

Carbon Camera Sensor Characterization for the TANGO Scout Mission

Ryan R. Cooney*, Paul Tol, Mario Vretenar, Joris van der Vlugt, Jochen Landgraf, Karin Louzada
SRON Space Research Organisation Netherlands, Niels Bohrweg 4, 2333 CA Leiden, the Netherlands

*r.r.cooney@sron.nl

ABSTRACT

TANGO (Twin Anthropogenic Greenhouse Gas Observers) is a small satellite mission targeting total column measurements of greenhouse gases (CO_2 , CH_4) at a relatively high spatial resolution (300 m). The TANGO mission is to be launched in 2028, under the ESA Scout Programme.

The measurements of CO_2 and CH_4 in the 1.6 μm absorption band will use a short-wave infrared (SWIR) Carbon Camera based on a commercial off-the-shelf (COTS) InGaAs detector. Measured performance for several units of the commercial detector are provided here. This includes critical parameters such as dark current, noise, and quantum efficiency. Quantum efficiency is critically important to TANGO observations as the InGaAs cut-off wavelength typically occurs in the same spectral region as key methane absorption features. The performance reported here will be used to substantiate the selection of the TANGO flight model. It also offers an indication of performance tolerances that can be expected from these COTS devices for future applications.

Keywords: greenhouse gas, spectroscopy, SWIR detector, InGaAs, TANGO

1. INTRODUCTION

The TANGO mission is under development by a Dutch consortium comprising ISISpace (Innovative Solutions in Space), TNO (Netherlands Organisation for Applied Scientific Research), SRON (Space Research Organisation Netherlands), and KNMI (Royal Netherlands Meteorological Institute). The mission will be implemented in the ESA Scout programme, which is defined by significant programmatic constraints limiting both financial investment and development timelines.

The mission consists of two agile 16U satellites operating in low earth orbit (LEO) to provide measurements of NO_2 , CO_2 , and CH_4 , where NO_2 sensing is motivated in part to improve the CO_2 plume detection. Each satellite hosts a custom dispersive pushbroom spectrometer, targeting specific atmospheric species. One spectrometer operates in the visible spectral region and is focused on nitrogen compounds. The second, of interest to this contribution, intends to provide total column measurements of CO_2 and CH_4 using observations in the 1.6 μm absorption band from 1590 nm to 1675 nm.

The selected SWIR absorption band for the carbon observations implies a limited range of commercially available detector technologies, and lattice-matched InGaAs has been selected due to favourable mass, power, and volume relative to alternative technologies. The specific selected device is the Snake SW from Lynred. As noted elsewhere [1], the residual performance uncertainty related to the InGaAs quantum efficiency (QE) and the temperature dependence of the typically stated cut-off wavelength of 1.67 μm [2][3] has been resolved, where warmer operating temperatures are generally preferred. However, the cut-off wavelength may still demonstrate device-to-device variability, presumably resulting from variations in the relative doping fraction. Manufacturer stated specifications for the cut-off wavelength are 1.67 $\mu\text{m} \pm 0.1 \mu\text{m}$, which would be detrimental for planned observations in the 1.6 μm absorption band. This possible variability suggests the importance of characterizing the performance of the commercial devices to substantiate selection of the flight model. A summary of the device level testing is provided below.

2. DEVICE LEVEL TESTING

This section summarizes the opto-electronic performance of seven Snake SW sensors procured from Lynred for the development of the TANGO Carbon Camera. The sensors will be listed in alphabetical order from SNKB up to and including SNKH, in order of serial number between 396681 and 407561. The principal purpose of the performance testing is to inform the selection of the flight model and flight spare, though the data can also be used to assess performance tolerances that can be expected from these COTS devices for future applications. The opto-electronic performance reported here will be limited to the dark current, read-noise, and the quantum efficiency as these parameters are the most impactful on the achievable signal-to-noise ratio (SNR), and hence precision of the TANGO observations.

Methodology

The Snake SW is an FPA consisting of a $15\text{ }\mu\text{m}$ pitch, 640×512 element detector array made of photovoltaic (PV) InGaAs on an InP substrate connected by indium bump technology to a silicon ROIC (Readout Integrated Circuit). The device contains a single stage TEC (Thermoelectric Cooler) and a metal package to hermetically seal the FPA (Focal Plane Array) and TEC under neutral gas. Some publicly available specifications appear in Table 1. Note, the Snake SW can be operated in both IWR (integrate-while-read) and ITR (integrate-then-read) modes with three different capacitor gains. The intended operations of the sensor for the TANGO mission are ITR mode with mid gain (gain 1). High gain (gain 0) has a three times smaller full-well capacity and low gain (gain 2) has a much larger read-out noise.

Table 1. Manufacturer specifications of the Snake SW device.

