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Non-linear responsivity characterisation of a CMOS Active Pixel Sensor for high resolution imaging of the Jovian system

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ABSTRACT: The Jovian system is the subject of study for the Jupiter Icy Moon Explorer (JUICE), an ESA mission which is planned to launch in 2022. The scientific payload is designed for both characterisation of the magnetosphere and radiation environment local to the spacecraft, as well as remote characterisation of Jupiter and its satellites. A key instrument on JUICE is the high resolution and wide angle camera, JANUS, whose main science goals include detailed characterisation and study phases of three of the Galilean satellites, Ganymede, Callisto and Europa, as well as studies of other moons, the ring system, and irregular satellites.

The CIS115 is a CMOS Active Pixel Sensor from e2v technologies selected for the JANUS camera. It is fabricated using 0.18 μm CMOS imaging sensor process, with an imaging area of 2000 x 1504 pixels, each 7 μm square. A 4T pixel architecture allows for efficient correlated double sampling, improving the readout noise to better than 8 electrons rms, whilst the sensor is operated in a rolling shutter mode, sampling at up to 10 Mpixel/s at each of the four parallel outputs.

A primary parameter to characterise for an imaging device is the relationship that converts the sensor's voltage output back to the corresponding number of electrons that were detected in a pixel, known as the Charge to Voltage Factor (CVF). In modern CMOS sensors with small feature sizes, the CVF is known to be non-linear with signal level, therefore a signal-dependent measurement of the CIS115's CVF has been undertaken and is presented here. The CVF is well modelled as a quadratic function leading to a measurement of the maximum charge handling capacity of the CIS115 to be 3.4×10^4 electrons. If the CIS115's response is assumed linear, its CVF is 21.1 electrons per mV (1 / 47.5 μV per electron).

KEYWORDS: CIS115; JANUS; CMOS APS; non-linear calibration, CVF, mean-variance method, responsivity.

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1. JUpiter ICy moon Explorer (JUICE)

JUICE is a European Space Agency spacecraft planned for launch in 2022 and following an 8 year cruise phase should arrive in the Jovian system in 2030 [1, 2]. Its goal is to remotely characterise the planetary surfaces of Ganymede, Europa and Callisto, and the upper atmospheric layers of Jupiter in addition to exploring the radiation and magnetic environment local to the spacecraft.

1.1 JANUS: an optical camera for observing the Jovian system

JUICE includes a camera, named JANUS, designed to observe the Jovian environment across the visible wavelength range from 350 nm to 1100 nm. A 14-space filter wheel will allow for multi-colour observations to provide spectral information to aid surface material and feature identification. The optical design and detector arrangement are optimised to provide an angular resolution of $15 \mu\text{rad pixel}^{-1}$, which combined with an orbital distance from the surface of Ganymede of 200 km will allow effective surface imaging of Ganymede at resolutions better than 10 m pixel^{-1} [3].

The image sensor selected for JANUS is the CIS115, a CMOS image sensor with a photosensitive area of 2000 rows by 1504 columns, where each pixel is $7 \mu\text{m}$ square [4]. The $14 \times 10 \text{ mm}^2$ sensitive area provides a field of view of $1.72 \times 1.29 \text{ degrees}^2$ when integrated into the JANUS optics. The CIS115 image area is divided into 4, where each group of 376 columns has its own output driver with separate analogue reset and signal levels taken off-chip for reset level subtraction and consequent conversion into the digital domain.

The CIS115 operates in a row-by-row rolling shutter mode, where an entire row of pixels is selected, reset and signal levels recorded, and reset in turn. After the storage of a row's reset and signal levels in a 'CDS buffer' structure, each pixel's stored levels are read out from the CDS buffer. Following the read out of an entire row, the next row is then selected and the process is repeated. Therefore in the standard 'Full frame' mode, the integration time for all pixels in a row starts after it is reset, and ends when all other rows in the device have been read out and the readout process has looped through the entire image area. A pause occurs once the entire image area has been read out, allowing the integration time to be varied.

