

# Smart FPA's : are they worth the effort?

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## ABSTRACT

CMOS APS technology allows including signal processing in the sensor array. Inclusion of functionality however will come at a cost both financially and in the field of limited applicability. Based on two real world examples (micro digital sunsensor core and lightning flash detector for Meteosat Third Generation (MTG)) it will be demonstrated that large system gains can be obtained by devising smart focal planes. Therefore it is felt that the advantages outweigh the disadvantages for some applications, making it worth to spend the effort on system integration.

### 1. CCD versus APS imagers.

One of the main choices that needs to be made when designing any imager that operates in the visible or near infrared wavelength region is the choice between a Charge Coupled Device (CCD) or Active pixel sensor (APS). Although this trade may look quite simple in actual practice it is not. In case we try to put the pros and cons of both sensors in a listing it becomes obvious why.

#### CCD:

##### Pros:

- High quantum efficiency(QE).
- High fill factor.
- Low noise.
- Good pixel response non uniformity (PRNU).
- QE fairly constant over wavelength.
- UV responsive versions available.
- Time delay and integration (TDI) mode of operation possible.
- High technological maturity

##### Cons:

- Uses dedicated imager processes during manufacturing
- Various voltages required for proper operation.
- Exhibit smear causing signal contamination.
- High capacitances on the drive lines, requiring high drive power and overall power consumption.
- No integration of peripheral functions possible due to process incompatibilities.
- Always full readout required (windowing mode complicated)
- Lower resistance to radiation

Above characteristics make the CCD the imager of choice for high performance and scientific equipments where smear can be avoided or accepted.

## APS

### Pros:

- Standard CMOS imager processes used (low cost high volume production possible)
- Single voltage supply common.
- Virtually no smear or blooming
- Integration of peripheral functions and signal processing possible, thus reducing number of components needed for a full system drastically
- Low power
- Windowing possible
- Electronic shuttering possible
- High resistance to radiation possible

### Cons:

- Lower quantum efficiency
- Lower fillfactor
- Higher noise (especially 1/f)
- Higher PRNU
- Comparatively large QE variations over wavelength.
- Rolling shutter

Above characteristics make APS the imager of choice for high volume low cost equipments or equipment where smear would lead to unacceptable data. Given the above each of the imagers would have their own territory, but in actual fact apart from some very obvious applications, like astronomical telescopes (where every photon counts) CCD's are challenged more and more by APS imagers whose QE and noise performance is ever improving. On the other hand CCD imagers have been designed for portable telephones, an application area which was always considered exclusive for APS imagers.

Therefore, driven by the total system design, the choice for a CCD or an APS imager in many instances is becoming more difficult.

## **2. Imagers for space applications.**

Space applications in general can be considered high cost and therefore the use of CCD imagers would seem very likely to be the preferred solution. The actual trade however is not so straight forward. While selecting an imager for space applications, a number of trades are influenced by the specifics of spaceflight. Especially the radiation environment and system power requirements are trades that are very much influenced by the application in a space environment. This is due to the fact that most satellites experience a much elevated radiation exposure as compared to terrestrial applications (due to the absence of shielding provided by the earth magnetic field) and power always comes at a premium (larger solar panels and thermal radiators needed in turn increasing system mass which is a cost driver for launch costs). A last but by no means insignificant factor is the maturity of the technology used.

For space applications therefore every application will have to be examined in order to find the best detector technology to use. Currently two products are under development at TNO in combination with the Delft university of Technology (micro digital sunsensor) and Supaero(lightning imager), for which active pixel sensors actually might prove to be the best option.

### 3. Example one: The micro digital sensor.

The micro digital sensor is one of these products under development at TNO in cooperation with the Delft University of Technology. It is developed in frame of the Dutch Microned program. This program is intended to increase the knowledge and stimulate the application of micro system technology in the Netherlands.

