Mini-DSS: MINIATURIZED HIGH-PRECISION SUN-ANGLE MEASUREMENT
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ABSTRACT
High precision sun angle measurement has long been associated with costly, bulky and comparatively power hungry solutions. With the advent of TNO’s mini-DSS this is no longer necessary. What started out as the development of a fully autonomous wireless digital sunsensor a number of years ago, has lead to a sunsensor on chip ASIC development called the APS+. This CMOS device includes a 2-d array image sensor and processing electronics on the same chip. In the current approach, the device will neither be autonomous nor wireless. The design uses a conventional low drop out regulator to supply the mini-DSS from a pre-regulated (secondary) DC power source and an RS422 data link. The housing for the mini-DSS though will allow the implementation of several I/O options (including PnP interface). A prototype sensor has been built and was exposed to a performance test in a laboratory sun simulator set-up, demonstrating accuracy in the range of a few arc minutes and a resolution of less than one arc minute in the whole of its 100° x 100° FOV.

1. BACKGROUND
A well known activity of TNO in the field of space instrumentation is the development, qualification and small series production of high reliability coarse and fine sun sensors. Examples of these sensors are the Coarse Sun Sensor (CSS), the Attitude Anomaly Detector, the analog Fine Sun Sensor (FSS) and the Cosine Sun Sensor (CoSS). In the past decades, dozens of these sun sensor products found their way into space platforms, for missions in different orbits (LEO, MEO, GEO, interplanetary), including commercial constellations of spacecraft. The latter require relatively high volumes (up to hundreds of units). Examples of such products, which are produced by TNO together with its industrial partner Bradford Engineering from the Netherlands, are depicted in Fig 1. These units are applied on telecommunication and navigation spacecraft and constellations.

Fig. 1. High volume “Space off the Shelf (SOTS)” sun sensor products (left: CSS, middle: FSS, right: CoSS)

Recurring production projects for these “Space-off-the-Shelf” type of standard sun sensors will be taken up by industry. This way, high quality products can be offered at competitive prices, without impairing performance or reliability. Lower equipment cost is beneficial to any program. Smaller dimensions are attractive too and for smaller spacecraft, reduced equipment sizes are crucial. So in order to introduce the “power of numbers” also in future sun sensor products, miniaturization is a key factor in the development. TNO is concentrating on such new developments and on special applications of sun sensors.

2. INTRODUCTION OF THE MINI-DSS: A “SUNSENSOR ON CHIP”
Miniaturization efforts are made for different products, such as Cosine Sun Sensor, quadrant Fine Sun Sensor and a digital sun sensor on a chip (see also fig 2).
The redundant Cosine Sun Sensor has dimensions of 45 x 367 x 6 mm³ and weighs 15 grams (exclusive cables). The quadrant FSS is a passive version of a fine sun sensor with a size of 50 x 45 x 17 mm³ and a mass of 50 grams. These devices have attractive small sizes, but offer coarse to moderate accuracy of sun angle measurement and are handicapped by their sensitivity to spurious light input from S/C reflections and more importantly from planetary albedo. Therefore TNO has started the development of a device called mini-DSS, based on an array of pixels (CMOS active pixel sensor) positioned behind a pinhole type aperture. This lay-out for a sun sensor would offer inherent immunity for straylight and planetary albedo.

The original idea was to aim for a sensor that could be made fully autonomous in terms of power supplied by an integrated solar cell. Initial study revealed that the planar dimensions of a miniaturized sensor would be dominated by the size of this generator, which should be large enough to produce enough supply power. So the target of the new development was to arrive at minimal power consumption. The axial dimension of the miniaturised sun sensor would be dominated by the size of a connector. At first TNO aimed for a wireless interface, so that the unit would need no connector at all. An outline of such an approach is depicted in fig 3.

Advanced experiments on a fully autonomous and wireless sun sensor were carried out by TNO in a demonstration device flying on-board the cubesat Delfi-C3 from the Delft University of Technology. Although the feasibility was proven, the lack of communication standards for space application and the lack of prospects on short-term implementation of wireless technologies on the “receiving AOCS side” have guided TNO to a more pragmatic approach. The current design is based on the inclusion of power conditioning circuits suited for a pre-regulated low level (3.5 to 5.5V) supply voltage input and with established RS-422 data communication, all through a special miniaturised connector interface.

This paper describes the mini-DSS sun sensor on a chip that resulted from our development work and presents the first performance test results.

3. APS+: THE HEART OF A “SUNSENSOR ON CHIP”

The heart of the system is an advanced active pixel sensor (APS) as detection module behind a pinhole sized aperture mask, through which sun light penetrates and incidences on the pixel grid.
The principle of operation is shown in fig 4 and is based on the measurement of the location of the centre of luminosity of sunlight projected onto the image area of the chip, with respect to the “boresight pixel”.

