## MAUS and IBIS the Jalapeno’s under the Sunsensors

**Principal author name [(1)], Johan Leijtens [(1)], Dick Broekmans [(2)]**

*(1) Lens R&D, ‘s-Gravendijckseweg 41b 2201CZ Noordwijk The Netherlands,*
*071 2020 123, jls@lens-rnd.com*
*(2) Lens R&D, ‘s-Gravendijckseweg 41b 2201CZ Noordwijk The Netherlands,*
*071 2020 123, dbs@lens-rnd.com*

## ABSTRACT

The IBIS (short for Intensity Based Image Sensor) Sunsensor is a small digital Sunsensor currently under development in frame of an ESA Artes contract. Based on an application specific CMOS sensor, the sensor combines albedo insensitivity with low power operation and a high radiation tolerance. As such, it will be a small but very potent sensor to which a parallel with the Jalapeno pepper can be drawn.

In frame of the IBIS developments, some demonstrators had to be designed. As these demonstrators were based on the use of a nano-D connector, this led to a very low-profile setup which for the time being has been transformed into a low profile analogue Sunsensor. This MAUS Sunsensor is small enough to be accommodated on a CubeSat and with a reliability better than any other CubeSat component.
The presentation will focus on the development status of both the IBIS and the MAUS products.

## 1 Analogue versus digital Sunsensors

Lens Research and Development is a Dutch SME specialized in development and production of high reliability Sunsensors.

Sunsensors are mainly used during the launch and early orbit (LEOP) and safe mode phases of a mission. During LEOP the sensors provide inputs for de-spinning and initial orbit acquisition. In safe mode the sensors provide a rock-solid signal that can be used to point the solar panels to the Sun, thereby assuring optimum charging of the batteries in the period any failure is investigated and the system is brought back into normal operational mode.

The BiSon64-ET and BiSon64-ET-B Sunsensors, shown in Figure 1, are specifically developed for direct mounting on extendable solar panels of Geostationary satellites. The very wide operating temperature range, high rigidity and small size however make them suitable for just about any mission.


**Figure 1 BiSon64-ET and BiSon64-ET-B Sunsensors**

The design of these analogue sensors is optimised for volume production and the sensors have been rigorously qualified in frame of an ESA GSTP program. Being highly reliable, small and affordable, the sensors have all desired properties with exception of two:

1. Albedo insensitivity
2. Digital data interface

### 1.1 Albedo insensitivity

The accuracy of all Sunsensors is affected by the influence of Earth Albedo. Depending on the satellite's altitude, the Field Of View (FOV) of the sensor and the orientation, the albedo error can surpass the accuracy of the sensors by more than an order of magnitude. At 500km, a ±60° Sunsensor can show albedo errors in the order of 20°, even when the base accuracy of the sensor is as low as 0.5°. Adding a baffle to the sensor limits this error a bit but not to the extent that the overall error will stay in the range of the base accuracy. As albedo errors lead to significant disturbances in the control loop of the satellite (and can even lead to an Earth lock if not properly handled), these errors are to be seen as the main drawback of analogue Sunsensors.

Albedo insensitivity can only be achieved by using multiple detectors, each covering a small portion of the FOV or using multiple sensors with a much smaller FOV. The latter are still albedo sensitive but because of the reduced FOV the albedo signal will become insignificant as compared to the direct Sun illumination. This will turn the sensor into an albedo insensitive analogue Sunsensor.

### 1.2 Digital interface

Over the years, on-board computers (OBC) have become more complex and potent and analogue interfaces are becoming increasingly rare. One notable exception is for Sunsensors which are still using analogue interfaces in case a high reliability solution is required.

As a fully digital OBC is preferred, people have been looking to create Sunsensors with a digital interface already for decades but no modern high reliability Sunsensors with a digital interface exist today that is commercially available. Adding a digital interface to an analogue Sunsensor doesn't influence the albedo sensitivity. Just adding a digital interface therefore doesn't create a true digital Sunsensor, although several companies do market their sensors as such by lack of a formal definition.

