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IBIS, a true digital Sunsensor in a package.

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Abstract

Ever since the inception of Lens R&D in 2012, the focus has been on innovating high reliability Sunsensors. After seven years of innovating, testing, modifying and qualifying, our BiSon Sunsensors have shown not only an unprecedented performance, but also an unprecedented price to performance ratio and scalability of production. The assembly principles developed for these sensors will be used to assemble the first miniaturized high reliability true digital Sunsensors dubbed IBIS (Intensity Based Image Sensor). This sensor will be based on a dedicated Sunsensor ASIC, specifically designed to fulfil the requirements of very demanding long duration missions. (15 years in GEO after 1 year electric orbit raising). It is expected that this sensor will become the sensor of choice for many satellites, due to the inherent albedo insensitivity in combination with a very high reliability.

The fact that there are many different ways in specifying a Sunsensor makes the comparison of various products difficult. Therefore, ESA is producing an unambiguous specification to which Sunsensors can be specified and verified. The IBIS sensors will be specified and qualified in line with this standard and will use the correct definition to discriminate between accuracy and resolution, an analogue Sunsensor with a digital interface and a true digital Sunsensor and many other relevant parameters.

The presentation will focus on the state of the IBIS development and planning and the implementation of this new ESA standard.

Keywords: high reliability, Sunsensor, miniaturized, Standard

For many years, there has only been one high-reliability digital Sunsensor available on the market. These devices were developed and sold by the US company Adcole.

Fig. 1. Adcole digital Sunsensor

The patent on the operating principle prevented many potential contenders from developing an alternative for many years, leading to a monopoly in the field of digital Sunsensors for several decades.

Early 2000, Galileo Avionica (now Leonardo) in Italy and TNO in the Netherlands developed a digital Sunsensor based on a radiation hardened active pixel sensor, developed on separate ESA contracts.

Of these two sensors, only the Galileo Avionica units (dubbed S3) made it to the production stage, although the product was never a commercial success due to the high product costs.

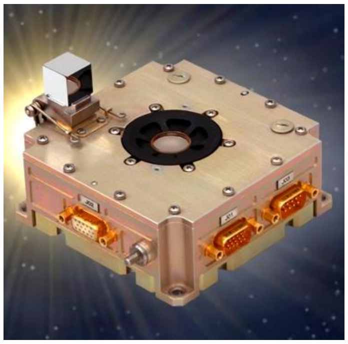

Fig. 2. Galileo Avionica S3

Instead of focussing on the sales of a product known to be overly expensive, TNO focussed on miniaturisation of the digital Sunsensor through the development of a dedicated imaging chip with integrated signal processing.

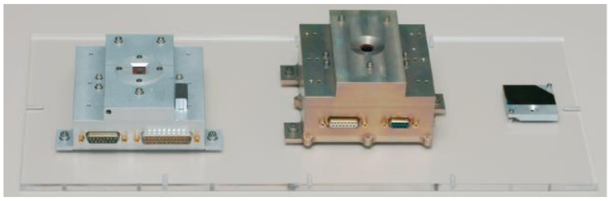

Fig. 3. TNO's miniaturisation efforts

Core to these developments were lowering the power consumption of the sensor so as to allow autonomous powering by a dedicated solar cell. These developments however came to a halt in 2010 when the underlaying Microned program came to completion, more or less leading to a stop on digital Sunsensor developments in Europe. This despite the good progress made in the program, as reported in various papers (see ref[1] and ref[2] as some examples)

The advent of electric orbit raising (putting more emphasis on albedo insensitivity) and the increased digitalization of spacecrafts by removing analogue interfaces and replacing them with digital interfaces, increased the desire to have a true digital Sunsensor over time. The main issue however is that the associated costs with going digital were deemed too high, whereas the digital Sunsensors desired should not only be affordable but also highly reliable, small and with low power consumption

An attempt to miniaturize the Sunsensors by Leonardo in the period 2013 - 2017 proved to be unsuccessful, mainly due to the expected costs for the final product, leading to a termination of these miniaturisation efforts in 2017.

