

International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas



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International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 10563, 105633W · © 2014 ESA and CNES
CCC code: 0277-786X/17/\$18 · doi: 10.1117/12.2304088

HOW GOING MAD CAN HAVE ITS ADVANTAGES

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I. INTRODUCTION

Going mad is not commonly looked upon as a positive event. Going MAD however (where MAD stands for Multiple Analogue Digital) can have its advantages. The MAD concept is a new concept of sun-sensing which will allow producing highly radiation tolerant, low power quasi digital sensors on a chip which will be able to operate from a single power supply and even at higher temperatures.

The concept brings small but fully autonomous digital sensors within reach and could lead to a shift in the way sensors are applied on items like satellites, interplanetary rovers or even trackers used for concentrated photo voltaic applications (which is a terrestrial application)

This paper will discuss the initial MAD concept as well as an implementation which can be used to produce a sensor on chip.

II. The MAD concept

The “invention” of the MAD concept was driven by discussions on albedo sensitivity of analogue sensors and the related desire to develop digital sensors which don't exhibit this issue due to the fact that digital sensors discriminate between Earth's albedo and the sun by looking at the amplitude as well as the angular extent of the source. As the Albedo [1] sensitivity is largely driven by the field of view of an analogue sensor the measured attitude can deviate considerably from the actual attitude of the spacecraft. Depending on orbit height of the S/C and on the angular configuration of S/C, Sun and Earth, albedo signal can be a significant part of the measurement signal generated in analogue sensors. This may even result in attitude measurement errors up to 10 to 15 degrees generated in low Earth orbits. Due to the large FOV of coarse sensors, these sensors are affected by albedo effects the strongest. Fine sensors (which use an additional aperture at a specified distance above the actual detector are much less affected, but these sensors are more complicated and consequently significantly more expensive than coarse sensors. The aperture in analogue Fine Sun Sensors restricts light from external objects (like solar panels, antennae or body parts of the spacecraft) as well as light reflected from the earth from entering the sensor to a large extent. The actual reduction of these signals largely depends on the field of view of the sensors. Depending on the way the sensors are constructed, the angular range to which a sensor is sensitive for albedo inputs in general significantly extends beyond the actual measurement range (Field of View) of the sensors. As an example of this we can have a look at the BiSon 64 sensor which is a typical fine sensor based on a four quadrant photodiode. As indicated in Figure 1 the measurement field of view of this sensor is 64.5 degrees (in diagonal). This measurement range however is defined by the angle for which the sun spot created by the aperture is shifted to one side of the quadrant detector. Up until this angle signal is generated in all four channels of the sensor. For angles extending beyond this range, the sunspot will be on one detector half only, causing a decreasing intensity over increasing angle. Light from disturbing sources (including Earth albedo) may reach the detector for any input angle up to 80.9 degrees of arc (in diagonal) and cannot be discriminated from direct sun input

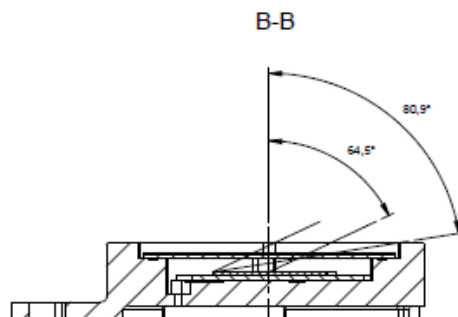


Figure 1 BiSon 64 field of view restrictions

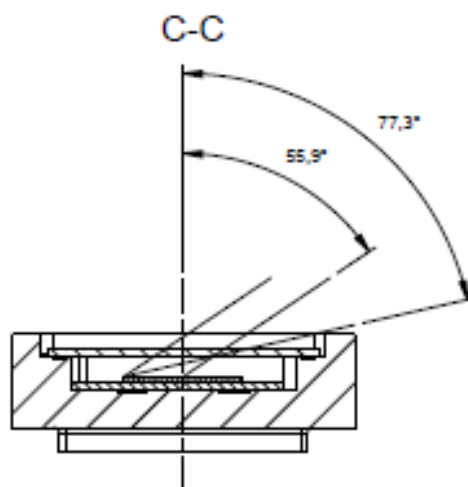


Figure 2 BiSon 64 sensitivity angles in symmetry planes.