However, the 'Full frame' mode is limited in terms of the minimum integration time possible, since the entire image area takes 171 ms to be read out (using a pixel sampling rate of 5 MHz and with standard row sampling speeds). To obtain integration times shorter than 171 ms, an alternative 'Rolling mode' has been devised where rows are reset at a given time before they will be read out. For example, if the signals from row N are read out from the CDS buffer, row N+m can then be reset before row N+1 is sampled into the CDS buffer. The effective integration time of row N+m is now limited by the row readout time (2.1 ms in this mode) rather than the readout time of the entire image area. Note that the row readout time in Rolling mode is significantly limited by the additional timing overheads of the Rolling mode so is not equivalent to the image readout time (171 ms) divided by the number of rows (2000), but introducing this mode allows integration times that are a factor of 80x shorter.

A previous publication [4] describes the CIS115 architecture in more detail, and presents some initial characterisation results performed at the Open University including a calibration measurement achieved using an iron-55 radiation source. The calibration allows conversion of the sensor output from a voltage into electrons detected at the pixel, but the responsivity must be assumed to be linear with signal level in order to extrapolate the measurement across the full dynamic range of the detector. The characteristic X-rays from an iron-55 source are at 5898 eV (approximately equivalent to 1616 electrons in silicon), whilst the full well of the sensor is expected to be $>3 \times 10^4$ electrons (measured as 3.4×10^4 electrons in Section 3.4), therefore a calibration across the entire range of the sensor is required.

1.2 Detector characterisation

A standard method for determining an image sensor's responsivity is to construct a mean-variance curve by plotting the mean sensor output against the variance of the sensor output for a range of illumination levels. The technique exploits the fact that at signal levels where the variance in the signal level is dominated by the shot noise from the arrival of the optical photons, the variance and signal levels should be equal when measured in electrons.

However, the disadvantage with the mean-variance technique is that it assumes the responsivity does not vary with signal level, an assumption which is known to be invalid for low-voltage image sensors [5, 6]. The accumulation of electrons on a pixel's charge storage node will change the node's capacitance therefore when a large number of electrons are already present, additional electrons will make a smaller difference in the potential of the node than if the same number of additional electrons were added when no electrons were already present. The signal-dependent change in capacitance results in a non-linear response of the transistor amplifying the signal within pixel resulting in a non-linear output from the sensor. In the following work, the responsivity will be determined across the CIS115's full dynamic range accounting for its non-linearity.

2. CIS115 experimental setup

An experimental setup has been developed to operate the CIS115 whilst it is being illuminated by a flat field from a red Light Emitting Diode (LED) with a wavelength of 660 ± 20 nm. The LED is kept permanently on to prevent any short-term heating effects and is supplied by a constant current source. Results presented in later sections were obtained using a front-illuminated CIS115 14901-24-24E (Figure 1) which was held at room temperature and pressure whilst being read out at a pixel rate of $5 \text{ MPixel output}^{-1} \text{ s}^{-1}$. A 16-bit ADC system was used in a mode optimised for sensitivity across full dynamic range.

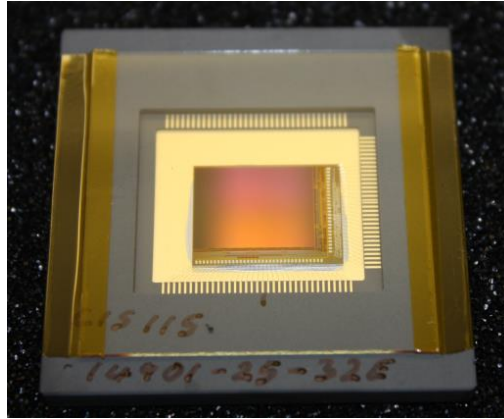


Figure 1. A front-illuminated CIS115 is shown here glued into its blue/gray ceramic packaging, covered by a removable quartz window. The die is 2-side butt-able, with wire-bonding providing electrical connection to the package on two sides. The JANUS flight sensor will be back-illuminated and thinned for optimum sensitivity.

3. CIS115 gain and linearity characterisation

For data capture, the mean and variance was calculated for images captured with a given integration time on a pixel by pixel basis. The pixel values were then averaged across a region of interest in one of the four image areas of the sensor to provide a mean sensor output voltage and variance in the sensor output voltage for that integration time.