As Lens R&D is a company specialized in high reliability Sunsensors optimised for volume production, we answered to an ESA tender to develop a highly reliable, small and affordable true digital Sunsensor which can be used on many different missions and platforms.

It is the intention to develop a high reliability true digital Sunsensor which can be sold at a price level compatible with current high reliability analogue Sunsensors. This paper will focus on the current state of development and future prospects.

Core to the increased cost effectiveness is the reasonably open specification underlaying the development. As the development is in frame of the ESA ARTES program (Advanced Research for TElecom applicationS), the development is focussed on telecom satellites using electric orbit raising to get to geostationary orbit. However, the most profitable application will probably be constellations of LEO satellites like Oneweb, Leosat, Telesat etc., purely based on the turnover in number of units expected. These applications set the fairly stringent radiation requirements that need to be met. Especially the LEO applications would also set some very stringent requirements on the high number of thermal to be sustained over lifetime. Producing a design that can cover both applications with their stringent requirements is therefore very challenging.

Fortunately, the accuracy requirement has been drastically decreased over previous programs (from 0.01° to 3°) and the type of digital interface has been left undefined for the time being. This opened up the possibility to propose a highly integrated Sunsensor with a low power, digital interface, a 1° angular accuracy and without using any calibration compensation, thereby significantly saving both production costs and implementation costs at spacecraft level.

This program, only intended to verify the viability of the concept by producing a functional demonstrator, has led to the design of our true digital Intensity Based Image Sensor (IBIS).

Fig. 4. Preliminary design of IBIS

Core of the sensor is a specifically developed, single chip with an integrated CMOS detector array, called IPS (**IBIS Photonic Sensor**).

The following performance parameters have currently been estimated.

Table 1. predicted IBIS performance

	unit	Remarks
Field of view	>±60°	>±70° goal
Accuracy	1°	Non-calibrated
	0.1°	Calibrated
Rotation rate	>100°/s	
Supply voltage	3.3V ±10%	
Power	<50mW	
Data interface	LV-SPI	Differential
size	<50*50*15mm^3	
mass	<50gr	<30g goal

It should be noted, that size and mass performance parameters are largely driven by the functionality and radiation resistance of the dedicated IPS chip . The number of external components required will largely drive the costs per sensor in the end as well as the size of the package. The obtained radiation tolerance on the chip, will determine the level of shielding required at sensor level to ensure proper operation over the lifetime of the missions under consideration. Consequently, insight in the radiation tolerance and obtainable functionality of the chip is vital to successful development. Given the financial constraints on what was originally intended to be a study contract, the current focus is on showing the functionality of the chip, selecting the right digital interface and estimating the final performance characteristics of the sensor in anticipation of the next stages of the program.

The first step in reducing the number of external components is try to eliminate as many external components as possible and integrate as much of the functionality as possible on a single chip. For this type of tasks, standard CMOS processes are very well suited as they allow to implement optical sensitive elements as well as analogue and digital circuits on a single chip This saves development costs, real estate area and implementation costs. As the main advantage of a Sunsensor is that it can work with direct Sun illumination, thus generating relatively high signal levels and signal to noise ratios, there is no need to focus on the optical sensitivity of the chip. Consequently the focus can be on integrating as much signal processing as possible. For the implementation a 0.18µm Xfab CMOS process has been chosen as this process is mature, expected to be radiation tolerant and available for multi project wafer projects (allowing to save significant money for producing some prototypes)

3. The IBIS Photonic Sensor chip (IPS)

As mentioned above the majority of key performance indicators are heavily depending on the design implementation of this application specific IPS chip. The more functionality that can be integrated in this chip, the fewer external components are required. The higher the radiation tolerance achieved, the less radiation shielding is required to meet the lifetime goals. Less shielding also leads to a smaller size and lower mass.

How we optimised the design of this chip to achieve the best possible performance will be described in below paragraphs. It should be noted that throughout the entire design optimisation, reduction of power dissipation has been given a high weighting factor, because the creation of hotspots and associated accommodation problems should be avoided.

