The Sunsensor of the future.

Bragging spree or reality?

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1 Summary

In the period 2004 to 2010, the Dutch contract research organisation TNO developed a small digital Sunsensor called the mini-DSS. This sensor was based on a dedicated active pixel sensor called APS+ and the prototype build, showed very good performance (as reported during the ESA GNC conference in 2011). Despite this, the development was never taken to the next level and as far as known digital Sunsensor developments at TNO have stopped in 2010.

The TNO systems engineer at that time involved in the digital Sunsensor developments (Johan Leijtens) founded Lens R&D in 2012 and has been involved in the development of high reliability Sun sensing solutions ever since. Lack of funding however prevented the development of a compact and affordable high reliability digital Sunsensor even though this has been on the development roadmap from the beginning.

Recently, an ESA Artes contract has been signed between ESA and Lens R&D that is to lead to a small but highly reliable (and affordable) true digital Sunsensor dubbed the Intensity Based Image Sensor (IBIS). A dedicated imaging chip is under development in frame of this contact which is expected to lead to a solution that not only provides a small and highly reliable Sunsensor, but also exhibits a very low power dissipation while providing an accuracy that is sufficient for 99% of all space missions.

2 Specifications

It is expected that in the future large telecommunication satellites will use all electrical propulsion to raise the orbit from the initial GTO to Geostationary orbit. This all electric propulsion will have a very high specific impulse, but will provide only limited thrust capabilities. Consequently, manoeuvring is not easy and it is expected that each satellite will use several Sunsensors to provide a full spherical field of view. Given the low perigee of the GTO, these sensors should be albedo insensitive to avoid significant pointing errors at or near this perigee. As the satellites are expected to use normal solar cells without concentrators, the power output of the solar panels will be cosine dependent on the angle of incidence. This in turn means that a very high pointing accuracy is not required. Furthermore, there is a desire to have sensors with a digital interface only so as to improve on the ease of integration.

Discarding the albedo issues, an analogue Sunsensor with a digital interface could fulfil all the requirement and provide a very robust solution, but the desired albedo insensitivity will mandate the use of a true digital Sunsensor for which ESA has defined the system requirements in frame of the digital Sunsensor for telecom applications.

The defined specifications are given below.

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

Figure 1 specifications provided by ESA

As can be seen the desired sensor is not specifically small, low weight, low power or accurate, but rather the hemispherical field of view, the high rotation rate and the environmental requirements are most demanding. Furthermore, there is one driving requirement which is not mentioned in this table which is the target price of 35k€ for an internally redundant system.

3 Digital Sunsensor implementation

At this moment in time, it is strongly believed that a hemispherical field of view Sunsensor is not the optimum solution.

The only ways known to produce a true digital Sunsensor is to use a 2D imaging array and a pinhole or multiple slit detector arrays. It is strongly believed that the most cost-effective way to produce a small digital Sunsensor is to use a CMOS sensor and a pinhole instead of a CCD or slit based designs because a lot if not all processing and interface electronics can be integrated on chip and a compact solution can be created that uses very few components. The disadvantage of using a slit or pinhole-based design is that it will be impossible to provide a full hemispherical view without using imaging optics which in turn will largely increase the complexity and consequently the price of the sensor.

Next to this, accommodation on a satellite without obstruction in at least some part of the field of view will be very difficult to achieve due to the large number of protruding parts on a satellite. (solar panels, antennae, electronics boxes, etc)

Consequently, the new focus is on a (single chip-based) small digital Sunsensor which uses a single pinhole aperture to image a Sun spot on a small 2D detector array which contains all the required active components needed for power regulation, clock generation, signal processing and interfacing. Although it will be impossible to use this circuit without some supporting electronic components, the development target is that no (expensive) active components will be required and the auxiliary components can be limited to capacitors (for decoupling and timing purposes) and resistors only. Once proven, this will limit the bill of materials and will strongly contribute to producing Sunsensors cost effectively in the future.

In order to make a high-quality cost effective Sunsensor it is deemed necessary to design a detector that avoids the use of a (costly) intensity reducing filter but still prevents (pixel) saturation. Next to this a detection principle will be selected that uses as little power as possible. The latter is needed because a Sunsensor is looking directly at the Sun as a precursor to operation and consequently is prone to absorption of solar radiation. This means that a sensor with a small exposed surface will absorb less solar radiation and will be easier to manage from a thermal point of view. This also means that it will be necessary to limit the power consumption as much as possible, because (given the small size of the sensors) any substantial power dissipation can quickly lead to hotspot generation internal to the sensor. As the exterior of the sensor will have to be minimized as far as possible, the available radiator surface to reject heat is also very limited and any heat absorbed or dissipated will have to be transported out mainly through the mounting feet.

