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The new CMOS Tracking Camera used at the Zimmerwald Observatory

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Abstract. *During the last years the use of tracking cameras for SLR observations became less important due to the high accuracy of the predicted orbits. Upcoming new targets like satellites in eccentric orbits and space debris objects, however, require tracking cameras again. In 2013 the interline CCD camera was replaced at the Zimmerwald Observatory with a so called scientific CMOS camera. This technology promises a better performance for this application than all kinds of CCD cameras. After the comparison of the different technologies the focus will be on the integration in the Zimmerwald SLR system.*

Zimlat

The 1-meter Zimmerwald Laser and Astronometry Telescope (ZIMLAT) was installed in 1997. It allows for state-of-the-art satellite laser ranging (SLR) and also serves as astronomical telescope for the optical observation of astrometric positions and magnitudes of near-Earth objects, such as space debris, using Charge Coupled Device (CCD) or Complementary Metal Oxide Semiconductor (CMOS) cameras. The telescope is monostatic w.r.t. SLR (transmit and receive paths are identical between the primary mirror and the transmit/receive mirror located at the lower end of the Coudé path). The dichroic mirror (DBS) located in the fork of the mount (Figure 1) allows for the use of tracking cameras simultaneously with SLR observations. The Deflection Mirror (DM) is used to select one of 4 corrector lenses and cameras. The focal length varies between 1 m, 4m and 8 m.
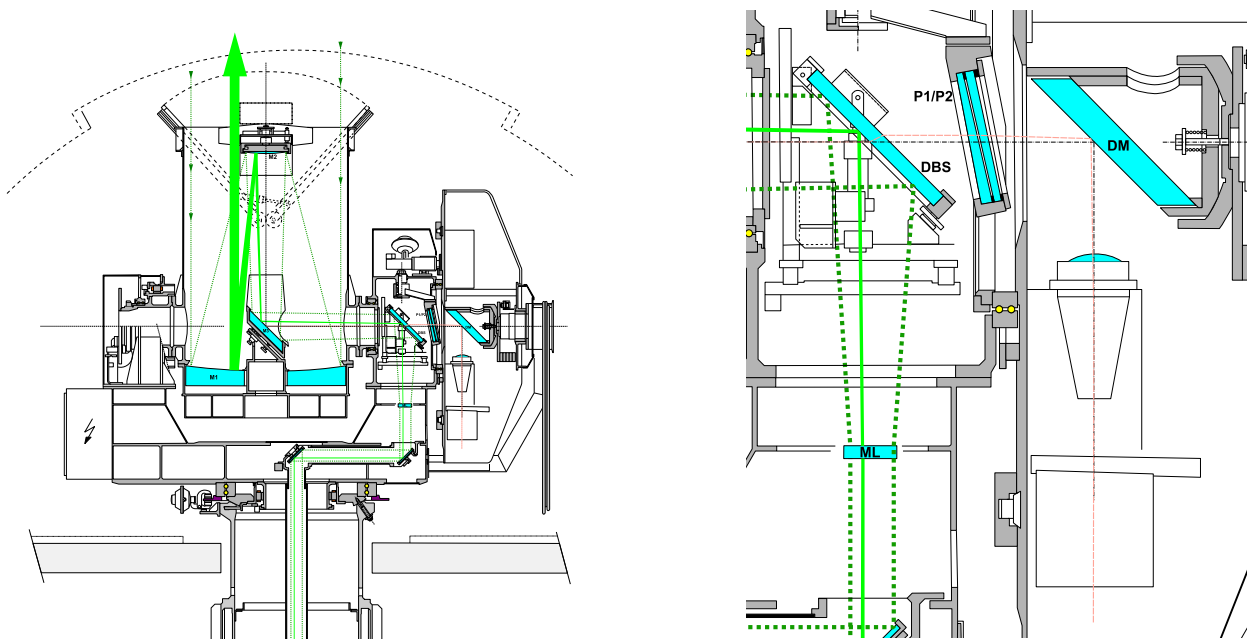

Figure 1. Drawing of the ZIMLAT telescope and the derotator platform.