Parameter	Value
Format	640×512
Pixel pitch	$15\text{ }\mu\text{m}$
Maximum full-frame rate	300 Hz
Full-well capacity	120 ke^- (gain 1)
Read-out noise	30 e^- (gain 0)
Dark current	$187\text{ ke}^-/\text{s}$ (200 mV bias)
Spectral response	$0.9\text{ }\mu\text{m}$ to $1.7\text{ }\mu\text{m}$
Quantum efficiency	70% ($1.0\text{ }\mu\text{m}$ to $1.6\text{ }\mu\text{m}$)

Proximity electronics are required to operate the Snake SW, and the laboratory characterization of the sensors reported here make use of the Megalink PEL069D from Lynred. Note, the bias voltage is an important parameter and is set indirectly via a ‘detector common voltage’ VDETCOM, from which a voltage inside the sensor is subtracted. The default value of VDETCOM suggested by Lynred is 3.06 V, corresponding to a bias voltage of approximately 200 mV. This value is used for the characterization of all sensors. Additionally, it should be noted that the Megalink electronics do not include the functionality to control the Snake SW TEC. As such, the temperature of the InGaAs is simply allowed to increase during operation, typically reaching steady-state conditions of $22\text{ }^\circ\text{C}$ in the laboratory test environment.

Test Plan

Dark Current

In the absence of an external illumination source, the signal integrated over a certain period of time is determined by the offset and the dark current. The main source for dark current is within the photodiode (detector pixel) itself due to the applied reverse bias. This leads to a dark current that is strongly dependent on both the magnitude of the bias voltage (detector voltage minus internal reference voltage) and on the detector temperature.

A series of measurements were performed in dark conditions to characterize the dark current and dark current non-uniformity (DCNU). For each pixel, the dark signal is acquired for a range of exposure times. The selected exposure times sample a wide range of the available full-well capacity, while avoiding saturation, and maintaining reasonable measurement times. In a linear fit of the resulting dark signal fitted against exposure time, the slope yields the dark current in counts/s, which can be converted into electrons/s using the conversion gain (to be determined later in the test sequence associated with read-out noise). This allows the determination of the dark current for each pixel, which in turn will provide the DCNU of the sensor.

The dark current has an exponential dependence on the temperature of the FPA. As mentioned above, the Megalink electronics do not include the functionality to control the Snake SW TEC. This results in temperatures of approximately 22 °C while measuring the performance. To adjust the measured dark current to the intended operating temperatures of the TANGO application (15 °C), the known temperature dependence [1] is used to scale the measured results.

Read-out Noise

To determine the conversion gain and read-out noise, the measured sensor photoresponse is often described by a noise model such as:

$$N = \sqrt{(N_0^2 + S/c)} \quad (1)$$

with the offset-corrected signal, S , read-out noise, N_0 , conversion gain (in e^-/count), c , and the total noise, N . However, it has been previously shown that this offers an incomplete description of many sensors due to the occurrence of additional noise sources, most easily observed at long exposure times [1].

A preferred noise model is:

$$N = \sqrt{(N_0^2 + (S_{\text{rsp}} + I'_{\text{drk}}\tau_{\text{exp}})/c)} \quad (2)$$

where the total noise is expressed as a function of the background-corrected signal, S_{rsp} (i.e. not only offset but also dark signal removed). Here N_0 , c , and N maintain the foregoing definitions. τ_{exp} is the exposure time, and an extra fit parameter I'_{drk} has been introduced that represents the effective dark current necessary to explain the observed noise. The read-out noise and conversion gain extracted from this model will be retained, and the effective dark current will be contrasted with dark current derived from the intuitive accumulation of signal discussed above.

While the determination of the read-out noise and conversion gain is often performed separately, fitting one model for both to all data ensures that the model is consistent for the whole signal range at varying light intensities. Multiple illumination levels are used to sample the low-signal range dominated by read-out noise, the high-signal range dominated by shot noise, and the transition range. One included illumination level is the absence of light. Measurements to sample the noise model include many frames acquired at several exposure times without co-addition. The measured signals appearing in the above equation are corrected for the offset and dark signal, previously determined in the dark measurements. The total noise in a given signal is then determined by taking the standard deviation over the frames. A fit with the noise model yields the three fit parameters.

Experimental methodologies to sample the noise model are conceptually identical to those previously reported [1]. The selected illumination levels (and associated LED drive currents) will be listed for each sensor in the figure legends of the results section. At each illumination level approximately 20 exposure times are used, spanning low signals to saturation for each intensity. For each LED drive current indicated, the correspondence to an extracted signal rate is based on a linear fit with the exposure time. The regime of signal currents anticipated to be most applicable to the TANGO carbon instrument spans approximately 0 counts/ms to 400 counts/ms.

Quantum Efficiency

Here the QE is defined through the responsivity, R , the photoresponse current converted to counts per photon on a detector pixel. As the QE of InGaAs-based detectors is known to blue-shift as the temperature of the photo-active region is lowered [2][3], the QE depends not only on wavelength λ of the photons, but also the temperature T of the detector.

