been successfully used in rocket launchers to support inertial navigation, demonstrating compatibility of the technology with space applications.

AQUILA is a very high performance rad-hard accelerometer based on Innalabs quartz-pendulum accelerometer technology. It uses the same pendulum subassembly as the AI-Q-2000 family, but electronics have been developed to meet space PA/QA standards. A hybrid electronics component populated with thoroughly-selected high-reliability EEE parts has been designed for that purpose. Furthermore, performance is specified to meet the most demanding space navigation applications, in particular with the objective of supporting delta-v manoeuvres measurement.

AQUILA was developed with the primary goal of qualifying an alternative to non-EU Navigation Grade Space accelerometers currently used on board ESA missions and other European Primes' platforms (with similar fit, form and function). Performance specifications include, among others, very low noise, stringent bias and scale factor stability (i.e. 0.1µg short term stability, 2µg over 1 hour, 50µg over 1 month, and scale factor stability over 1 month of 100ppm) under full operating conditions (i.e. temperature, time, launch environment), including more than 15-years exposure to Space radiations (100krad goal). AQUILA is re-using the electro-mechanical cell used in the InnaLabs AI-Q-2000 series of COTS accelerometers which are proven insensitive to radiations and robust to stringent mechanical shock and vibration levels.

3 Axis Accelerometer (3AA) is a new equipment designed to provide acceleration and delta-v measurement on boards satellites and space systems. It includes 3 AQUILA accelerometers mounted in orthonormal orientation to provide measurement along 3 axes. 3AA is equipped with a standard 28V power interface and UART communication bus to easily interface with the main on board computer. The equipment allows for accelerometer compensation and calibration in flight (temperature, misalignment, etc.), providing the main on board computer with a high precision acceleration and delta-v measurement.

This paper describes the specification and design of AQUILA Dry Pendulous Servo

accelerometer and of the 3 Axis Accelerometer. The paper will also present testing results from AQUILA development models built so far, showing that the product meets the specified performance. Schedule of the development till completion of the qualification will be presented.

1 INTRODUCTION

High-performance accelerometers delivering sub-1mg accuracy are used in space applications to perform several different functions, as delta-V monitoring for interplanetary missions, navigation for launchers and rovers, and Entry Descent and Landing (EDL) control for landers. In some other applications, high-precision accelerometers would also be required for angular momentum or vibration monitoring.

Although significant efforts have been placed over the past 10 years on the development of space grade MEMS accelerometers, they still do not meet the bias, scale factor and output noise requirements set for high value space missions [1]. In this time, the Dry Pendulous Servo Accelerometers technology [2] has made significant progress, both in terms of technology maturity and manufacturability, with high pass yields, robust designs and miniature dimensions proposed today for tactical and navigation grade applications [3][4].

In that context, InnaLabs, a European inertial sensors and systems company based in Dublin, Ireland, has been selected by ESA to develop AQUILA, a European space navigation-grade Dry Pendulous Servo Accelerometer meeting the requirements of both institutional and commercial space applications.

Compared to InnaLabs AI-Q-2000 series, the performance specification of AQUILA demands, among others, improved bias stability over temperature, time, and through harsh launch environments. Scale factor stability over a 15-years exposure to radiations is also requested. To address as many space applications as possible, AQUILA also provides a low output noise and a large bandwidth, in a small size and low weight form factor. Additionally, the accelerometer embeds a thermal sensor that allows thermal compensation of bias, scale factor and misalignment at system level (AMU, IMU, INS, etc.). A preliminary specification is provided in Table 1 below:

Table 1: AQUILA specifications

Parameters	Unit	Value / comments
Input Range	g	±25
Bias one-year stability (3-sigma)	μg	80
Bias thermal model residuals (peak)	μg	30 (4^{th} order polynomial model)
Bias repeatability to launch environment	μg	400
Scale Factor	mA/g	1.2 to 1.46
Scale Factor one-year stability (3-sigma)	ppm	70
Scale Factor thermal residuals (peak)	ppm	70
Scale Factor repeatability to launch environment	ppm	150
Vibration Rectification	$\mu g/g^2_{RMS}$	<15 (DC - 500 Hz)
		<40 (500 Hz - 2kHz)
Intrinsic Noise	μg_{RMS}	<7 (0-10 Hz)
		<70 (10 Hz-500 Hz)
		<1500 (500 Hz-1kHz)
Bias instability	μg_{RMS}	0.1
Velocity Random Walk	μg.s/√hr	48
Operating Temperature	°C	-35 to +80

Shock survival (half-sine)	g, ms	500 g, 0.5 ms
Total Ionising Dose	krad	50
Resolution/Threshold	µg	<1
Warmup: distance to steady state	µg	<20 (3 to 10min after turn-on)
		<5 (>10min after turn-on)
Bandwidth	Hz	>800
Quiescent Power @ ±15VDC	W	<1
Electrical interface		Temperature Sensor included
		Voltage Self-Test
		Current Self-Test
		Power/Signal Ground
Input Voltage	V_{DC}	±13 to ±18

In terms of design, AQUILA is re-using the electro-mechanical cell, pendulum and magnetic circuit of the InnaLabs AI-Q-2000 series shown in Figure 1 (left). That design has shown insensitivity to radiation and high robustness to stringent mechanical shock and vibration levels for a range of land, marine, and aerospace applications.

Figure 1: AI-Q-2000 accelerometer (left), AQUILA accelerometer (right)

Therefore, the main development activity is focused on, (i) the accelerometer electronics design to achieve radiation hardness and single event immunity, and (ii) the demonstration of performance in the space environment after ground operations and the launch phase. In particular, and for demonstration purpose, a hybrid electronics component populated with selected high-reliability EEE parts was designed. Final fitting tests of the hybrid within the accelerometer will confirm whether the Off-The-Shelf AI-Q-2000 housing can be used or whether a limited extension of the accelerometer height is needed.

AQUILA initial design was presented in [6]. This paper cover design evolution since that time as the hybrid has now been designed and samples have been manufactured.