Image Sensors

The operation of a CCD or a CMOS image sensor is quite simple in principle (Figure 2). In both technologies pixels are covering a two-dimensional array. During the acquisition process incident photons are generating photoelectrons which are stored in these pixels. In case of a CCD sensor during the readout process these electrons must be transported to an output amplifier where the amount of electrons is measured. In case of a CMOS there are output amplifiers for each pixel. Hence the readout time is much faster for CMOS than for CCD. In addition much shorter exposure times are possible using a CMOS sensor as no a mechanical shutter is required. But there are also significant disadvantages of CMOS sensors. On-chip binning and on-chip stacking is not possible. Both methods can be used to increase the sensitivity of the CCD sensor by improving the signal-to-noise ratio (SNR). Binning is the process of combining charge from adjacent pixels in a CCD during readout. This process is performed prior to digitization in the on-chip circuitry of the CCD by specialized control of the serial and parallel registers. Stacking of multiple images can also be used to reduce the SNR. In case of a CCD (full-frame or interline) this can be done on chip. Using a so called scientific CMOS sensor (developed by Andor, Fairchild and PCO) multiple images can only be added by software after the readout process. The great advantage of on chip stacking is the better performance with respect to the SNR.
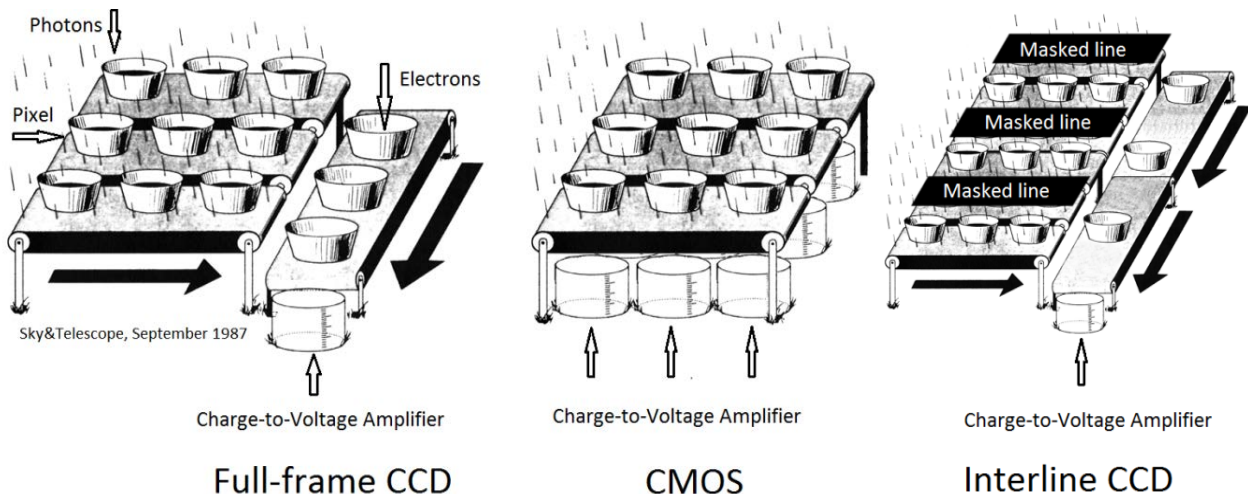

Figure 2. Different image sensors.

