International Conference on Space Optics—ICSO 2004

Toulouse, France

30 March–2 April 2004

Edited by Josiane Costeraste and Errico Armandillo

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International Conference on Space Optics — ICSO 2004, edited by Errico Armandillo,
Josiane Costeraste, Proc. of SPIE Vol. 10568, 105680S · © 2004 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2307969

AUTONOMOUS STAR TRACKER BASED ON ACTIVE PIXEL SENSORS (APS)

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ABSTRACT

Star trackers are opto-electronic sensors used on-board of satellites for the autonomous inertial attitude determination. During the last years, star trackers became more and more important in the field of the attitude and orbit control system (AOCS) sensors. High performance star trackers are based up today on charge coupled device (CCD) optical camera heads.

The Jena-Optronik GmbH is active in the field of opto-electronic sensors like star trackers since the early 80-ties. Today, with the product family ASTRO5, ASTRO10 and ASTRO15, all marked segments like earth observation, scientific applications and geo-telecom are supplied to European and Overseas customers.

A new generation of star trackers can be designed based on the APS detector technical features. The measurement performance of the current CCD based star trackers can be maintained, the star tracker functionality, reliability and robustness can be increased while the unit costs are saved.

1. INTRODUCTION

The active pixel sensor (APS) technology, introduced in the early 90-ties, offers today the beneficial replacement of CCD detectors by APS detectors with respect to performance, reliability, power and mass.

In the frame of an ESA contract, the Jena-Optronik GmbH develops an APS based star tracker for geo-telecom applications. A tested engineering model will be available in the 1st quarter of 2005.

The APS detector technologies investigated for that project are the active 3-transistor cell technology from Fillfactory / Belgium and the Thin Film on CMOS (TFC) technology from IMS-Chips Stuttgart / Germany.

The application of matrix detectors in star trackers requires a high detector sensitivity and low read out noise due to the detection and centroiding of faint (limiting) star magnitudes. This disqualified the use of APS detectors in the past for low light level applications because of their high read out noise, low fill factor & quantum efficiency. With the advanced 3-transistor active pixel technology or the Thin-Film on CMOS (TFC) technology, the drawbacks of the conventional APS detectors in terms of sensitivity and noise were solved. The combination of the well-known flexible and radiation-hard CMOS ASIC technology with the photodiode technology was the gateway to optimized APS detectors for the use in star trackers and other high performance optical control systems.

The key features of the APS detectors are: a true xy-address random access, a single supply (+5V or + 3.3V only), the high on-chip functional integration level including the AD-converter and the inherent radiation robustness compared to CCD’s.

2. APS DETECTOR TECHNOLOGY

APS detectors can be manufactured on standard CMOS process lines. This gives a high level of confidence during the detector design and manufacturing, taking benefit from the heritage of the CMOS design tools and wafer processing.

The light sensitive pixel element is realized by a photo diode, which is read-out and buffered by 3 or more pixel cell transistors. The APS detector photo element matrix can usually addressed directly by enabling an x- and y-address to the column- and row-decoder for direct pixel access (see fig. 1). A so called direct and random pixel access is possible with this architecture. For star tracking, only the track windows (ROI’s) have to be read out, which amounts approx. to 0.04% of the whole detector matrix. In contradiction to that, in CCD detectors all pixels have to be read (or dumped) to reset the signal charge, which needs time and additional electrical power consumption.

The integration time period is realized at APS detectors by the so called “rolling shutter” (sequential start of the integration time window line-by-line), typical for the STAR1000 device from Fillfactory / Belgium. Other detectors like the TFC APS from IMS-Chips Stuttgart support an full field synchronous shutter (equivalent to CCD's). Both principles can be used for the application in star trackers.

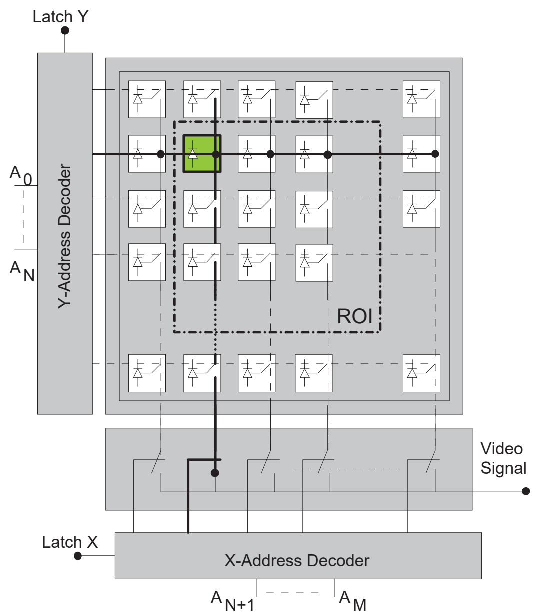

Figure 1 Typical APS detector matrix configuration

There are two main pixel cell technologies applied in active pixel sensors, the 3(4)-transistor cell characterized by the lateral configuration of photodiode and pixel electronics (left figure below) and the TFC cell characterized by the 3-dimensional layer structure of photodiode and electronics (right figure below).

