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VIRGO-2K 2.5 μm HgCdTe Dark Current

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ABSTRACT

Careful measurements for an engineering grade 2K² 2.5 μm cut-off VIRGO detector in a sealed, cold enclosure have yielded dark current twenty five times less than previously reported for these devices, putting Raytheon detectors in contention for low background applications. Global reset followed by Sample Up the Ramp readout was used to allow zero point drifts at the exposure start to be separated from true dark current and mux glow. In a sub-array selected to be far from two photo-emitting defects, mean dark current stabilized 10 hours after power-on, at 0.025 e-/s/pix at 79K (-0.1K, +0.8K). Dark current showed no evidence of the onset of a floor in the 79-104K range, but the temperature dependence was softer than expected, implying a band gap that is 20% below nominal. Shot noise from the dark current will not dominate the 18 e- read noise, unless a substantial noise reduction is achieved through multiple sampling. Hundreds of non-destructive samples will be possible without impact from multiplexor glow, which contributes only 0.04e-/pix/read for a 6 μs pixel. Reset Anomaly is dependent on exposure time, settling to -60e- for long exposures, and dominating dark current in exposures less than 2400s. Reference pixels do compensate for these effects, but imperfectly, requiring further study. Attempts to explain Reset Anomaly in terms of self heating were inconclusive.

Keywords: Detectors, dark current, multiplexor glow, self heating, reset anomaly.

1. INTRODUCTION

Since June 2002, when Raytheon won the contract for the 2.5 μm cut-off HgCdTe detectors for the VISTA telescope, there has been widespread speculation as to whether multi-vendor procurements are now also viable for *low background* applications of 2K² arrays. Raytheon have claimed very good QE, without such severe J-band roll off as has been seen in the Rockwell arrays. However, with no contracts requiring dark currents less than ~ 5 e-/s/pix, VIRGO detectors had not been tested in the <0.05 e-/s/pix dark current regime required for low background astronomy. Therefore, we have tested an engineering grade VIRGO-2K array with 2.5 μm cut-off HgCdTe material grown by Liquid Phase Epitaxy (VISTA #19) in a thoroughly light tight enclosure, and conclude that the VIRGO arrays are in fact worthy of consideration.

2. TEST CONDITIONS

The detector was mounted on the inner side of the access hatch to a sealed Aluminum chamber (Figure 1) with complete light seals and labyrinth style gas pumping path requiring typically nine reflections from blackened surfaces for light to enter. The flex circuit serving as a cryogenic cable was potted into the access hatch with silver filled epoxy to exclude light leaks while providing a thermal short to 77K. A mask with a pattern of small holes was placed ~ 2 mm above the detector so that any light leak would be signaled by a series of bright spots in the images: no light leak was detected, even in exposures greater than 10 hours.

Infrared LEDs placed within the dark chamber provided illumination through the focal plane mask (not shown in Figure 1) to confirm correct detector operation and to allow measurement of the inverse gain (e-/ADU). This agreed to within 10% with the value estimated from the output sensitivity (4.58 $\mu\text{V}/\text{e-}$) quoted in Raytheon's test sheet for this device, and the gain of the signal chain.

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Figure 1: Cross-sectional view showing detector mount in dark chamber. The surface at right is bolted to the liquid nitrogen tank (not shown) . The serpentine groove at this interfaces provides a light baffled gas pumping path from the otherwise sealed enclosure.

All tests described here were done under the following conditions:

2.1. Detector and hardware

Table 1: System parameters

Detector	Raytheon VIRGO-2K
Unit serial number	VISTA #19
Gain	3.33 e-/ADU
Sensitivity	4.58 $\mu\text{V}/\text{e-}$
Reset mode	Global
Sample mode	Sample Up the Ramp (SUR)
Detector Common	1 V (lower values increase photo emitting defect intensity)
Other voltage biases	Default
Output mode	16 channels
Temp. stability	1.4 mK rms (see text)
Pixel read time	5.8 μs
Controller	Astronomical Research Cameras (SDSU-III), 16 ch.