3.1 Initial CIS115 linearity observations

The average sensor output level observed as a function of integration time when illuminated by the LED is shown in Figure 2a. The Rolling mode and Full mode data points are in good agreement across a wide range of integration times, and from the reciprocals of the fit in Figure 2b the sensor appears relatively linear, at least up to 0.2 s which is roughly equivalent to 60% of the dynamic range.

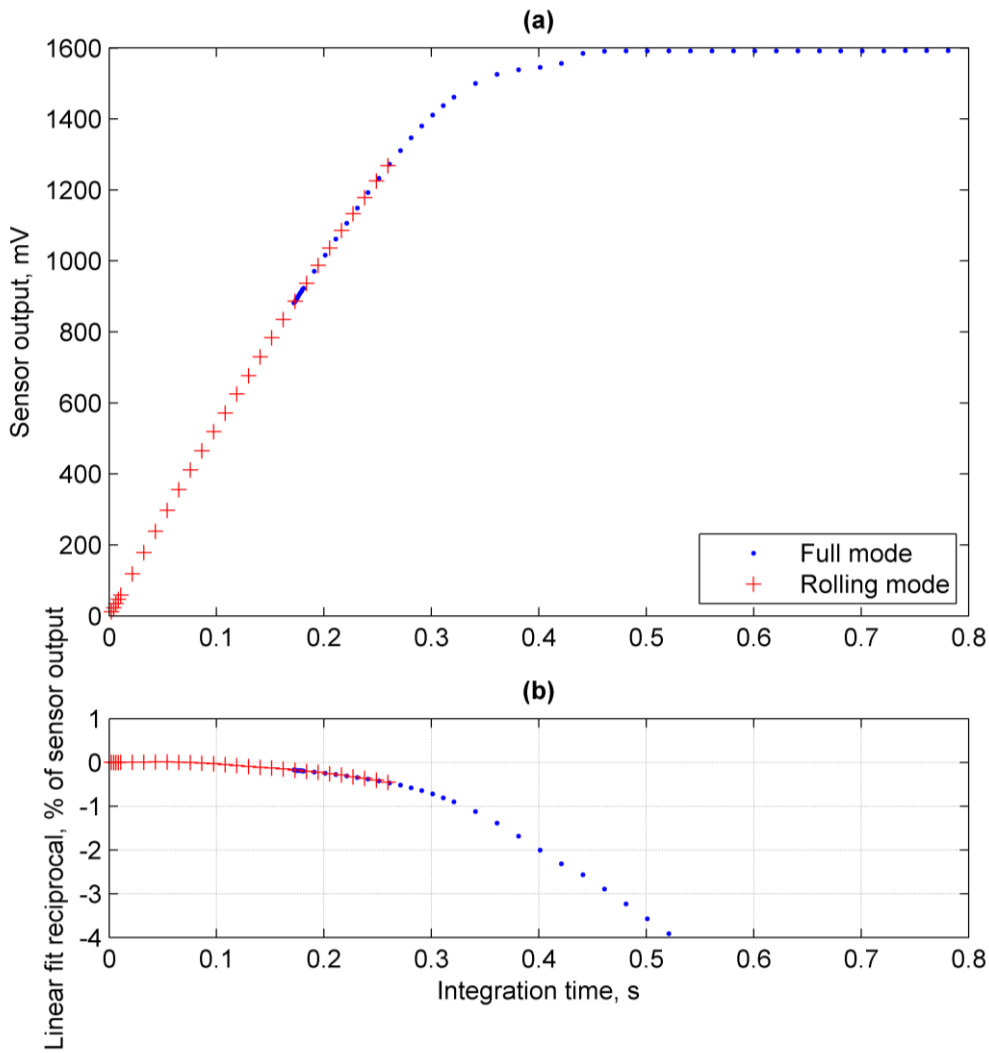


Figure 2. (a) The average sensor output from a region of interest when the sensor is exposed to a flat illumination appears approximately linear when the sensor output is up to 1400 mV. The offset for zero signal level (sensor output with no signal) has been subtracted by extrapolating a linear fit of the 5 data points with shortest integration time. (b) The reciprocals from extrapolating the linear fit are shown up to an integration time of 0.8 s. The magnitude of the reciprocals remains small across at least half of the dynamic range (up to 0.2 s) demonstrating that the sensor is relatively linear at lower signal levels.

