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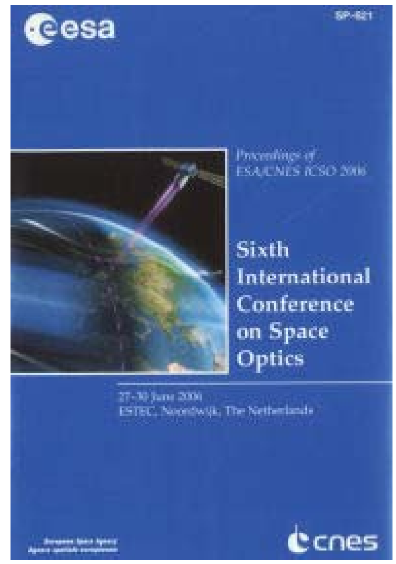

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BACKTHINNED TDI CCD IMAGE SENSOR DESIGN AND PERFORMANCE FOR THE PLEIADES HIGH RESOLUTION EARTH OBSERVATION SATELLITES

A. Materne [(1)], A. Bardoux [(1)], H. Geoffray[(1)], T. Tournier[(1)], P. Kubik[(1)], D. Morris[(2)], I. Wallace[(2)], C. Renard[(3)]

[(1)]*CNES, 18 Av Edouard Belin, 31401 Toulouse Cedex 9, France, Email :alex.materne@cnes.fr*
[(2)]*e2v technologies ltd, 106 Waterhouse Lane, Chelmsford, Essex,UK, CM1 2QU, Email:David.Morris@e2v.com*
[(3)]*Alcatel Alenia Space,100 Bd du Midi, 06156 Cannes la Bocca, France,*
Email:Christophe.Renard@alcatelaleniaspace.com

ABSTRACT

The PLEIADES-HR Earth observing satellites, under CNES development, combine a 0.7m resolution panchromatic channel, and a multispectral channel allowing a 2.8 m resolution, in 4 spectral bands. The 2 satellites will be placed on a sun-synchronous orbit at an altitude of 695 km. The camera operates in push broom mode, providing images across a 20 km swath. This paper focuses on the specifications, design and performance of the TDI detectors developed by e2v technologies under CNES contract for the panchromatic channel. Design drivers, derived from the mission and satellite requirements, architecture of the sensor and measurement results for key performances of the first prototypes are presented.

1. INTRODUCTION

The PLEIADES-HR Earth observation satellites are part of the Franco-Italian ORFEO programme, dedicated at the development of a dual military and civilian capability for providing both optical and SAR images. The first satellite will be launched in 2009.

The genesis of the programme and mission specifications have been previously presented [1]. The specifications were mainly directed toward the concept of low cost mini-satellites capable to reach higher resolutions for defence and civilian needs. The satellites, developed by EADS-Astrium, are based on a very compact architecture with the instrument embedded in the platform, for higher compactness and agility [2].

The instrument, under Alcatel Alenia Space responsibility, includes a Korsch telescope and a highly integrated detection unit composed of a focal plane supporting the panchromatic and multispectral lines of detectors, and a video electronic unit, shortly connected to the detectors, that ensures sampling and digitalisation of the video signal [3].

The panchromatic detection line results from the optical butting, in the focal plane, of 5 TDI CCD detectors.

The PLEIADES-HR mission main characteristics

Altitude	695 km	Sun synchronous orbit
Swath width	20 km	
Panchromatic (Pan) resolution	0.7 m nadir	Less than 1 m in a 30° half-angle cone from nadir
Pan spectral band	[480-830] nm	
Multi-spectral resolution	2.8 m nadir	
Multi-spectral bands	[450-530] nm [510-590] nm [620-700] nm [780-910] nm	Blue Green Red Near infrared
Accessibility	Daily	With 2 satellites
Stereo capability	- 20 km - 300 km - tri stereo capability	With B/H = 0.15 With B/H=0.7
Single-pass coverage	80 x 80 km2	With 20° off-nadir angle

