Advent of the IBIS

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1 Summary

Lens R&D B.V. is well known for their high-quality analogue Sunsensors which fulfil most of all essential requirements (small, rigid, high quality and cost effective), except two:

1. Albedo insensitivity

2. A digital interface

Several vendors market analogue Sunsensors with processing electronics as digital Sunsensors, but these sensors are still hampered by significant albedo errors and therefore don’t qualify as a true digital Sunsensor. The only way to mitigate the albedo error is by using multiple element detectors and discriminating on the intensity of the light received per detector element. There are only very few known examples of a real digital Sunsensor but they are either obsolete (TNO and Leonardo digital Sunsensors), or non-radiation hardened (Where the TNO digital Sunsensor never made it into production, the Leonardo digital Sunsensor never turned into a commercial success because it was too expensive and relatively large for small satellites).

Whereas geostationary satellites more and more use electrical propulsion for orbit raising, Sunsensor can be a very attractive component as it requires significantly less power than a Star Tracker and will save valuable power (and associated costs) during the critical phase of orbit raising as long as it is not hampered by albedo sensitivity.

Analogue Sunsensors are not that attractive for this purpose as the albedo errors would lead to large disturbances in the control loop. As a result, ESA decided to ask Lens R&D B.V. to design a small and low power, yet radiation hardened true digital Sunsensor in frame of an Advanced Technology ARTES (Advance Research for TElecom ApplicationS) contract.

The design of the chip has been approved and the chips is being taped out by the time of this symposium due to some experienced delays, but this paper will already give a glimpse of the final design and expected properties. This includes a description of the unique trade-offs leading to the current design. The sensor is housed in a small package and presents a low power yet cost effective solution for missions looking for high fidelity albedo free Sun sensing.

2 Specifications

As presented before during this same symposium back in 2019 [1] as highlighted in Table 1, the number of specifications given by ESA in the tender for the IBIS were limited.

Fields	Requirements	Specification
Functional	Output	Sun direction in SC frame
Performance (over full thermal & dynamics environment)	Angular accuracy (including tolerance to solar flares, SEU, albedo and stray light)	- Over full FOV: 5° (3 sigma) - Over accurate FOV: 1° (3 sigma) (target 0.5°)
	Field Of View full cone	- Full FOV: Hemisphere - Accurate FOV: +/-30°
Interfaces	Full system Mass	400 g
	Sensor Dimensions (without electronic)	120 x 120 x 60 mm
	Electronics Dimensions (if deported)	100 x 100 x 50 mm
	Average power consumption	2 W
	Average power dissipation	2 W
	Thermal accommodation	No radiator shall be used
	Supply voltage	5V regulated OR 12V OR 28V OR 50V unregulated
	Data interfaces	Digital: type TBD
Design and PA	Redundancy	Internal
	Lifetime	15 years in GEO
	Thermal cycles	7000
	Reliability	100 FIT @ 30°C
	Radiation	-Electronic components: 100Krad -Optics: 300 Krad -Detector if any: 1 Mrad -SEU tolerant
	No ITAR components	ITAR free
Environment	Dynamics	Angular rate: +/- 100°/s
	Temperature	-Storage and operational: -40 to +75°C -Extension for Solar Array accommodation: -80 to +100°C (TBC)
	Vibration and shocks	-Sine: 20 g peak -Random: 27 g rms -Shock: 3000g from 2 to 10kHz

Table 1 specifications provided by ESA

Currently we are working on a prototype which is expected to exceed all of these specifications with the exception of the Field Of View (where ±64° FOV in diagonal is targeted), the power supply (currently 3.3V is foreseen), the internal redundancy and the detector radiation sensitivity (currently >250krad is expected for the chip but 1MRad is uncertain due to lack of available test data)

Last but not least, the high operating temperature for Solar Array accommodation can potentially be demonstrated but is currently not taken as a design parameter and will not be verified by test as part of the current program.

3 History of a Sunsensor

Mid 1990's ESA concluded that the on-board computers of spacecrafts should preferably become digital I/O only, and developments were initiated to produce all core components with digital outputs. This initiated developments within both Galileo Avionica (IT) and TNO (NL) that would lead to a radiation hardened true digital Sunsensor based on detector developments initiated in Belgium with the company Fillfactory. Both developments resulted in a true digital Sunsensor that didn't exhibit any albedo errors and had a digital RS422 interface.

