EVERYTHING YOU ALWAYS WANTED TO DEMAND FROM A DIGITAL SUNSENSOR BUT COULDN'T GET

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ABSTRACT

True digital Sunsensors have been under development for several decades. Until now however it has proven to be difficult to produce a radiation hardened device that is cost-effective enough to find widespread use.

Analogue fine Sunsensors would be ideal sensors if not for the albedo sensitivity and need to add processing electronics.

Contrary to many statements, most digital Sunsensors are analogue Sunsensors with a digital interface only, thus leading to a solution that is still hampered by potentially large albedo errors and associated accommodation and control issues.

It is our believe that a cost-effective radiation tolerant solution can only be found if this solution is based on the use of a single chip that integrates all the required functionality within a single active component. Such a chip is currently under development in frame of an ESA ARTES AT contract [3]

In order to reach such a solution a number of trade-offs had to be made leading to a chip that uses a single 3.3V power supply, a digital interface optimised for low power and a fixed Field Of View (FOV) of 64 degrees in diagonal nominally.

1 DIGITAL SUNSENSORS

When searching the internet, several suppliers can be identified who claim to be selling digital Sunsensors. This cannot be disputed as there is basically no generally accepted definition of what a digital Sunsensor is. As such it is good to first discuss the designations used throughout this paper in order to avoid misunderstandings or misinterpretation.

1.1 Analogue Sunsensors

Analogue Sunsensors are attitude sensors that determine the position of the Sun on basis of either the absolute current generated (coarse Sunsensors) or the ratio of a number of currents generated (Fine Sunsensors)
Coarse Sunsensors are typically either single photodiodes for which the attitude of the Sun is determined on the basis of the cosine of the incidence angle or based on multiple photodiodes

positioned on a pyramidically shaped support structure, not only increasing the measurement FOV, but also allowing to determine the direction of the impinging Sun light. Although the latter generally has a limited FOV at which the ratio of the currents can be used to determine Sun pointing with an increased accuracy, the general angular accuracy is limited to a number of degrees.
Fine Sunsensors are typically based on either four quadrant photodiodes or a position sensitive device (PSD) in combination with an aperture that restricts the Sunlight from entering the sensor. These sensors typically have a FOV that is restricted to some 60° on axis, are directionally sensitive and have a higher level of shielding for cosmic radiation than coarse Sunsensors.
All analogue Sunsensors have in common that they determine the centroid of the light coming in and are therefore sensitive to albedo signals which can be generated either by reflections from the Earths surface and atmosphere or spacecraft parts like booms, antennae or solar panels.
As all known on-board attitude control systems are nowadays digital, all analogue Sunsensors will require a multi-channel analogue to digital converter before the measurement data can be processed. The construction of which will be discussed later in this paper.

1.2 Analogue Sunsensors with a digital interface

To reduce the need for processing electronics and in order to allow the use of a full-digital on-board computer, some companies have developed digital interfaces for their analogue Sunsensors and sell them as digital Sunsensors.
The earliest example (and the only one known to be radiation hardened) is the Adcole digital Sunsensor. This sensor uses a large format silicon photodiode array and comparators with dedicated thresholds to directly turn the analogue currents into digital format. Although this is an excellent example of direct conversion, it is well documented that the sensors are sensitive to major bit-flips as a result of albedo signal.
All other analogue Sunsensors with a digital interface known to the authors of this paper either use a four-quadrant photodiode or PSD in combination with conversion electronics to generate some digital outputs. These sensors are inherently albedo sensitive in the sense that they only react to the centroid of the light coming in and can therefore not be used to generate albedo insensitive data.

1.3 Albedo insensitive analogue.

In order to achieve albedo insensitivity, there are only two mechanisms known:

1) To use multiple elements
2) To use detectors that are only sensitive to wavelengths that are strongly absorbed by the Earth’s atmosphere.

The Jena Fine Sun Sensor used to be a good example of the first implementation but not only lacked a digital interface but also used a quite big detector with a lot of readout circuits to reduce the albedo sensitivity. Although this was a high reliability device that was radiation tolerant and has even reached TRL9 by flying on the Galileo testbed satellites, the sensor was never a commercial success due to the high costs and other less optimized properties (size, mass, power consumption required interfaces etc.)
Albedo insensitive analogue Sunsensors have never been a success due to the relative immaturity of wide bandgap electronics and manufacturing and verification difficulties. [1]
As a result of the above, albedo insensitive analogue has never found widespread use.