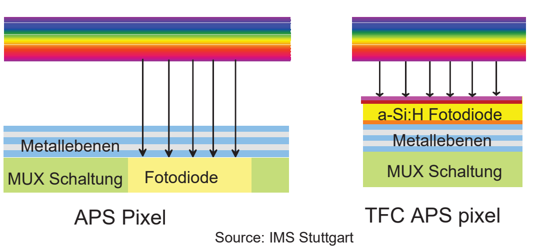

Figure 2 State of the art pixel cell technologies of APS detectors

The APS pixel on the left hand side shares the pixel area between the photodiode and the necessary pixel electronics. This limits the pixel pitch of the detector array. The fill factor x quantum efficiency product of such cell technologies amounts to 35…45% for advanced technologies.
A layer of amorphous silicon as photonics detector medium covering the whole pixel area realizes the photodiode of the TFC cell. Fill factors near 100% can be feasibly realized. The figure below shows the spatial sensitivity distribution of a TFC pixel, measured at the Jena-Optronik laboratories.

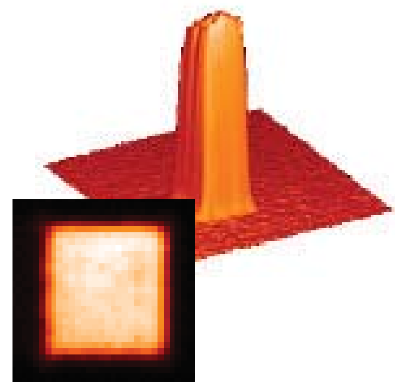

Figure 3 Spatial sensitivity distribution of a TFC pixel with near 100% fill factor

The amorphous silicon as photonics detector material reaches up to 75% peak quantum efficiency and in the range of 500…630nm up to 64%. This results in a highly sensitive APS pixel, which is important for limiting (faint) star tracking and feasible optics design solutions. The TFC technology allows due to the high sensitivity and fill factor up to 10mm smaller optics apertures compared to crystalline silicon APS detectors. This is one of the key parameters for extreme compact designs. The optics size drives the size of the star tracker system. Figure 3 shows the perfect homogeneity of the TFC pixel area sensitivity. Measurements in the laboratory have shown star centroiding accuracies of up to the 1/100 part of a pixel, which enables also high accuracy star tracking with APS detectors. Under real in-orbit conditions 1/50 pixel single star centroiding accuracy can be expected. This includes the usage of the on-chip non-destructive read-out feature (NDRO) that allows noise reduction by digital averaging (applied at the TFC APS, IMS-Chips Stuttgart). A pixel field can be read multiple times without destroying the signal charge. The impact on the total read out time can be neglected, e.g at 5MHz read out frequency for star fields with 9x9 pixels and 10 readings (162µs).

Feasible star tracker system solutions could be shown using the STAR1000 APS and the TFC APS.

3. THE APS STAR TRACKER TECHNICAL CHARACTERISTIC

The table below shows the key technical parameter of the APS based star tracker. The values herein define a new level of compactness compared to the state of the art CCD based star trackers for the geo-telecom marked.

Mass	< 1.5kg
Size	120 x 120 x 230 [mm] incl. baffle
Power	< 5W
Output	Attitude quaternion 3-axes angular rate
Field of View	approx. 20deg x 20deg
Limiting Star	5.8mi
Coverage	9 stars 100%
Accuracy	xy-axes: < 9 arcsec (3σ) EoL z-axis: < 65 arcsec (3σ) EoL
Update Rate	10Hz
Data Interface	RS422 synchronous or MIL-STD-1553
Sun Exclusion	26deg (also 30deg, 45deg)
Radiation	Equivalent 25years Geo-orbit, 100krad parts level
SEU Tolerance	> 2.300 SEU's per frame
Lifetime	15year geo orbit