The difference between a full-frame CCD and an interline CCD is that in the latter case every second column of the sensor is masked for storage of the photoelectrons (Figure 2). During readout all photoelectrons are first shifted into the adjacent masked pixels. In a second step these photoelectrons are transported to an output amplifier in the same way as during the readout of a full-frame CCD. The interline technology allows very fast exposure times down to a few microseconds due to the fact that there is no mechanical shutter necessary. On the other hand the fill factor of the image is reduced by a factor of 2 due to the fact that every second line is masked. Therefore also the quantum efficiency would decrease by an equivalent amount. Hence many manufactures of interline CCD sensors are placing a microlens array on the surface of the sensor. These microlenses are directing the light away from the opaque region. This technology leads to a significant increase of the quantum efficiency up to 75%. But be aware that there are only minor differences in the readout time between both technologies because the photoelectrons have to be transported to an output amplifier in identical manner. The readout of an interline CCD sensor can be done during the acquisition of the next image.

Read Noise

One of the main parameters characterizing an image sensor is the read noise. Using a CCD sensor the charge of all pixels will pass the same output amplifier and analog digital converters (ADCs). The situation is completely different for a CMOS sensor where each pixel has its own charge-to-voltage amplifier. The read noise must be measured for every individual pixel by taking a large number of bias frames. A CMOS sensor has no well-defined read noise value but it is characterized by a read noise distribution. The read noise of our sCMOS tracking camera has been determined by taking 1000 bias frames of 512x512 pixels. Figure 3 (left side) shows the signal level distribution of two individual pixels. The read noise, i.e. the standard deviation of the signal level distribution, varies considerably from pixel to pixel. The bias signal of low noise pixels is normally distributed whereas the high noise pixels often exhibit a double peaked distribution. The distribution of the read noise over all 512x512 pixels is shown in Figure 3 (right side). The curve clearly shows that the read noise is distributed over a wide range in contrast to a CCD with a well-defined noise value. Due to the extended tail towards high noise values a bias frame is interspersed with bright pixels. CMOS sensors cannot be characterized by a single read noise value like a CCD. Andor, the manufacture of Zimmerwald's tracking camera, uses the median value in their specification of the read noise value. More details on the characteristics of the sCMOS used in Zimmerwald camera can be found in [3]. General information on the Andor sCMOS capabilities is given in [1] and [2].
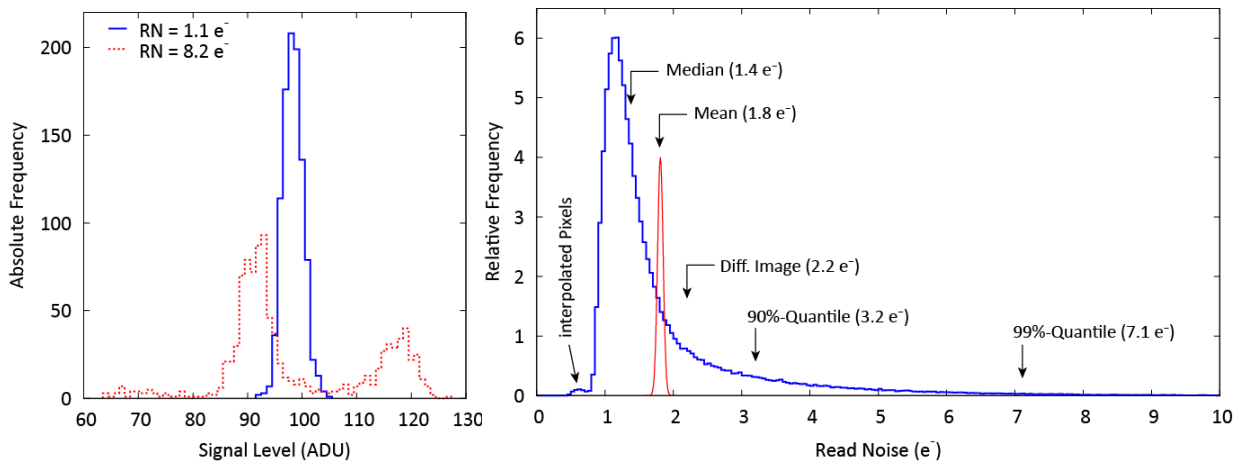

Figure 3. Distribution of the signal levels of two individual pixels (left) and for 512x512 pixel area (right)**.**

