Qualification and flight of a cutting edge Sunsensor for constellation applications

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ABSTRACT

Satellites for a constellation can be build in a significantly more cost-effective way because the Non-recurring Engineering charges (NRE) can be spread over multiple units. A further significant cost reduction can be achieved if the units and subsystems are optimized for volume production and the units are produced in a continuous production line with a sustainable throughput. Though this optimized production can lead to significant improvement in cost effectiveness, this should in no way impair the reliability of the products. It can be reasoned that the approach implemented by Lens R&D will even increase the reliability of production as it allows for statistical process monitor and control of the product quality.

As reliability and cost effectiveness in volume production are core to the Return On Investment (ROI) for constellation owners, these properties have been core design drivers for the BiSon Sunsensors discussed in this paper.

After a design change that led to the development of an automated assembly robot, the cutting edge BiSon64-ET and BiSon64-ET-B Sunsensors developed by Lens R&D went through a full ESA qualification program. This means that for the first time ever, a Sunsensor optimized for volume manufacturing has finished a full ESA qualification program. A flight contract has been signed to fly 20 sensors on the two ESA science satellites making up the Proba-3 mission. Flight data however already will be received earlier, through a precursor 3U Cubesat mission, flown through the Dutch company Innovative Solutions In Space (ISIS).

This paper focusses on the novel manufacturing approach used, the qualification performed and the processes needed to cost effectively produce large quantities of Sunsensors for constellation applications.

Key words: Sunsensor, high reliability, volume production, low cost, RoS, ROI

BISON64-ET AND ET-B

The BiSon64-ET and ET-B Sunsensors (see Figure 1 and Figure 2) are Extended Temperature fine Sunsensors optimized for volume production.

Figure 1: BiSon64-ET with pigtail

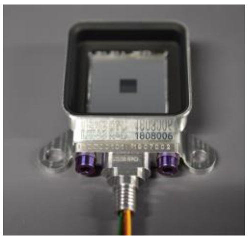

Figure 2: BiSon64-ET-B with pigtail

The 64 indicates that the Field of View (FoV) in diagonal is larger than 64 degrees, as specified in the interface control document and interface control drawing (which can be downloaded from https://lens-rnd.com) and shown in Figure 3. This allows the sensors to cover a full sphere (with overlap) by placing one sensor on each face of a cubical satellite.

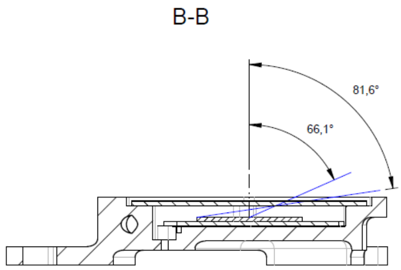

Figure 3: BiSon64-ET diagonal FoV

The sensors have an on-axis FoV of 58° and are built on basis of a housing integrated, wire-bondable connector with ceramic insert and a sapphire membrane.

The housing integrated, wire-bondable connector allows the use of gold wirebonds internal to the sensor as the best and most reliable connection technology.

The use of an automatic wirebonder for the assembly of the sensors avoids cleaning the sensors after assembly.

The excellent match between the various CTE's of the materials used and the special glue developed for Lens R&D, leads to a very wide operating temperature range and makes them suitable for direct solar panel mounting.

In order to meet the specified -125°C to +125°C operating temperature range, a special glue is developed and ESA qualified (outgassing, long-term survivability at high temperatures and resistance to thermal cycling).

The BiSon64-ET-B is a BiSon64-ET to which a straylight reduction baffle is mounted that limits the sensitivity to Earth albedo signals coming from outside the measurement field of view.

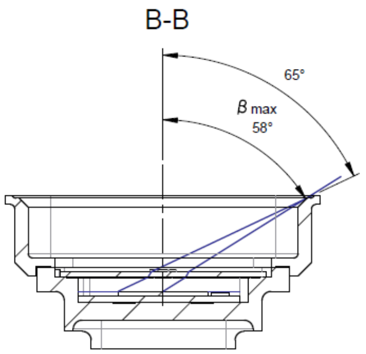

Figure 4: BiSon64-ET-B on-axis FoV

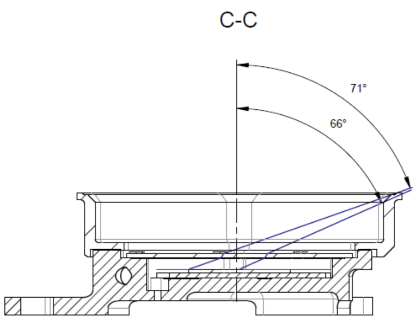

Figure 5: BiSon64-ET-B-diagonal FoV

As can be seen by comparing Figure 3 and Figure 5, the baffle is designed in such a way that the measurement FoV is kept, but only the Sun exclusion FoV is limited. This way the reduction of signals reflecting from Earth and Moon while outside of the measurement field of view are reduced to the largest extend possible.