1.4 True digital Sunsensors

True digital Sunsensors in frame of this paper are Sunsensors that are both albedo insensitive and outputting the measurement data in a digital Format.
Despite the fact that there are many manufacturers claiming to build digital Sunsensors, there are only two manufacturers on the market known to the authors of this paper that would quality for this title.

1) Newspace S411
2) Cubespace DSS

Although small and cost effective, neither of these devices are to be considered radiation hardened and suited for long duration mission outside of Low Earth Orbits <600km (LEO)
There used to be two other companies offering radiation hardened true digital Sunsensors (Leonardo and TNO) but these devices were based on the use of commercially available general purpose CMOS active pixel sensors rendering them relatively large and expensive. As a result, these devices never proved to be the commercial success that was originally foreseen.

As albedo insensitivity and a digital interface would still present significant advantages over more common analogue Sunsensors, Lens R&D B.V. and Systematic Design B.V. are engaged in the development of a single chip digital Sunsensor in frame of an ESA ARTES program. This single chip approach is expected to provide the cost advantages in combination with the sought for radiation tolerance that should lead the device into becoming a commercial success.

2 Digital Sunsensor requirements

The ARTES program started off with the specifications as given in Table 1. In order to reach a workable solution though, a number of compromises had to be made and the sensor under development will not meet all of these specifications.

- Sun direction in spacecraft frame is not implemented as a feature as it would require implementation of programmable memory. This would lead to increased radiation sensitivity and autonomy during start-up. Therefore, the sensors will only provide Sun direction with respect to mounting reference.
- As the Sunsensor will use a membrane to generate a Sun Spot, it is impossible to achieve a hemispherical FOV without using some pretty complicated (and expensive) optics. Furthermore, a FOV compensation for the varying intensity over the hemispherical field of view is nearly impossible. This resulted in limiting the FOV to 64° in diagonal so as to allow reaching a full spherical FOV either using five sensors only or a sensor mounted on every face of a cubic satellite.
- In order to limit the power dissipation in the sensor it had to be decided to reduce the supply voltage to 3.3V
- No internal redundancy is taken into account as this would only increase the price of the sensors
- The extended temperature range is currently discarded due to lack of available verified simulation data thus making it impossible to simulate the behavior of the circuit for both the very low temperature and the high temperature.
- The 1Mrad radiation tolerance for the detector is contradicting the 100kRad requirement for the electronics and the target for the complete chip has been set to 250krad.

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

Table 1 initial specifications from ARTES

This limited number of adaptations has led to the ability to design a preliminary sensor that is expected to fulfill all other requirements as given. Based on preliminary analysis data the below paragraph will detail the requirements we feel can be achieved.

2.1 Performance

The requested accuracy is 5° without calibration. Based on the experience gathered with the current BiSon and MAUS sensors this accuracy should be achievable over the entire FOV.
The requested calibrated accuracy is 1° and again based on experience gathered this is not seen as a real limitation at this moment and accuracies better than this are expected, especially under normal operating conditions (no solar flares or SEU active). Extensive Design Against Radiation Effects (DARE) activities have been performed to prevent noticeable deviations to the largest extent possible.

2.2 Design goals against Requirements

Required mass is <400gr, where the projected mass is <50 gram.
Required dimensions are < 120*120*60mm3 where projected dimensions are < 50*50*15 mm3.
There are no deported electronics needed unless the supply voltage needs to be reduced to the required 3.3V, but this is not considered to be part of this design project
Required electrical power is <2W where projected power consumption is <75mW
Required power dissipation (Sun absorption) is less than 2W whereas the total area of 5*5cm will account for 3.4W of impinging Solar power and the average reflection is expected to be more than

50% also this requirement is not considered as critical and as a result of this we don’t expect to need any radiator.
The low power data interface will be separately discussed and is not really a requirement as it is listed as TBD, but definitively something that needs to be taken into account if a viable solution is to be reached.

