Effects contributing to Dark Current in Loral and Tek CCDs.

TECHNICAL NOTE 99.

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CONTENTS

1.) Introduction.

Dark current is the signal produced by a CCD in the absence of light. In certain circumstances it can limit the signal to noise ratio of astronomical measurements. The purpose of these tests was to characterise dark current in several CCDs. The effects of overexposure, elevated temperature and settling effects after switch-on were measured. A thinned Tek chip identical to those used at LPO was investigated. A thinned Loral 3 edge buttable device, shortly to be commissioned at LPO was also characterised. Some brief measurements were also made of a thick Loral Lick3, thinned versions of which will be used in the INT prime focus mosaic. All devices were operated in “Standard” mode, with voltages and clocks as listed in Appendix A. further information on the CCDs can be found in Appendix B.

2.) Dark Current Measurement Procedure.

Precise dark current measurements at low temperature require great care given the very low signal levels encountered. The chip cryostat must be in complete darkness and its temperature must be accurately known, since a change of only 5C can produce an approximate doubling of dark current. Low currents require long exposures to give a measurable signal. This in turn introduces the additional complication of removing cosmic ray induced charge from the measurements. At higher temperatures shorter measurement exposures are required, so as not to exceed the full well capacity of the chip. If too short, the read-out time will become comparable to the exposure time and the signal will show a gradient along the y-axis of the image.

To ensure complete darkness the cryostat window was taped over, with a piece of aluminium foil between the tape and the glass, to block fluoresced light from the tape reaching the CCD. Additionally a thick black blanket was placed over the whole assembly. The temperature was recorded using the CCD controller, however, the controller showed considerable errors that had to be modelled out. A DVM was used to measure the actual temperature. The resistance of the Platinum resistor and the Reference resistor located close to the CCD were measured and the following properties assumed:

Reference resistor (-cable resistance) =51 Ohms
Platinum resistor (-cable resistance)= 100 Ohms @0 ^{o}C
Platinum temperature coefficient=-0.385 Ohms/^{o}C

The Loral chip was firmly bolted to an invar block that ensured rapid cooling and stabilisation of the device. The Platinum resistor was bolted to this block and accurately indicated the true CCD temperature. In the case of the Tek chip, however, it was necessary to attach the temperature sensor directly to the chip package. This was essential as the block temperature differed from the chip temperature by as much as 20 degrees.

Dark current was automatically logged on the VME system during overnight runs where the CCD temperature was incremented in 5 degree steps. Before each run sufficient time was allowed for electronic settling. When each target temperature was reached, a delay loop waited 500s prior to the commencement of a dark exposure. The temperature of the CCD before and after each exposure was stored on the parameter stack of the VME to ensure that the temperature control servo was operating correctly. When measuring the dark current of the Tek CCD as a function of temperature, the measurements had to be made manually. Here the chip required at least one hour to stabilise at its new temperature and this needed to be confirmed by a manual check of the Platinum sensor resistance.

Images were transferred from the VME system to the Suns for analysis, the VME system being inadequate for the purpose. In order to exclude both cosmic rays and faulty pixels and columns, two programs were written in IRAF script. The first calculates the mean of the bias signal by looking at pixel values in the serial underscan. The calculation is made using only pixels that lie between certain values input by the user, after a suitably scaled histogram has been examined. The second program is very similar but calculates the mean of image area pixels. Listings of these tasks can be found in Appendix D. Each dark current frame that was recorded included a section of serial underscan. The dark current signal was then equal to the mean signal in the image area minus the mean signal in the underscan area. Cosmic rays would produce a series of histogram spikes clearly separate from the main histogram peak produced by actual dark current signal. The cosmic rays could then be easily filtered out by judicious placement of the upper pixel value boundary.

The statistical significance of the results depends on the read noise and the number of pixels in the image. The smallest images used contained 240000 pixels, read noise was typically 10e RMS. The measurement software produces highly repeatable results to sub-electron accuracy.

3.) Dark current as a function of temperature.

3.1.) Theoretical models.

The equation for the leakage current in a diode(Beck & Ahmed, “Physical Electronics”, p100) has been widely quoted by other researchers as a description of the dark current in a CCD. This equation is :

$$I=I_oEXP(-E_g.q/2kT)$$

where:
E_g = Band gap voltage of Silicon
q = Electronic charge

This equation did match the experimental data for both the Loral and Tek CCDs.

3.2.) Dark Current in the Tek.

This chip followed the theoretical model well only down to a temperature of -95 degrees. Below this the dark current levelled off at about 1.3 electrons per pixel per hour. If the data is extrapolated to +20 degrees it corresponds to a current of XXXX nA/cm^{-2}. The best fit theoretical curve to the data can be obtained by using the following co-efficients :-

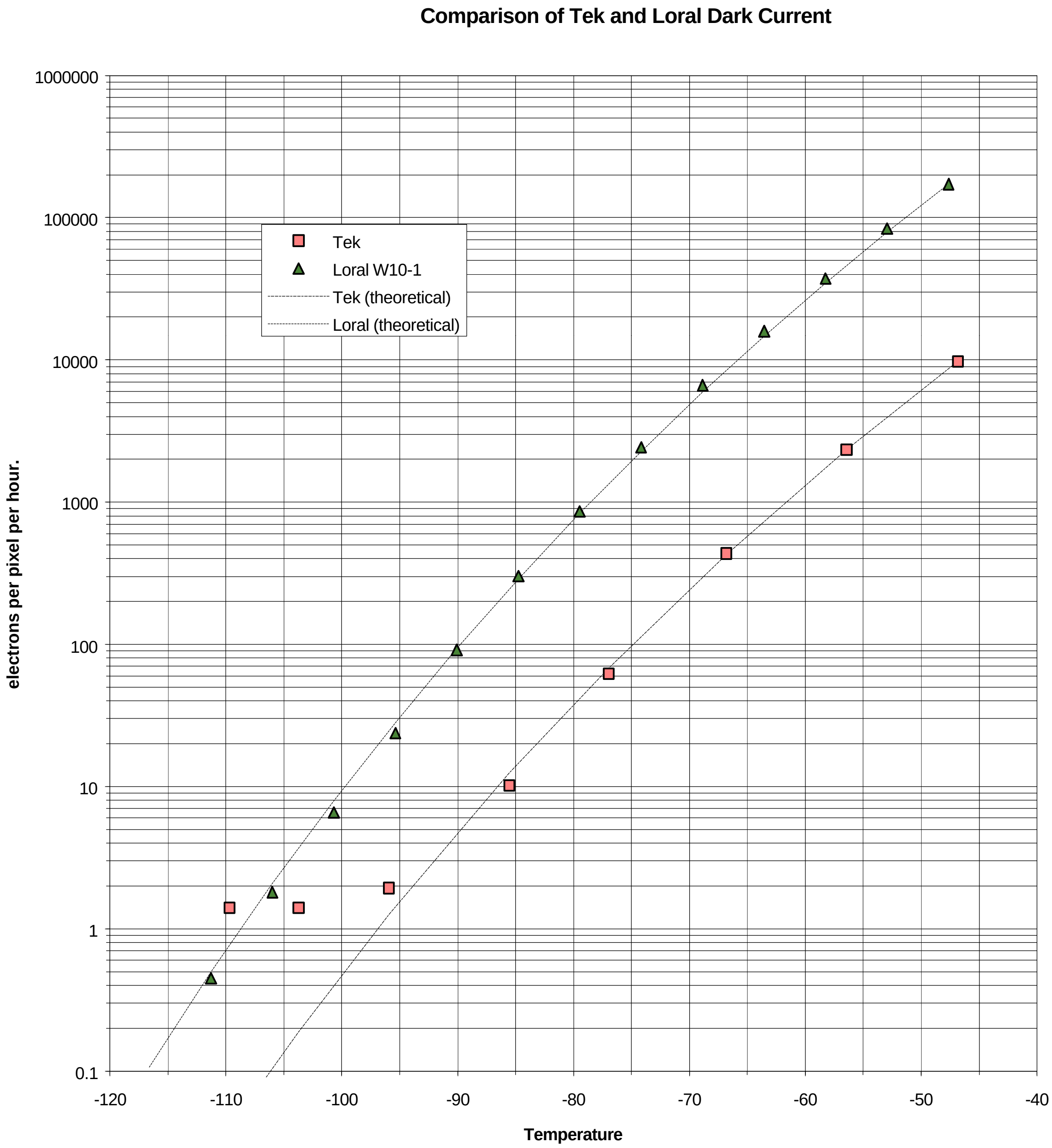
E_g= 1.26eV
I_o= 8 x 10^{17} e^- pix $^{-1}$ hr^{-1} .