In addition, this baffle eases accommodation on the spacecraft as it prevents reflections on other spacecraft parts from disturbing the Sun attitude measurements.

The BiSon64-ET and ET-B are an evolution of the regular BiSon64 and BiSon64-B sensors which have been selected (and are flying) on several missions.

The increased ease of accommodation and cost effectiveness of the BiSon64-B has led to selection by several customers of this sensor for a multitude of missions. Luxspace is flying the sensors on their ESAIL mission and recurring TRITON platforms. SSTL is flying the BiSon64-B on a multitude of missions and is expected to fly the BiSon64-ET-B on any new mission to be designed. General Atomics has selected the BiSon64-B sensor for their OTB2 and OTB3 platforms etc.

The only mission currently envisaged to fly the sensors without baffle is the ESA Proba-3 mission, where the majority of the 10 sensors per satellite will be used in coarse Sunsensor mode (by taking the four generated currents together and sacrificing the dual axis sensing).

PRODUCTION OPTIMIZATION

Realizing that the satellite market is changing and discussions on constellations of small satellites were getting more and more serious, Lens R&D started to design the BiSon Sunsensors back in 2012, well ahead of tangible plans for constellations like Oneweb, LEO-Sat, Starlink or Kuiper.

Although some of the associated companies have gone into bankruptcy already, there is an undeniable tendency to seriously consider building large constellations. Due to the required production volumes, components and systems for such constellations can no longer be manufactured on basis of extensive manual labor as has been common practice in the space industry for decades, but will have to implement automation to the largest extend possible. This is needed in order to achieve the required cost savings that are core to the affordability of these large constellations. In order to ensure a good return on investment (ROI), a high reliability for the satellites is needed. With the proper design approach, it is possible to both decrease the price per sensor for volume production and increase the reliability at the same time. This drastically increases the quality to cost ratio and will enable the design of cost effective but highly reliable satellite constellations.

Core to the design of the BiSon Sunsensors (intended to have the highest possible quality to cost ratio in volume applications), is the use of the housing integrated wire-bondable connector. This connector technology, developed in cooperation with Axon Cable, allowed the sensors to be build using wirebonding only.

The use of a high accuracy laser-cut sapphire membrane and careful balancing of the product tolerances led to a high reliability sensor that could be cost effectively produced in smaller batches while being optimized for larger series. (Bison64 and BiSon64-B)

In the meantime, Lens R&D was considering to expand the operating temperature range by a more careful tuning of the CTE of the various materials and use of a ceramic injection molding process. When Lens R&D got a substantial ESA contract to show the capabilities of such a sensor for direct solar panel mounting, the sole membrane supplier able to produce the required accuracy dropped out (because they saw better profit margin on other products). This essentially led to a major switch in the manufacturing approach, first based on manual assembly with high tolerances on components, but now switching to an active alignment by means of a to be designed assembly robot with less accurate components.

The development of this robot has been successfully completed and this so-called MAMA-tool (Mechanical Automated Membrane Aligner) has been successfully commissioned and turned Lens R&D into the only company capable of assembling high reliability Sunsensors in a fully automated setting.

Figure 6: MAMA-tool in salles-noir

The MAMA-tool is positioned in the Lens R&D salles-noir. The room is dubbed this way because in French a cleanroom is called salle blanche (white room) but our cleanroom is painted black and gray to reject straylight as much as possible to ensure the highest assembly and calibration accuracy.

As the tool must position and assemble the membrane with micrometer precision, a special stable table had to be developed along with the tool to ensure stable and repeatable performance. Although we are still in the process of gathering sufficient statistical data and determining the offset parameters needed to achieve even more optimum performance, the first results have been very promising and we expect to be able to report even further accuracy improvement over the coming year.

To look at the improvement in accuracies in more detail, we can compare the results obtained in an ESA ARTES (Advanced Research for TElecom applicationS) program with current results. Within this program we found that all sensors stayed within the quoted 3.5° non-calibrated accuracy as shown in below Figure 7. (sensor number 7 was a reject)

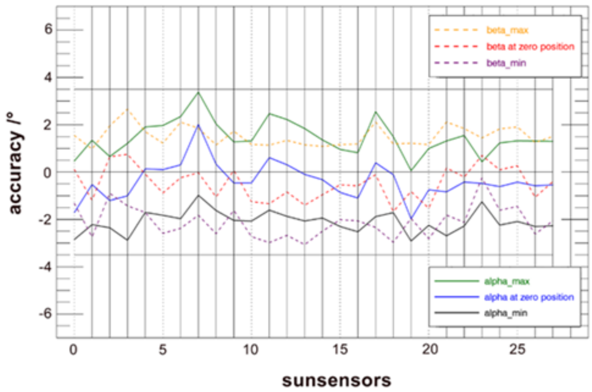

Figure 7: non-calibrated accuracy for manual assembly

This graph shows the maximum errors measured over the entire field of view for a series of 28 BiSon64 sensors. These sensors were assembled manually while relying on the component accuracies of the used components and proficiency of the operator.