2.3 Design and PA.

As mentioned before, no internal redundancy is foreseen. The 15 years lifetime in GEO orbit will finally be determined by the radiation tolerance of the actual device as this will determine the amount of shielding. Currently the design of the chip is aimed at reaching a radiation tolerance level of at least 250krad for the entire chip.The actual radiation tolerance will have to be established before a final design can be produced that is capable of sustaining 15 years in GEO orbit.
The number of cycles is quite low for a LEO satellite and quite high for a GEO satellite but, not taking the extended temperature range for solar panel mounting into consideration, is deemed achievable given the fact that more stringent testing has already been performed on our BiSon Sunsensors. Given some innovations in the connection technology foreseen however and the prolonged test duration of this type of test, this is seen as one of the most challenging specifications to prove.
The FIT number seems achievable if the implementation can stick to a single chip solution with an absolute minimum of external components.
ITAR free seems the easiest specification to fulfill unless the US government decides to put some glues on the ITAR list which are used but not currently listed.

2.4 Environment

All specifications listed ,with exception of the number of cycles over the extended temperature range, have already been used or exceeded during our BiSon qualification and are deemed manageable. As mentioned before, especially the low operating temperature over the high number of thermal cycles is going to be costly and time consuming to verify. Given the fact that this temperature range exceeds the temperature range of available simulation and test data, it is unclear if the final device will function properly over this temperature range. It should be noted that the sensor doesn’t need to function if the satellite is in eclipse and solar panel temperatures are very low. Therefore it is deemed acceptable if the sensor stops functioning correctly if a (to be defined) low temperature is reached, as long as it returns to proper functioning after coming back into the nominal temperature range.

3 Trade-offs

During the design of the chip a number of trade-offs had to be made, all of which were related to reliability and system costs that need optimising in order to reach a commercially viable solution.
In essence, the summary of the trades is quite simple. In order to reach a commercially attractive solution all active components will need to be integrated in a single silicon chip which has an as low as possible power dissipation.
Some previous attempts to produce a single chip digital Sunsensor were also driven by low power operation [2] but at that time the driving force behind this optimisation was the desire to power the sensor autonomously from a dedicated solar panel. This time it is driven by the conviction that

thermal control issues will otherwise lead to significant issues during use of the sensors.
The strong desire to concentrate all active components in a single silicon chip is driven by cost issues. As modern CMOS processes allow to combine a lot of different functionalities onto a single chip it is possible to avoid the use of relatively expensive active components thus driving down the cost per system. Although the implementation required a switch to a more costly multi-layer mask (MLM) approach, the overall cost per chip for the series is not negatively influenced. This is due to the large number of chips per wafer and the certainty that no additional devices will have to be ordered if the test chip turns out to be functioning correctly. Furthermore, it avoids buying a full mask set for future deliveries.
One of the first choices that had to be made,was the selection of the technology node. Based on the facts that DARE libraries are available, no high speeds are needed, and an aluminum backend (local interconnect system) is preferred, the choice was made for a low power 0.18µm XFAB CMOS process. As this process basically runs on a 1.8V power supply and the "high voltage" transistors cannot handle much more than 3.3V, it was decided to have the entire sensor run on a 3.3V platform. Designing for the minimum voltage as stated in the requirements shown in Table 1 initial specifications from ARTES would mean that external buffers would be required, adding an additional low drop-out regulator to reduce the 5V to 3.3V and thus adding additional power dissipation. In addition this would lead to a larger package, more solar power absorption etc. As the majority of circuits run on 1.8V, a major part of the power dissipation is already produced by the integrated low drop-out regulator and increasing the supply voltage even further would have caused additional power dissipation next to additional complexity, cost and increased size of the sensor.
Another choice that was made, was to go for a digital interface that neither needs a high accuracy oscillator, nor high power interface drivers. The high accuracy oscillator would have added a potentially very expensive and mechanically less robust component to the sensor (quartz crystal or mechanical resonator), increasing costs and power consumption while reducing reliability. Standard RS422 or LVDS interfaces would have led to more power dissipation in the drivers only than in the rest of the sensor. Consequently, it was chosen to use a self-clocking SPI interface with low voltage CMOS outputs and internal synchronization. The internal synchronization is needed to avoid reading out incomplete or inconsistent datasets.
Last but not least it was decided to implement all systems on-chip required to produce a full functional system which will autonomously switch on after power up and run as continuous as possible.

4 Implementation

The current implementation of the chip has led to a chip which has a chip size of 6.0*5.35 mm2 and generally looks as shown in Figure 1.