Table 1 Geo-telecom APS star tracker technical data

These improvements in system compactness and performance are realized with the replacement of the CCD detector by the APS detector and the usage of the improved digital processing H/W and S/W technology.
The mass budget for existing equivalent CCD based star trackers is >3.5 kg with the accordingly higher dimensions and envelope. The mass and envelope benefit is based on the very high functional integration of the APS detectors. The whole analogue read-out and sampling electronics including the AD-conversion is placed on the detector chip. This saves at least one PCB compared to CCD based systems. Also the driving electronics for APS devices is reduced to standard digital signals, whereby CCD's need sophisticated driving signal clock levels and multiple supply voltages. Therefore, further PCB space for driver electronics and DC/DC converter can be saved. The parts count for an APS based star tracker is reduced accordingly. Along with that the unit costs are reduced and the system reliability is increased.

The APS detector can be directly wired to the digital electronics (processor, ASIC, FPGA).
Figure 4 shows a minimal configuration for a star tracker system that takes full benefit from the APS detector technology. The detector is part of the processor memory environment due to its compatible interfaces. The TFC APS supports processor compatiple address and control signal interfaces.

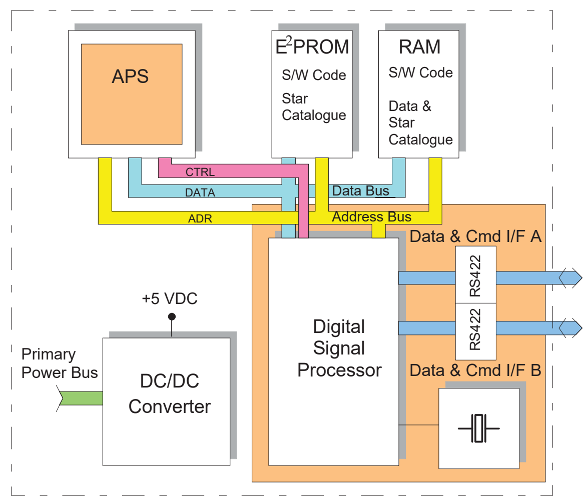

Figure 4 Block diagram for an APS based star tracker reduced to the absolute minimum extend of functional blocks

The compactness of the electronics as well as the low power consumption results in a feasible smart single box design. Figure 2 shows the design solution with a 26deg sunshade.

This unit single box contains all the processing electronics that is necessary to provide attitude quaternions as output information. There is sufficient space (two side cavities) for the implementation of the customer specific data (MIL-1553 and RS422) and primary power interfaces.

The single box unit can operate under both environmental conditions, at first, fully thermal isolated from the s/c mechanical interface plane by using its own radiator and secondly thermal conductive to the s/c interface.

The unit can be mounted with 3 screws on flat interface surfaces without the need of special brackets or cut-outs.

Figure 5 Geo-telecom APS star tracker configuration as a single box design solution

4. CONCLUSIONS

The APS CMOS detector technology has improved its electro-optical parameters during the last years significantly, such that CCD's can be replaced by this detector parts even for the unique requirements of high reliability AOCS sensors like star trackers and other optical instruments (Sun sensors, imagers, etc.).

The unit compactness can be improved leading to a new class of smart high performance and robust sensors. The benefit of the introduction of the APS CMOS technology into space instruments can be summarized in the following paragraphs:

- The APS detector technology allows designing a new generation of high reliable and compact star trackers for long-term missions especially geo-telecom.
- The radiation hardness of the APS detectors makes their operation in harsh environments (gamma, proton, ions, etc.) possible. High SEU rates, forced by solar flare events, can be managed simply by the data reduction reading only the track star windows via the xy-random pixel access. By this approach the APS star tracker provides valid quaternion output information during solar flare events, which is essential for star trackers operating as main attitude sensor in the satellites attitude and orbit control system.
- Due to the savings in parts count and budgets the unit cost can be reduced.

5. ACKNOWLEDGEMENTS

Many thanks are given to the "Institut für Mikroelektronik Stuttgart (IMS-Chips)" and the "Institut für Physikalische Elektronik (IPE), Universität Stuttgart". These institutes develop an optimized APS detector for the star tracker application using the Thin Film on CMOS (TFC) technology.

The technical support by Fillfactory NV, Belgium is highly appreciated in the APS star tracker development activities of Jena-Optronik.

The APS star tracker development is supported by "Deutsches Zentrum für Luft- und Raumfahrt e.V." (DLR) and the European Space Agency.