Both systems were quite large and expensive though and when it was decided to find a cheaper alternative for the Galileo constellation, the fate of these sensors was more or less decided. The TNO digital Sunsensor never made it beyond flight demonstration and not a single commercial product was sold. The Galileo Avionica digital Sunsensor was sold in small numbers to specific projects but never found widespread use.

As it was recognized that especially the price of the available digital Sunsensors was prohibitively high and mixed signal CMOS technology was rapidly maturing, it was decided to initiate a Sunsensor On a Chip (SOAC) development that should ultimately lead to the existence of single chip (and radiation tolerant) true digital Sunsensors which had both a digital signal interface and no significant albedo sensitivity.

Where Galileo Avionica (now Leonardo) had an ESA contract to develop the so called SOAC, TNO had a national program to develop a small digital Sunsensor as a demonstrator in a technology program aimed at increasing the knowledge about MEMS technologies (MicroNed).

Even though the latter program has to be considered very successful and led to the demonstration of a functional prototype (as reported during the ESA GNC conference in 2011 [2]), the developments were stopped. As the commercialization of Sunsensor production including product development had led to a knowledge transfer to Bradford Engineering, the new development should have been coordinated by Bradford. Disagreement on the final specifications however led to the founding of Lens Research & Development, leaving Bradford without the possibility to submit a timely offer to ESA. Consequently, the follow-on development was performed by Leonardo only. This development however resulted in technical difficulties that prompted Leonardo to cease the development in 2017.

Based on knowledge and experience gathered during the TNO developments and matured during further developments at Lens R&D B.V., the development of the Intensity Based Image Sensor (IBIS) was taken up again by Lens R&D B.V. in 2019 in frame of an ESA ARTES advanced technologies contract.

Contrary to the initial limited plan for the IBIS, covering a proof-of-concept / function model approach, the current design is not only a functional prototype build in a multi project design flow, but a radiation hardened full functional sensor with increased testability optimised for volume production and produced in a multi-layer mask process flow. This means that if the chip turns out to be fully functional there will be no need for additional design improvements or mask investments before flight standard sensors can be produced.

4 Digital Sunsensor implementation

For several reasons a 0.18µm XFAB CMOS process was selected to produce a single chip, true digital Sunsensor. This is related to the increased reliability associated with an aluminium back-end processing, the availability of DARE libraries and the low static power consumption as well as availability of verified design and simulation libraries.

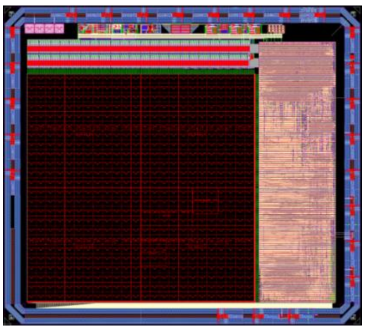

Figure 1 layout of the IPS+ chip

The chip itself measures $6.0*5.35mm^2$ and has extra-large bond-pads which allow producing redundant wire-bonds for every connection. (Further increasing reliability). In order to optimise costs, the chip includes an on-board latching current limiter and low drop regulator (which supplies the 1.8V core processor supply voltage) and the output buffers. This allowed to design a very compact test bed, as shown in Figure 2, for which apart from the SOAC chip only three resistors and four capacitors are required (two of which can potentially still be removed but are there for backup in the test phase only). In order to minimize complexity and costs, the chip is using a free running oscillator and a self-clocked external interface which are internally synchronized.

The chosen implementation allows to produce a testbed that can fit on the available assembly and test equipment as used for the Lens R&D B.V. analogue BiSon and MAUS Sunsensors. (seeFigure 3). This not only allows to assemble and test the devices with minimum investments in production and test equipment, but also leads to the availability of a small sensor that can be flown on CubeSats. This sensor (dubbed µ-IBIS) is expected to be the world's first radiation hardened true digital Sunsensor. With the chip being inherently latch-up free and expected to have a TID tolerance of more than 250kRad, the 650µm sapphire membrane is expected to lead to a radiation tolerance that is more than sufficient to sustain tens of years in orbits below 600km or fulfil for instance the requirements for the original Oneweb constellation.

