Camera Model for the COSMO K-Coronagraph

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Summary: In this note we calculate the tolerances on the camera system for the COSMO K-coronagraph.

Telescope and Camera Model
The telescope is modeled as having ideal polarization properties unless stated otherwise. Perfectly efficient modulation and dual-beam analysis is assumed, except where noted otherwise. For photon flux purposes the telescope is assumed to have an effective aperture of 17 cm, a bandwidth of 30 nm at 735 nm, and 5” pixels.
We first consider several camera properties from a theoretical perspective. Next, we set up a realistic model of a camera using properties and measurements of the PhotonFocus MV-D1024E-160-CL-12 CMOS camera (henceforth referenced as MV-D1024E), currently baselined for the COSMO K-coronagraph. It has a QE of 30% at the wavelength of interest, 180 ke\textsuperscript{-}full well depth, 220 e\textsuperscript{-}readout noise, and 135 Hz readout rate.

Modeling Procedure
Where appropriate, we employ the following procedure to validate the MV-D1024E. A known Stokes vector is sent into the telescope model. It is modulated, analyzed, and converted into an electron count in the camera. The electron count is then sampled using an ADC model. 506 readouts (approximately corresponding to a 15-s observation) are accumulated in each modulation state, then summed, demodulated and calibrated. The experiment is repeated 500 times to gather statistical information on the noise of the measurement. The resulting measured Stokes vector is compared with the input Stokes vector.

The parameter space is scanned in intensity from 2 to 18×10\textsuperscript{-6} L\textsubscript{sun} with a 7-ms exposure (though the results can be scaled to different intensity/exposure ranges), and in degree of Stokes Q polarization from 0 to 10%. These conditions cover excellent to poor sky conditions. We assume that no U or V polarization enters the telescope, unless noted otherwise.

Digitization
Analog-to-Digital converters (ADCs) in the camera convert electrons captured in the wells into a digital readout. The process of digitization introduces a systematic error. A measurement at a specific intensity nearly always returns the same discrete data number
if the combination of shot and read noise is much smaller than the LSB. The actual average readout then differs from the expected average readout. Figure 1 shows the systematic error induced by discretization assuming a Gaussian noise profile with standard deviation $\sigma$.

For the MV-D1024E, the wells are nominally expected to be filled to approximately 25% of their capacity, i.e., approximately 45 ke\textsuperscript{-}e\textsuperscript{−}. In order to reach $10^{-4}$ accuracy, we must be able to determine an average to better than $1.0\times10^{-1}$ DN. From Figure 1, we see that the standard deviation of the noise must be at least 0.25 DN or 11 e\textsuperscript{−}. This is easily satisfied by the combination of 220 e\textsuperscript{−} read noise and 212 e\textsuperscript{−} shot noise.

Cameras with 8-bit output can suffer from problems related to digitization. To reach $10^{-4}$ accuracy, the average must now be determined to $6.4\times10^{-3}$ DN, so the standard deviation of the noise must now be about 0.5 DN. Assuming the same numbers as the MV-D1024E, this corresponds to 350 e\textsuperscript{−}. The condition is not satisfied until the shot noise reaches 272 e\textsuperscript{−}, corresponding to 74 ke\textsuperscript{-} in the well, or 41% filled. While the problem is less severe for cameras with shallower wells than the MV-D1024E (e.g., for a well depth of 60 ke\textsuperscript{-}, the noise must have a standard deviation of at least 117 e\textsuperscript{−}), it still disqualifies most 8-bit cameras from our search.

**Bit Errors**

In a perfect ADC, the value of each bit is exactly half that of the next more significant bit. However, in practice the bits exhibit small variations in size that we will call “bit errors”. Bit errors manifest themselves as systematic offsets in the demodulated measurements. The ADCs in an MV-D1024E were characterized by the procedure described in K-Coronagraph Technical Note #17 under “Light Transfer Curve Measurement”. 16 images were collected at dark and 30 levels of illumination. Two normalized histograms were derived for each ADC by splitting the image in half. The first histogram is used to model the ADC behavior. Figure 2 shows the systematic and random errors resulting from the bit errors in one of the ADCs of the MV-D1024E.
PhotonFocus modified a camera with a drop-in replacement 14-bit ADC. This camera will be referred to as MV-D1024E-14. The ADC in this camera was characterized in the same way as the 12-bit camera. Figure 3 shows the systematic and random errors resulting from bit errors in one of the ADCs in this camera. While the systematic errors are reduced by about a factor of two, they remain at about $10^{-3}$ of Stokes $I$.

The simulated observations can be corrected using either of the two histograms, optionally with noise added. Figure 4 shows the systematic and random errors from the same ADC in the MV-D1024E-14 if a lookup table is used to correct the individual readouts. In this case, the lookup table is constructed from the same histogram used to encode the bit errors, but with 0.5% normally distributed random noise added, and returns a number that can be represented by a 22-bit integer. This allows sufficient space to accumulate
1024 exposures in a 32-bit integer without the risk of overflow. The errors are at the $10^{-4}$ level. Notice that systematic errors in $I$ are similar in size to the random errors. Since the errors are determined on the basis of 500 model evaluations, the statistical noise on the determination of the systematic error is $1/\sqrt{500}=0.044$ of the random error. The noise in the lookup table dominates the systematic errors.

From these experiments, we conclude that the relative occurrences of bits in the ADCs of the MV-D1024E-14 camera must be characterized to better than $5 \times 10^{-3}$ in order to have systematic errors at the $10^{-4}$ level.

**Calibration**

Finally, the model was extended to include dark current and sensor nonlinearity. The dark current is given as an electron per second rate. For the nonlinearity we use the 3rd order polynomial fit given in the EMVA 1288 Standard test of the PhotonFocus MV-D1024E-160-CL-12 camera by AEON Verlag & Studio. It is corrected by applying an 4th order polynomial inverse in the lookup table. Furthermore, the modulation matrix is based on a realistic design (and thus non-ideal), and the telescope matrix is taken from the ZEMAX model. The analyzer is assumed to be a 99.9% polarizer in one beam, 99% in the other, but otherwise perfect.

First, 50000 sets of calibration observations are synthesized. In this process the calibration polarizer is modeled as a 99.9% polarizer and a diffuser intensity of $10^{-3} \, \text{L}_{\odot}$ is used. These sets are then individually and independently processed to generate 50000 sets of calibration data consisting of the dark current, gain, and modulation matrix in each beam. The calibration data are then used in a model run to calibrate the observations. Each model experiment uses a randomly chosen set of calibration data. Figure 5 shows the results of this model run. The random noise is slightly increased compared to the perfect calibration (as can be expected). The systematic errors in $Q$ are at the $10^{-3}$ level or below. The systematic errors in $I$ are large, at the $10^{-2}$ level. Since $I$ is not a difference measurement, it is much more sensitive to errors in the determination of the dark current, gain,
nonlinearity, etc. An absolute error of 1% is not unreasonable of in real-world measurements. Still, in this model the error seems larger than I would expect. I could not find a programming mistake. Because the calibration reduction procedure requires the modulation matrix to adhere to physical constraints, the random distribution is truncated on one side. It is possible that this is the cause of the large error in I.

Figure 5. As Figure 4, but including sensor nonlinearity, dark current, a realistic modulation matrix, a telescope matrix derived from the ZEMAX model, and synthesized calibration.