FLI PL16803 Standard Grade Camera Characterization: Photon/Dark Transfer Curve Analysis and RBI Decay / Noise Characteristics

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Scope of Work

- A standard grade FLI Proline PL16803 was characterized to quantify its performance in several areas
  - Specific parameters measured included:
    - Read noise
    - Full well capacity
    - PhotoResponse NonUniformity (Pn or PRNU)
    - DarkSignal NonUniformity (Dn or DSNU)
    - Camera Gain
    - RBI Trap capacity
    - RBI Trap leakage characteristics
- Photon Transfer* methods were used for the analysis coupled with RBI** decay measurements ranging from –5C to –50C operating temperatures

*click:
http://www.narrowbandimaging.com/ptc_method_wsp2009_page.htm
**click:
http://www.narrowbandimaging.com/rbi_paper_crisp_page.htm

Summary of Measured Results

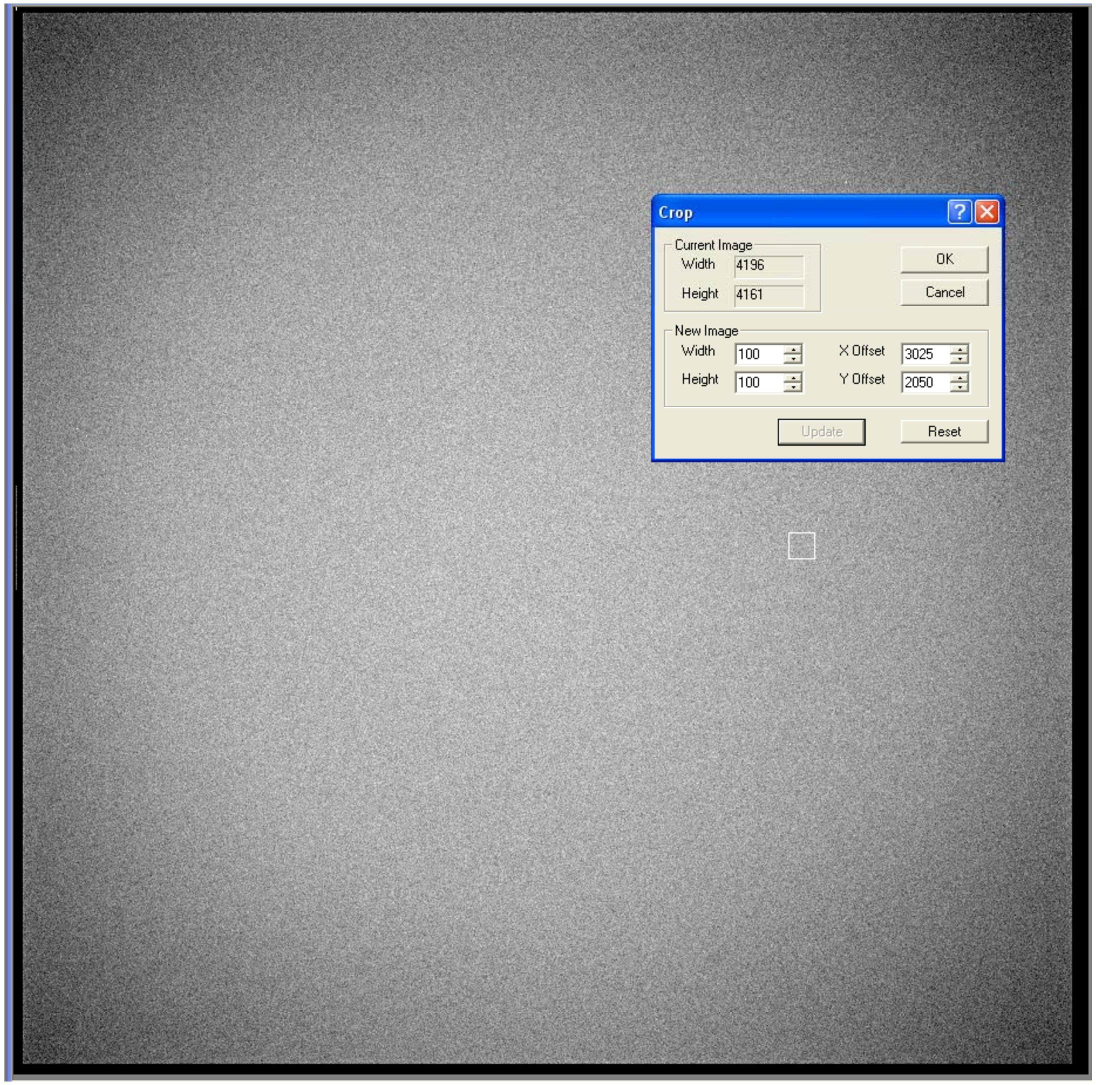
Parameter	Measured value
Read Noise	5.74 (e-)
Full Well Onset	90,000 (e-)
PRNU	0.357%
DSNU	100%
Camera Gain	1.4 e-/DN
RBI Trap Capacity	~140 e-

Details of Characterization

Photon Transfer Procedure

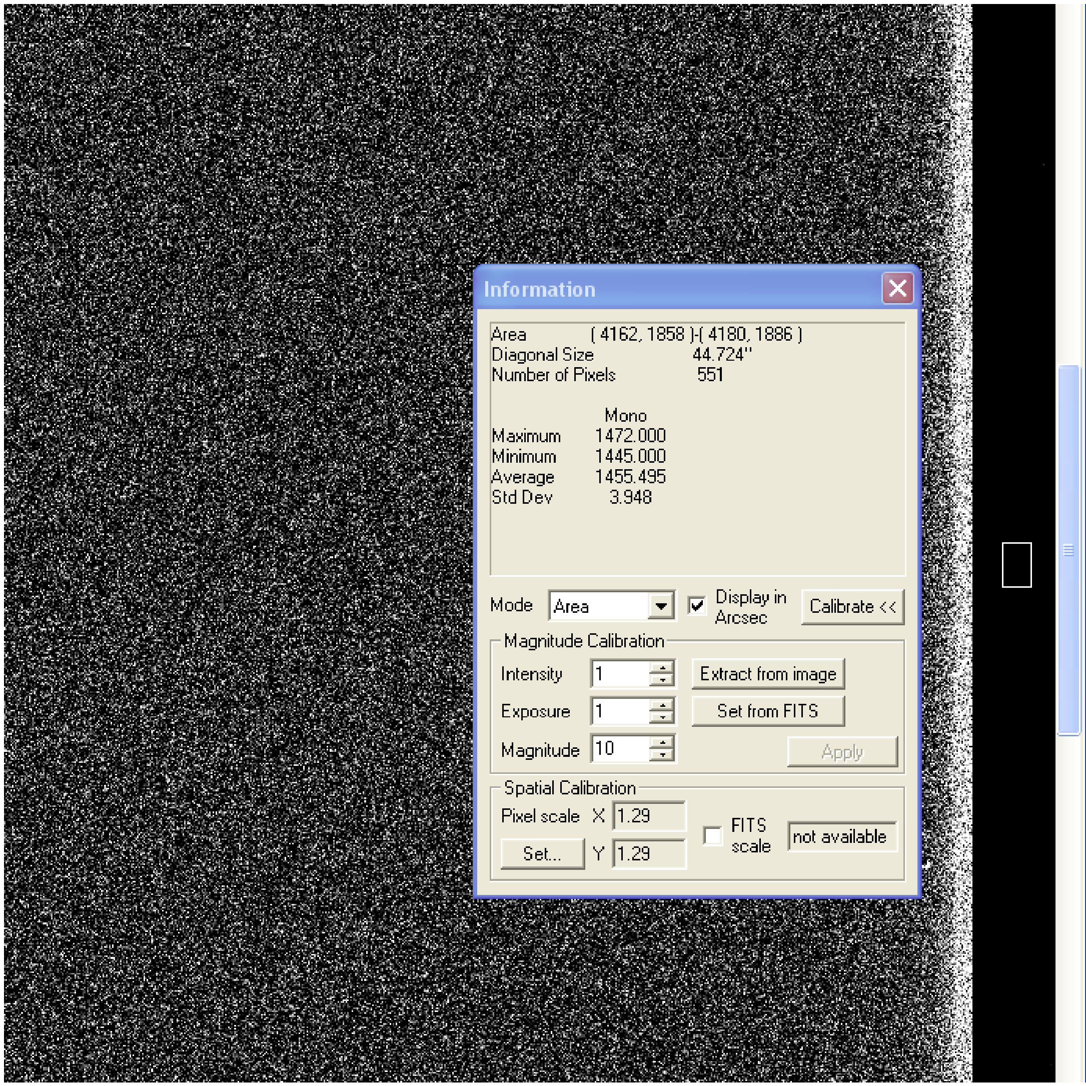
- For non-RBI related tests, standard photon transfer measurements of a flat field were performed
  - Using ambient lighting, pairs of identical exposures were made beginning with minimum exposures and ending with full well: all light-on tests were made at –25C
    - All exposures were made using overscan to precisely determine the offset value (bias frames aren't good enough)
    - A specific selection box location containing 10,000 pixels was used for all measurements (light on, dark, RBI)
  - Dark measurements were made at +15C using pairs of identical darks starting with minimum exposures to a maximum of two hours at +15C. Minimum signal dark tests were made at –15C to reduce amount of charge collected to minimal values
  - Standard Photon transfer data reduction methods were used
  - The read noise value was measured in the overscan region and was used for the Y axis intercept for the PTC/DTC since near zero valued signal counts are difficult to obtain.