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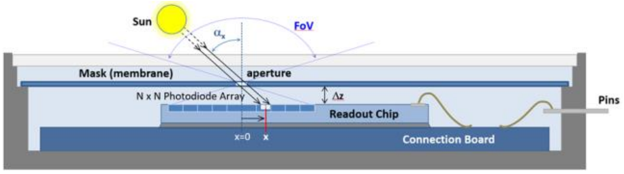
3.1 the detector array sizing

One of the first parameters to be fixed was the size of the sensing array. A larger array leads to a better resolution over the field of view, and consequently a higher expected accuracy, but also increases design complexity and power dissipation. A too low number of pixels will cause issues with the output resolution and especially with reduced accuracy in case of a single pixel failure. As the sensor will have to cover a field of view of at least 120° (±60° or preferably even ± 70°) the standard pixels provided through the Xfab library weren't small enough to fit the bill and a modified pixel design was needed. The minimum size feasible in the given process proved to be 10*10µm² and this pixel was used to determine the number of pixels in the array.

Fig. 4. Array sizing of IBIS



As the size of the array required is determined by the height of the membrane with respect to the imaging array (Δz in fig.4), and this height is production-technically limited to 1mm, the size of the array needed to achieve a ±60° FOV must be 3.46mm square. With 10µm square pixels this result in 346*346 pixels. As 346 pixels over 120 degrees FOV amounts to a resolution about 1/3 °/pixel, this is deemed sufficient to guarantee a 1° accuracy, even if one pixel fails. This number of pixels is also not so large that it will have a significant effect on the power dissipation of the sensor, given the fact that the sensor will be readout at approximately 100Hz only.

3.2Power interface

It is common for CMOS active pixel sensors to require a relatively high power supply voltage, so as to be able to cope with larger signals , but in case of the IPS, a careful tuning of the pixel to the analogue to digital converter allowed to have both a high signal handling capability and a low operating voltage. This means that the entire chip can not only be operated at 3.3V ± 10% as for the standard specification, but is also expected to operate properly at 2.5V. This in turn will allow to use a power supply directly from a triple or quadruple junction solar cell, when more advanced versions of the Sunsensor are to be developed. As the current consumption is mainly determined by the digital part of the chip which runs at a core voltage of 1.8V, reducing the supply voltage from the original 5V to 3.3V produces a power dissipation reduction of almost 33%.

3.2 Sun detection

The primary goal of the sensor is to detect the Sun and calculate the X/Y coordinates of the Sun centroid on the detector surface. The first of these two actions should be carefully evaluated because it is essential to avoid taking any reflections from either Earth, Moon or spacecraft parts to become a potential secundary Sun input.

The presence of bright or dark pixels in the Array, which can be expected to appear over time due to radiation damage, should have an as low as possible influence on the detection fidelity. In order to achieve this, the IPS implements a deglitching algorithm which mitigates the effect of single pixel upsets to the largest extend possible.

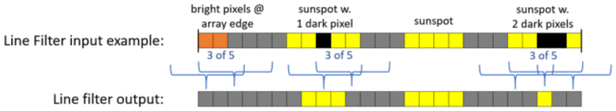


Fig. 5. 3 out of 5 deglitching

Sun Presence will only be indicated if at least three consecutive pixels have been illuminated with an intensity that supersedes the pre-set threshold. This will avoid Sun detection on basis of reflections off the Earth's or the Moon's surface and limits the potential detections to direct Sun illumination or specular reflections from Spacecraft parts. As most satellites will be in an Earth orbit, the rotation rate will ensure that specular reflections are only temporary phenomena (unless the satellite is Sun pointing) and can be avoided by proper placement of the sensors and appendices.

The 'three out of five' deglitching implemented will avoid detection of the Sun at the end of the field of view until the Sun has at least entered the field of view for a significant part and will mitigate the effects caused by any dead pixels in the array. It should be noted that the centroid of the line filter output is not deviating much from the actual centroid that would be calculated without the deglitching. As the size of a pixel is approximately 0.3° in the FOV, it is felt that it should be possible to guarantee the targeted 1° accuracy even when one or two dead pixels are present.