Measurements on the QE use a narrow-band tunable laser across the spectral region of interest. Identical to previously reported techniques [1], determination of the QE relies on the total integrated device signal relative to the scaled total

integrated power of the laser measured at a monitoring location. Prior to the measurement sequences, the laser power is measured as a function of wavelength with a photodiode at the sensor and at the monitoring position. The ratio of these powers provides a calibration factor, τ , which is used as a correction factor to scale the power measured at the monitoring position, P_{mon} , to the power incident on the Snake SW. Photoresponse current I_{rsp} is summed over all detector pixels x , and divided by the corresponding power, converted to a number of photons per second using the photon energy hc/λ :

$$R[\lambda, T] = \frac{hc \sum_x I_{\text{rsp}}[x, \lambda, T]}{\lambda P_{\text{mon}}[\lambda, T] \tau[\lambda]} \quad (3)$$

The resulting quantum efficiency, η , defined as the number of electrons accumulated per incident photon, is then the responsivity scaled by the conversion gain, c_{gain} , determined in the noise measurements:

$$\eta[\lambda, T] = R[\lambda, T] c_{\text{gain}}[T] \quad (4)$$

The QE measurements reported here include losses from the reflectance of the InGaAs surface and Snake SW window.

The measurements are performed in 10 nm increments of the laser wavelength over a range of 1600 nm to 1720 nm to resolve the InGaAs band edge. Similar to considerations of the dark current, the Snake SW is operating at a temperature of approximately 22 °C. To correct the measured QE values to the intended operating temperatures of the TANGO application (15 °C), the known temperature dependence [1] is used to scale the measured results.

Results

Dark Current

Figure 1 reports the raw dark signal as a function of exposure time for all Snake SW sensors. Plots of the signal as a function of exposure time show graphically the expected signals, offset, signal current and signal range. Instead of only showing the median over the detector at a given exposure time, the detector pixels are sorted by signal current and divided into equal-sized cohorts, which allows for an initial indication of the non-uniformity. The signals and fits are shown for each cohort, identified by colour, where the linear fit to the signals is indicated by dots instead of crosses. The median offset and dark current (in counts and counts/ms respectively) over the full array are reported above the individual figure panels.

The DCNU is given as histograms of the values per pixel in Figure 2. Above each histogram the median value is given in ke/s, using the conversion gains appearing in Table 3. Also reported is a measure for the width of the distribution using the square root of the biweight midvariance, here called ‘biweight spread’ for short [4]. It is an alternative measure for the standard deviation that is resistant to outliers and converges to the same value as the standard deviation for an uncontaminated normal distribution. Histograms show all values but are clipped, where bars at the edges of a histogram include outliers outside the main range. Occasionally apparent in the histograms is a small “bump” of an elevated dark current near 150-160 ke/s (panels (a) (b) (f) (g)). This is a feature of the 1-pixel perimeter of the sensor, common to all sensors. For SNKD, SNKE, and SNKF (panels (c) and (d) and (e)) the small bump associated with the perimeter is still present but appears as the major contributor to the clipped bin outside the main range. Panel (h) displays the histograms of all devices together for a device-to-device comparison.

The measured median values of the extracted dark currents are reported in Table 2 for all sensors. The table includes the values in counts/ms, as well as the median values and biweight spreads converted to ke/s when using the determined conversion gain of the following section (see Table 3). All sensors have a measured dark current that is significantly smaller than given in the manufacturer specifications (see Table 1), but the temperature was not specified. As a final point it should be noted that there is some variability in the FPA temperature during the measurements. An appropriate correction based on the known temperature dependence is applied when the dark currents are tabulated (see Table 5).

