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CMOS-APS sensor with TDI for high resolution Planetary Remote sensing

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1. Introduction

High resolution imaging systems for planetary exploration are mostly based on CCD sensors. Linear CCD sensors are the preferred sensors for earth- and planetary remote sensing because of their wide image-field and their simple architecture. The Sensor Technology group of the Institute of Planetary Research at the German Aerospace Center (DLR) have successfully used linear CCDs on their High Resolution Stereo Camera for Mars Express. These CCD detectors are excellent imaging devices that provide high contrast images with a wide dynamic range.

However, their advantages have to be weighed against their relatively high power consumption and mass. Therefore, they cannot often be used in deep space planetary missions. For this reason we have developed an alternative concept based on APS detectors, which are less demanding in terms of power and mass.. This concept was proposed for the imager of the European Mercury mission 'Bepi-Colombo'.

2. CCD and APS for Planetary Imagers

Most Planetary cameras are based on CCD devices, either framing CCDs or linear CCDs. Linear CCD imagers are based on the push-broom- principle that can cover very wide fields because of the large number of pixels available rectangular to the scan (flight)- direction. Linear CCD detectors also have a large full-well capacity that results in a large dynamic range.

Nowadays, linear CCD imagers can be replaced by linear,low-power CMOS APS sensors, which have straightforward architecture and require relatively simple camera electronics.

However, there is only a short dwell time in very high resolution planetary remote sensing that limits the integration time and results in weak signal levels with a low signal-to noise ratio (SNR). A solution for getting a higher SNR at short dwell times is the TDI-operation

3. TDI (Time–Delayed Integration) -Operation

Nearly all high-resolution cameras, such as HRSC, OSIRIS, are based on the concept of integrating not longer than half of the dwell time in order to prevent smearing. The result is an optical system with a high aperture ratio, in order to reach the required high signal flux and SNR.

However, a higher integration time can be achieved by operating a CCD-detector in the TDI mode or simply by summation of images.

In TDI-mode, image sections of the same object-space, taken during N-successive push-broom steps, are added to form an image with effectively a higher integration time.

The signal to noise ratio after *N* added images is approximately:

$$SNR_N = \sqrt{N} * SNR_O \qquad (3.1)$$

with SNR_N: signal-to-noise ratio after N added integrations
and SNR_O: signal-to-noise ratio of a single image

The analog signal summation by a TDI-CCD is the preferred concept because the signal is added within the detector and before reading the signal through the noisy CCD output amplifiers and signal processing chain , which can negatively affect the SNR at low signal levels.

The TDI concept can easily be implemented with the CCD technology because of the inherent charge-transport mechanism that can be synchronized with the scan-velocity of the spacecraft. However, modern CMOS APS sensors have a readout structure, which consists of single detector- cells that are addressed by a multiplexer structure. Therefore, a charge transport mechanism cannot be implemented easily.

4. APS with TDI-operation

Today, APS sensors are very attractive for deep space planetary exploration because of their low power consumption, their high radiation hardness and the relatively simple electronics needed for the camera system. Therefore, our goal was to find a simple concept for TDI operation with CMOS APS sensors.

Our main motivation was the European Space Agency's requirement for a high resolution camera that has to be operated with very low mass and low power consumption for a new mission to Mercury..

The Max –Planck Institute for Solar System Research and the German Aerospace Center (DLR) have proposed a camera that is based on a digital TDI concept with a CMOS APS sensor.
The reason for the digital approach is that, in contrast to the CCD TDI operation which is based on charge transport, the signal in standard APS- sensors cannot easily be accumulated in the charge domain. Even if charge accumulation appears possible by a dedicated pixel-architecture, this concept appears to be too complex for short-timescale and successful implementation.
Therefore, the proposed APS- concept for Bepi-Cam is based on signal-summation of the digitized signal, which is described below.

