

THE CMOS BREAKTHROUGH FOR SPACE OPTICAL DETECTION: RECENT ADVANCES AND SHORT TERM PERSPECTIVES

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RESUME : Résumé français

Compte tenu de leurs excellentes performances électro-optiques, les technologies CMOS et CCD permettent toutes deux de répondre aux besoins de la grande majorité des senseurs et instruments visibles spatiaux. Désormais, et pour une application donnée, le choix de la technologie la plus appropriée s'effectue principalement à partir de leurs caractéristiques et limites fonctionnelles et technologiques. La première partie de l'article présente des résultats de caractérisation d'imageurs CMOS (CIS) réalisés en utilisant un procédé CMOS optimisé, démontrant les importants progrès de leurs performances électro-optiques. La seconde partie de l'article balaie les avantages de la technologie CMOS pour les applications spatiales, illustrés par des exemples de développements de CIS menés par EADS Astrium et Supaéro/CIMI pour des programmes spatiaux en cours ou devant démarrer prochainement.

ABSTRACT : English abstract

Today, both CCD and CMOS sensors can be envisaged for nearly all visible sensors and instruments designed for space needs. Indeed, detectors built with both technologies allow excellent electro-optics performances to be reached, the selection of the most adequate device being driven by their functional and technological features and limits. The first part of the paper presents electro-optics characterisation results of CMOS image sensors (CIS) built with an optimised CMOS process, demonstrating the large improvements of CIS electro-optics performances. The second part reviews the advantages of CMOS technology for space applications, illustrated by examples of CIS developments performed by EADS Astrium and Supaéro/CIMI for current and short term coming space programs.

1 - INTRODUCTION

Today, both CCD and CMOS sensors can be envisaged for nearly all visible sensors and instruments designed for space applications. Indeed, detectors built with both technologies allow excellent electro-optics (EO) performances to be reached (detection efficiency, Modulation Transfer Function (MTF), read-out noise, dark current density...), the selection of the most adequate device type being driven by their functional and technological features and limits. Optical sensor and instrument designers have therefore to consider CCD and CMOS as complementary technologies

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rather than competing ones, which allows optimal instrumental concepts to be devised. The advantages and drawbacks of the CCD are well known: this paper puts emphasis on the CMOS detectors to illustrate this complementarity.

The first part of the paper presents EO characterisation results of CMOS Image Sensors (CIS) developed by EADS Astrium and Supaéro/CIMI teams built with an optimised CMOS process, demonstrating the recent improvements of CIS EO performances.

The second part reviews the advantages of CMOS technology for space applications, illustrated by examples of CIS developments performed by EADS Astrium and Supaéro/CIMI for current and short term coming space programs.

2 - CIS ELECTRO-OPTICS PERFORMANCES IMPROVEMENTS

CIS developed during the infancy of this technology were manufactured using standard mixed signal CMOS processes. They featured good EO performances [1], close to the ones achieved by standard front-side illuminated CCDs usually used for space programs developed in the nineties [2]. Such results allowed design engineers to consider this technology for applications which strongly benefited of CIS functional and technological advantages, such as star trackers and miniature cameras [3]. Nevertheless, some of these EO performances were not sufficient in order to fulfil high-end applications for demanding applications such as Earth observation. Despite possible performances improvement thanks to specific in pixel electronics designs [4], only CMOS technology modifications were able to bring strong improvements for some of the major CIS EO parameters [5]. Since the end of the 90s, and as the photonics market was strongly growing, several CMOS foundries invested in order to propose optimized CMOS technologies able to offer high performances for large volumes applications (mobiles, digital cameras, computer peripherals, toys....).

The space community can today benefit of such technological improvements, as recently demonstrated by devices (see figure 1) developed by EADS Astrium and Supaéro/CIMI [6] using a 0.35 μm CMOS process optimized for imaging applications.