In 2021 the ESA CTP contract was amended to include the development of a complete 3 axis accelerometer equipment, named 3AA, to provide accelerometer and velocity information to the main on-board computer whenever needed. While AQUILA is the core sensor in 3AA, 3AA provides normal equipment interfaces such as 28V power supply, RS422 digital data interface, ground stimuli possibility. It also allows in-flight recalibration of accelerometer bias error that enables a higher precision of the output to be reached.

2 AQUILA DESIGN

2.1 InnaLabs Pendulous Accelerometer Technology

InnaLabs pendulous accelerometers house a high-purity fused quartz pendulum, etched to delimit an outer rigid beam, two thin hinges and a central circular region (the flapper) that is the core of the sensor. The outer beam is clamped between two nickel-iron alloy cases to form the accelerometer cell. Each side of the flapper features a gold-deposited track facing a finely lapped surface on the matching case to create a system of two pick-up capacitors used for detecting the flapper position relative to the cases. Additionally, a high remnant magnetic field is generated by a stable AlNiCo magnet, that lays at the centre of each case. Each magnet matches a coil mounted on each side of the flapper. The subassembly made by the flapper and the coils is the accelerometer proof mass and can be displaced by a Laplace force generated by running a current through the coils.

Any acceleration perpendicular to the flapper plane induces a displacement of the flapper, which is detected by the pick-up capacitors. A servo-control loop implemented on a proximity board, from the pick-up signal, generates a current in the coils to counter-act the effect of acceleration and keep the flapper centred between the cases. The amplitude of the current needed is proportional to the applied acceleration [3].

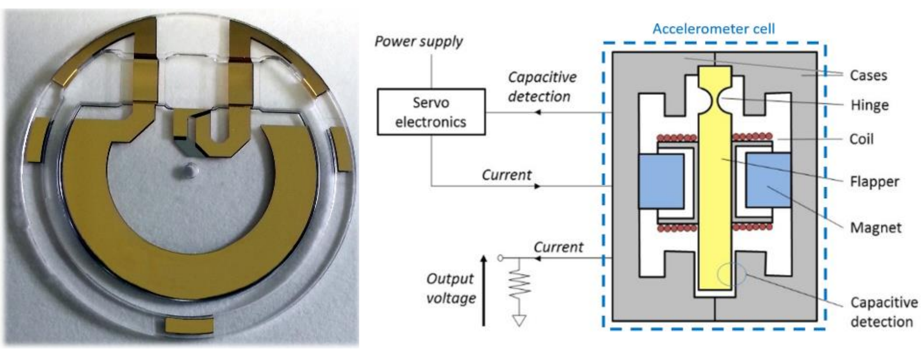

Figure 2.a. Quartz pendulum – 2.b. Accelerometer outline schematics

The electronics assembly and accelerometer cell are mounted in a stainless-steel housing, and great care is being taken to align the cell sensitive axis with the housing geometrical axis. The housing is outgassed, filled with an inert gas at atmospheric pressure and hermetically sealed.

2.2 Mechanical Design

Most of AQUILA mechanical design is inherited from InnaLabs off-the-shelf AI-Q-2000 series accelerometers with a re-use of the cell, the pin cover assembly and most of the housing design with an identical mounting surface. The main mechanical design activities were thus driven by the electronics sub-assembly design: *i.e.* adapting the housing to fit a radiation hardened electronic, designing flex cable to withstand the harsh shock and vibration environments, etc.

Overall dimensions of the accelerometer are ⌀25.4 x 24.6mm, as shown in Figure 3. The height of the final product from mounting surface to pins will depend on the final height of the electronics sub-assembly, which is currently in final design iteration.

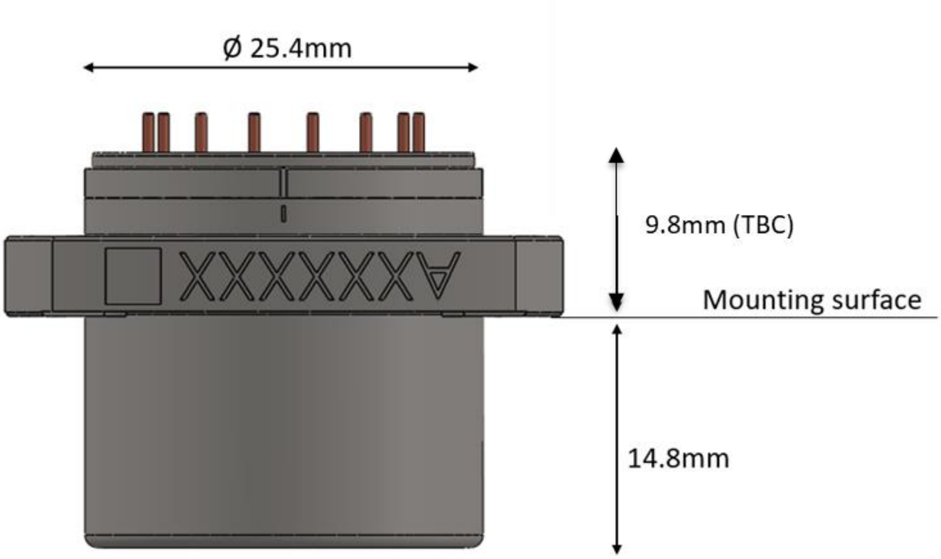

Figure 3: AQUILA main dimensions

2.3 Electrical Design

AQUILA electronics is designed to provide the same functions, performance, and electrical interfaces as the InnaLabs AI-Q-2000 series. Most electrical design activities were focused on the "spatialisation" of the components, *i.e.* the selection of space-grade components with suitable performance, capable of withstanding the specified total-dose radiations, and single-event immune. Utilisation of die-packaged active components was favoured to avoid bulky encapsulations, in an effort to keep the overall mechanical volume of the accelerometer as close as possible to the original AI-Q-2000 form factor.

The electronic components in die format are to mounted on a ceramic-substrate hybrid circuit. All active are in class 1 equivalent parts, whereas some of the passive need to be procured in lower quality (e.g. AEC-Q) due their lover volume in order to fit into the limited space available. An early sample of the ceramic hybrid is presented in Figure 4.