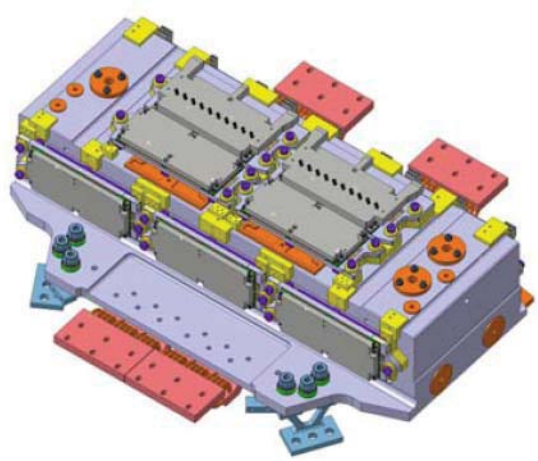

Fig. 1. PLEIADES focal plane

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Fig.1 presents the focal plane, where 2 TDI detectors with their close electronics can be seen on the top, optically butted to 3 TDI devices on the hidden side. The multispectral detectors are symmetrically mounted.

2. THE SATELLITE MAIN REQUIREMENTS

Pan Radiometric and MTF satellite specifications

Panchromatic Radiance dynamic range	L1= 14 W/m^2.sr.µm L2 = 98 W/m^2.sr.µm L3 = 206 W/m^2.sr.µm L4 = 324 W/m^2.sr.µm
Specular reflexion local radiance	Lmax=9 10^5 W/m^2.sr.µm
SNR(L2)	> 90
Pan MTF @ Nyquist	> 0.07
MTFx SNR(L2)	> 7
Pointing agility	Roll or pitch 15° within 10 s; Roll or pitch of 60º within 25 s

Radiance levels and MTF requirements when transferred at the detector level do not constitute a challenging breakthrough. The telescope primary mirror diameter, 0.65 m, is firstly optimized to meet the MTF requirements. The dynamic range [E1;E4] of irradiance flux entering the Pan detector, resulting from the instrument aperture and transmission, is typically [5.10^{-3}; 0.15] W/m^2. The demanding specifications result from the hardly reduced along track sampling time for a 0.7 m resolution – when agility objectives forbid satellite slowing - and the levels of specular reflexions to be dealt with. The impact on the design priorities at the sensor level are developed in chapter 3.

3. MAIN DESIGN DRIVERS

For high resolution applications the integration time associated with pushbroom mode is short. Slowing the satellite during image shot extends the integration time but degrades the satellite agility.
Time Delay and Integration (TDI) sensors bring an answer to the integration time limitation, disconnecting the integration time from the along track sampling period thanks to the vertical transfer and summation of charges. Slowing the satellite is thus no more required and summation of up to 60 times the sampling period is technologically achievable.
Thanks to TDI solution, the signal level necessary to achieve the SNR requirement can be tuned at the detector level by selecting the appropriate number of TDI stages, and no more at the telescope level by sizing the camera aperture. As a consequence, this aperture can be designed at the MTF limit, reducing dramatically the size and inertia of the satellite, and thus improving agility performance and reducing the global cost of the satellite.
The limitation in the number of TDI summation, or stages, is not at the detector level but lies in the limitation of TDI registration discrepancy which comes from several factors:

- stability of the line of sight, which is implemented by the Attitude and control system of the platform during imaging periods
- optical distorsion which limitation is a design driver of the telescope combination
- on-ground projection effects, when imaging with a forward or backward viewing angle.

This TDI registration discrepancy degrades the image contrast at the specified resolution, described by the Modulation Transfer Function (MTF). For a too long integration time or for a too high number of TDI stages, the MTF degradation may become unacceptable (Fig. 2).
Moreover, the sensitivity of MTF degradation to each of these factors is very high. The level of stability of the line of sight can remain quite uncertain till advanced phases of satellite development, especially for a satellite with a compact architecture including moving elements. It is thus important to choose a limited number of TDI stages in order to reduce the risk of MTF loss later in the development progress.