Another aspect that needs due consideration is the on-chip signal processing performed in order to increase the robustness of the Sunspot detection against bright, bad or dead pixels. Such signal processing helps to prevent (especially when the sensor reaches end of life due to radiation damage) false Sunspot detections or missing Sunspot detection, and so improves the robustness of the sensor.

In order to further improve upon the Sun detection reliability, it is currently foreseen to implement digital line filtering after pixel threshold detection as shown in Figure 2. For every pixel independently it is determined if the Sun detection threshold is exceeded. As the Sun will be imaged on several consecutive pixels, at least three out of 5 pixels shall exceed this threshold before a sunspot detection is signalled. This avoids a false detection even if two bright pixels adjacent to each other exist, and still provides a positive Sun detection even if two bad or dead pixels fail to exceed the threshold signal. Theoretical analysis of two-dimensional filtering of the array data using this '3 out of 5 deglitching' algorithm in combination with a 10 pixel large Sunspot image have shown to give a very reliable and accurate Sun-angle detection even under circumstances where multiple deficiencies in the imaging array exist.

NOTE: Despite the fact that the proposed filtering will avoid a false sunspot detection, it should be obvious that multiple bad pixels will influence the calculated sunspot accuracy. Therefore, this algorithm not only prevents a false sunspot detection (or failure to detect a Sunspot) it also provides a graceful degradation mode as to the Sunsensor functioning if over time deficiencies would form in the sensor array.

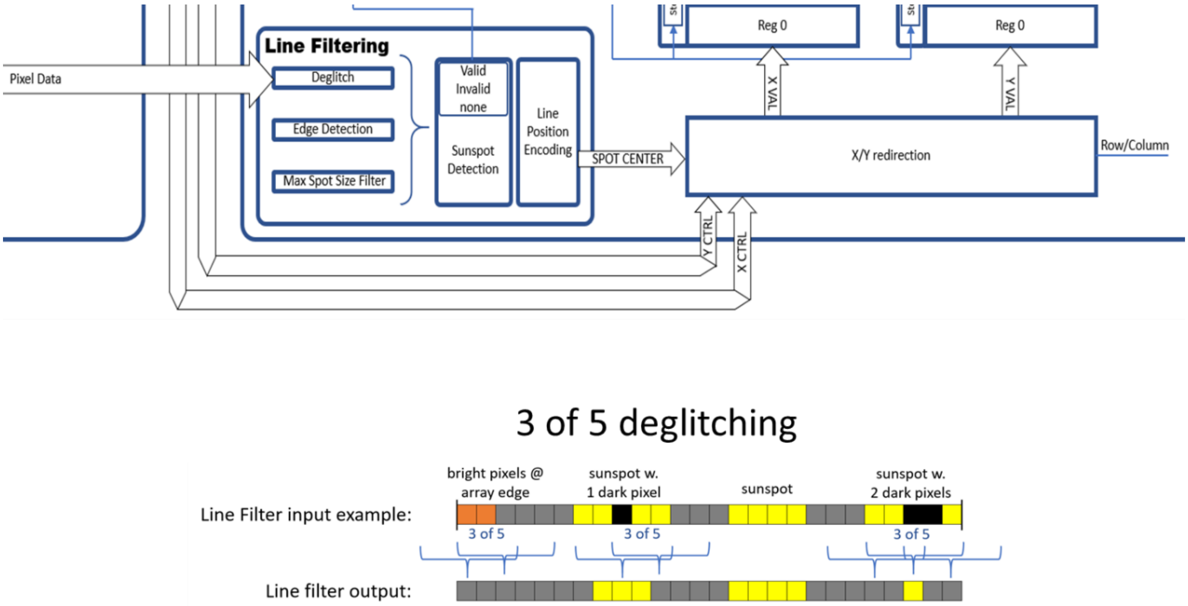


Figure 2 Sunspot detection improvement scheme

Although the data interface to be used is currently still under evaluation, it has become obvious that the overall power consumption of the sensor will - to a large extend - be driven by the power consumption of the data interface selected. This is due to the fact that a high-fidelity data communication generally requires significant currents on the data interface. Limiting the currents or lowering the voltages on the data interface increases the susceptibility to electromagnetic interference (EMI). Therefore, selection of the optimal hardware interface and protocol to be used for the data communication is one of the critical trades in consideration for this Sunsensor development.