3.3. Dark Current in the Loral W10-1.

This device followed the theoretical model across 6 orders of magnitude in dark current. It showed no levelling off at low temperatures. Below -115C the dark current was un-measurable. At higher temperatures the device showed 25 times greater dark current than the Tek. This is very surprising as the Loral has 15um pixels, the Tek 24um pixels. The difference is probably indicative of varying surface treatments in the two devices. The best fit theoretical curve to the data can be obtained by using the following co-efficients :-

E_g= 1.26eV
I_o= 2 x 10^{19} e^- pix $^{-1}$ hr^{-1} .

Data for both chips is shown on the following page.

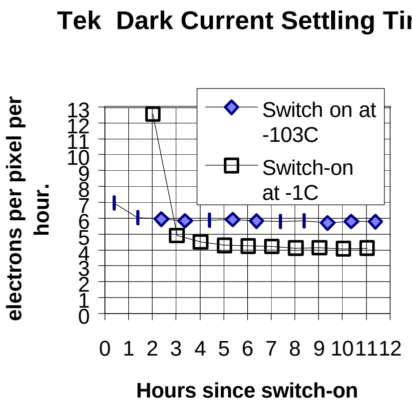


4.) Settling time after switch-on.

Immediately after switch-on, the dark current of a CCD is at an elevated level. It is thought that this is due to the presence of trapping centres and surface states. In time, these states will be filled and their contribution to the dark current will fall. The settling time of a CCD will be the time taken for dark current generated in this way to fall to acceptable levels. This period was established for both Loral and Tek CCDs.

4.1.) Settling Time for the Tek.

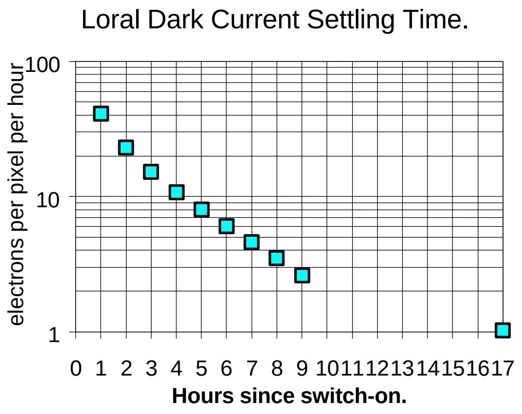
The Tek was found to settle very rapidly, its dark current reaching a floor only 3 hours after being switched on. If the device was switched on at -1C and then cooled to operating temperature, the settling time was found to be similar. The baseline dark current in these two cases are not identical, as can be seen from the following graph. This, however, is not significant and is probably due to a small temperature servo offset error.



These measurements were made on a Tek chip which had no directly attached temperature sensor, the quoted operating temperature in the graph of -103C corresponds to the block temperature only. The true chip temperature was about 15C higher.

4.2.) Settling time for the Loral W10-1.

This CCD showed an exponential drop in dark current after switch-on. It took 4 hours to fall below 10 e^- pix^{-1} hr^{-1}. Approximately 24 hours are needed to fall below 1 e^- pix^{-1} hr^{-1}. The chip was switched on at operating temperature.

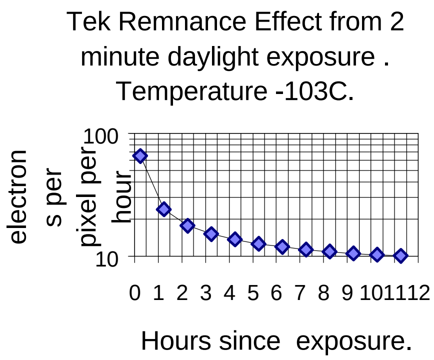


5.) Overexposure Remnance Effects.

Massive overexposure of a CCD can produce a remnant image which manifests itself as spuriously high dark current in the affected areas. Ghost images can result on subsequent frames. It may be overcome by special clocking schemes whereby the electrode potentials are modulated during integration, but these were not implemented at the time of the tests. Remnance effects were assessed by massively overexposing the CCDs to either room lights or the pre-flash LEDs. This was followed by several clearings of the chip to remove any accumulated charge. A series of dark frames was then recorded for up to 12 hours.

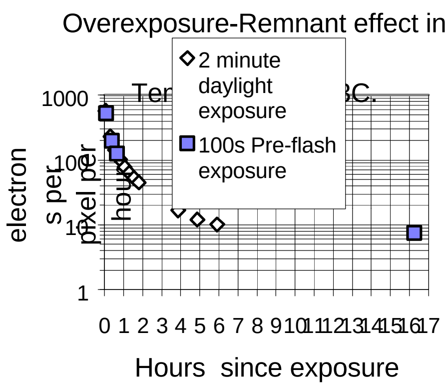
5.1.) Remnance in the Tek.

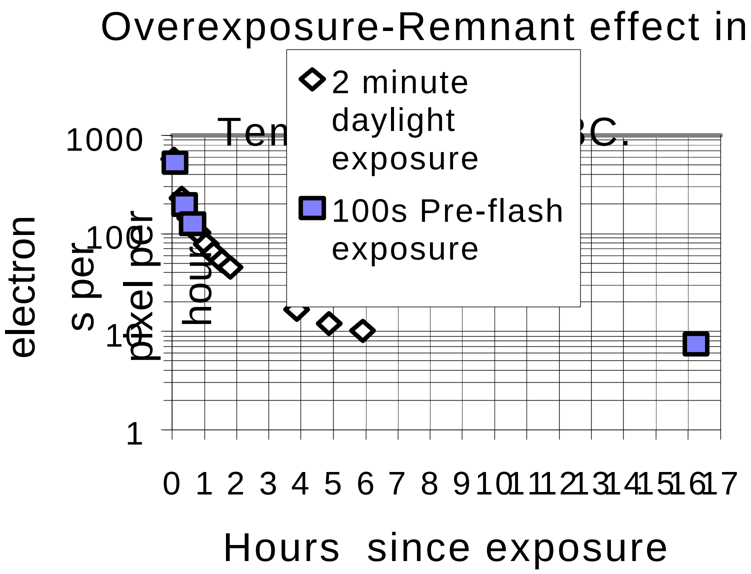
The Tek chip was exposed to room lights for 2 minutes. After 1 hour, a remnance current of 30 e^- pix $^{-1}$ hr^{-1} persists and even at the end of a 12 hour run it still measures 10 e^- pix $^{-1}$ hr^{-1}.



5.2.) Remnance in the Loral W10-1.

The Loral CCD was also given a 2 minute daylight exposure. The dark current took 6 hours to fall below 10 e^- pix $^{-1}$ hr^{-1}. It was subsequently given a 100s exposure using the preflash LEDs. The remnance effect was very similar to that produced by daylight despite their different spectral characteristics. The graph indicates that several days may be required for the Loral to reach its baseline dark current following daylight exposure.





6.) Accuracy of the Cryostat Temperature Servo.

