Solar-B **EIS** * EUV Imaging Spectrometer	Radiation concerns for the operating temperature ranges for the EIS CCDs - initial discussion

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1 Introduction

The CCD array must be cooled well below room temperature to reduce two degrading effects:

- thermal generation of charge will lead to large dark signals at high temperatures leading to a loss of signal to noise
- "loss" of charge, and degradation of image quality may result through charge transfer inefficiency (CTI). CTI will vary with temperature, and an optimal temperature needs to be selected to minimise CTI

It is important that the temperature selected is sufficient to ensure that the detectors perform to specification through to the end of the mission, by which time their properties will have been degraded sometime from their initial performance values due to the radiation dose encountered over the mission lifetime.

2 Achieving the Required Temperature

The low temperatures needed to cool the CCD will be provided by a radiator, thermally connected to the CCD. Ideally, a sufficiently large radiator could be constructed to provide a very low temperature. However, the allowable size (and mass) of the radiator is constrained. Savings made in radiator size can thus be traded against increases in mass elsewhere in EIS.

In the following sections, the effect of temperature on dark signal and CTI will be reviewed, and a best-case for operating temperature (given the constraints on radiator size) will be suggested.

3 Minimum temperature requirements

3.1 Dark signal

Intial dark signal performance

There are a number of criteria that could be adopted to help select the operating temperture that will yield acceptable levels of dark signal. For example:

- the dark signal could be choosen to be at a similar level to the read noise achievable from the CCD electronics;
- the dark signal could be choosen to be equal to 1 DN if the CCD electronics are to be operated in a high gain mode (about 7 e- per DN or so).

Ultimately, the choice of acceptable dark signal must be made on scientific grounds. In the absence of any firm drivers thus far, the temperature required to achieve a dark signal equal to the rms read out noise of the electronics will be discussed in detail. Equivalent figures for a dark signal of 7 e- will also be presented.

The dark signal from the CCD will depend on whether an MPP or non-MPP device is selected (both such designs are available for the EEV 42-10).

Figure one shows the variation in dark signal with temperature for the EEV CCD-4210 operated in MPP mode (called Inverted Mode Operation (IMO) by EEV). Figure two shows the total dark signal (in electron/pixel) which would occur at given temperatures for a range of integration times namely: ten seconds; one minute; and fifteen minutes. A resonable dark signal to aim for would be where the dark signal is equal to the overall readnoise from the device (which for the 42-10 is 2 electrons). This value corresponds to about -68°C for 15 minutes total integration time, or -55°C for 1 minute integration time.

To achieve an integrated dark signal of 7e- over the times shown would require the following temperatures for an MPP device:

ten seconds	:	-38°C
one minute	:	-42°C
fifteen minutes	:	-62°C

In contrast, a non-MPP device will have a dark signal which is about 100 times greater than the MPP values. To achieve 2 electrons total noise for a 15 minute integration at this value would require a temperature of -90°C to -100°C or so. However, this noise can be substantially reduced if dither clocking is used. Dither clocking ("charge sloshing") reduces the dark signal by switching the high electrode between phases during an integration. The effect of this switching is to periodically drive each phase into inversion. If the phases are switched more quickly than the time constants of the surface traps associated with that phase, then the surface traps will effectively be suppresed, reducing the dark signal.

An example of how dither clocking can reduce the dark signal is shown in figure three which shows the reduction in dark signal found for different dither clocking rates, measured on an EEV full frame device. With a dither time of 100µs, a reduction in the dark signal by a factor of around 50 can be achieved - this value is starting to approach those achieved for MPP devices, and should would correspond to a required temperature of around -73°C for a 15 minute integration.

Dark signal at the end of mission lifetime

The effect of ionising radiation will be to increase the dark signal as the mission progresses. The expected Solar-B radiation environment is discussed in discussion note 3.

The behaviour of EEV devices to radiation is well characterised and it should be possible to specify the increase in dark signal noise reasonably well. For a non-MPP device, the increase in dark signal will be about 100pA/cm2/krad. This corresponds to 1139 electrons/pixels/s/krad increase which would lead to a dark signal of around 21300 e/p/s for the 10krad dose, or 18000 e/p/s for the 7krad dose. However, both would be reduced by dither clocking by a factor of 50 or so. The effect of this on the overall noise expected is shown in figure four. Using the 7krad dose figure, to achieve 2 electrons noise for a fifteen minute integration (using 100µs dithering) would now require a temperture of about -75°C.

For a MPP device, the increase in dark signal would be much lower - 17 e/p/s/krad which would lead to an increase in the dark signal from ~100 e/p/s to ~219 e/p/s for a 7 krad overall dose. Thus, a slightly colder temperature would be required to achieve 2 electrons noise for a 15 minute integration (around -75°C).

It should be remembered that in the EIS wavelength ranges (170-290 Å) approx, each photon detected by the CCD yields 20 electrons @170 Å and 12 electrons @ 290Å.

