To boldly go where no sunsensor has gone before.

Johan Leijtens, Johan Uittenhout, Alexander Los, Stefan Schmidt

Lens Research and Development

Space Business Incubation Centre (SBIC)

Kapteynstraat 1 2201BB (the Netherlands)

Email: jls@lens-rnd.com Tel: +31 (71) 2020 123

Abstract: Lens R&D has built and tested *sunsensors* (in frame of an ESA Artes 5.2 contract) that exhibit an unprecedented operating temperature range. A combination of ceramic injection moulding and careful material engineering has led to sensors that have shown to be able to operate over a temperature range spanning -125°C to +125°C.

Figure 1: BiSon74-ET-RH

The titanium housing and 2mm sapphire window provide 3mm Aluminium equivalent circumferential radiation shielding, which (together with the diodes that have been tested up to 1.1Mrad and 10^{16} 1MeV electrons) leads to sensors that are capable of surviving even the most demanding radiation environments.

This paper describes the tests performed and results obtained during the test program which is covering on-ground and launch loads but must be augmented with a thermal cycling program before a full qualification can be claimed. Due to some issues experienced during the test program the actual test levels applied have been significantly more severe than foreseen in first instance but the sensors were still functional at the end showing the resilience of the BiSon74-ET-RH to environmental loads.

1. INTRODUCTION

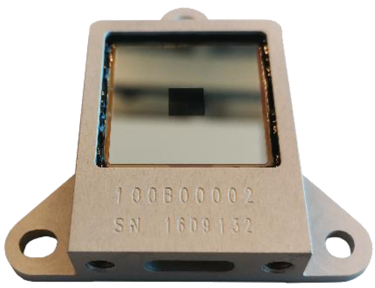


Figure 2: BiSon64

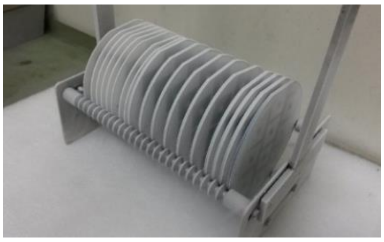
Lens R&D is a small company specialized in the design and manufacturing of high reliability *sunsensors*. The main product is called BiSon64 and is a fine sunsensor build by using radiation hardened four quadrant photodiodes, sapphire windows and an aluminium housing with a wirebondable housing integrated connector. These components give the BiSon64 a unique combination of properties combining a low mass and profile, with high reliability and cost effective production. The BiSon64 has been fully qualified and has been delivered to several customers in Europe.

The main limiting factors for the BiSon64 are the aluminium housing and the PEEK connector insert as they limit the operating and storage temperature ranges. The BiSon74-ET-RH is basically an enhanced version of the BiSon64 where the Aluminium housing and PEEK insert have been replaced by a Titanium housing and injection moulded ceramic insert. The improved CTE matching obtained by doing so in combination with careful selection of the glues used has led to a design, that has shown to be able to at least survive ground testing and launch conditions successfully. Further, by increasing the membrane thickness from 0.65mm to 2mm sapphire (equivalent with 3mm Aluminium) the radiation tolerance has been increased. This in turn caused the addition of the ET to the name. The 74 instead of 64 is an indication that the measurement field of view has increased from 64° in diagonal to 74° in diagonal. Although it is not expected that the high number of thermal cycles associated with prolonged operation in either GEO or LEO will present any problems (due to the materials and especially the glues used), it will take some time before this capability is demonstrated.

2. PRE-TESTS PERFORMED

In frame of the Artes 5.2 program, two series of 6 BiSon74-ET-RH sensors were built in order to reduce some of the risks in the program. This was done however only after a number of pre-tests were performed on component level showing that the various components used were capable of sustaining low temperatures. These tests were performed on various components belonging to precursor units dubbed BiSon64-ET. Much like the BiSon64 these units had a 64° field of view in diagonal and a thin (0.65mm) sapphire membrane.