2.2. Sample Up the Ramp readout

Initial measurements using conventional Correlated Double Sampling exhibited negative dark signal for short exposures, which asymptotically approached a positive value as exposure time was increased. The reason for this is apparent when comparing a series of non-destructive, “Sample Up the Ramp”, measurements taken at different temperatures, as shown in Figure 2a. The dark response can be modeled as the sum of a negative zero point shift, which is independent of temperature, plus a linear and strongly temperature dependent dark current. The zero point drift, often called “Reset Anomaly”, was -60 e- when sampling every 300s, decreasing to -50 e- when sampling every 12s, reflecting the change in duty cycle. The dark currents reported here are based on samples taken after the first 300s or more to avoid contamination from zero point drift.

Figure 2: a) Non destructive (SUR) readout at different temperatures, 300s per sample. B) sampling every 12s at 79K shows that the initial zero point drift takes 200s to settle (dots). While reference pixel subtraction (gray line) removes the slow drift component, it increases the initial negative offset with respect to the first sample (see y axis scale at right). Reference pixel subtraction also increases the scatter.

2.3. Statistics

Statistics were computed for a 50,000 pixel sub-array (Figure 3), uncontaminated by the two photo emitting defects. Since this is an engineering grade device, we disregarded the many hot pixels by one of the following methods, which gave comparable results.

3. Median Filter: 5x5 median boxcar filter, then average.
 - b) Truncated Mean: mean after discarding low and upper tails of histogram (Figure 3)
 - c) Midpoint: IRAF's approximation to the median (using the imstat routine)

Figure 3: a) statistics box was chosen to be well clear of photo emitting defects and high hot pixel density; b) dark current histogram showing cut level for hot pixel exclusion.

Figure 3b shows the histogram of a difference of two frames in a "Sample Up the Ramp" sequence, not including the first frame after reset, which always contains an unexplained offset often called Reset Anomaly.

Our dark current measurements assume uniform inverse gain (3.3 e-/ADU) for every pixel, which is an approximation based on the sensitivity figure (4.58 μ V/e-) provided by Raytheon. Our photon transfer measurements, which are also based on the simplifying assumption that all pixels have equal gain and noise, are in close agreement with the Raytheon figure.

4. POWER ON TRANSIENT

Dark current decays significantly over a period of about ten hours. The stimulus for this transient is any change in detector bias. This was tested both by pulsing “Detector Common” briefly to zero and by injecting a step change. Cycling the power on the controller, resetting the software (which sets all biases back to zero) or just shutting down the digital supply to the mux, will induce similar transients. This elevated dark current after changes in detector bias may manifest itself as image latency, which we have not yet attempted to measure.

Figure 4 shows ten consecutive Sample Up the Ramp (SUR) sequences started soon after the array was powered. The gaps mark the start of individual three hour SUR sequences. Clearly the transient is not induced by resetting the array, as occurs at each gap. We have yet to determine whether this settling effect is a noiseless drift in detector offset voltage or gain, or whether it exhibits the shot noise one would expect from a true dark current. These very long sequences revealed a smaller and faster transient every 12 hours, which is unexplained but presumed to be an artifact of our test setup due to its regularity (power glitch? Liquid N₂ refill?).

Figure 4: Power On transient, reference pixel subtracted and unsubtracted

Raytheon measured 0.9 e-/s dark at 80K. Their ± 1 K temperature uncertainty amounts to a factor of two in dark current (see Section 6). Their measurement was made about 2000 seconds after power up, which would explain another factor of five higher dark current (see Figure 4). Following their practice of calculating mean dark current (rather than median) using the entire array, except for dead pixels or those with $I_{\text{dark}} > 8$ e-/s, we find that our estimate of mean dark current at 80K increases from 0.037 e-/s to 0.3 e-/sec, another factor of 8. The peak of the histogram (~ 0.037 e-/s) is still very much lower than this, so that the even after clipping at 8 e-/s, the mean is still dominated by the hot pixels. To illustrate this we excluded all values greater than 2 e-/s, finding that the mean was reduced to from 0.3 to 0.1 e-/s. The combination of temperature uncertainty, lack of adequate settling time, and dominance of hot pixels over the mean, easily accounts for the factor of 25 between Raytheon’s measurement and ours.