5. Sensor Architecture

The baseline for the detector system of Bepi-Cam is a two dimensional APS sensor array consisting of eight sub-sensor rectangular arrays, one each per filter channel. Each sub-sensor has a format of 2560_v x $16_{h(}(256)$ pixels and is coated on-chip (or on a pre-focus glass substrate) with customised interference filters.
The main feature of the APS sensor is the flexible pixel accessibility that allows the usage of the (so-called) digital TDI that is based on an extraneous pixel summation (at FPGA- level). With this technique, the signal-to-noise ratio (SNR) can be enhanced by multiple exposures and read-outs of the target fields, well in synchronisation with the image motion across the 16 columns. The gain in the SNR increases nearly with the square root of the number of lines used for TDI integration. With the help of the digital TDI technique, the obtained radiometric performance is comparable to the performance of high performance CCDs, but with more modest requirements in terms of power, mass and volume.
All pixels of the addressed sub-sensors are sampled at least once within a dwell time (for longer dwell times also 2 or 4 times) and the data is correspondingly added to the data of the previous sample. At the end of each read cycle, the TDI accumulation for the last column is completed. The required data processing is provided by an (external) FPGA and a SRAM buffer as shown in Figure 2.
Furthermore, the sensor can also operate in a standard staring (snapshot- mode) and in window modes, where only a small part of the array is used.
The sensor shall have an integrated snapshot shutter* architecture for synchronous integration.
The number of pixel per column has to be 2560 and the number of pixels per row is proposed to be : $(N_{SC}+1)*256$, where N_{SC} is the number of spectral channels. In the simplified Figure 1 is assumed that $N_{SC}=3$ (SC1, SC2, SC3). Therefore the sensor has four sub-arrays of 2560x256 pixel (TBC).
Each sub-sensor array has a separate output, digitized with 12bit; see simplified block-diagram in Figure 1.

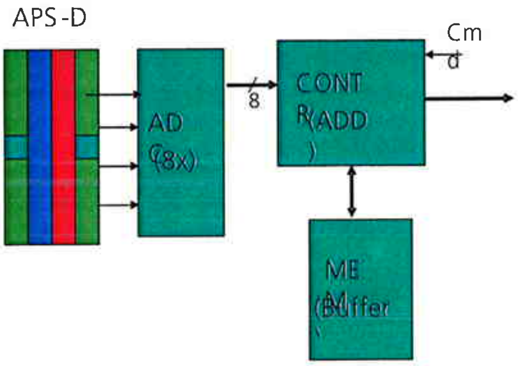

Figure 1: Principle of the proposed APS detector with 4 digital outputs and four spectral segments

5.1. Operation Mode

The sensor can operate in three modes, the Digital TDI- Mode, the Staring Mode and the Window Mode, which are described below.

5.1.1. Digital TDI-Mode

As explained in item 3, the digital TDI mode is very similar to a push-broom mode (known from operation of linear CCDs in earth remote sensing).
In the digital TDI-mode, it is proposed to read-out N-successive columns from each of the spectral segments. The operation sequence consists of the following main steps:

1. Reset the whole array
2. (Open the shutter – for the whole array) and start integration
3. Close the shutter within T_{dwell}
4. Readout the N-columns of all required spectral segments (3) within T_{dwell}.
5. Repeat with step 1.

The necessary readout rate (f_r) of N columns per spectral channel is: $f_r = N*N_p/T_{dwell}$.
With N= 1…16 and $T_{dwell} \geq 3.8\ 10^{-3}$ s, N_p=2560: $f_r \geq N*0.67$MHz.

At N=16 and three spectral channels the readout rate per output is about 10Msps (Msps: Million samples per second) which is state of the art for most CMOS-APS.
The sensor data will be saved in a memory-buffer, one per each APS-output, where the data are synchronously added. The synchronous summation will be performed for all of the N-columns that have been exposed with the same image-segment. The summation of the columns provides data with a higher signal to noise ratio than with single exposures. The pixels are always successively exposed and the data obtained are accumulated in the TDI memory-buffer for accurate synchronisation with the image motion.
The APS is exposed and read continuously in synchronisation with the image motion across the acquired 16 columns (left). After each readout, the pixel data is then added to the data in the TDI buffer (right) and the buffer content is then shifted by one position to the right to be prepared for the next sample. Each TDI sequence takes 16 readouts and accumulations to obtain the result on the overflow.
The estimated dwell time depends on the actual orbital parameters of the S/C. Consequently, appropriate orbit parameter input from the spacecraft is continuously required and must be attached to the image header. The number of TDI-steps is normally equal to 16. Only one output is needed for each sub-sensor yielding a data rate of about 16 Msps. The window-mode, as described below, can be used to verify and update the synchronization time autonomously.

5.1.2. Staring Mode

The sensor can also operate in a staring mode by exposure and readout of the full sub-sensor arrays. The exposed image segments need some overlapping for fitting a mosaic (image strip). That is particular useful in part of the orbit (Apogeum), where the dwell time is large enough for having long exposure times without TDI. Therefore, the sensor performs sequences of full frame images with some overlapping to cover the swath width with all spectral colours. The overlap in time (T_{OL}) is: $T_{OL} = R_O * T_{dwell} * W_{SEGM}$ (7)
with: R_O = ratio of overlapping: 0.5…0.9
* T_{dwell} = 4 msec (variable, depends on orbit)
W_{SEGM} = width of the segment: 256

5.1.3. Window-Mode

The window-mode is used for determination/verification of the motion vector of the spacecraft. The knowledge of the motion vector is important in order to optimize the overlap of the spectral image-sections in the staring modes (see T_{OL} and R_O in Equation-7) and to control the imager in the 'optimized push-broom mode', as explained later. The motion vector can be estimated by taking two subsequent window-images (see Figure 1) and calculating the correlation between them. One result of the motion vector estimation is the dwell time, which depends on the orbit and position of the spacecraft within the orbit. The location of two windows is drafted in Figure 1. They are located at both ends of the APS sensor at the spectral channels with the highest signal flux (green channels).