Summary

It is possible to predict the required operating temperatures needed to minimise dark signal to acceptable levels (providing the radiation dose is reasonably known). Using a non-MPP device would lead to unacceptably large dark signals unless a very low temperature (-90°C) or so could be achieved. The best option is to either operate the CCD in MPP mode, or to dither clock at a frequency of <100µs. The following table summarises the CCD performance with respect to dark signal for both an MPP and non-MPP device:

Mode	Dark signal @ 20°C (electrons/pixel/s)	Temperature required for 15 min integration to achieve 2e-
MPP	100	-68°
non-MPP (dithered)	219	-72°
MPP after 7krad	119	-72°
dithered after 7krad	360	-77°

Table one: dark signal for an MPP and non-MPP device

3.2 Charge Transfer Inefficiency

CTI results from the trapping of charge within a pixel either during integration, or as a charge packet passes through the pixel during transfer. This trapping will reduce the total charge in each pixel. During signal readout, an individual charge packet may have to be shifted through many pixels, potentially leading to a large loss in signal.

CTI is related to temperature as trapping time constants (and hence the effective trap cross-section) will vary with temperature. For example, at sufficiently low temperatures, the time constant of a particular trap may be longer than the time taken to shift out a charge packet, consequently, all traps will be filled by the first charge cloud that passes through a pixel (the "sacrificial" charge), and subsequent charge packets will not be affected. Alternatively, the rate at which a charge cloud is shifted through a pixel will also affect the extent to which charge is lost - if the charge is shifted at a rate approximate to the trapping constant, then most of the trapped charge will be returned to its original charge packet. A third issue which must be considered is the density of charge in each charge packet. The volume over which a charge packet is distributed is not directly related to the amount of charge present and smaller packets will proportionally interact with more traps.

Thus, CTI is very complex, depending on temperature, charge density and clocking rate. In addition, most CTI calculations are done for "simple" flat field type images. For complex images such as spectra, the effect of CTI (particularly on image degradation) is very difficult to work out. Consequently, it is not possible to come up with a definitive answer as to the CTI level that we can tolerate (unlike dark signal).

The degradation of CTI with respect to total radiation dose is not so straightforward as it is for dark signal. The rate of defect production (and hence ultimately CTI) will be proportional to the Non-ionising Energy loss (NIEL) in the silicon. Very roughly, it appears that trap concentration varies linearly with fluence (Hopkinson et al. 1996). CTI degradation also appears to be related to the device's initial CTI (Holland et al. 1990)

CTI can be a particular problem at low temperatures, where the clocking time of the CCD may be similar to the emission time constants of the electron traps. For example, Hopkinson et al. (1996) predicted the effects of radiation induced defects on the CTI of a CCD using data from a EEV CCD02 device. They demonstrated that measurements at high temperatures (-20°C or so) would lead to unacceptably high CTI rates (of the order of 0.003). However, they emphasised that sufficient cooling should reduce the CTI dramatically.

Holland et al. (1990) demonstrated that the most severe radiation damage encountered on the CCD was the potential effects of CTI which could produce a noticable degradation in X-ray spectroscopic performance (for which they required a CTI value at least better than 0.00003). They measured the CTI induced on a number of CCDs after a dose of 2 krad and at a temperature of -90°C (no clocking time was stated) and found that in some cases the CTI was degraded to <0.0001. Several devices showed large increases in CTI, going from about 2.5e-4 after 10 rad (23% charge loss) to 1e-3 CTI (64 % charge loss) at 10krad.

Dale and Marshall (1991) calculated the potential rediation induced CTI changes using the radiation parameters arising from the HST orbit. The CTI was calculated using damage factors measured on the CRAF/CASSINI CCD (Ford 1024x1024 operating @50 kHz and -50°C). The potential change in CTI over three years was measured for three different densities of shielding as follows:

Density of Al	CTI change	% charge loss for 1000 transfers
0.1 g/cm2	.00076	87%
4g/cm2	.00025	78%
10g/cm2	.00014	47%

Table two: the predicted change in CTI for a CCD within the HST orbit

They emphasise that the increase in CTI would be much lower for lower temperatures or faster clocking rates.

The actual charge transfer problem in the WFPC/2 appears to have increased over time (Whitmore, 1998), with the charge transfer loss from a pixel at the top of the CCD undergoing up to 22% charge loss. However, the long integration times used often produce a high background which substantially reduces this overall CTI, in addition, software corrections enable users to correct for the charge loss usually to an accuracy of around 4% or so.

Hardy et al. (1998) derived a theoretical basis for charge loss and compared the predictions with charge loss measured on a CCD after a range of radiation doses. After a proton flux of 6E9 protons/cm^2 and an initial charge density of 1000 electrons, the charge loss measured @ 155K for 200µs clocking rate was about 300 deferred electrons.

Dale et al. (1993) derive a very simple analysis for estimating the potential CTI for a discrete charge packet within a CCD (This analysis is discussed in appendix 1). Figure five shows the CTI and equivalent charge loss from a pixel which is situated 220 pixels behind an similar charge packet, and which assumes the parameters listed in appendix one and figure five. The figure of 220 pixels spacing has been taken as a "reasonable" distance seperating individual spectral lines and represents the sort of charge loss that could occur for the first pixel in a widow bracketing a spectral line. The following pixels within the window would not suffer such noticable charge loss, as the vast majority of traps would have been filled by the charge in this initial pixel.