Figure 1 - Left: 1024x1024 pixels 2D array with 13 μm pixel pitch; right: 3078 pixels linear array with 6.5 μm pixel pitch: both devices have been manufactured using a 0.35 μm CMOS process optimized for imaging applications

The improvements of the performances achieved for these devices are impressive. Figure 2-a compares the dark current density measurements (defined over the full pixel area) versus temperature for 2 standard mixed signal processes (0.7 and 0.5 μm) and for the 0.35 μm improved process. It should be noticed that a constant 60% pixel geometric fill factor applies for the three devices, despite the pixel pitch change (respectively 30, 20 and 13 μm pitch for the 0.7, 0.5 and 0.35 μm processes). For 293 K, 200 pA/cm^2 is now achieved. Using the most advanced CMOS processes, dark current density lower than 50 pA/cm^2 at 293 K (equivalent to the performance of CCD operated in inversion mode) have been reported [7]. Figure 2-b compares the spectral

detection efficiency for the standard 0.5 μm and improved 0.35 μm processes. Peak detection efficiency close to 50% has been measured for the new device (no microlenses have been implemented). Using microlenses, that improves the geometrical fill factor, spectral detection efficiency as high as 70% has been demonstrated even for 5 μm pixel pitch using a 0.25 μm optimized CMOS process [8]. For the 3k linear array featuring 6.5 μm pitch, peak detection efficiency close to 70 % has been measured (geometric fill factor close to 100%).

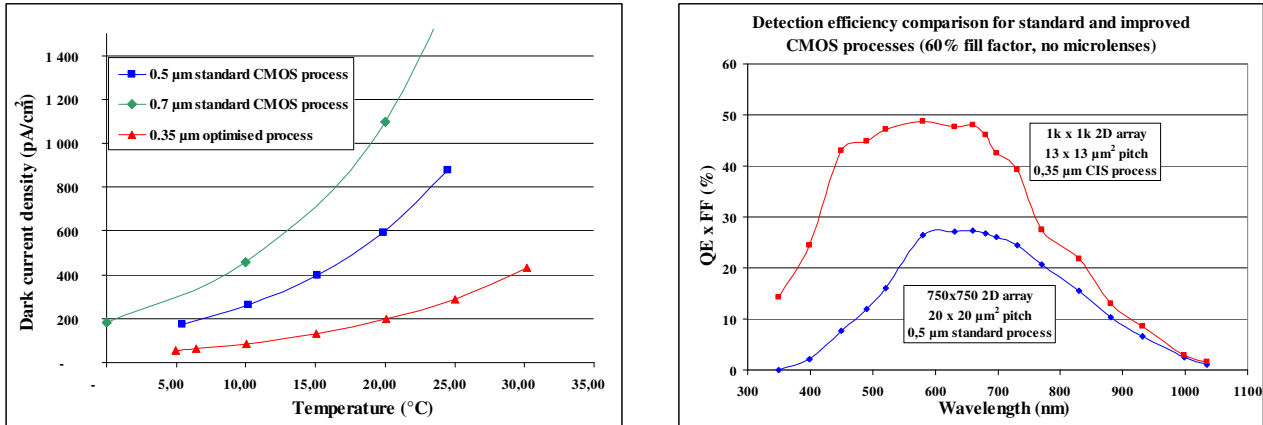


Figure 2 - a (left): dark current density (defined over the full pixel area) versus temperature for a 0.7 μm (30 μm pixel pitch) and a 0.5 μm (20 μm pixel pitch) standard CMOS processes (photoMOS) and for a 0.35 μm (13 μm pixel pitch) optimized CMOS process (photodiode); b (right): spectral detection efficiency for a 0.5 μm (20 μm pixel pitch, photoMOS) standard CMOS process and for a 0.35 μm (13 μm pixel pitch, photodiode) optimized CMOS process

Maybe the most impressive improvement concerns the image quality evaluated through the measurement of the Modulation Transfer Function (MTF) and the inter-pixel cross-talk. Figure 3 compares the spectral MTF at Nyquist frequency for a 0.5 μm standard process (20 μm pixel pitch) and the 0.35 μm optimized process (13 μm pixel pitch). The improvement is particularly impressive for the longest wavelength.