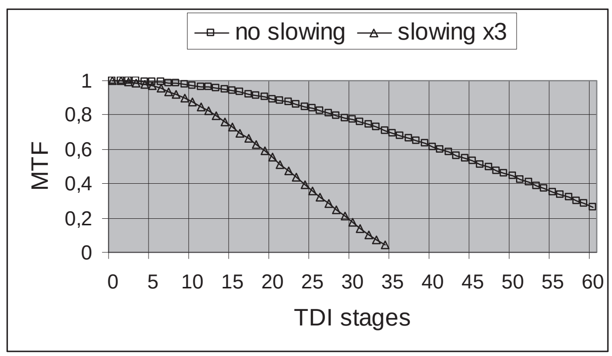

Fig. 2. Loss of MTF due to registration discrepancy- PLEIADES-HR case

3.1 Quantum efficiency

It is of prime importance to reach the requested signal level, for the radiometric requirements, with a minimum number of TDI lines, for MTF requirements.
Backthinning technology offers detection efficiency around three times higher than what is achievable with standard photoMOS detectors arrays.
The TDI detection architecture coupled with the backthinning technology was the key to enter into the restricted domain of the high resolution imagers.

3.2 Readout frequency and conversion gain

Without any satellite slowing, the mission parameters enforce a readout period of 103µs for the complete 30,000 pixels panchromatic line, that is to say about 300MHz readout frequency for the line.
Specific attention must be devoted to the architecture and design of the output amplifiers in order to maintain low consumption while ensuring short video signal settling times which are necessary to guarantee smooth and flat useful signal levels for correlated double sampling. The design of the output amplifier must also take into account the need of a high electron to tension conversion gain in order to reduce the weight of the electronic noise of the video chain in the overall SNR.

3.3 MTF

The MTF satellite requirement before restoration has been split into allocations to TDI registration discrepancy, telescope, stray light and detector.
The MTF allocated to the detector itself – MTF = 0.50 over the Pan spectral band, excluding the already identified contribution from the number of stages – gave rise to several constraints:
- at the architecture level : pixel size and four phase vertical transfer,
- at the manufacturing level : for the selection of the best silicon thickness and doping concentrations.

3.4 Antiblooming structure

Instruments which do not integrate anti-blooming structure in the detection sensitive area of the sensor show a specific signature of charge overflow along the columns that degrades the image interpretation.
The occurrence of such figures increases as the aimed ground pitch is reduced and increases for urban areas where the probability of surfaces with high specular reflections is high : roof windows, metal chimneys, car windshields.
Using the relative Sun/Earth/Satellite positions in the programming center allows to avoid specular reflections over horizontal surfaces like seas, rivers or lakes. But for an agile satellite like Pleiades, small human-made glossy surfaces cannot be avoided because they are randomly distributed both in elevation and azimut. One can compute the elementary probability of a given “specular” landscape to be viewed at satellite level, as a function of the elevation range of its normal vector [θ_{min}, θ_{max}] :

$$\text{Proba} = \Omega_{sun}/8\pi.[\cos\theta_{min} - \cos\theta_{max}] \quad (2)$$

where Ω_{sun} is the solid angle of the sun viewed from the Earth (6.8e-5 sr). Let d be the spatial density of bright objects, we can compute the expected number of specular objects in a given urban Pleiades scene of A=20x20 km^2 with Eq. 3 :

$$\text{Nb\_specular} \sim \text{Proba} * d * A \quad (3)$$

For example, roof windows oriented in the range [15°, 30°] lead to approximately 11 specular spots per scene, with a density hypothesis d=1000 windows/km^2. This is far to be negligible, because large saturated artifacts may hide useful information and lead to systematic poor image quality over urban areas. Moreover, system products are pan-sharpened coloured scenes in which any specific Pan default is magnified : it is worth avoiding Pan overblooming where XS detectors do not saturate.
Fig. 3 shows the advantage of the antiblooming structure compared to sensors only equipped with antiblooming structure along the readout register. These simulations have been performed for two types of specular objects :
- a small car windshield, equivalent to a 20cmx20cm plane mirror
- a small roof window of 80cmx80cm.
Each picture is an extract of 66 columns x 66 rows. The circular spot due to the camera point spread function is partially covered by a thin vertical segment without antiblooming.