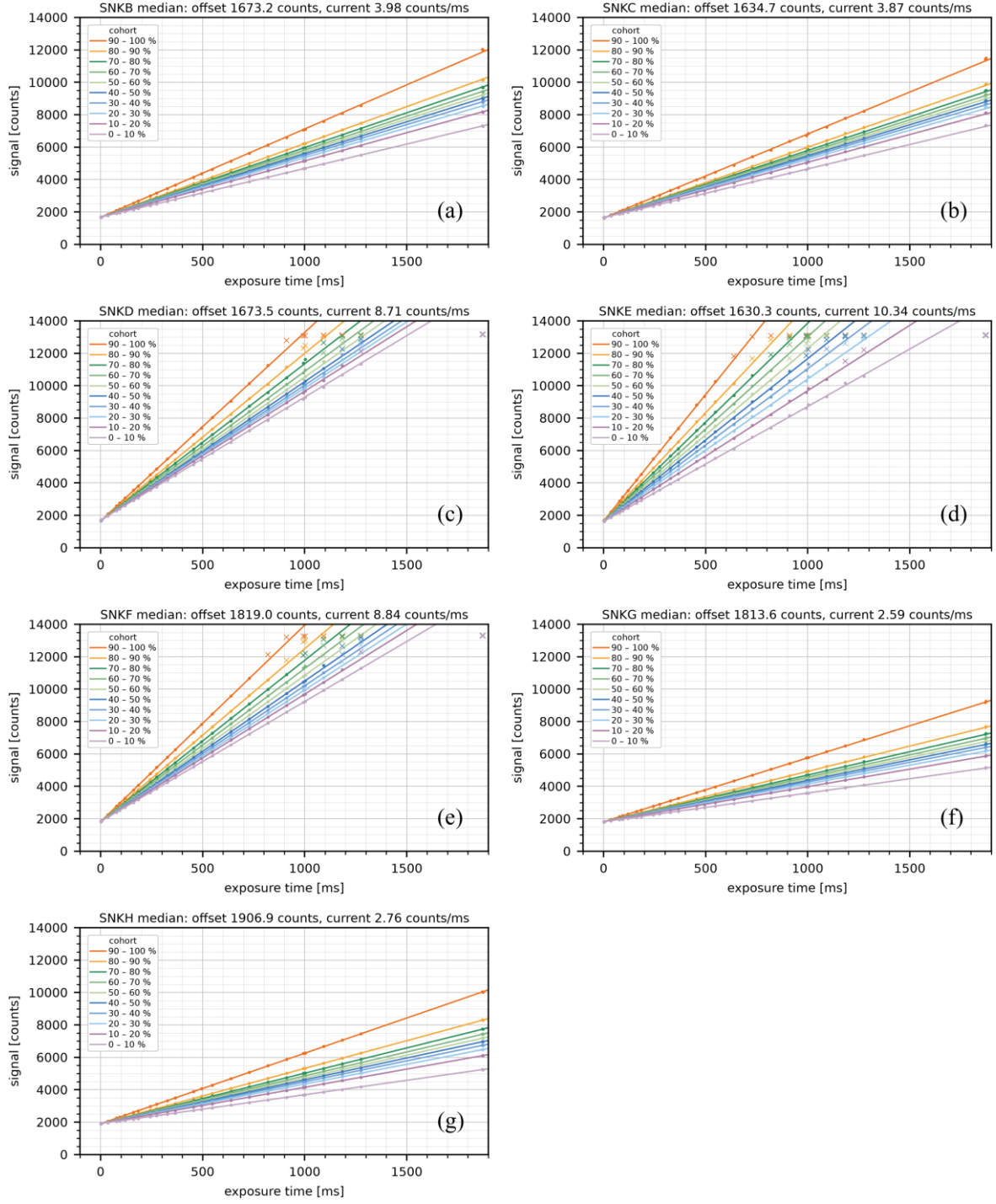


Figure 1. Raw dark signal as a function of exposure time for all Snake SW sensors. $V_{\text{DETCOM}} = 3.06 \text{ V}$ and $T_{\text{FPA}} \sim 22^\circ \text{C}$ (see Table 2). A linear fit to the signals is indicated by dots instead of crosses. Symbol colours indicate pixel cohorts with similar fitted signal currents. Data is provided for SNKB through SNKH in panels (a) through (g). Individual captions report the median offset and dark current in counts and counts/ms respectively.