In essence a fine sunsensor is less complex. It consists of a membrane suspended above a four-quadrant photodiode. In order to keep these two parts together a housing with integrated connector is used where the diode is isolated from the housing by means of a ceramic. This means essentially there are only four parts and their connections to test (membrane, housing, ceramic and diode).



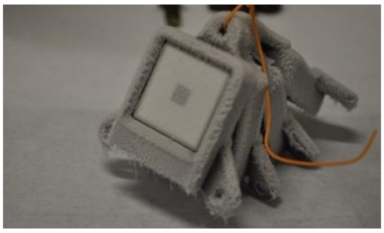


Figure 4: LNOX test of housing-sub

All membranes (also the ones we use for the BiSon64 are always tested by dipping them in liquid nitrogen, as this has proven to be a very effective way to identify any inclusions in the coating or adhesion problems. Therefore, the only test we needed to do was test if the 2mm wafers can also withstand the LNOX dipping (which proved to be no issue).

Therefore, the connector and membrane to housing glued connections were left as the main risk at package level. These components have been tested in various stages of assembly by means of dipping in liquid nitrogen. These tests happened on inserts with the pins mounted, connectors mounted in the bare housing and membranes mounted on the housing with connector.

Although during these tests several small issues were detected, (some of which have been corrected immediately) no major issues were found and it was decided to continue with the program. The tests did indicate however that the main risks were associated with the glues used.

Last but not least, the glued connections between the ceramic and the housing as well as between the photodiodes and the ceramic had to be tested. As this basically entails building full sensors, it was decided to do these tests at sensor level only, but in two different configurations so as to optimise the chances of success.

Between the BiSon64-ET and the BiSon74-ET-RH a number of design changes have been made in order to test a sensor that is optimised for use on one of the major mega-constellations currently under discussion. As for this constellation, a larger field of view is desired, no hemispherical coverage is required but the radiation tolerance has to be so high that it cannot readily be obtained with coarse sunsensors, it seems logical to use a fine sunsensor with an extended field of view and additional radiation shielding. Trying to meet the goals of this particular high volume application has led to the development of the BiSon74-ET-RH.

3. THE QUALIFICATION TESTING PERFORMED

As mentioned before, in November 2016 two series of 6 devices have been produced which (as also standard for the BiSon64) received 10 thermal shock cycles and a PIND test at First Sensor Lewicki (GER). Due to the limited temperature range of the standard BiSon64 normally the tests are limited to -45°C and +85°C, but in case of the BiSon74-ET-RH the full military temperature range was used of -55°C till +125°C.

This dual chamber thermal shock test according to MIL-STD-883 Method 1010A is performed as a workmanship test and will be performed for any future device as part of the factory acceptance testing. The Particle Induced Noise Detection test according to MIL-STD-883 Method 2020A consists of 6 periods of 20g sine each followed by 3 pulses of 1000g 1ms in-between the vibration periods. This means that each unit will see 12 1000g shocks in total after the thermal cycling and before final electrical inspection and shipment to Lens R&D for calibration.

Although this type of testing is a bit harsh for standard equipment it is part of a standard military hybrid manufacturing process and because our sensors should be capable of sustaining these tests, we have decided to include them in the standards production program so as to avoid individual acceptance vibration testing and safe costs for our customers.

After the factory acceptance testing two batches of 6 sensors were send to Lens R&D calibrated and 6 of the sensors were put through a compact but effective risk mitigation test sequence. This program consisted of:

1. Calibration,
2. 12 thermal vacuum cycles -125°C till +125°C
3. Calibration
4. Vibration tests (3 axis 30g sine and 38.9g random)
5. Calibration
6. Pyro shock testing (3000g and 10.000g)
7. Calibration

As flight hardware typically only goes through three thermal vacuum cycles and 6 in case an issue was found with the correlation between test data and the thermal model, the twelve cycles mean we have a margin of 2 over the on-ground thermal cycles. As vibration and pyro-shock testing are intended to simulate the launch environment one could state that the test program provides evidence that the sensors withstand on-ground testing and launch. This leaves high endurance thermal cycle testing as the main issue before a full qualification can be claimed. As after launch there are no other significant mechanical loads to be expected than those caused by differences in the thermal expansion of the materials used, the risk of the sensors failing in orbit is completely different from the risk of the sensors failing during launch. The risk of sensors failing during launch was deemed to be the largest risk. As this risk can only be properly mitigated by going through the standard manufacturing sequence and above program, this was the minimum program required to mitigate the largest risks in the program.