Fig 4. Operating principle of a pinhole aperture, giving access to sun beam impinging on the APS image area

Compared to high-quality APS devices from specialist companies (Cypress, CMOSIS), it was considered essential for our “sun sensor on a chip” approach to include not only the 2-d pixel grid, but also processing steps, like AD conversion of pixel data, sunspot location determination and input/output functionality, all integrated into one chip, further named APS+. The design of it is performed in close cooperation with Harvest Imaging, a Belgian SME with recognized expertise, and with the Technical University Delft (faculty of Electronic Engineering).

The APS+ is in fact an application specific integrated circuit (ASIC), specially designed and optimized for sun sensing application. The circuit combines an imager section with FPGA functionality, embedded in a single chip. This is the only way to achieve a compact, rugged and reliable sensor device, suitable for all kind of sun sensor applications in sun acquisition, in safe mode and in normal operation. Low power consumption (target less than 50 mW), low operating voltage and a high tolerance to particle radiation have been other important design criteria. A function block diagram of the APS+ device is depicted in fig 5, together with the chip outline.

Fig 5. Functional block diagram of the smart active pixel sensor and the physical location of functions on chip

The main sub-circuit functions in the APS+ device are:

- Active pixel array of 368*368 pixels with pixel size of 6.5 micron
- Pixel array control signal generator
- Analog to digital converter
- Digital signal processor for sun acquisition and sun spot centroid determination
- Digital communication sub-circuits to feed the UART for digital communication with the sensor across a RS422 physical layer (note: input not obligatory; sensor operates autonomous when not commanded)

The array controller, digital processor and communication circuits together are called “algorithm” in fig. 5.
Manufactured in 0.18 micron TSMC multi project wafer technology, the APS+ chip shows some very interesting properties that are well suited to low cost application in space like:

- radiation tolerance up to at least 100 krad which is sufficient to withstand the doses received during the majority of missions
- low power dissipation
- High quality and uniformity of performance due to large volume of circuits produced.
- Low recurring costs due to the used multi project wafers and standard processes.

With regard to power dissipation, the design of the APS+ includes special features. The device has two basic modes of operation: acquisition mode and tracking mode. The power consumptions in both operational modes should not differ too much, particularly not in applications in which the device has to rely on self generated power from an integrated solar cell. In the acquisition mode, typically the entire pixel frame would be read-out to find the approximate position of the spot of sun light. In tracking mode only a small “window” around the sunspot is read-out, in which a centroiding algorithm finds the coordinates of the luminous centre. As in CMOS circuits the power consumption is largely depending on the switching frequency, the power consumption required in the acquisition mode would then be much higher than in tracking mode.

In the APS+ design, this has been overcome by dedicated on-chip functionality to ensure a balanced power demand for the two operating modes. This functionality brings the acquisition mode down to a ‘winner takes all’ approach, in which the brightest pixel in rows and columns are determined. This leads to row and column profiles which are read-out by the system to find the appropriate location of the tracking window. The principle is visualized in fig 6. In this way, acquisition and tracking mode have similar power demands.

![Fig6. Visualisation of winner takes all principle of “low power” sun acquisition](image)

### 4. SENSOR CORE

Apart from the APS+ chip, peripheral electronics are needed which comprise voltage leveling (to bring the external pre-regulated supply voltage down to internal voltages of 3.3 V and 1.8V, required by the circuitry), a crystal oscillator and logic input/output circuitry. The APS+ and its peripherals are installed on a ceramic (Al2O3) substrate.

In order to make a solar aspect sensor out of it, the APS+ must be put at the right distance behind a pinhole type aperture mask. The latter is made by etching a hole in a layer of metallization deposited on a glass. This mask carrier is made of synthetic sapphire (Al2O3), which is radiation tolerant. The metallization is treated with a special overcoat to suppress multiple reflections between the chip and the aperture mask. The distance between the chip and the pinhole mask (also called collimator length) is a key parameter in the conversion from pixel coordinates into solar aspect angles. The larger its stability in time and with temperature, the better the sensor performance will be. In the sensor core of the TNO mini-DSS this distance is controlled by ceramic (Al2O3) spacers, adhered to the ceramic chip substrate on one side and to the sapphire mask carrier on the other side. In this way, a very stable sensor core is achieved with materials that have a perfect match of their coefficients of thermal expansion (CTE).