If the sensor's responsivity is linear, the mean-variance distribution is expected to show a linear relationship until the variance is close to maximum, however the results show clear curvature between the zero level and a sensor output of 1000 mV (Figure 3). If the response is assumed linear, mean-variance analysis by fitting to the low signal data points in Figure 3 results in a calibration factor of $57.0 \mu\text{V electron}^{-1}$.

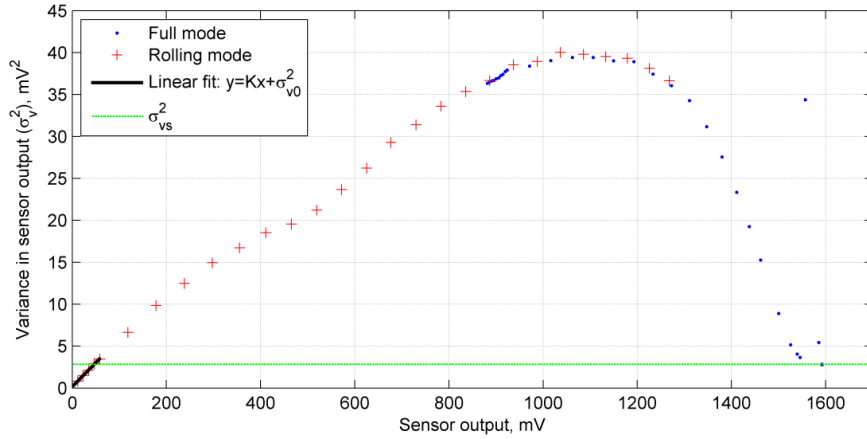


Figure 3. A typical mean-variance plot is used for determining factors such as the conversion gain for linear photosensitive detectors. The CIS115 shows a non-linear response during part of the curve with a positive gradient, demonstrating non-linear responsivity that is typical of CMOS APS. The variance values (σ_v^2) from this data plot are used in the calculations that follow: σ_{v0}^2 , the variance at zero signal, is obtained from extrapolating a linear fit down to zero; and σ_{vs}^2 , the variance at saturation is taken to be the average of the points at the saturation level (shown by green horizontal line).

3.2 Accounting for non-linearity

It has been demonstrated by Pain and Hancock [5] that a non-linear estimation method can be used to determine the signal-dependent CVF. A relationship for converting from a sensor output voltage to the number of electrons that were captured in a pixel can then be determined. Following Equation 19 from [5], the relationship shown in Eq. 1 can be derived, where the terms are described below.

$$\sigma_v^2 - \sigma_{vs}^2 - (\sigma_{v0}^2 - \sigma_{vs}^2) \left(\frac{V'(P)}{V'(0)} \right)^2 = \frac{P(V'(P))^2}{\eta} \quad \text{Eq. 1}$$

σ_v^2	Variance of the sensor output voltage as a function of illumination level
σ_{vs}^2	Variance of the sensor output voltage at saturation level
σ_{v0}^2	Variance of the sensor output voltage at zero signal
P	Illumination level
$V(P)$	Sensor output voltage as a function of illumination level
$V'(P)$	Gradient of the sensor output voltage with respect to illumination level
$V'(0)$	Gradient of the sensor output voltage with respect to illumination level at zero signal
η	Number of electrons detected per illumination level unit

Measuring the illumination level in photons pixel⁻¹, as originally described in [5], means that η represents the Quantum Efficiency (QE) of the device, i.e. the proportion of electrons detected relative to the number of incident photons. However, obtaining a measurement of the conversion factor can be obtained through recording the illumination level in units of time,

when using a constant illumination level. This removes the requirement of accurately measuring illumination level in an experimental setup.

In the work presented here, the illumination level P is the duration of the integration experienced by the pixel, measured in units of seconds. The units of η will therefore be electrons $\text{pixel}^{-1} \text{s}^{-1}$. $V'(P)$ is calculated by differentiating the sensor output voltage with respect to integration time as shown in Figure 4. The change in sensor output per unit of integration time varies with the integration time despite the illumination being constant, demonstrating the signal-dependent conversion gain.