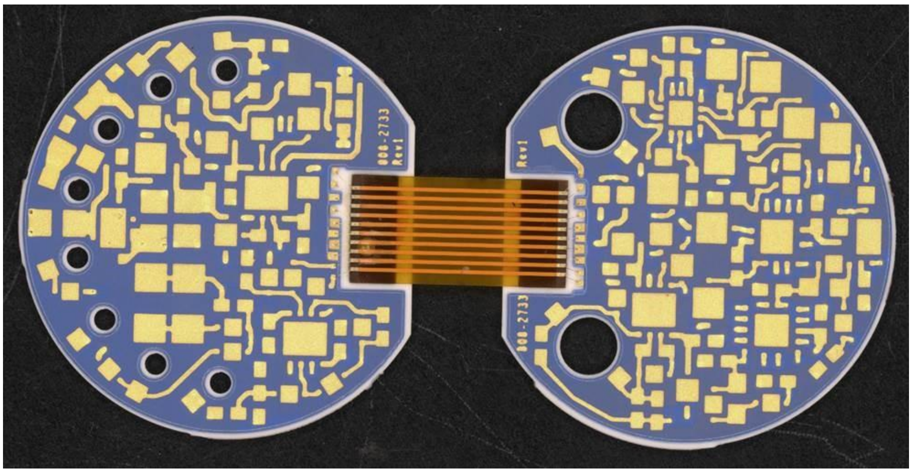

Figure 4: sample of ceramic substrate

3 BREADBOARD MODELS

3.1 Breadboard Models Presentation

Breadboard models were designed and manufactured as first development models allowing validation of functionality and partial assessment of performance of the AQUILA design. As most of the changes from InnaLabs Off-the-Shelf accelerometers to AQUILA are on the electronics parts and design, the Breadboard models were built with off-the-shelf accelerometer cells and AQUILA Breadboard PCB specifically designed for the occasion, as depicted in Figure 5. The breadboard uses COTS EEE equivalent to the Hi-Rel parts selected for the final product. Therefore, from a functional and performance point of view, the BB is expected to be very representative of the final product behaviour. Although such models could not be fully encapsulated in a standard, hermetically sealed InnaLabs housing and therefore did not allow for an inert-gas atmosphere inside the housing, they were suitable for functionality tests at room temperature, as well as some performance and environment tests.

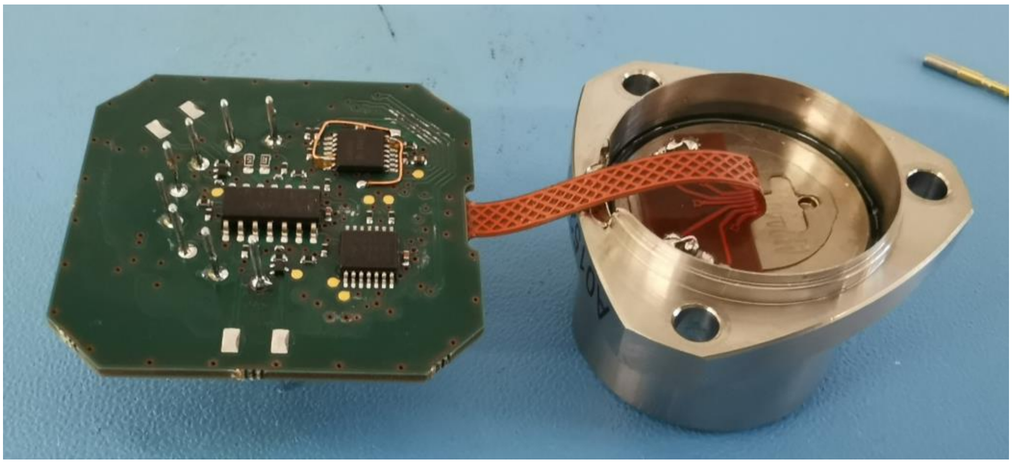

Figure 5: AQUILA Breadboard model

The following points of AQUILA specification were measured on the breadboard models (BB), as part of functionality and performance validation:

- Power consumption
- Bandwidth & Frequency response
- Scale factor over temperature range

- Bias over temperature range
- Allan variance (including bias instability and Velocity Random Walk)
- Integrated Noise
- Warm up time

As with all InnaLabs qualification and acceptance tests, the breadboard models were tested in accordance with the IEEE standard 1293-1998 [2].

3.2 Breadboard Model Test Results

Breadboard Model test results were presented in [6]. Summary of the main outcome is collected in the sequel.

Scale factor and bias of the breadboard models were measured through a static multipoint test [3] over the full temperature range used for production units of AI-Q-2000s, from -55°C to +95°C. The residuals of the performance parameters, after application of a 4th order polynomial function of temperature, are presented in Figure 6. The accelerometer-embedded thermal sensor output is used here, as it will be at system level, therefore the results reflect the accelerometer self-heating. As depicted on the Figure 6, the thermal residuals are meeting the requirements. The next development models, starting with EM, will allow a hermetic sealing of the accelerometer, which will lead to thermal performances more representative of the final product.