3.3 *Data interface*

The IPS chip has been designed specifically while taking a low power consumption into consideration. This is required in order to avoid the formation of hotspots in a sensor which is facing the Sun in vacuum, a combination which makes thermal control one of the major issues to consider during the design process.

In essence the data interface only needs to transport a comparatively small amount of data (an X and Y coordinate plus some status information at a maximum of 16 Hz) and 1kbit/s would be enough to properly interface the Sunsensor.

An extensive study on commonly used interface standards has shown that there are basically no standards available for devices operating from a 3.3V power supply and at such low data rates.

Early studies indicated that a CANbus interface could probably be the best solution, despite some potential customers objecting to this interface. This conclusion was driven by the inclusion of CANbus interfaces on the standard control computers of a number of large prime contractors.

The CANbus interface has seen a certain level of standardisation and acceptance within the space community and would allow to mount several sensors on a single computer bus, thus potentially saving some mass on harnesses.

During the study however it was realized that one of the drawbacks of the CANbus interface is the quite complicated electronics needed to generate the protocol but more importantly the need for quite stringently kept timing accuracies.

The latter causes the need to include an external timing element (resonator or crystal for instance) as a free running oscillator generated on board the integrated circuit would never be able to stay within the required accuracy over any significant temperature range.

Wheras a wide temperature range of operation is one of the other major goals of the development, even toallow for direct solar panel mounting, it was concluded that an SPI interface would probably be better suited, while the clock signal is provided by the spacecraft so there are no synchronisation or timing accuracy issues. Next to this, an SPI interface is simple to implement, transparent and deterministic in its operation and easy to test.

The main disadvantage of an SPI interface is the fact that it is not generally a differential interface as it has been designed to be used for communications between chips on a PCB with short distances and a common ground). In order to avoid EMC issues, it has therefore been decided to augment the standard SPI interface with differential drivers so as to improve upon the EMC behaviour (reducing both radiated emissions and susceptibility)

For this differential interface the mode of operation had to be selected. Although 3.3V LVDS signals are standardized, the line currents associated with this type of interface are so high that this would lead to a situation where the data interface is consuming twice the power of the rest of the chip. In order to avoid this situation, and preserve the low power operation, it has been decided to put a 3.3V differential voltage output interface on the sensors. Given the low data rate, this is not expected to generate any issues. Neither with EMC nor with signal integrity.

4. Field of view expansion

The current project only entails the development of a functional demonstrator chip to show that the unique detection principle currently under investigation is working as expected. Discussions on the commercial attractiveness of the sensor however have led to the conclusion that the applicability would probably be increased if the field of view could be extended from the currently implemented ±64 degrees in diagonal to some ±68° on axis.

The current measurement angle would provide a full spherical field of view with single sensor failure tolerance while using 10 Sunsensors. The expanded field of view however would allow to do the same while using only 8 sensors.

This not only saves cost on Sunsensors, but also wiring and the number of digital inputs on the on-board computer.

Based on the above, Lens R&D and SystematIC design B.V. are currently in discussion with ESA to see if the program can be expanded to include a design with a wider field of view.

There are however a number of uncertainties couple to increasing the field of view. One of this is for instance that the signal intensity varies with the cosine of the input angle and 68° on axis leads to an even larger angle in diagonal. Another issue might be related to internal shadowing or reflection effects on sensor level. Therefore, this apparently small change leads to significant design challenges which will need to be resolved and proven by analysis and test.

5. Radiation tolerance

One of the main concerns for the design of the Sunsensor and one of the major discriminators with respect to other available Sunsensors is expected to be the radiation tolerance.

In the past, the total dose resistance used to be a major issue due to electron trapping in the CMOS oxides, but for modern deep sub-micron processes it has been proven that the radiation tolerance is significantly improving due to the ever-decreasing oxide thicknesses.

This increased radiation tolerance has been investigated by ESA and has been recently reported in a paper [3]. Although this report was not known to the development team, it appears we have selected the most inherently radiation tolerant process that has been investigated. The selected 0.18µm Xfab process has demonstrated a total dose tolerance exceeding 600krad. This means that there is a high likelihood that the device can be shielded to such an extend (without using ludicrous amounts of material) that the planned lifetime of 18 years in GEO after electric orbit raising can be achieved.

