International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

Advent of the IBIS as the digital sunsensor for the future

J. Leijtens

D. Broekmans

S. Schmidt

G. van der Horn

et al.

International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 111807U · © 2018 ESA and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536201

Advent of the IBIS as the digital Sunsensor for the future.

Leijtens J [1]) , Broekmans D [1]) , Schmidt S [1]) , van der Horn G [2]) , Visee R [2])
[1]) Lens Research & Development, Noordwijk, the Netherlands
[2]) SystematIC Design B.V., Delft, the Netherlands

ABSTRACT

For many years there have been attempts to eliminate the earth albedo sensitivity for Sunsensors. This is best done through development of a true digital Sunsensor.

The best known digital Sunsensor was designed (and patented) by Adcole back in the 1970's only to be followed by the Leonardo smart digital Sunsensor and a small digital Sunsensor developed by Sinclair interplanetary some 30 years later. The first two sensors are relatively large and expensive, whereas the later is small and affordable but lacks the required radiation tolerance and quality level required for longer duration ESA missions. Although TNO attempted to develop a small but highly reliable Sunsensor between 2004 and 2010, this development did not lead further than the prototype called mini-DSS.

From this TNO research and developments it became apparent that the detector technology and detection principle used are key to delivering the desired properties: high reliability, low cost, small form factor and low power consumption.

While Leonardo stopped the development of a small digital Sunsensor in 2017, Lens R&D is now developing such a device in frame of an ESA Artes 5.1 contract signed in April 2018.

Based on insights developed during the TNO mini/micro-DSS program and a new operating principle, the Intensity Based Images Sensing (IBIS) principle is expected to lead to a producible sensor that is low power, highly reliable and cost effective.

The dedicated imager (dubbed IPS) required for the demonstrator to be built within the framework will be designed by SystematIC Design and is expected to show a very low power consumption and low operation voltage. These properties are important in order to allow for further design optimizations related to potential autonomous powering or power over data applications.

The presentation will focus on the status of the Artes program design considerations for the IBIS sensor and the optical design of the sensor, which is core to providing a highly reliable but cost-effective sensor.

Keywords: Sunsensor, AOCS, albedo insensitive, low power

1. INTRODUCTION

In order to determine the subject of this paper, we first need to define the scope of the subject a bit more clearly. Commonly used Sunsensors are analogue Sunsensors. This can be either coarse Sunsensors that use the cosine response of the incident light as the basic measurement principle, or fine Sunsensors which either use a position sensitive device (PSD) or a four-quadrant photodiode and a membrane to sense the centroid of the incoming light spot. All of these devices have in common that they either generate currents or currents transformed into voltages by sensor external electronics.

There are two issues associated with these sensors:

1) They don't provide a digital output and consequently need additional signal processing electronics
2) They are sensitive to albedo signals generated by the Sun reflecting of the Earth, Moon or satellite parts.

By adding some signal processing and conversion electronics to these sensors, one can create an analogue sensor with a digital interface. Although several suppliers have chosen this approach and are selling analogue Sunsensors with a digital interface as a digital Sunsensor, none of these sensors mitigate the significant loss of accuracy associated with albedo inputs. Consequently, these sensors are generally not considered to be true digital Sunsensors but only analogue Sunsensors with a digital interface.

A true digital Sunsensors uses a means of determining the position of the Sun by dividing the field of view in several discretely determined sections for each of which it is determined if the intensity of the signal exceeds a specified threshold.

There are various implementations of a digital Sunsensor known that satisfy this definition.

1) The Adcole Maryland digital Sunsensor, which uses two 2D arrays and two slits for directly outputting a digital code to separate signal processing electronics.
2) The Sinclair Interplanetary SS411 which uses a single linear array and four slits as well as sensor internal ADC and microprocessor.
3) The Jena Optronik Fine Sunsensor which uses two slits and one detector with two orthogonal linear section (but is generally seen as an albedo insensitive analogue Sunsensor because the electronics needed to convert the generated signals to a digital signal is not included in this sensor.
4) The Leonardo Smart SunSensor 3S which uses an active pixel sensor with integrated ADC and a signal processing ASIC
5) The TNO Digital SunSensor DSS which uses an active pixel sensor with integrated ADC and an FPGA

All of these are large and expensive, except for the Sinclair Interplanetary Sunsensor, which is small and affordable but not designed to achieve the reliability levels needed for long duration missions.