While looking at the profiles it can be noted that the error band is more or less constant in most cases, it was established that a major part of the inaccuracy was related to the shift of the membrane in X/Y direction with respect to the center of the four-quadrant photodiode. Most of this shift was associated with operator proficiency as demonstrated when a new operator assembled a batch for which a number of units had to be rejected due to a membrane shift that led to out of spec performance.

This human error factor has now been mitigated to the largest extend by the MAMA-tool.

MAMA-tool operation

The MAMA-tool has a build-in Sun simulator and actively aligns the membrane to the photodiodes. After reaching the optimum position, the membrane is fixed in position and optimum accuracy is ensured.

Data obtained on a first set of sensors shows that the accuracies are at least as good as previously obtained with manual assembly (if the manual assembly is correctly performed).

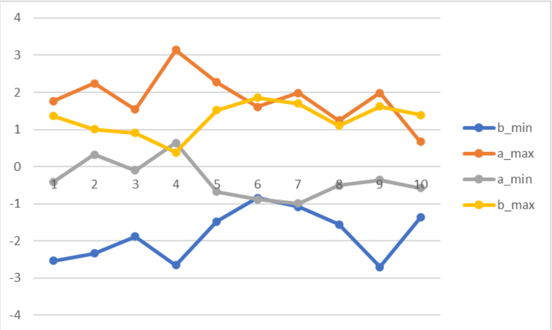

Figure 8: non-calibrated accuracy for automatic assembly

It should be noted that this graph is depicting the results of the very first MAUS (Figure 9) units assembled with the MAMA-tool.

The MAUS is a BiSon sensor which is not based on the housing integrated connector technology but uses a standard nano-D connector, as often used in the more reliable nano-satellites. This provides the units a lower profile, which in turn allows them to be used on nano-satellites with less accommodation restraints.

Figure 9: MAUS Sunsensor

The MAUS uses a slightly different titanium housing, the same membranes and the same photodiodes as the BiSon Sunsensors. This means that for instance radiation tolerance is the same and accuracy is comparable for both sensors. As this sensor is also assembled with the MAMA-tool, the results can be used to evaluate the performance of the assembly process.

As shown in Figure 8, the accuracy obtained for the very first set of sensors already was as good or better than the batches that were manually assembled. Due to a large reduction of manual labor the tool has therefore already increased production reliability. It is to be expected that the use of the tool will significantly increase the production consistency over batches.

From the gathered data however, it can be seen that there is still a significant potential for improvement. Below Figure 10 shows that the performance is significantly improved if both X and Y offsets are corrected.

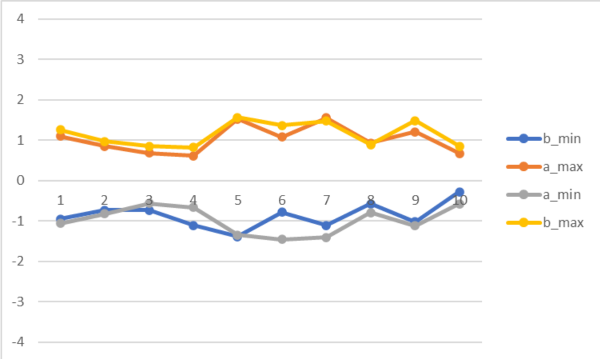

Figure 10: Accuracy for automatic assembly after offset correction

Above graphs basically show that with only an offset correction the accuracy increases from 3.5° 3σ to 2° 3σ, which is well below what most missions require (3 to 5 degrees is commonly requested) and this can avoid the implementation of calibration compensation. This in turn significantly de-complicates on board software and required storage capacity, as the solar aspect angle can be simply calculated by using below formulas:

$$S_a - C\alpha = \frac{Q_1 + Q_4 - Q_2 - Q_3}{Q_1 + Q_2 + Q_3 + Q_4} = \frac{\tan(\alpha)}{\tan(\alpha_{max})}$$

$$S_b - C\beta = \frac{Q_1 + Q_2 - Q_3 - Q_4}{Q_1 + Q_2 + Q_3 + Q_4} = \frac{\tan(\beta)}{\tan(\beta_{max})}$$

Formula 1 angle calculations

In the above formula, $C\alpha$ and $C\beta$ are the offset parameters and α_{max} and β_{max} will always be similar and represent the maximum FoV angle.