Figure six shows the CTI and charge loss that would be associated with a similar pixel if the charge cloud size was only 1000 electrons (about 80 photons) compared with an initial charge cloud size of 10000 (about 800 photons) for figure five. It can clearly be seen that the potential CTI (and hence charge loss) from a particular pixel is very dependent on the initial charge size. Above 10000 electrons/pixel, the relative CTI per pixel begins to decrease dramatically, and the percentage charge loss becomes very small. It should be noted that the effect of thermally induced electrons (i.e the dark signal) may reduce the CTI shown here above -50°C or so due to a "fat zero" effect.

Table three summarises some CTI figures, calculated using the equations discussed in appendix one, for a charge packet size of 1000 electrons (corresponding to about 70 photons at the EIS wavelengths). As will be seen from applying the equations in appendix one, the CTI is heavily dependent on the initial assumptions, not just for the number of traps per unit radiation dose, but also the initial packet size, and the clocking speed. The parameters used to calculate the figures in table three and four are presented in appendix 1. A clocking speed of 20µs was selected to represent the case where the clocking speed of the device has been slowed down from its nominal 500kHz (i.e 2µs) in order to minimise the read out nose.

Dose (krad)	Operating temp °C	CTE	% charge loss
1	-80	.99992	0.2
1	-70	.99997	0.6
1	-50	.99978	4.8
1	Room temp	.99983	3.6
7	-80	.999957	1
7	-70	.99984	3.4
7	-50	.99875	23
7	Room temp	.999	19

Table three: predicted CTI for 1000 electrons charge packet size

Table four shows the same calculations, but this time assuming a charge packet size of 10000 electrons (corresponding to about 700 photons) and 220 pixels between each charge packet.

Dose (krad)	Operating temp °C	CTE	% charge loss
1	-80	1	0
1	-70	.999997	0.1
1	-50	.999977	0.5

1	Room temp	.999983	0.4
7	-80	1	0
7	-70	.999984	0.4
7	-50	.99988	2.7
7	Room temp	.99991	2

Table four: predicted CTI for 10000 electrons charge packet size

The dependence of CTI on initial charge packet size is clearly shown by comparing results from the two tables.

Measurements on EEV CCD 25-20

An extensive series of tests were carried on behalf of ESA by Sira Ltd. (Hopkinson, 1995). This type of EEV CCDs were procurred for the MERIS (Medium Range Imaging Spectrometer) flying on ESA's ENVISAT mission. These CCDs are thined, back-illuminated, with 780x576 pixels, 22.5μm x 22.5μm in size. Measurements of the per-pixel CTI were made after a range of radiation doses. For example, after a 4krad dose, a serial CTI per-pixel of about 0.0005 was observed for a signal size of 10,000 electrons (measured at -25°C with a 2μs clocking time). This corresponds to a charge loss (at -25°C) of around 11%. It was observed that the CTI was dramatically reduced for large dark charge background due to this charge providing a "fat zero" effect.

Using the data from Hopkinson (1995) the equations derived in appendix one were used to predict a CTI figure at -25°C. A CTI figure of 0.00013 was found, slightly underestimating the value found from the MERIS measurements. This corresponded to a charge loss of 20%. The equivalent CTI at -80°C was 4.3E-7 (~0) and at -50°C was .000016 (0.36%) . Using the same figures, but with a very low charge packet size of around 1000 electons lead to a CTI at -80°C of 4.3E-6 (0.1%) and 0.000165 at -50°C (3.5%). The simulation was "forced" (by altering the trap density profile) to produce the MERIS CTI figure at -25°C. Such a figure gave a CTI at -80°C of 2.5E-6 (effectively zero charge loss) and 0.00009 at -50°C (2% charge loss).

Summary

It is clear from the assumptions made in appendix 1, that the confidence levels that can be attached to the above figures is quite low. This is because the calculations are necessarily simplistic, and extrapolation of data(such as the number of displacments corresponding to a known radiation dose) has had to be read in from other sources. Nevertheless, a pessimistic assumption may be that there may be problems with CTI in certain operational configurations, particularly at higher temperatures.

The variation in CTI will be heavily dependent on the proton fluence over the mission lifetime.

If the required operating temperature cannot be reached, then there are a number of options which may be able to reduce the effect of CTI:

- reduce the overall radiation dose by the addition of suitable shielding (see discussion note three);
- fabricate the CCD to include a notched channel to confine small charge packets;

- increase the clocking rate and trade off with increased read out noise;

4 Maximum operating temperature

The maximum operating temperature required will be determined by the need to heat up the CCD periodically to:

- remove contaminants that will have condensed on the CCD as the coldest surface;
- anneal out some of the radiation induced damage.

It may be possible to reduce the radiation-induced radiation damage somewhat by a room temperature annealing for several hours. Experience gained with the HST WFPC CCDs has found that a room temperature anneal of 6-10 hours is normally sufficient to remove up to 80% of the hot and flickering pixels which have been accumulated due to radiation. In contrast, from tests on EEV devices, Holland et al. (1990) showed a reduction of up to 50% of the CTI after a room temperature anneal for 16 hours. To anneal out any hot and flickering pixels, a high anneal temperature was required (160°C) or so. However, the ability to anneal out CTI at room temperature has not generally been found. For example, Hopkinson et al. (1996) state that a temperature of at least 100°C will be necessary to begin to improve CTI. Measurements on EEV CCD 25-20's for the MERIS programme showed that a 168 hours anneal @ 100°C improved the measured CTI by around 25%.