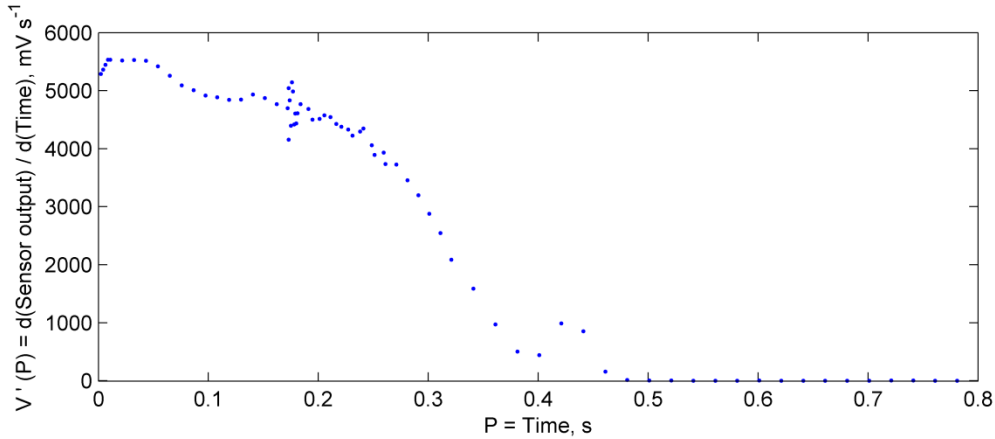


Figure 4. The change in sensor output per unit time for a constantly illuminated detector with a perfectly linear response is expected to be a constant until the detector reaches saturation, where it becomes zero. The response of the CIS115, shown here, varies with signal level until the integration time approaches saturation at 0.2 s, and reaches saturation by 0.5 s. The data points taken using ‘Full mode’ at short integration times (around 0.18 s) are more widely distributed due to the larger error in the small time steps.

3.3 Calibrating the illumination level

σ_v^2 and $V'(P)$ have been presented in Figure 3 and Figure 4 respectively. The variance at zero signal level $\sigma_{v_0}^2$ and at saturation $\sigma_{v_s}^2$ can be determined using the data present in Figure 3 and $V'(0)$ is extrapolated from Figure 4. It follows without rearranging Eq. 1 that η is equal to the gradient of $P(V'(P))^2$ plotted against $\sigma_v^2 - \sigma_{v_s}^2 - (\sigma_{v_0}^2 - \sigma_{v_s}^2) \left(\frac{V'(P)}{V'(0)} \right)^2$, as demonstrated in Figure 5. From the linear fit a value of $\eta = 1.07 \times 10^5$ electrons $\text{pixel}^{-1} \text{s}^{-1}$ is calculated, which corresponds with the expected illumination level, considering full well is inferred by design to be approximately 4×10^5 electrons, and the sensor is observed to saturate within approximately 0.4 s (Figure 2) with the illumination levels used here. Calibration of the illumination levels on the detector in photons pixel^{-1} would allow the QE to be calculated in further analysis.