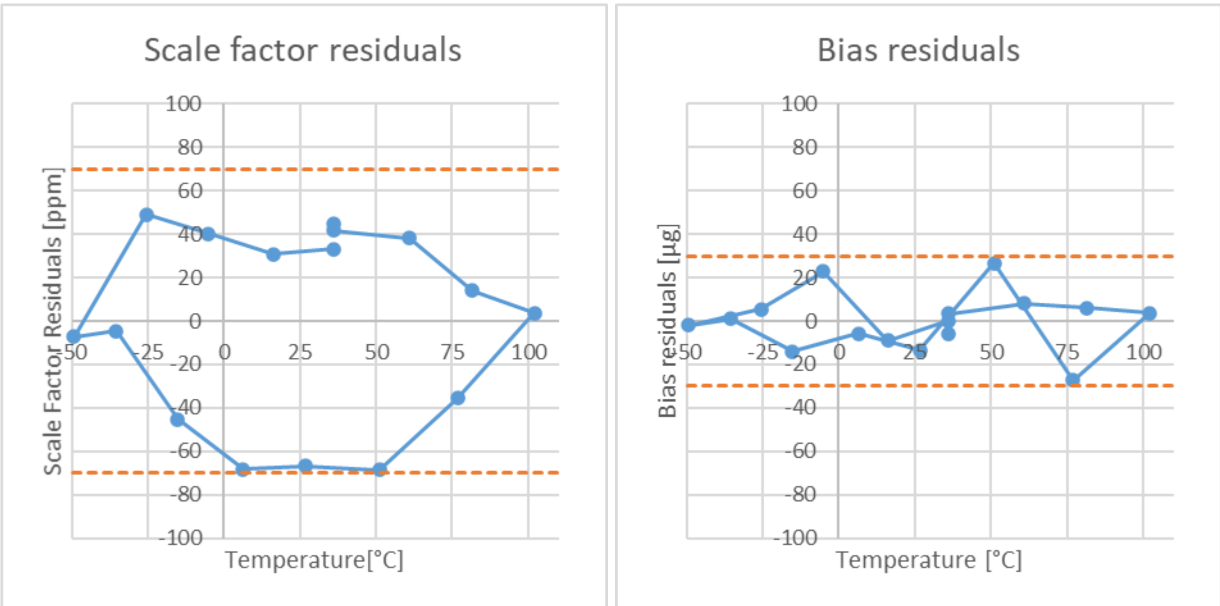

Figure 6.a. AQUILA BB scale factor residual - 6.b. Bias residual (dashed orange specification limits)

The short-term stability of the breadboard models was assessed by calculating the Allan variance with resulting plots shown in Figure 7. The Allan variance is obtained by computing the standard deviation of the measured data over a varying integration time. The data used for this test are not thermally compensated. The lowest point denotes the accelerometer bias instability and is as low as 30 nano g_{RMS} (for integration times between 50 and 100 seconds) and thus within specification (100 nano g_{RMS}). The Velocity Random Walk (VRW) of 10µg.s/√hr is below the specified 48µg.s/√hr.

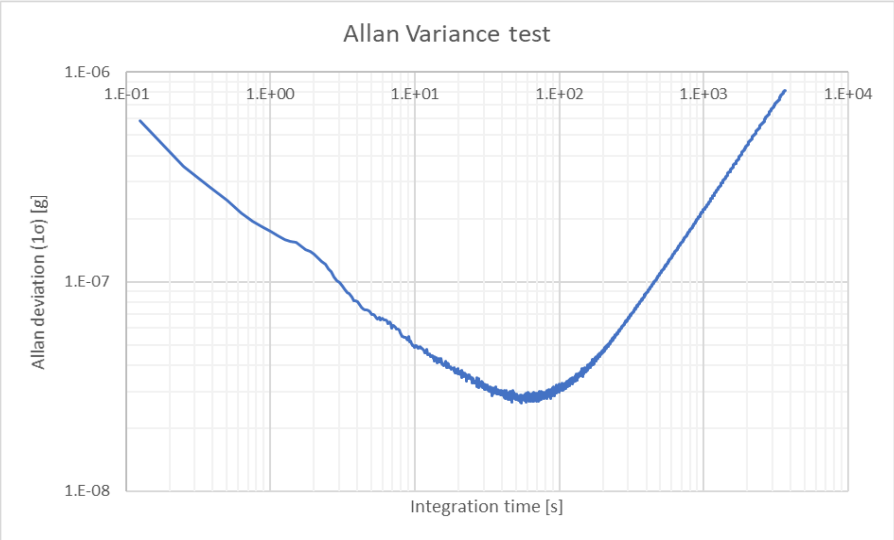

Figure 7: AQUILA BB Allan variance plots

The noise content was evaluated with a spectral noise measurement to get to integrated noise values. The test was performed using a spectrum analyser in three frequency ranges (namely [0.1Hz; 10Hz], [10Hz; 500Hz] and [500Hz; 10,000Hz]). The noise results, which are within the required limits, are shown along with corresponding specification levels in Figure 8 and key figures summarised in Table 2.