The EPIC CCD cameras on RGS will be heated up to +40°C for 48 hours after the opening of the door immediately after launch to evaporate any contamination on the CCDs. There is a provision for heating the CCD up to 100°C to attempt to anneal out poor CTI should an unexpected serious degradation occur. However, it should be noted that such an option is a "last resort" option and is only forseen in the event of a serious degredation.

Thus, it is currently unclear whether it is useful increasing the maximum CCD temperature to reduce CTI unless temperatures of 140°C or so can be reached (these temperatures correspond to the thermal activation energies of the traps in question). Consequently, the maximum operating temperature for the CCD required at present is thought be around +30°C or so.

5 Final Temperature selection

It can be appreciated that the data used in this discussion paper comes from a number of sources and have varying levels of confidence attached to them. However, this data must be used to try and reach at least a ball park figure for the CCD operating temperature. Consequently, table five summarises this data, and provides an estimation as to the level of confidence that can be attached to it.

Data	Data value	Source of data	Comments	Confidence level
42-10 dark signal		EEV data sheet		High
Projected radiation environment	7 krad over 5 years mission @ solar min	EEV and MHUI calculations using known orbital parameters (see discussion note 3)		Medium

dark signal after irradiation	400 e/p/s at room temp using dither clocking	EEV technical note	Assuming a 7 krad total dose	High - but also depends on radiation dose.
CTI variation	Calculated using simple simulations based on ref Dale et al. 1993		The simulations are very simplistic and only provide a ball park estimation	Low

Table five: data assumptions and confidence levels

Thus, There should be high confidence in the levels of variation in dark signal with temperature, both before and after irradiation (providing the total radiation dose can be estimated with confidence).

However, two issues hamper the final selection of operating temperature. Firstly, the radiation environment to which Solar-B will be operating does not seem to have been firmly established. Secondly, the simulations of CTI are very simplistic and should only be taken as a guide to the behavior of a device. Consequently, it is difficult to come up with a definitive temperature at which the CCD should be operated. Once a suitable radiation flux is established, it should be possible to come up with "ball park" figures for the CTI variation - however, as explained above, it will still be very difficult to translate this into image degradation.

Consequently, it is recommended that laboratory measurements on irradiated 42-10s are used to establish the precise behavior of the CCD. This should be done as soon as possible.

Until such figures are available however, a best estimate of CCD operting temperature is summarised below.

minimum operating temperature

In choosing the minimum operating temperature, it is important to consider the worst case radiation dose at the end of the mission, in addition, it would be expected that the thermal properties of the EIS radiator would be degraded to some extent by the end of mission. Consequently a conservative choice of operating temperature seems prudent.

To achieve a dark signal approximately equal to the read out electronics noise could require a temperture as low as -78°C if long (15 minutes or so) integration times are required.

It is more difficult to derive an operating temperature to sufficiently minimise the CTI. Adopting a low risks strategy, it can be seen that temperatures of -80°C or so may be required to ensure sufficient performance at the end of mission.

Maximum operating temperatures

Unless quite high temperatures (>140°C) can be achieved, a maximum operating temperature of +30°C to remove contaminants and reduced radiation-induced hot pixels should be taken as the maximum operating temperature.

6 References

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Appendix 1

Estimation of potential CTI values.

Some simplistic simulations have been done, estimating the effect on CTI of clocking rate, electron charge cloud size, and initial radiation dose. The calculations are based on Dale et al. (1993) and also make use of the theory outlined in Hardy 1998 and Gendreau (1995).

The emission time constants for an electron trap is given by

$$Q_{trap} = \frac{g}{\sigma x V_t x N_c} \text{ x } \exp(\frac{E_t}{kT})$$

where g = the level degeneracy (0.5)

σ_n = the electron trapping cross-section

Vt = the electron thermal velocity

Nc = the conduction band density of states ($v_t N_c$ = 1.6 E21 x T2 $s^{-1}cm^{-2}$)

E_t = the trapping state energy band below the conduction band

If we consider a charge being transferred into a pixel into which no charge has previously been transferred (i.e all traps are empty) then the percentage of the charge packet that will be trapped within this pixel is given by CTI_{trap}:

$$CTI_{trap} = \frac{V_s * N_t}{N_s}$$

where V_s = volume of the signal charge packets

N_s = the number of electrons in the charge packet

N_t = the trap density

Due to the finite emission lifetime of the traps, some of this trapped charge will be re-emitted whilst the charge packet is still within the pixel. However, a proportion Q_{remain} of the charge will be retained and will be lost from the charge packet as it transfers out of the pixel, thus, the higher the value of Q_{remain} (for example, at low temperature) the higher will be the CTI (as more charge is retained):

$$Q_{remain} = \exp(\frac{-T_t}{T_s})$$

where T_t = the time the charge remains in the pixel (approximated by the clocking time)

T_e = the emission time constant

Finally, if it is assumed that the charge packet is n pixels behind another charge packet, then as the charge packet is clocked towards the readout register, it will encounter charge that is emitted from traps containing charge from the previous charge packet. This will tend to reduce the CTI (as the charge packet size increases). For example, at very low temperatures, none of the previous trapped charge will be re-emitted, and consequently the CTI will not be reduced

$$Qemit = 1\text{-}\exp\left(-\frac{Ts}{Te}\right)$$

Thus, the effective CTI per pixel is:

$$CTI = CTI_{trap} \times Q_{remain} \times Q_{emit}$$

Assumptions

There are simplifications with the above derivation which mean that the calculation of CTI per pixel should be seen only as providing a "ball park" estimation of potential CTI. It is particularly useful however in seeing how the effects of charge packet size and clocking speed can have dramatic effects on the CTI.