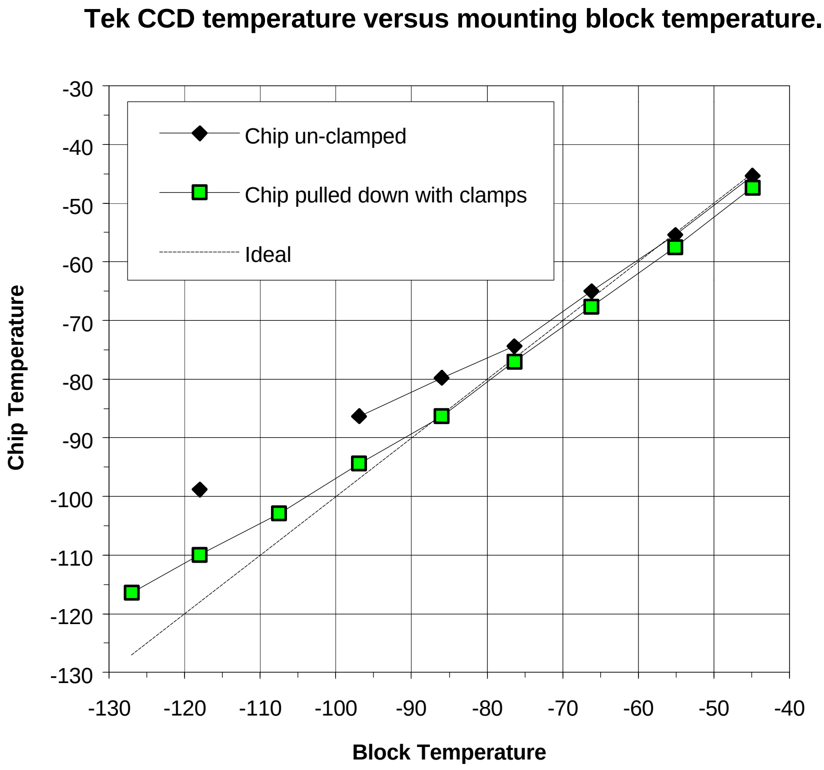
In order to obtain good quality dark current data, the performance of the temperature control systems in the cryostats were characterised in detail. As a 5K temperature error corresponds to an approximate doubling of dark current, the true temperature of the CCD must be known to within 1 or 2 degrees for worthwhile measurements to be possible.

Firstly, the performance of the CCD controller temperature servo crcuitry was examined. Manual measurements of the internal Platinum resistance thermometer were compared with the value returned using the 'TEMP' command on the VME system. Errors of up to 3 degrees were found. The results are in Appendix C.

Secondly, the actual temperature of the Tek CCD was compared to the temperature of the copper mounting block which contained the Platinum thermometer. A second thermometer was glued directly to the CCD package for tthis purpose. The Tek package is rather inconveniently at substrate potential. Since we generally operate with substrate at -6V, an insulator must be placed between CCD and copper mounting block. This produces a high thermal resistance resulting in a temperature differential of up to 20K. Above -75^{0}C the differential is small, but as the block cools further it is thought to contract away from the bottom of the CCD package. This effect can be reduced by pushing the CCD down hard onto the block using two insulated metal clamps. The results can be seen in the following graph.

The true temperature of the Loral CCD was not measured and it was assumed that the temperature differential across the chip package - mounting block interface was small. Since the package was held down with 4 metal bolts this seemed like a fair assumption.

This was further backed up by the results of attempting to match the observed dark current to a theoretical model (see section 3.1.).



APPENDICES

A. Operating voltages of CCDs

Potential	Tek	Thick Loral Lick3	Loral W10-1
RD	7	6.5	6.5
OD (read)	16	15	15
OD (Integrate)	7	7	7
OG	-6	-6	-6
VSS	-7	-7	-7
ABG	-7	-6	-6
BG	3	3	3
ABD	7	7	7
V++	-4	-3	-4
V-	-15	-15	-11
H++	3	-2	-2
H-	-9.5	-12	-12
R+	3	1	1
R-	-9	-7	-7

B. CCD Physical Parameters

Type	Tek	Loral Lick3	Loral 3EB
Pixel size	24um square	15um square	15um square
Package	ZIF mount	ZIF mount	Bolt-down mount
Format	1k square, thinned	2K square, un-thinned	2K square thinned. 3EB
Serial Number	1374BR1702R		W10-1

C. Temperature Calibration Data

Tek CCD + Development controller.

Indicated Temp (C)	Platinum Resistance	Reference Resistance	Actual Temperature (C)
-120.7	57	55.4	-123.1
-45.8	87.1	55.4	-44.9
18.6	113.2	55.5	22.6

Tek CCD + Prototype CCD controller.

Indicated Temp (C)	Platinum Resistance	Reference Resistance	Actual Temperature (C)
-96.7	65.9	55.3	-99.7
-60.7	80.5	55.3	-61.8
-28.5	93.2	55.3	-28.83

Loral W10-1 + Prototype CCD controller.

Indicated Temp (C)	Platinum Resistance	Reference Resistance	Actual Temperature (C)
-120.7	57	55.4	-123.12
-45.8	87.1	55.4	-44.94
18.6	113.2	55.5	22.6

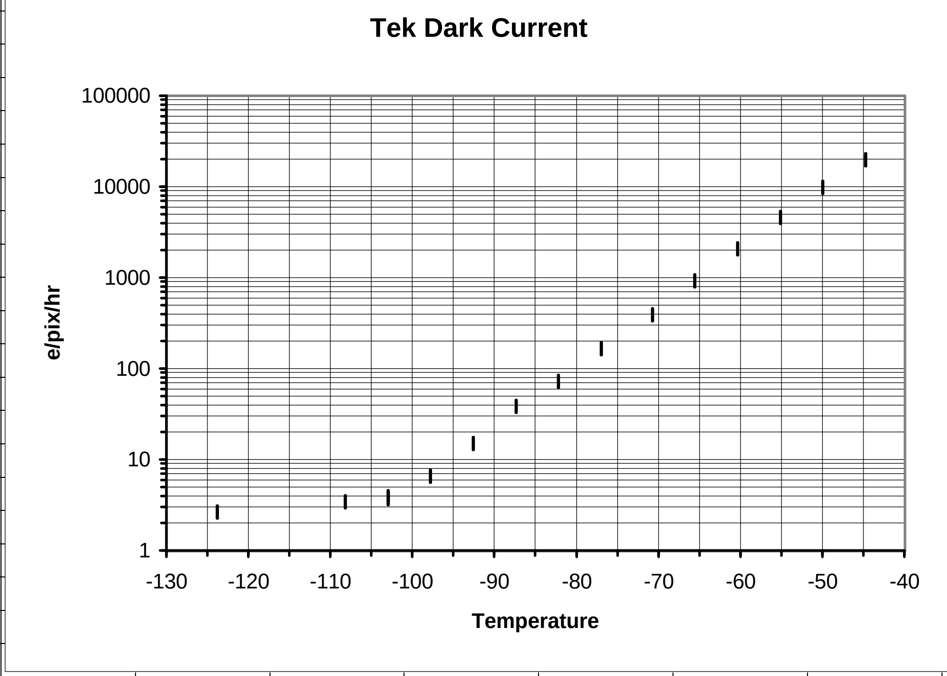
Loral W10-1 + Development CCD controller.

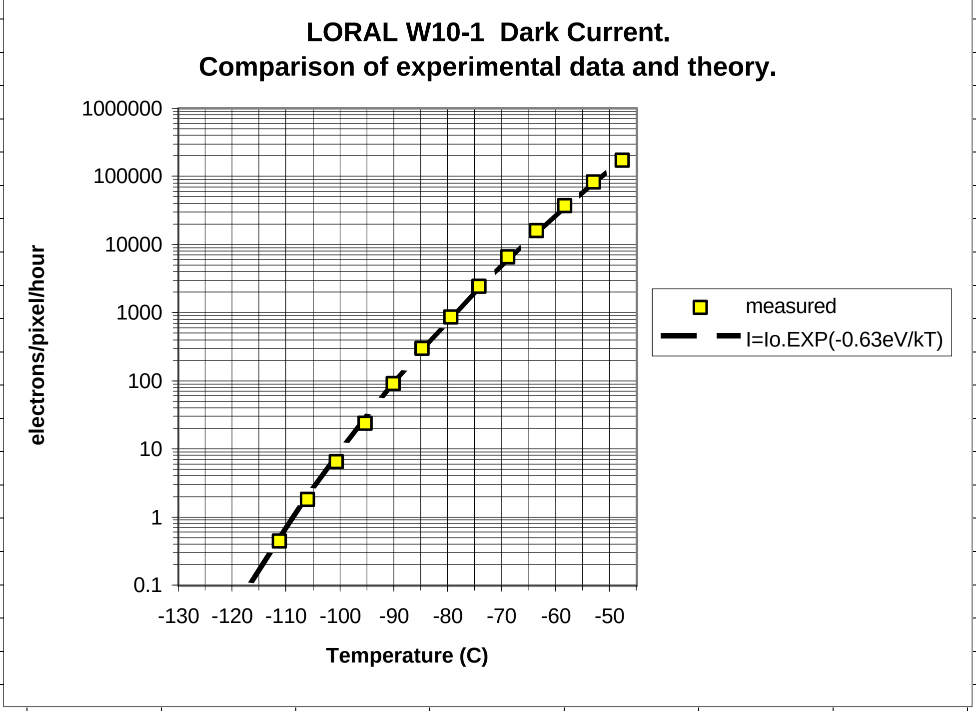
Indicated Temp (C)	Platinum Resistance	Reference Resistance	Actual Temperature (C)
-120.5	58.4	56.2	-121.6
-61.9	82	56.2	-60.3
-83.2	73.3	56.2	-82.9