Wavelength (nm)	MTFx for standard 0.5 μm process	MTFx for CIS 0.35 μm process	MTFy for standard 0.5 μm process	MTFy for CIS 0.35 μm process
500	46%	69%	54%	74%
650	31%	67%	40%	73%
800	28%	63%	35%	68%

Figure 3 - For three wavelengths, MTF measurement at Nyquist frequency along row and column direction for a photoMOS pixel built with a 0.5 μm standard process (20 μm pitch) and a photodiode built with a 0.35 μm optimized process (13 μm pitch)

It should be noticed here that the MTF measurements corresponding to the improved process feature values higher than 63%, which is the expected maximum limit due to the spatial sampling effect. This is explained by the non 100% pixel fill factor. Calculations of the theoretical geometric MTF using the real shape of the photosensitive area lead to 70% for MTFx and 78% for MTFy, very close to the experimental figures measured for 500 nm wavelengths [9].

As expected, the same behavior arose during the spot scan characterizations. Figures 4 compare intra-pixel responses and cross-talk measurements at two wavelengths for both 0.5 μm standard and 0.35 μm optimized CMOS processes. Once again, the improvement is particularly noticeable for the longest wavelength.

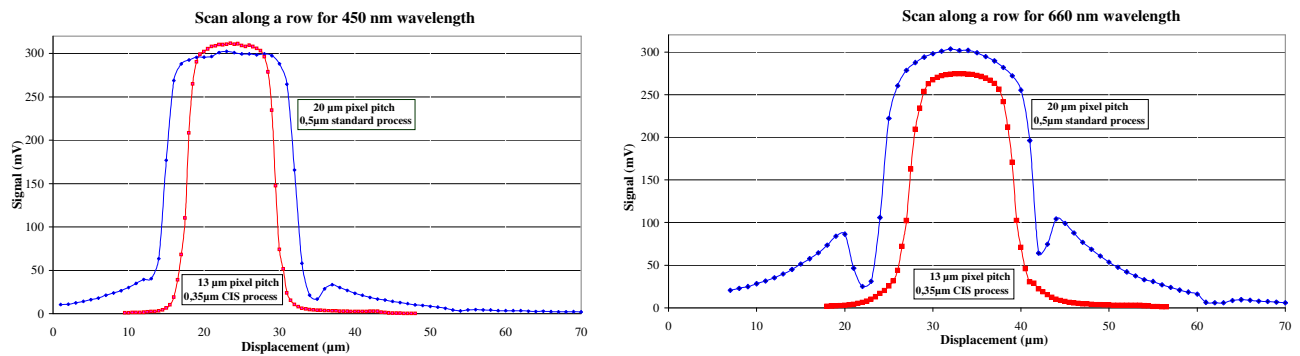


Figure 4 - Left: comparison of an intra-pixel spot-scan response along the row (450 nm wavelength) for a 20 μm photoMOS pitch manufactured using a standard 0.5 μm CMOS process and for a 13 μm photodiode pitch manufactured using an optimised 0.35 μm CMOS process: right: same figure for 660 nm wavelength. Nearly no cross talk can be seen for the optimised process, while in the case of the standard process, the pixel response is non negligible when the spot is located in the neighbouring pixel, particularly for the longest wavelength.