The main simplifications and assumptions made are:

- The probability of encountering an electron trap (CTI_{trap}). The actual charge distribution within a pixel will vary greatly, depending particularly on the amount of charge present, and the pixel structure (for example, whether a "notch" is present to help confine the charge). Effectively, the electron trapping cross section will vary depending on the charge distribution, with proportionally more charge being trapped from smaller packets (for example, see Hardy 1998 for a plot of simulated charge concentrations.
- The values assumed for trap energies, trapping cross-sections, etc. - in particular the values that we should use to estimate the CTI near the end of the mission.

Thus for an approximate estimation of the CTI that could be expected at the end of the mission we can use the figures presented in discussion note three. The values determined for the trap concentrations depends on the total proton flux (and the overall dose). As can be seen, there is a linear relationship between the total proton flux (converted to the equivalent flux @ 10 MeV) and the displacement damage in Silicon.

Trap concentration	Total proton flux (@10 MeV equivalent)	Total dose
5.2 E 10 displacements/cm2	6 E 9 protons/cm2	-
1.3 E 10displacements/cm2	1.5 E 9 protons/cm2	-
	1.79 E 9 protons/cm2/	1 krad
	1 E 10 protons/cm2	7 krad

Table six: the approximate relationship between proton flux, trap concentration and dose

It should be remembered that this dose rate assumes 3mm of Al shielding.

Thus, the values assumed are:

Vs = 3 E-11 cm-3 (13.5µm x 4.5µm x 0.5 µm . - It is assumed that the charge will be found accross the pixel dimension, and all accross one gate of the pixel in the vertical dimension. The approximate depth into the CCD is taken from calculations in Hardy et al. 1998. (Thus, the CTI is quite sensitive to the depth assumed for the pixel -it is also assumed that all the charge is collected under one phase)

Nt = 8.4 E 10 cm-2 for 7 krad dose (end of mission dose)