The technologies and materials chosen are well known in semiconductor industry and in micro-electronic applications. They lend themselves for accurate “automated” assembly by means of pick and place machines. To this extent TNO has sought cooperation with Lewicki Microelectronics in Oberdischingen (Germany). This company has been involved with detailed design of the construction of the sensor core and with the high reliability pick and place tasks and other hybrid manufacturing alike technologies for assembly of the sensor core and for installation of this core in a dedicated sensor package.
5. SENSOR PACKAGE

The design of the mini-DSS is driven by criteria which were found most important for potential customers of this sun sensor product. These criteria, which rendered from consultations made with space industries including ASTRIUM, Thales Alenia Space, OHB, SSTL, AAC and others are:

- low production cost
- low power consumption
- versatility in use in different applications and in large and small satellites
- relative ease of qualification

Although small sensor sizing was a target too, the miniaturisation of dimensions has not been pushed to the limits. Nevertheless, TNO searched for an adequate micro-connector, as the axial size of the package is dominated by connector size. The French company AXON’Cable, specialist in this field, was consulted to support TNO with a package design and a special single in line micro-connector type. The chassis connector part is to a large extent “hermetic” and is adhered inside a slot in the sidewall of the package.

The package casing is machined from aluminium with alodine treated outer surfaces (instead of the more commonly used nickel iron alloy (Kovar) with gold plating). Aluminium is lighter, inherently non magnetic, easier to obtain and easier to machine. Furthermore aluminium has a good thermal conductivity which is advantageous from thermal point of view and the package material matches perfectly well with (small) S/C panels and brackets, which are typically made from aluminium as well. The alodine treated surfaces of the package provide a better interface for adhesion of the ceramic chip substrate and of the body of the chassis connector. A schematic outline of the package design and a photo of the casing are presented in fig 7.

![Schematic outlines of sensor package and a photograph of the casing with ceramic chip substrate](image)

The design shown above renders a chip cavity which is to a large extent “hermetically” sealed to avoid contamination of the sensor core during the lifetime on the ground. The top-cover is attached to the casing with bolts in four corners. In the interface plane of the casing rim is a seal is vulcanised made from conductive rubber. In the top cover a seat is created to hold a radiation tolerant sapphire window. The window is coated with an optical attenuation filter to avoid saturation of the APS image sensor. Although sapphire can be welded into aluminium packages, it has been decided to clamp the window in the package with conductive rubber seals on both sides, vulcanised into the top-cover and triangular window clamp respectively. This construction allows exchanging of the filter if needed.

An important feature for internal and external alignment of the sun sensor is the lay-out of the three mounting feet. They are coplanar and designed such that one foot has a calliper hole, a second foot has a slotted hole and the third foot has a slightly oversized hole. Applying specific fasteners with calliper shafts, rotational alignment of the sensor can be assured. This provision is also used during the assembly of the sensor core to ensure alignment of the planar axes of the sensor (co-aligned with column and row directions of the image section of the APS+) with the mounting feet. These provisions in combination with the use of pick and place technologies for assembly of the sensor core and the integration in the package allow low-cost production of devices with high batch uniformity of performances.

All materials applied in the construction of the device and in its connector are chosen with ECSS standards regarding outgassing, corrosion resistance, particle radiation tolerance and other environmental constraints for space hardware. Prototype hardware manufactured according to this design is virtually flight worthy.
6. PROTOTYPE SENSOR AND ITS PERFORMANCE

A number of prototype sensor modules have been manufactured, one of which is chosen to undergo a test program as preparation for a demonstration flight on a nano-satellite program. A photograph of one of the prototype devices is presented below in fig 8.

![Photograph of prototype of the mini-DSS, built around a “sun sensor on a chip” sensor core](image)

Fig8. Photograph of prototype of the mini-DSS, built around a “sun sensor on a chip” sensor core

A summary of important performance characteristics is presented in table 1 below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved performance</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>69x52x14 (incl mounting feet)</td>
<td>mm³</td>
</tr>
<tr>
<td>Weight</td>
<td>70</td>
<td>grams</td>
</tr>
<tr>
<td>Supply current</td>
<td>10 (note 1)</td>
<td>mA</td>
</tr>
<tr>
<td>Power consumption</td>
<td>35-55 (note 1)</td>
<td>mW</td>
</tr>
<tr>
<td>Field of view</td>
<td>51 x 51 (note 2)</td>
<td>Degrees of arc</td>
</tr>
<tr>
<td>Non calibrated Accuracy</td>
<td>&lt;&lt; 0.5</td>
<td>Degrees of arc (3σ)</td>
</tr>
<tr>
<td>Calibrated accuracy</td>
<td>&lt; 0.1</td>
<td>Degrees of arc (3σ)</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.01</td>
<td>Degrees of arc</td>
</tr>
</tbody>
</table>

Table 1. “Achieved performance characteristics

Note 1: The supply current is close to 10 mA, irrespective of the supply voltage level. The power consumption depends on the choice for the pre-regulated supply voltage offered to the sensor.