# 2 True digital Sunsensor and the ESA requirements

**DEFINITION:** A true digital Sunsensor uses a multi-element array to determine the sun presence with one or more of these elements, and outputs the attitude of the Sun with respect to the defined reference plane of the sensor as a digital value with limited sensitivity to Earth albedo.

## 2.1 ESA requirements and rationales

Development of the first radiation-hardened true digital Sunsensors was started in the mid nineties of the last century, followed by the development of a digital Sunsensor on a chip. Several years of investigations and developments have led to the conclusion that this is by no means a simple task, and that success for the development is not only determined by achieving the technical specifications. At the end of the line, the success of the development will be measured by market penetration.

If the performance is not good enough, nobody will buy the product. If the product is too expensive, only very few can afford to use the product. If the product is able to strike the right balance between technical performance and procurement costs, this will lead to many companies selecting the device and associated market penetration.

Looking at the ongoing ARTES program, a number of key success criteria for the development of the new digital Sunsensor are defined. These criteria are clearly driven by the desire to create an as high as possible market penetration and commercial success for the product.

Requirements currently defined are therefore neither very restrictive nor very detailed, but are focussed on defining a product that should be able to achieve an as high as possible commercial success:

1) The sensor shall have an accuracy better than 3°, including Earth albedo effects
2) The sensor should reach this accuracy without calibration compensation
3) The sensor shall have a digital interface
4) The sensor shall have a high reliability
5) The sensor shall have an as wide as possible operating temperature range
6) The sensor shall be cost competitive to analogue Sunsensor implementations

The rationales for these five simple main criteria are as clear as they are logical

1) LEOP and SAFE mode operation don't require accuracies higher than those that can be provided by a simple analogue sensor, if it were not for the albedo errors that disturb the control systems
2) There is a long-felt desire to remove all analogue interfaces from the OBC.
3) LEOP and SAFE modes are critical modes requiring the highest possible reliability
4) A wider temperature range increases the application potential
5) If the sensor is not cost competitive it will not be able to challenge the existing status-quo of using analogue Sunsensors

## 3 Digital Sunsensor on a chip implementation

As the Sun generates a significant signal level and basic signal to noise ratio is not an issue, a highly integrated sensor that uses mainstream CMOS technology and small pixels is the most logical choice when looking for optimum performance.

Integration of all functionality in a single chip definitively increases the reliability of the overall solution. To this respect, it has to be realized that no optical sensor can beat the reliability of a simple analogue Sunsensor, but the (non-) reliability of the signal processing chain will have to be taken into account as well. The latter will significantly reduce the overall reliability of the solution over the base reliability of the sensor. Integrating all processing electronics on a single chip is therefore a solution that will provide a higher overall reliability when properly engineered.

There are some significant caveats to integrating all functionality on a detector chip that directly outputs digital signals though. The sensor will be more prone to temperature and radiation effects than an analogue sensor. As the sensor needs to be located on the exterior of the satellite it will be directly exposed to the Sun's energy impinging on the sensor. Therefore, temperature control will be a critical activity in the design of the sensors. This in turn means that power dissipation should be as low as possible to avoid creating hotspots.

The need to develop a low power solution in order to avoid thermal control problems was realized by the TNO/TU-Delft team working on a small digital Sunsensor earlier this century. This has led to some innovative means to significantly reduce the power consumption of a digital Sunsensor chip like row and column profiling. (Ref. [2]). Minimal power consumption (in order to avoid the creation of hotspots) is an important parameter to be optimised during the design of the sensor. The less stringent the thermal control requirements, the easier the sensors will be to accommodate. This again will increase ease of application and is seen as a major contributor for commercial success. As a consequence, lowering the power consumption as much as possible is an important design goal.

As the sensors are located on the outside of a satellite, the temperature excursions experienced by the sensors are in general significantly larger than those associated with processing electronics located in an electronics box at the inside of the satellite. Stability of detection thresholds as a function of temperature and the effects of varying leakage currents and other parasitic phenomena are also critical design goals for these sensors. Fortunately, the temperature differences within the single chip are limited and changes with temperature will track quite well. But still, the main factor limiting the use of the sensor will be the temperature range, leaving certain applications like direct solar panel mounting to the use of analogue Sunsensors. This however can only be proven when the final design is finished, simulated and tested. Optimising the operational temperature range however is a strong focus during trade-offs as a wider temperature range will increase the number of potential applications.