Typical Flat Field Frame used for PTC



- Selection box is 100 x 100 pixels
- X-offset: 3025
- Y-offset: 2050
- Location selected for nominal pixel behavior: no "junk" pixels, and measurement convenience while avoiding gradients
- Used 2 hour +15C dark to pick location for analysis
- Same identical pixels used for all tests

Using overscan region to measure read noise for PTC Y axis intercept determination



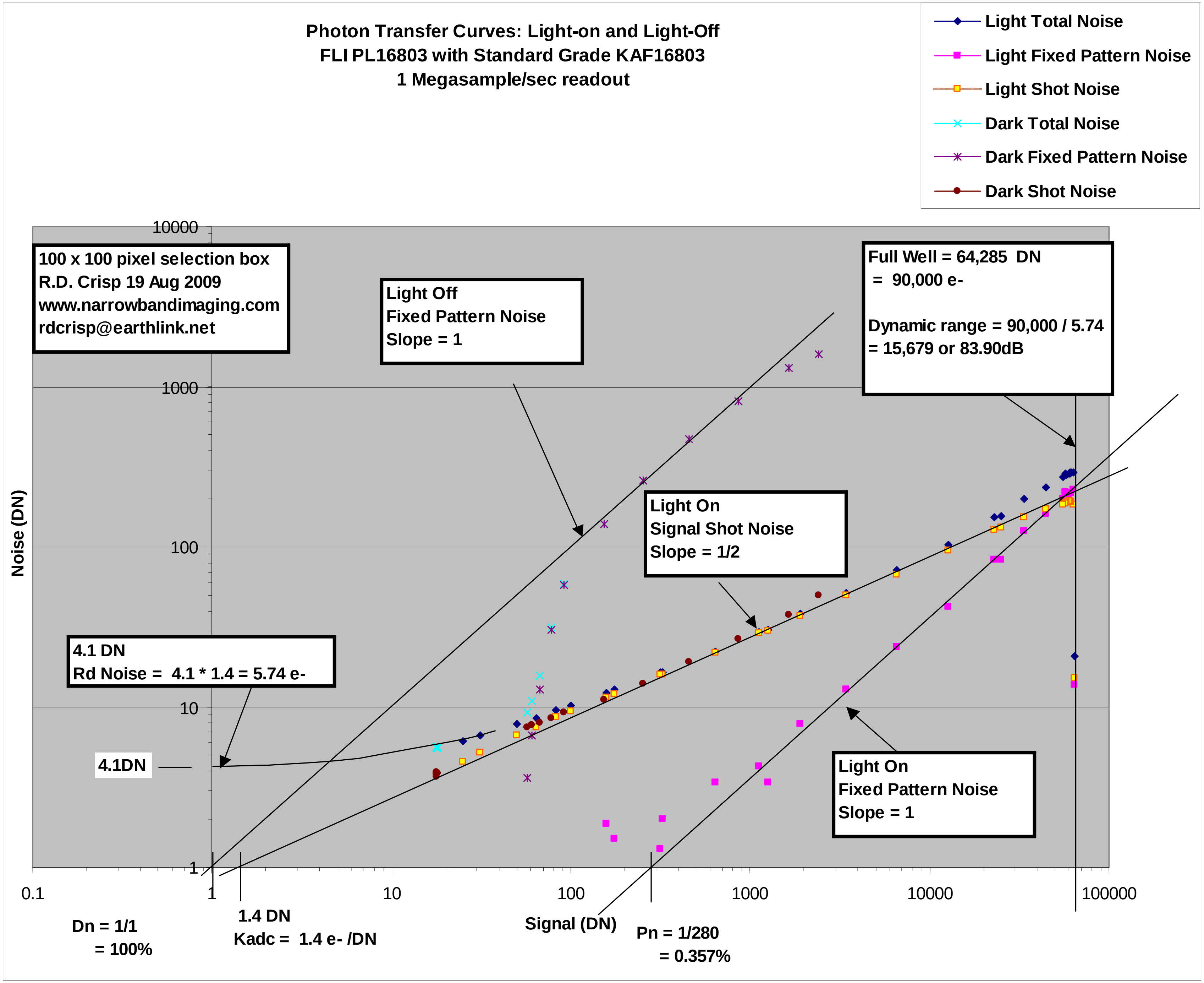
- Measured values ranged from 3.9 to 4.1 DN for the std deviation in the overscan region
- Took worst case measured value of 4.1 DN as the Y axis intercept for the PTC (this example shows 3.98 DN for the value)

Portion of DTC/PTC Spreadsheet showing format

		+15C	dark tests										
signal-offset	std_dev	avg signal	total noise	delta_std_dev	rd+shot	dfpn	DSNU	read noise	dark shot	offset	signal	stdev	delta std
2400.9	1601.6									1467.1	3868	1601.6	
2396	1600.4	2398.45	1601	70.494	49.84678543	1600.223827	100.00%	4.1	49.67788258	1466	3862	1600.4	70.494
1632.8	1307									1466.1	3098.9	1307	
1639.97	1307	1636.385	1307	53.299	37.68808433	1306.456508	100.00%	4.1	37.46440578	1466.03	3106	1307	53.299
853.76	814.477									1465.24	2319	814.477	
855.2	815.03	854.48	814.7535	38.385	27.1422938	814.301272	100.00%	4.1	26.83084256	1465.8	2321	815.03	38.385
455.48	469.3									1465.6	1921.08	469.3	
454.9	470.3	455.19	469.8	27.721	19.60170708	469.3908958	100.00%	4.1	19.16812251	1465.7	1920.6	470.3	27.721
253.8	260.8									1466.3	1720.1	260.8	
252.7	260.5	253.25	260.65	20.663	14.61094742	260.2401635	100.00%	4.1	14.02390047	1465.9	1718.6	260.5	20.663

signal-offset	std_dev	avg signal	total noise	delta_std_dev	rd+shot	fpn	PRNU	read noise	Sig shot	offset	signal	stdev	delta std
		-25C	light tests										
64076.7	22.056									1456.3	65533	22.056	
64077.9	19.91	64077.3	20.983	22.474	15.8915178	13.70204186	0.36%	4.1	15.35351224	1455.1	65533	19.91	22.474
63358.5	291.687									1456.5	64815	291.687	
62828.7	295.045	63093.6	293.366	260.836	184.4389044	228.1357063	0.36%	4.1	184.3933281	1456.3	64285	295.045	260.836
60996	289.772									1457	62453	289.772	
61267.4	291.608	61131.7	290.69	271.196	191.7645306	218.4651938	0.36%	4.1	191.7206958	1456.6	62724	291.608	271.196
61438.6	290.113									1457.4	62896	290.113	
60142.9	288.032	60790.75	289.0725	270.237	191.0864152	216.907566	0.36%	4.1	191.0424248	1457.1	61600	288.032	270.237
60558.6	289.589									1457.4	62016	289.589	
60516.6	291.685	60537.6	290.637	273.317	193.2643041	217.0685941	0.36%	4.1	193.2208096	1457.4	61974	291.685	273.317
59314	285.698									1457	60771	285.698	
59353.2	288.846	59333.6	287.272	272.385	192.6052806	213.1394095	0.36%	4.1	192.5616372	1456.8	60810	288.846	272.385
58168.9	282.946									1457.1	59626	282.946	
58083.7	282.265	58126.3	282.6055	269.594	190.6317456	208.627434	0.36%	4.1	190.5876502	1457.3	59541	282.265	269.594
56998.4	279.571									1457.6	58456	279.571	
57390.9	297.833	57194.65	288.702	265.945	188.0515129	219.055868	0.36%	4.1	188.0068124	1457.1	58848	297.833	265.945
55191.9	272.223									1457.1	56649	272.223	
55279.3	273.4	55235.6	272.8115	261.351	184.8030644	200.6836863	0.36%	4.1	184.7575779	1457.7	56737	273.4	261.351
44756.6	235.404									1458.4	46215	235.404	
44666.7	238.231	44711.65	236.8175	244.985	173.2305548	161.4735371	0.36%	4.1	173.1820288	1458.3	46125	238.231	244.985
33880.3	197.134									1458.7	35339	197.134	
33815.1	199.88	33847.7	198.507	217.774	153.9894722	125.268797	0.36%	4.1	153.9348808	1458.9	35274	199.88	217.774
24927.1	155.319									1457.9	26385	155.319	
25136.8	159.166	25031.95	157.2425	187.95	132.9007195	84.03929174	0.36%	4.1	132.8374618	1458.2	26595	159.166	187.95