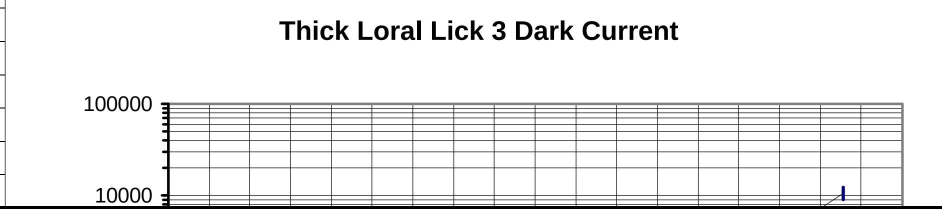
D. IRAF scripts to measure dark current and bias levels.

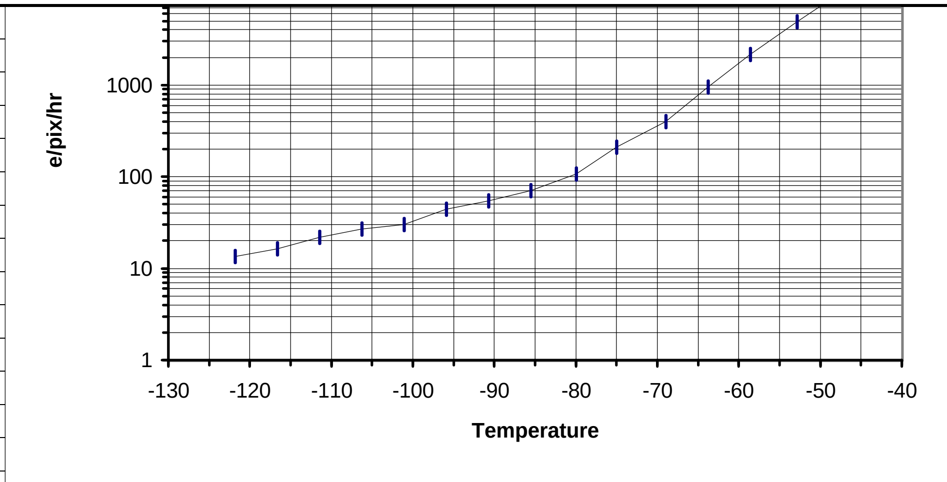
```
procedure findark (im,up,lw)

# Finds signal level in the image area of a dark frame.

file im {prompt="Image file name ?"}
int up {prompt="Upper image pixel value?"}
int lw {prompt="Lower image pixel value?"}
struct *clist

# SMT August 3 1995
# Program expects a chip format file called "cformat"
# Format of file as follows :
# uscan x-min,uscan x-max,uscan y-min,uscan y-max
# image x-min,image x-max,image y-min,image y-max

begin
string dframe,cfile,tstring
int d1,d2,d3,d4,x1,x2,y1,y2,bs
real res
print(" ")
print("PROGRAM TO CALCULATE DARK CURRENT")
dframe = im
cfile = "cformat"
clist = cfile

# Read  bias format data:
if ( fscan(clist,x1,x2,y1,y2) == EOF ) print(" ")
tstring=dframe+"[" + x1 + ":" + x2 + "," + y1 + ":" + y2 + "]"

# Get rough idea of the bias value
imstat(tstring,fields="mean",format=no) | scan(bs)

# Read image area format data
if ( fscan(clist,x1,x2,y1,y2) == EOF ) print(" ")

# Select measurement area from image
tstring=dframe+"[" + x1 + ":" + x2 + "," + y1 + ":" + y2 + "]"

# Find mode and set x-axis limits for the histogram plot.
imstat(tstring,fields="mode",format=no) | scan(x1)
if ((x1-bs)<50)
        # For very low dark signals we need extra horizontal resolution
        imhist(tstring, z1=(0.93*x1), z2=(1.07*x1), binwidth=2)
        else
        # For large signal levels courser resolution will suffice
        imhist(tstring, z1=(0.6*x1), z2=(1.6*x1), binwidth=2)

# Find mean of pixels with values between user specified limits
imstat(tstring, fields="mean",lower=lw,upper=up,format=no) | scan(res)

print(" ")
print("Image region mean of file '",dframe ,"' = ",res," ADU")
print(" ")
end
```

```
 procedure findbias (im,up,lw)

# Finds signal level in the serial underscan of a dark frame.

file im {prompt="Image file name ?"}
int up {prompt="Upper bound of bias pixel values?"}
int lw {prompt="Lower bound of bias pixel values?"}

struct *clist

# SMT August 3 1995
# Program expects a chip format file called "cformat"
# Format of file as follows :

# uscan x-min,uscan x-max,uscan y-min,uscan y-max
# image x-min,image x-max,image y-min,image y-max

begin
string dframe,cfile,tstring
int x1,x2,y1,y2
real res,std
print(" ")
print("PROGRAM TO CALCULATE BIAS LEVEL")
dframe = im
cfile = "cformat"
clist = cfile

# Read bias area format data
if ( fscan(clist,x1,x2,y1,y2) == EOF ) print(" ")

# Select measurement area from image
tstring=dframe+"[" + x1 + ":" + x2 + "," + y1 + ":" + y2 + "]"

# Find mode and set x-axis limits for the histogram plot
imstat(tstring,fields="mode",format=no) | scan(x1)
imhist(tstring, z1=(0.92*x1), z2=(1.09*x1), binwidth=2)

# Find mean and stddev of pixels with values between user specified limits
imstat(tstring, fields="mean,stddev",lower=lw,upper=up,format=no) | scan(res,std)
s2=str(std)
s1=substr(s2,1,5)
print(" ")
print("Bias mean of file '", dframe ,"' = ",res,"ADU")
print("Bias stddev (RMS noise) = ",s1," ADU")
print(" ")
end
```

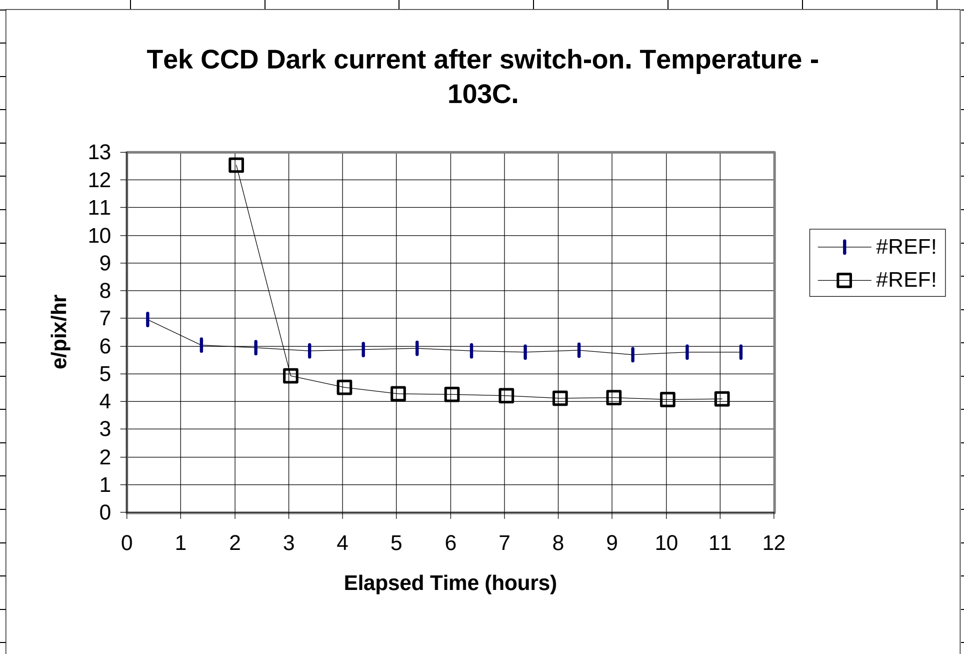

Tek Dark Current
e/pix/hr
100000
10000
1000
100
10
1
-130
-120
-110
-100
-90
-80
-70
-60
-50
-40
Temperature