Besides the fact that the albedo sensitivity of analogue Sunsensors lead to several accuracy issues (especially for low Earth orbiting satellites) the size and foremost the price of the systems have prevented wide spread use. As there were strong indicators that micro systems technology (MST or MEMS) could lead to small and affordable varieties, and potential end users are still looking for an affordable (and reliable) digital Sunsensor, ESA has had such a device on its roadmap for almost two decades now.

Since approximately 1995, TNO in the Netherlands and Galileo Avionica in Italy (now Leonardo) and Jena Optronik have been working on digital Sunsensor implementations. During that time, the developments were driven by the Galileo constellation and ongoing digitization of satellites. Due to the comparatively high price of these digital Sunsensor implementations, the Galileo project opted to use analogue Sunsensors instead. By that time however, both TNO and Galileo had also started a further miniaturization of Sunsensors. Galileo on basis of a startracker-on-chip contract for ESA (after all the Sun is also a star) and TNO in frame of a micro systems technology advancement program called MicroNed.

2. SMALL SUNSENSOR DEVELOPMENT AT THE BEGIN OF THE CENTURY

Jena Optronik won the bid for the initial Galileo test bed satellites, but missed out on the final full deployment contract (which went to TNO). For unknown reasons this has led to Jena Optronik more or less leaving the Sunsensor market all together. Where TNO won the Galileo contract, Galileo Avionica managed to qualify their digital Sunsensor to ESA requirements where TNO failed.

Although the TNO DSS was finally flown on the Proba-3 satellite, they never managed to sell another unit of this digital Sunsensor. This was partially due to the fact that, by then, TNO was dominating the analogue Sunsensor market with high production volumes associated with the Galileo and Globalstar projects, and was also working on a miniaturized digital Sunsensor version called µDSS. This device was to be much more cost effective (thus mitigating the major drawback of the DSS) and facilitating new operating modes like autonomous powering and wireless data communication.

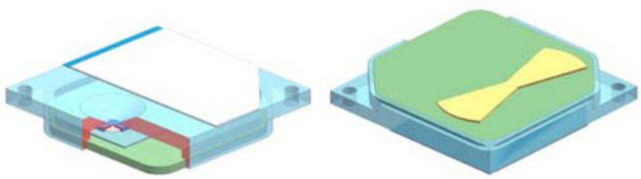

Figure 1: TNO µDSS impression [1]

As the µDSS project was a more or less academic research project the concepts generated were rather futuristic and at a low TRL level but of high interest to satellite builders around the world. At the size of half a triple junction solar cell, and with its own integrated solar panel and a wireless datalink, the concept shown above, it was intended to be mounted directly on extendable solar panels. Such an implementation would still be welcomed in the satellite market, 15 years after the first concept drawings were made.

Although two wireless autonomous Sunsensors were flown on the Delfi-C3 satellite, the complexity of the µDSS showed to be too high to implement in a first design iteration of an integrated digital Sunsensor. It was therefore decided to limit the first demonstrator to the mini-DSS shown below.

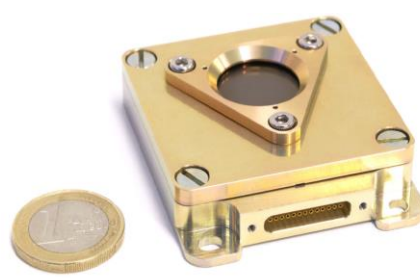

Figure 2: TNO mini-DSS [2]

During performed tests the device showed a very good accuracy, and consequently the development of this prototype can be considered a technical success.

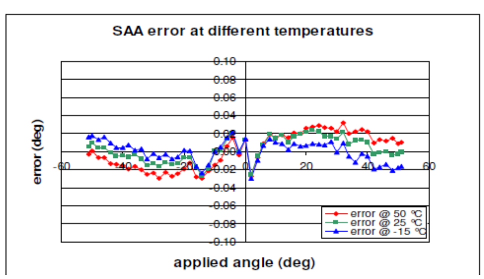

Figure 3: measured errors on prototype mini-DSS [2]

Despite the success, development of this digital Sunsensor was never continued.

In the meantime, Galileo Avionica (as a renowned Starsensor manufacturer) had obtained a contract to develop a Startracker on a chip (Low Cost low Mass Startracker LCMS). For this chip, which was to include core functionalities like sensing, analogue to digital conversion, centroid determination and data communication, one of the proposed applications was to build a Sunsensor using the same chip.