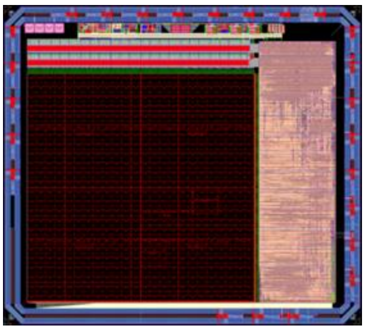

Figure 1 IPS+ chip

The chip has an 383 x 383 imaging array with a pixels size of 10 µm square. The pixels are optimized for Sun sensing and radiation tolerance and guaranteed single event latch up (SEL) free. The picture generated by this array is turned into an 0/1 picture by means of comparators which determine if the pixel is illuminated with an intensity compatible with the Sun intensity or with a lower intensity (Earth, Moon or diffuse reflection). Further on board (hard coded) processing minimizes the effect of dead pixels or sporadic hot pixels.

As a 383 x 383 pixel array with a 120 degree FOV means about 0.3° per pixel and with the selected aperture some 50 pixels are activated at the same time, we are pretty confident that the 1° calibrated accuracy can be achieved, and even 0.1° even is most likely possible. The required 5° can be guaranteed without doubt though.

The hard coded data processing will remove the effect of any dead pixel or pixel influenced by cosmic radiation before calculating the centroid of the image on the array and the associated X/Y coordinates. These coordinates will be stored in the output register which is then synchronized with the data interface.

Next to the core processing functionality, the chip also contains numerous support circuits to ensure stable operation. These circuits not only consist of a reference source and oscillator but also items like a watchdog timer, power on circuit (to ensure correct startup), a low dropout regulator as well as a temperature sensor and latching current limiter with automatic reset. The latter should theoretically not be necessary and can be bypassed in any final application. It is however implemented to ensure that even if SEL's would develop or a single event upsets (SEU) would cause large current spikes, the circuit will not be damaged and will automatically return to full functionality.

Although triple voting redundancy has been implemented on critical nodes and other automatic correction measures are taken, any action taken is indicated in the output data-stream to allow the spacecraft on-board computer (OBC) to evaluate the fidelity of the data provided and take appropriate action.

Changing to a single dedicated chip optimized for Sun sensing applications, has allowed us to implement a complete system with advanced error correction capabilities in such a way that minimum power is consumed.

One of the advanced features that has been implemented (and which cannot be offered for any analogue Sunsensor) is what is called exclusion zone programming.

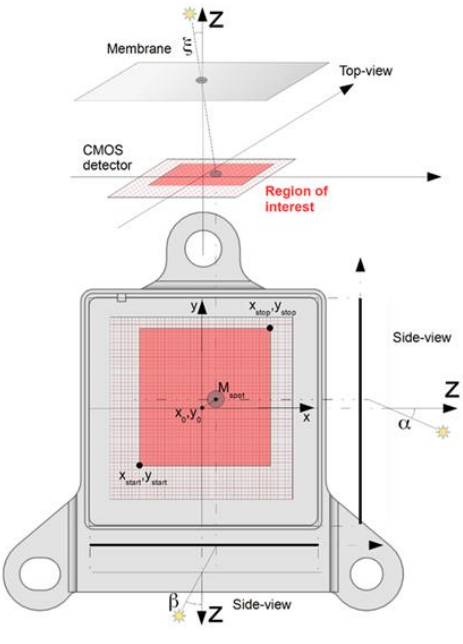

Figure 2 Exclusion zone programming

In exclusion zone programming, X/Y start and stop coordinates are programmed into the device after startup. After these coordinates are programmed, the zones outside the defined coordinates are excluded from processing.
As such this proves the same functionality as a large baffle for analogue Sunsensors. The angular extend thus programmed, will allow to have reflecting spacecraft parts within the programmed exclusion zone without running the risk of false Sun detection. It is believed that this feature improves the accommodation flexibility of the sensor as well as the data fidelity.
It should be noted that after power up, the sensor will autonomously start up with the full FOV. During programming, the coordinates are stored in triple voting protected registers to ensure reliable operation. Therefore, once programmed the restriction will stay in place as long a the component is powered up. Furthermore, regular checking of the output data can be used to verify that the start stop coordinates are still as preferred.

