Everything you always wanted to know about flat-fielding but were afraid to ask*

Richard Crisp

24 January 2012

rdcrisp@earthlink.net

www.narrowbandimaging.com

* With apologies to Woody Allen

Outline

- Purpose
- Part 1: Noise
- Part 2: Photon Transfer Analysis: basic concepts (tools we'll use)
- Part 3: Flat Fielding Basic Concepts: what it does, how it works, performance measurement
- Part 4: Making Master Flats: what level of signal, how many exposures
- Part 5: Field Techniques: taking sky flats, qualifying a master flat prior to deployment

Purpose

- The purpose of this material is to teach
  - What flat fielding does
  - How it works
  - How to quantify results
  - Introduction and use of basic camera analysis tools/techniques
  - How to design an optimized flat fielding protocol for your camera

Goals and Methods

- Our goal is to take optimum flats and know they are optimum
- We want to know how many flat frames to shoot and of what signal level
- The approach we'll follow:
  - Characterize camera to measure full well, camera gain, read noise and Photo-Response-Non-Uniformity ("PRNU")
  - Use these parameters to select the signal level for the flat frames and number of frames used for the master
- To do this we will start out with a brief overview of noise followed by a brief overview of photon transfer analysis.

Part 1: Noise

- Image noise sources
- Noise Equation
- Graphical Representation

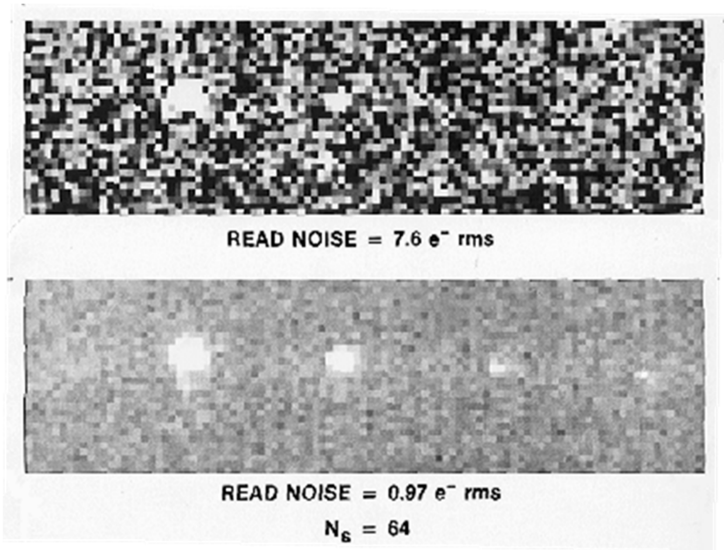
Image Noise Sources

- For an unmodulated image (flat field image), the key noise sources* are
  - Read noise
  - Signal Shot Noise (aka: photon noise, photon shot noise: it will be called Shot Noise or Signal Shot Noise for the remainder of this document)
  - Fixed Pattern Noise
- Depending on signal level any of them can dominate the noise in a single image frame

*neglecting dark signal noise sources which can be managed by cooling

Read Noise

- The read noise is the noise observed in an image when no signal is present
- The noise in a bias frame approximates the read noise
  - zero length exposure
  - no light applied
  - bias frame noise differs from read noise floor by dark signal accumulation during finite readout time
- Read noise can obliterate faint signals

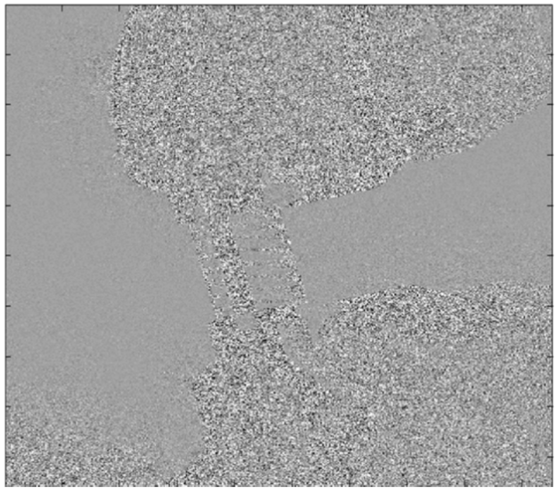


Shot Noise

- The discrete nature of photons results in a variation of the intensity of the incident light as viewed on a photon by photon basis as a function of time
- The variation is the cause of photon shot noise or shot noise as it is also known
- The more intense the image, the greater is the shot noise
- Shot noise is inherent in the image and cannot be avoided and represents the noise floor
- Shot noise in a final image can be eliminated by combining multiple images