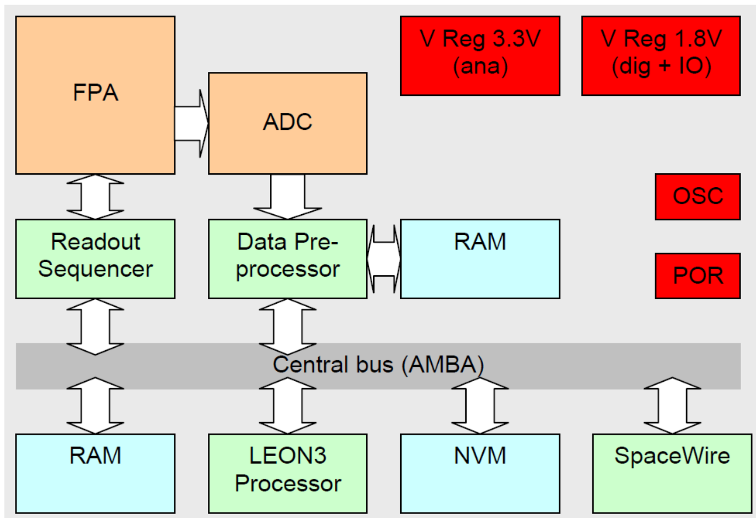

Figure 4: Intended functionality of the LCMS chip [3]

Although several breadboards have been built over the years, it proved difficult to make a small and cost effective Sunsensor on basis of a Startracker chip. The results of many tests have been reported in [4] but until the time of that paper (2011) no working Sunsensor has been shown that really fitted in the mockups presented.

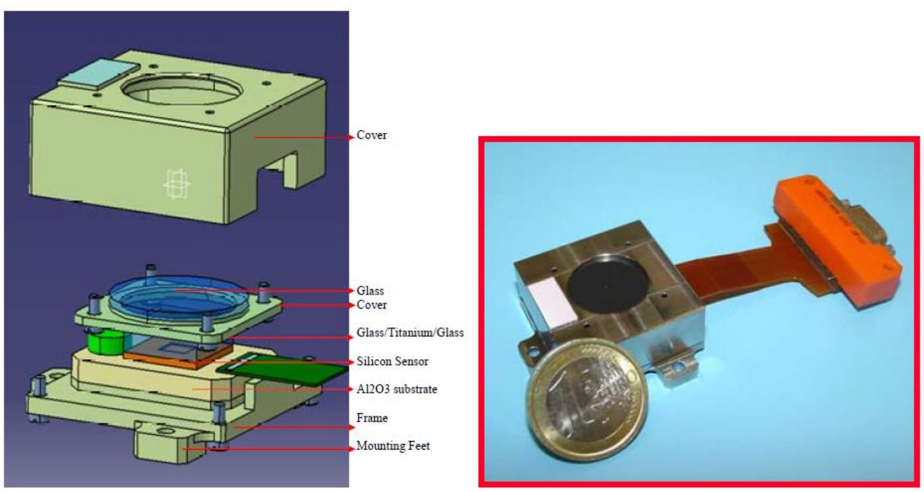

Figure 5: Galileo mini-DSS [3]

When Galileo Avionica changed its name to Leonardo in 2016 they were still working on the completion of the sensor in frame of the ESA SSoAC contract (Sun Sensor on A Chip). According to a spokesman of Leonardo, it proved to be very difficult to produce a true digital Sunsensor that will be able to compete with analogue Sunsensors currently on the market. Consequently Leonardo has decided to stop further developments of miniaturized digital Sunsensors.

3. CURRENT DEVELOPMENTS IN THE FIELD OF MINIATURIZED DIGITAL SUNSENSORS

In order to continue the development of a small digital Sunsensor, ESA has emitted a request for proposal for the development of such a device in frame of the Artes program (new technologies for telecom applications). The contract was granted to a consortium consisting of Lens R&D as the main contractor and SystematIC Design as the developer of the required dedicated chip.

Lens R&D is a small company in Noordwijk specialized in the development of high reliability Sunsensors like the BiSon64-ET-B shown below.