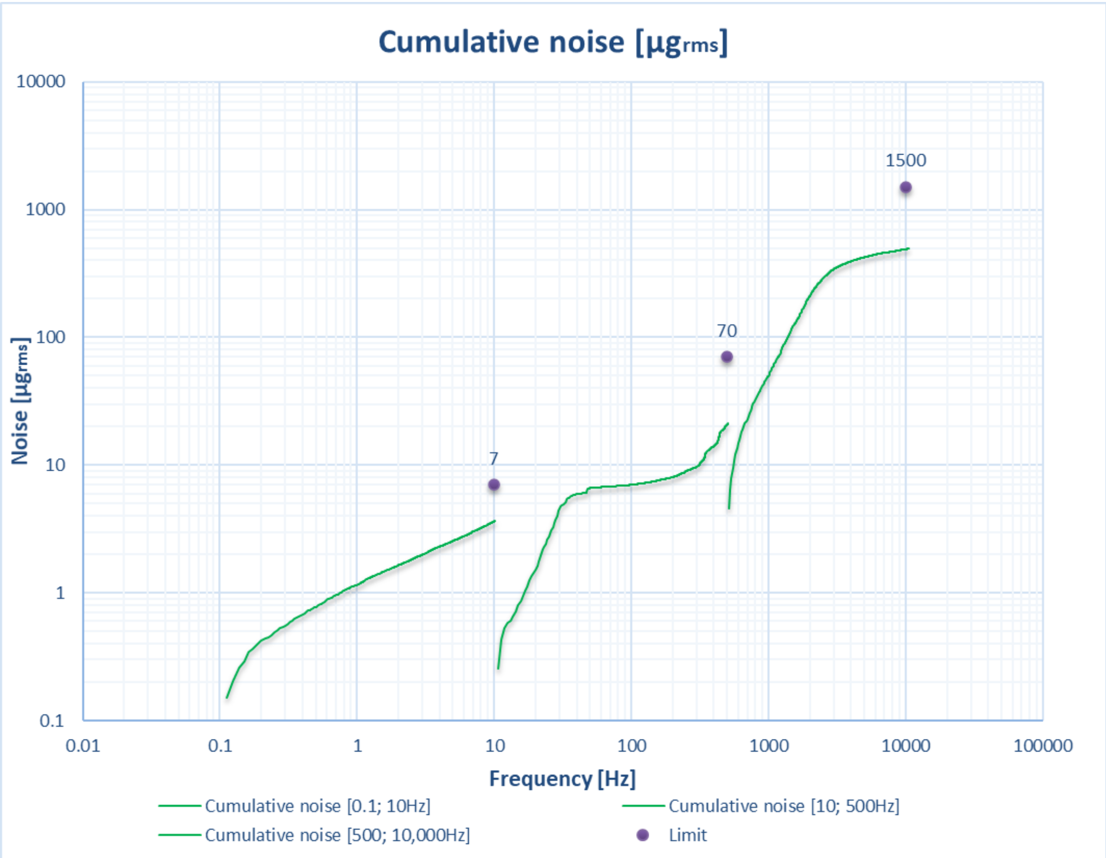

Figure 8: AQUILA BB Integrated Noise

Table 2: AQUILA BB Integrated noise summary

	AQUILA BB [μg$_{RMS}$]	Specification [μg$_{RMS}$]
Integrated Noise over [0.1; 10Hz]	3.64	7
over [10; 500Hz]	20.8	70
over [500; 10'000Hz]	489	1500

The warm-up was characterised by recording the accelerometer output from turn-on until steady

3.3 Environmental Tests

Derisking of AQUILA accelerometer with respect to mechanical environments, i.e. random vibrations and shocks was presented in [6]. As a summary 500g 0.5ms shocks (half sine) test campaign was performed on Innalabs AI-Q-20x0 COTS accelerometer. Figure 9 and Figure 10 depict the calibration difference induced by shock along the accelerometer input axis (IA). These plots show the residuals of pre-shock and residual post-shock static multipoint tests, using the pre-shock thermal model.

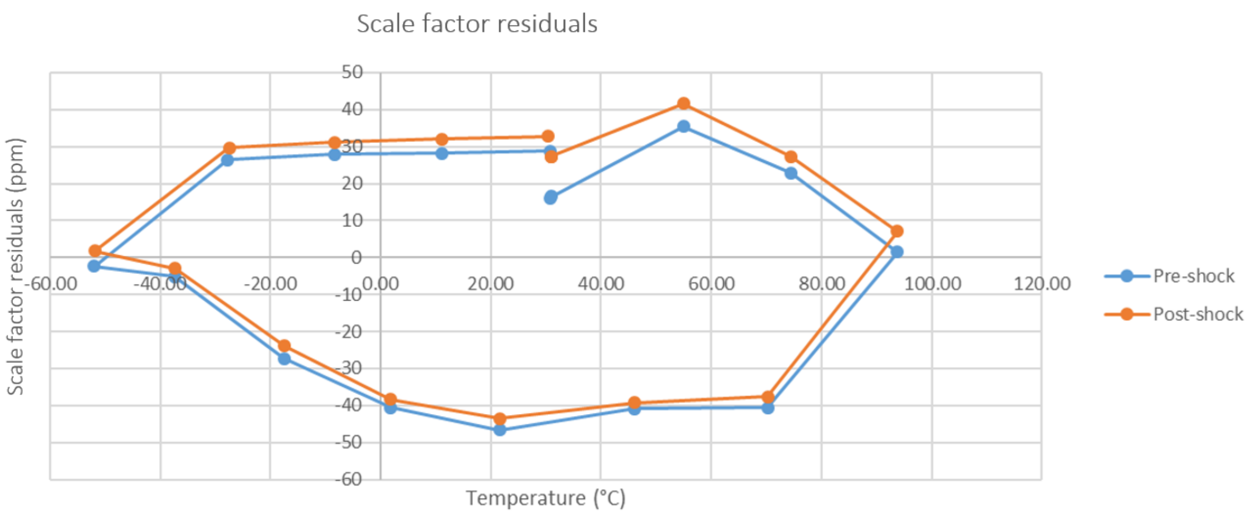

Figure 9: Scale factor (k1) residuals prior to (blue) and after (orange) a 500g shock along IA

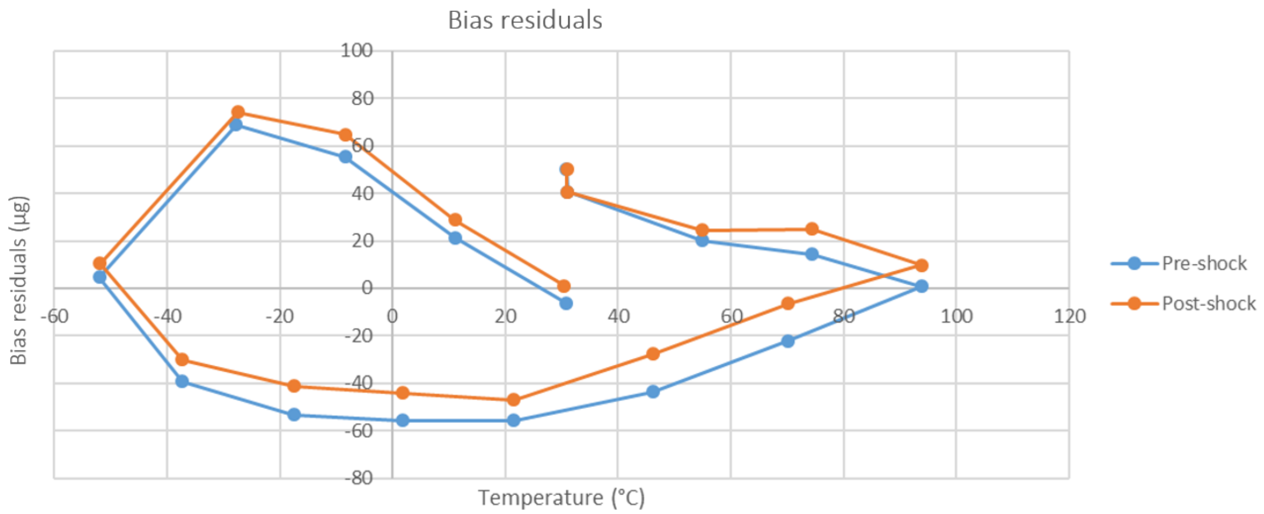

Figure 10: Bias (k0) residuals prior to (blue) and after (orange) a 500g shock along IA

The scale factor (k1) change after shock, and then averaged over the temperature range, is approximately 5ppm. Bias (k0) change after shock, averaged over the temperature range, is 16µg. A control accelerometer, whose bias and scale factor were measured along with the units under test, that did not undergo the shock, had a 2ppm scale factor change, a 3µg bias change between the two tests. Thus, both scale factor and bias meet the launch repeatability requirements. These limits are 150ppm and 400µg with margin.