EO performances of CMOS processes optimised for imaging applications are continuing to increase [10]. Coupled to CMOS technology scaling, this leads to CIS strong improvements. Today, even consumer high quality reflex [11] or digital video [12] cameras are increasingly equipped with CIS instead of CCDs. In addition, thanks to a strong R&D activity, alternative ways that could be foreseen for consumer and/or niche imaging markets (such as space, military and medical ones) are explored:

- the hybrid approach, which main advantage is to allow independent optimisation for the photodetectors layer and for the read-out circuit layer. In addition, hybridisation approach permits to reach nearly 100% fill factor and gives more rooms for the in-pixel circuitry. Two different ways are today investigated. The first one is close to what is done for IRCMOS, i.e. indium bump flip chip assembly of a monocrystalline silicon detection layer on top a CMOS read-out circuit [13]. The second one is based on the deposition of amorphous silicon thin film on top of the read out circuit [14].
- The thinned and back side illuminated approach [10], derived from what is developed for CCD, which should allow to improve quantum efficiency/fill factor, particularly for the shortest wavelengths, even for small pixel pitch.

3 - CIS ADVANTAGES FOR SPACE APPLICATIONS

3.1 - GENERAL OVERVIEW

The previous paragraph has demonstrated that CIS EO performances allow these detectors to fulfil demanding applications. As mentioned in the introduction, the selection of the detection technology has therefore to be driven by the functional and technological features and limits, which generally become the discriminating point between CMOS and CCD. Whatever the photodetector selected for photons to electrons conversion, all the approaches listed in the previous paragraph stay compatible with the mixed signal core process and would offer several technical advantages with respect to CCD, such as (non exhaustive list):

- Very low power consumption, which could be a driver for solar system exploration or optical instruments on board microsattellites: without any optimisation, the 1k x 1k array presented above feature less than 20 mW power consumption (2 Mpixels/s output rate) to be compared to several hundreds mW for a CCD with equivalent format. The power

consumption ratio between CIS and CCD would even more increased when including all peripheral electronics.

- High frame rate operations, which cannot be offered by CCD technology (CIS are inherently fast devices), explaining why all recent imagers developed for large frame rates are based on CMOS technology. In addition, it should be noticed that the temporal noise of CIS will not degrade as fast as the one of CCD with increasing read-out rate, as CIS pixel bandwidth is better matched to the sampling frequency.
- Read-out flexibility, such as spatial sub-windowing, very fast access to the useful informations, temporal gating, multiple read out in order to reduce temporal noise, provide images deglitching and/or manage a large dynamics, use of rolling or snapshot read-out, in order to avoid artefacts present in CCDs used for space applications such as smearing
- Simple electrical interfaces and integration of peripheral functions (such ADC), in order to decrease power and mass budgets, to reduce instrument integration effort and to improve reliability
- Ability to design photodetectors topologies dedicated to the applications. Contrary to CCDs, which pixel size and topology are constrained by charges transfer need, CIS pixels can match the ultimate requirement for a given application, such as photosensitive size and shape. In addition, very small pixels (less than $3\ \mu\text{m}$) can be addressed thanks to advanced lithographic design rules and very large photodiodes can be designed too
- Strong antiblooming capability without strong impact on the other parameters
- Better behaviour with respect to radiation environments for both ionising dose effects and displacement damages, even using standard CMOS technologies, thanks to the use of specific design rules (figure 5). This advantage is particularly important for intermediate or elliptic orbits around Earth and missions close to the Sun (Bepi Colombo and Solar Orbiter for instance).

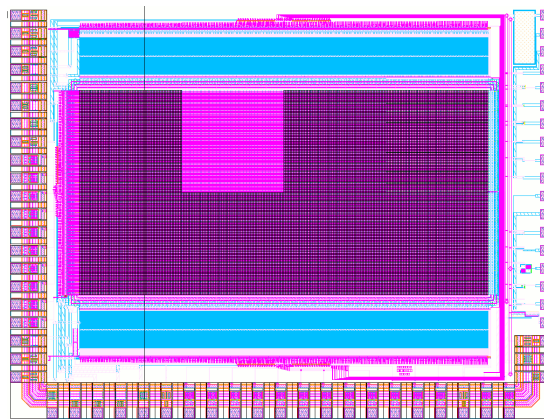


Figure 5 - Test vehicle developed by EADS Astrium and Supaéro/CIMI using a standard $0.35\ \mu\text{m}$ CMOS process. Several pixel types have been implemented on this vehicle with optimised designs in order to improve their behaviour with respect to ionizing dose effects