LORAL W10-1 Dark Current.
Comparison of experimental data and theory.
electrons/pixel/hour
1000000
100000
10000
1000
100
10
1
0.1
-130 -120 -110 -100 -90 -80 -70 -60 -50
Temperature (C)
measured
I=Io.EXP(-0.63eV/kT)

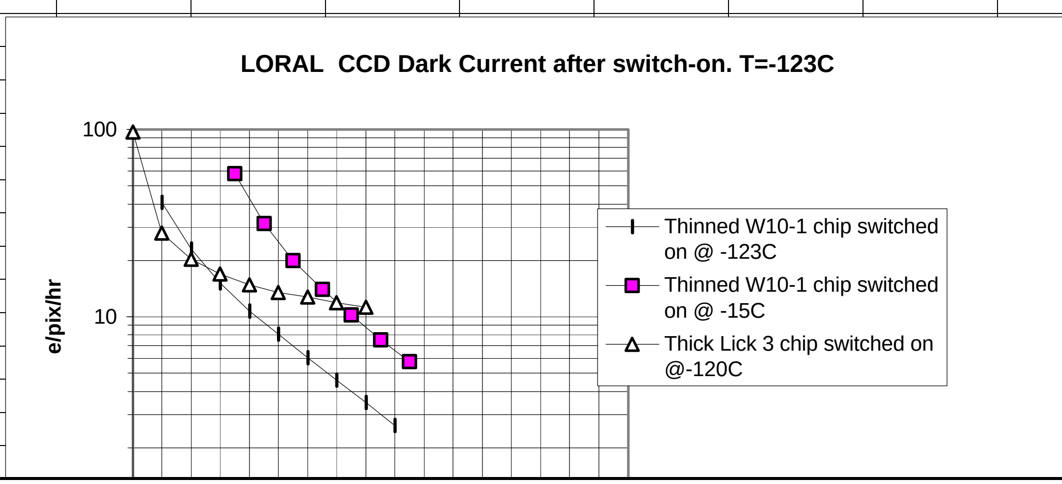

Thick Loral Lick 3 Dark Current
100000
10000



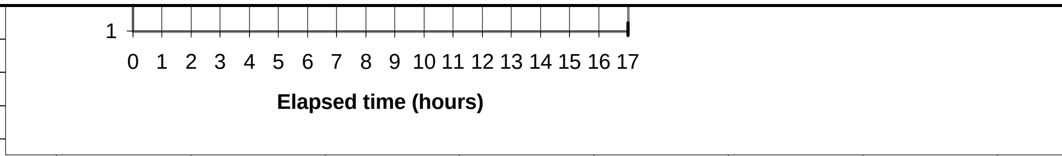
e/pix/hr
1000
100
10
1
-130
-120
-110
-100
-90
-80
-70
-60
-50
-40
Temperature

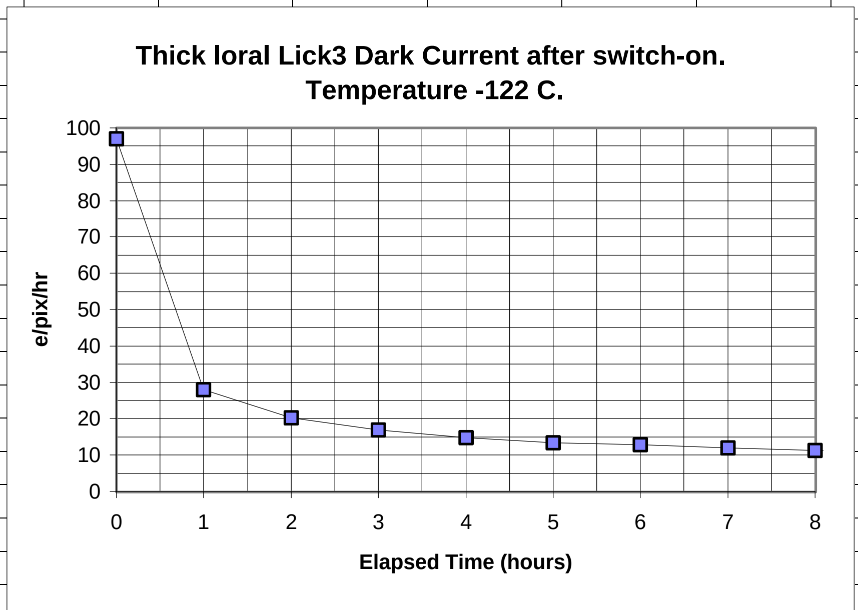


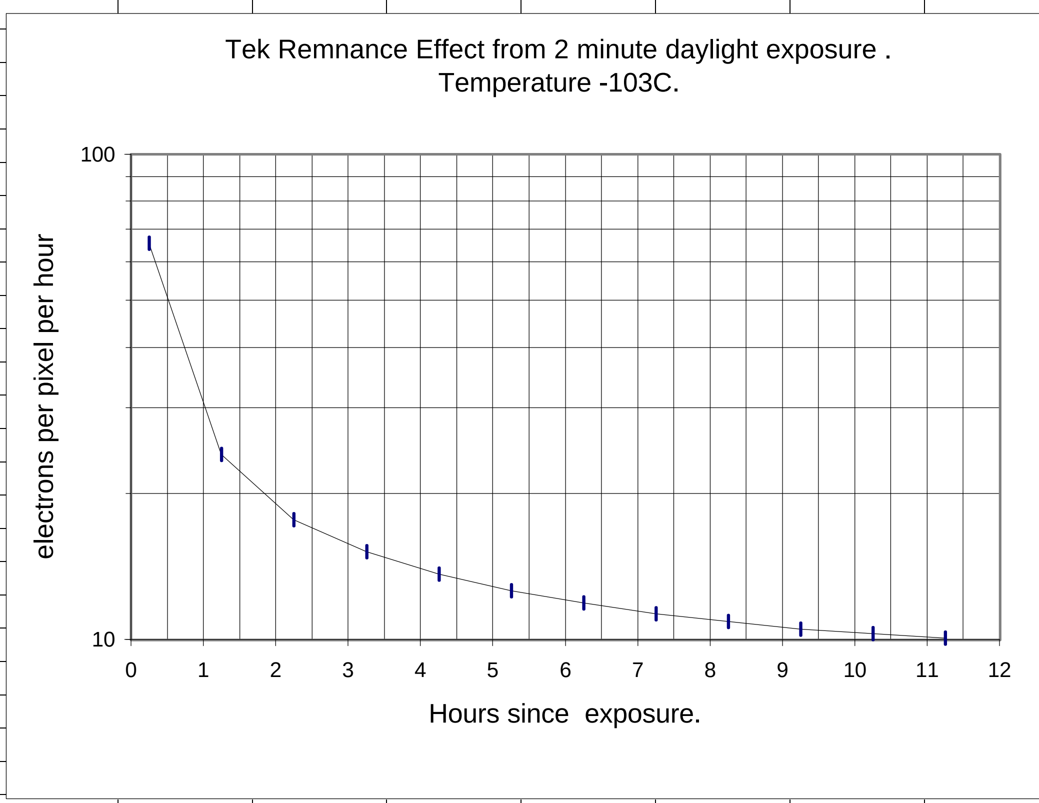
Tek CCD Dark current after switch-on. Temperature -103C.
e/pix/hr
Elapsed Time (hours)
#REF!
#REF!