Full well onset threshold


Photon Transfer Curves: Light-on and Light-Off
FLI PL16803 with Standard Grade KAF16803
1 Megasample/sec readout
Light Total Noise
Light Fixed Pattern Noise
Light Shot Noise
Dark Total Noise
Dark Fixed Pattern Noise
Dark Shot Noise
100 x 100 pixel selection box
R.D. Crisp 19 Aug 2009
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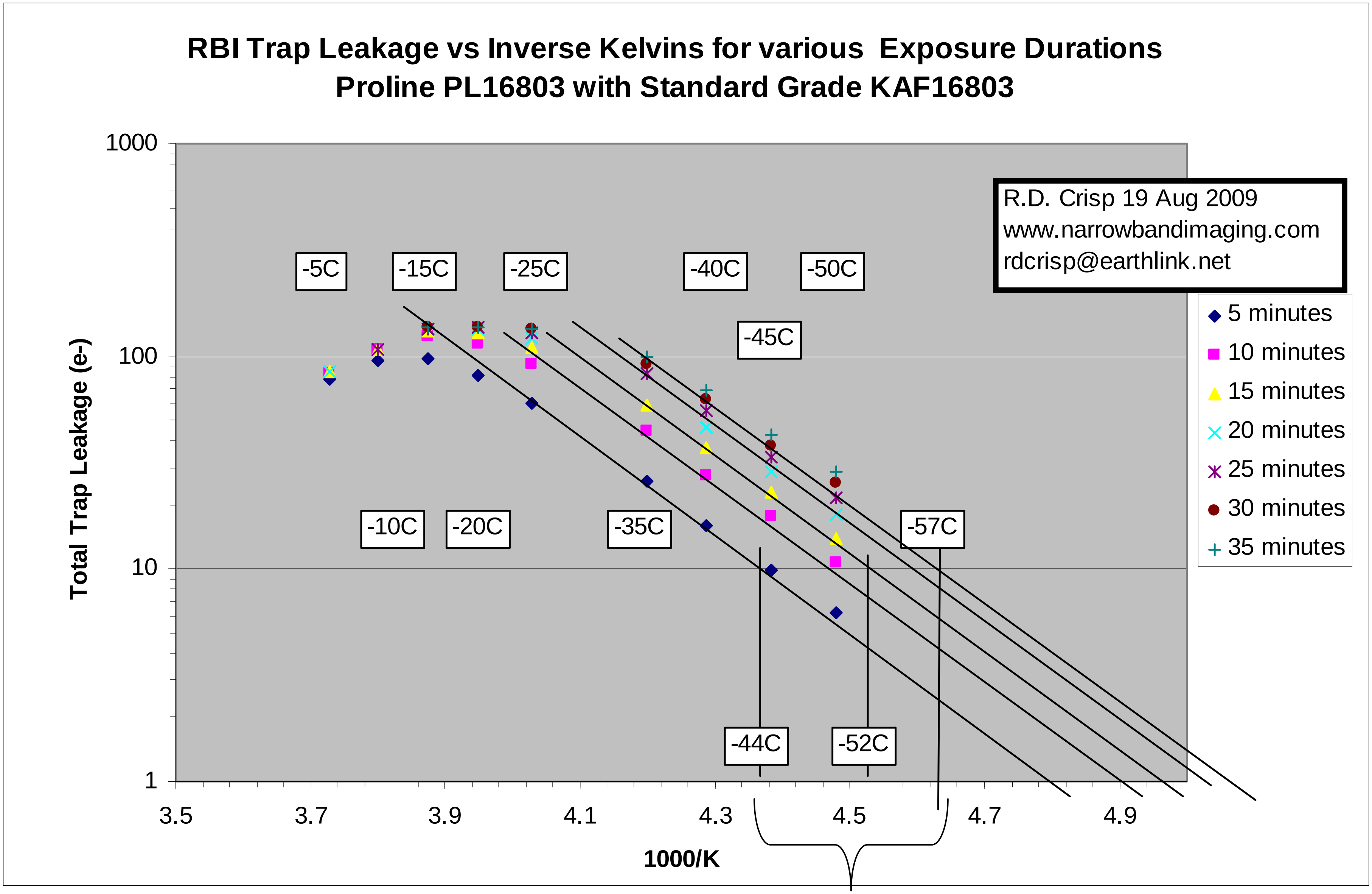
Light Off
Fixed Pattern Noise
Slope = 1
Full Well = 64,285 DN
= 90,000 e-
Dynamic range = 90,000 / 5.74
= 15,679 or 83.90dB
Light On
Signal Shot Noise
Slope = 1/2
4.1 DN
Rd Noise = 4.1 * 1.4 = 5.74 e-
4.1DN
Light On
Fixed Pattern Noise
Slope = 1
Noise (DN)
10000
1000
100
10
1
0.1
1
10
100
1000
10000
100000
Signal (DN)
Dn = 1/1
= 100%
1.4 DN
Kadc = 1.4 e- /DN
Pn = 1/280
= 0.357%

Results Measured from PTC/DTC

Parameter	Measured value
Read Noise	5.74 (e-)
Full Well Onset	90,000 (e-)
PRNU	0.357%
DSNU	100%
Camera Gain	1.4 e-/DN

RBI Testing Procedure

- The method used was exposing a reference dark frame at each operating temperature followed by exposing an equal length dark taken after flooding and flushing the camera, followed by a sequence of equal length dark exposures noting the signal level in the sequence dark exposures. Once the reference dark level was reached in the decay sequence, the traps were deemed exhausted.
- Method: cold start, stabilize operating temperature
  - Five minute dark recorded (300 seconds)
  - Five floods/flushes of five seconds of NIR light was flashed onto the sensor, then a 300 second dark was captured
  - Additional 300 second darks were captured in sequence until traps completely decayed



10e- RBI Trap leakage reached
5 minutes @ -44c
15 minutes @ -52C
30 minutes @ -57C