4. REFERENCE PIXEL SUBTRACTION

In Figure 4 and Figure 5, it can be seen that dark current data corrected by subtracting the mean of the row of reference pixels is more stable, particularly during transient conditions. It is however puzzling that the reference pixels only

partially remove these transients. The fact that the reference pixel subtraction has no effect on the slow settling of dark current (Figure 4) indicates that drifts in the output amplifier, downstream electronics, or bias voltages are not responsible.

Figure 5: Effect of reference pixel subtraction on dark current estimates

5. MULTIPLEXOR GLOW

To separate the dark current from multiplexor glow, we performed the SUR sequences at 12, 24 and 600 seconds per sample. The total dark signal, *including* mux glow, is shown in Figure 6. Comparing the dark signals sampled at 600s with those samples at 12s intervals, we infer that the mux glow is 0.04 ± 0.01 e-/pix/read. Other pairs (e.g. 12s and 24s) give results consistent with this.

Figure 6: Total dark signal including amplifier glow, versus sample rate

6. DARK CURRENT VERSUS TEMPERATURE

To measure the dependence of dark current on temperature, without confusion with any settling time effects due to reset or interruption of the readout cadence, a single Sample Up the Ramp sequence was left running while the temperature setpoint was increased in 5K steps every two hours. Figure 7 shows the dark current as a function of time. (The settling time after a temperature change is less than the 600s between reads.) Grey points include some saturated pixels, so only the black points are included in the dark current versus temperature curve, Figure 8.

Figure 7: Dark current versus time, with temperature steps every 2 hours

Figure 8: Measured versus theoretical dark current

The theoretical dark current formula [1],

$$D(T) = CT^{1.5} e^{-E_g / 2KT}$$

fits the data very well for the band gap, $E_g=0.402\text{eV}$, which is slightly less than the canonical value [2], 0.496eV , for $2.5\mu\text{m}$ cutoff HgCdTe, indicating that some surface conduction may be occurring. The absence of a floor in this temperature range indicates that significantly lower dark current can be achieved through cooling a few degrees. For

example, the measured dark current, $0.025\text{e-}/\text{s}/\text{pixel}$ at 79K, implies a dark current of $0.013\text{e-}/\text{s}/\text{pix}$ at liquid nitrogen temperature (77.4K).

7. TEMPERATURE STABILITY & ACCURACY

To allow the tightest possible thermal control, the detector mount was designed to have less heat capacity than the detector. The sensor for the detector temperature servo, a calibrated Lakeshore diode, was located on the heater plate, rather than the using the sensor on the detector itself. By minimizing the time delay in the servo loop, greater immunity to changes in Nitrogen tank temperature was achieved.

Heater plate temperature *readings* acquired with the Lakeshore 340 temperature controller indicate 1.4 mK rms variation, if we ignore the -12 mK offset during readout. These temperature offsets are believed to be due to rectification of clock interference by the sensor. Other groups using diodes as temperature sensors have seen similar fast transients, which have disappeared when the sensors were replaced with RTDs. Figure 9 was acquired during a long series of SUR exposures: the spikes correlate with readouts.

Figure 9: Detector temperature stability

In Figure 9 the servo compensates for drift in the sensor reading so the apparent thermal stability is misleading. The detector was supplied with a temperature sensor, but our wiring to it was found to be faulty. Had this sensor been available it would have provided a better measure of thermal stability, not only because it is on the detector package, but also because it would not be inside of the servo loop.