Fig. 3. Comparison of antiblooming in the imaging area versus antiblooming along register.

Each surface has a reflectivity equal to 0.08, which leads to an equivalent radiance level of 900000 W/m2/sr/µm for standard viewing conditions in the panchromatic band.
The TDI hypothesis are : 16 useful TDI lines, 9 hidden lines, charge capacity Qsat=120ke.
The typical length of an overblooming artifact is 40 rows and can therefore hide many useful details.
An architecture with an antiblooming structure in each elementary detection site of the TDI array cancels this drawback. This need was an important design driver since it was requested to integrate this structure in each elementary detecting pixel without any loss of quantum efficiency.

4. THE SENSOR ARCHITECTURE

Taking into account the sensor performance requirements and the design drivers, a CCD architecture with the following main features has been designed:

- a pixel size and pitch of 13µm square,
- four phase parallel transfer electrode structure, implemented in four levels of polysilicon,
- longitudinal antiblooming structures in every pixel, optimised for back-illumination to maintain 100% fill factor,
- 6000 active pixels per line, with a maximum of 20 TDI lines, (see Fig. 4.)
- Selectable number of active TDI lines in flight,
- 10 serial readout registers, each with an optimised output amplifier, each output therefore serving 600 pixels per line.
- Custom Aluminium Nitride package, with AR coated window.

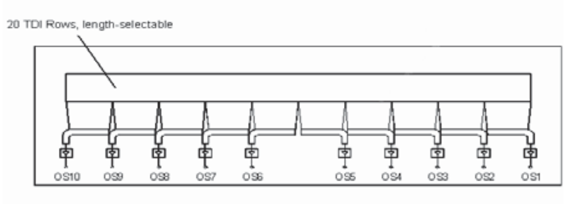

Fig. 4. Outline schematic

4.1 TDI mode optimisation

The design of CCDs for TDI mode operation requires some specific architectural considerations over and above those for linear or area imaging arrays. In order to achieve the good control necessary over the parallel charge transfer to accurately match the optical image motion, and to keep the phase consistent along the length of the detector, a specific transfer electrode bus structure was used. This has interconnection of the electrodes of each phase between lines within the image area, allowing the parallel transfer electrode bus structure to be sited along one long side of the detector, hugely reducing the time constant and phase delays associated with driving such a device from the short sides.

For accurate matching of the optical and charge images on the detector the pixel was designed with four parallel transfer phases. Various clocking schemes are then available, but for the electro-optical characterisation, charge is moved from phase to phase within the pixels at appropriate periods within the line time (intra-pixel matching), and the serial readout registers are operated near continuously to minimise the pixel readout rate from the output amplifiers. This makes it necessary to have a separate transfer gate electrode between the parallel and serial registers, allowing the charge from the parallel register to be transferred very rapidly into the serial register, and decoupling the needs of the TDI operation for charge positioning and timing from the readout operation.

4.2 TDI length selection

The average device illumination is anticipated to vary during the mission, and therefore to optimise the trade-off between the integration time, the platform stability and the maximum charge capacity of the pixels the device has been designed with the ability to select the number of active TDI lines in the image area. The maximum number of lines is 20, with selectable reduction to 16, 13, 10 or 7 lines electronically during flight. Unwanted photocharge generated in the unused part of the image area is removed via the antiblooming structure to prevent any potential corruption of the image in the operational part of the device.