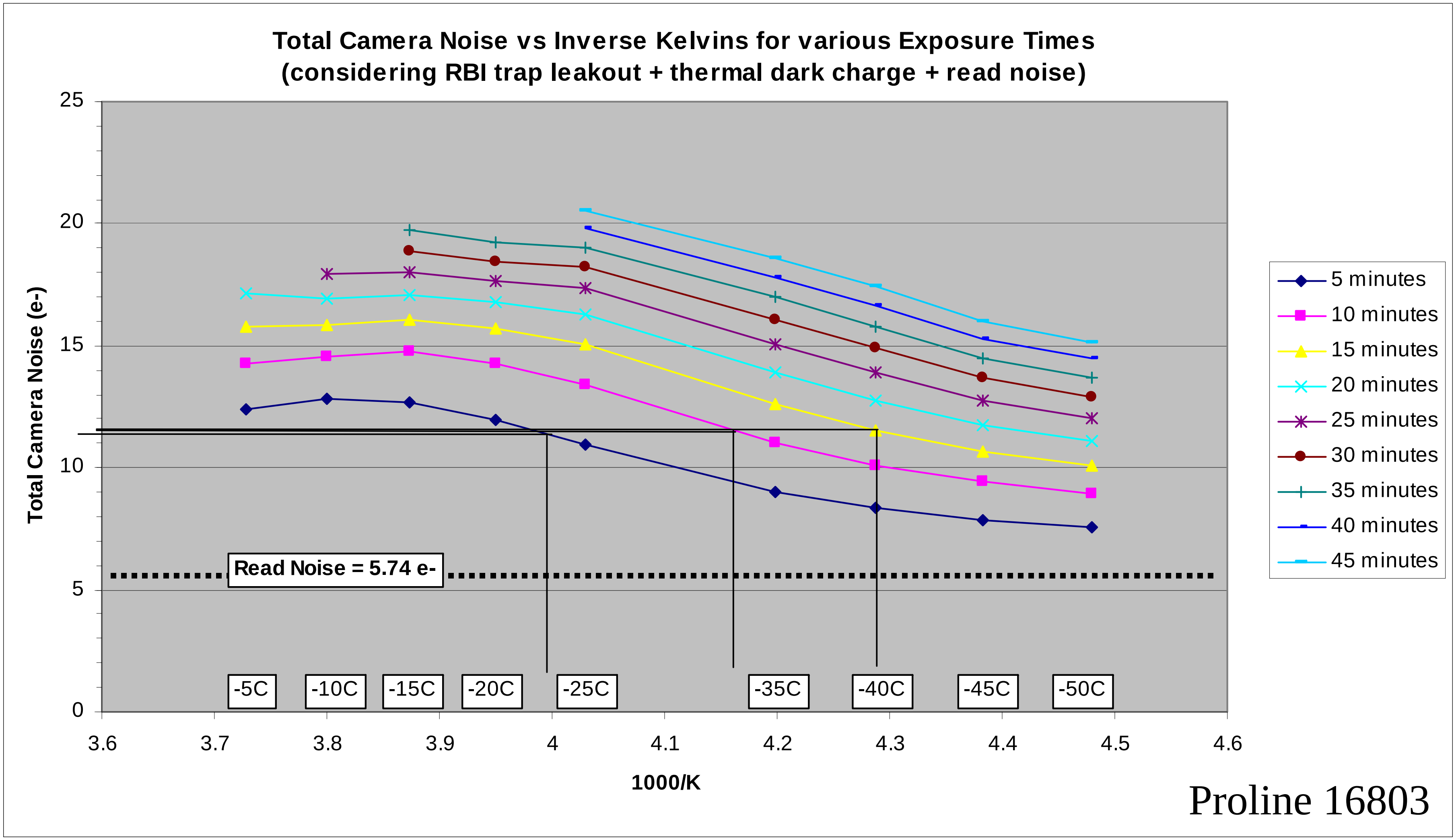
Measured Capacity
RBI Traps: ~140 e-

Reading the RBI Chart

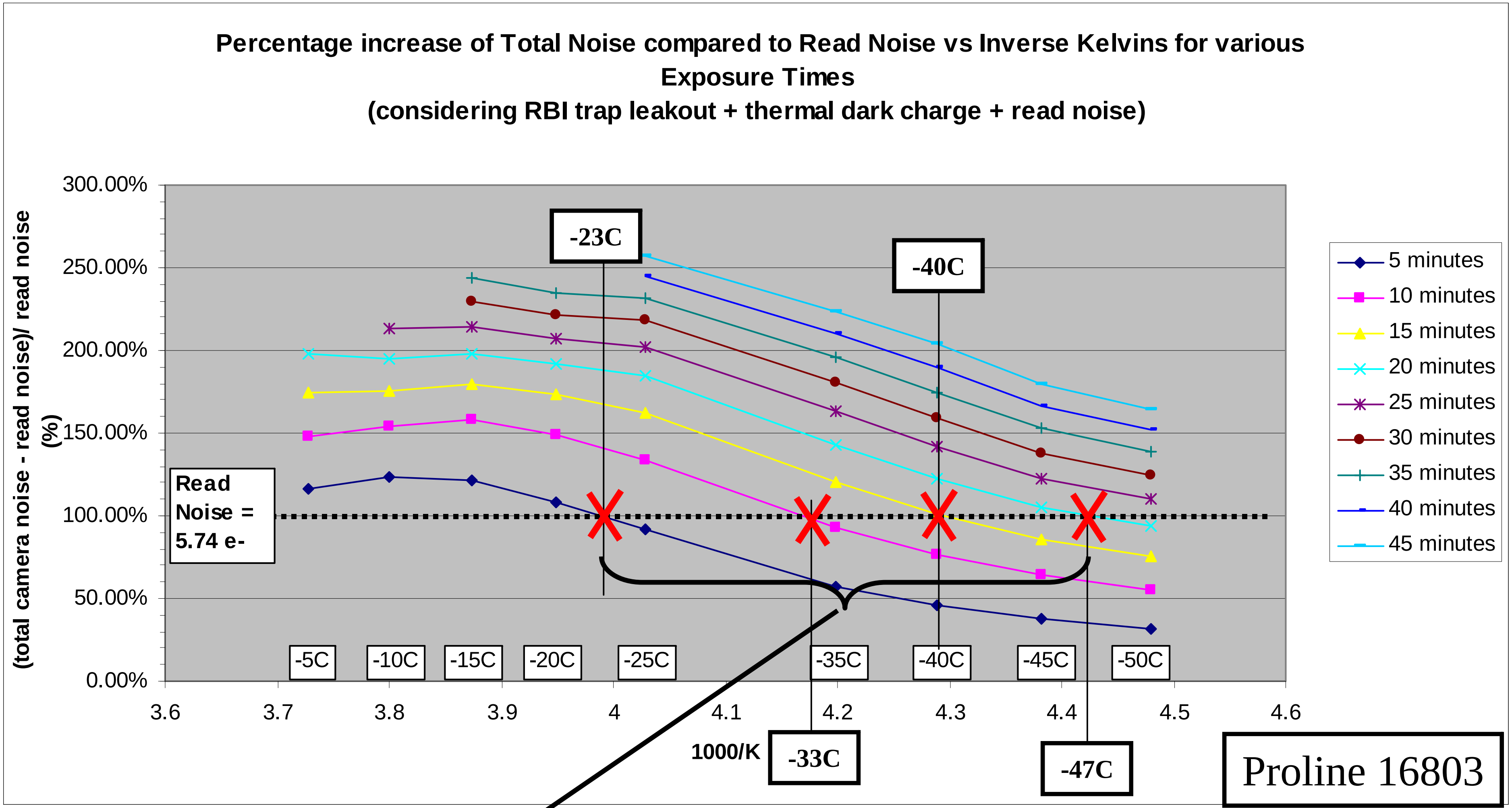
- The vertical axis shows total trap leakage on a logarithmic axis
- The horizontal axis shows inverse temperature (1000/Kelvins): taken together this is known as an Arrhenius Plot (see appendix A for description of the math behind Arrhenius Plots)
- Total camera noise considering RBI Trap Leakage, Thermal Dark Signal, and Read noise is

$$Total\_camera\_noise = \sqrt{(trap\_leakage + thermal\_dark\_signal) + read\_noise^2}$$

- **<u>A significant error source in these RBI leakage measurements</u>**:
  - The camera flushes prior to any integration:
    - *<u>Charge is lost that is not measured</u>*
    - Warmer temperatures *<u>aggravate the problem:</u>* have higher trap leakage rate
  - Ways to reduce this error source:
    - Use Camera's High Speed Mode : faster flushes/faster readout (less time for charge to leak).
    - Taking single integrations of the expected decay time instead of multiples (to minimize # of flushes): Risk, getting the exposure length wrong. Very costly in terms of time.
    - Custom firmware that prevents flushes (camera modifications)

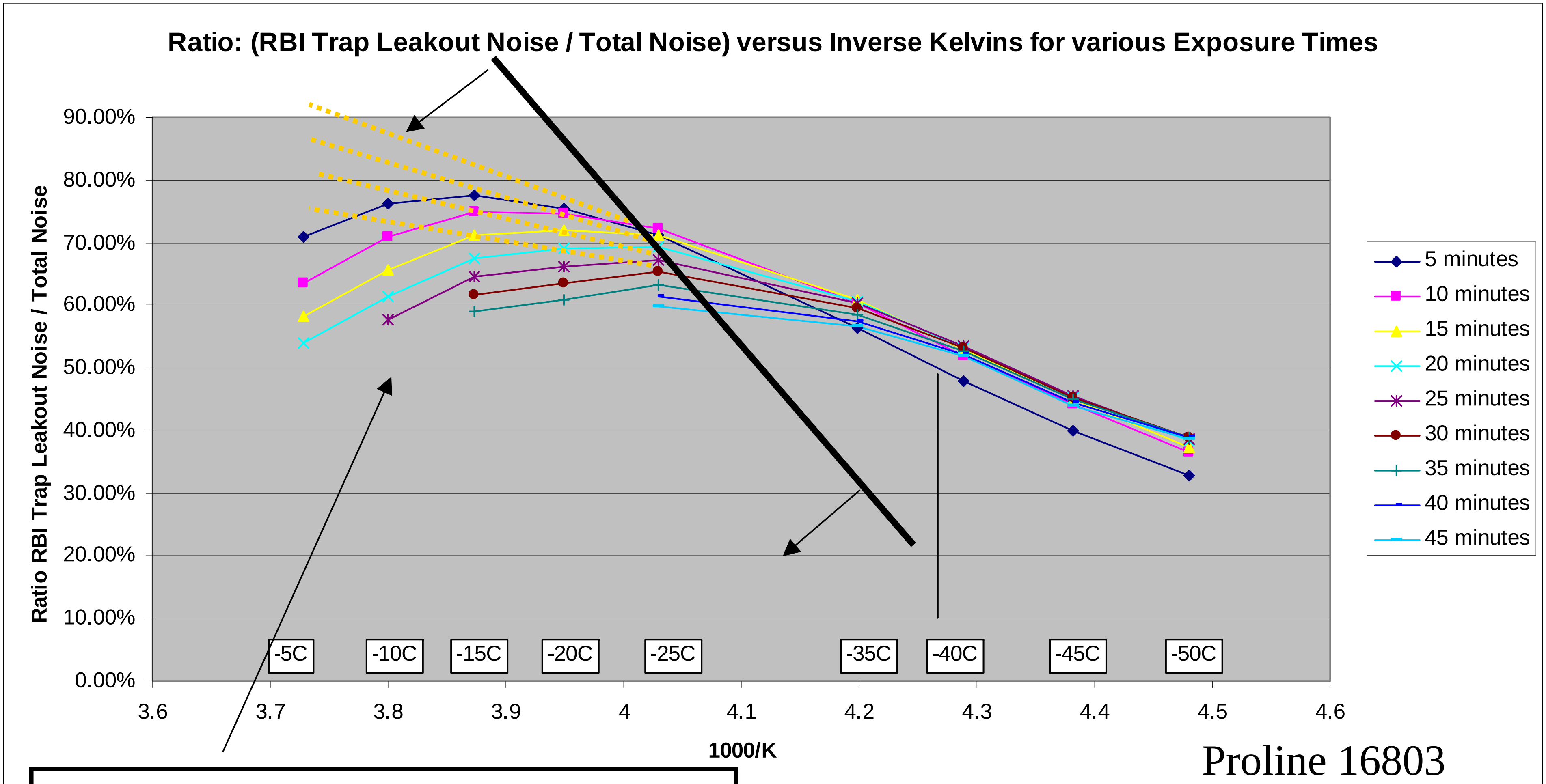


$$Total\_camera\_noise = \sqrt{(trap\_leakage + thermal\_dark\_signal) + read\_noise^2}$$