On top of that, over the last couple of years Innalabs AI-Q-20x0 accelerometers have been successfully used into navigation system in rocket launchers. This means that Innalabs AI-Q-20x0 have shown survivability and performance during operation in the high vibration and shock environment of rocket launchers. They also showed survivability to space environment as well for a timescale of hours (compared to multi-year need for AQUILA).

4 THREE-AXIS ACCELEROMETER

The 3-axis accelerometer unit is a fully independent satellite equipment that can be connected to the main on-board computer by means of an RS422 link. The unit can be powered by both regulated and unregulated 28V.

Main functionality of 3AA is to provide to the AOCS subsystem a very precise measurement of acceleration or integrated velocity. While this information can be used for a number of purposes, main appliaction of the equipment is to monitor delta-V manoeuvres with high precision. This is mostly driven by ESOC requirements in terms of delta-V precision especially in scientific mission that operates in Sun-Earth Lagrangian Point #2 (L2). Such accuracy is needed both for maneuvres to inject into L2 orbit and for stationkeeping around L2. The need for a very precise measurement of delta-V Such drive the equipment design towards has a fine performance range in the order of magnitude of mg with the precision in the order of magnitude of µg.

Figure 11 depicts the 3-axis accelerometer unit. Such unit is designed based on Innalabs experience in the design of ARIETIS and ARIETIS-NS ([7], both of them 3-axes gyros). This is a very preliminary view, subject to optimization during the design phase.

The size of the equipment as per this preliminary design is equal to: 166 x 166 x 72 mm.

Figure 11 – 3 axis accelerometer unit, external view

Figure 12 shows the internal organisation of the unit and its main building blocks:

- 3x AQUILA accelerometer
- A cluster mounted on dampers that supports the 3 accelerometers. Dampers are needed as accelerometer are sensitive to high shock environment. Dampers and clusters are derived from ARIETIS [7]
- An electronic assembly derived from ARIETIS-NS gyro [7], i.e. using mostly COTS EEE that have been upscreened for radiation by means of Lot Acceptance Testing.
    - 1 Digital Board (DB) that performs
        - accelerometer output data acquisition, conditioning, and digitisation
        - acceleration compensation (temperature) and data processing to extract delta-v measurement as well as calibrations, based on either a microcontroller or an FPGA
        - unit modes management
    - 1 Interface board (IFB)
        - data communication with the main on-board computer (RS422)
    - 1 Power supply board (for unregulated or regulated 28V bus)
    - A flexi rigid system that connects the 3 accelerometers to the digital board. This could be split in 3 flexi rigid.

Note: such design is very preliminary and will be subject to optimisation to reduce volume and mass.

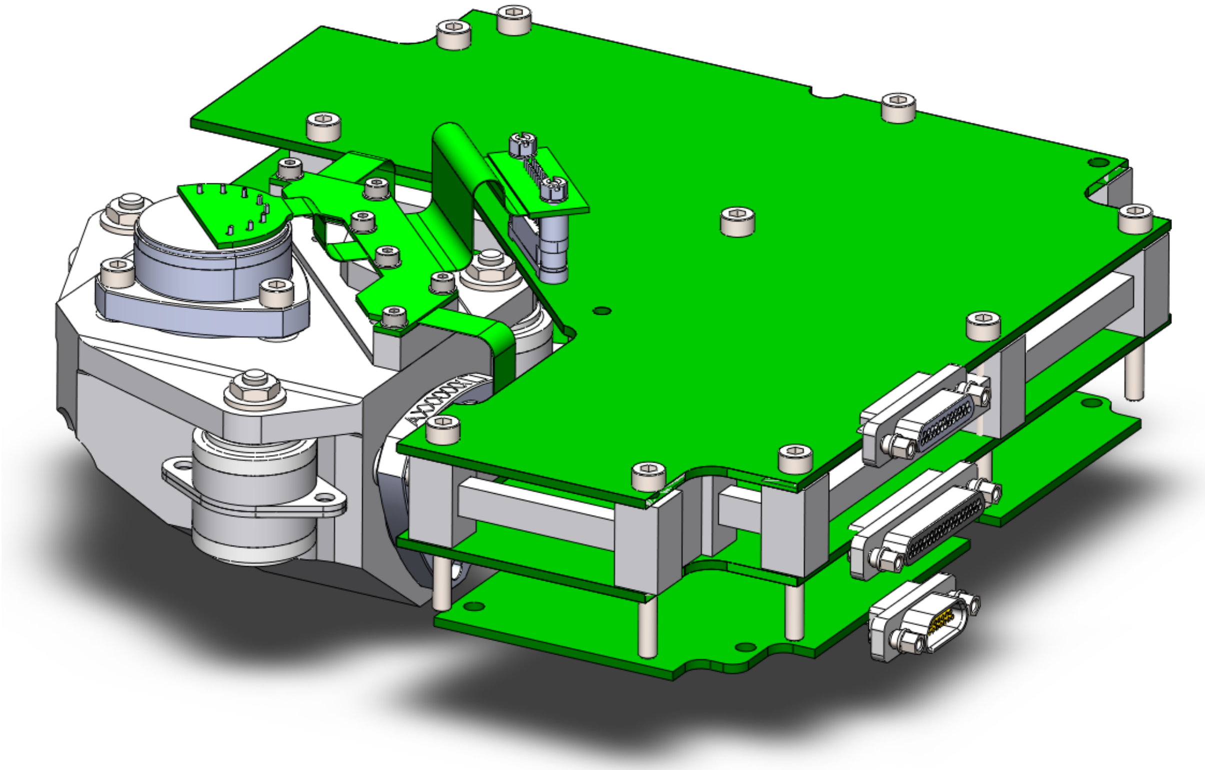

Figure 12 - 3 axis accelerometer unit, internal view

The overall architecture of the unit is derived from ARIETIS and ARIETIS-NS 3-axis gyros. While cluster and boards size and schematics need to be adapted for the application a similar overall product design can be seen.