= 1.5 E 10 cm-2 for 1 krad dose

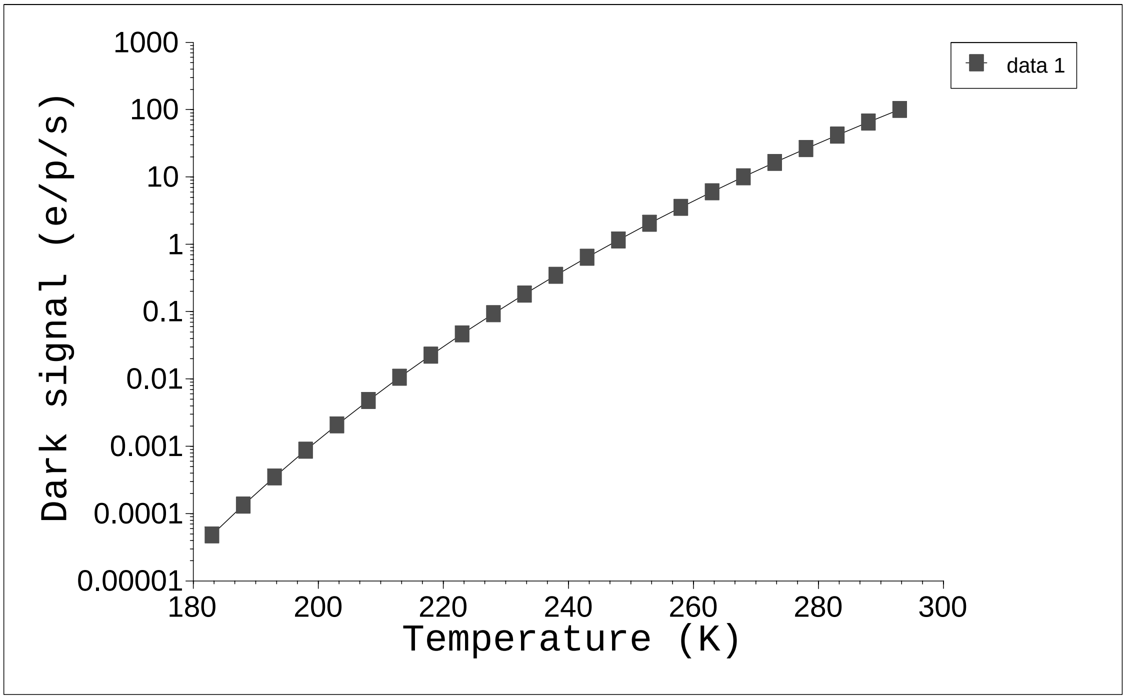


Figure one

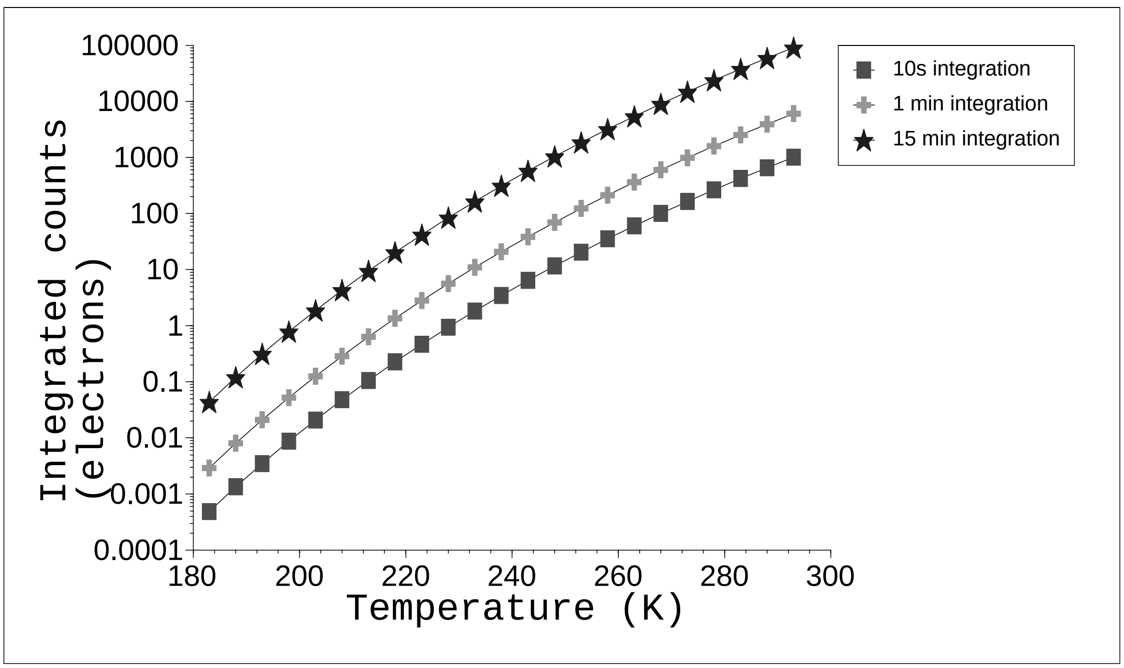
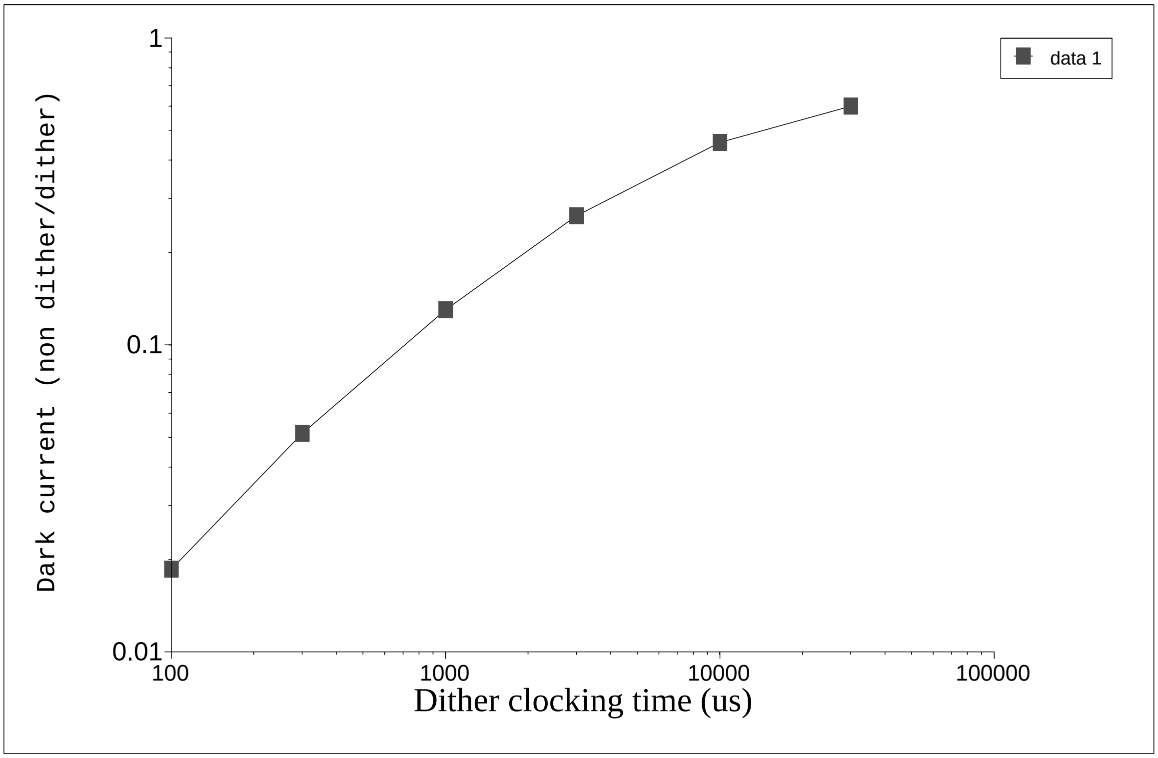
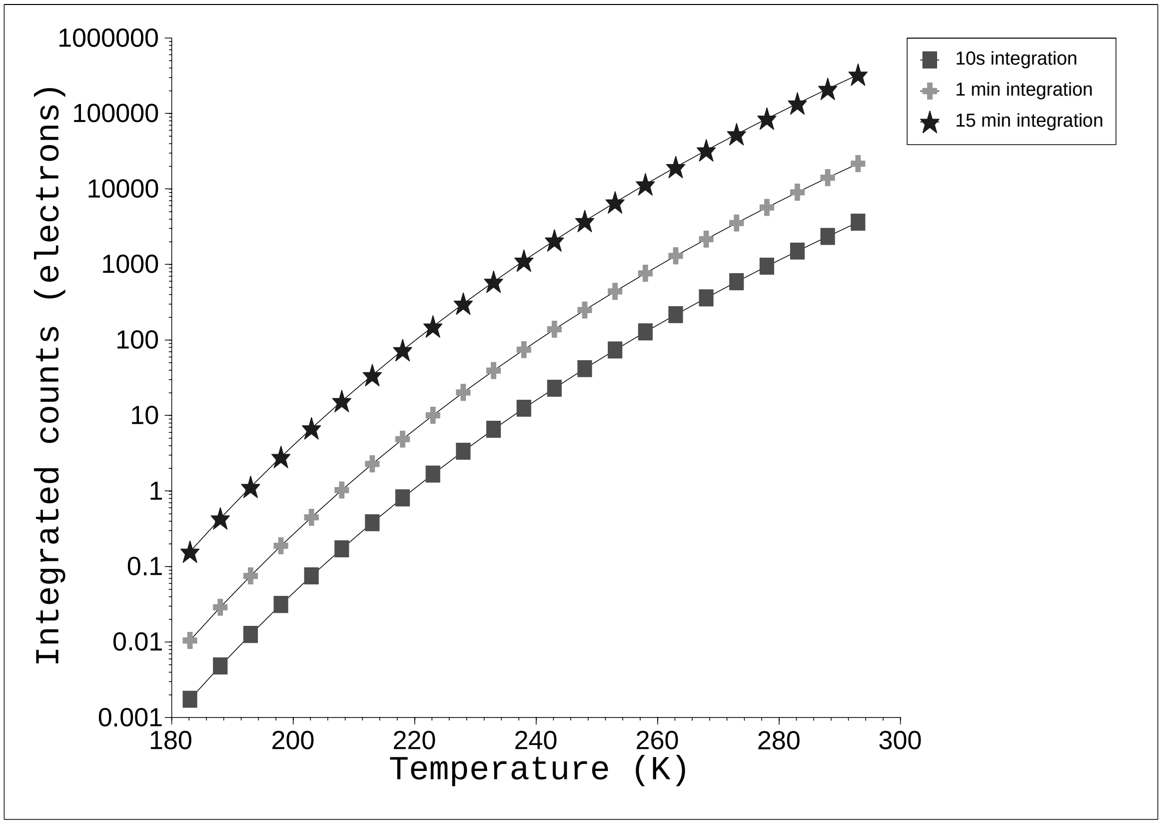