For these reasons, current based interfaces (like LVDS) or multi user Realtime protocols (like Spacewire) have been discarded. As the sensors are expected to be used in a safety critical situation where the use of busses is generally avoided (to avoid lockup in case of a babbling idiot failure mode for instance) it is expected that it is sufficient to connect the sensors using a direct point to point interface. One of the best-known point to point interfaces is the SPI interface. The main disadvantage of this type of interface is the fact that it has been designed for short distance local (on-board) communication between integrated circuits. Consequently, this interface is single ended and doesn’t lend itself to communication at higher speeds or over longer distances due to the poor EMC properties. Adding differential drivers and receivers operating in voltage mode does solve the majority of issues associated with the use of an SPI interface at the expense of using double the amount of lines and a slightly higher power dissipation.

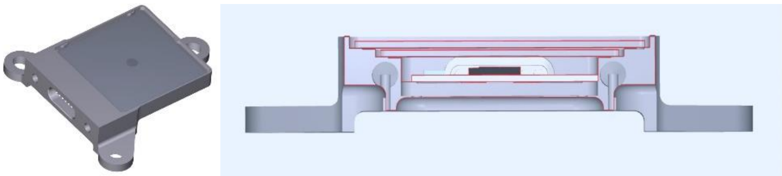
For a Sunsensor, the limited data-rate of an SPI interface is not an issue as the amount of data generated is very limited.

Based on the above reasoning, a differential SPI interface has been selected for implementation on the chip currently under design. The merits of this interface will be investigated and reported upon and depending on the outcome of these investigations the final interface might well be changed in the future, although at this moment in time no compelling arguments have been provided to do so.

4 Bragging spree or reality

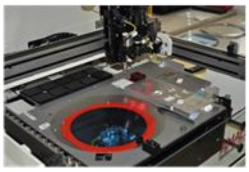
Lens R&D has engaged in this ESA design activity being convinced that the current team will come up with a working demonstrator that meets all posed requirements with exception of the hemispherical field of view. Lessons learned from past developments and new ideas developed in the cause of the last 7 years of Lens R&D's existence in combination with some critical

requirements that have changed will be core to the solution. Probably the most critical design driver will be the desire to have a redundant system for a recurring cost of less than 35k€. As membrane based systems can only have fields of view in the order of ±60° without the use of imaging optics (which would drastically increasing system costs) it is proposed to limit the field of view and use more sensors to provide the spherical coverage provided. Spherical coverage will require two hemispherical field of view Sunsensors and in the ESA case this would mean a budget of 70k€ per satellite. Most often, only the prime sensor is redundant though which means that 6 sensors plus 1 redundant sensor should be able to cover the required functionality. This leads to a budget of only 10k€ for a non-redundant but fully ESA qualified sensor which will be a daunting task to achieve but doesn't seem impossible given the current state of developments.

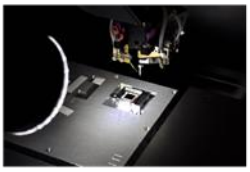


The current design (which resemble the BiSon Sunsensors quite closely) entails a design with two membranes (one with a small pinhole and the other with a secondary mirror reflector to keep the heat from the Sun out) and is based on a single chip 5*5mm^2 0.18µm CMOS chip produced in a European foundry. Using various Design Against Radiation Effects (DARE) measures to increase the resistance to cosmic radiation is expected to produce a very resilient sensor. Utilising the results obtained during several years of product and production optimisation for the BiSon Sunsensors (some of which are shown below) should allow to produce the sensors in a cost-effective way as long as there are enough units to be manufactured.

Wire-bondable integrated connector

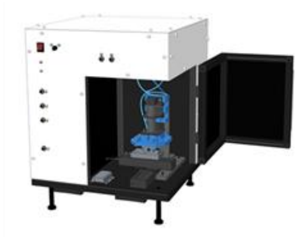


Vision based Pick and place assembly



Automated Wire-bonding

Wafer-scale Membrane Production



Automated final assembly

Despite the fact that a lot of the production flow foreseen is quite well understood, it is by no means ensured that the sensors can be very cost-effectively produced, as much will depend on how effectively known good die (KGD) can be selected and how many and which peripheral components are needed. For analogue Sunsensors, it is known that dark-current measurements are a good way to select KGD, but for a CMOS sensor, there is much more functionality that needs to be verified. Part of the functional tests required for KGD selection can be built in and accessed through the main data interface or a dedicated test interface (like a JTAG scanport to be added) but especially the analogue functionality provided by the imaging array and Analogue to digital conversion will potentially require design optimisations as well as external stimuli.