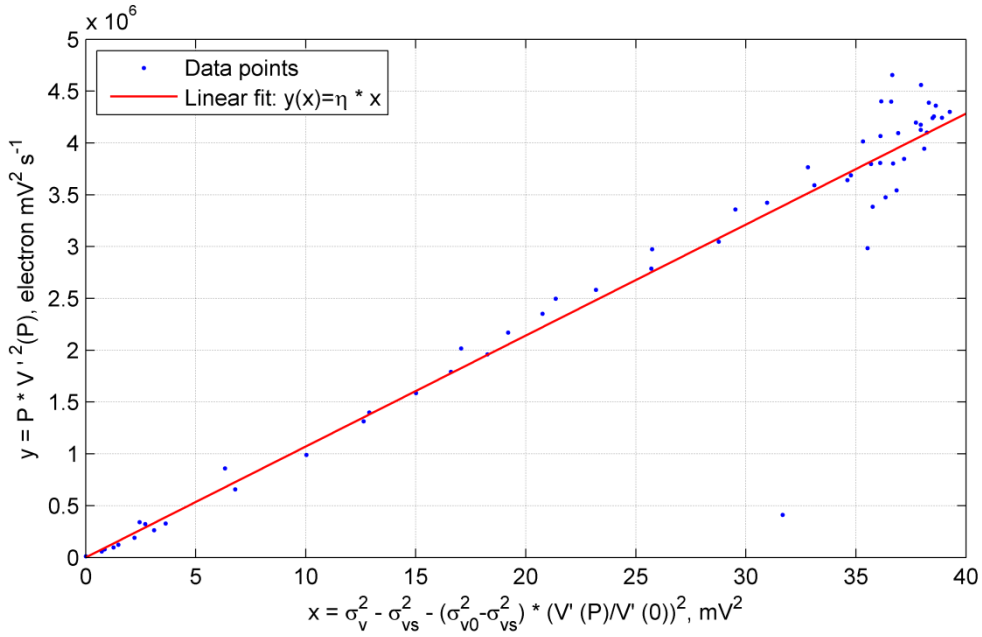


Figure 5. η is calculated from a linear fit with no offset to the data points, as shown in this figure. A value of $\eta=1.07 \times 10^5$ electrons $\text{pixel}^{-1} \text{s}^{-1}$ has been determined.

It follows that the η value can be used to convert the exposure level from integration time into electrons pixel^{-1} , as shown in Figure 6a. It is then straightforward to calculate the CVF as a function of sensor output voltage by taking the gradient of the sensor output voltage against the signal in electrons, as shown in Figure 6b. Several features are observed in the signal-dependent CVF. An initial increase in CVF is observed at low sensor output voltages (low signal levels) which may be due to image lag, where the few electrons are not all being transferred out of the photodiode. Further work characterising the lag performance of the sensor will help to determine if this is the cause, however this non-linear calibration may account for image lag by incorporating its effect on the mean sensor output levels for small signals.

The CVF reduces as the sensor output voltage increases, changing by 30% from approximately $51.5 \mu\text{V electron}^{-1}$ down to $40 \mu\text{V electron}^{-1}$ at a signal level of 1100 mV. At increasingly higher output voltages, the CVF reduces to $0 \mu\text{V electron}^{-1}$ because more electrons are required to generate the same increase in output voltage until the sensor reaches saturation.