IMAGE

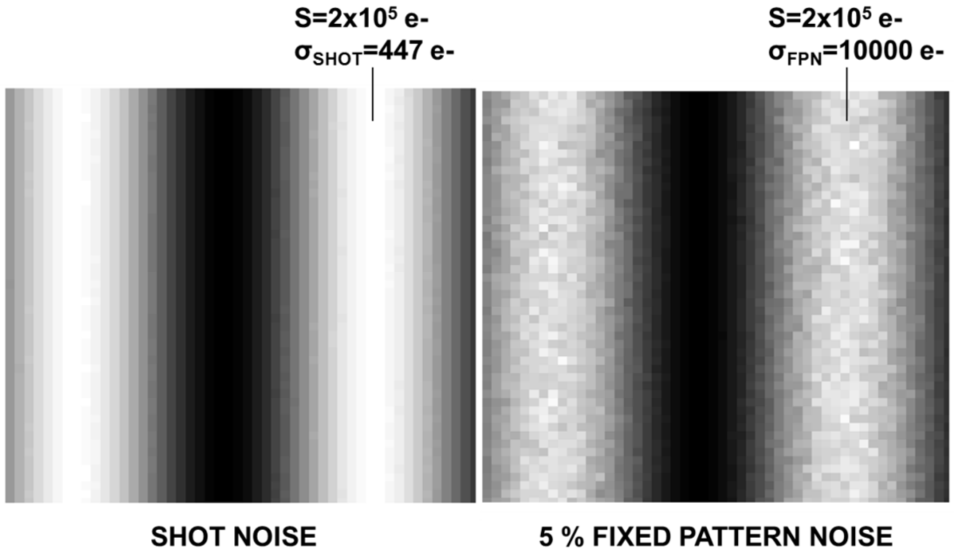
PHOTON SHOT NOISE



Fixed Pattern Noise

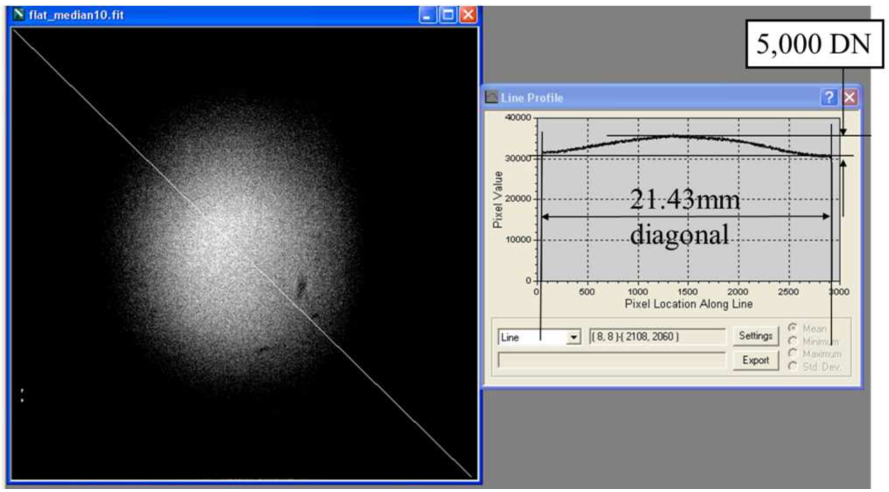
- For a flat field exposure, any modulation observed that remains constant from frame to frame is Fixed Pattern Noise (FPN)
- For perfect flat-field illumination of the sensor the FPN observed is caused by variations in the photoresponse of each pixel. This represents the floor of the FPN of the system
- For the camera installed on a practical optical imaging system, variations of light intensity are generally observed
  - Non-uniform light intensity across the frame (ie, "hot centers" or vignetting)
  - Dust motes
  - Filter transmission variations
- These Optical FPN components add to the FPN inherent in the sensor and frequently dominate the overall FPN of the system
- Once FPN dominates the noise of the image, collecting additional signal does not improve the Signal to Noise Ratio (SNR). FPN places an upper limit on the SNR of the system unless removed
- FPN is removed via Flat Fielding (explained later)

Examples of Fixed Pattern Noise



Sensor FPN

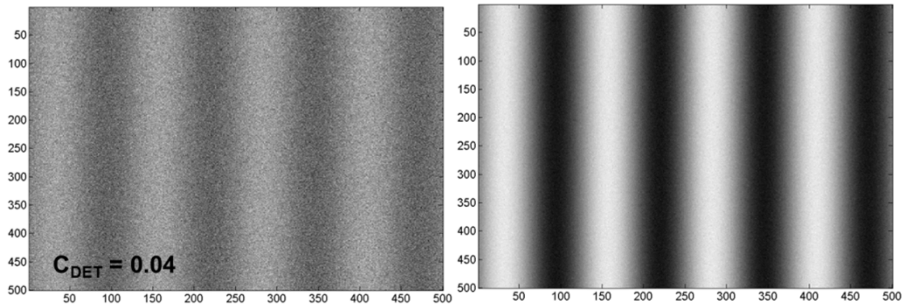
Optical FPN



Richard Crisp rdcrisp@earthlink.net www.narrowbandimaging.com

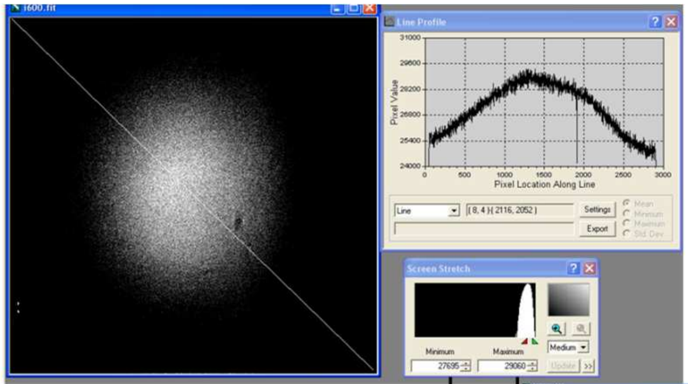
Flat Fielding for FPN Removal

RAW CORRECTED

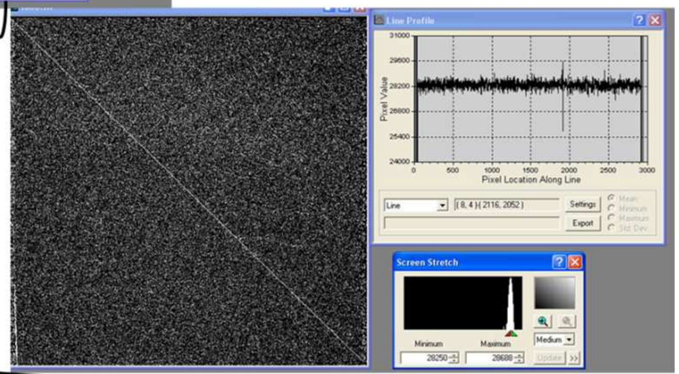


Sensor FPN removal

Optical FPN removal



More uniform light distribution than measured lens before Flat field: less noise at outer parts of image post/flat field