Integration

The laser system used at Zimmerwald for the SLR measurements is a diode pumped solid state Nd:YAG laser manufactured by Thales Laser, France, with a primary wavelength of 1064 nm. The pulses with an energy of about 21mJ (before frequency doubling) and a pulse width of 58 ps are generated by a 100 MHz oscillator, a regenerative amplifier and a double-pass amplifier. A KDP (Potassium Dihydrogen Phosphate) crystal in the second harmonic generator (SHG) produces a 9 mJ pulse at 532 nm. The pulse rate can vary between 90 – 110 Hz and is controlled by a Field Programmable Gate Array (FPGA) card designed and programmed by the Technical University of Graz. The maximum frame rate of 100 fps of the sCMOS camera allows the exposure of the sensor between the transmitted laser pulses. It is not possible to expose the CMOS sensor during the full

time span of about 10 ms between two consecutive pulsesdue to fluorescence effects in the dichroic mirror after transmitting a laser pulse (Figure 4).
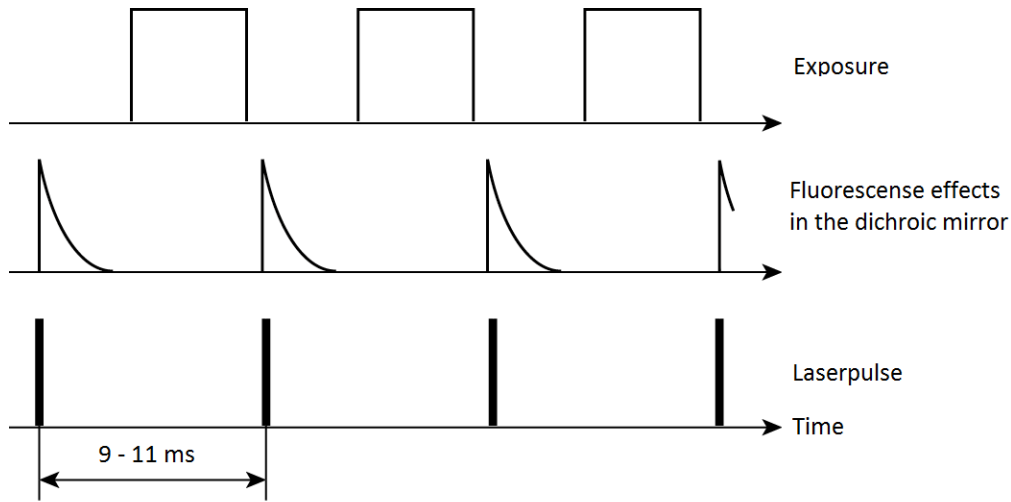

Figure 4. Timing diagram of the image acquisition.

The FPGA card transmits a pre-pulse with variable delay and pulse width. This pulse can be used for triggering the exposure of the camera and for controlling the exposure time (Figure 5). The camera is well suited for bright objects like Low Earth Orbiters. For fainter objects, the exposure time must be increased by co-adding several short exposures. There is one remarkable disadvantage compared to the formerly used interline CCD camera manufactured by PCO where the photons of all subexposures were accumulated on chip and read out only once. This is not possible with the sCMOS camera. The sub-exposures must be read out individually and co-added by software which degrades the SNR.
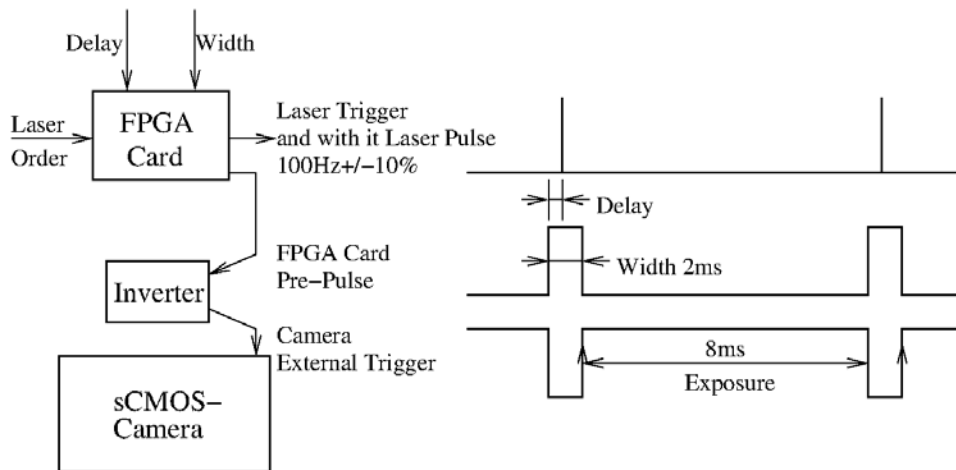