Regime of read noise dominance of camera noise
(often called maximum practical exposure limit)

Texp	Temperature
< 300 Sec	-23C
< 600 Sec	-33C
< 900 Sec	-40C
< 1200 Sec	-47C



Significant charge "skim" causing uncounted charge: due to camera flushing between integrations. Values actually higher than charted on low end Aggravated at warm temperatures

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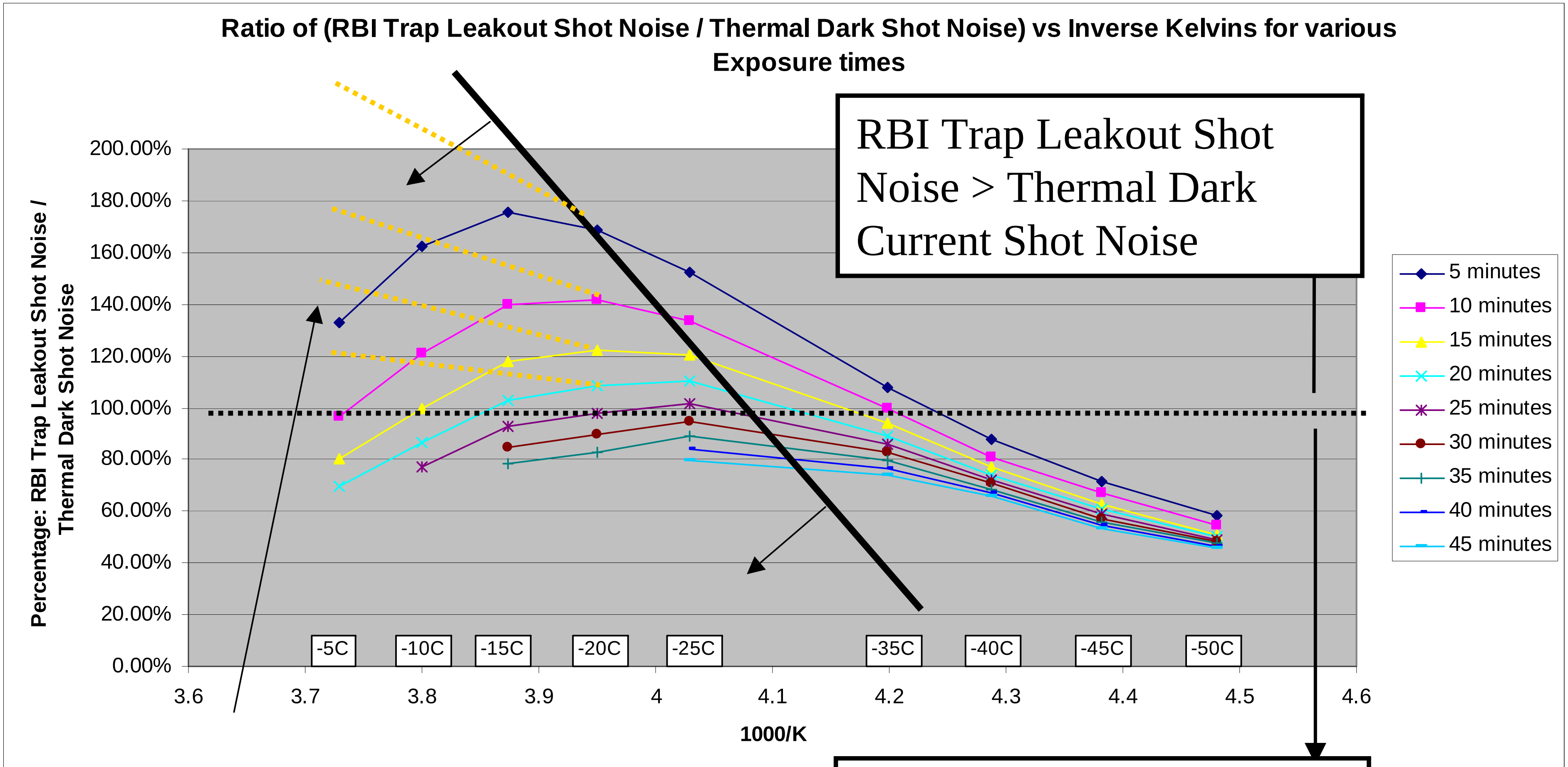
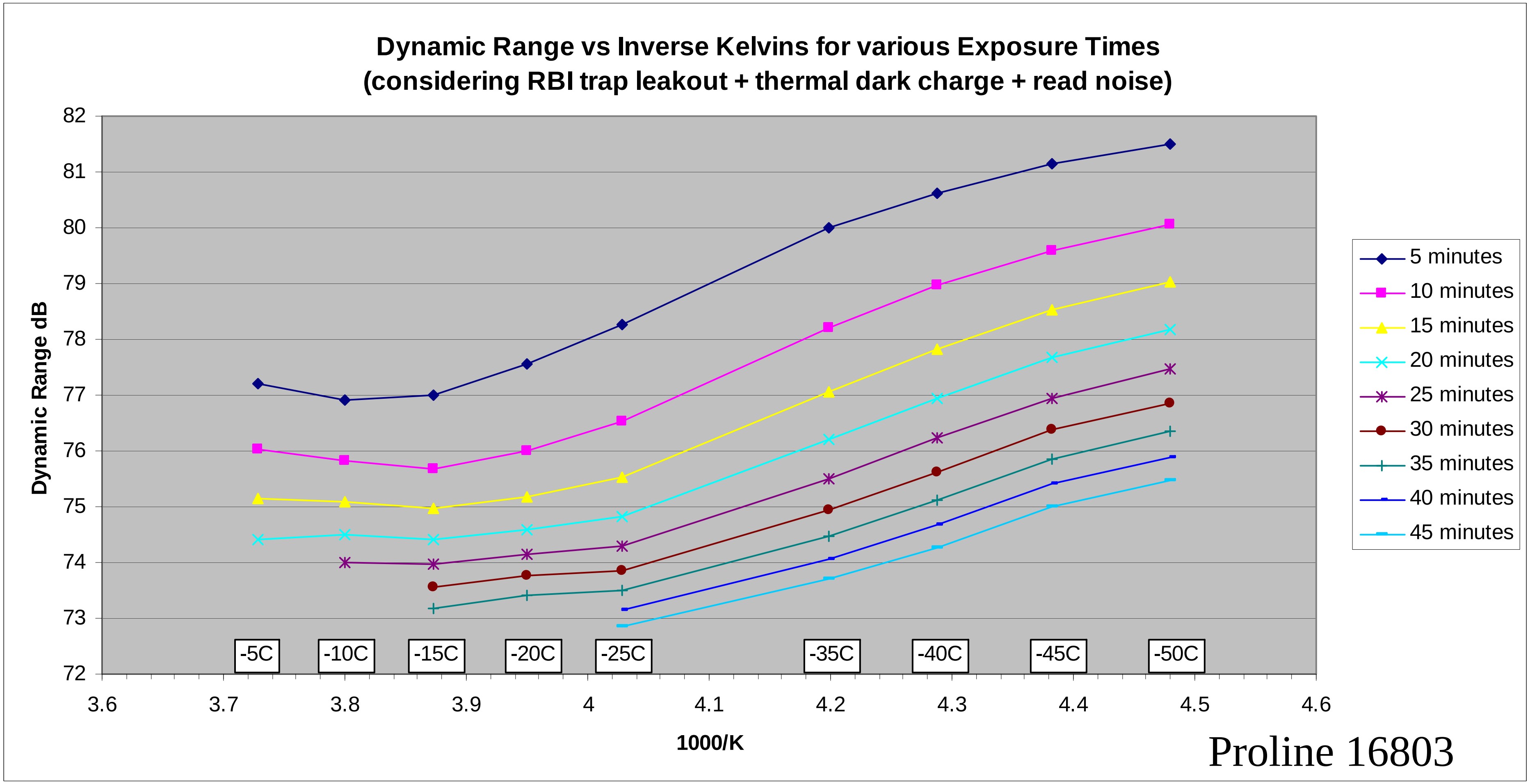
Proline 16803