Tighter range of data values than measured lens in image DN histogram prior to flat field operation

Very tight range of data values in image DN histogram after flat field operation

Noise Equation

- To quantitatively analyze noise it must be described mathematically
- When combining the effects of multiple noise sources that are uncorrelated, quadrature summation is used (square root of the sum of the squares of the noise from each separate source)

Noise Equation*

$$Total\_Noise = \sqrt{(read\_noise)^2 + (signal\_shot\_noise)^2 + (fixed\_pattern\_noise)^2}$$

- Assumptions:
  - Flat field target: no modulation
  - Dark signal sources are negligible

Noise Equation Cont'd

$$Total\_Noise = \sqrt{read\_noise^2 + signal\_shot\_noise^2 + fixed\_pattern\_noise^2}$$

recognizing:

$$Signal\_Shot\_Noise = \sqrt{signal}$$

$$Fixed\_pattern\_noise = Signal \times PRNU$$

PRNU is Photo-Response-Non-Uniformity
(this will be covered in depth later)

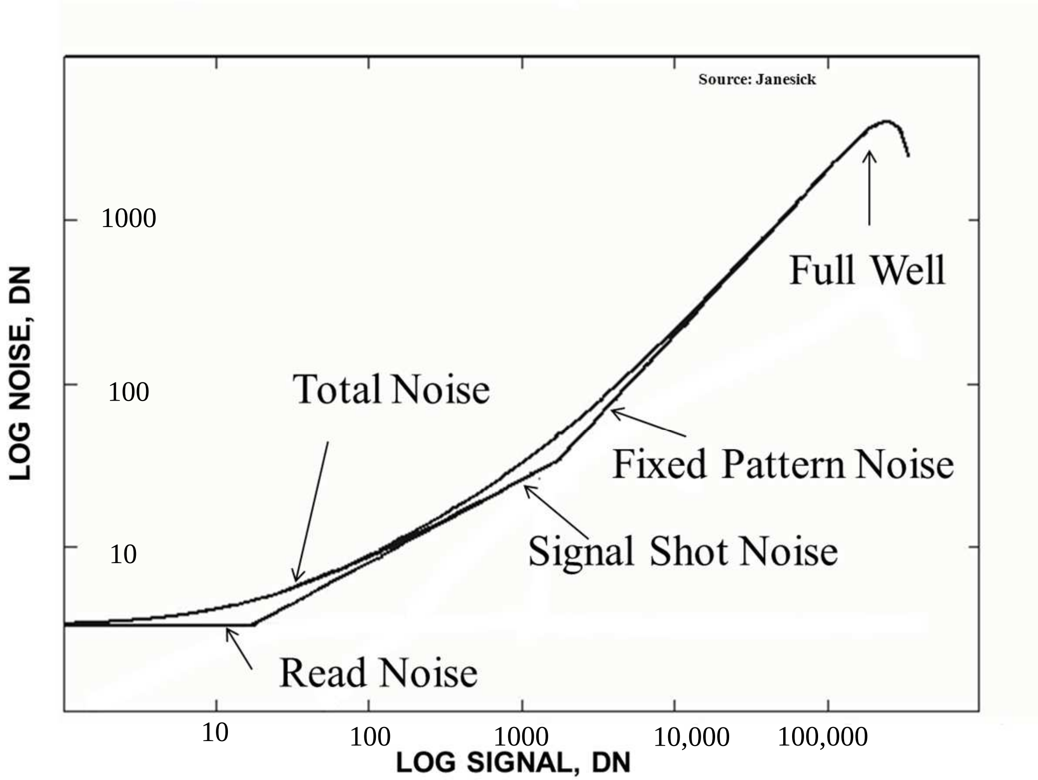
we get:

$$Total\_Noise = \sqrt{read\_noise^2 + signal + (signal \times PRNU)^2}$$

Graphical Representations

- The noise performance of electronic imaging systems is commonly analyzed using graphical techniques
- Noise is plotted on the Y axis with Signal level plotted on the X axis
- Because the noise and signal may range over several orders of magnitude, it is convenient to use logarithmic axes for the plots to accommodate the large range of data extent