Contrary to the current applications, where the analogue sensor is space exposed and the processing electronics is in a spacecraft internal electronics box, all electronics of an integrated digital Sunsensor will be directly exposed to the space radiation environment and thus shielded only by the sensor package.

From available solutions it is known that analogue Sunsensors which are build using P-substrate photodiodes can be extremely radiation tolerant. Total ionizing dose (TID) and total non-ionizing dose (TNID) resistance for these solutions is unprecedented and the devices are guaranteed single event effect (SEE) free. Most common CMOS based technology is also P-substrate based, and deep sub-micron technology has shown an increased resistance to TID.

On the negative side, with shrinking geometries, single event upsets (SEU) and single event functional interrupts (SEFI) are becoming more and more common. Single event latch-ups (SEL) are both process and design related, and are becoming more of an issue as well. At the same time, TID testing like those performed with Co-60 gamma radiation becomes less relevant and more complicated and expensive Proton and Heavy Ion tests are required to demonstrate the circuits capabilities to survive the space radiation levels associated with the application.

This knowledge more or less mandates the use of dedicated DARE (Design Against Radiation Effects) libraries to ensure SEL free operation and an extra high radiation tolerance in general. By using these libraries, a sensor can be designed which does fulfil the requirement of being able to sustain electric orbit raising (EOR) as well as 15 years in Geostationary Orbit (GEO) as requested within the ESA ARTES program, assuming sufficient shielding is added.

One question associated with this, is still: are we targeting the right market? Although the ARTES program requirements dictate 15 years in GEO after EOR as the target, the high-volume market seems to be in Low Earth Obit (LEO). For LEO orbits there are tens of constellations being deployed, hundreds of constellations in concept and several tens of thousands of satellites projected. Although some of these constellations will be operational in orbits between 1000km and 1500km, leading to significant radiation requirements, especially proton resistance, all off these sensors can do with a significantly lower radiation tolerance than needed for 15 years in GEO after EOR. Consequently, the actual level of radiation shielding for the base sensor is still under evaluation and may well be lower than currently specified in order to improve on the cost per sensor, size and weight.

### 3.1 Design status

After a preliminary design phase showing the general implementation and properties of the IPS+ as the sensor chip is dubbed, it was concluded that there is a high degree of confidence in the chosen implementation approach. As a result of this evaluation, it has been decided to incorporate some extra features in the prototype design that improve the testability of the chips as well as the use of the above-mentioned DARE libraries. This enhanced design will then be functionally tested in frame of the running program, but will also enable to perform some sensible radiation tests with while monitoring the performance in a follow-on project.

This approach is expected to speed up the entire development significantly thereby enabling a faster market introduction.

## 4 Sensor implementation

Aiming to develop a reliable and affordable true digital Sunsensor, Lens R&D, in cooperation with Systematic Design B.V., has selected a 0.18µm XFAB CMOS process using the IMEC DARE libraries to develop a dedicated Sunsensor on a chip. This chip (dubbed IPS+, short for IBIS Photonic Sensor) will fit in a housing small enough to be used on Lens R&D’s assembly robot and Calibration Setup. This in turn will avoid significant investments in production and verification equipment, thus adding to the cost effectiveness. This has led to the preliminary design as shown in Figure 5.

**Figure 2 IBIS digital Sunsensor**

In order to increase the radiation tolerance, this design uses two sapphire membranes, providing approximately 2mm Aluminium equivalent radiation shielding. In favour of a more cost-effective approach, this setup may be altered using a single membrane, as will be done in the demonstrator.

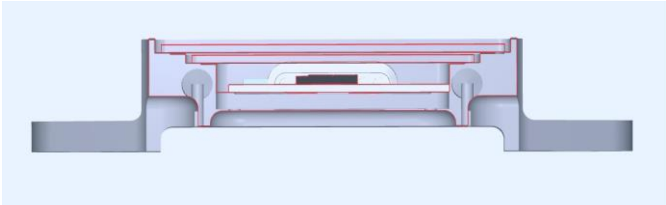

**Figure 3 cross section of IBIS preliminary design.**

The IBIS (short for Intensity Based Image Sensor) will use the same mounting interface and will be based on the same housing integrated wire-bondable connector technology as the BiSon Sunsensors. This will turn the IBIS into a small but potent addition to the Lens R&D sensor portfolio.