The combined systematic error of the Lakeshore sensor and model 340 controller is claimed by the manufacturer to be $\pm 110\text{ mK}$ at 77K. However in normal use the variations in detector self-heating may dominate these errors

8. OUTPUT OFFSET VS. TEMPERATURE

We have measured output voltage variations versus temperature to be -4.4 mV/K , during exposures when the output transistor's gate is isolated. During readout when the pixel transistor and load are involved, the temperature dependence rises to -7.5 mV/K . It is somewhat disappointing that the temperature dependence during readout is only reduced to -1.5 mV/K by reference pixel subtraction. (At $4.58\text{ }\mu\text{V/e-}$, these figures correspond to -1650 e-/K for raw data and -330 e-/K after reference pixel subtraction.)

Figure 10: Raw signal for non-destructive *readout* sequence during which temperature is increased by a 5K step every 2 hours. The output changes by -1650 e-/K .

Figure 11: Output source voltage, during *exposure* time, after an offset and gain of -5 , showing the effect of a 1K increase in the detector temperature setpoint. This is equivalent to -960 e-/K .

9. SELF HEATING

To gain some insight into detector self heating in the absence of access to the on-detector sensor, servo power was switched off so that the temperature sensor in the detector heater plate would reflect changes in power dissipation of the detector. (There are no other significant heat inputs to the detector.) The heater plate temperature rises by 100 mK relative to its heatsink when the detector is powered on and begins long exposure an immediately.

The heater plate temperature *decreased* by 50mK during an hour long exposure following a prolonged continuous erase, returning to the original level during the next hour of continuous erasure. This indicates that the detector self heats more during readout than during an exposure. This was to be expected, since the pixel buffers do not conduct during the exposure. The power does not drop to zero during exposure since the output transistor is always conducting.

The thermal resistance from detector to the heater plate is estimated to be about half the resistance from heater plate to its heatsink, so one would expect self heating of the detector relative to a servo controlled heater plate to be $\sim 50 \text{ mK}$ during exposure, rising to $\sim 75 \text{ mK}$ during readout.

Figure 12 shows that the offset voltage changes by the *equivalent* of a 750 mK temperature rise when an SUR exposure is started immediately after power on, which, if real, will increase dark current by 33%. This measurement is a factor of fifteen larger than the expected increase and should be regarded with some caution since it relies on there being

negligible leakage into the transistor gate, which is floating during the exposure. In retrospect, the post reset levels in a series of short exposures would have been a more reliable estimator.

Figure 12: Output offset voltage during a sequence of 600 second SUR exposures immediately after power-on, scaled to units of temperature based on the measured -4.4mV/K temperature dependence. The transients after each read scan may not be thermal in origin.

10. RESET ANOMALY

The dark signal from non-destructive readout sequences at various temperatures is shown in Figure 2a. These data can be extrapolated back to a common y-intercept to show that the component due to zero point drift is both reproducible and independent of temperature, at least for a given sample rate, and initial condition (continuous erase). This negative transient at the start of the exposure is often referred to as “Reset Anomaly”. At temperatures near 77K, it dominates the total dark signal for most practical exposure times.

Figure 2b shows a non-destructive readout curve with more closely spaced samples. The 12s sample time was clearly adequate to resolve the negative going transient (black diamonds in Figure 2b), while being slow enough that mux glow was only 15% of dark current. The initial transient takes 200 seconds to settle to -49 electrons. It should be noted that although this is generally called “Reset Anomaly”, Figure 2b shows that the effect lasts for several hundred seconds after the reset, and may not be related to reset at all. Global reset (not line-by-line) was employed for all tests reported in this paper.

A detailed investigation of Reset Anomaly is warranted, since it is a potential source of significant error in low light applications dominating dark current for most likely exposure times. Riopel et al.[4] have suggested that the effect may be thermal in origin. They show that by maintaining a stable read out cadence during the idle time prior to the exposure and throughout the exposure, the Reset Anomaly subtracts out during CDS processing. They hypothesized that the Reset Anomaly is due to the temperature dependence of the output offset and that their strategy works by reproducing the thermal conditions between the initial and final samples. However this may not always be possible. For better signal-to-noise ratio we often need to perform multiple non-destructive reads at start and end of the exposure, at the fastest available sample rate. To maintain constant readout cadence, one would then be necessary to read at maximum speed all the time. This is undesirable due to the associated mux glow.