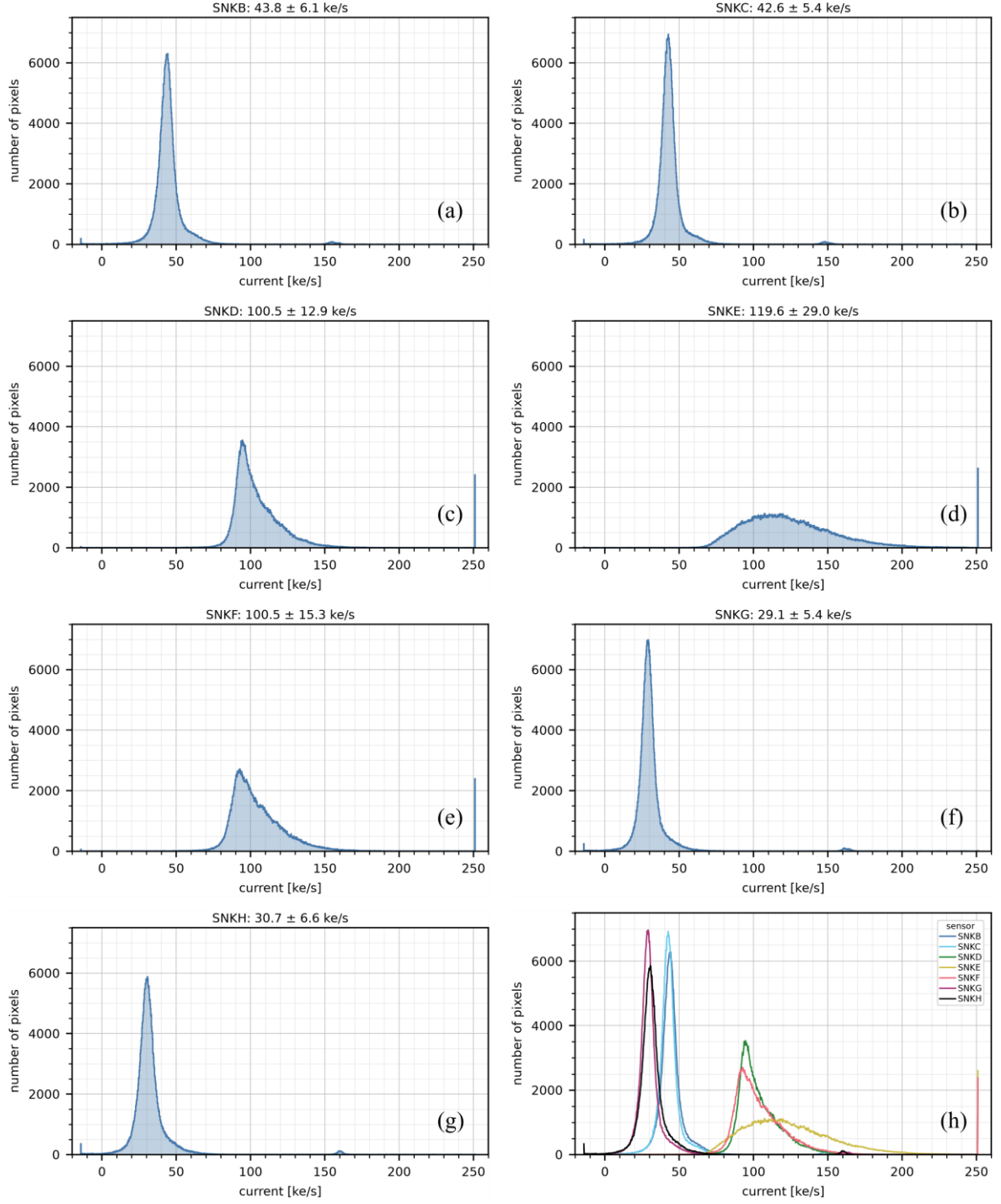


Figure 2. Dark-current histograms for all Snake SW sensors. VDETCOM = 3.06 V and $T_{FPA} \sim 22^\circ\text{C}$ (see Table 2). Data is provided for SNKB through SNKH in panels (a) through (g). Individual captions report the median dark current and biweight spread in ke/s. Values are converted from counts/s using the conversion gain determined below. Panel (h) displays the histograms of all devices together for comparison.

Table 2. Snake SW dark current and DCNU when operating in gain 1 with VDETCOM = 3.06 V.

name	dark current [counts/ms]	dark current [ke ⁻ /s]	biweight spread [ke ⁻ /s]	FPA Temperature [°C]
SNKB	3.98	43.8	6.1	22.6
SNKC	3.87	42.6	5.4	21.8
SNKD	8.71	100.5	12.9	22.1
SNKE	10.34	119.6	29.0	22.1
SNKF	8.84	100.5	15.3	22.1
SNKG	2.59	29.1	5.4	22.1
SNKH	2.76	30.7	6.6	22.1

Read-out Noise

To determine the read-out noise and conversion gain accurately, the noise is measured over a wide range of signals with and without light. The resulting noise as a function of offset-corrected signal appears in Figure 3 for all Snake SW sensors investigated. As indicated in the figure legends, 5 separate signal currents (including the dark signal) are investigated in each case. Also included in the figure is the resulting fit to the noise model of Eq. (2). To avoid influences related to saturation and non-linearity, only data when the offset-corrected signal is less than 80% of the full well are used when fitting to the noise model. Following Eq. (2), the fit used in Figure 3 is against the background-corrected signal. Here the dark signal has been reintroduced (offset-corrected signal) only to simplify the plotting. If this was not done the 0 mA dark signal would form a vertical line. The resulting read-out noise, conversion gain, and effective dark current are provided above the individual panels. The results additionally appear in Table 3. In general, consistent with previous observations [1], the effective dark current is significantly larger than the values extracted from the dark signal dependence on exposure time (see Table 2 and Table 5).

Table 3. Snake SW read-out noise, conversion gain, and effective dark current

name	read-out noise [e ⁻]	conversion gain [e ⁻ /count]	effective dark current [ke ⁻ /s]
SNKB	67.4	11.02	70.6
SNKC	65.4	11.01	68.1
SNKD	64.8	11.53	113.9
SNKE	61.4	11.56	125.7
SNKF	63.2	11.37	119.7
SNKG	61.8	11.21	55.4
SNKH	56.9	11.13	59.2