Having a lot of processing capabilities on board it has been decided to add the possibility to program a flexible field of view for the sensor as shown in Figure 4.

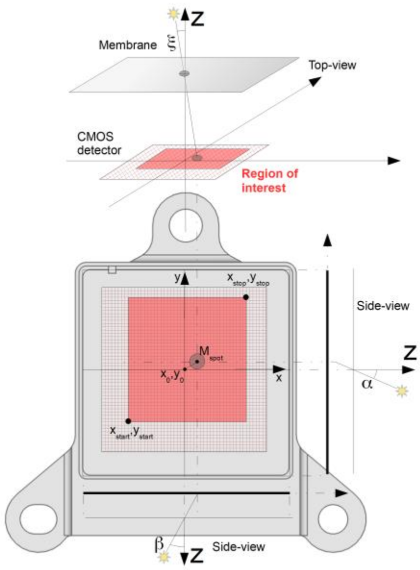


**Figure 4 programmable field of view by start stop coordinates**

By programming start and stop coordinates, the field of view within which the Sun will be detected can be defined. This feature will allow an easier accommodation on the satellite as it will allow to exclude certain portions of the field of view where reflections on spacecraft components could lead to false Sun detection. As such this is seen as a powerful tool to avoid using mechanical Sun exclusion baffles.

## 5 IPS testing

One of the main differences between the housings of a BiSon and an IBIS is the fact that 9 pins will be needed for the IBIS electrical interface instead of the 7 pins for the BiSon. This would require major investments in injection moulds for the ceramic inserts, and therefore an alternative has been sought (and found) for the demonstrator in using a standard nano-D connector.

**Figure 5 nano-DSS**

Using a 9-pin nano-D connector has led to the temporarily name of our Digital Sunsensor: nano-DSS. This sensor is to be seen as a testbed for the IPS testing, even though it is not unrealistic to consider that a design like this would fly on a nano satellite in the future. Pending the detailed design of the SOAC, further development of this test bed is currently halted, but the idea has been taken further into the design of another small analogue Sunsensor for CubeSat applications, the MAUS.

## 6 MAUS

By using the same nano-D connector, but the membrane and detector of the BiSon sensors, an analogue Sunsensor with a very low profile has is designed and which we call the MAUS: Miniature Analogue Ultimate Sunsensor. A number of these sensors are built already and were found to serve a purpose as the first radiation-hardened CubeSat Sunsensors in the world.

**Figure 6 MAUS**

Where CubeSat designers at first were focussed predominantly on small size, high functionality and low cost, the more mature companies among them are starting to make a transition to ever increasing reliability. Driven by the demand of true commercial (constellation) applications and applications beyond LEO, CubeSat builders also have to answer customer questions regarding flight heritage and reliability. Where flight heritage is relatively easy to come by in the CubeSat world, finding components that have been thoroughly tested is a much more difficult task.

As our sensors used diodes that have been tested to at least $8.10^{14}$ 1MeV electrons (equivalent to 19.2Mrad TID and $25.10^{9}$ MeV/g TNID) and the membrane provides 1mm equivalent shielding, this small but potent sensor will be able to sustain any radiation environment to be experienced by any CubeSat. Being inherently SEU/SEL free, the sensors are a good choice for people trying to build a reliable safe mode, insensitive to South Atlantic anomaly crossings and capable of going to the Moon or Mars (or even stay in GEO transfer orbit)

Having tested and flown several other Sunsensors over the last 15 years, ISISpace (Delft, the Netherlands) has seen their share of issues while applying small third party Sunsensors. As a result, they already evaluated the use of BiSon Sunsensors on their satellites but even with their small size, the accommodation did lead to several issues. Most of these issues were related to the height of the sensor and accommodation of the shielded connector. As the MAUS solves both issues to a large extend, ISISpace now is the first company that has adopted the MAUS as their core Sunsensor solution. Currently, several satellites are equipped with MAUS sensors, Some of which have been launched on the Falcon heavy transporter 2 mission. (KLEOS polar patrol constellation of 4 satellites each carrying 3 MAUS sensors and NAPA-2 also carrying 3 MAUS Sunsensors)

### 6.1 MAUS design.

The MAUS is using the same core components and basic design principles as for the BiSon Sunsensors.