4.1 Specification

3AA performance main specifications are reported in Table 3. Note that 3AA performance is driven by AQUILA accelerometer sensor specification.

Table 3 – 3AA Performance Specification

Performance Parameters	Value
Measurement range	10mg (fine range – can be adapted) 1.5g (coarse range)
Switch-on response time	≤ 10s
Bias instability	≤ 0.1μg
Noise PSD up to 10Hz	≤ 1μg/√hr
Bias stability over 1hr (steady temperature)	≤ 2μg (1σ)

Table 4 – 3AA design specification

Key Features	Value
Output	Cumulated velocity, in fine or coarse ranges along three axes
Data Interface	RS422 Data Interface
Reliability (baseplate temperature of 30°C)	1000 FIT
Mass	~2 kg
Power consumption	~9W,
Radiation	Designed for at least 10 years in ON state with space environment
Power Interface	28VDC
In-orbit calibration functionalities	Yes
Temperature range	Qualified to a temperature range of -20°C to +65°C
Vibration profiles during launch	26 grms random
Shock	SRS 2000g @2000Hz

4.2 Functional Architecture

Figure 13 represents 3AA functional architecture with all the main functions split between the main equipment components. Functional architecture is inherited from ARIETIS-NS gyro with obvious change related to accelerometer specific analogues signal and analogue to digital conversion needs.