4. TEST RESULTS

Initial calibration of the sensors showed very nice results, an example of which can be seen in below

Figure 5.

It should be noted that these errors are determined on basis of the general formula only, so without the use of any calibration table. The large errors at the ends are caused because the sensor goes out of its measurement range while still calculating the angles as if the sensors are within measurement range. From the graphs, it should be obvious that an accuracy of 1° (while using a calibration table) can be guaranteed quite easily.

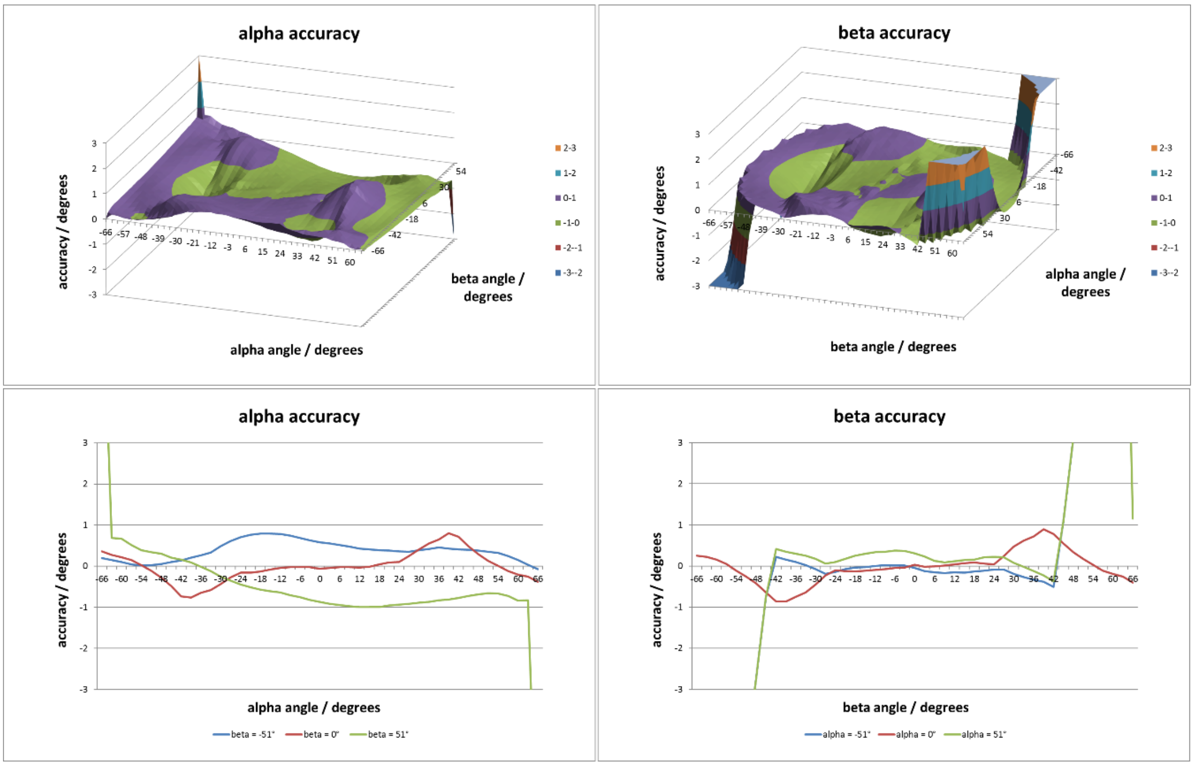


Figure 5: Errors in alpha and beta of BiSon74-ET-RH – SN1637030

The thermal cycling was performed in ESA's VIRAC facility which was tuned to get the highest possible rate of change by adding some heaters in the upper compartment which is also illuminated by means of a solar simulator. The lower compartment contains a liquid nitrogen dewar and the test samples switch between compartments by means of an internal elevator.