1. The same photodiodes
2. The same membranes
3. The same titanium housing material
4. The same glues
5. The same mounting hole pattern

This leads to a sensor that looks very similar to a Bison Sunsensor, apart from the connector.

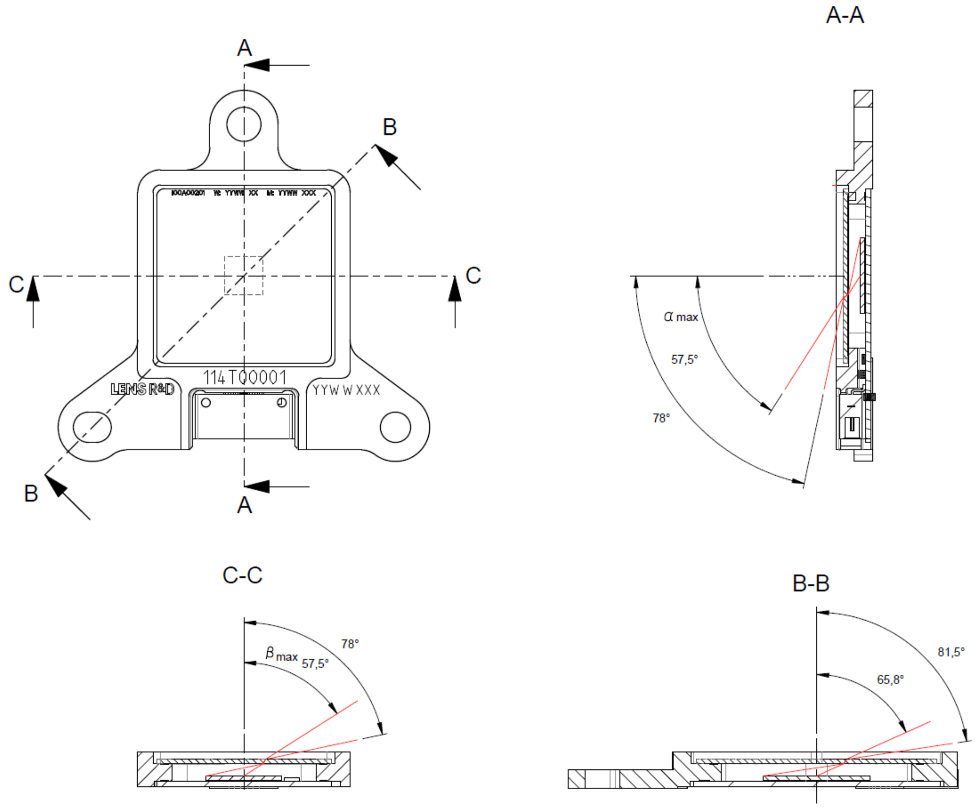


**Figure 7 MAUS optical interfaces and basic construction**

Most of the discussions have been on the use of the same mounting interface, as this still limits the mounting possibilities on a CubeSat, despite the compact build. This is because the sensor will require approximately 5cm spacing between the mounting points where standard solar cells are only 4cm wide. Changing this interface however would have meant that both our assembly robot and calibration setup would need to be altered, leading to a drastic price increase for the component. As CubeSat applications are above all cost critical, it was decided not to make such an expensive change and keep the mechanical interfaces “as is”.

Where the BiSon sensors have a solid titanium housing and use a ceramic substrate to mount the diodes, the MAUS uses a regular PCB with ENEPIG coating to allow both soldering of the connector and wirebonding of the diodes. This however leads to lower resistance to thermal cycling and radiation shielding as well as a lower mechanical rigidity. As the radiation tolerance of the diodes used is extremely high, the lower level of shielding is not seen as an issue. The front side is shielded with a sapphire window providing 1mm Al equivalent shielding. The backside is only shielded by the PCB and the bulk of the photodiode, which will be slightly less than 1mm Al equivalent, but this is not taking the shielding of the satellite itself into account which can be expected to be well above 1mm Al equivalent.