Figure 2



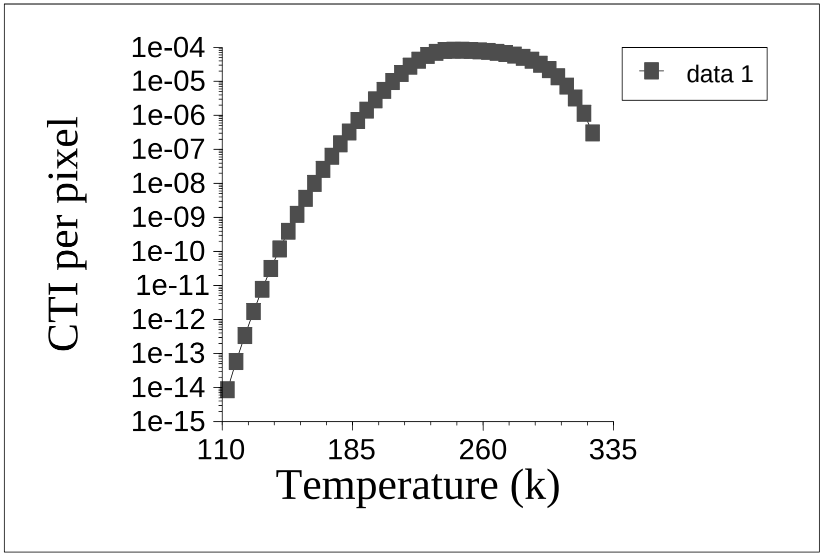
1
0.1
0.01
Dark current (non dither/dither)
100
1000
10000
100000
Dither clocking time (us)
data 1