Photo 1: *ESA's VIRAC facility*

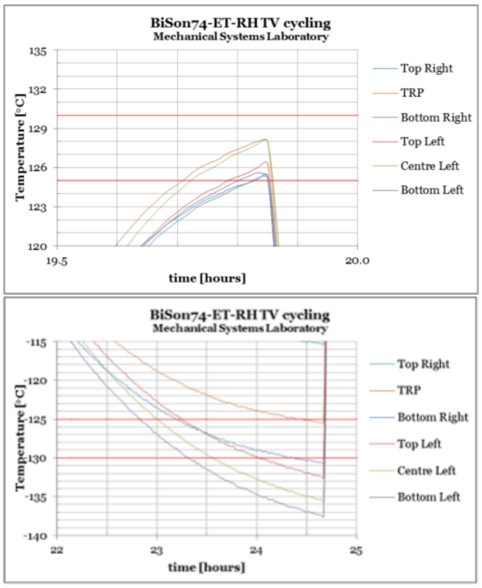


Figure 6: TVAC - reached test limits

Due to speed optimisation and heat leakage through the connection wires of the connected sensor used for signal monitoring, the temperature spread for the low temperatures was above the normal ±3K test margin. The coldest sensor went down to as low as -138°C and the hottest sensor stayed above -116°C.

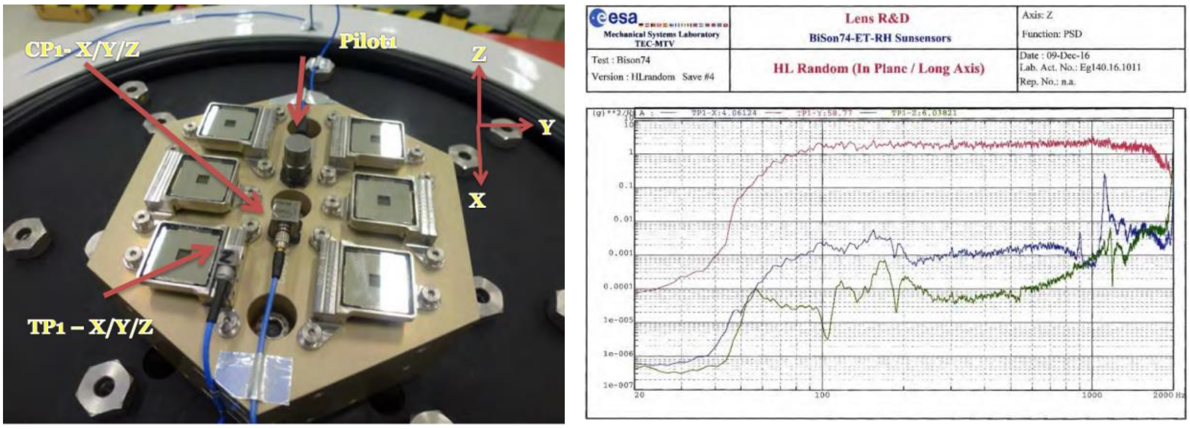


Photo 2 vibration testing setup and administered vibration profile in Y

Also, the vibration testing did not go flawlessly as due to saturation in the pilot channel, the random vibration levels went up to as high as 58.77g during Y axis testing. Fortunately, this did not lead to any sensor failures and the test program was continued with pyro shock testing.