5 The pros and cons of a true digital Sunsensor.

The pros and cons of a true digital Sunsensor will have to be weighted at system level. It should be obvious that nothing can beat the reliability, radiation tolerance and temperature range of an analogue Sunsensor when evaluated at sensor level. What is therefore left at sensor level are the albedo sensitivity and improved utility, while accommodation issues associated with albedo effects are minimized.
At system level however the discussion becomes totally different as can be seen from Figure 3.

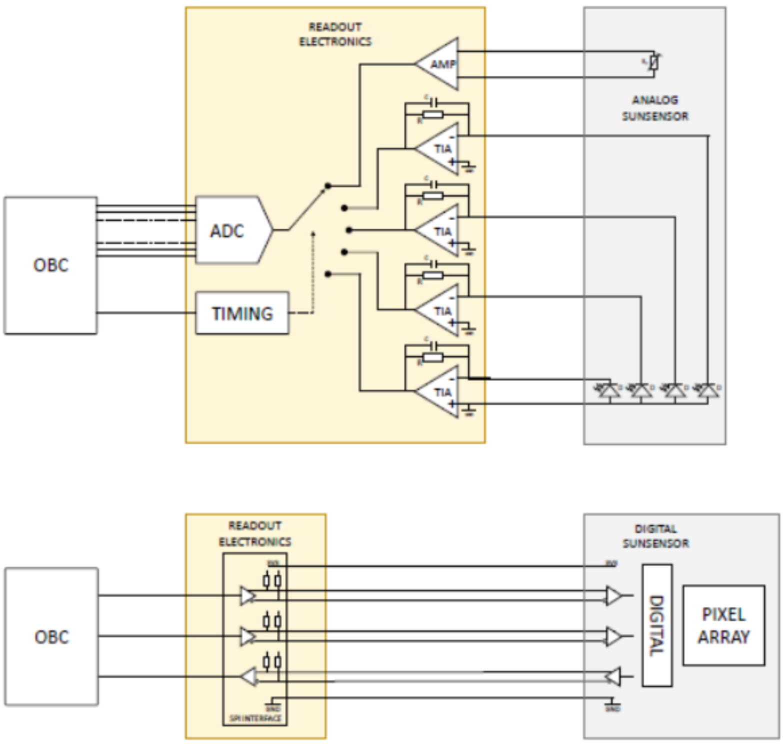

Figure 3 analogue versus digital Sunsensors at system level

Where analogue Sunsensors typically require a significant amount of interface electronics, a digital Sunsensor only requires some buffers and a power supply. Although a power supply can be quite complicated, the low power requirements for a single chip digital Sunsensor means the supply can be easily generated from an available supply whereas the analogue interface electronics will typically require several amplifiers, a multiplexer and Analogue to Digital converter (ADC) as well as a quite complex timing circuit needed to provide all the required sequencing.
As the ADC and multiplexer as well as the amplifiers and timing circuit tend to be expensive components that need multiple supply voltages and a significant amount of power, the overall cost for all components is significantly reduced if a single chip true digital Sunsensor is used, despite the fact that the digital Sunsensor will be more costly than its analogue counterpart.
Furthermore, because a lot less components are used, the system reliability will be significantly increased.
Last but not least, the Size, Weight and Power (SWaP) for the overall system will be much more advantageous for a single chip digital Sunsensor implementation, all in all leading to below trade-off table.

	analogue	digital
Radiation tolerance	++	0
Temperature range	+	0
utility	0	++
cost	0	++
reliability	0	+++
SWaP	0	++

Table 2 Trade-off table

6 Conclusions

With the advent of a single chip, radiation tolerant and true digital Sunsensor, it is expected that these sensors will take over the majority of Sunsensing applications due to their inherent advantages.
Accepting these sensors will have to lead to adaptation of the on-board computers as the other way around will probably render the sensor useless due to aggravated thermal issues and higher costs per sensor.
For applications requiring interfacing to existing hardware, very high radiation tolerance or an extreme temperature range, analogue Sunsensors are likely to prevail for the time being (rendering them not completely obsolete).
A low power true digital single chip Sunsensor core could even be used to expand again into different scenarios like autonomous powering and wireless communication, thus completing an idea that was generated at TNO in 2003 and leading to a situation where you get everything from a digital Sunsensor you always wanted.

7 REFERENCES

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