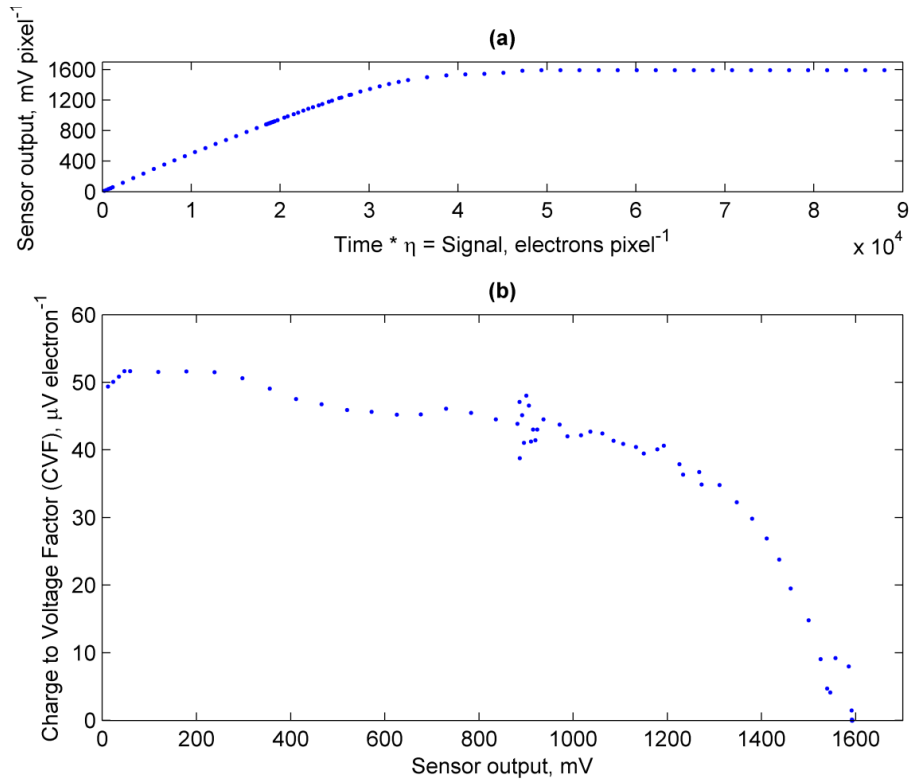


Figure 6. (a) Using the η value determined from Figure 5, illumination level measured in units of time can be converted into the signal level in electrons pixel⁻¹. **(b)** The gradient of (a) provides the conversion gain as a function of the sensor output level, i.e. the increase in sensor output voltage that would be observed if a small number of additional electrons were detected in the pixel. For the practical purpose of converting an array of pixel values from voltages to numbers of electrons, the camera operator requires the integral of the conversion gain from zero signal to the recorded sensor output, equivalent to the inverse of (a), and shown in Figure 7a.

3.4 Non-linear calibrations

A calibration factor, function or curve is required by a user of the sensor in order to convert the sensor output measured as a voltage into a signal level in electrons. The calibration curve is shown in Figure 7, but interpolation of the points for converting every pixel is an intensive process and it is more ideal if the curve can be modelled using a simple fit. Initially, the response curve is compared to a linear response. The linear fit results in a calibration factor (C_g) of 21.1 electrons mV⁻¹ and therefore a CVF value of 47.5 μV electron⁻¹. However, the reciprocals of the linear fit are large, being greater than 5% of the signal for between zero and 10⁴ electrons (Figure 8).

The quadratic fit shows improved accuracy for converting a sensor output in the voltage domain into a signal in electrons, where the fit parameters C_p and C_q are 18.9 electrons mV⁻¹ and 0.00228 (electrons mV⁻¹)² respectively corresponding to conversion gain parameters of 53.0 μV electron⁻¹ and 4.48 x 10⁵ (μV electron⁻¹)².

Full well is often defined as the signal level at which a sensor's response deviates by 5% from a linear fit. By definition this is not applicable for a non-linear response function, the full

well may be defined as the signal level where the calibration fit reciprocal is greater than 5% of the signal level, resulting in a maximum charge handling capacity of the device of 3.4×10^4 electrons pixel⁻¹ when using the quadratic calibration fit.

Instead of using a function as the calibration, it may be directly interpolated from the measured relationship (Figure 7). Interpolation would result in the most accurate conversion, but is more computationally intensive to implement. The computational load may be reduced through the generation of a look-up table with single digital number resolution. However, from the perspective of general sensor characterisation, interpolation does not allow easy comparison between different sensors or cameras.

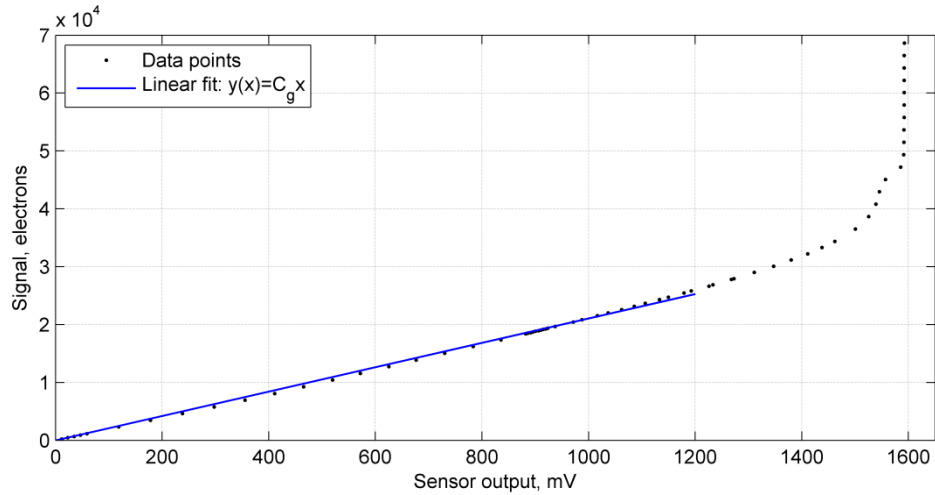


Figure 7. This calibration graph is the practical result required to determine the number of electrons detected for a given device voltage output (equivalent to the inverse of Figure 6a). For practical application, the response can be modelled linearly by fitting to the most linear portion of the data (blue solid line). Alternatively, a quadratic may be fitted (not shown). The reciprocals of these two fitting functions are compared in Figure 8.