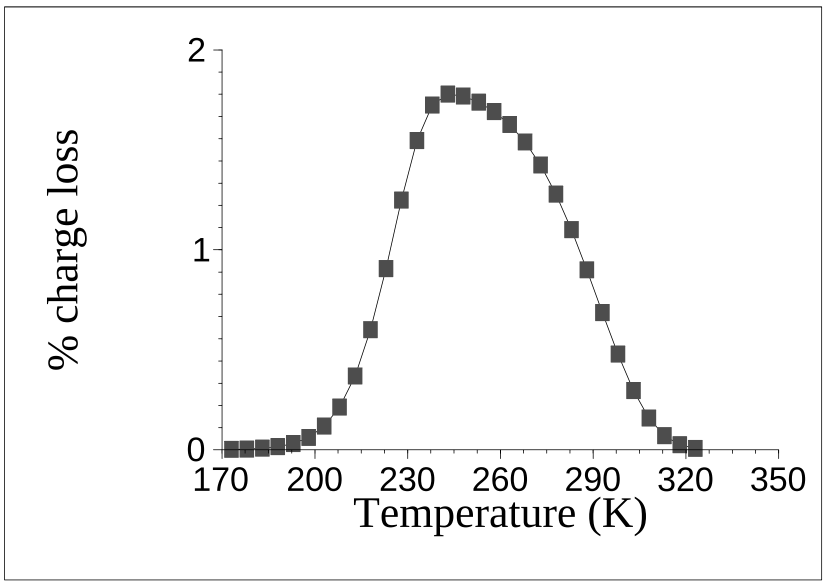
figure 3



Integrated counts (electrons)
1000000
100000
10000
1000
100
10
1
0.1
0.01
0.001
180
200
220
240
260
280
300
Temperature (K)
10s integration
1 min integration
15 min integration

figure four

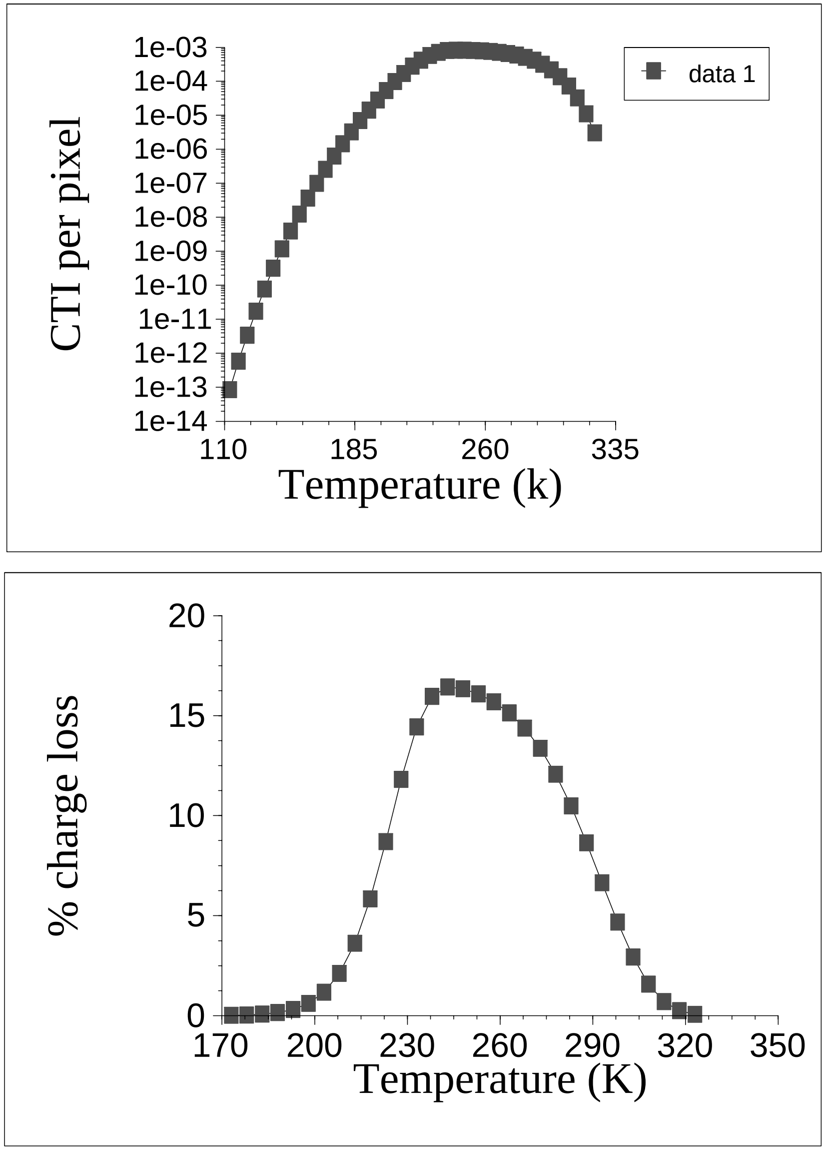




The CTI per pixel and associated charge loss

Values used:

no pixels	220
clocking rates	20us
electron packet size	
size	10000



The CTI per pixel and associated charge loss

Values used:

no pixels 220

clocking rates 20us

electron packet size

size 1000