A sunsensor is an attitude control sensor that senses the position of the sun with respect to its mounting plane. This type of sensor typically operates as a photo diode of which the current produced is proportional to the angle of incidence (coarse sensors) or a photo diode array with a suspended membrane.(fine sensors) in case the photodiode array is a real 2D array, the sensors are called digital sensors. TNO's digital sensors currently use a standard active pixel sensor array and a standard FPGA for signal processing. The APS sensors are selected because the amount of light available is much more than the signal required for proper operation and their ability to do windowing (create a window of interest on the sensor which is read out at a higher speed while discarding the information from the other part of the sensor.) this has lead to fairly compact (11cm\*12cm footprint ) sensors that have a high degree of flexibility and allow you to readout the sun position at a very high rate while having a low power consumption (1.3W without and 1.7W with DC/DC converter) During the design of the qualification model (which includes a DC/DC converter), it was however noted that the power supply subcircuits actually account for a large part of the mass and power budgets.

The idea behind the digital sensor is quite simple. A sunsensor can only do a sensible job in case the sun is present. This observation has lead to the concept of a sunsensor powered with a self-standing solarcell power supply. During the phase A of the sensor design it was concluded that three main items would eventually limit the size of the package:

- Size of the connector used.
- Power consumption
- Size of the patch antenna

Analysis indicated that the size of the sensor could be such that two connectors and 1 meter of cable would easily outweigh the sensor and therefore it has been decided to add a radio frequency datalink to the sensor. This way:

- The need for filtering interference that might be caused by other pieces of equipment on board of spacecraft is avoided (zero power drawn from spacecraft bus)
- The size of the solarcell can be adapted to the power demand of the sensor
- The mass of the sensor is reduced
- The sensor becomes a fully autonomous system in a package
- The mechanical rigidity of the system can be improved
- The size of the package is determined by the size of the solarcell and patch antenna required

The micro digital sunsensor consists of a dedicated Active Pixel Sensor (APS) that includes both an Analog to Digital converter and the required digital signal processing for centroid calculation of the sunspot incident on the APS sensor. The sunspot is generated by means of a membrane pinhole in front of the detector device that is directly bonded to the APS chip. This APS+ (= APS imager including ADC and processing electronics) leads to a very small and low power device (estimated APS+ size 6\*7\*2mm<sup>3</sup>).

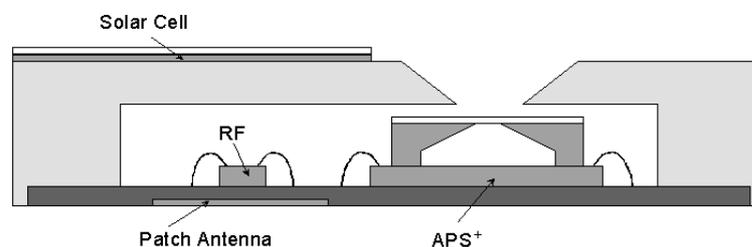


Fig. 1.  $\mu$ DSS cross section.(not to scale)

This highly integrated sensing core can be used to device small but capable sensorsystems that can provide sun attitude information with an accuracy that is currently only available for much larger sensors. The level of integration foreseen for this sensor can never be achieved with CCD's, which makes it a logical choice to use a CMOS APS. The total functionality as projected for the APS+ is quite high as can be seen in fig 2.