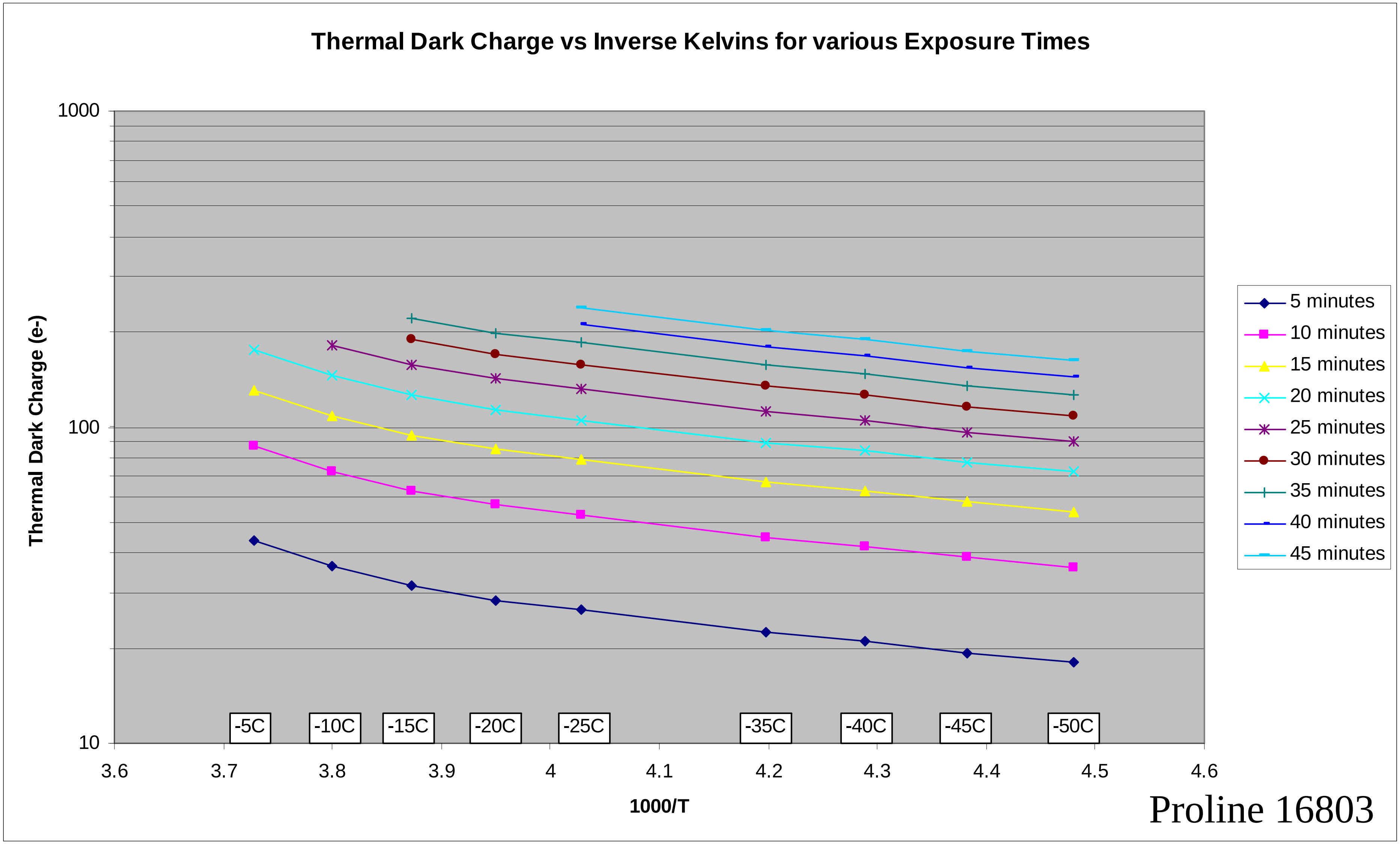
<u>Significant charge “skim” causing uncounted charge: due to camera flushing between integrations. Values actually higher than charted on low end Aggravated at warm temperatures</u>

Thermal Dark Current Shot Noise > RBI Trap Leakout Shot Noise



$$Dynamic\_range = Full\_well / total\_camera\_noise$$

$$Total\_camera\_noise = \sqrt{(Trap\_leakage + Thermal\_dark\_signal) + read\_noise^2}$$



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Closing Comments on Camera Performance

- This is a very high performance camera featuring sub 6e- read noise (measured 5.74 e- worst case)
- The shot noise from the RBI trap leakage for this camera's sensor dominates the camera noise for exposures at temperatures warmer than –38C. Cooling is very important to the proper management of RBI. On a quick test on a hot evening this camera reached –22.7C with an ambient of 88F (33.1C). This works out to be a delta of 53.8C. It should be noted that this was only a spot check and the camera may not have reached thermal equilibrium.
- It is worth noting that lower the read noise of the camera the more it can benefit from deep cooling.
  – If the read noise were 50% higher (ie 9 e-), the RBI shot noise would not be as high of a proportion of the total noise but the overall noise would be higher and the cooling would not be as effective at reducing the noise: it cannot improve high read noise
  – There's little point in deep cooling if the read noise is high.
- The full well limit was reached with a DN count of 64,285. The measured full well capacity of 90,000 e- is not the full saturation signal specified on the Kodak datasheet: it is instead the point where the noise begins to decline as signal is increased. This is the *threshold of full well*.

Recommended Operational Temperature/Exposure Limits for Minimum Camera Noise (where camera noise being dominated by read noise and with a very low read noise* of 5.74 e-)

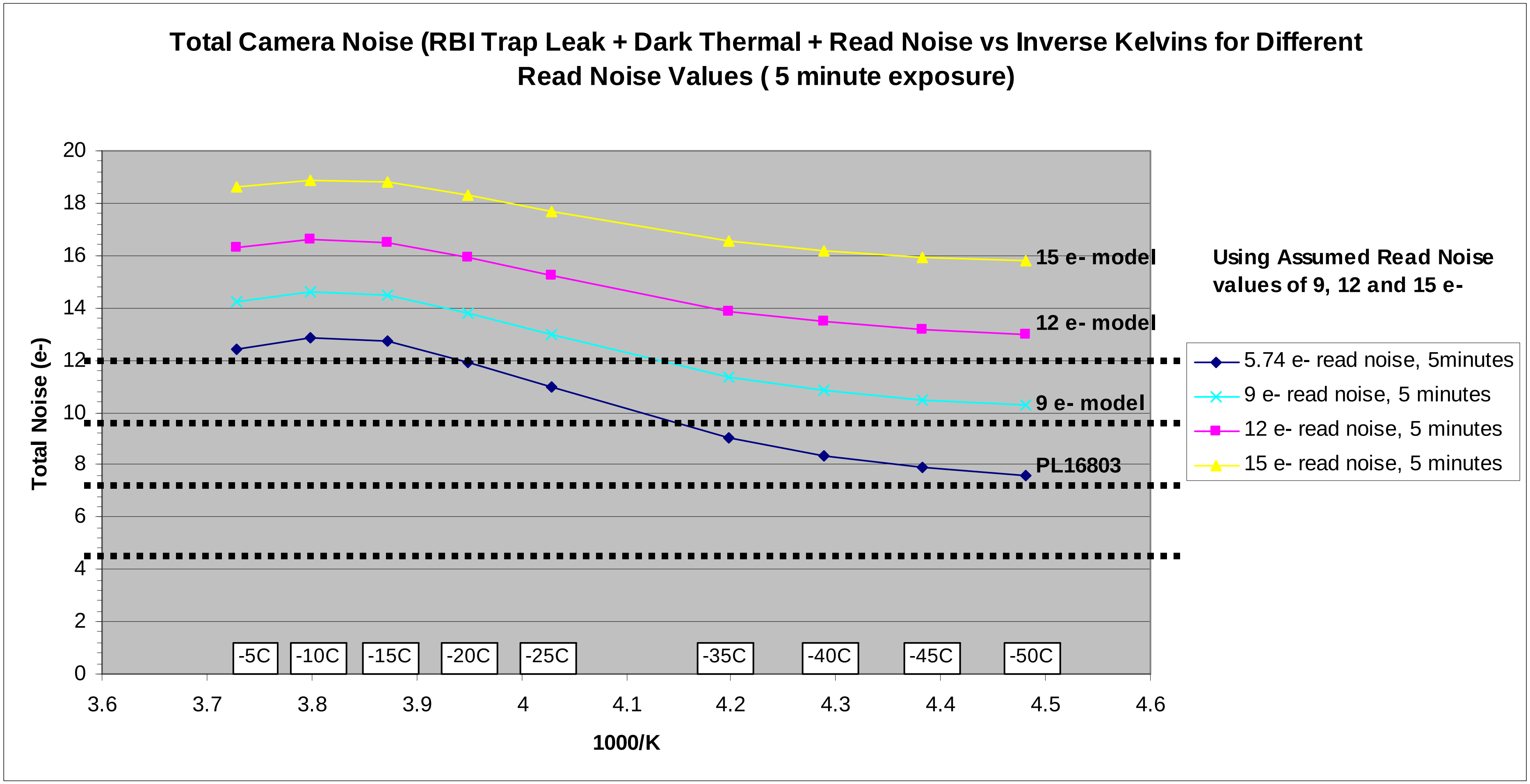
Thermal Dark + RBI Trap Leakout noise </= Read Noise criterion