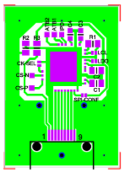

Figure 2 test-bed PCB design

Figure 3 µ-IBIS

In order to limit power consumption and price, it has been decided to use a 3.3V power supply for the sensor as this is the maximum the chip can handle without the use of an external low dropout regulator (LDO). As the sensor core runs on 1.8V that means an additional on-chip LDO is implemented to provide the correct voltage for the sensor's core processor. In order to further minimize power consumption, all processing is hard coded and only minimum configuration registers are used as they need triple voting redundancy and error correct to allow correct operation in high radiation environments. Finally, a 3.3V balanced SPI CMOS interface has been implemented to save interface power. This interface requires six wires, is self-clocking and as a peculiarity has the load resistors all located at the on-board computer side (thus saving power consumption at the sensor side). This in turn allowed to optimise the power consumption to be as constant as possible so as to allow inserting a simple RC filter in the power input line. This filter protects the chip from surges on the power line and, together with the constant power consumption, minimizes conducted electromagnetic interference.

Anticipated specifications for the µ-IBIS are:

FOV >64° in diagonal, accuracy better than 1° over the entire FOV including albedo effects

Supply voltage 3.3V ±5%, supply current <25mA (50mA LCL implemented)

Digital interface balanced open drain SPI, SEL free >65MeV, >250krad with 0.9mm Al equivalent shielding.

5 Analogue versus digital.

There are very few examples of true digital Sunsensors which are both albedo insensitive and provide a digital output. The only implementations known to the authors of this paper are the Newspace systems SS411 and the cubespace digital Sunsensor. Neither of these are to be considered radiation hardened though.

All other known implementations of what are called digital Sunsensors are in actual fact analogue Sunsensors with a digital interface. Figure 4 shows the difference between these two in a generic fashion.

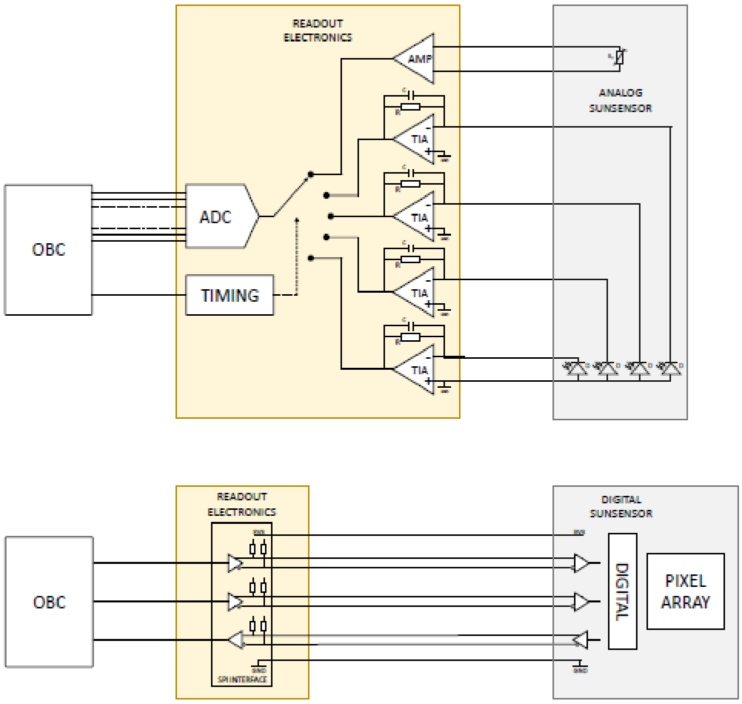

Figure 4 analogue versus digital Sunsensor

Where an analogue Sunsensor like the BiSon or MAUS Sunsensors sold by Lens R&D B.V. typically require a number of amplifier stages, a multiplexer, an analogue to digital converter and some timing circuits, a single chip digital Sunsensor only requires a number of buffers through which digital signals are transmitted and received. For analogue Sunsensors based on four quadrant diodes that are sold as digital Sunsensors, all this functionality is either implemented in discrete electronics, a dedicated application specific integrated circuit or a micro controller with support electronics. In all known cases multiple components are used which leads to decreased robustness and reliability and increased complexity and costs.

Whereas true digital Sunsensors use multiple element arrays that allow to discriminate between the intensity of direct Sun illumination and the intensity of an albedo signal, analogue Sunsensors with a digital interface are still hampered by albedo sensitivity which will lead to significant errors in most cases unless special precautions are taken. The BiSon64-ET-B for instance has an integrated baffle which allows to position the sensor in such a way that albedo signal is avoided for Earth pointing satellites by tilting the sensor with respect to the top surface.