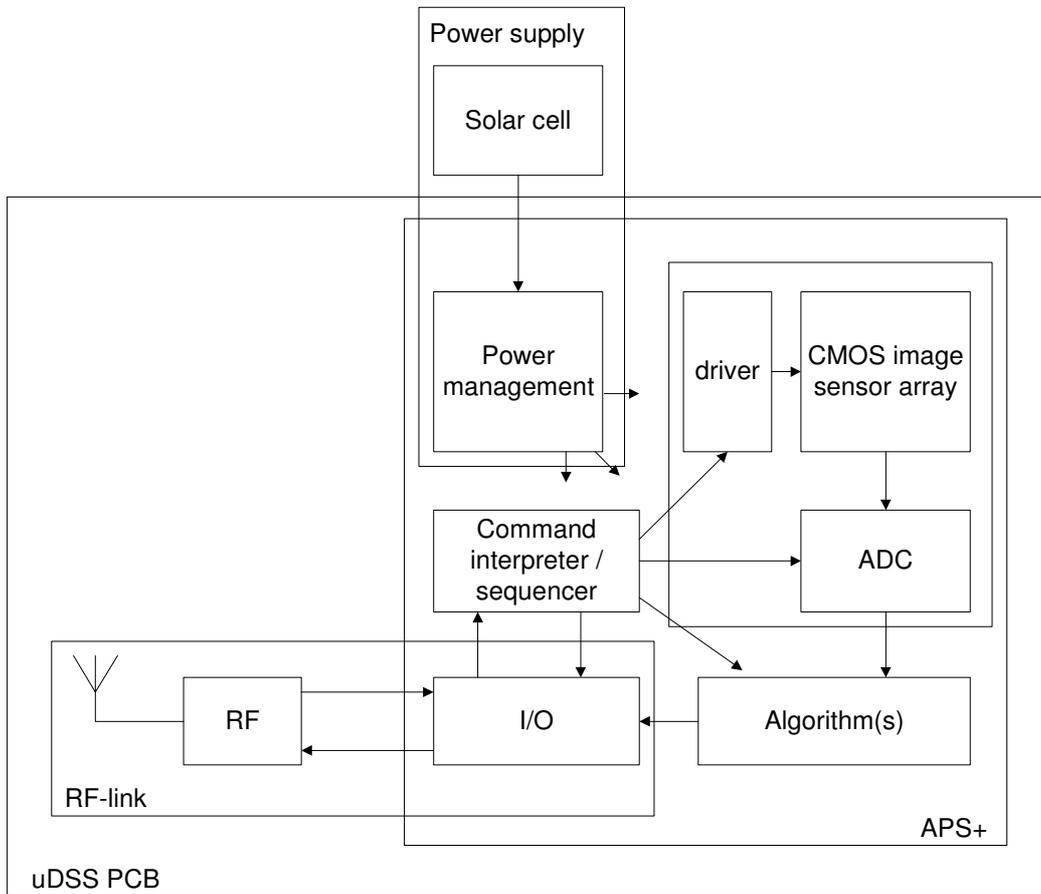


Fig.2. Block Diagram

The main elements of the sensing core (CMOS image sensor array, driver and ADC) is developed by TU-Delft, and the support circuits (I/O block, Command interpreter /sequencer and algorithms) are developed by TNO. If possible we would also like to include the power management subcircuit, but due to technical difficulties in implementing power subcircuits in deep sub-micron CMOS technologies it has been decided not to do this in the first issue of the sensor. Since low power operation is one of the core issues during the design of the sensor, the internal clockspeeds have been reduced as much as possible. The use of APS technology offers some very specific advantages to this respect.

The sensor has basically two main modes of operation:

- Sun acquisition mode
- Sun tracking mode

During sun acquisition the entire array is scanned and checked for sun presence. During sun tracking only the sun illuminated portion of the sensor and some small parts around it are scanned in order to reduce the number of readout cycles as much as possible (thus reducing power consumption). By lowering the frame rate during the sun acquisition mode, the power consumption can be kept more or less constant for both modes of operation (thus easing the power subsystem design). The windowing function is essential for the tracking mode of operation. Which is one of the main reasons to use a CMOS APS. The mockup of the final sensor is given in fig. 3.

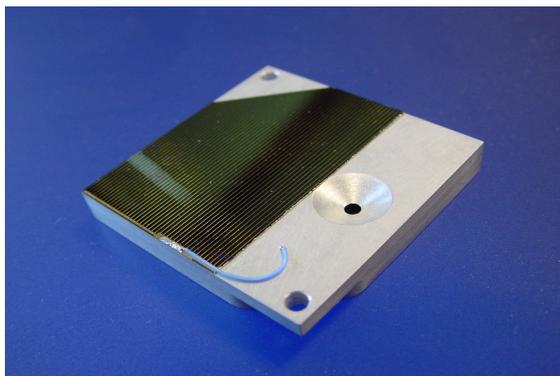


Fig. 3. Micro digital sensor ( $\mu$ DSS)

### **3.1. Sunsensor APS : is it worth the effort ?**

The time and costs involved in the development of the APS+ sensor core is far from insignificant, but questions raised as to the usefulness of this type of development can be positively answered (we feel). The Microned program is intended to strengthen the knowledge about micro systems technology within the Netherlands, and as such is a goal in itself. Despite of this, the development could well prove its economic viability through changing the market for sunsensors drastically.