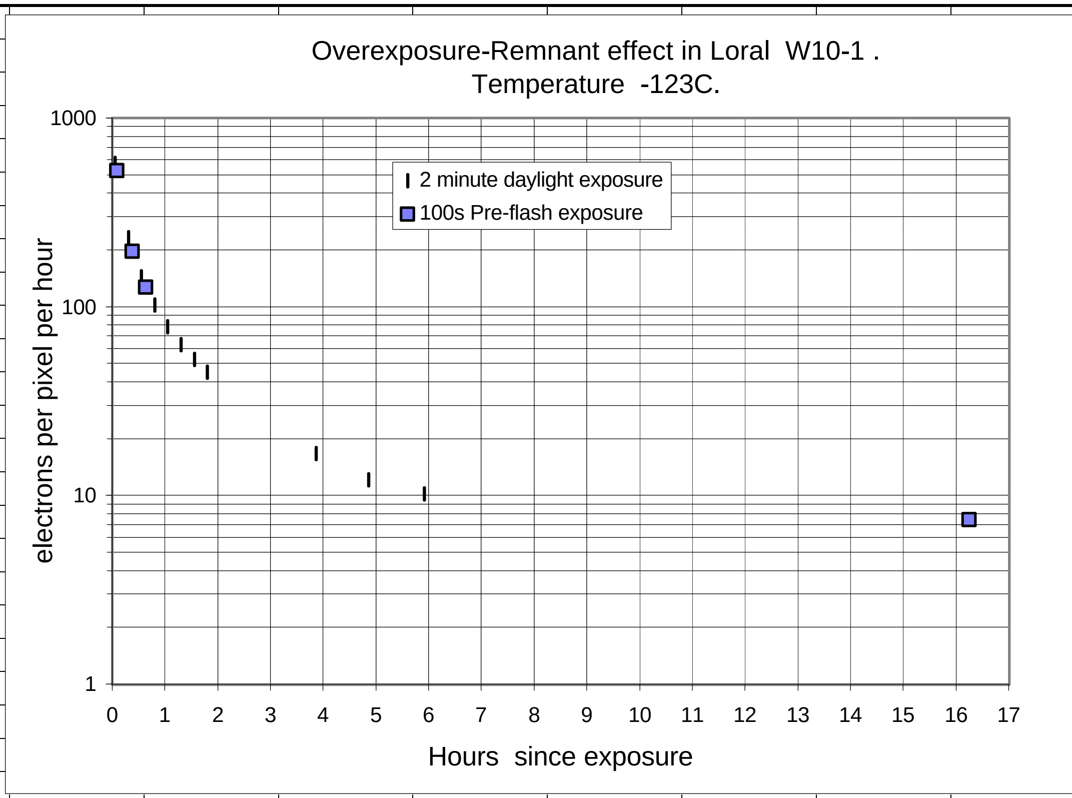


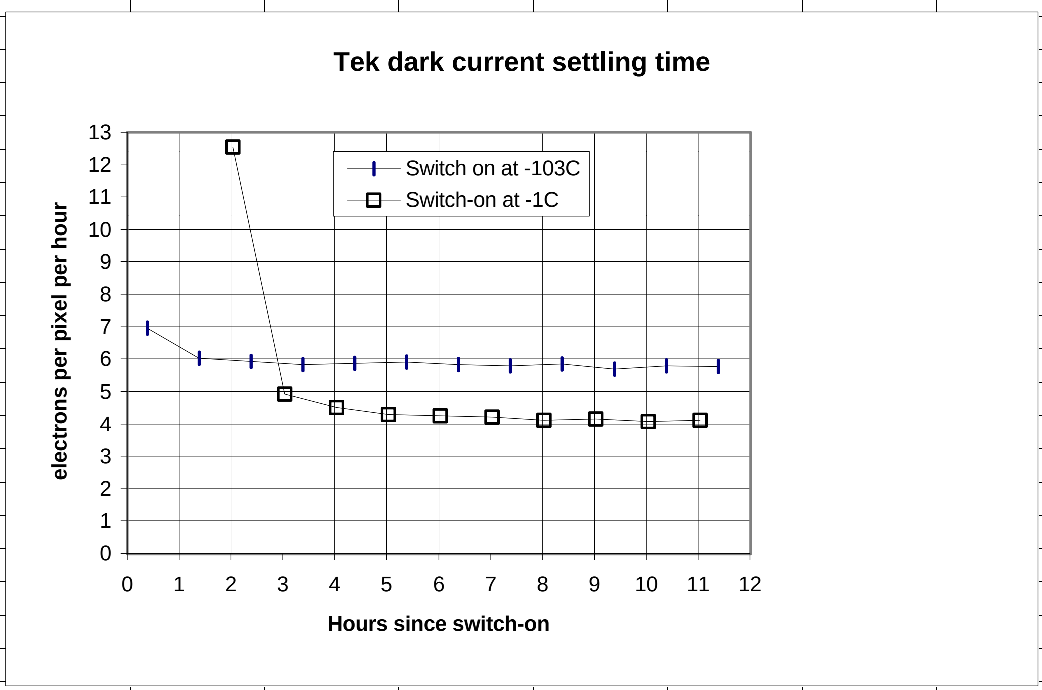
LORAL CCD Dark Current after switch-on. T=-123C
e/pix/hr
100
10
Thinned W10-1 chip switched on @ -123C
Thinned W10-1 chip switched on @ -15C
Thick Lick 3 chip switched on @-120C

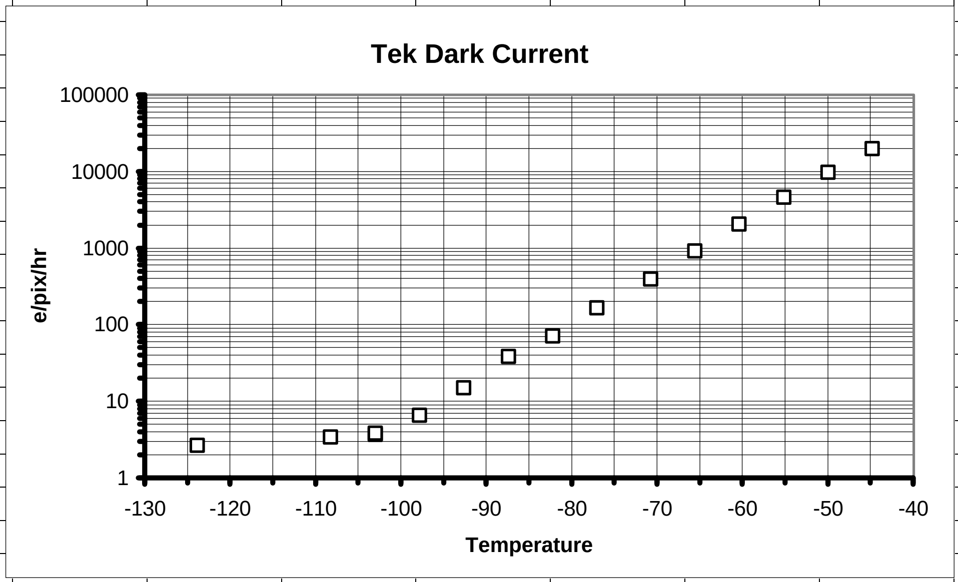

1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Elapsed time (hours)