For a true digital Sunsensor this is easier to achieve as it is possible to implement an algorithm that allows excluding certain zones of the sensor array from evaluation. (see fig Figure 5). This is a useable feature as despite the ability to discriminate between direct and diffusely reflected Sun light, even a digital Sunsensor cannot discriminate between direct illumination and illumination through a specular reflection.

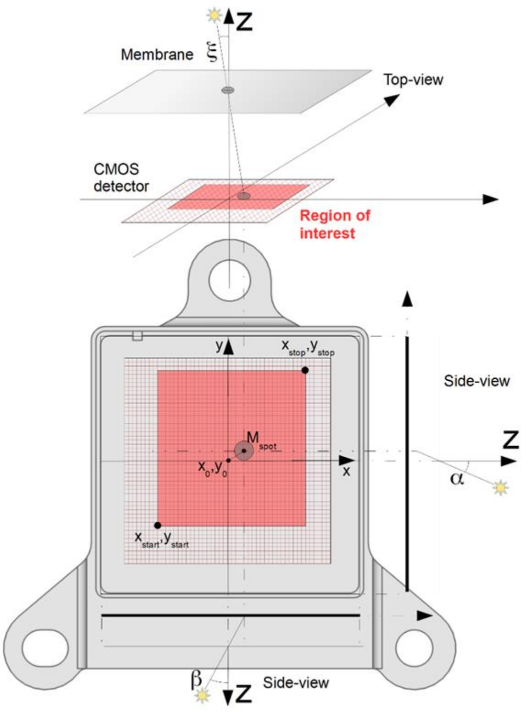

Figure 5 exclusion zone programming.

By programming start and stop coordinates the field of view of the sensor can be limited without mechanical baffling or tilting the sensor. This has major advantages, as it significantly eases accommodation on board of the spacecraft.

6 Major trades

In order to reach the current implementation a number of major trades had to be performed. These trades were related to a number of core properties that are indispensable for a single chip sensor intended for space applications:

- Low power.
- Radiation hardened.
- High reliability
- Small size

By far the most important parameters is the low power as it is directly related to all other major parameters to consider. Operating in vacuum, the overall power consumption is likely to lead to hotspots that can easily exceed the maximum junction temperatures of a standard silicon chip if the overall power dissipation is not kept as low as possible. Major sources of power dissipation anticipated where the size of the pixels and the digital interface selected in combination with the frequency of operation. As a result of the trades performed, we chose to use a free running oscillator in combination with a self-clocking SPI interface with internal synchronisation. For EMC reasons this interface has been implemented as a differential interface with a nominal clock speed of 1 MHz.

As one of the least important parameters for a Sunsensor pixel is the quantum efficiency (QE) and one of the most important ones are low power operation and radiation tolerance, it was decided to design a special pixel which is inherently latch-up proof, TID resistant and small. These properties came at the expense of a low QE but due to the direct Sun illumination there is an abundance of signal generated, so this was a minor price to pay.

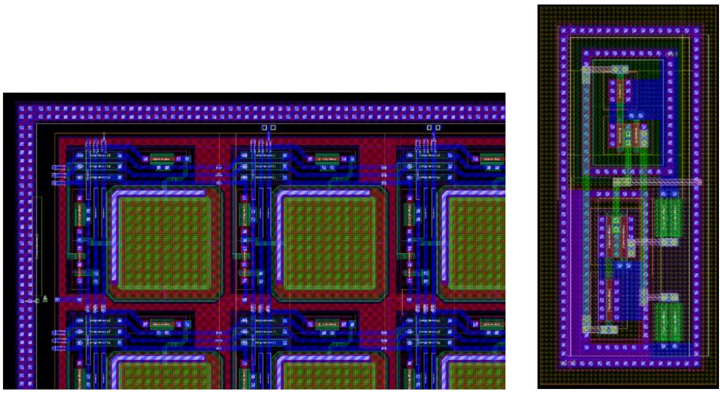

Figure 6 10µm pixel and reference circuit designs

Although the design doesn't fit the design rules of Xfab as can be seen in above Figure 6, the design was optimised in close cooperation with the Xfab designers and approved for implementation.