The sensor is developed in such a way (general I/O) that several systems can easily adapt to using the sensor. Once flight proven, the choice between a small, rigid and lightweight sunsensor which can be cost effectively mass-produced and a much larger custom made comparatively expensive sunsensor will have to be made over and over again. It is to be expected that when flight heritage increases, the number of times the micro sunsensor is chosen will increase also, eventually leading to a situation where in majority micro sunsensors are chosen en custom sensors will be limited to special applications only.

In case this scenario becomes true, the costs involved with the development of the sunsensor could well be recuperated and even further development steps can be foreseen.

#### 4. Example two: The Lightning Imager Detector.

The lightning imager instrument as designed for the third generation Meteosat satellites is a dedicated imager that looks at the light generated by lightning in the oxygen bands to detect lightning frequencies and energy contents. The instrument is to be put in geostationary orbit and should give an instantaneous recording of all lightning discharges over the visible part of the earth's dish.

The instrument will be used to estimate the amount of naturally generated nitric oxides and to assist in hurricane prediction.

The detector-trades for this instrument have been particularly interesting because of the specific characteristics of the instrument. The light collected originates from three small oxygen lines in the 777.4 nm range. Therefore only very narrowband radiation is detected and only limited signal is available. This would naturally call for a CCD imager with the associated high quantum efficiency and high fillfactor backed by the fact that a very high signal to noise ratio is required to reliably detect all events. (Note: for CCD imagers the effective fillfactor is generally not specified and accounted for in the overall quantum efficiency) The required field of view in combination with the ground resolution requires the use of a comparatively large array (2k\*2k) which can be devised in CCD technology.

For radiometric reasons, the pixel size should be in the order of 50  $\mu\text{m}$ , leading to an extremely large detector (10\*10 cm<sup>2</sup>). In addition to this, the large viewing angles required would not allow using the very narrow band filters used for the current instrument due to wavelength dependency of the centre frequency with angle of incidence (physical phenomenon which cannot be avoided). Consequently the instrument was split in four identical cameras each covering one quarter of the earth.

When looking at the statistics of lightning, it should be realised that the average number of flashes over one quarter of an earth's dish is about 100 /s and these flashes last for about 0.5 ms on average and very seldom last longer than 20 ms. Reliable detection of these flashes is the main issue that needs solving. In order to obtain a large detection efficiency and low false alarm rate the signal to noise ratio should be as high as possible.

When looking at the intensity of the light received the flash energy is superimposed on the background signal that has a very high dynamic range when comparing day and nighttime operation (fig. 4). During the nighttime, the detection threshold could potentially be set very low because there is little background signal, and therefore the noise generated by the background signal (which is proportional to the square root of the signal) is also very low. During daytime however the threshold will have to be substantially increased in order to reduce the number of faulty event detections or so called false events. The required measurement accuracy dictates the use of a comparatively high sampling frequency of > 2kHz which leads to an interesting situation. In case we read a 2k\*2k array with a high resolution (>12 bits) at 2 kHz, the associated data rate is >100Gb/s (2048\*2048\*2000\*12 bits/s). The final science data is limited to some 100 sets of data concerning intensity and location of the flash per second which will be less than 50 kb/s only. (NOTE these data are per camera and there are 4 camera's needed to cover the earth dish). The massive signal reduction will have to be provided by the instrument electronics.