The resistance to thermal cycling may be less than for the BiSon, but a Sunsensor for a CubeSat nobody will not need a -125°C to +125°C operating temperature range. This is why this requirement has been reduced to -40°C to +80°C. Given the size of the sensor and its construction, it is expected that the sensor will be very resilient to mechanical loading despite being less resilient than a BiSon. This is why the specifications have been reduced, even though the actual validation has been performed at significantly higher levels.

The qualification testing was done along with the BiSon in the GSTP program and consisted of 40g sine and 34.2g random tests

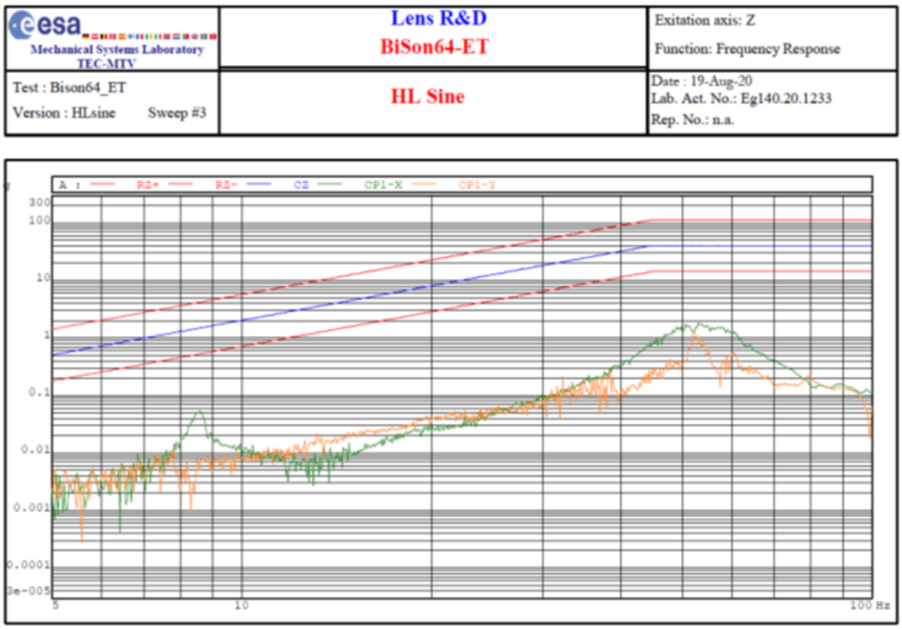


**Figure 8 40g sine test**

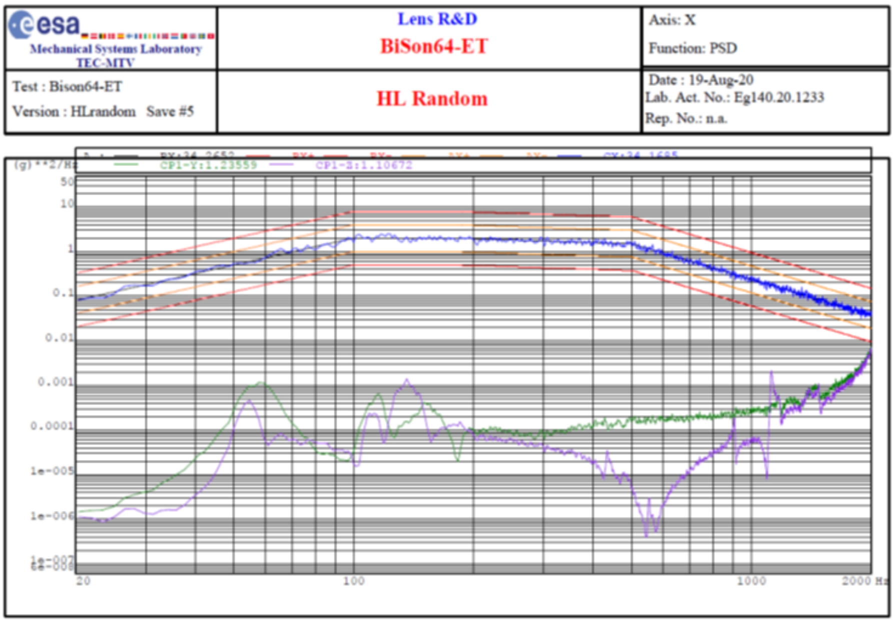


**Figure 9 34.2g random tests**

Although the sensor finally failed a 3000g pyroshock test because the bleed resistor released from the PCB, it was established that there was an amplification of more than a factor of 3 in the Z-direction while testing in X, leading to an actual test level in excess of 10.000g. Based on the results of these tests, the design has been improved but the shock tests were never repeated.

Despite this, there is confidence that the sensors will survive the lower 1500g level specified with sufficient margin and an opportunity is sought to redo the test in a cost-effective way in the near future.