Based on radiation test data provided by ESA it was decided to use 1.8V transistors to the largest extend possible, thus increasing the radiation tolerance. As a result, the entire chip is running on 1.8V with exception of the I/O circuits. This is expected to increase the radiation tolerance significantly. In order to increase upon the latch-up resistance, extensive use is made of guard rings and multiple grounding points as can be seen in Figure 6. Furthermore, the digital timing and processing circuit was laid out by IMEC using a dedicated DARE library. Minimum total ionizing dose resistance is specified to be >250krad and the circuit is designed to be latch-up proof. Future testing will have to establish the real tolerance levels.

Increasing the reliability of the circuit is possible by minimizing the power consumption (thus limiting self-heating and high junction temperatures) and minimizing the number of components used (integrating as much functionality on board as possible). As a result, high reliability can be translated into the least number of components and interconnects. Alternatively, double wirebonds can be used to increase interconnect reliability.

As a result of the trades performed, the circuit has a minimum number of connection pads to which redundant wirebonds can be made to increase reliability. Furthermore, only passive components are used and the circuit is designed to operate without additional buffer capacitors and is expected to be fully functional with R1and C2 mounted only. (the other pads are reserved for safety reason so additional capacitors can be added if desired).

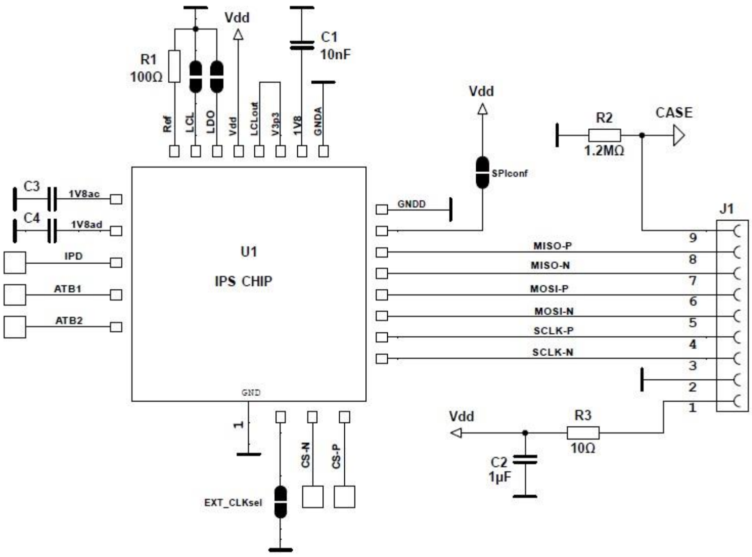

Figure 7 µ-IBIS circuit diagram

Minimizing the number of components automatically leads to optimised reliability and lowest cost, but this by no means should be seen as an indication that the sensor has minimum functionality.

Apart from the already mentioned windowing capability, the sensor has a number of functionalities on-board such as an integrated latching current limiter, under voltage lock-out, watchdog timer, oscillator and even a thermistor. The digital electronics is triple voting redundant and includes a dedicated test bus for failure investigation and diagnostics as well as a synchronizer ensuring data integrity even though the readout clock is running a-synchronous from the internal clock. The core functionality however exists in determining if the Sun spot fulfils the size criteria, correcting for pixel deficiencies and determining the X/Y coordinates of the centroid.

Last but not least there are significant benefits to having a sensor that is small enough to fit on the existing assembly and calibration equipment and can re-use available qualification tooling as this saves both significant time and costs for reaching the ultimate goal. Having the first radiation hardened true digital Sunsensor operational in space.

As for this ultimate goal, it is expected that a functional demonstrator can be shown end of Q1/2024. Results for this demonstrator are then expected to lead to a first qualification model by Q1/2025and a qualified design by 2026. It is the goal to have first ESA qualified sensors in space by 1st of April 2027 when Lens R&D B.V. is expected to celebrate its 15th anniversary.

7 References

[1] J.A.P. Leijtens et all, The Sunsensor of the future. Bragging spree or reality? 12th IAA symposium on small satellites for Earth observation, Berlin, Germany, 2019. IAA-B12-1402

[2] C. de Boom et all, Mini-DSS: MINIATURIZED HIGH-PRECISION SUN-ANGLE MEASUREMENT, 8th international ESA conference on guidance navigation and control systems. Karlovy Vary, Czech Republic, 2011