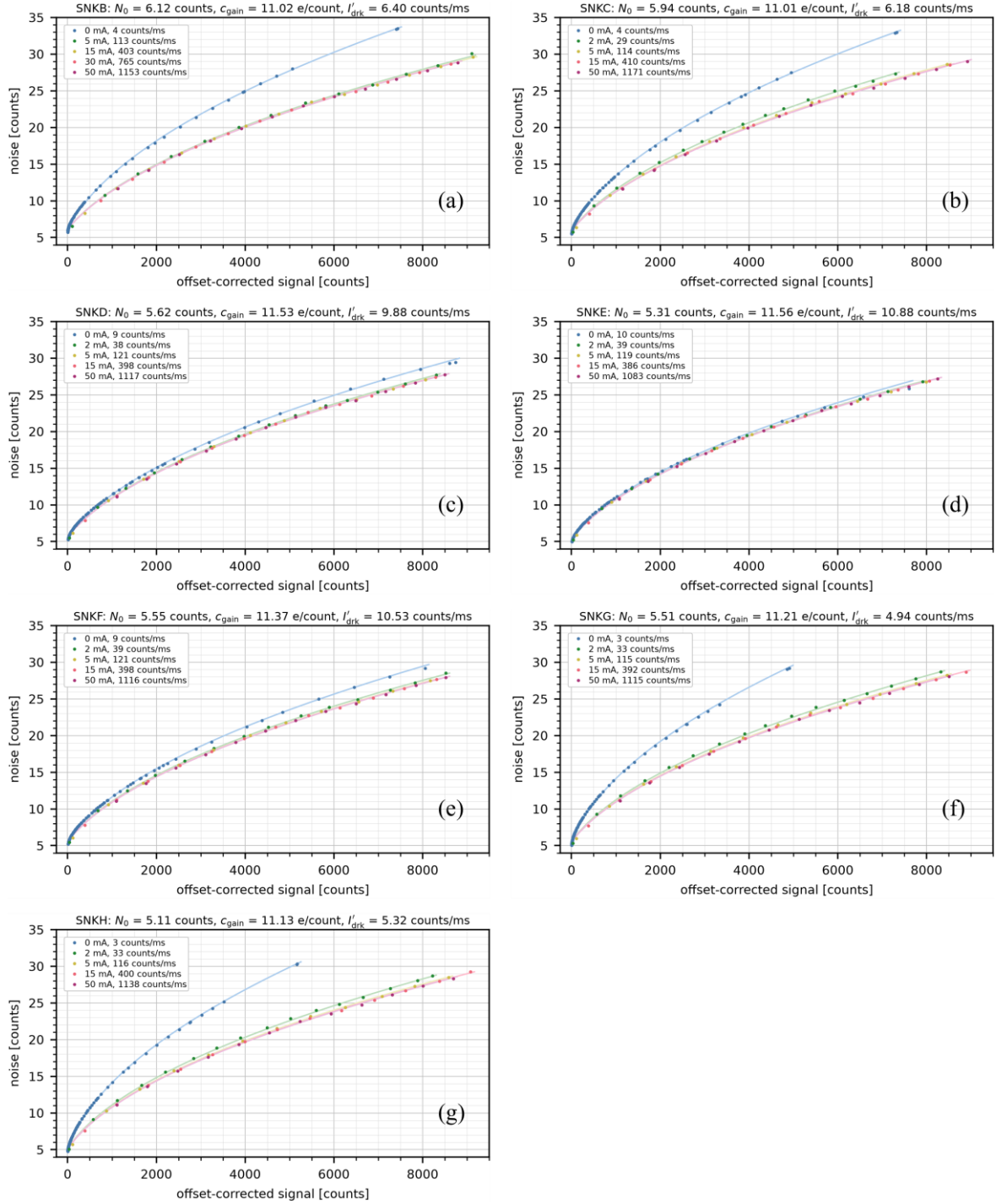


Figure 3. The measured noise as a function of offset-corrected signal at several signal rates (LED currents) given in the legend. VDETCOM = 3.06 V and $T_{\text{FPA}} \sim 22$ °C. Data is provided for SNKB through SNKH in panels (a) through (g). A fit using the noise model (Eq. (2)) is indicated by a curve per signal rate with a similar hue as the corresponding points. The fitted parameters are given above the individual panels. Note that all curves are instances of the model with the same parameter values.