Note 2: The FOV of this design was deliberately chosen to be around ±50 x ±50 degree of arc, in view of the possibility to implement autonomous power generation (optional) with an integrated solar cell. For larger solar aspect angles, the power output drops off too much.

Sun angle measurement capability and related performance aspects were verified whilst the sensor was adjusted in a sun simulator test set-up. This set-up includes a Xenon-arc source based lamp unit which produces a near collimated beam of light with intensity (on silicon detectors) equivalent to one solar constant. The sensor unit is illuminated whilst being mounted on a two axis rotation set-up (resolution 0.001 degree of arc, accuracy of set-up 0.01 degree of arc).

In this set-up the size of the FOV has been determined (result reported in table 1 above), taking into account the size of the image area of the APS+, the size of the collimator length and the size of the tracking window around the sunspot. Criteria for FOV cut-off are the generation/absence of the sun presence signal and a flag of the tracking window approaching the rim of the chip.
Furthermore, the immunity for disturbing straylight or planetary albedo was qualitatively demonstrated by simultaneous illumination of the sensor with the sun simulator beam and a bright (cold-light) hand-held torch. The sun simulator set-up has also been used to investigate the solar aspect angle measurement performance, by means of scanning with the sun through the FOV. An example of such a scan is depicted in fig 9, which presents the relationship between the applied solar aspect angle (the setting of the rotary tables) and the measured solar aspect angle. The theoretical line is the diagonal in the plane of the plot (pink line); the measured angles are obtained for rotation table settings with steps of 2 degrees in applied angle.

![FOV scan](image)

**Fig9.** Measured solar aspect angle versus “applied” solar aspect angle for a scan of the Sun through the FOV. The inset in the top-left corner shows the difference between measured and applied angle, plotted against its own vertical scale of 0.02 degrees per interval.

The measured data in fig 9 is obtained without any correction, other than choosing a single best fitting collimator length (distance between chip and aperture mask) in the algorithm for conversion of pixel coordinates to solar aspect angle. In this “uncalibrated” condition, the difference between measured and applied solar aspect angle remains already in the order of a few hundreds of a degree (i.e. about 3 arcmin). The error profile along the scan of the sun through the FOV is rather systematic. This suggests that with a correction on-board the computer of the S/C, based on ground calibration data, the residual errors can be even further reduced. Of course, many more scans through the FOV should be made under different temperature conditions. But the results so far are encouraging and above considerations have led TNO to claim accuracies as presented in table 1.
In order to quantify sensor resolution, i.e. the ability to detect small angular changes, the sun was scanned through the FOV near the sensor boresight in steps of 0.1 degree of arc. Because of the non-linearity in the tangent relationship between the solar aspect angle and the lateral shift in the sunspot projection on the image area, detection of small changes in the solar aspect angle is most difficult for sun incidence near the sensor boresight. The plot in fig 10 reveals the measured changes in solar aspect angle versus the applied ones.

![Resolution demonstrated in steps of 0.1 deg of arc](image)

Fig 10. Indication of sensor resolution from the measurement of sun angle steps of 0.1 degree of arc.

The difference between applied steps (of 0.1 degree of arc) and measured steps is very small, in fact less than 0.01 degrees of arc. This indicates a resolution of better than 0.01 degree of arc near the centre of the FOV and thus also in the rest of the FOV.

7. **CONCLUSION**

A miniaturized version of a digital sun sensor is developed and produced as prototype for performance assessment. The device uses a specific design of an Active Pixel Sensor with on-chip processing of sun data rendering the pixel coordinates (with sub-pixel accuracy) of the sun luminous centre. The accuracy of solar aspect angle measurement in a FOV of 100° x 100° will be in the order of 0.1 degree of arc; the resolution of the sensor is 0.01 degree of arc. By nature of its design, the mini-DSS performance will not be adversely affected by (S/C) straylight and planetary albedo.

The device has small dimensions, low mass and low power consumptions to make it suitable not only for applications in conventional spacecraft missions but also for micro- and nano satellites. The design to cost approach and automated assembly technologies enable batch production of devices with high batch uniformity and for comparitatively low cost.

A prototype sensor is being prepared for a demonstration flight on board the Swedish QuadSat. This satellite program is a joint venture between Angstrom Aerospace Corporation from Sweden and OHB in Germany and is designed to demonstrate the potential of Plug and Play interface technology.

TNO gratefully acknowledges the financial support of the Dutch micro-technology development program MICRONED for the development of the APS+ and the Netherlands Space Office (NSO) for their financial support of the design and development of the sensor core and the packaging.