As shown in Figure 2 in main symmetry planes of the sensor the angles are different but still very significant. For small field of view sunsensors like the BiSon 6 shown in Figure 3 the albedo sensitivity field of view will be nearly 3 times as large as the measurement range. Nevertheless this range will always decrease if the measurement range decreases which is why the measurement range should be restricted as much as possible. For this reason the BiSon 64 sunsensors have a measurement range of ± 64 degrees in diagonal instead of the more common ± 64 degrees on axis. This seems only a small difference, but significantly improves the albedo sensitivity due to the geometric properties of the earth/satellite combination (as will be explained later)

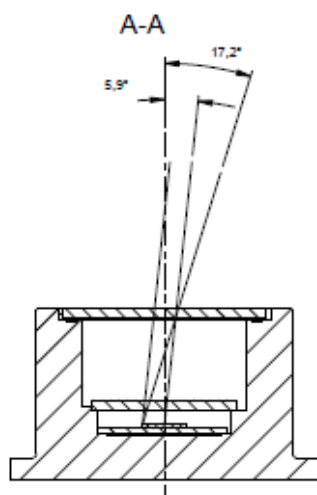


Figure 3 BiSon 6 field of view definition

Although the input outside the measurement field of view can be restricted by means of additional baffles, it means a clear distinction has to be made between the measurement range and the albedo sensitive range when considering albedo issues.

The MAD concept takes the albedo sensitivity as well as the measurement range of the sunsensors into account. The principle is based on the presumption that the majority of satellites will be earth pointing. In case the satellite is earth pointing, it will be dependent on the altitude of the orbit at which aspect angle the sun will appear when getting out of eclipse.

This fact is demonstrated in Figure 4 where a (fairly low) altitude of 500km is taken for the satellite. From this figure it can be seen that the sun will only impinge upon the satellite with an angle which is 22 degrees (or more for higher S/C altitudes) inclined with respect to the normal of the satellite side panel.

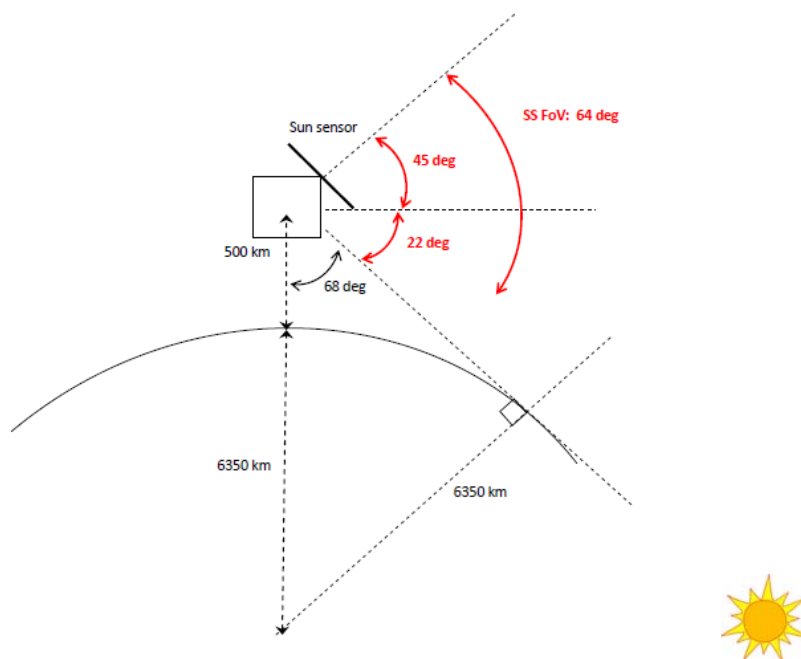


Figure 4 End of eclipse angles for MAD configuration

This automatically means that any albedo signal can only enter the sensor at angles larger than 22 degrees with respect to the normal of the side panel as otherwise the signal is not reflecting from either clouds or the earth's surface.

When the sensors are tilted by 45 degrees with respect to the satellites panels, and the measurement angle of the sensors is 64 degrees (on axis) it can be seen that the albedo signal will never give any signal within the measurement range of the sunsensor (as $45+22=67$). This means that with a common analogue sensor tilted over an angle of 45 degrees (for instance) and a baffle it should be possible to create a situation where earth's albedo will have no influence on the attitude measurement. As multiple analogue sensors will be required to measure the attitude over the orbit (until the sun goes into eclipse at the other end of the trajectory) without albedo sensitivity (which is the main reason why people want digital sensors) the concept is dubbed multiple analogue digital sensor.



Figure 5 Moog Bradford (TNO) FSS and BiSon 64 sensors

As mentioned the field of view for albedo signal will have to be restricted by means of a baffle, but this baffle will drastically increase the size and mass of the sensors. (see Figure 5). The shown FSS has a field of view of

138*138 degrees (on axis) in which no albedo signal shall be generated to ensure the rated accuracy. This means that a MAD configuration can be provided on basis of these sensors for spacecraft altitudes higher than 600km.