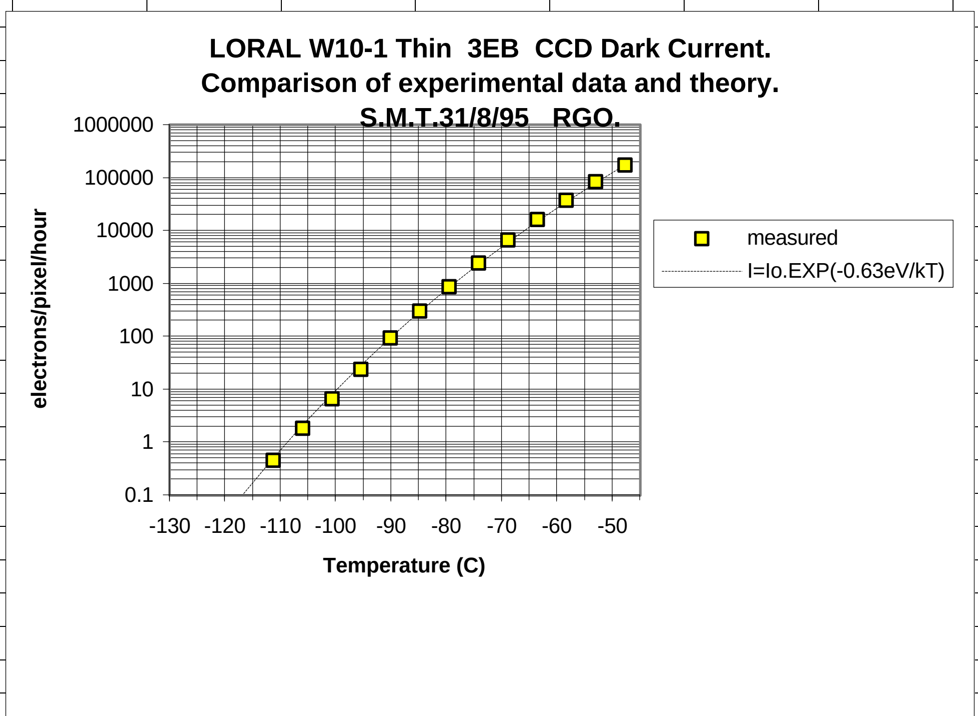

Thick loral Lick3 Dark Current after switch-on.
Temperature -122 C.
e/pix/hr
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8
Elapsed Time (hours)

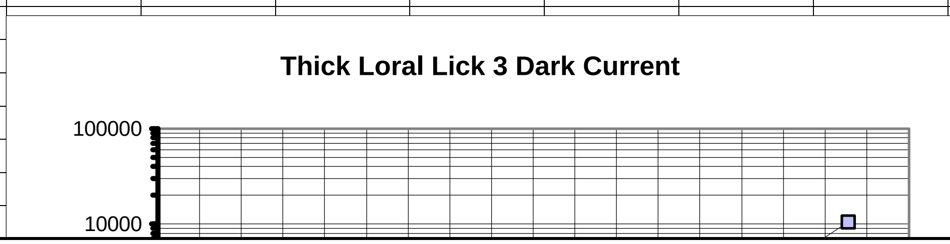

Tek Remnance Effect from 2 minute daylight exposure .
Temperature -103C.
electrons per pixel per hour
100
10
0 1 2 3 4 5 6 7 8 9 10 11 12
Hours since exposure.

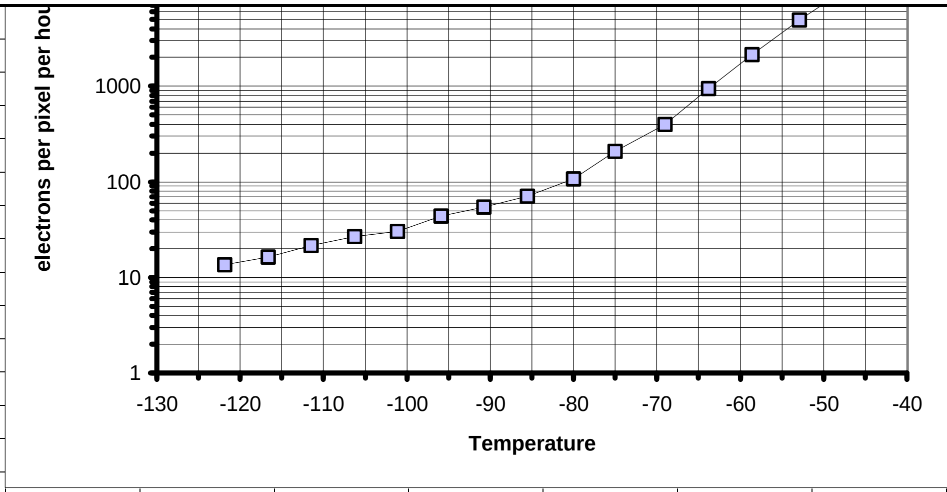

Overexposure-Remnant effect in Loral W10-1 .
Temperature -123C.
2 minute daylight exposure
100s Pre-flash exposure
electrons per pixel per hour
1000
100
10
1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Hours since exposure

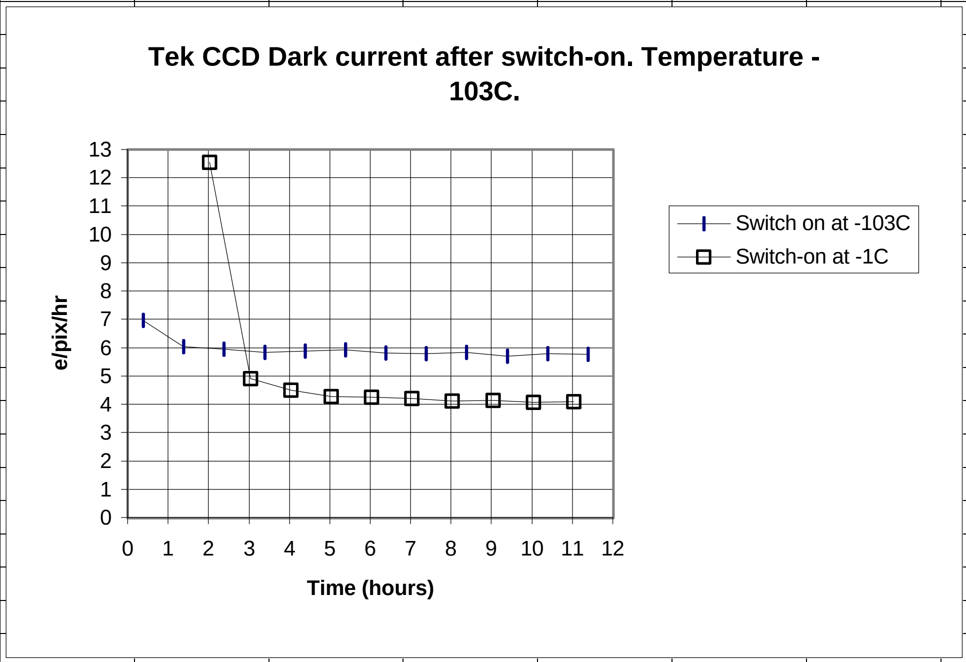

Tek dark current settling time
Switch on at -103C
Switch-on at -1C
electrons per pixel per hour
13 12 11 10 9 8 7 6 5 4 3 2 1 0
0 1 2 3 4 5 6 7 8 9 10 11 12
Hours since switch-on

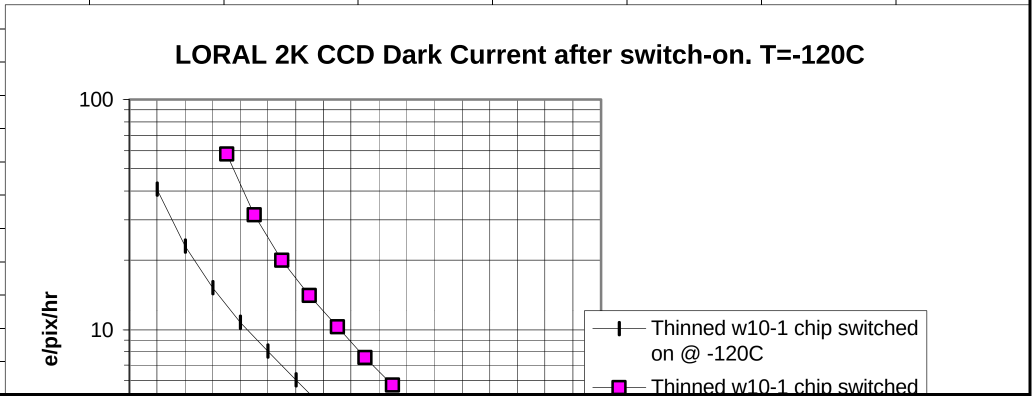

Tek Dark Current
100000
10000
1000
100
10
1
e/pix/hr
-130
-120
-110
-100
-90
-80
-70
-60
-50
-40
Temperature