Consequently, the main emphasis of the project should be on resistance to and mitigation of events caused by heavy Ions and Protons. It should be noted to this respect that improving the radiation tolerance of the design is explicitly excluded from the current project as this only entails the development of a functional demonstrator.

5.2 Single event latch-up mitigation

Single event latch-ups are events caused by high energy particles leaving a trail of electrons in the silicon which manage to trigger a parasitic silicon controlled rectifier (SCR). This SCR triggering leads to a low ohmic path between the power supply and ground, thus causing excessive currents to flow. When the generated current is capable of lifting the substrate potential to such a state that the current is sustaining itself, a single event latch-up occurs which basically shortcircuits the power supply and can only be reset by means of power cycling. Due to the high energy densities involved, latch-ups are not seldom destructive and in most of the cases detrimental to the reliability of the circuit involved.

Special design precautions can limit the potential to latch-ups occurring, but in order to know if the mitigation measures are effective, heavy Ion testing is required. (which is not part of the current program).

Further optimisation of the latch-up performance is currently under discussion with ESA in frame of a program extension which is proposing to include several radiation mitigation measures in the design and to further extend the program to include radiation testing.

Implementing these design changes and performing the tests will be a major step towards availability of a radiation hardened small digital Sunsensor.

5.3 Single event upset mitigation

For the current demonstrator chip, no further single event upset mitigation has been implemented, apart from the implementation of some triple voting redundant memory locations that hold the result of the centroid calculations.

A detailed analysis of the digital circuitry should reveal if implementing triple voting redundancy or other locations is expected to help improving the single event upset rate. As for the latch-up improvements, increasing the SEU performance is part of the contract extension currently under discussion with ESA for which we hope to have a disposition Q4/2019

5.4 Single event functional interrupt (SEFI) mitigation

Single event functional interrupts are basically single event upsets that lead to the circuit halting operation. The most likely cause of such an interrupt is the entering of a forbidden state by one of the sequencers used within the chip.

Special design techniques can avoid forbidden states but complicate the sequencer design and the size of the implementation. This is why these techniques were not employed for the functional demonstrator which is not required to meet any radiation requirements.

For a final design however, it is foreseen not only to design all sequencers in such a way that they don't have any forbidden states (basically leading to a restart of the circuit in case of a SEFI), but also to include a watchdog timer which will cause a circuit reset in case there is a prolonged period of inactivity.

As the circuit will internally operate at a sample rate of approximately 100Hz, but the external data interface will be limited to 16Hz as a maximum, this watchdog operation could be completely transparent to the user and is expected to mitigate at least the majority of events detected without the user ever noticing. This is expected to dramatically improve the operability of the sensor, providing availability of valid data if requested.

5.5 Rotation velocity check

An additional check that can be performed on the sensor data is checking the position variation between samples. As the rotational rate of the sensor is expected to be more or less constant, presuming there are no high torques acting on the satellite, the velocity vector should be more or less constant.

Externally checking the velocity vector to determine if the value doesn't exceed the predetermined value is a way of increasing the confidence in the values output by the sensor.

5.6 Heavy Ion testing

Heavy Ion testing will be needed to determine the linear energy transfer sensitivity (LET). A LET of more then 60MeV.cm² /g will lead to the confirmation that the circuit is single event upset free. According to ESA rules. A LET of less than 60 but more than 15 MeV.cm² /g will require the implementation of a latching current limited which autonomously detects any latch-ups and cycles the power supply. A LET of less than 15Mev.cm²/g is in most cases not acceptable.

Even though heavy Ion testing is quite complicated due to the fact that it cannot be done at many places and requires a vacuum compatible setup, performing this type of tests is quite vital to the viability of the design as a low LET resistance can lead to a rejection of the entire sensor.

5.7 Proton testing

Proton testing is generally only required if the heavy Ion tests show a low LET threshold (leading to a situation where high energy protons could trigger a latch-up. Alternatively, proton testing can be performed to verify that displacement damage caused by high energy particles is not causing shifts in the analogue circuitry that leads to a loss of performance or functionality over time.