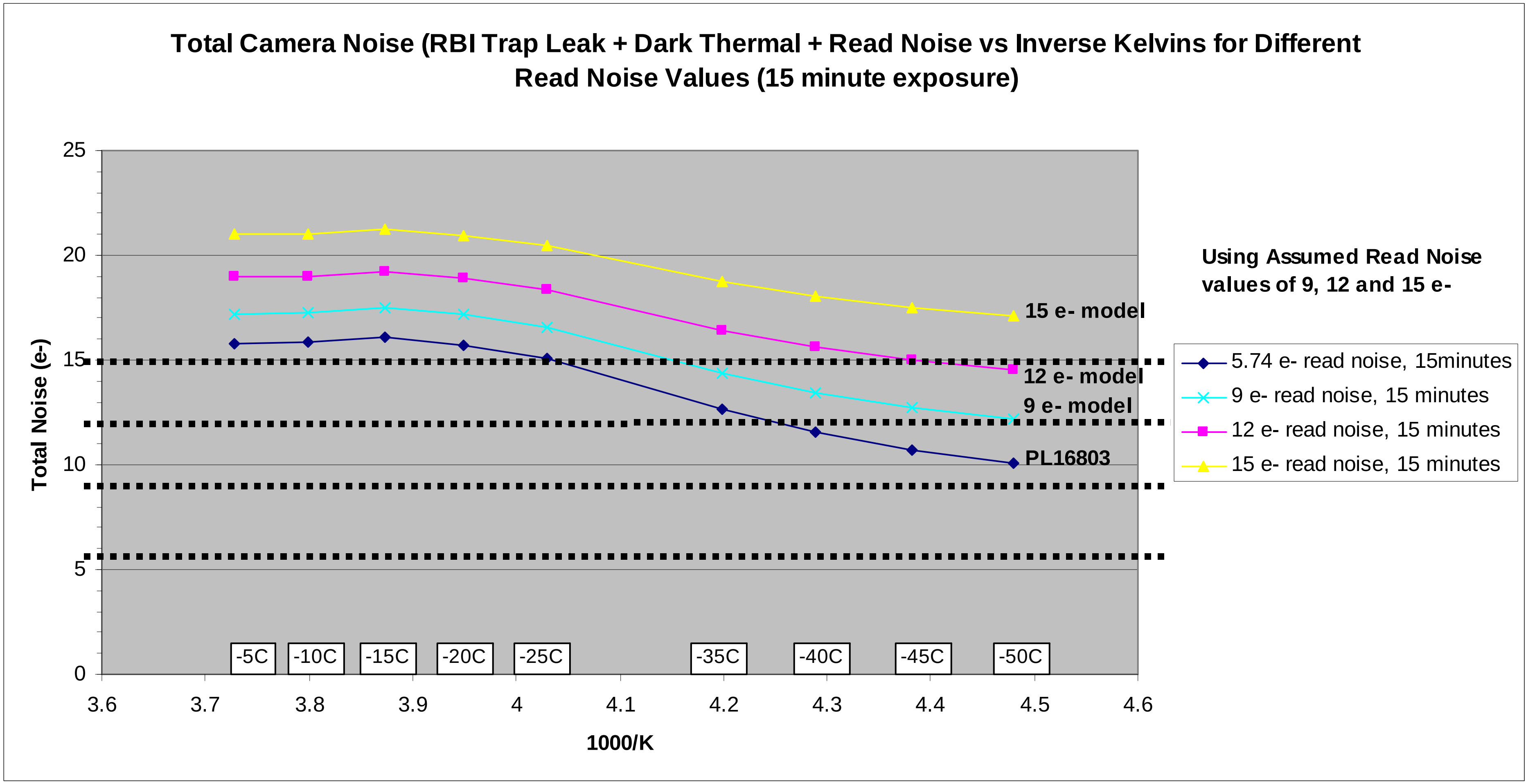
Texp	Max Temperature
< 300 Sec	-23C
< 600 Sec	-33C
< 900 Sec	-40C
< 1200 Sec	-47C

*a higher read noise would not need as much cooling to maintain read noise dominance, but the overall noise would be higher. The lower the read noise, the greater the camera can benefit from deep cooling. The higher the read noise the higher will be the noise across the board. This is a very important point that can be easily misunderstood.

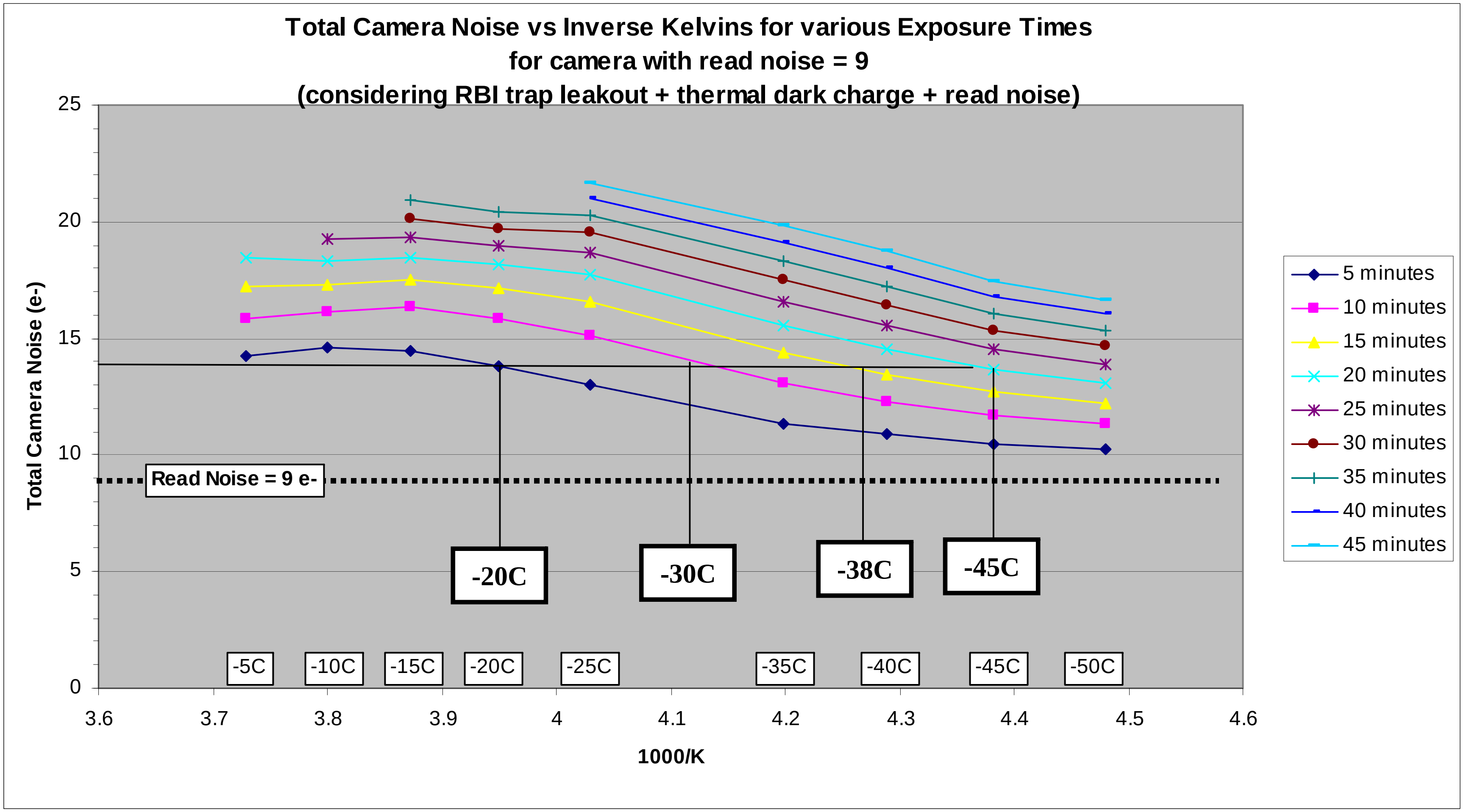
What does this all mean? Comparison with other cameras with higher read noise

(use the same leakage and dark current characteristics with arbitrary read noise = 9, 12, 15 e-)