The brute-force approach would be to use a CCD imager which will require significant power due to the large imaging area and high speed of operation, convert the data into the digital domain using again high-speed and power consuming Analog to Digital Converters and process all of the data in the digital domain. The used digital electronics will need a lot of computational power and therefore will be bulky and power hungry again. Active Pixel Sensor technology however could push the design in a totally different direction. APS technology allows you to put a limited amount of signal processing electronics in every pixel and readout an area of interest. Therefore the following scenario has been considered:

- Track the average illumination level at pixel level
- Determine the threshold voltage depending on the illumination level at pixel level
- Generate an event detection trigger if the energy received exceeds the threshold
- Poll the event register with a high frequency and readout those pixels that have an active event for 30ms after first event registration

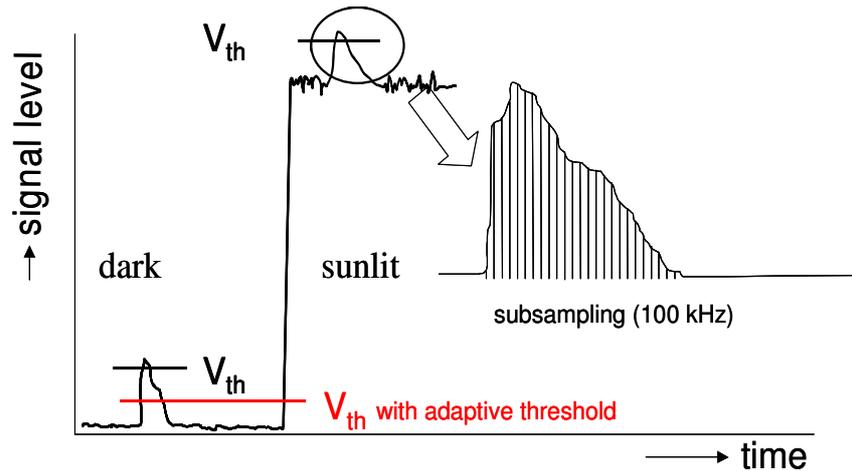


Fig. 4. Intensity distribution for day-and nighttime operation.

Considering an average flash duration of 1ms and 100 flashes/second, the amount of data read from the sensor can be drastically reduced. Therefore it can be decided to increase the polling and readout frequency to a high value of for instance 100kHz (which may prove to be to high but can be used for the principle). 100 flashes/s and a readout period of 30ms (to make sure that all energy is captured) would lead to a situation where only 3 flash positions would be actively measured on average, and even with a 100kHz per pixel sample rate the speed of the ADC could be limited. The high sample repetition rate can be used to reconstruct the shape of the flash and accurately determine things like the full width half maximum and contained energy.

The advantage of above approach would be that no high-speed ADC's are needed nor elaborate signal processing or a high level of power consumption in the sensor. Moreover, the ADC's can be integrated on chip, reducing the number of components as well as power consumption.

The main question would be: is it feasible to include this level of functionality in every pixel?

As mentioned before, for radiometric reasons it is necessary to use fairly large pixels (50  $\mu\text{m}$ ) that allow to incorporate a significant amount of circuitry on pixel without drastically reducing the fillfactor. This is especially true in case deep sub-micron CMOS processes are used. On the other hand a low fillfactor will require a higher speed optical design, again leading to filter design problems and loss of light, so the main parameters to consider would be quantum efficiency . Given the limited wavelength sensitivity required, the quantum efficiency could be much increased by tuning the top layers of the sensor, the so-called optical stack. These isolation layers are in general responsible for the bad response over wavelength of APS sensors (leading to a bad average QE) but could be optimised for the lightning sensor.

Recent work at Supaero has shown that it is possible to include a large functionality per pixel without dramatic loss of fillfactor when using deep sub-micron technologies. The general layout of the circuit produced is given in fig. 5. The sensor implements a pixel array, column and row decoders, two encoders to encode events addresses, a digital block named "Control readout" for the generation of the readout addresses and an analog circuits for pixels readout. This sensor makes use of global shutter architecture with a photodiode pixel. This operating mode allows the readout of pixels values during the following integration.