It is to be expected that with increased experience the membrane positioning can be improved to such an extend that a 2° 3σ can be guaranteed over time, but for the time being the specified 3.5° 3σ non-calibrated accuracy will be maintained. This is one of the areas where volume production experience and statistical process control is expected to contribute to a higher overall process reliability and product quality.

ASSEMBLY SEQUENCE AND REPEATABILITY

The assembly sequence for a BiSon64-ET has been optimized over time to be highly efficient and repeatable and based on a high re-mounting accuracy, ensured by the mechanical interface as shown in below Figure 11.

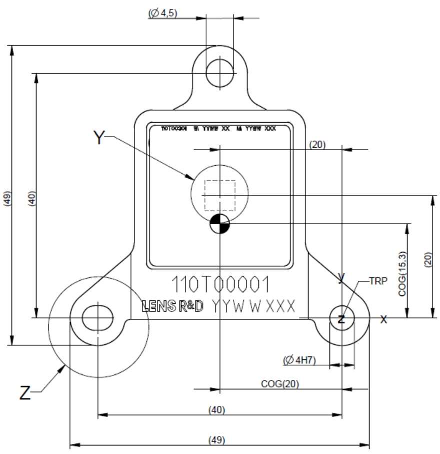

Figure 11: Mounting pattern

A highly accurate re-mounting of the sensor is ensured by means of three mounting holes. The reference hole as shown on the bottom right has a 10µm tolerance and the slotted hole on the bottom left has the same tolerance on the slot. This scheme ensures a proper alignment of the sensor in rotational sense to both our assembly and calibration tools and thus also in the final when the same mechanical mounting interface at satellite level is used. The oversized hole in the top middle ensures that the sensor is bolted flat to the satellite and ensures alignment in the Z direction.

Using this same mechanical interface, a pre-assembled sensor housing is mounted in a vision assisted pick and place die bonder. This equipment mounts the diode to micrometer and sub degree precision in the middle of the sensor to ensure the measurement axis is aligned with the mechanical axis.

After curing of the glue, the housing (with diode mounted) is assembled further in an automated wire-bonder. This process provides very reliable interconnects without the need for post assembly cleaning.

This semi assembled unit together with a membrane is put in the MAMA-tool for automated assembly of the membrane which is actively aligned as previously discussed.

As this tool contains its own Sun simulator, it can be used to check the Zenith alignment of the membrane after mounting and will not work unless the sensor is fully functional. This basically provides certainty that the sensor is fully functional directly after assembly, thus avoiding a functional check. In addition, there seems to be a very strong correlation between the final accuracy and the zenith accuracy after assembly. Given the fact that this can only be certified after a statistically significant number of sensors, no percentage can be attached to this yet, but over the more than 50 assemblies performed not a single instance was found where a sensor was found to be out of specification. This means that there is a very high degree of confidence that any sensor assembled with the MAMA-tool will meet the accuracy specifications as stipulated in the product specification.

With the MAMA Tool it has shown that it is possible to assemble between 8 and 10 sensors a day. For a sustained production scenario and after full optimization of the tool it is expected that this can potentially be increased to 12 sensors per working day.

Taking a conservative 8 sensors per normal working day and taking holidays into account, with a single tool would some 2000 sensors a year can be produced, which should be sufficient to cover most programs currently being realized or discussed.

Next to the BiSon Sunsensor production, we are currently working on the development of different types of Sunsensors like the MAUS and a small true digital Sunsensor dubbed IBIS. It therefore has been decided to build a second MAMA-tool in order to have one tool for production and another for development (and as a back-up for production). This tool will basically double the sustained production rate obtainable.

Therefore, it can be safely concluded that the BiSon Sunsensors are suitable for constellation applications even while considering very large constellations like Starlink or Kuiper. This is not only due to the basic design but also due to the deliberate selection of scalable and well controlled processes and development and commissioning of the appropriate tooling.

DESIRED PRODUCT PROPERTIES

In essence, there are four major parameters important for any sensor or system used in constellations:

1) Performance
2) Reliability
3) Cost
4) Consistent quality and sustained delivery

If we reflect on these desired properties, it is obvious that a minimum performance shall be achieved as otherwise the sensors will not be useful for the task they are intended to perform. In order to ensure the maximum possible lifetime for the mission, a safe mode sensor like a Sunsensor should have maximum reliability. Furthermore, the lowest possible costs are always seen as a major advantage as it will drive the level of initial investments needed. It should be realized that the total costs are driven by more than the product cost only.

As the non-calibrated performance obtained by the BiSon Sunsensors is more than sufficient for initial safe mode positioning (generally requiring 3° to 5° accuracies), the final implementation can be very cost effective. Not needing any calibration or compensation data upload allows to mount the sensors on a satellite in a connect and forget approach without performing any other checks but a functional one.