Noise Versus Signal



$$Total\_Noise = \sqrt{read\_noise^2 + signal + (signal \times PRNU)^2}$$

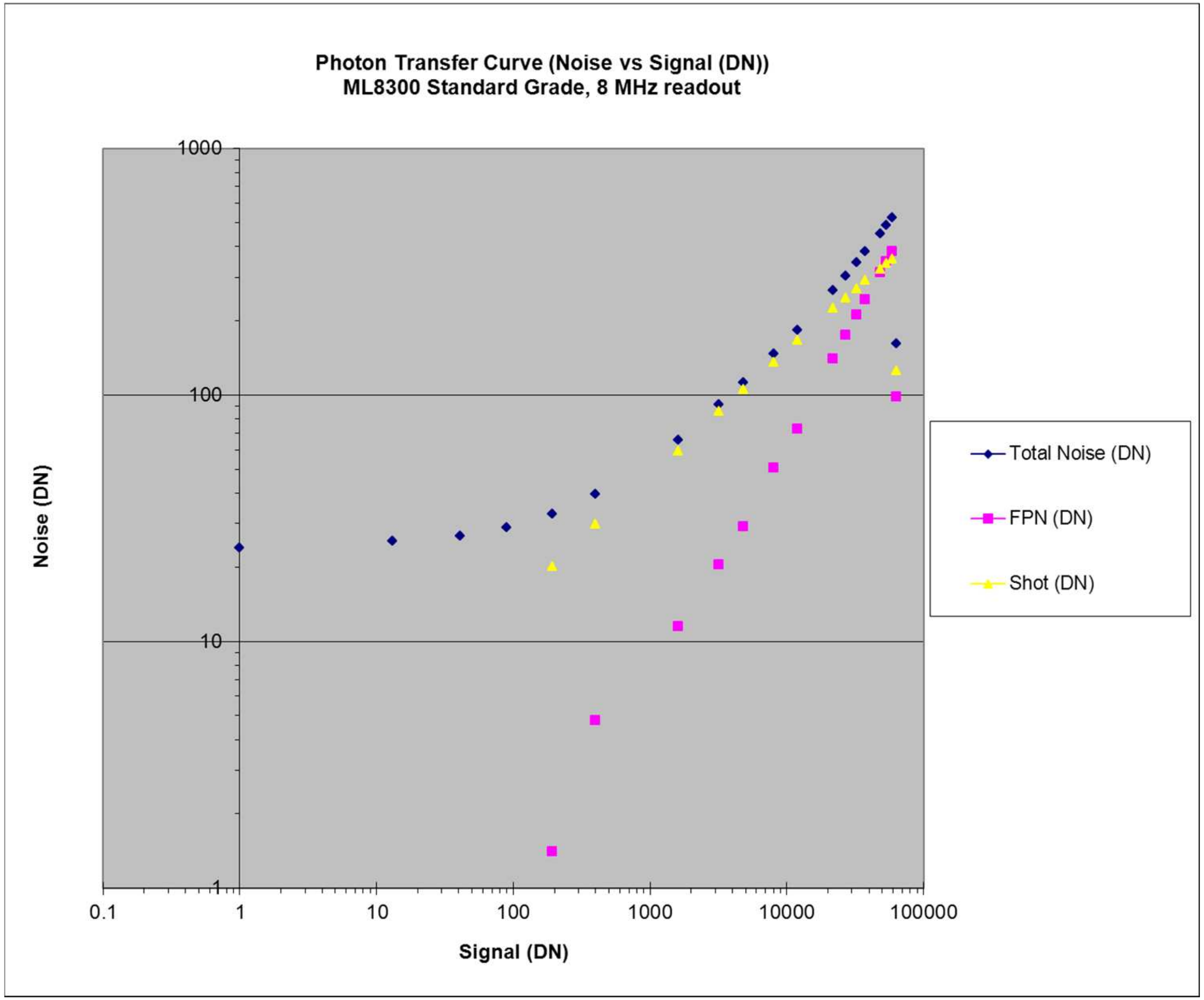
Part 2: Photon Transfer Analysis Basic Concepts (tools we will use)

- Basic PTC and what we learn from it
- How to make a PTC
- Common PTC errors and how to diagnose and fix them
- Other types of PTCs

Basic PTC and what we learn from it

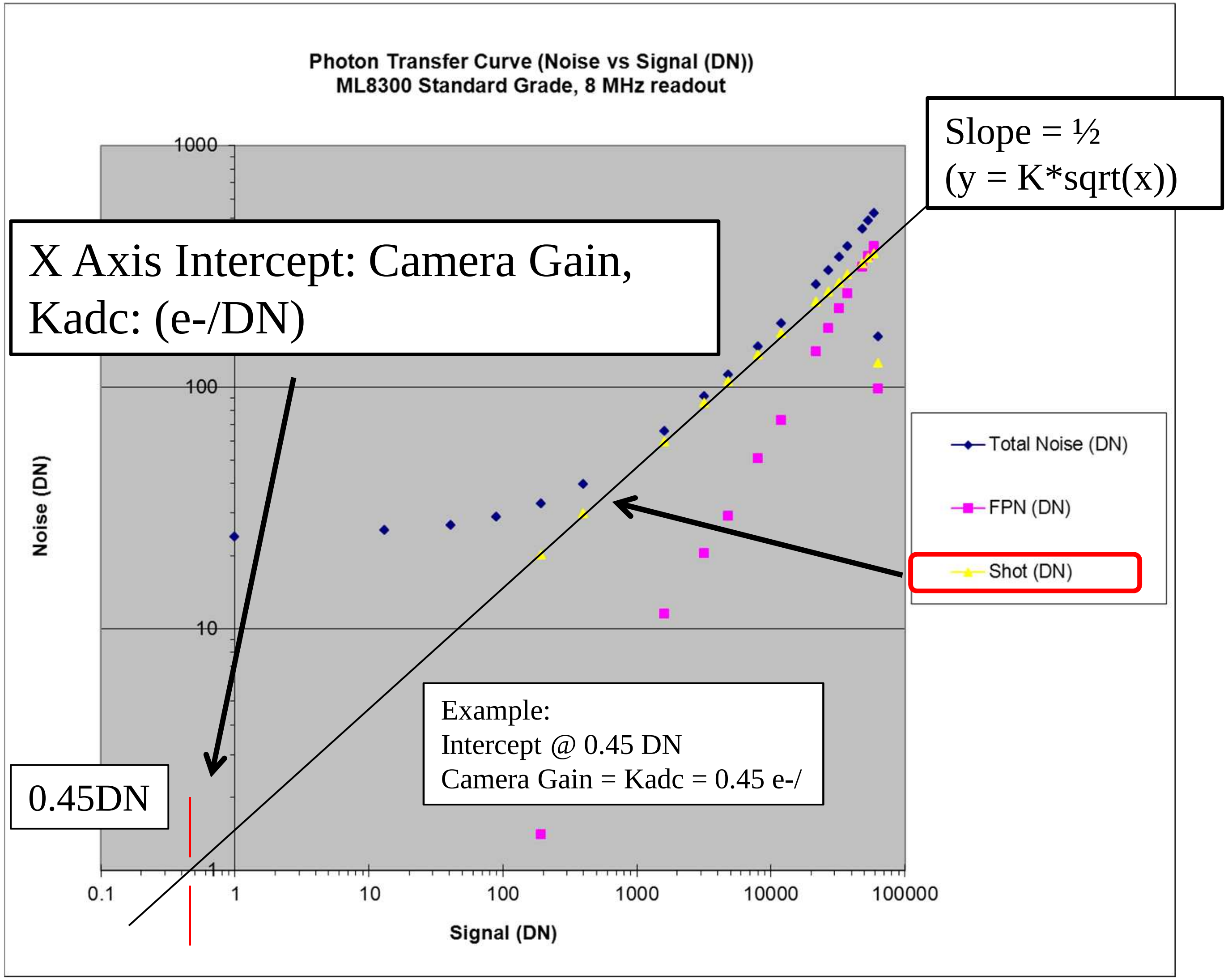
- A basic Photon Transfer Curve (“PTC”) is a graph of Noise versus Signal measured from a collection of identical pairs of flat-field images of varying signal levels. Typically the noise parameters plotted are Total Noise, Fixed Pattern Noise and Shot Noise
- The signal level of the source images used to make the graph span the range from very low signal level to full well
- Each signal level captured is used as a data point for making the graph
- Once the data is plotted in graphical form we can graphically measure
  - Full well
  - Read Noise
  - Camera Gain (“Kadc”)
  - PRNU
- We can supplement the PTC with dark frame data and learn the DSNU (Dark Signal Non Uniformity: a measure of how noisy the chip is to assist you in establishing a proper operating temperature: ie using an engineering grade sensor without suffering from excessive noise
- We can also make a separate chart to track linearity by plotting Kadc vs Signal using the same dataset