For the extended program currently under discussion it is proposed to include proton testing to specifically determine the sensitivity of the imaging array and conversion electronics to proton radiation.

5.8 Total dose radiation testing

As mentioned before, reference [3] describes the results of Co60 total dose tests on the standard components available in the selected 0.18µm Xfab process. Consequently, it is expected that the radiation tolerance is at least matching the given 600krad total dose resistance.

Given the efforts to design an imager and conversion section capable of sustaining higher levels of radiation, it is expected that the actual design will be able to withstand more than this.

As a higher radiation resistance means less need for radiation shielding, leading to smaller size, lower mass and lower costs, it is interesting to test the actual radiation resistance of the design, despite the fact that it is already quite high through the use of the standard process.

Total dose radiation testing however is not expected to lead to any design modifications if the LET and displacement damage tests have been successful. The testing will rather be done in frame of an overall system design optimisation.

6. Parameter standardisation

Back in 1970, NASA published a report on Spacecraft Sunsensors [4] which contained a list of definitions, which since then seems to have long been forgotten by most Sunsensor manufacturers.

Nowadays it is difficult to compare the specifications of available Sunsensors and very little proof about performance parameters like absolute accuracy and alignment stability is being provided in any of the datasheets. Moreover, in some cases it seems likely that there is even a mix-up between accuracy and repeatability or accuracy and resolution.

Measurements performed by independent parties on various devices could not confirm accuracy claims in many instances and transparency on qualification status is seldom provided. Poorly defined parameters, such as precision, are sometimes replacing better defined parameters like absolute alignment accuracy. Sometimes there is even evidence that competitor's accuracy claims are just copied in order to convince potential customers they are just as good without providing any proof.

The above has led to a situation where ESA has identified the need to have a clear set of definitions for various parameters associated with Sunsensors, in order to be able to compare Sunsensors in an objective way.

The work on this standard is still ongoing, although it was expected to be ready by the time of this publication, but it is obvious (from trying to fill in the preliminary specification tables) that a lot of information to objectively compare Sunsensor performance between various suppliers is a daunting task.

Availability of a standard definition would allow for an independent verification program. Within this program, a comparison between specified performance against achieved performance can than be made, using a clear and common definition of the parameters involved.

Without doubt many Sunsensor suppliers would not be happy with such a program, but it would allow to identify those parties that provide a trustworthy and verifiable specification over companies that perpetrate specology by using fuzzy parameters to pretend a high performance only to attract customers.

7. Conclusions and way forward

The Artes 5.1 program currently run by Lens R&D in cooperation with SystematIC design B.V. is on track to deliver a small but highly reliable (and affordable) true digital Sunsensor. This sensor is expected to fulfil the accuracy requirements for the majority of missions while withstanding the radiation environments associated with these missions.

As the radiation tolerance of the current design is expected to exceed the radiation tolerance of any small digital Sunsensor available on the market, the current chip could be good enough to serve the needs for small satellites staying in low Earth orbit for a limited period of time.

The demonstrator design however is not optimised enough to be able to sustain the radiation environment expected for 18 years in GEO orbit after 1 year of electric orbit raising as asked by the specification. Neither is the radiation tolerance high enough to sustain 15 years in higher LEO orbits (where currently some very large constellations are projected).

Given the good results of the critical design review of the demonstrator chip however, all parties involved have agreed to look into a project extension that would allow to increase the radiation mitigation measures (thus improving upon radiation tolerance and availability). The proposed program extensions have been discussed in the respective paragraphs

In order to prove the radiation tolerance, it is proposed to perform a full set of radiation tests consisting of heavy Ion, Proton and gamma ray tests.

When the prototype sensor is produced and tested, the final sensor design would need to be taken at hand. In order to allow for a fair comparison to the competitors offerings, Lens R&D is in favour of establishing a clear set of requirements specifications.

These clear specifications with their definitions can then be used to distinguish the well-defined and verified sensors from the poorly defined ones through independent performance verification.

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