4.3 Design for Back-illumination

In common with most e2v imagers, the PLEIADES TDI sensor is designed for back-illumination. The active device wafer is mounted onto a silicon support wafer, and the substrate material removed to leave the required active thickness of epitaxial silicon. The back surface (now the optical input surface) is then passivated by ion implantation and laser annealing, and an antireflection coating optimised for the panchromatic wavelength range is added. Finally, an opaque light shield is added to the devices to prevent optical input to all but the imaging TDI lines of pixels. The wafers are then sawn and packaged.

The final thickness of the active silicon was selected after a trade-off analysis between the MTF, the red quantum efficiency, and the spectral photoresponse dispersion. Several wafers were produced with a range of active silicon thicknesses, and the parameters measured to confirm the outcome of the trade-off. An example of these results is shown in Fig. 6.

The antiblooming structure used was a 'shielded' drain design. This structure is ideal for back-illuminated devices since the surface drain is 'shielded' by a deeper diffused doping region, which produces a potential that prevents photogenerated charge from being attracted to the drain from the bulk of the active silicon. This means that there is virtually no loss of quantum efficiency with the addition of the antiblooming functionality.

4.4 Readout register and output circuit design

The constraints on the pixel rate per output, the line time and the number of pixels per line have resulted in a device design with 10 readout registers, each ending in a single output amplifier. The readout registers are of standard two phase design, with a single separately connected last electrode at the output end of each to allow optimisation of the output timing without the load of the whole register phase. The output circuits are of conventional two stage source follower design, DC coupled with common drain connections, loads for the first source follower transistors are on chip, and the second stage loads are off-chip.

The nominal output pixel rate per output is 6.6MHz, but the bandwidth of the outputs has been designed to accommodate significantly faster settling than would normally be required for this rate. This allows margin in the electronic drive and readout electronics timing for drifts due to ageing and radiation effects in the mission without adversely affecting the instrument performance.

4.5 Package design

The package is a co-fired Aluminium Nitride (AlN) construction, with bottom brazed Pin Grid Array(PGA) interface. Fig. 5 shows a picture of the device in its package, with the window removed for clarity.

Fig. 5. The packaged CCD

In order to achieve the demanding geometrical and flatness tolerances required by the focal plane construction, the reference and mounting surface of the packages have been precision ground. Image plane flatness of a few microns is routinely achieved.

5. PERFORMANCE OF THE PROTOTYPES

A custom electrical and electro-optical measurement system has been designed and constructed for the assessment of the performance of the PLEIADES PAN TDI CCDs. This system operates the devices in representative conditions for temperature, clock sequencing and frequencies, with calibrated spectrally appropriate optical input of representative intensity range.

5.1 MTF and Quantum Efficiency

Measurements to support the trade-off between the long wavelength quantum efficiency and the short wavelength MTF were performed on a series of devices produced with varying active Silicon thicknesses. The results are shown in Fig. 6.

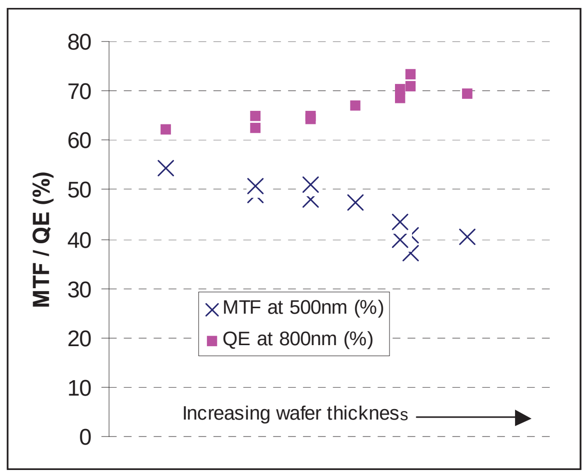

Fig. 6. MTF and QE trade-off vs thickness

5.2 Charge to voltage conversion

The charge to voltage conversion factor of the 10 output amplifiers on the device average approximately 2.5µV/electron, with a standard deviation of ~1%.