Total Camera Noise (RBI Trap Leak + Dark Thermal + Read Noise vs Inverse Kelvins for Different Read Noise Values (5 minute exposure)
Total Noise (e-)
1000/K
15 e- model
12 e- model
9 e- model
PL16803
Using Assumed Read Noise values of 9, 12 and 15 e-
5.74 e- read noise, 5minutes
9 e- read noise, 5 minutes
12 e- read noise, 5 minutes
15 e- read noise, 5 minutes
-5C
-10C
-15C
-20C
-25C
-35C
-40C
-45C
-50C


Total Camera Noise (RBI Trap Leak + Dark Thermal + Read Noise vs Inverse Kelvins for Different Read Noise Values (15 minute exposure)
Total Noise (e-)
1000/K
25
20
15
10
5
0
3.6
3.7
3.8
3.9
4
4.1
4.2
4.3
4.4
4.5
4.6
-5C
-10C
-15C
-20C
-25C
-35C
-40C
-45C
-50C
15 e- model
12 e- model
9 e- model
PL16803
Using Assumed Read Noise values of 9, 12 and 15 e-
5.74 e- read noise, 15minutes
9 e- read noise, 15 minutes
12 e- read noise, 15 minutes
15 e- read noise, 15 minutes

Arbitrary Camera with read noise = 9e-



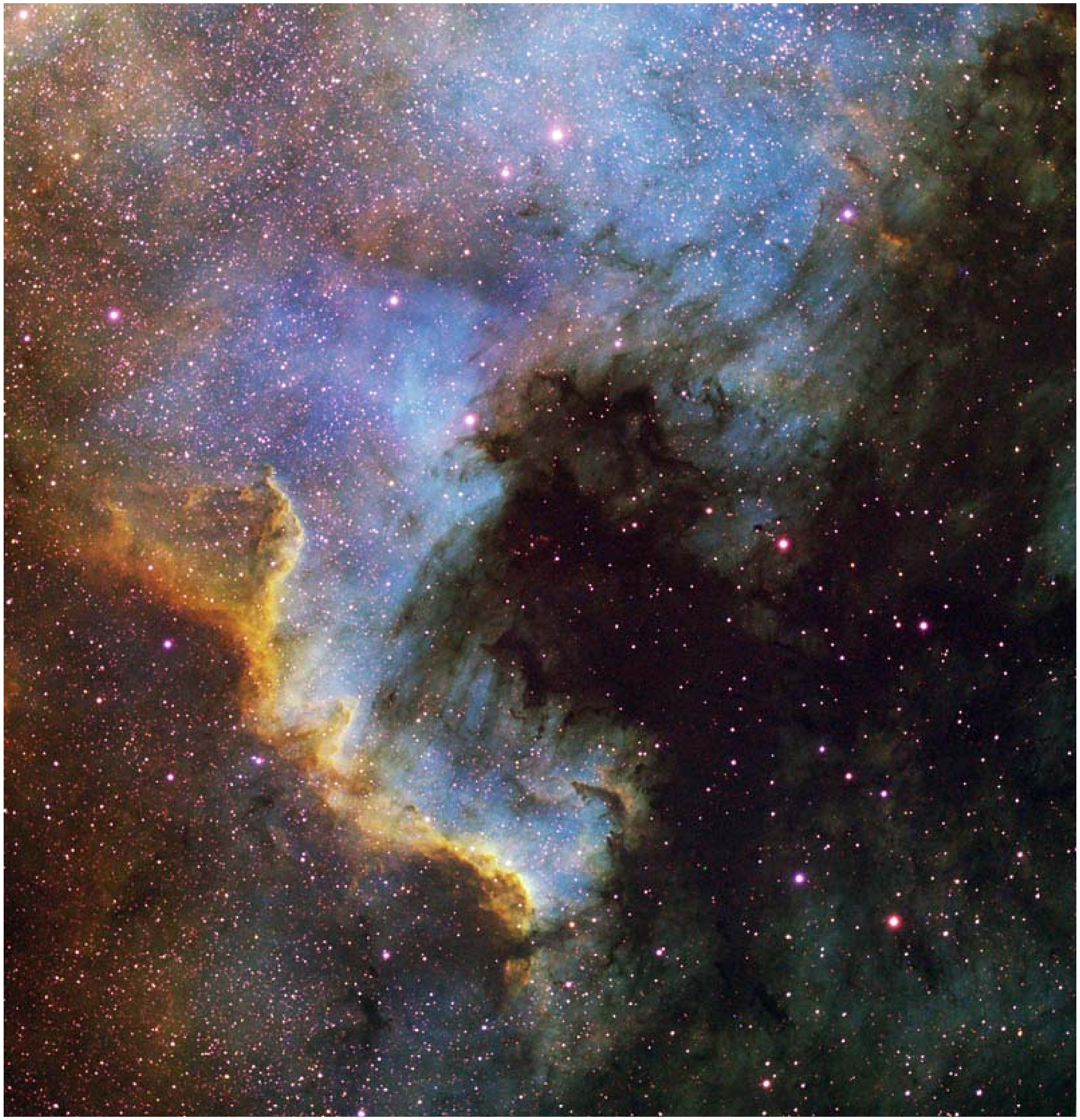
$$Total\_camera\_noise = \sqrt{(trap\_leakage + thermal\_dark\_signal) + read\_noise^2}$$

Comparison of Noise for PL16803 with optimum cooling versus a 9 e- read noise camera with optimum cooling optimum cooling defined as:

Thermal Dark + RBI Trap Leakout noise </= Read Noise criterion

Exposure time	Optimum Temp	Total Noise @ optimum temp (5.74 e- RN)	Total Noise @ optimum temp (9 e- RN)
300sec	-23C	11.5e-	
300sec	-20C		14e-
600sec	-33C	11.5e-	
600sec	-30C		14e-
900sec	-40C	11.5e-	
900sec	-38C		14e-
1200sec	-47C	11.5e-	
1200sec	-45C		14e-

Images



PL16803
7 hours 15 minutes total exposure time:
AP155EDF f/7 with 100mm field flattener
FLI Research Grade [SII], Halpha and [OIII] filters

Image Link:

http://www.narrowbandimaging.com/ngc7k_ap155edf_f7_pl16803_fli_s2hao3_page.htm

PL16803
2 hours 15 minutes
total exposure time:
AP155EDF f/7 with
100mm field flattener
FLI Research Grade
Halpha filter

Image Link:

http://www.narrowbandimaging.com/ngc6995_ap155_pl16803_fli_halpha_page.htm

PL16803
3.75 hours unfiltered luminance combined with 6 hours color data from 39 megapixel one shot color PL39000C

AP155EDF f/7 with 100mm field flattener Baader Planetarium IR blocking luminance filter used with PL39000C OSC camera

Image link:

http://www.narrowbandimaging.com/m31_lrgb_ap155_pl39K_pl16803_page.htm

PL16803
3.25 hours unfiltered luminance combined with 2.75 hours color data from 39 megapixel one shot color PL39000C
AP155EDF f/7 with 100mm field flattener
Baader Planetarium IR blocking lum filter used with PL39000C OSC camera

Image link:
http://www.narrowbandimaging.com/m33_lrgb_ap155edf_pl39K_pl16803_page.htm

Appendix A:
Arrhenius Plots

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Thermally regulated physical processes

- Many physical processes proceed at a rate regulated by temperature
- Chemical reactions, and thermal dark current generation in semiconductors are examples
- Mathematically the rate equations take the form:

$$Rate = K_1 \bullet e^{k_2 / T}$$

Arrhenius Plot Analysis

- The constants, K_1 and K_2 can be determined graphically by first applying a simple mathematical transformation

$$R = K_1 \bullet e^{k_2/T} \qquad (1)$$

$$Ln(R) = Ln(K_1 \bullet e^{k_2/T}) = Ln(K_1) + Ln(e^{K_2/T})$$

$$Ln(R) = Ln(K_1 \bullet e^{k_2/T}) = Ln(K_1) + K_2/T \qquad (2)$$

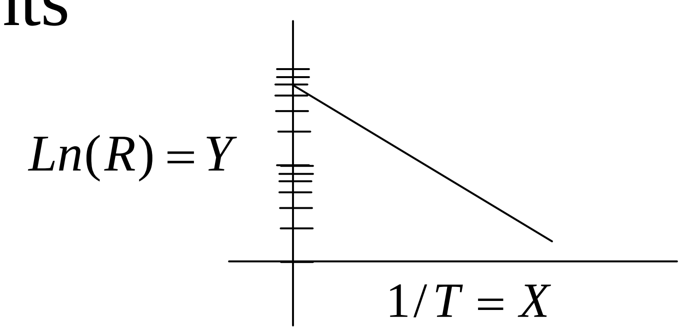
Arrhenius Plot Analysis

$$Ln(R) = K_1 + K_2 / T \qquad (2)$$

By making the transformation of

$$Ln(R) = Y \quad \text{and}$$

empirical data can be plotted on a graph and simple algebraic analysis can be used to determine the constants



Graphical determination of rate constants

The equation of the line: $Y = m X + b$

Graphically the constants m and b are measured: