New detectors and detector architectures for high resolution optical sensor systems

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Abstract — **The Institute of Optical Sensor Systems (OS) as member of the Robotics and Mechatronics Cluster of the German Aerospace Center (DLR) has more than 30 years experiences with high-resolution imaging technology. The technology changes in the development of detectors, as well as the significant change of the manufacturing accuracy in combination with the engineering research define the next generation of spaceborne sensor systems focusing on Earth observation and remote sensing. The combination of large TDI (time delay and integration) lines, intelligent synchronization control, fast-readable sensors and new focal-plane concepts open the door to new remote-sensing instruments. This class of instruments is feasible for high-resolution sensor systems regarding geometry and radiometry and their data products like 3D virtual reality. Systemic approaches are essential for such designs of complex sensor systems for dedicated tasks. The system theory of the instrument inside a simulated environment is the beginning of the optimization process for the optical, mechanical and electrical designs. Single modules and the entire system have to be calibrated and verified. Suitable procedures must be defined on component, module and system level for the assembly test and verification process. This kind of development strategy allows the hardware-in-the-loop design. The paper gives an overview about the current developments at DLR OS in the field of innovative sensor systems design for spatial and spectral high resolution remote sensing instruments.**

Keywords - Focal plane technology, large TDI, BTDI sensors, sCMOS Focal Plane Earth observation instrument, geometric accuracy, radiometric accuracy, instrument optimization process, large focal plane, high mechanical accuracy

I. INTRODUCTION AND MOTIVATION

The state-of-the-art CCD/CMOS high-resolution sensor line and matrix technology in combination with special optics or telescopes are one of the typical applications. In particular, to meet the user requirements high end spaceborne or airborne projects/sensor designs are needed. Therefore DLR forms partnerships with companies focused on detector development.

Under different environmental, mission and illumination conditions the current technologies have mostly noise and contrast problems. The users of such systems have to install a lot of auxiliary light sources for terrestrial indoor applications in order to fulfill the image quality requirements. The high-resolution spaceborne applications require an accurate pointing mechanism to manage the typical space systems jitter and pointing requirement. In order to meet the best performances parameter these instruments shall manage a ground speed which is typical for low earth observation between 6500 m/s up to 7500 m/s just depends on the orbit. This parameter under the constraint of one pixel smear drives the following equation.

$$System\text{-MTF}=\text{Instrument-MTF}\cdot\text{AOCS-MTF}\cdot\text{Smear}[\tfrac{2}{\pi}] \quad (1)$$

Based on this constrain the MTF (modulation transfer function) of the smear can be just influenced by decreasing the integration time which influenced the SNR by the square root. To overcome some of these difficulties was exact the motivation to invest work in the next generation of new low-noise sensor technology. The second generation of photogrammetric and remote sensors should be able to control the sensor parameters or senor behaviour in dependency on the mission conditions meaning that the sensor should have a possibility to control the SNR (signal-to-noise ratio) and MTF or QE (quantum efficiency).

The resolution is the main objective for high-resolution systems. Particularly good spatial and radiometric resolution (contrast) is the intuitive goal for an excellent camera. Objects as small as possible with low grey value differences shall be dissolved or detected.

Resolution is a value without a standardized definition. One frequently uses the definition of RAYLEIGH. Two dot-like objects can be divided after that if a certain contrast is reached between the two maxima and the minimum. This criterion gives a relation between resolution in a world space (in angle distances) and the visible result in the image space.

One can notice generally that a scene definition is required for the solution determination. Examples of it are the three- or four-bar binary pattern (Airforce Target) and the radial grating (Siemens Star).

The spatial resolution is related according to the system theory with the kernel in the input output relation and the contrast with the noise of the system. Measures derived from it are quality criteria for the handing over to a customer, permit the comparability of systems and reject open systemic but also manufacturing defect to. Known performance parameters are e.g.:

- MTF,
- NPS (noise power spectra), and

- DQE (detective quantum efficiency)

A typical parameter which is derived from the MTF is the MTF-value at the sampling (Nyquist) frequency. To include the form of the MTF better, one also can determine the area under the MTF curve up to a certain frequency (MTF area or MTFA).

The MTF components sampling (Nyquist) frequency, which an intelligent sensor can control can influenced showing in the following equation.

$$System_{MTF} = MTF_{Optics} \bullet MTF_{Pixel} \bullet MTF_{Electronics} \bullet [MTF_{Smear} \bullet MTF_{Sync} \{f(Pixel_{Control})\}] \qquad (2)$$

Another important impact is given by the new technologies like CMOS, sCMOS detector systems, new BTDI detector for space application and the new generation of FPGA’s. DLR-OS is concentration of the developments which are based on the newest detector technology and the scientists verify the performance of the systems and the technology as a proof-of-concept scientific work. An additional qualification and requirement traceability process is established for spaceborne applications which will allow usage of newest technologies. This paper will give an overview over three examples of the last three year of investigation in this scientific field. The new technology developments are:

- The KompSat3 FPA design, NMOS TDI and BTDI line
- The EnMap FPA design, sCMOS
- The MTF measurements without target synchronisation for TDI applications

II. THE KOMPSAT3 FPA DESIGN, NMOS TDI AND BTDI LINE

DLR-OS developed for the Korea Aerospace Research Institute (KARI) the KompSat3 FPA of the Payload. The design is able to meet the synchronization requirement because of the free programmable line rate up to 14.2 KHz. Other important key design feature are 24 k Pixel, 14 Bit A/D conversion, CCD error correction algorithms for the real time Photo Response Non-Uniformity, the Dark Signal Non-Uniformity correction, focusing mechanism, FPA-MTF at NY is higher than 52%, SNR end of life will be better than 150 e- and the dark signal control allows an optimization of the dynamic range. Fig. 1 shows the new sensor generation for the LEO high-resolution [GSD: 0.7 m].

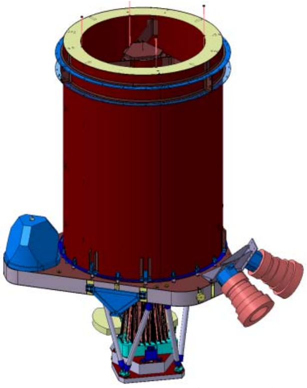

Figure 1. KompSat3 Telescope design

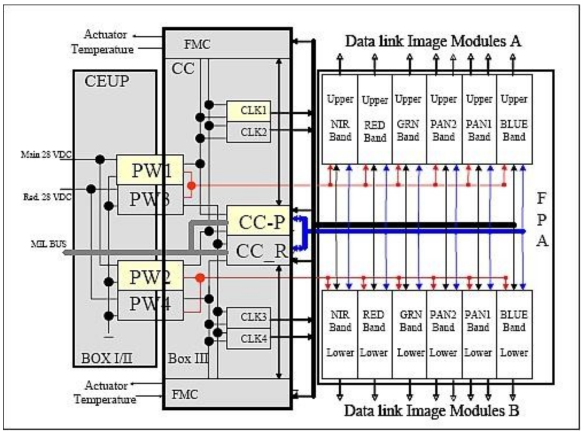

Figure 2. KompSat3 FPA Bloc Diagram

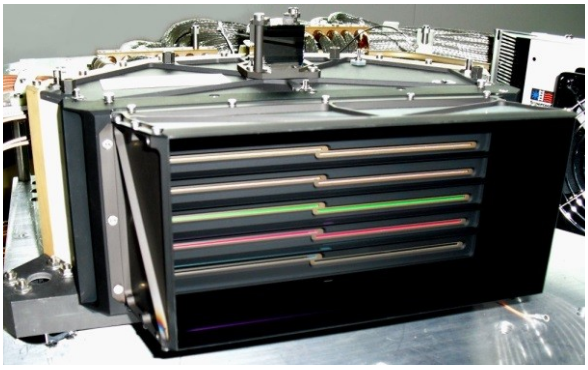

Figure 3. KompSat3 FPA Flight Model

Opposite the M5 mirror of the KompSat3 instrument, there is the FPA located. Its block diagram is depicted in Fig. 2 and the FPA flight model is shown in Fig. 3. How the design could fulfill the requirements is shown by the block diagram. The design based on main and cold redundant panchromatic TDI detectors with overlap for radiometric correction. The multispectral sensors are equipped with tow overlapped TDI detectors. In the case of the different multispectral channels, each of their detectors are controlled and powered individually thanks to the redundancy concept. The one-clock generator requirements guarantee that the phase shift between the different channels is fixed and is lower than two clocks.

III. THE ENMAP FPA DESIGN, SCMOS

The state-of-the-art and new developments of CCD/CMOS high resolution sensor line and matrix technology in combination with special optics or telescopes are key components of the remote sensing instruments. In particular, space-borne or high-end airborne chip designs are required to meet the user expectations. For such projects, DLR form partnerships with companies which are focused on detector developments to influence the system performances from the beginning of the development process with the focus on the optimization of the instrument behavior. Such processes are only possible by simulation of the whole instrument, satellite sensor system and the environment. In case of spectral high resolution systems the ground sampling distance will be in the range of 10 up to 30 m.

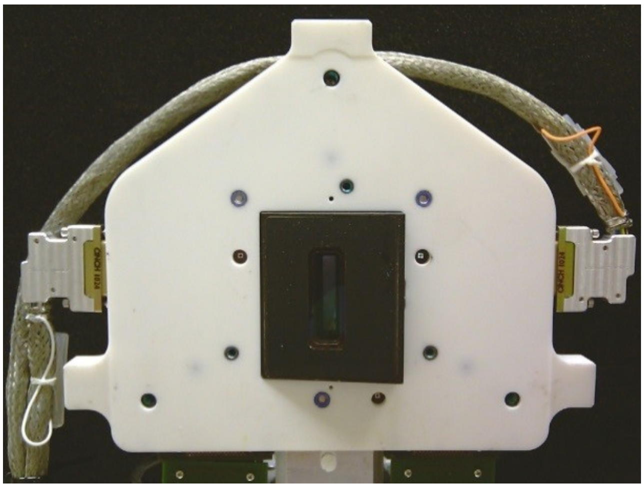

Figure 4. EnMAP VNIR Focal Plane Assembly - The detector design includes also the 13 Bit AD conversion and the cover glass and baffle design according to the Spectrograph needs of EnMAP.

In these applications under different environmental, mission and illumination conditions the design should be able to keep the required performance. Another challenge to such instruments is the noise and contrast problematic because of the F-number and grating. For all of these design aspects it is absolutely necessary to trace all of the performance related parameters especially the SNR and MTF values throughout the whole development. The EnMAP FPA is shown in Fig. 4.

Spectral responsivity is the ratio of measured signal (with subtracted dark signal) to incident illumination measured in various spectral bands (responsivity measurement). A comprehensive curve gives the shape of the responsivity in a broad spectrum containing each measured spectral band.

The QE at a given wavelength expressed as a percentage is the ratio of the number of photoelectrons at the detector output (signal with subtracted dark signal) to the number of incident photons in a given integration time.

Measurement Principle: The QE is measured at various wavelengths using narrow band filters. The dark signal DS is subtracted before the QE is being calculated using the following formula. Here the QE is calculated in %.

$$\eta_{\lambda}^{qu} = \frac{(\langle s \rangle - DS)\cdot h \cdot c}{G_S \cdot \tau_{int} \cdot E \cdot A_{pix} \cdot \lambda} \cdot 100\% \qquad (3)$$

Where:

$\langle s \rangle$	camera output signal	[DN]
h	Planck constant	[Js]
c	Speed of light	[m/s]
$G_S = \eta_{DV} \cdot \eta_V$	Overall system gain	[DN/e$^-$]
E	Irradiance	[W/m^2]
τ_{int}	Integration time	[s]
A_{pix}	Pixel area	[m^2]
λ	Center wavelength of incident light	[m]

The overall system gain G_S is determined by using (4). The irradiance E of the ISS is measured using a calibrated photodiode with a reference to the National Standards situated in the same plane as the detector array. The measured QE is calculated as a mean signal value over the number of pixels.

Measurement conditions: The camera is operated under its nominal operating conditions with nominal frame rate/operational temperature/parameter settings/etc. The illumination can be uniform or a spot, covering several pixels. A number of pixels could be averaged. The procedure could be repeated for a number of locations on the array. Wavelength bands and the maximum signal level (e.g. 80% linear full well) should be defined before.

Results: The test results (Fig. 5) show, that the required spectral QE values will be reached, except at 625nm.