Example PTC

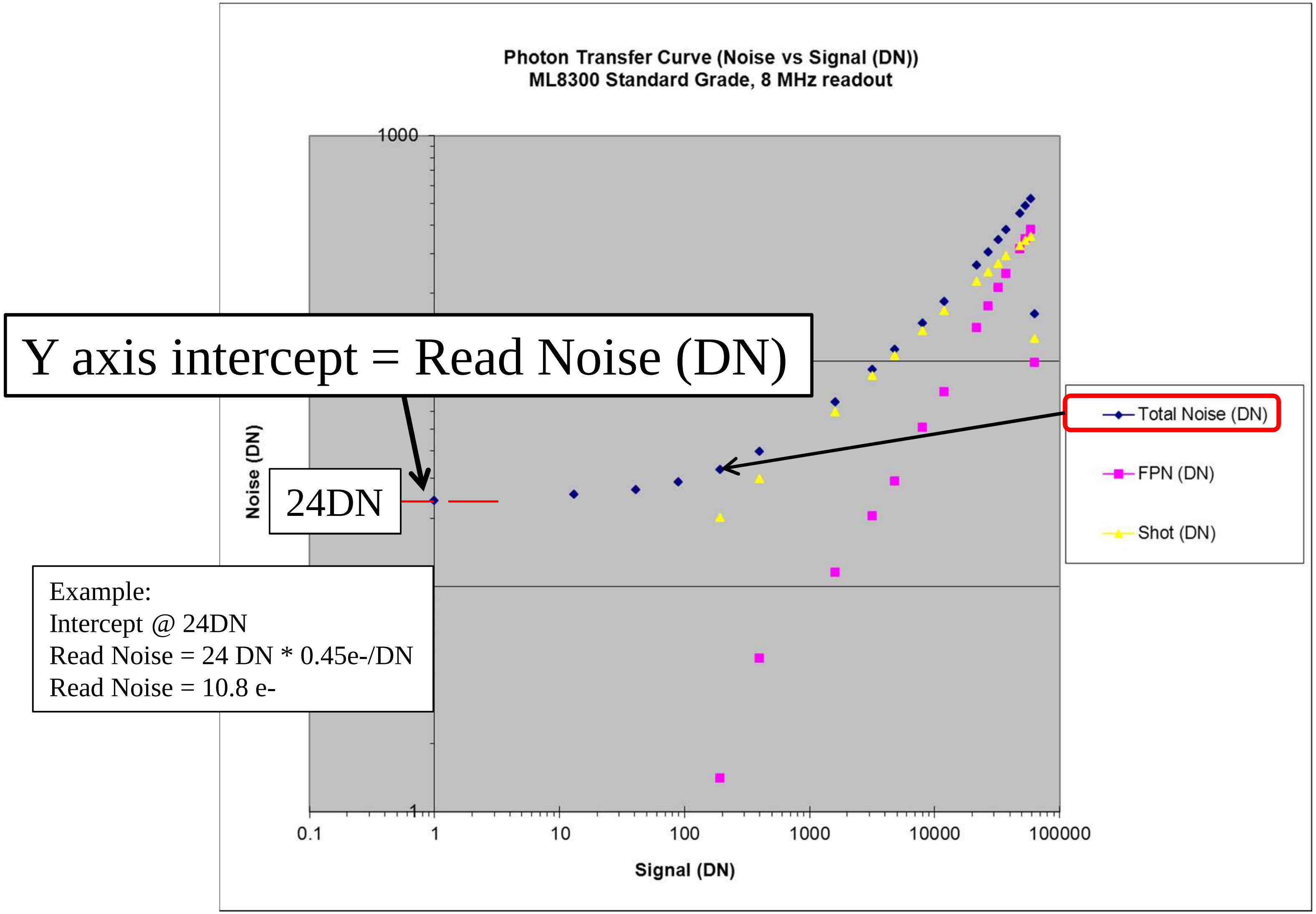

Photon Transfer Curve (Noise vs Signal (DN))
ML8300 Standard Grade, 8 MHz readout
1000
100
10
1
Noise (DN)
0.1
1
10
100
1000
10000
100000
Signal (DN)
Total Noise (DN)
FPN (DN)
Shot (DN)