Although the current pricing as listed on the Lens R&D website is already very competitive as compared to other high reliability solutions, this price can be further reduced for constellations large enough to allow setting up a constant manufacturing flow. For the moment the pricing is still determined by a batch size of 25 to 50 units per batch and includes starting up each batch separately. In addition, some of the technologies selected are optimized for volume production and require significant Minimum Order Quantities (MOQ) in order to keep the production attractive.

Allowing to startup a continuous production will lead to a significant cost reduction as it will lead to:

- Lower prices for the components as frame contracts can be initiated
- Lower documentation costs as documentation can be standardized
- Lower costs for managing and storing MOQ stock

Starting up volume production will need a lead time of approximately 10 months and is only sensible if production is kept above a certain level for more than a similar period. This sustained production level however can be as low as 20 units per Month in order to make it attractive to change to continuous production mode instead of the current start/stop mode. It is quite obvious though that a continuous production mode will lead to both a more consistent quality and a sustained delivery rate that can be altered flexibly when a timely warning is given.

QUALIFICATION PROGRAM

Repeated and reliable production of high quality Sunsensor is only one part of the equation. As Reliability Of Service (ROS) and Return On Investment (ROI) are very important aspects for end-users and investors, any space component to be used in a commercial application needs to be rigorously qualified. Without a proper qualification, entities like ESA, NASA and large system integrators will not accept any component for use in any of their high value systems.

In order to achieve such a qualification, Lens R&D started an ESA GSTP program in November 2017 to lead to a full ESA qualification but even before the actual qualification started, we ran into the before mentioned supply chain issue leading to the development of the MAMA-tool. The development and qualification of this tool in turn led to a delay in the qualification program of approximately one year. The qualification was finally completed in November 2019 only.

In order to use the sensors without any further delta qualification for just about any mission, this qualification program has been extremely stringent and covered most missions with a significant margin. In addition, to save time, both the ECSS qualification and life test programs were combined in a single qualification flow. A visual representation of the final program is given in below Figure 12.

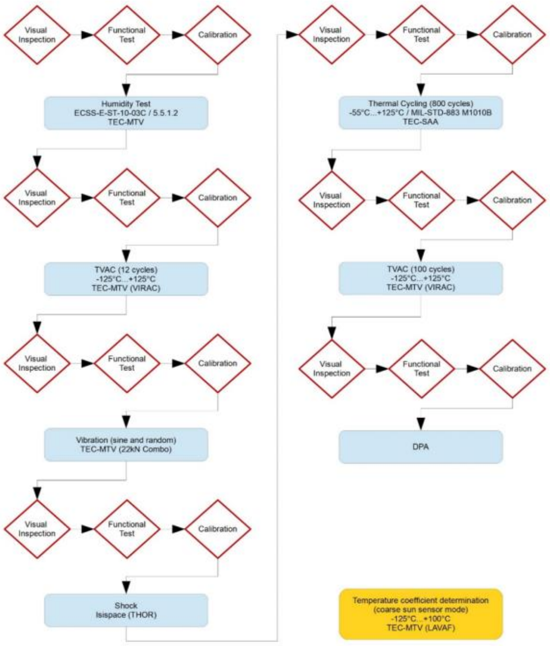

Figure 12: GSTP qualification program

This program consisted of a standard qualification program according to ESA ECSS-E-ST-10-03, with the exception of some additional thermal vacuum cycles before vibration testing and a lot more thermal cycles at the end. The initial thermal vacuum cycles were added to cover the thermal balance testing generally performed during on-ground satellite testing but not included in the general ESA qualification approach. In addition to the qualification for the thermal balancing tests, the cycles were also added as a risk mitigation measure because meeting the extremely wide temperature range was seen as the largest risk for the program. The large number of thermal cycles at the end of the program were added in an attempt to combine qualification and life time testing in a single program.

The humidity test program according to ESA ECSS-E-ST-10-03 is meant to qualify equipment for ground handling and consists of various transfers and dwell periods with varying humidity levels as shown in below Figure 13

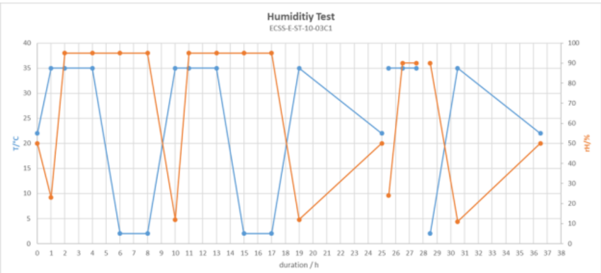

Figure 13: Humidity test profile

In order to administer the profile correctly some dedicated modifications had to be made to the humidity chamber at ESTEC but in the end the tests were correctly performed without major effects on the performance of the sensors and the rest of the testing could commence.