If we calculate the limit angle at which albedo can still reach the sensor for different altitudes Figure 6 it can be seen that the angle only very slowly goes down with the altitude of the spacecraft.

The difference between 500km and 1500km altitude is only some 14 degrees. For a BiSon 64 sunsensor with 56 degrees measurement angle on axis (64 degrees in diagonal) the on axis exclusion angle is 77.3 degrees (see Figure 2) for a similar sensor with 64 degrees in main symmetry plane this would be 80.8 degrees. Although this doesn't seem much of a difference, it has a significant effect on the albedo sensitivity. Where the first sensor will be completely insensitive to earth albedo for altitudes higher than 1160km's, the latter will only reach this for altitudes higher than 1500km.

Although exact calculations would involve taking the curvature of the earth and the exact field of view for various input angles of the sensors into account it can be reasoned that the albedo generated signal will change approximately to the square of the observation angle as the strip of the earth will not only get higher but also wider. If we then compare the expected performance of a sunsensor with 64 degrees in diagonal (which is needed to provide full spherical coverage with 6 sensors) of a sensor with 64 degrees in main symmetry planes, we can see a clear difference (see Figure 7 where the spacecraft angle is the limit albedo angle seen by the spacecraft given as 68 degrees in Figure 4)

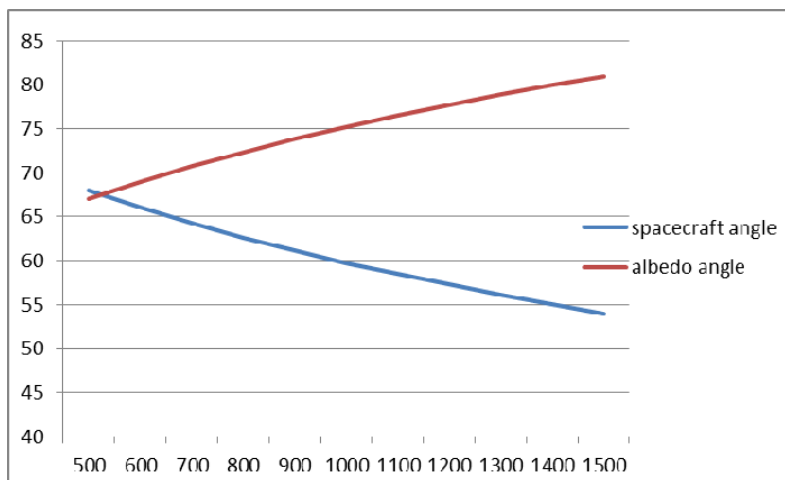


Figure 6 albedo limit angle for different altitudes @45 degree sunsensor rotation:

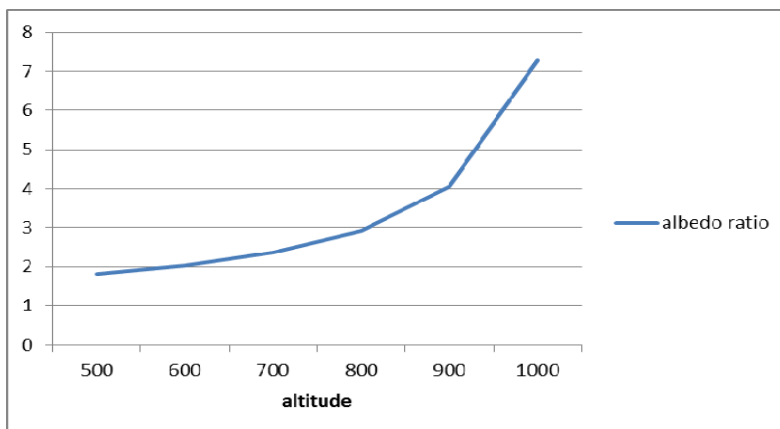


Figure 7 relative albedo sensitivity in MAD configuration of sensor with 64 degrees in diagonal or 64 degree in main symmetry plane

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Based on the above it can be concluded that a BiSon 64 sunsensor is ideally suited to provide near 0 albedo sensitivity when mounted in the MAD configuration. The main disadvantages associated with this solution are the fact that the BiSon 64 sunsensors output analogue signals which require the addition of some extra processing electronics and would need to be tilted for this specific configuration.