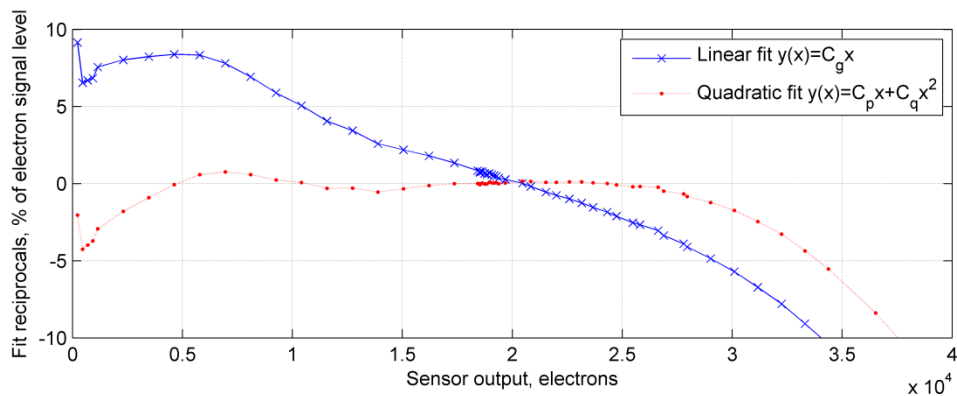


Figure 8. The reciprocals of the calibration fits from Figure 7 are shown here where the linear and quadratic fit reciprocals are shown by blue 'x' symbols and red dots respectively. A smaller fit reciprocal demonstrates that the calibration model is a more accurate fit to the data and therefore it is clear that the calibration is more closely modelled by the quadratic fit than a linear one. The fit

parameters C_g , C_p and C_q are 21.1 electrons mV^{-1} , 18.9 electrons mV^{-1} and 0.00228 (electrons mV^{-1})² respectively.

4. Conclusions

The CIS115 is the prime candidate for integration into JANUS, an optical camera being designed for the next ESA mission to Jupiter. The conversion gain of a front-illuminated CIS115 has been measured here using a non-linear estimation technique, without requiring a measurement of the photon flux onto the sensor. The CIS115 shows a non-linear conversion gain with respect to signal level, as expected for this sensor technology. The non-linear conversion has been well fitted using a quadratic function, allowing a full well of 3.4×10^4 electrons $pixel^{-1}$ to be measured.

The conversion gain measured using the methods described here can be compared to the conversion gain measured using an iron-55 source of $48.3 \mu V$ $electron^{-1}$ [4]. An iron-55 calibration uses manganese K_{α} X-rays (5898 eV) that on average generate approximately 1616 electrons in silicon; therefore the iron-55 technique provides a calibration at a single signal level. The iron-55 measurement is close to the CVF obtained using a linear fit to the conversion relationship of $47.5 \mu V$ $electron^{-1}$. Linear interpolation of the conversion relation results in an expected sensor output of 82.7 mV for a signal of 1616 electrons which corresponds to an effective CVF of $51.2 \mu V$ $electrons^{-1}$. The small difference between these measurements may be related to the different operational conditions and timings that were used.

Future adaptations to the experimental setup will include a calibrated photodiode in order to monitor and measure illumination level on the sensor's pixels. Once this measurement has been reliably obtained, determining the QE of the sensor is straightforward from η . Other parameters of the sensor's behaviour will also be characterised, including the lag performance, which may further understanding of the behaviour of the CVF, such as in the small signal domain.

Having a simple and accurate procedure for determining the CVF is important for both assessing the performance of the CIS115 during the design and radiation campaigns, as well as in the mission itself. A robust and appropriate procedure for determining the calibration in-flight and applying it to the images will continue to be developed in the future.

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