Consequently, it is expected that a substantial part of the final costs will be dependent on how effectively the required KGD can be selected and substantial design efforts are consequently expected to be devoted to design for test activities which should lead to a better testability for the final design.

As the content of the current program is very limited and focussed on providing a functional demonstrator to show the principle of operation is functioning as expected, the prototype to be devised will not exhibit the full radiation resistance to be expcted from the final design (even though some mitigation activities will be performed). In order to limit development costs, it has futher been decided that the prototype mechanical design will be based on the nanosatellite analogue Sunsensor design as used for the MAUS. (Miniature Analogue Ultimate Sunsensor)

Figure 3 MAUS

This 4mm high analogue Sunsensor is specifically designed for cubesat applications that require significantly higher reliability than any available analogue Sunsensor along with a non-calibrated accuracy that is high enough to allow using it without calibration compensation of temperature correction (thus significantly reducing the on-board processing and configuration control activities)

Using the MAUS as a basis for the digital Sunsensor demonstrator is expected to open up some flight opportunities for the demonstration unit, thus increasing flight qualification status.

Based on current insights, this small digital Sunsensor (for the time being dubbed Nano-DSS) will look remarkably the same as the MAUS.

Figure 4 Nano-DSS

When comparing the high reliability versions and the related nano satellite components, it should be noted that in essence the core technology used will be the same as for the BiSon64-ET and IBIS sensors with exception of the packaging.

This means that the MAUS will use the same radiation hardened photodiodes and the same sapphire membrane, thus leading to similar radiation tolerance for both sensors.(at least from the frontside)

The main differences are related to:

1. The connector which is not (as per ESA requirement) connected to the mechanical housing with a resistance of <10mΩ.
2. The pigtail which has no provisions to connect an EMC shielding
3. The connector which is soldered to the PCB instead of using double wirebonds

The first two points lead to a situation where the sensors will not be acceptable for ESA missions (potentially with exception of some nano-satellite missions for which the bonding and shielding requirements can probably be waved), but where the sensors are more reliable and radiation tolerant than any other nanosat solution known to us today. This conclusion is reached, because all nanosatellites fly sensors that are soldered, many nano-satellites use nano-D connectors and most Sunsensors use plastic connectors and unshielded wires,

The Nano-DSS sensor will use a similar sapphire membrane (but with a much smaller aperture) and glues and processes for manufacturing as used for the BiSon64-ET, IBIS and MAUS sensors. This also means that no performance decrease with respect to the IBIS is expected with exception of the radiation tolerance (because the IBIS uses a second window to increase the radiation tolerance to a level that will allow operation in GEO for 15 years) There will be a need for a couple of passive components though which means that it is likely some SMD components will be mounted within the package next to the dedicated IPS chip which is under development. For the IBIS we are currently considering wire-bonding these components, where for the nano-DSS these will be soldered. This will lead to a lower reliability of the Nano-DSS as compared to the MAUS, but it should be realized that the MAUS still requires some analogue interface electronics and data conversion. Consequently, it is strongly believed that the MAUS will be a good short-term solution where the Nano-DSS is expected to replace the MAUS in due time.
The common mechanical and optical interface between the BiSon, MAUS, IBIS and Nano-DSS sensors is key to an efficient calibration and will allow replacement at a late stage of design without any major issues.

As it is not the intention to run a full qualification program to demonstrate the mechanical rigidness of the design the MAUS (and eventually the Nano-DSS) sensors can be offered much more cost effective than the BiSon64-ET or IBIS sensors. As this approach is very common in the nano-satellite industry, we presume this will not be a blocking point for any of our customers. In the unexpected case it is an issue though, we can run a very effective qualification program because all test tools are already available and proven due to the use of the common mounting interface.

Although the current project only entails the concoction of a functional demonstrator, the results are expected to show that claiming to be able to develop a small and affordable high reliability Sunsensor is not just a bragging spree but that some first steps on a realistic path to producing the Sunsensor of the future have been taken.