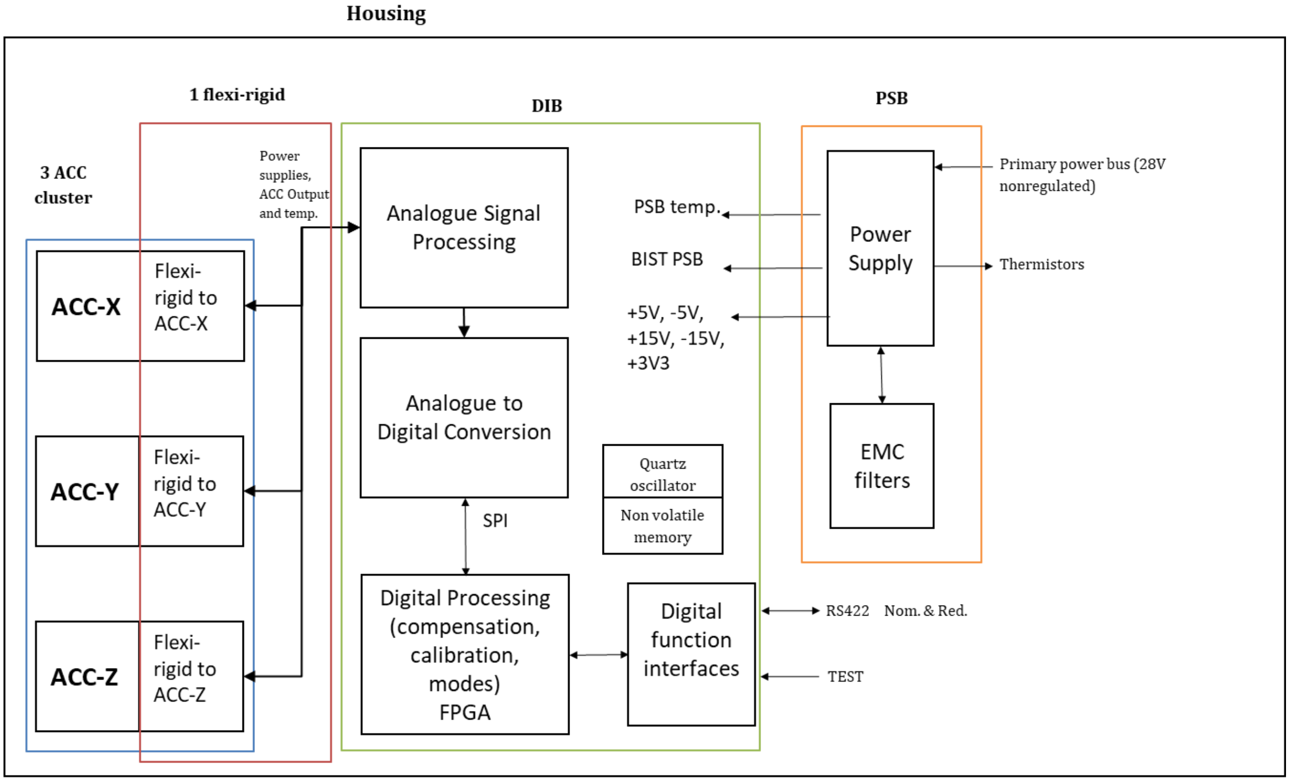

Figure 13 – 3AA functional architecture

4.3 Modes description

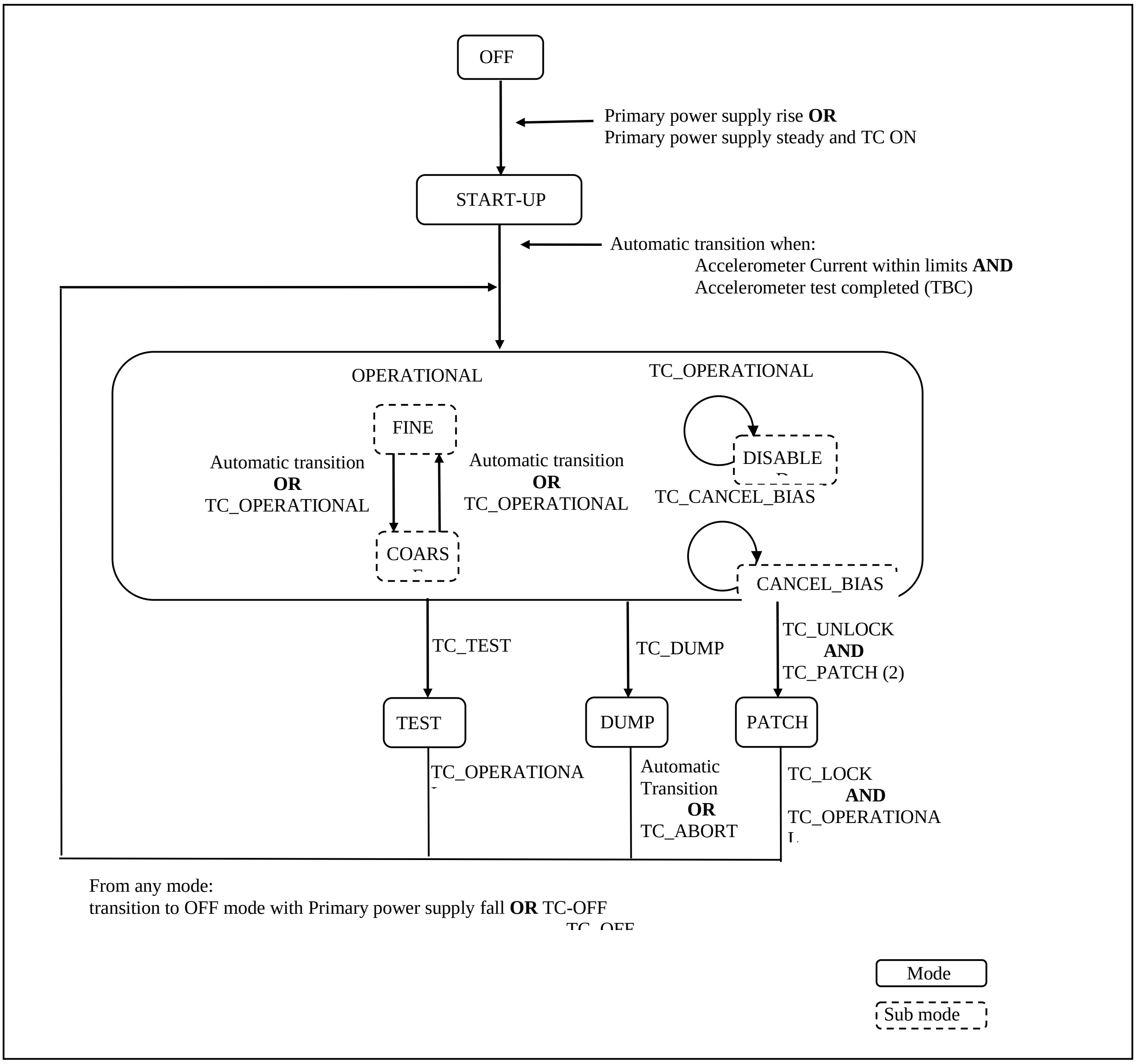

Figure 14 – 3 axis accelerometer unit functional architecture

Figure 14 provides a functional architecture of the 3-axis accelerometer modes. Need for a startup mode is still TBC.

The main operating mode requires a number of submodes. This includes the possibility of doing a correction of bias error (TC_CANCEL_BIAS) before delta-v integration.

Also, considering that the unit needs to be tested on ground, a coarse mode may be needed to support testing in a +1g environment, whereas fine mode may be calibrated for specific flight needs to few milli-g.

By means of patch and dump modes it will be possible to upload and download content parameters stored in non-volatile memories, in particular accelerometer temperature compensation coefficients.

It is expected that the unit will be able to provide in its telemetry

- Delta-v measurement (acceleration integrated over time)
- Time-stamp of measurement
- Bias correction error

5 CONCLUSION

Based on its Pendulous Servo Accelerometer technology, InnaLabs is developing a high performance, ITAR free accelerometer for space application named AQUILA. Main applications are delta-V monitoring as well as navigation. Design of the product has been validated by means of breadboards while engineering models are currently being manufactured. So far all tests have shown that AQUILA specification can be met. After validation of the design by means of Engineering Models, Qualification models will be built and tested to complete formal qualification of the AQUILA product.

InnaLabs is currently developing a three-axis accelerometer unit that incorporates three AQUILA sensors, power interface to a 28V bus as well as UART data interface. This equipment will include calibration functions to optimise performance with the main goal of supporting delta-V monitoring on board satellites.

6 ACKNOWLEDGMENTS

Innalabs would like to thank the European Space Agency and Enterprise Ireland (i.e. Irish delegation to ESA) for the continuous support and funding of its space products portfolio including AQUILA and 3AA.

7 REFERENCES

[1] IPC – Technology Harmonisation Advisory Group (THAG), European Space Technology Harmonisation Dossier, *AOCS Sensors and Actuators*, 30 September 2020.

[2] IEEE Standard 1293-1998, *Guide and Test Procedure for Linear, Single-axis, non-gyroscopic Accelerometers*.

[3] J. Beitia, A. Clifford, C. Fell and P. Loisel, *Quartz pendulous accelerometers for navigation and tactical grade systems*, DGON Inertial Sensors and Systems Symposium (ISS), 2015.

[4] J. Beitia, P. Loisel and C. Fell, *Miniature Accelerometers for High-Dynamic, Precision Guided Systems*, The 4th IEEE International Symposium on Inertial Sensors & Systems, 2017.

[5] ECSS-M-ST-10C, *Space Project Management – Project Planning and Implementation*, Revision 1, 2009.

[6] Q. Trizac, J. Beitia, A. Torasso, P. Loisel, J. Vandersteen*: AQUILA: Development of a European high-accuracy accelerometer for space applications,* 11th International ESA Conference on Guidance, Navigation & Control Systems, 22 - 25 June 2021, Virtual.

[7] Oubellil R., Beitia J., Torasso A., Diram R., Potel N., and Kowaltschek S., *ARIETIS and ARIETIS-NS, new highly competitive gyro solutions for space applications*, 11th International ESA Conference on Guidance, Navigation & Control Systems, 22 - 25 June 2021, Virtual.