- Read-out compatibility with other spectral domains. For instance, the same electronics can be used for different spectral channels, from UV to IR
- On-chip analogue and/or digital signal processing integration in order to improve data processing while avoiding expensive and power hungry off-chip processing such as those required when using CCDs

3.2 - EXAMPLES OF CURRENT OR SHORT TERM COMING DEVELOPMENTS

Based on EADS large experience in optical instruments and sensors design and considering that our team has now 10 years of experience with CMOS and more than 20 years of experience with CCDs, some lessons have been learnt about the use of CIS for space applications:

- the use of CIS allows performances similar to CCD to be achieved in some applications, while decreasing instrument/sensor cost. Even if it is misleading to consider that the price of a state of the art CIS dedicated to an ambitious space mission will be low, it is true that the price of the complete imaging function would be lower using a specific CIS instead of a CCD for a great number of space applications.
- Thanks to its architectural / technological advantages, CIS can improve some instruments and sensors performances
- CIS allows new instruments designs that were not feasible based on CCDs usually used for space applications
- In some specific cases, CCD cannot easily be replaced by CIS: this is mainly the case when charges transfer is a specific advantage/need for the application (Time Delay and Integration (TDI) observation for instance)
- System architecture global optimisation can be done by the design of a dedicated CIS, which can be considered as a real Imaging-ASIC
- Mimic what is done with CCD when designing a system based on CIS will rarely lead to the optimum result

The following examples demonstrate that CIS is now considered as a mature technology by our team and that current developments are based on this technology.

3.2.1 - Star trackers and optical terminals

Star trackers were among the first equipments for which CIS were foreseen as featuring strong advantages over CCDs. Figure 6 shows a 2D array developed by EADS Astrium and Supaéro/CIMI for such applications [15], including a 750x750 pixels photosensitive area (20 μm pixel pitch), CDS stages and a powerful integrated programmable timing and control function offering several read-out modes: autonomous read-out, adjustable integration time, fast charges damping, multiple read-out and sub-window dynamic mode able to randomly read a large number of windows even if superimposed.

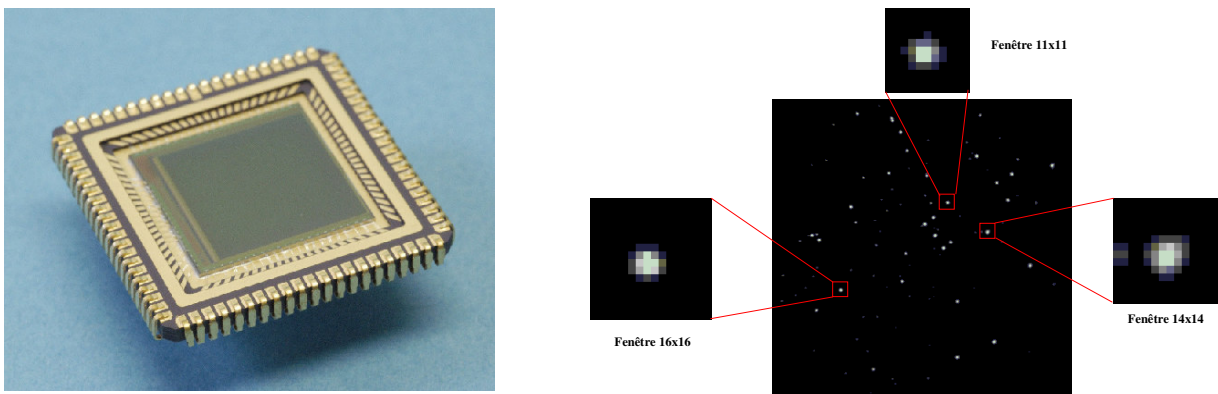


Figure 6 - Left: 750x750 pixels (20 μm pitch) CIS developed for star tracking applications, including a dedicated programmable timing and control function: right: example of application for the sub-window dynamic mode for this CIS

In the nineties, EADS ASTRIUM developed the SILEX (Semi-conductor Inter-satellite Link Experiment) system for the ESA, and gained a strong know-how in optical communications [16].