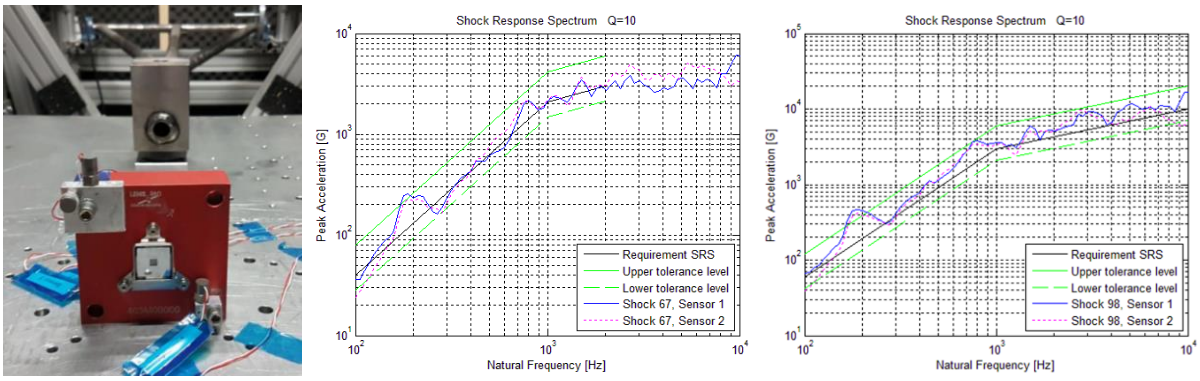


Photo 3 THOR facility at ISISpace and measured shock profiles

Contrary to the previously described tests, the shock tests were not performed at ESTEC, but at ISISpace in Delft. The setup was tuned to provide the specified 3000g shock very nicely. Because there was some time left on the testing day and Lens R&D wanted to scout the limits of our sensors, one out of three sensors was put through a much heavier shock loading basically determined by the limit of the setup as provided that day. This shock which was at least 10.000g but could also be argued to have been 15.000g did not damage the sensor either as proven by the post shock calibration.

5. CALIBRATION RESULTS

The calibration results obtained during the various stages of the program proved to be very interesting.

Normally spoken a fine *sunsensor* uses a generic formula to determine the actual sun angle coarsely, and a second interpolation step in combination with calibration tables to find the actual sun angle. After performing this interpolation step it is more difficult to see how the accuracy is changing and evolving due to added interpolation errors and uncertainties.

This is why Lens R&D prefers to look at the non-corrected error profile.

Some first results of the performed calibrations are already given in

Figure 5. Very similar results were obtained for all the other sensors that were calibrated. From the general profiles acquired it can be seen that all sensors behave quite predictably especially when corrections are applied for the shift between the membrane and the photodiode and for the collimator length (height between the membrane and the photodiode.

In order to illustrate this, we will show the calibration results of all twelve sensors produced as well as some statistical analysis performed on the 1000+ measurement points collected over the entire field of view.

serial number	glue version	max. accuracy at 68.2°	max. accuracy at 67.7°	max. accuracy at 66.6°	max. accuracy at optimal max. angle with x-y offset compensation
SN1637014	1	4.84	4.83		0.94
SN1637019	1	2.92	2.31		0.88
SN1637025	1	3.09	2.67		1.01
SN1637028	1	2.11	1.50		0.79
SN1637030	1	3.16	2.48		0.88
SN1637035	1	3.13	2.59		0.99
SN1634003	2	6.32		5.56	0.85
SN1634004	2	4.09		1.96	0.88
SN1634006	2	3.68		1.48	0.81
SN1637024	2	3.78		1.78	0.83
SN1637009	2	3.38		1.25	0.89
SN1637031	2	4.34		2.19	0.92

Table 1 non-calibrated, batch optimised and individually tuned sensor accuracies

Above table shows the maximum errors determined for the twelve sensors produced under various conditions. The first row is the non-calibrated accuracy using the theoretical maximum angle currently mentioned in the interface control drawing. The second and third row show the same accuracy while using a batch optimised angle (as there were two batches with distinctly different maximum angles) The last row shows the maximum errors obtained after optimising for both membrane shift and maximum angle. It should be noted, that the first sensor of each batch is a teaching unit which exhibits a large membrane to diode shift. These units are taken along in the test program in order to be able to see the influence of such a shift.