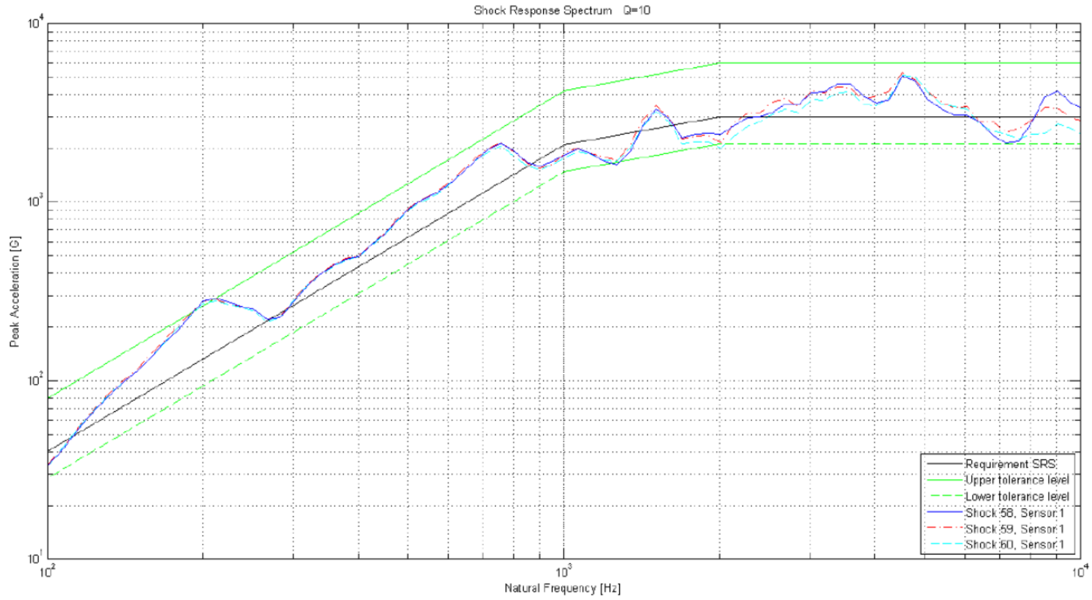


**Figure 10 spectrum of shock administered in X direction.**

## 7 Conclusion

The development project intended to lead to the availability of a small and radiation-hardened, true digital Sunsensor, currently running in frame of an ESA ARTES contract, is already successful even before the first iteration of the required Sunsensor chip (IPS+) is completed.

The development of a cost-effective testbed for the digital IPS chip led to the existence of the analogue MAUS Sunsensor for CubeSat applications. This sensor is the only known radiation-hardened CubeSat Sunsensor. As such it is small but potent and can be cost effectively offered to the market as the assembly and verification is performed using existing production and verification equipment. Its qualification was combined with the qualification program of the BiSon Sunsensors.

Even though the IBIS Sunsensor is not produced yet, preliminary design analysis has shown that it is reasonable to expect very good performance of this small sensor, and that it will turn out to be a small but potent sensor that can be cost effectively produced and used on the majority of satellites.

Therefore, it can be concluded that the MAUS is (and the IBIS will be) a small and potent product, much like a Jalapeno Pepper.