First SILEX optical communication was successfully performed in December 2001 between the two optical terminals respectively mounted onboard geostationary ARTEMIS spacecraft and Low Earth Orbit SPOT4 spacecraft (figure 1-a). The SILEX Terminal Optical Bench is equipped with two CCDs:

- The Acquisition Sensor Detection Unit (ASDU) is a 288 x 384 pixels CCD which allows the spot detection in the terminal Field of View, at the beginning of the Acquisition phase.
- The Tracking Sensor Detection Unit (TSDU) is a 17x17 pixels CCD which allows to track the spot at the center of the terminal Field of View, at high frequency at the end of the Acquisition phase, and during all the Communication phase.

Both CCDs offer a 3Mpixels/s rate, and frames rate are adjusted depending of required SNR, typically respectively to 30Hz and 4kHz. The SILEX system demonstrated in-flight expected performances, but the Assembly, Integration and Test phase of the terminal optical benches was long and meticulous, due to separated Acquisition and Tracking sensors.

Since end of 2003, EADS ASTRIUM develops for the DGA, a new optical terminal to be mounted onto an aircraft to demonstrate the possibility to communicate with the terminal mounted on board ARTEMIS. An APS750FAST chip, derived from the one designed for Star Tracker applications and offering a 8Mpixels/s output rate has been developed in the frame of this project, to realize both the Acquisition and Tracking functions [17]. Acquisition frame rate is 10Hz and Tracking frame rate can be adjusted until 12kHz depending of required SNR. Figure 1-b shows the combined Acquisition and Tracking Sensor before integration on the Optical Bench. This sensor simplifies dramatically the Assembly, Integration and Test of the terminal Optical Bench and illustrates the possibilities offered by CMOS Imaging Sensors in such complex system as optical communication terminal.

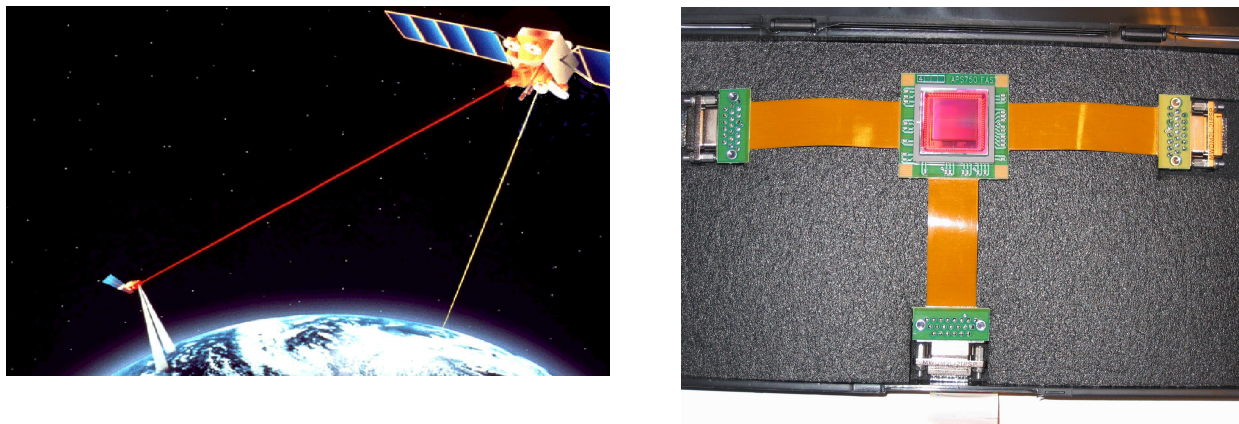


Figure 7 - Left: SPOT 4 images transmission down to ground via optical link and ARTEMIS relay overcomes intermittent radio electrical visibility from its ground network; right: CIS acquisition and tracking sensor developed by EADS Astrium and Supaéro/CIMI