Figure 6: BiSon64-ET-B

The same technologies used for the production of these sensors (wire bondable housing, integrated connector, vision based pick and place, and wafer scale manufacturing of the optical membranes) can be used to produce very cost effective but highly reliable digital Sunsensors. In order for this to be realized, it is needed to develop a dedicated imaging chip that combines a number of core properties:

1) Robust to direct Sun illumination
2) Low power consumption
3) Suitable for a wide Field of View (FoV)
4) High enough accuracy
5) A common standard digital interface
6) Robust for significant levels of cosmic radiation
7) Reasonable (low) price level, when produced in larger quantities

This is why a capable and reliable partner was sought and found in SystematIC Design, a chip design house based in Delft. SystematIC Design is in the process of designing and developing a dedicated IBIS Photonic Sensor (IPS). This chip is to be core to the Intensity Based Image Sensor (IBIS) Digital Sunsensor, to be demonstrated first as a prototype during the Artes project.

As there are no other known high reliability digital Sunsensor design activities ongoing in Europe, the title of this paper seems justified.

3.1 Digital Sunsensor chip design considerations

The IPS chip will consist of a 2D array of photo diodes with readout circuitry that efficiently convert photocurrents into digital signals. The digital signals are processed on board of the IPS chip itself to extract the x-y sunspot position on the array of photo diodes with high enough accuracy. These coordinates can be readout through a standard digital interface. The coordinate values are updated after each autonomously repeated array-scan, so the sun angle can be determined at a certain sample rate (related to expected maximum angle velocity). The construction of the IBIS and positioning of IPS chip and membrane is such that there is an accurate and precise (calibrated) relation between sunspot coordinates and sun-angle in both x and y direction with respect to the perpendicular of the Sunsensor, see Figure 7. The sunspot in the middle of the array (so on the perpendicular) will lead to output coordinates (0,0). In the targeted FoV of the IBIS the angle accuracy specification can be related to the photodiode pixel dimensions.

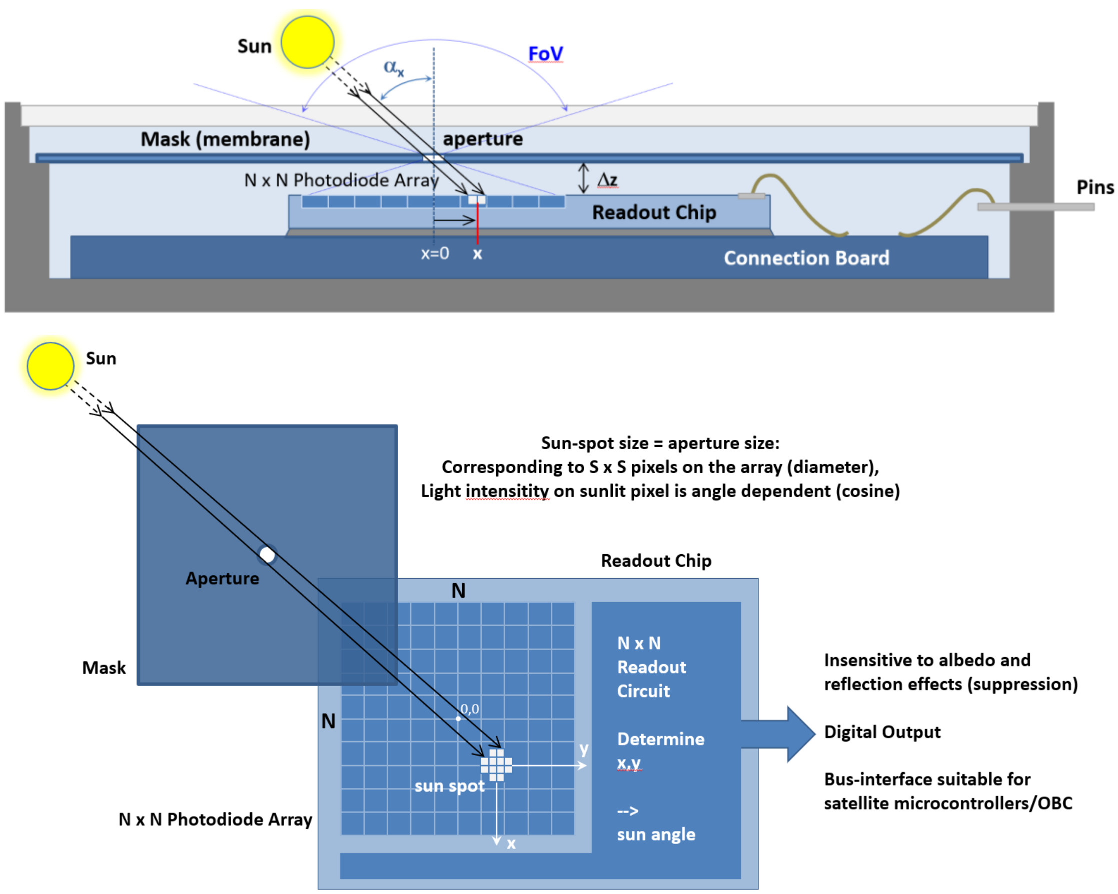

Figure 7: Illustration of the digital sunsensor chip applied in the IBIS sunsensor.