Richard Crisp rdcrisp@earthlink.net www.narrowbandimaging.com

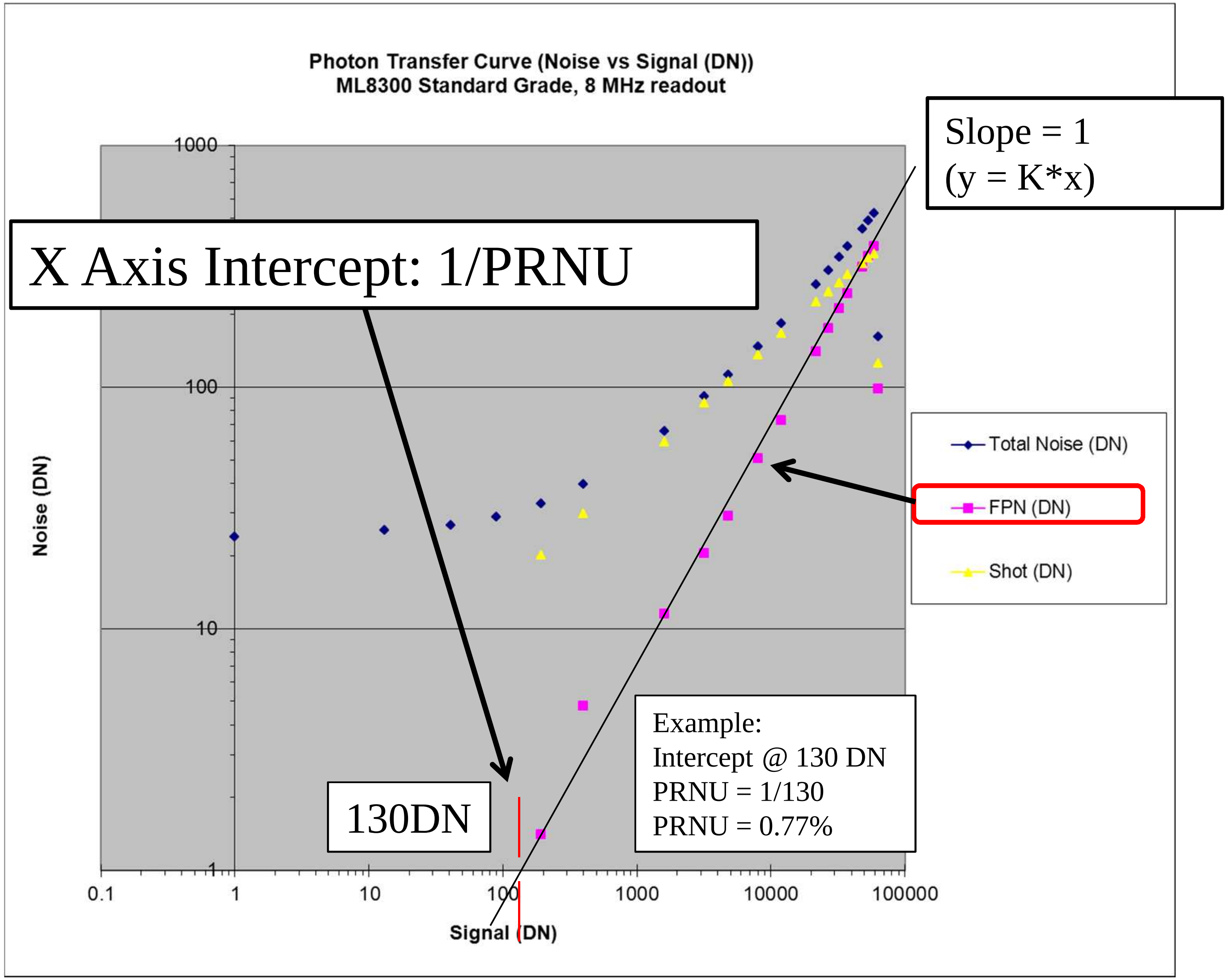
Example PTC: Measuring Gain



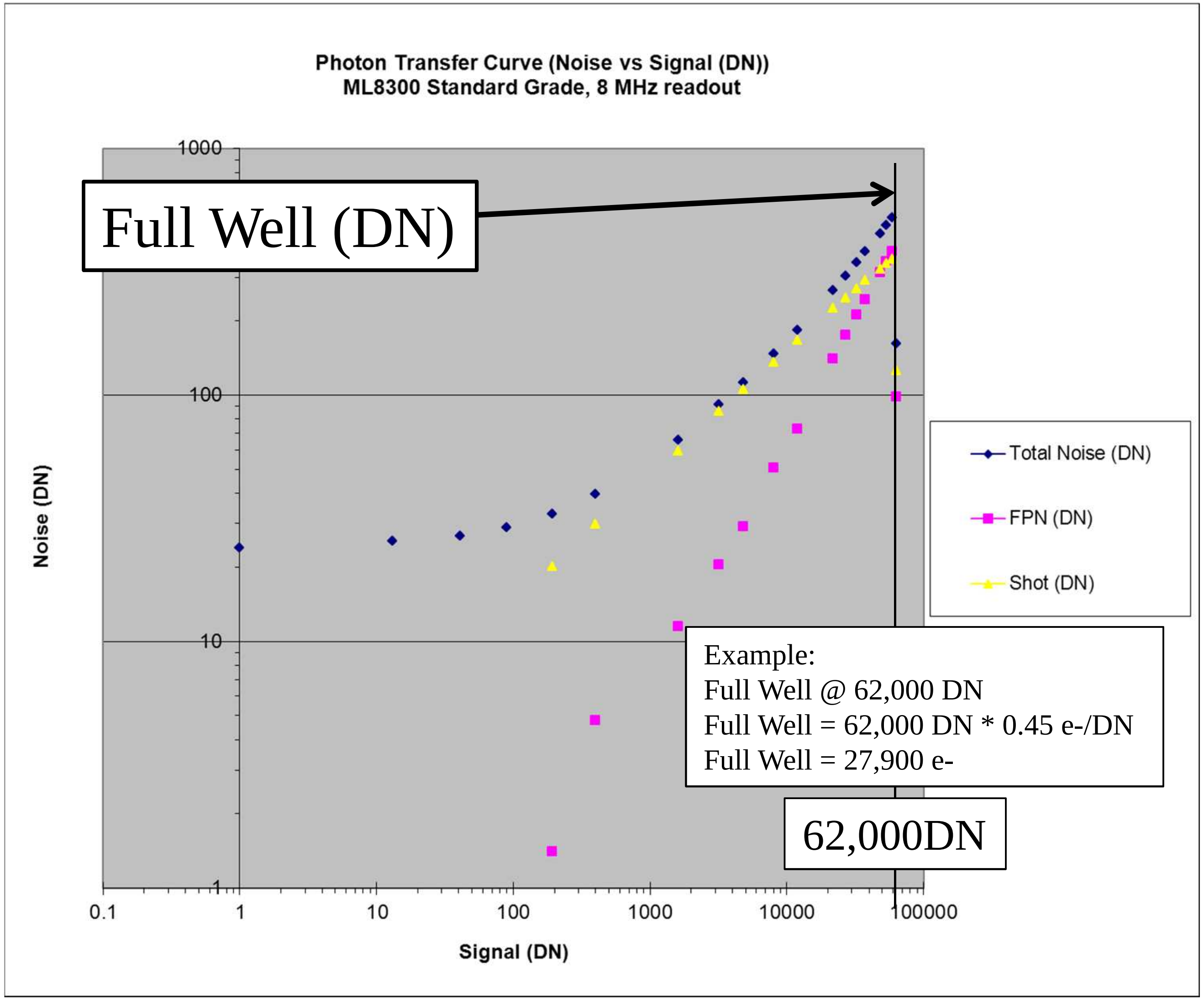
Example PTC: Measuring Read Noise



Example PTC: Measuring PRNU



Example PTC: Measuring Full Well



How to make a PTC

- Data Collection:
  - Operate the camera at -25C for the collecting the data below so that dark signal is negligible
  - Collect pairs of identical flat field exposures of varying intensity: ranging from nearly dark to fully saturated. You can do this inside a house with the bare camera looking at a ceiling in a dimly lit room (preferably adjustable light intensity level)
  - Take one bias frame
  - Usually about 16-20 flat pairs is sufficient

Reducing the data

- Using Excel or some other spreadsheet program label several columns for recording data
  - Raw Signal, Offset, Standard Deviation, Delta Standard Deviation, Signal – Offset, Average Signal –Offset, Total Noise, Shot + Read, Read(DN), FPN, Shot, Offset Correction

- Recording measurements from the collected data (this is where it gets tedious)
  - Pick analysis region to use for all data: 100 x 100 yields accuracy of 1% (sqrt(#pixels) = accuracy)
  - Crop the bias frame using the size/location chosen above and measure the average signal level and record that into the OFFSET column in the spreadsheet
  - Crop each image within a flat field pair to the analysis region size/location
  - Using the spreadsheet program record the average value of each cropped frame into the Average Signal column and the standard deviation into the Standard Deviation column (measure this using Maxim DL's "Information" window in "Area" mode)
  - Using Pixel Math in Maxim, subtract one cropped region from the other while adding a fixed value of 5000DN to the minuend (to prevent negative numbers).
    - Record the standard deviation of the difference into the Delta Standard Deviation column in the spreadsheet
  - Repeat for each pair of flats