3.2.2 - Earth observation

Earth (or other Solar system planets) observation is an important field within space business. Since the beginning of the 80s, most of the visible sensors dedicated to remote sensing from space are built around CCD detectors. The availability of high performances CIS offers a powerful alternative, an not only for the generic advantages of CIS with respect to CCD. For instance, the use of CIS will be beneficial for hyperspectral instruments (based on a dispersive spectrometer): read-out of spectral line of interest, selectable gain and/or dynamic range per spectral line, no smearing artefact, and higher read-out rate. More generally, smearing is often a difficult problem for 2D CCDs in space (particularly for large –and therefore slow- devices), as it degrades the quality of the useful data, requires specific processing and can strongly reduce the useful dynamics per pixel.

Interline architecture would remove this weakness but is not offered by CCD manufacturers working within the space niche market. Mechanical shutter is an other available approach, but at the expense of higher risk, budget and vibrations. In the framework of a development for an Earth observation instrument located in GEO, EADS Astrium has selected CIS rather than CCD technology in order to manufacture the flight models of the requested 2 Millions pixels detectors. This choice is mainly driven by the absence of smearing and by the larger available charge handling capacity per pixel. The launch of the instrument is planned before end of 2008.

3.2.3 - Smart sensors

CIS offer the capability to mix within a single chip detection and signal processing functions. This opens the door for new applications thanks to this "smart sensors" approach, when compared to a more classical way; where pixel/image acquisition and data processing are separated. Some processing can be performed using analogue sub-functions, for instance the calculation of the energetic centroiding in a sub-window [18] or the delayed summation of TDI samples [19]. The use of deep sub-micron CMOS process would allow to integrate one ADC per pixel [20], offering the capability to design local and global data processing via numerical way.

An illustration of CIS smart sensor advantages when compared to CCD is what can be called smart events detectors. This example also demonstrates that system architect have now to master new capabilities offered by CIS in order to achieve the optimal sensor/instrument architecture and design. Events detection means that within a field imaged on the imager photosensitive area, some events have to be detected and localized. In some case, the signal level of the events need also to be measured. Using a CCD, and because of its serial read-out architecture, all the pixels of the frame have to be read out, transferred to a dedicated electronics function and processed in order to determine which pixels contain informations related to the events to be detected (in general, the fraction of hit pixels is very low). The criticality of such a sensor increases with the amount of pixels (large 2D arrays for instance) and with the temporal accuracy specified for the events detection process (few kHz is required in some case). For demanding applications, a design based on CCDs leads to hundreds of fast video outputs coupled to a power hungry analogue and digital electronics, making its implementation very difficult for space applications. Thanks to CIS advantages, elegant architectures can be designed. Indeed, it is possible to integrate for each pixel a comparison function able to detect at high rate if its photodetector has been illuminated or hit by the event to be detected. If this is the case, the in pixels comparators will made available on dedicated busses the addresses of the (few) pixels to be read-out, dramatically reducing the data rate and removing any off-chip data processing dedicated to events detection. Several fields of applications, such as high energy particles detection, photons counting, flash detection...will benefit of such "events detectors" architecture and operation for short term coming space applications.

4 - CONCLUSIONS

The previous paragraphs demonstrated that CIS are now able to fulfil the requirements for many space sensors or instruments and that they offer real advantages with respect to CCDs for some applications. The mastering of CIS capabilities is therefore a necessity for a team willing to manufacture new generation of optical sensors and instruments. New ways are today investigated in order to further improve their EO performances and functional features. CIS should therefore be one of the key element allowing to take up future space imaging systems challenges.

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