Doing so has provided some remarkable insights. As can be seen in Figure 7, using a batch dependent maximum angle already largely improves the error histogram. It is however obvious that the red line has a bias to the left side, and the blue line has a bias to the right side. If in addition for the measured XY shift between the membrane and the photodiode is corrected, the histograms become nicely Gaussian as an indication that the remaining errors are getting more independent and randomised (see Figure 8).

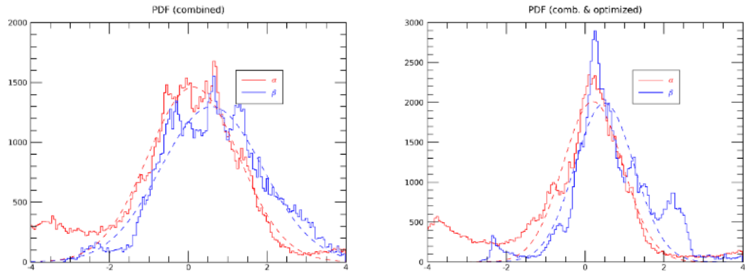


Figure 7 accuracy histograms for un-calibrated sensors and uncalibrated sensors with batch dependent maximum angle

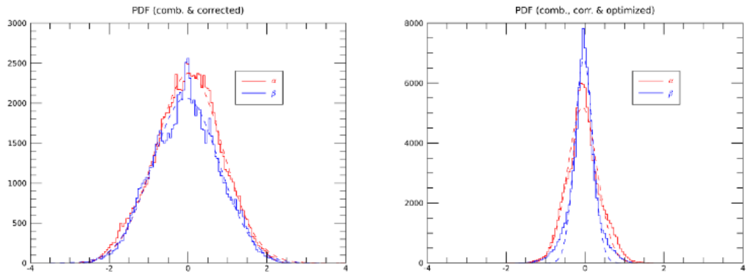


Figure 8 accuracy histograms for XY shift compensated sensors and fully optimised sensors

The last histogram is produced by not only correcting for the XY shift of the membrane but also optimising the maximum angle per sensor. The results of these actions are remarkable in the sense that even the worst sensors that were well out of specification and showed an accuracy of some 4.5 and 6.5° are now within an accuracy of ±1° 3σ and 1.5° 6σ. It should be noted that these accuracies only hold at room temperature and before aging effects launch effects etc. But all other accumulated effects are expected to be within 0.25° for the final sensors. Because only 12 sensors were produced and measured, it is too early to say that this level of accuracy can be guaranteed, but it must be concluded that the sensors seem to be very accurate.

Looking at the calibration results obtained throughout the qualification process, there are also some conclusions that can be drawn. In order to be able to withstand the large temperature excursions specified for the BiSon74-ET-RH the glue systems used are mainly based on silicone glues. The membrane however was tack attached with epoxy to avoid shifts during the silicone application (for both series produced). This led to some surprising conclusions (fortunately).

Below Figure 9 depicts the differences between calibration profiles of the same sensor after various tests. The first row is the difference between the pre-test calibration and the post thermal cycling calibration. The second row is between the pre-test and the post vibration and the post thermal cycling and post vibration. The third row is similar to the second but for the shock test. From these graphs, it can be concluded that the maximum angle shifted a bit because the epoxy connection was destroyed during thermal cycling but the silicone connection only sustained the overly heavy vibration testing and shock testing without issues.