Quantum Efficiency

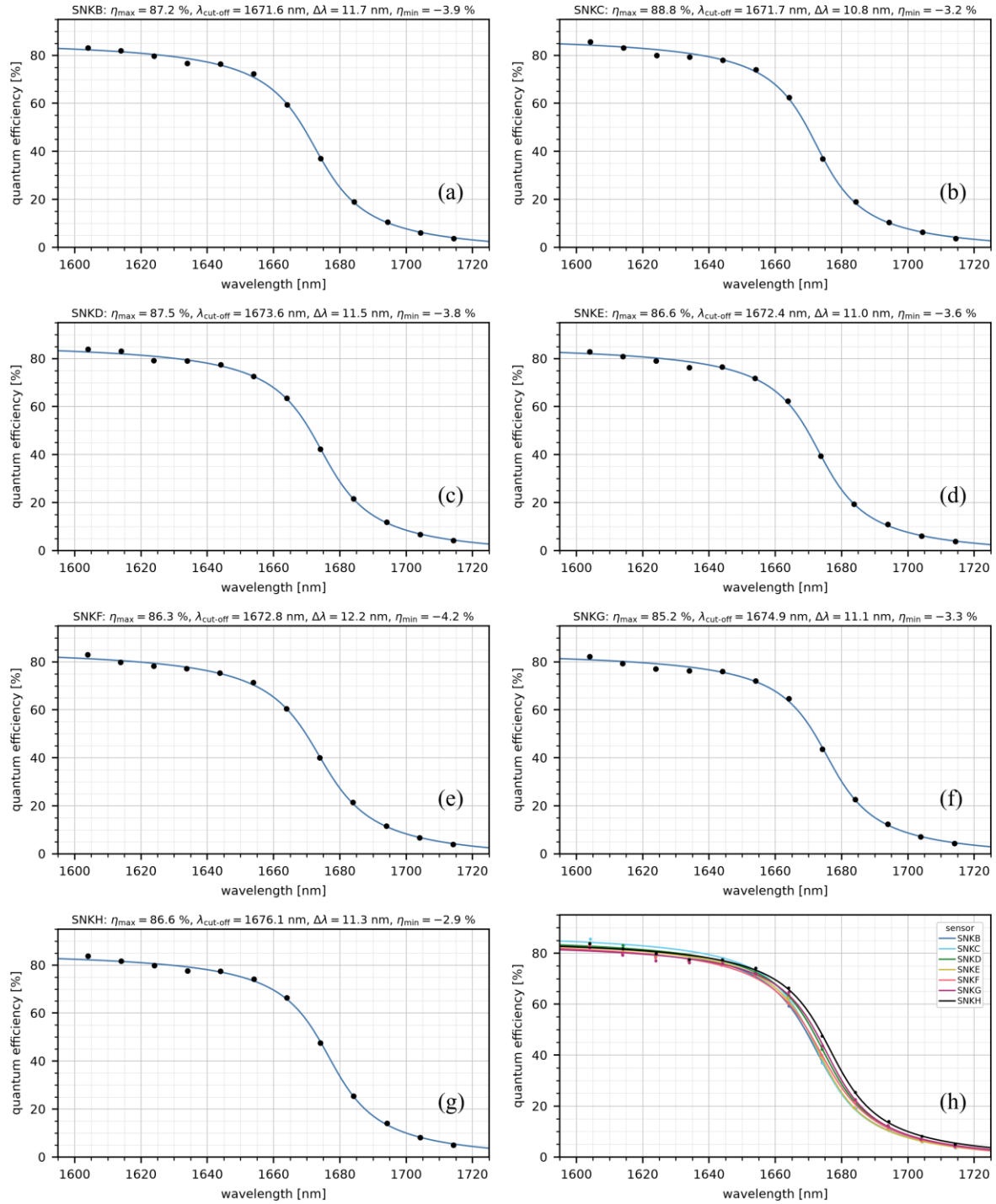


Figure 4. Temperature-corrected data for the Snake SW quantum efficiency. VDETCOM = 3.06 V, T_{FPA} corrected to 15 °C. Data is provided for SNKB through SNKH in panels (a) through (g). Measurements are in 10 nm increments (dots) from 1600 nm to 1720 nm. A fit (line) based on Eq. (5) is included. The fitted parameter values are given above the panel. Panel (h) displays the QE of all devices together for comparison.

The measured quantum efficiency η as a function of wavelength λ is fitted with the function:

$$\eta = \frac{\eta_{\max} - \eta_{\min}}{\pi} \arctan \left[\frac{\lambda_{\text{cut-off}} - \lambda}{\Delta\lambda} - \tan \left(\frac{\pi}{2} \frac{\eta_{\min}}{\eta_{\max} - \eta_{\min}} \right) \right] + \frac{\eta_{\max} + \eta_{\min}}{2} \quad (5)$$

with maximum quantum efficiency $\eta_{\max}$, cut-off wavelength $\lambda_{\text{cut-off}}$ (where $\eta = \eta_{\max}/2$), transition half-width $\Delta\lambda$ and minimum quantum efficiency $\eta_{\min}$. The last parameter has unphysical negative values but helps to describe better the range covered by the points at the longest wavelengths. If $\eta_{\min}$ was forced to zero, minimal change in the cut-off wavelength would be observed (0.1 nm). Note that $\eta_{\max}$ and $\eta_{\min}$ are asymptotic values that are not reached inside the performance wavelength range.

Temperature-corrected data for the Snake SW quantum efficiency when operating the FPA at 15 °C appear in Figure 4. Measurements are provided in 10 nm increments (dots) from 1600 nm to 1720 nm. A fit (line) based on Eq. (5) is included. Due to the absence of a functional TEC, the measurements of QE here have the same approximate variations in temperature reported in Table 2. To remove this variability, the previously observed linear shift of InGaAs quantum efficiency with temperature (0.820 nm/°C, smaller when colder) [1] is used. This allows the measured data to be corrected to a uniform operating temperature of 15 °C. The resulting fit parameters of the QE are provided in Table 4. As can be seen in the table the observed variability of the InGaAs cut-off wavelength is well below manufacturer specifications.