The smart signal processing is dedicated to discriminate disturbances from the sunspot based on several possible differences (discrimination factors). In that way a solid robustness for albedo, reflections or defective pixels can be achieved. Two of these discrimination factors are highlighted below.

1. Sunspot size: majority voting between neighboring pixels

As the photo array information is quickly digitized it is possible to digitally filter out information that is not of interest, such as deviating bright or dark spots. Areas that could contain reflections of satellite parts can be discarded from further evaluation by programming the area to be evaluated. Based on the mechanical construction of the IBIS and the membrane aperture the sunspot will cover a certain area on the photodiode array. This area is basically independent of the angle (due to the small opening angle of the Sun illumination) and will cover a certain number of pixels. So, we are looking for a group of adjacent photodiodes (‘pixels’) with a current corresponding to the intensity of the sunlight (rather constant once outside the planet’s atmosphere). We choose, for example, the size of the pinhole such that the sunspot will be about 8 pixels in diameter. We can filter out smaller ‘spots’, for example with a ‘triple pixel or 2-out-of-3 vote’. Looking in one dimension: if the pixel intensity deviates from each two neighboring pixels, we overrule it with the intensity of those two neighbors. In dark and bright: if a bright pixel is in between two dark pixels it becomes dark, and if a dark pixel is in between two bright ones it also becomes bright. Similarly, one may overrule pixel intensity by a ‘majority of 5 voting’ filter: for a pixel to be black, 3-out-of-5 pixels need to be black, among itself and two neighbors on both sides. In this way a digital low-pass filter is implemented. Effectively single deviating pixels or double deviating pixels will be wiped clean, as illustrated in Figure 8. This way the sensor becomes immune to single or double defective pixels or small spot reflections. The filter function can be optimized further to overcome some imperfections as visible in

Figure 8. In a similar way it is also possible to create a digital high-pass filter, meaning that bright areas larger than the sunspot size can be ignored/filtered out as well. With both filters applied properly the coordinates of the remaining bright area similar to the expected spot size will be determined digitally.

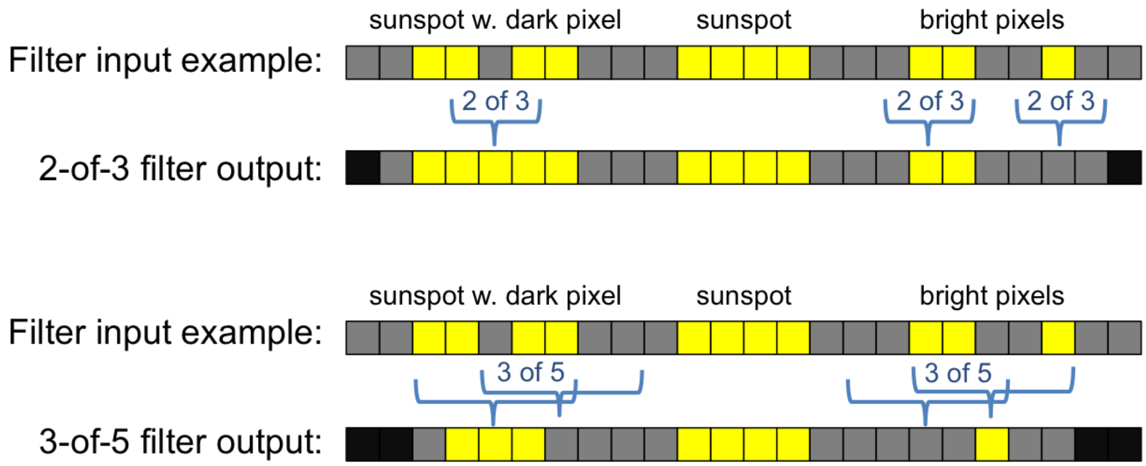

Figure 8: pixel majority voting principle, 2 out of 3 and 3 out of 5

2. Rate of change: majority voting on successive samples (x-y coordinates)

With the maximum angular velocity of the satellite and the chosen sample (scan) rate also a maximum displacement of the sunspot on the IPS between consecutive samples is expected. To filter out disturbance by reflections, glitches and albedo we include a digital triple voting algorithm on consecutive samples: each coordinate sample is compared to the previous sample, and if the delta is larger than the expected maximum displacement, that sample will be flagged. A possible approach is illustrated in Figure 9. For simplicity of the implementation we have chosen to display the situation for using three new consecutive samples before updating new output coordinates, rather than showing a 'moving average' algorithm. The later is also possible, and would enable updating the output and error flag at each new sample, rather then every three samples.