Figure 5. Generation of the trigger signal for the image acquisition.

Camera Specifications

Comparing the specifications of the cameras currently used at the Zimmerwald observatory (Table 1), you will notice beside the differences in the readout frequency and readout noise (as described above) remarkable differences especially in the sensor and pixel size. The higher full well capacity and therefore higher dynamic range of the SI1100 camera is a result of the larger pixel size in

comparison with the NEO resp. Sensicam camera. Another advantage of the SI1100 camera is the very high quantum efficiency. The SI1100 camera uses a back-illuminated sensor while the other two cameras are using front-illuminated sensors.

Table 1. Camera specifications

	Full-frame CCD	sCMOS	Interline CCD
Factory	Spectral Instruments	Andor	PCO
Model	SI1100	NEO	Sensicam SVGA
Array Size (mm)	31 x 31	17 x 14	9 x 7
Number of Pixels	2048 x 2064	2560 x 2160	1280 x 1024
Pixel Size (µm)	15	5.5	6.7
Quantum Efficiency (peak)	95 %	60 %	40 %
Full Well Capacity	150 000 e$^-$	30 000 e$^-$	25 000 e$^-$
Scan Rate	4 x 1 MHz	2 x 280 MHz	1 x 12.5 MHz
Readout Frequency	1 fps	100 fps	8 fps
Readout Noise	8 e$^-$	2 e$^-$	8 e$^-$
Cooling	Peltier / Water	Peltier / Air, Water	Peltier / Air
Main Field of Application	Astrometric Observations	Trackingcamera Lightcurves	Trackingcamera

Status of Work

The mechanical and electrical integration of the tracking camera into our laser system has been completed. First tests during some satellite passes have been carried out successfully, but some problems were identified that prevent to use the camera on a routine basis:
- The GUI is not user friendly
  - the default settings cannot be stored (more than 40 modes of operation available);
  - there is no continuous acquisition mode available;
  - adjustment options for contrast and brightness of the displayed images are not flexible enough;
  - there are no cross hairs available for marking the point of highest echo rate on the image;
  - the rotation of the image w.r.t. zenith resp. moving direction of the satellite is unknown. The unknown rotation complicates manual corrections of the pointing direction of the telescope for the operator.
- There is no autofocus function available. The best focus value varies not only in dependence of the ambient temperature, but also with the elevation of the telescope. Therefore the focus has to be adjusted by the operator during each satellite pass.

References

[1] Schildknecht, T., A. Hinze, P. Schlatter, J. Silha, J. Peltonen, T. Säntti, T. Flohrer, *Improved Space Object Observation Techniques using CMOS Detectors,* 6th European Conference on Space Debris, 22 – 27 April, ESOC, Darmstadt, Germany, 2013.

[2] *Neo and Zyla sCMOS Cameras. Imaging Without Compromise.*
http://www.andor.com/pdfs/literature/Andor_sCMOS_Brochure.pdf
[3] *Scientific CMOS Technology. A High-Performance Imaging Breakthrough.*
http://www.scmos.com/files/high/scmos_white_paper_8mb.pdf