Richard Crisp rdcrisp@earthlink.net www.narrowbandimaging.com

Spreadsheet View

signal	offset	std_dev	delta-std	signal-offset	average_signal-offset	total noise	shot+rd	read(DN)	FPN	sig_shot	offset_correction
2088	2088	24.147	33.853								
2087	2087	23.922									
2097	2088	24.924	35.366								
2097	2088	24.775									
2111	2088	25.521	36.174								
2111	2088	25.613									
2139	2088	26.506	37.678								
2139	2088	26.884									
2188	2088	28.88	40.866								
2188	2088	28.91									
2292	2088	32.776	46.31								
2292	2088	32.777									
2496	2088	39.729	55.851								
2495	2088	39.833									
3703	2088	65.913	91.78								
3703	2088	65.9									
5305	2088	91.551	126.564								
5304	2088	92.031									
6908	2088	112.26	153.468								
6907	2088	112.476									
10111	2088	147.108	195.242								
10109	2088	147.151									
14107	2088	184.69	239.094								
14102	2088	183.669									
23754	2088	266.283	319.866								
23752	2088	266.137									
29119	2088	304.443	352.58								
29110	2088	304.917									
34466	2088	343.677	383.58								
34465	2088	345.222									
39792	2088	384.786	416.567								
39795	2088	381.22									
50381	2088	454.617	461.335								
50382	2088	450.876									
55626	2088	486.514	485.382								
55621	2088	490.762									
60840	2088	522.294	505.087								
60854	2088	526.425									
65477	2088	160.53	181.48								
65476	2088	162.704									

Filling in the Equations

- The next task is to create equations for the remaining columns
- First fill in the value zero into the Offset Correction column. This value may need to be changed after plotting the data
- Use the following equations for the remaining columns (see the next page)

Equations

- Signal – Offset:

  = (signal – offset – offset correction)

signal	offset	std_dev	delta-std	signal-offset	average_signal-offset	total noise	shot+rd	read(DN)	FPN	sig_shot	offset_correction
2088	2088	24.147	33.853								0
2087	2087	23.922									0
2097	2088	24.924	35.366								0
2097	2088	24.775									0
2111	2088	25.521	36.174								