Three consecutive samples: $\mathbf{N_A}$ $\mathbf{N_B}$ $\mathbf{N_C}$	*Next consecutive samples:* $\mathbf{N_D}$ $\mathbf{N_E}$ $\mathbf{N_F}$
Calculate: $\Delta_1=N_B-N_A$, $\Delta_2=N_c-N_B$	*Calculate:* $\Delta_1=N_E-N_D$, $\Delta_2=N_F-N_E$
Check deviations against max Δ *and choose* $N_{out,1}$:	*Check deviations against max* Δ *and choose* $N_{out,2}$:
If $\lvert\Delta_1\rvert<\Delta$ & $\lvert\Delta_2\rvert<\Delta$ then $N_{out,1}=N_C$ **(flag=0)**	If $\lvert\Delta_1\rvert<\Delta$ & $\lvert\Delta_2\rvert<\Delta$ then $N_{out,2}=N_F$ **(flag=0)**
If $\lvert\Delta_1\rvert>\Delta$ & $\lvert\Delta_2\rvert<\Delta$ then $N_{out,1}=N_C$ **(flag=1)**	If $\lvert\Delta_1\rvert>\Delta$ & $\lvert\Delta_2\rvert<\Delta$ then $N_{out,2}=N_F$ **(flag=1)**
If $\lvert\Delta_1\rvert<\Delta$ & $\lvert\Delta_2\rvert>\Delta$ then $N_{out,1}=N_B$ **(flag=1)**	If $\lvert\Delta_1\rvert<\Delta$ & $\lvert\Delta_2\rvert>\Delta$ then $N_{out,2}=N_E$ **(flag=1)**
If $\lvert\Delta_1\rvert>\Delta$ & $\lvert\Delta_2\rvert>\Delta$ then $N_{out,1}$**=ERROR (flag=1)**	If $\lvert\Delta_1\rvert>\Delta$ & $\lvert\Delta_2\rvert>\Delta$ then $N_{out,2}$**=ERROR (flag=1)**

Figure 9: triple voting algorithm on successive samples

Both above described sunspot discrimination methods allow to include a fault detection: in case ‘irregular information’ is found and filtered we may choose to set a fault flag in the output data. For example, when two sunspots are found (sun + earth albedo) or in case the triple sample voting detects a deviation. The satellite OBC or the controller reading out the sunspot data may then be prepared to act like (double) check data against that of a redundant Sunsensor.

The design and development of the IPS prototype chip is currently prepared for a suitable process of a European foundry. The above described digital algorithms are to be refined, simulated, and included on-chip with the sensor readout electronics. Excellent performance in accuracy (<0.5 degree) and sample rate (<1ms) at a low-power consumption (<100mW) and at a low operating voltage (2.5V) are expected to be feasible.

4. CONCLUSIONS

There have been several attempts in the past to develop a low-cost high-reliability digital Sunsensor, but none of them have led to a workable solution.

It is deemed essential for a low-cost high-reliability digital Sunsensor to develop a dedicated ASIC providing a low power solution capable of servicing a multitude of missions with a good enough performance. This comprises:

- Robustness to albedo and other reflection effects
- Low voltage operation (2.5V)
- Wide enough field of view (±60° per sensor)
- Good enough resolution (0.5°)
- Commonly used digital interface
- Inherent robustness to radiation effects (ionizing radiation,displacement damage, heavy ion's)
- As few external parts as possible

The IBIS sensor currently under development within an ESA Artes contract is planned to satisfy all of these requirements. If the expectations are met this will without doubt position the IBIS as the Sunsensor of the future.

REFERENCES

[1] Leijtens, de Boom "TNO and the "Kees" of the incredibly shrinking Sunsensor, ESA 4S2006
[2] De Boom et al, mini-DSS miniaturized high precision Sun angle measurement, ESA GNC2011
[3] Monnini et all "System on Chip Development for attitude sensors", ESA GNC2008
[4] Fidanzati et all, Miniature Sun sensor on a chip performance evaluation, ESA GNC2011