5.3 Video signal waveform

A typical video signal waveform from the output amplifier operating at 6.6MHz with moderate illumination is shown in Fig. 7. It can be seen that the waveform is well settled in the reference and signal portions, and that there are significant margins for electronic sampling, suggesting that the device could be operated with good performance at higher frequencies.

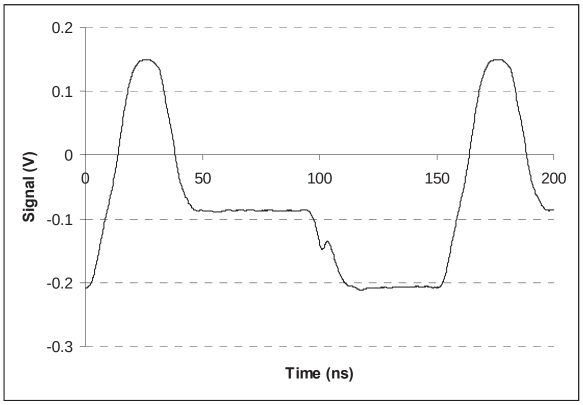

Fig. 7. Typical output waveform

5.4 Noise in darkness

The noise in darkness for operation with 20 TDI lines (maximum length), at a temperature of +15°C, with a line time of 106µs is ~130µV rms, with a dispersion of ~5% across the 10 registers.

5.5 Dark signal and non-uniformity

The dark signal for operation with 20 TDI lines (maximum length), at a temperature of +15°C, with a line time of 106µs is ~140µV, with a dispersion of ~3.5% across the 10 registers. The uniformity of the dark signal within each register is ~+/- 35µV, well below the noise level.

5.6 Charge capacity

The charge capacity of the pixels in the image area is a key parameter for the signal to noise performance of the instrument.

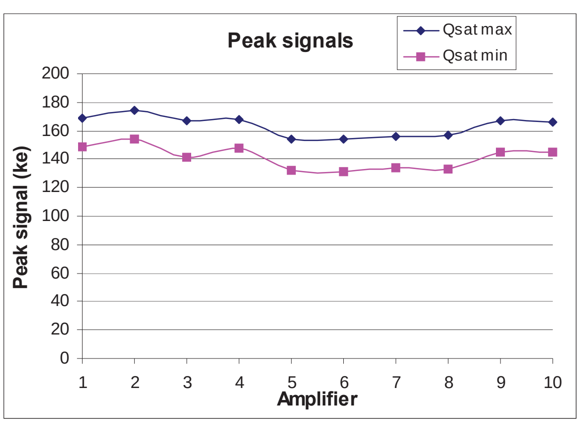

Fig. 8. Charge capacity

It is specified in terms of the lowest capacity pixel addressed by a given readout register (Qsat min), and the highest capacity pixel of the same register (Qsat max) giving therefore the lowest performance that can be achieved by the device, and the highest signal that will need to be handled by the output circuit and the video chain electronics. Fig. 8. shows the result for a prototype device.

6. NEXT STEPS

After prototype development under CNES management, flight phase procurement has been transferred to the instrument prime Alcatel Alenia Space.
In parallel to the nominal design, e2v has developed a three stage output amplifier designed to improve charge to voltage conversion gain.
Tests are planned in CNES laboratories to operate these devices at higher frequencies for higher resolution applications.

7. CONCLUSION

Thanks to the high photoresponse achieved via backthinned technology and detectors readout rate up to 66 MHz on 10 outputs, it is possible to meet the signal to noise requirement SNR(L2) with only 10 TDI lines selected, without any satellite slowing. Moreover, the performances of the sensor offer potentialities for higher resolution applications.

8. ACKNOWLEDGMENTS

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