6. Sensor Specification

The specified sensor parameters are summarized in Table 1.

Table 1 Parameter Specification of the Bepi-Cam APS Sensors

Parameter	Specification	Comments
Pixel number	2560_v x $16(256)_h$	per sub-sensor, TBC
Pixel size	8 μm^2	
Dark current	< 100 pA/cm^2	at 24° C
Full well	100 ke$^-$	
Readout Noise	35-50 e$^-$	rms
Readout rate	16 MHz	per output
QE: - peak - at 400 nm: - at 1000nm:	 40 % 24 % 2 %	incl. fill factor
PRNU, DSNU	<2 %	
Outputs	1	per sub-sensor
Power dissipation	100 mW	per sub-sensor (TBC)
Digitisation	10-12 bits 12 bits	on-chip external (back-up solution)

The sensor can be designed and fabricated in Europe. The baseline manufacturer is FillFactory. The performance of the sensor, as discussed with the manufacturer is summarized in Table 1.

7. Sensor Control- and Pre-Processing

The image acquisition is supported by a dedicated processing front-end to cover instrument specific on-line tasks, which is controlled by a FPGA (radiation-hardened Virtex II) that is located close to the sensor-FPA. The signal flow of the on-line processing tasks is shown in Figure (below)

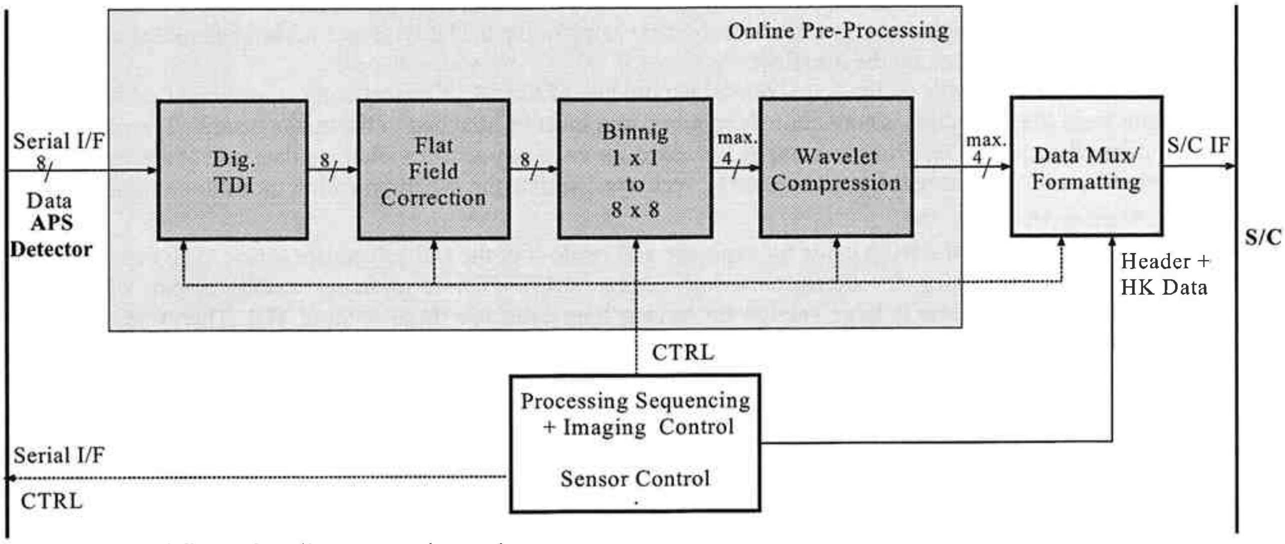

Figure2: Signal flow of on-line processing tasks

8. Conclusions

APS sensors can replace CCD imagers in many applications of planetary remote sensing. The main advantage of CCDs in high resolution remote sensing is their high sensitivity (quantum efficiency) and their inherent charge transport mechanism that makes time–delayed-integration (TDI) -operation very easy. However, with the described digital TDI approach it is possible to reach a similar performance with APS sensors but with more modest resource requirements than for CCD-cameras.

9. Acknowledgements

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10. References

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