III. Digital sunsensors on chip

In order to mitigate albedo effects, it is possible to image the sun on a 2D camera through a pinhole and use algorithms to discriminate between the intensity of the direct sun signal and the albedo signal. These so called digital sunsensors have been under investigation for many years by companies like Selex ES [2] and TNO [3],[4]. Although the principle is very simple and the algorithms by now are well developed there are a number of issues associated with these developments that need to be addressed before a high reliability and cost effective solution can be offered to the market.

For space applications, the reliability of the solution is a main driving factor. With the advent of (semi) commercial space applications and constellations, there is an increasing demand for more cost effective solutions though. Integrating all functionality on a single chip generally means that significant non-recurring charges will be incurred but recurring production is more cost effective. As several sunsensors are generally used on a single spacecraft, the associated production volume is sufficient to justify investing in a sunsensor on chip solution or production automation in general [5].

For this scheme to work, the sensors will have to be universally applicable and should not need modifications between applications. This calls for a number of properties:

- Universal electrical interface
- Wide operating temperature range
- Ease of mounting

Next to this the sensor should need minimum adjustments or calibrations in order to be able to cost effectively produce the systems.

For a digital sunsensor the above requirements pose a number of challenges.

Although there are a number of standard electrical interfaces available (RS422, I2C, Canbus, Spacewire, MIL-STD-1553 etc.) there is no interface which would fit all applications due to the lack of standardization of digital sunsensor interfaces. RS422 for instance seems to be the best option, but will not allow implementing plug and play functionality which is currently under development. I2C and Canbus don't fulfill the EMC requirements generally posed to flight hardware (no single point distributed ground configuration possible) and other interfaces are too heavy on either physical size or power requirements (or both)

The wide operating temperature range is needed for sunsensors as they are generally mounted on the exterior of the spacecraft and therefore exposed to significant temperature cycles and more extreme temperatures than electronics mounted inside the spacecraft. In order to avoid saturation of the pixels, a digital sunsensor will have to use an intensity reducing filter. This can be either a neutral density filter or a wavelength limiting filter or both. Doing so however means that the dark current generated within the pixel will become an issue as this current will increase with increasing sensor temperature and will eventually lead to saturation in the pixels for higher temperatures (thus rendering the sensor useless). This mechanism is the dominant factor which limits the operating temperature range of a digital sunsensor. It is evident that the temperature increase due to its own power dissipation of a common digital sunsensor should be limited to the largest extent possible to increase the working operating range.

The power dissipation is also related to the ease of mounting in the sense that the sensors are projected to be quite small, which consequently leads to high power densities (W/m^2) for any power dissipated which will be difficult to divert by means of radiation due to the low surface area available. This again means that power dissipated will have to be transported by means of conduction to the mounting feet of the sensors which will pose increasing constraints to the thermal properties of the spacecraft mounting positions with increasing power dissipation.

IV. MAD on Chip (MADoC)

The MAD principle described above seems to lead to a very high reliability and cost effective solution but would best be implemented while using an additional electronics box which has inputs for multiple analogue sensors and a single digital output (and an isolated DC/DC converter) to avoid a lot of analogue input channels on the on board computer. When implemented this way the most critical drawback would be the fact that the sensors have to be mounted in such a way that they are tilted 45 degrees with respect to the spacecraft thus needing an additional mechanical interface. As an alternative one could develop a MAD configuration on chip by dividing the field of view in multiple smaller fields of view by reducing the size of the aperture and selecting for instance an 8*8 matrix detector. This will effectively split the field of view up in a number of smaller fields of view, thus allowing discrimination between sun illuminated FOV sections and albedo illuminated FOV sections much like a standard digital sunsensor (where the field of view is split up in many more pixels). The advantage of this approach would be the fact that each FOV section can have its own analogue to digital converter associated with it, and there would be no need for an intensity reducing filter. The latter is a strong advantage as these filters are costly and difficult to tune to the full well capacity of the pixels of a standard digital sunsensor. As a result a MADoC sunsensor will be much easier to produce, will have a better reproducibility, will be able to operate over a larger temperature range (as pixel dark current is less of a concern if not of no concern at all) and therefore significantly cheaper.