In order to test the extreme wide temperature range, a special test setup called the VIRAC available at ESTEC was used. This facility consists of a vacuum vessel with a build in elevator stage which moves the test specimen between the upper compartment (during operation illuminated with a 1AM(0) Sun simulator and a liquid Nitrogen cooled lower compartment.

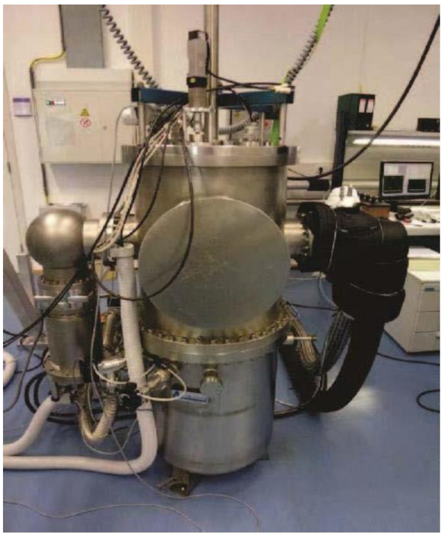

Figure 14: VIRAC setup (with covered Sun entrance port)

Below temperature profile acquired during these tests shows that the BiSon64-ET-B did meet the qualification temperature levels of -125°C and +125°C but the BiSon64 without baffle went even between -130°C and +130°C during these tests.

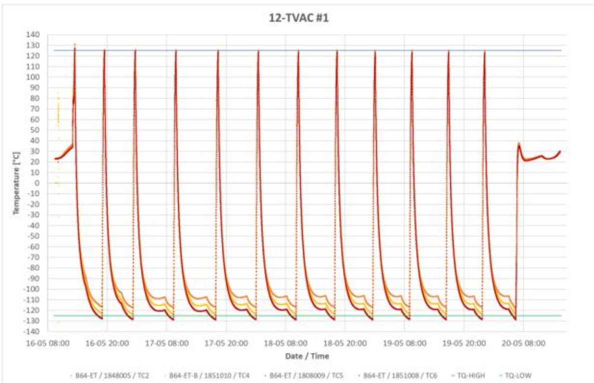

Figure 15: 12 thermal cycles test results

Post initial thermal cycle tests, no significant variations in performance have been established, showing the extreme temperature withstanding capabilities of the sensors.

After the first thermal cycles a vibration test program was concluded consisting of 40g sine in three axis and 41.6g random in three axis (120 seconds). In order to be able to test up to six sensors at the same time a dedicated test adapter had been developed before which has been re-used for this program. The configuration of this test for Z axis vibration testing is shown below.

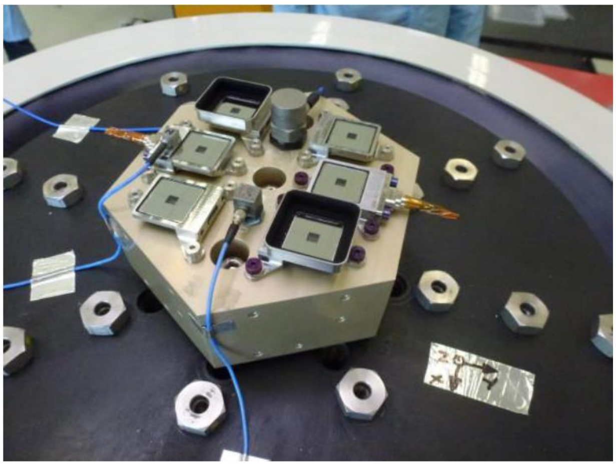

Figure 16: Z axis vibration testing

Some of the profiles acquired during the testing are shown below.

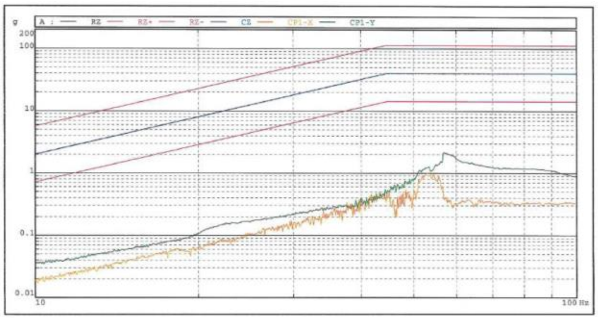

Figure 17: Sine vibration profile

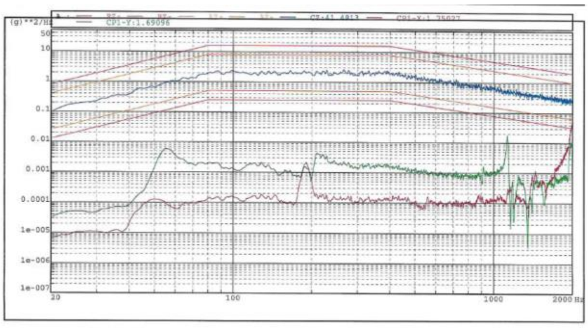

Figure 18: Random vibration profile

During these vibration tests, the eigenfrequency of the units has shown to be above 2000Hz which means that they can be seen as a rigid body for any sense and purpose.