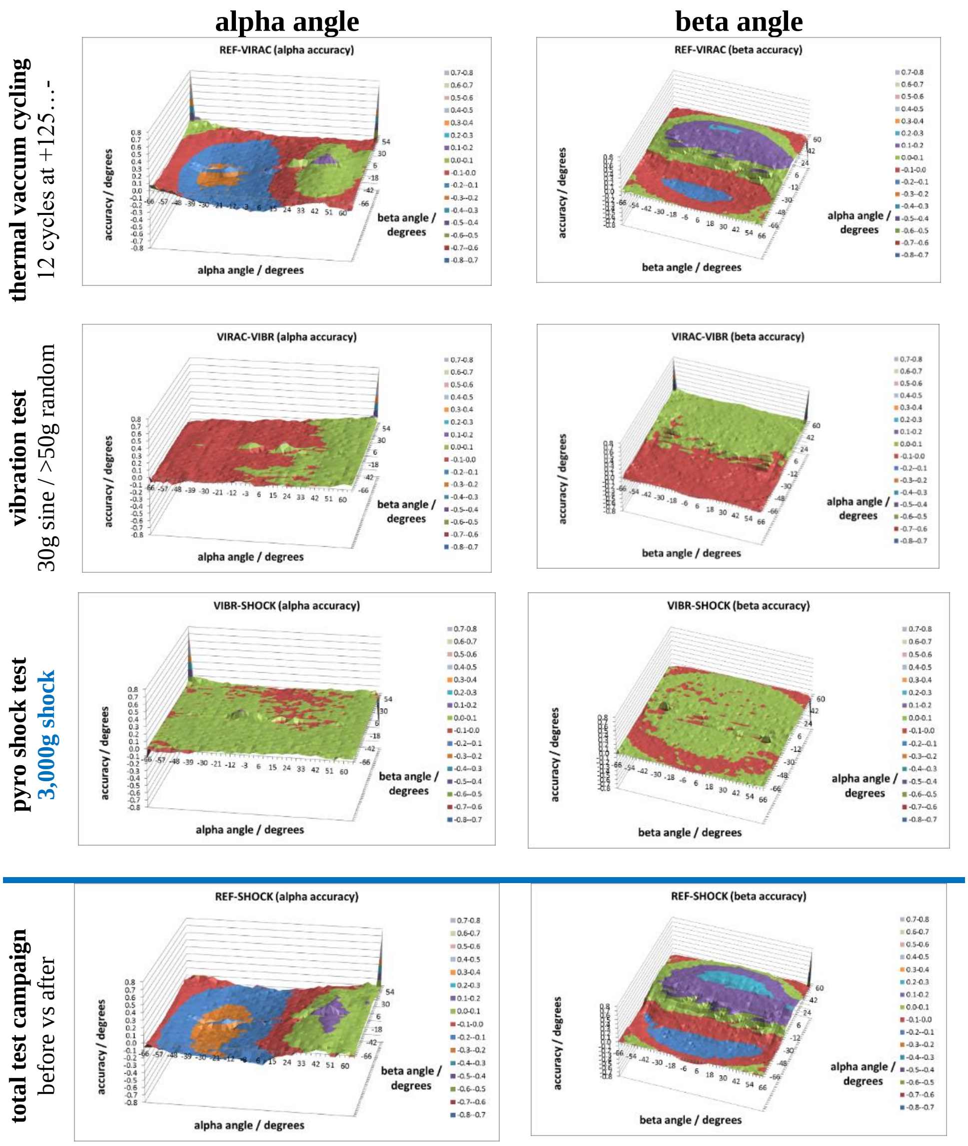


Figure 9 Accuracy difference post various tests

Consequently, the epoxy should be avoided in future devices. As the silicone is very likely to sustain a large number of large cycles in orbit and the described test program has shown the ability to survive even extreme levels of environmental testing, any new version of these sensors is expected to be very resilient.

6. CONCLUSION

The Artes 5.2 program has shown that it is possible to produce *sunsensors* that can withstand the large temperature excursions associated with direct solar panel mounting or interplanetary missions. Next to this the BiSon74-ET-RH have shown to be able to withstand extreme mechanical loads without failure. The high radiation tolerance and 3mm aluminium equivalent shielding in addition will allow to use these sensors in high radiation environments. It is the intention to produce some flight standard sensors and put them through a full qualification program, after which these sensors will have proven to be able *to boldly go where no sunsensor has gone before*.