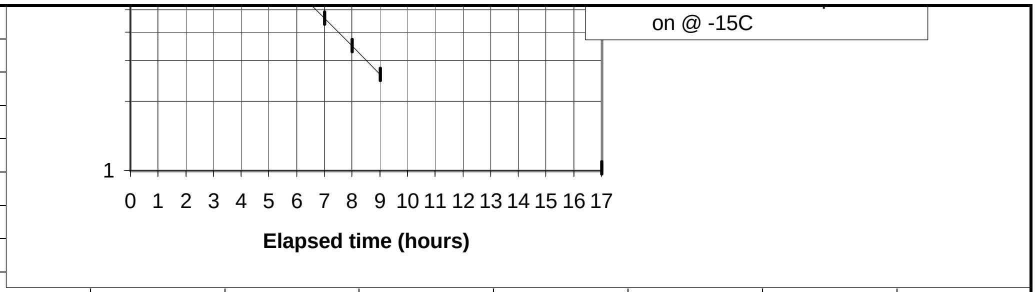

LORAL W10-1 Thin 3EB CCD Dark Current.
Comparison of experimental data and theory.
S.M.T.31/8/95 RGO.
1000000
100000
10000
1000
100
10
1
0.1
electrons/pixel/hour
-130 -120 -110 -100 -90 -80 -70 -60 -50
Temperature (C)
measured
I=Io.EXP(-0.63eV/kT)

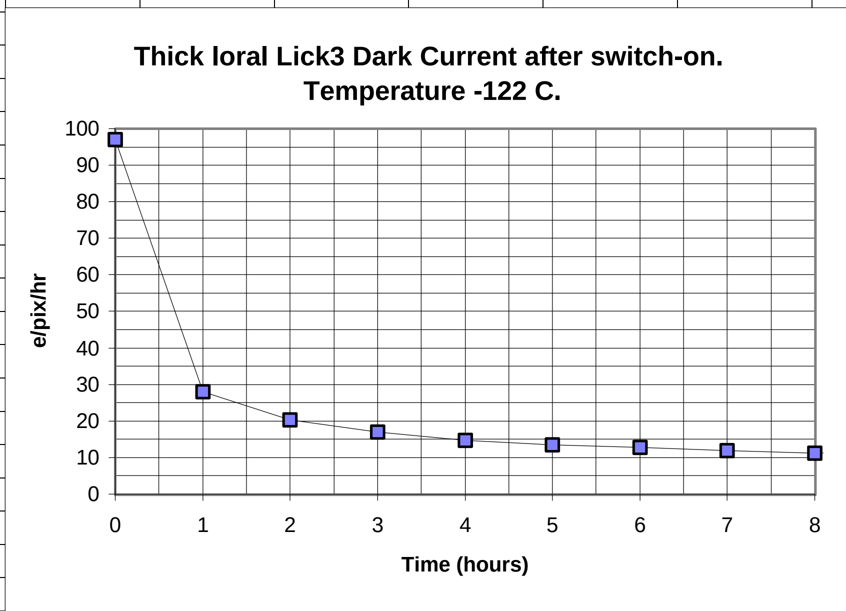

Thick Loral Lick 3 Dark Current
100000
10000

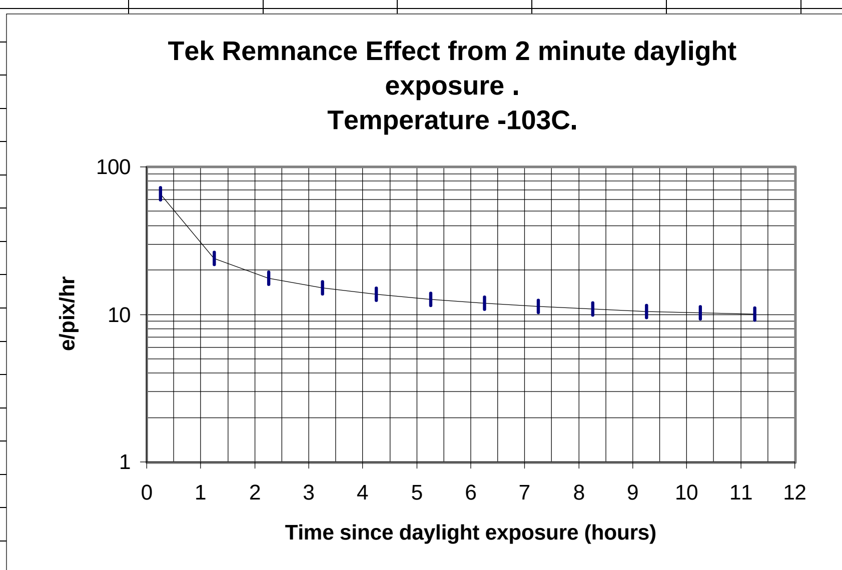

electrons per pixel per hou
1000
100
10
1
-130
-120
-110
-100
-90
-80
-70
-60
-50
-40
Temperature

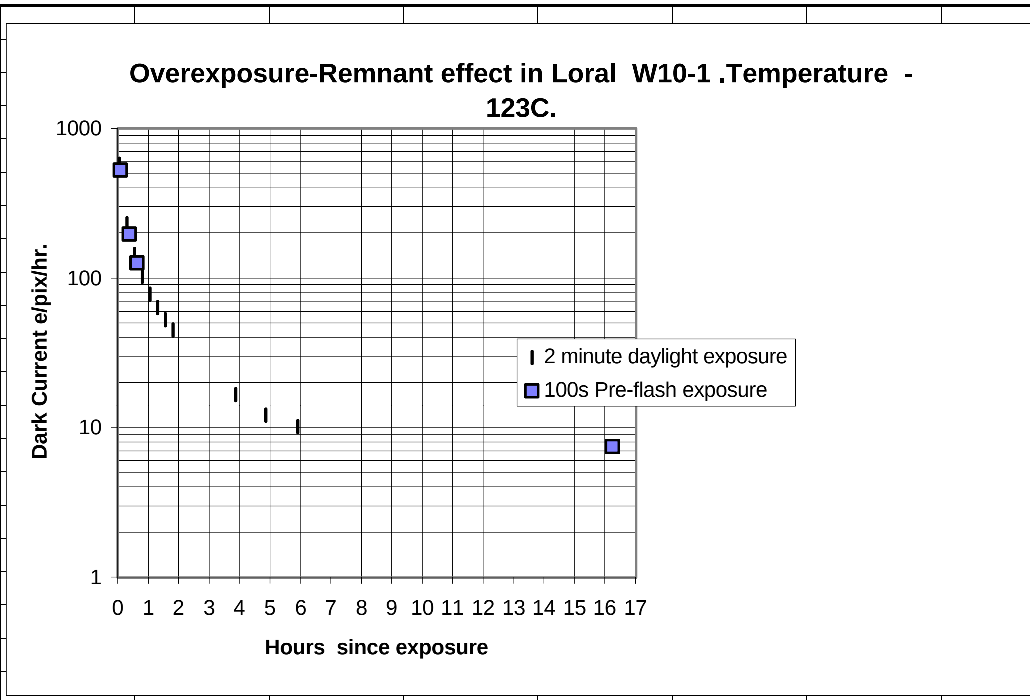

Tek CCD Dark current after switch-on. Temperature -103C.
e/pix/hr
Time (hours)
Switch on at -103C
Switch-on at -1C


LORAL 2K CCD Dark Current after switch-on. T=-120C
100
10
e/pix/hr
Thinned w10-1 chip switched on @ -120C


on @ -15C
1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Elapsed time (hours)


Thick loral Lick3 Dark Current after switch-on.
Temperature -122 C.
e/pix/hr
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8
Time (hours)


Tek Remnance Effect from 2 minute daylight exposure .
Temperature -103C.
e/pix/hr
100
10
1
0 1 2 3 4 5 6 7 8 9 10 11 12
Time since daylight exposure (hours)


Overexposure-Remnant effect in Loral W10-1 .Temperature -123C.
Dark Current e/pix/hr.
1000
100
10
1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Hours since exposure
2 minute daylight exposure
100s Pre-flash exposure