After vibration testing the units were shock tested.

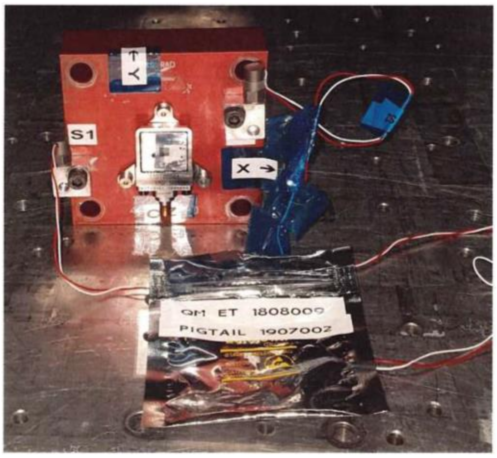

Figure 19: Pyro shock test setup Y axis

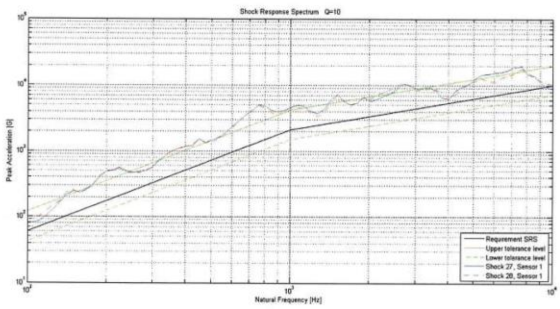

Figure 20: Pyro shock level

As can be seen in Figure 20, the applied shock level exceeded the specification significantly during these tests, causing the BiSon64-ET-B to lose its baffle. The BiSon64-ET however survived the excessive shocks without issues and all units performed without performance degradation.

In order not to hold up the base sensor's qualification program, it has been decided to continue the program with the BiSon64-ET only and continue with the thermal cycling.

This thermal cycling consisted of 800 thermal shock cycles between -55°C and +125°C according to MIL-STD-883 Method 1010B and were performed in a dedicated thermal shock setup again available at ESTEC. (see Figure 21). Unfortunately (for reasons to be discussed later) this chamber did not have a nitrogen flushing capability connected.

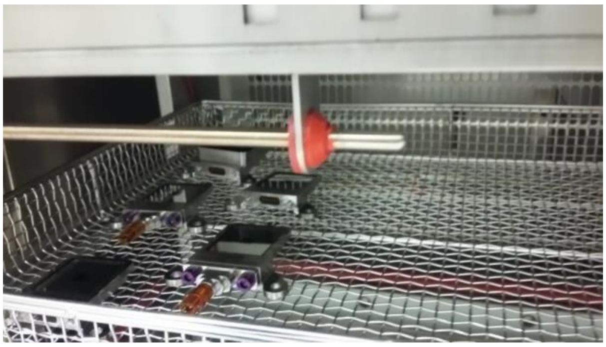

Figure 21: Sensors in thermal shock chamber

Measurements after the thermal shock tests showed a clear deterioration of the calibrated performance although the units were still within the specified non-calibrated accuracy.

Despite this deterioration, it was decided to complete the program by continuing with the agreed upon 100 TVAC cycles -125°C..+125°C, again in the before mentioned VIRAC facility. This has led to the thermal cycle profile as shown in below

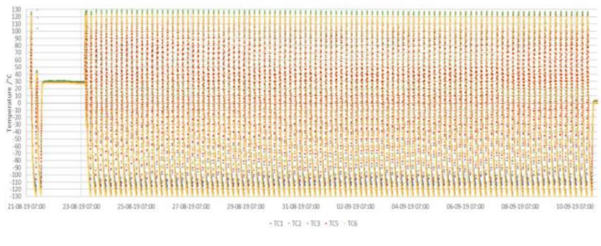

Figure 22: 100 TVAC cycles

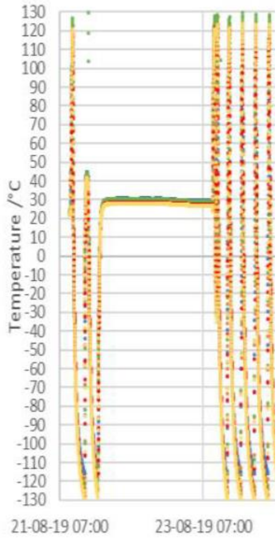

Figure 23: enlarged portion of thermal cycling profile

At the end of the thermal cycling tests, no further deterioration of the performance has been found and the program was concluded with a Destructive Physical Analysis (DPA).