Unlike the Rockwell HAWAII-2 examined by Riopel et al., the VIRGO and Rockwell HAWAII-2RG have reference pixels for correcting zero point drift. The solid grey line in Figure 2b shows the dark signal after subtracting the row of reference pixels at frame start:

$$\text{signal}(t) = [\text{image_pixel}(t) - \text{image_pixel}(0)] - [\text{ref_row_average}(t) - \text{ref_row_average}(0)]$$

While the dark signal becomes linear, without the slow initial transient, the negative offset is increased from -49 e⁻ to -701 e⁻ due to the large difference between the reference pixel level in the first and second read scans. It can be seen in Figure 2b that the reference pixel subtraction also makes the dark signal noisier in spite of the averaging of many

reference pixels. In view of these problems and our desire to understand the underlying transient effects we did not invoke reference pixel subtraction in the remaining tests reported here.

If it can be confirmed that Reset Anomaly is in fact a zero point drift associated with self heating, there may be other remedies such as using the on-detector sensor for closing the thermal servo loop and adjusting the load current during the exposure to maintain constant power in the output transistor.

Given the measured -4.4 mV/K temperature sensitivity of the output voltage during an exposure, and the $+4.58$ uV/e-sensitivity quoted by Raytheon, the -60 e- zero point drift in slow SUR sequences would require a temperature rise of the output transistor of (only) 50 mK. The change in temperature of the output transistor during the exposure time can be decomposed into a change in the temperature of the detector package due to the changing dissipation in the unit cells under each pixel, plus a change in the localized heating of the transistor junction relative to the underlying detector package. The pixel heating is uniformly distributed across the image area and thus should not produce steep gradients, unlike the localized heating of the output transistor, which might be expected to have a multi-time-constant response.

The negative going “Reset Anomaly” seen in Figure 2b requires a temperature *increase*, whether the measurement is made during readout (Figure 10) or during the exposure (Figure 11). However, the indirect measurements we have made (see section 9), indicate that the temperature of the detector package *drops* during the exposure, relative to the continuous erase prior to the exposure. For a net temperature increase at the output transistor, the self heating of the output transistor must increase sufficiently during the exposure to over-compensate the decrease in the underlying package temperature. This effect, if real, could be eliminated by adjusting the load current, when the voltage changes, to maintain constant transistor temperature. This can be achieved passively by choosing a load resistor and supply voltage such that $V_{dd} = 2V_o - 0.34$ in which case the operating point switches between two points with equal power dissipation on the inverted parabola:

$$\text{Power}(V_o) = V_o * I_o = V_o * (V_{dd} - V_o) / R_{load}$$

Figure 13: Temperature rise of output transistor during the exposure, *inferred* from output offset voltage change: a) linear plot, b) log-linear plot of residual; sum of two exponentials over-plotted to illustrate the twenty-fold range of time constants.

Figure 12 shows the change in output offset voltage (scaled to temperature) *during the exposure* when the pixel transistor’s thermal state is not in play since the gate of the output transistor is isolated. The polarity of the temperature change during the exposure is consistent with Reset Anomaly. The greater amplitude of the apparent output transistor temperature rise is also consistent with the idea that the pixels are cooling while the output transistor is heating, producing a smaller net increase in output transistor temperature with the correct polarity and approximate scale to explain Reset Anomaly.

There is however a major flaw in this explanation. The power dissipation of the output transistor was measured directly: the drain-source voltage is 3.70V during readout, decreasing to 3.36V during the exposure. The output load is 40 kilohm resistor to a 12V supply, so that the power in the output transistor *drops* from 768 μ W during readout to 725 μ W during exposure. With the underlying detector cooling and the power in the output transistor dropping, the output transistor must be *cooling* during the exposure, not warming as required to explain the reset anomaly.