Table 4. Sensor quantum efficiency fit parameters adjusted to an FPA temperature of 15 °C.

name	$\lambda_{\text{cut-off}}$ [nm]	$\eta_{\max}$ [%]	$\Delta\lambda$ [nm]	$\eta_{\min}$ [%]
SNKB	1671.6	87.2	11.7	-3.9
SNKC	1671.7	88.8	10.8	-3.2
SNKD	1673.6	87.5	11.5	-3.8
SNKE	1672.4	86.6	11.0	-3.6
SNKF	1672.8	86.3	12.2	-4.2
SNKG	1674.9	85.2	11.1	-3.3
SNKH	1676.1	86.6	11.3	-2.9

3. DISCUSSION

The FPA temperature impacts both the dark current and the quantum efficiency, and the measurements need to be corrected for the intended operating temperature of the TANGO application (15 °C). Temperature-dependent corrections to the measured quantum efficiency were seen in Table 4, and corrections to the dark current are provided below.

The dark current has an exponential dependence on the temperature of the FPA:

$$I_{\text{drk}} = I_{\text{drk,ref}} 2^{(T - T_{\text{ref}})/\Delta T} \quad (6)$$

with dark current $I_{\text{drk,ref}}$ at reference temperature T_{ref} and temperature interval ΔT over which the dark current doubles in size. The measured temperature dependence of both the dark current and effective dark current were reported previously [1], with characteristic values of $\Delta T = 4.99$ °C and $\Delta T = 8.74$ °C respectively. Values adjusted with these dependencies appear in Table 5 for the Snake SW sensors. As was previously noted, the effective dark current is significantly larger than of the values extracted from the dark signal dependence on exposure time.

Table 5. Sensor dark current performance adjusted to an FPA temperature of 15 °C.

name	dark current at 15 °C [ke ⁻ /s]	effective dark current at 15 °C [ke ⁻ /s]
SNKB	15.3	38.8
SNKC	16.6	39.7
SNKD	37.6	65.0
SNKE	44.8	71.8
SNKF	37.8	68.4
SNKG	10.9	31.6
SNKH	11.5	33.9

The dark currents appearing in Table 5, in combination with the QE model summarized in Table 4, and the read-out noise performance of Table 3 can be used to calculate the performance at an arbitrary wavelength for each sensor. This can be used to assess the radiometric performance of the devices for methane sensing planned in the TANGO mission, where the required SNR at 1665.8 nm in the methane absorption is 125 with a reference spectral photon radiance of $L_{\text{ref}} = 1.74 \times 10^{16} \text{ (nm} \cdot \text{s} \cdot \text{m}^2 \cdot \text{sr)}^{-1}$ (SZA = 70°, albedo = 0.15) [5]. Following the same argumentation previously published [1], the resulting SNR for each device when operating at 15 °C is provided in Table 6. Here the radiometric calculations use the nominal optical design and operations of the carbon spectrometer developed by TNO [6]. Note, when determining the SNR of each device, the effective dark current extracted from the noise model is preferred to the more conventional dark current extracted from signals. It is invariably more conservative and, more importantly, it provides a direct representation of the appropriate noise contribution of the sensor. In all cases the modelled SNR is compliant to the mission requirements with significant margin. SNKH and SNKG are designated as the preferred flight model and flight spare, respectively.

Table 6. SNR for each sensor at 1665.8 nm for a reference spectral photon radiance of $1.74 \times 10^{16} \text{ (nm} \cdot \text{s} \cdot \text{m}^2 \cdot \text{sr)}^{-1}$.

name	QE (1665.8 nm, 15 °C)	SNR (1665.8 nm)
SNKB	0.566	200
SNKC	0.588	209
SNKD	0.605	203
SNKE	0.582	199
SNKF	0.575	196
SNKG	0.612	223
SNKH	0.636	236

4. CONCLUSIONS

The performance of several commercial Snake SW detectors has been characterized for dark current, read-out noise, and quantum efficiency. The quantum efficiency demonstrates a much smaller variability than indicated by the manufacturer specifications, while the dark current consistently outperforms these specifications by a significant margin. The provided measurements offer an indication of performance tolerances that can be expected from these COTS devices for future applications. The measured performance has been extended to predictions of the on-orbit radiometric performance relevant to the TANGO mission. In all cases the tested sensors are appropriate technology for the high-precision satellite observations of CO₂ and CH₄ in the 1.6 µm absorption band. Specific devices were designated as the preferred flight model and flight spare.

It must be noted that the predictions of radiometric performance seen in Table 6 are based on beginning-of-life (BoL) values. Importantly, lattice-matched InGaAs has been shown to be sensitive to displacement damage induced by the total non-ionizing dose (TNID) [7]. Despite the relatively benign radiation environment predicted for the TANGO mission, estimated increases in the dark current to end-of-life (EoL) values can still be significant, with a strong dependence on the effective shielding available for the InGaAs sensor. In summary, the flight implementation of the Snake SW will require a mechanical structure with sufficient shielding to maintain acceptable EoL performance.

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