The DPA showed a clear deterioration of the epoxy specifically developed for this application. Further extensive testing showed that the deterioration can be attributed to repeated boiling of and freezing of moisture present in the thermal shock chamber (due to the lack of nitrogen flushing). Furthermore, this testing showed that the deterioration only takes place above 100°C

As the sensors had shown the ability to survive 12 thermal vacuum cycles between -125°C and +125°C and in another life test a similar glue and the diodes went through 36.000 thermal cycles between -80°C and +85°C without failing it had to be concluded that the moisture in the thermal chamber was a major contributor to the failure of the glue connection. As the failure of the epoxy connection didn't lead to a sensors failure but merely a deterioration in performance, it can be concluded that the sensors survived the entire qualification program albeit without meeting the 0.5° accuracy requirement for the calibrated accuracy.

CONCLUSIONS ON QUALIFICATION PROGRAM

Based on the qualification program performed a number of conclusions can be drawn:

If the life time testing program had not been combined with the ECSS qualification, the BiSon64-ET would have been qualified with a high degree of certainty, especially when the appropriate test conditions would have been provided during the thermal cycling.

Analysis showed that the glue connection between the housing and the baffle has insufficient margin to survive testing at 10.000g shock levels and a failure as a result of the over-testing could have been anticipated and must be avoided in the future.

As the units survived a very stringent environmental test program consisting of 40g sine, 41.6g random and more than 10.000g after surviving 12 thermal cycles between -125°C and +125°C as well as 36.000 thermal cycles spanning -80°C to +85°C in another test program, we feel confident that the sensors are suited for the majority of space programs even though the formal qualification has not been completed yet due to the failure during thermal cycling.

FUTURE ACTIVITIES

Due to the failed qualification the sensors still do not have the formal label "ESA qualified", which is highly unfortunate. In order to ensure that this status is achieved at the earliest possible convenience, a last and final qualification program has been agreed upon. This program will entail a full qualification program according to the ECSS standard with no deviations from that program (so excluding the 12 TVAC cycles in the beginning and including 10 TVAC cycles in the end only). Next to this the shock administered during the pyro shock testing will be limited to a level of approximately 3500g in order to cover the majority of flight programs while ensuring the survivability of even the ET-B units.

Parallel to this program (as per the ECSS requirements) a limited life time test program will be started consisting of four sets of thermal cycles.

1) 500 thermal vacuum cycles -45°C..+85°C

2) 500 thermal vacuum cycles -45°C..+85°C

3) 1000 thermal vacuum cycles -45°C..+105°C

This life test program will only establish the survivability for the Proba-3 mission with margin and it is the intention to perform further testing outside the frame of the intended program.

In addition to the new qualification cycle, a new batch of photodiodes will be qualification tested so the availability of space grade (and properly qualified) detectors is ensured for the first period of time to come.

Kick-off for the new program is agreed with ESA for Qs/2020, the first results are expected by the time of this conference.

ACKNOWLEDGMENTS

We would like to express our gratitude to the Dutch national Space agency NSO and the European space agency ESA for the continued financial and technical support for the development and qualification efforts. Our gratitude extends to the various technical and quality control support staff working within the supply chain for continuing to answer our sometime extremely detailed and relentless stream of technical questions.

CONCLUSIONS

Due to the availability of the MAMA-tool, Lens R&D is the only company known to be able to align and assemble high reliability Sunsensors in a fully automated way. This gives us confidence in the capability to supply even the largest constellations currently under discussion with true high reliability Sunsensors that can be used in a connect and forget type of approach. Current manufacturing capability is limited to some 2000 sensors a year but production capacity is expected to be double before Q4/2020. For these manufacturing capabilities there will be no change in the manufacturing flow, scaling up is purely a matter of logistics. A continuous production flow will not only lead to lower prices, but is expected to lead to even higher quality sensors as there are clear signs that process optimization via statistical process control can be obtained.

Although initially intended for direct solar panel mounting on Geostationary telecom satellites, the BiSon64-ET and BiSon64-ET-B can therefore be considered to be true high reliability constellation Sunsensors suitable to fly on any mission in any orbit.

Even though the formal qualification has not been completed successfully yet and a re-run is needed to correct for some testing related issues, there is a strong confidence that the sensors will be able to survive just about any mission currently under construction without issues. A re-run of the qualification program starting in Q2/2020 is scheduled to be finalized before the end of Q4/2020 and is expected to confirm this capability.