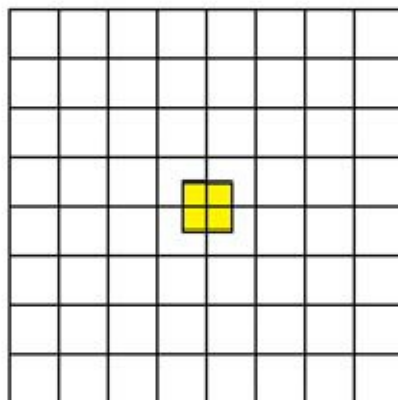


Figure 8 MADoC operating principle

Although the actual algorithm and configuration would need to be investigated, the size of the aperture would probably best be slightly larger than a single pixel to allow for an optimal determination of the sun position. The worst albedo sensitivity would be achieved just after coming out of eclipse or just prior to going into eclipse as shown in Figure 9. For this situation it even seems possible to reduce the albedo effects by presuming the albedo is constant over the earth's surface and compensating for the fact that some pixels are fully illuminated by albedo (7,8,9) some pixels are partially illuminated (4,5,6) and some pixels are looking towards deep space (1,2,3)

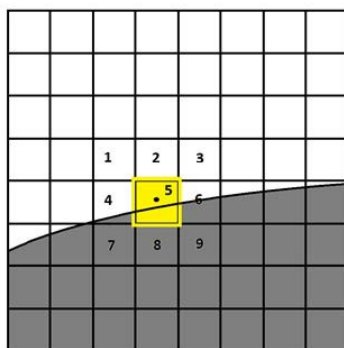


Figure 9 MADoC maximum albedo situation

Since a sunsensor only needs an update rate of some 100Hz as a maximum (for fast rotating satellites) and there is a very high level of photocurrent available, the ADC's can be high accuracy low power types and not much

power is needed for the signal processing. Due to this, it is expected that the power consumption for the entire chip will be determined for 90 % by the data interface and the power supply regulation circuits. It is in any event to be expected that the power for the entire implementation can stay well below 5 mW which will bring autonomous powering options within reach. To this extend it is suggested that only a series regulator is included on chip so as to allow supplying the sensor from a single triple junction solar cell directly or from a regulated or non-regulated power supply through a resistor or small passive filter.

When comparing published data available on other sunsensor on chip implementations like th Selex SE SSoaC and the TNO APS+ some expected performance improvements can be indicated. It should be born in mind though that the albedo sensitivity around the eclipse period will be less for this implementation (although nearly full albedo insensitivity can be guaranteed for a major part of the orbit.

properties	SELEX SE SSoaC	TNO APS+	MADoC
Size (mm ²)	8.6*8.7	5*5	5*5
Number of pixels	512*512	368*368	8*8
ADC resolution (bit)	10	12	14
Operating voltage (V)	5	3.3/1.8	1.8
Power consumption (mW)	186/91 ¹⁾	23.6	<5
Operating temperature	-40..+70	-40..+80	-40..+125
Data interface	Spacewire/RS422	Modified RS422 ²⁾	UART

1) power consumption of the chip largely depends on the data interface selected.

2) The interface used is an RS422 like interface but since the sensor is internally operating at 3.3V and 1.8V the required 5V for RS422 cannot be delivered.

V. MAD or MADoC that is the question

As indicated above there are advantages to using a MAD configuration and it seems that an on chip implementation is possible which will allow for some unique properties never found before in a sunsensor on-chip. Bearing in mind that sunsensor can be made very small but mounting accuracies will limit the obtainable size reduction for the packaging (the BiSon 64 has a mounting repeatability of 0.05 degrees with two high accuracy holes which need to be >4cm apart to be able to guarantee this) the main issue will not be size reduction but total system cost and flexibility of application.

MAD (using BiSon 64)	MADoC
Highest reliability sunsensors on exterior of satellite	0.18 μm CMOS has shown good radiation tolerance but design measures will have to be (and can be) taken to ensure radiation tolerance
Mounting under 45 degrees required which is a disadvantage for ease of mounting	Can be mounted directly on spacecraft panel
Needs an additional electronics box but this leaves the possibility to add isolated DC/DC converter and RS422 or spacewire interface	Needs a connection to the spacecraft for every sensor but this could possibly be made wireless
Can be available within short term	Requires significant investments and development time

Based on the above, no straight forward conclusion can be drawn but the fact that both solutions have advantages and disadvantages. The main advantage of a MAD configuration based on BiSon 64 sensors is the

fact that it can be applied very rapidly. As the sensors are already available and readout electronics can be either included in the on-board computer or a dedicated electronics box can be developed and qualified quite quickly this solution can be applied to just about any satellite for which the attitude and orbit control subsystem is currently being developed.

VI. Conclusions

The MAD concept is explained along with some reasoning as to why it can have advantages to go MAD for future spacecraft.

- [1] <http://en.wikipedia.org/wiki/Albedo>
- [2] P.Fidanzaty et al, Miniature sunsensor on a chip optimization, ESA GNC conference, 2011 Karlovy Vary.
- [3] C.W. de Boom et al, Flight experience of TNO sunsensors, ESA GNC conference 2011 Karlovy Vary,
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