Either we have made a mistake when measuring the polarity of these effects or some non-thermal explanation is required for Reset Anomaly. Access to the on-detector temperature sensor would certainly remove some uncertainty as to whether the detector really is cooling during the exposure. The idea that Reset Anomaly is related to self heating can be tested more directly by using the sensor on the detector package to close the servo loop while adjusting the load of the output transistor for equal power dissipation in the readout and exposure states. Further insight into the cause of Reset Anomaly may also be provided by investigating the differences in behavior of the reference pixels.

11. NOISE

The reason to study dark current is that it is a source of shot noise, so we conclude this discussion of dark signals with some comments on noise performance and the relative contributions of read and dark current noises. We have measured noise both temporally (the correct way) and spatially (the crude approximation) to determine how much difference is seen. A sequence of 100 minimum length dark images was acquired.

- **Spatial noise:** the standard deviation of a clean sub-array was computed for each image. The mean and standard deviation of these noise estimates are shown in table 2.
- **Temporal noise:** the standard deviation was computed one pixel at a time looking through the stack of images. The result of this operation is a matrix where each point represents the noise of one pixel. The mean and standard deviation of these true noise estimates are shown in table 2, and the histogram of the noise is shown on figure 8.

Table 2: Noise measurements

noise type (CDS)	value (e-)	stdev (e-)
Temporal	18.9	0.9
Spatial	18.3	2.5

A single value for e-/ADU was used to scale these numbers to e- introducing some inaccuracy to this analysis. However, it is striking how similar the simple spatial approximation is to the more rigorous temporal noise analysis, suggesting that the pixel to pixel variations in noise and gain are small. The spatial noise measurement technique is not only faster and easier, but is not affected by thermally induced offset drifts since these affect all pixels from the same output amplifier identically.

Figure 14: Temporal noise histogram in ADU

The read noise can be expected to exceed these figures for long exposure times due to the increasing contribution from low frequency noise sources in the detector material, multiplexor, bias voltages, or temperature. An important question, yet to be addressed, is the extent to which noise can be reduced by multiple sampling in long exposures.

Exposure times are typically limited to ~1200 seconds by cosmic ray hits. After 1200 seconds the shot noise from the dark signal at 79K will be 5.5 e- rms, degrading the 18 e- single CDS read noise by only 4%. If the multiple sampling is successful in reducing the read noise, to ~5 e- then the dark current can again be reduced to negligible levels by cooling a few degrees.

Will the mux glow limit the noise improvement from multiple sampling? Suppose that the noise is reduced to 5e- by multiple sampling. With mux glow of 0.04 e-/read, it would take 57 reads for the mux glow to degrade the noise by 10% -- more than four times the number of reads required for a noise improvement from 18 to 5 e- if the noise scales as $\sqrt{N}$. In general the noise does not improve this quickly but there is clearly significant safety margin.

CONCLUSION

Differences between our dark current measurements and Raytheon's have been traced to the settling effect after power on and the inclusion of hot pixels. We find that dark current and mux glow will be quite acceptable for most low background applications in astronomy, provided that the median dark current of "VISTA #19" can be reproduced in a device with many fewer hot pixels and no photo emitting defects.

Dark current is so low (and can be further reduced by cooling) that zero point drifts are much more significant contributors to measurement errors. Work remains to fully characterize the self heating and Reset Anomaly: we find that these are either separate, additive effects or there is an error in our analysis of the thermal behavior. The importance of such effects depends on the effectiveness of reference pixel subtraction, which also requires more study.

With single CDS read noise dominating the noise from the dark signal for cosmic ray limited exposure times, the extent to which read noise is reduced by multiple sampling will determine whether dark current will need to be reduced by cooling to slightly below liquid nitrogen temperature.

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