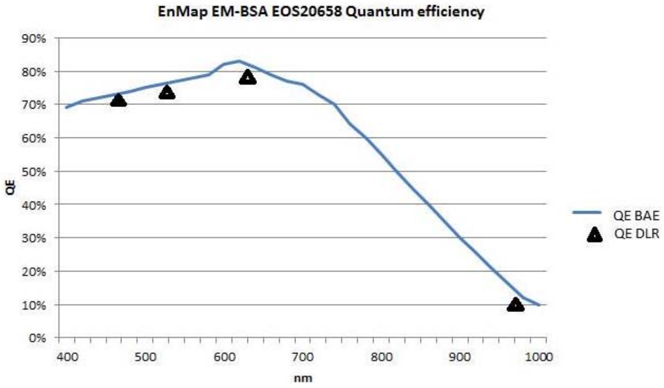

Figure 5. Evaluation data flow for QE of the EnMAP FPA

Spec.	ID	E0520634		0657		E0520524		E0520665		E0520534	
MTF[Ny] %	ʎ [nm]	MTF R[%]	MTF C[%]	MTF R[%]	MTF C[%]	MTF R[%]	MTF C[%]	MTF R[%]	MTF C[%]	MTF R[%]	MTF C[%]
0.44 % 900nm	980nm	38.4	41.6	38	37.2	37.1	39.4	37.0	42	38.9	38.3
0.38 % 600nm	660nm	53.5	53.1	51.9	52.2	53.9	54	54.1	51.6	53.3	53.1
0.35 % 400nm	450nm	51.5	51.7	49.6	50.2	52.2	53.2	51.2	53.7	50.8	51.7

Table 1. Measured MTF Performance over different wavelengths of the EnMAP FPA

Signal-to-noise ratio compares the level of a desired signal to the level of background noise. It is defined as the ratio of signal power to the noise power. Read noise (nread) is defined as the temporal system noise of the CCD in darkness.

The basic formulas for general SNR calculation are as follows:

$$SNR = \frac{Sig}{noise} \qquad (4)$$

where Sig: Signal

$$noise = \sqrt{Sig + dark\ current + (nread)^2} \qquad (5)$$

The quality of the signal can be expressed by the signal-to-noise ratio (SNR), which is defined with equation (4) and (5) as follows

$$\frac{\langle s\rangle}{\sigma_s} = \frac{(\langle n_{el}\rangle + \langle n_{el}^D\rangle)}{\sqrt{\left((\langle n_{el}\rangle + \langle n_{el}^D\rangle) + \frac{\sigma_k^2}{\eta_v^2}\right)}} \qquad (6)$$

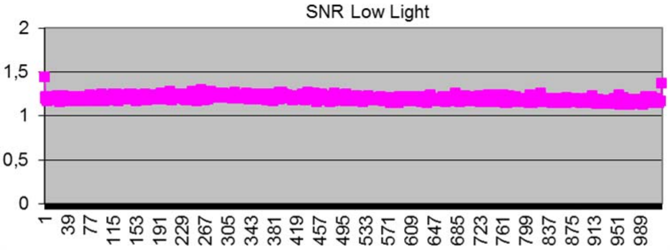

Figure 7a. FPA Noise Performance, signal to noise ratio (SNR) 1.2 LSB of 13 Bit or SNR of 6826

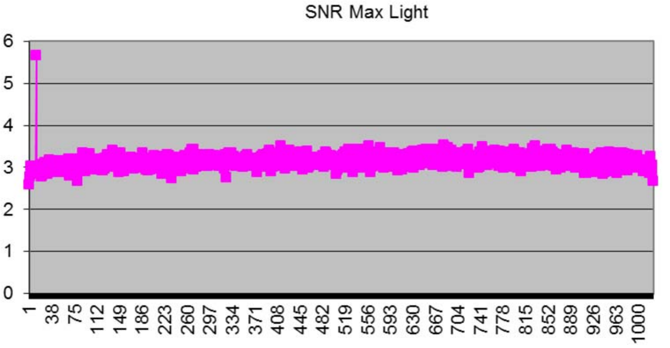

Figure 7b. FPA Noise Performance, signal to noise ratio (SNR) 3.5 LSB of 13 Bit or SNR of 2340

Some of the performances characterization of the VNIR sCMOS FPA for the German EnMAP instrument was now shown. In case of the foreseen usage in space for a life time higher than 5 years in orbit. It is clear that the FPA electronics based on a latch up protection capability.

Our experiences which can be shared with the community based on more than 30 years' work in this field are that this technology has so many advantages to keep the performances higher like CCD's. As you can see at the QE measurements the fringing is minimized and the QE in blue with 70 % is really good. The advantages of the internal 13 Bit AD conversion are just one side of the medal the other side is the required latch up protection. All these parameter which was measured based on the global shutter control of the detector, because this global shutter operation mode will be needed later in orbit. It is a matter of fact that the tolling shutter control of the detector will generate better results.

Here DLR-OS is working on new calibration and correction methods which maybe can solve that difficulty. DLR-OS will present the results next year on the SPIE conference.