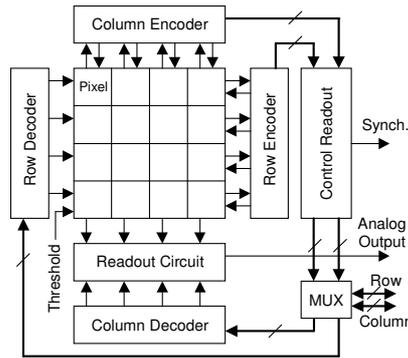


Fig.5. General architecture

The operating mode can be described as follows : at the beginning of the frame, all pixels are reset. If an event is detected by a pixel, a request is sent to row and column encoders. Row and column addresses of this event are then coded and stored in the “Control Readout” block. At the end of the integration all the photodiode voltages are stored in pixels. During the next integration, pixels that have detected an event are read as well as those in their neighborhoods. The actual circuit implemented per pixel is given in fig 6.

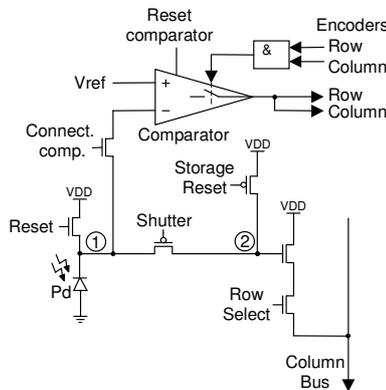


Fig. 6. Schematic of the pixel

As can be seen, the functionality per pixel is substantial, and therefore the obtained fillfactor is quite interesting to know. As it appears (see fig. 7.), the fillfactor is acceptable (around 45%) even for the used 0.35  $\mu\text{m}$  process. The more modern 0.18 or 0.13  $\mu\text{m}$  processes would lead to significantly improved fillfactors.

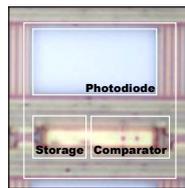


Fig 7 Microphotograph of the pixel

Above sample shows that it is currently possible to include a high level of functionality at pixel level in an APS imager without drastically reducing the fillfactor. Additionally, the integration capability of the CMOS technology allow for dedicated processing units including embedded memory to be included on the same chip beside the imaging array, (see fig. 8) thus allowing us to design an instrument which will have less power dissipation and significantly less data to handle. The question we hope to answer with this paper though is: is it worth the effort.

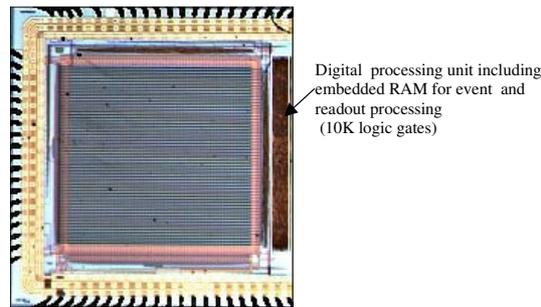


Fig 8 Chip organization demonstrating integration capability of processing unit

#### 4.1. Lightning imager APS : is it worth the effort ?

The lightning imager instrument will by no means be a mass produced instrument. Nevertheless the gains at system level will be significant. For an instrument using the smart APS, the mass and power consumption are estimated to be 58 kg and 24 W respectively, whilst for the brute-force approach it is estimated that these values will be in the order of 70 kg and 100 W unless dedicated signal processing ASICs are developed. Considering the fact that MTG will be constellation that consists of 3 to 5 satellites (plus spare) the additional launching costs and costs for a heavier power supply and cooling subsystem will be considerable and without doubt exceeding the additional costs involved in designing and qualifying the APS sensor (it should be noted that the CCD is also not a standard product and would require a specific development). Therefore it is felt that this development would definitely be worth the effort.

### 5. Conclusions

The presented paper describes some specific applications that highly benefit from the possibilities offered by designing APS imagers in sub-micron CMOS technology. Although a case-by-case analysis will have to be made, it is to be expected that APS imagers will fulfil the role of image sensor in more and more applications. For space applications the non-availability of space qualified and approved CMOS imager processes however is expected to remain an issue to be solved for the first couple of years. The demonstrated increased radiation tolerance for deep sub-micron processes (< 0.18  $\mu\text{m}$ ) however is likely to be a major contributor to the increased application of APS imagers not only for space, but also for terrestrial applications like medical imaging.

### 6. References

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