IV. THE MTF MEASUREMENTS WITHOUT TARGET SYNCHRONISATION FOR TDI APPLICATIONS

Here we do not calculate the MTF of a single pixel but a MTF which is averaged over a whole CCD detector line. A precondition for that method is the elimination of pixel PRNU and DSNU to have similar pixels.

Let the pixel centers be xk = (k+1/2)·Δ (k = 0, 1, 2,…) (a pixel occupies the interval xk - Δ/2 ≤ x < xk + Δ/2).

We suppose that the half width of the PSF extends over less than M pixels. Then we measure a signal at pixels

$$x_n^* = \left[(2\cdot n+1)\cdot M + n + \frac{1}{2}\right]\cdot\Delta = x_{(2\cdot n+1)\cdot M+n}, \quad (n=0,1,2,\ldots) \quad (7)$$

The pixels $x_{2\cdot n\cdot M+n},\ldots,x_{(2\cdot n+2)\cdot M+n}$ which occupy the interval

$$x_{2\cdot n\cdot M+n} - \Delta/2 \le x < x_{(2\cdot n+2)\cdot M+n} + \Delta/2 \qquad (8)$$

with the length $l = (2\cdot M+1)\cdot\Delta$ contribute to the signal at x_n^*. The pixels are covered by a dark screen which has slits with width δ at positions ˜ (slit m (m = 0, 1, 2,…) is defined by the interval ˜ ˜) which is defined by

$$\tilde{x}_{m+1} = \tilde{x}_m + (2\cdot M+1)\cdot\Delta + s,\ \ \tilde{x}_0 = \delta/2 + \varepsilon,\ \ \ \varepsilon \ll \Delta \ (9)$$

These slits are shifted over the pixels with a shift s << Δ. Slit m = 0 contributes to the signal in pixel x_0^*, slit m = 1 to the signal in pixel x_1^* and so on. That way the signals S_m at pixels x_m^* are the convolution of pixel PSF $H_\lambda(x)$ with the slit function

$$H_{slit}(x) = \begin{cases} 1 & for - \delta/2 \le x < +\delta/2 \\ 0 & elsewhere \end{cases} \qquad (10)$$

if the screen is illuminated homogeneously. Of course, that is true only if the screen covers the detector line array without any distance between them. If there is a distance d between the screen and the detector then diffraction at the slits must be taken into account which results in a broadened slit function $H_{slit}(x)$ which can be calculated in a similar way as above. Figure 8 shows an example with M = 2, ε = 0:

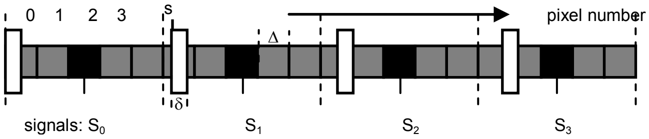

Figure 8: Screen for M = 2

V. CONCLUSIONS

The previous chapters described the performance characterization of the KompSat3-FPA and the VNIR sCMOS detector for the German EnMAP instrument. In order to realize a traceability of the key requirements, an example for the MTF verification on wafer, detector and FPA level was shown. In case of space applications with a planned life time higher than 5 years in LEO orbits, the technology concepts based on latch up protection capability.

DLR-OS brings experience gathered during more than 30 years' work in this field which can be shared with the community. With this in mind we are convinced that the sCMOS technology features many advantages to keep the performance higher than with CCDs. As you can see in the QE measurements, the fringing is minimized and the QE in blue with 70% is good. All these parameters which were measured based on the global shutter control of the detector, because this global shutter operation mode will be needed later in orbit. It is a matter of fact that the tolling shutter control of the detector will generate better results. DLR-OS is working on new calibration and correction methods which maybe can solve that difficulty.

In the presentation, there will be shown the technology in detail and furthermore DLR will brief the community on a new BTDI detector and planned developments of DLR-OS.

VI. ABBREVIATION

AD	Analog to Digital Conversion
AOCS	Attitude and Orbit Control System
BTDI	Bidirectional Time Delay an Integration
CCD	Charge Coupled Device
DLR	German Aerospace Center
NMOS	N-type metal-oxide-semiconductor
CMOS	Complementary Metal Oxide Semiconductor
FPA	Focal Plane Array
LEO	Low Earth Orbit
MTF	Modulation Transfer Function
NY	Nyquist Frequency
OS	Institute of Optical Information Systems
PSF	Point Spread Function
QE	Quantum Efficiency
sCMOS	Scientific CMOS
SNR	Signal to Noise Ratio
TDI	Time Delay an Integration

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