Equations

- Average Signal – Offset:

= AVG(signal – offset (n), signal – offset (n+1))

signal	offset	std_dev	delta-std	signal-offset	average_signal-offset	total noise	shot+rd	read(DN)	FPN	sig_shot	offset_correction
2088	2088	24.147	33.853								0
2087	2087	23.922									0
2097	2088	24.924	35.366								0
2097	2088	24.775									0
[illegible]	[illegible]	[illegible]	[illegible]								

Richard Crisp rdcrisp@earthlink.net www.narrowbandimaging.com

Equations

- Total Noise:

$$= AVG(std\_dev(n), std\_dev(n+1))$$

signal	offset	std_dev	delta-std	signal-offset	average_signal-offset	total noise	shot+rd	read(DN)	FPN	sig_shot	offset_correction
2088	2088	24.147	33.853								0
2087	2087	23.922									0
2097	2088	24.924	35.366								0
2097	2088	24.775									0
[illegible]	[illegible]	[illegible]	[illegible]								

Equations

- Shot + Rd:

= delta-std / sqrt(2)

signal	offset	std_dev	delta-std	signal-offset	average_signal-offset	total noise	shot+rd	read(DN)	FPN	sig_shot	offset_correction
2088	2088	24.147	33.853								0
2087	2087	23.922									0
2097	2088	24.924	35.366								0
2097	2088	24.775									0
[illegible]	[illegible]	[illegible]	[illegible]								

Equations

- read:

Write in the Y axis intercept value of Total Noise

signal	offset	std_dev	delta-std	signal-offset	average_signal-offset	total noise	shot+rd	read(DN)	FPN	sig_shot	offset_correction
2088	2088	24.147	33.853								0
2087	2087	23.922									0
2097	2088	24.924	35.366								0
2097	2088	24.775									0
[illegible]	[illegible]	[illegible]	[illegible]								

= Read (n-1) value
(recursive from previous row)

The value of the read noise will likely be adjusted later to correct a common PTC error

Richard Crisp rdcrisp@earthlink.net www.narrowbandimaging.com

Equations

- FPN:

=SQRT(Total Noise^2 – Read+Shot^2)

signal	offset	std_dev	delta-std	signal-offset	average_signal-offset	total noise	shot+rd	read(DN)	FPN	sig_shot	offset_correction
2088	2088	24.147	33.853								0
2087	2087	23.922									0
2097	2088	24.924	35.366								0
2097	2088	24.775									0
2111	2088	[illegible]	[illegible]								

Equations

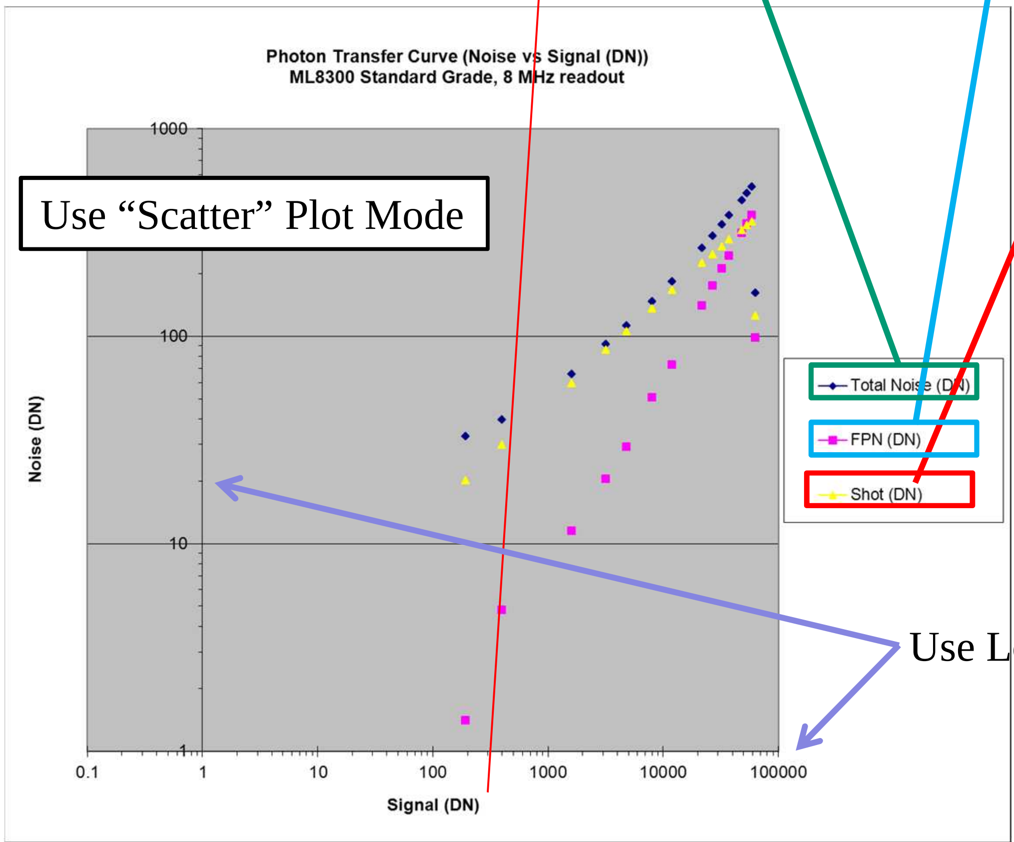
- Sig Shot:

=SQRT(Shot+Read^2 – Read^2)

signal	offset	std_dev	delta-std	signal-offset	average_signal-offset	total noise	shot+rd	read(DN)	FPN	sig_shot	offset_correction
2088	2088	24.147	33.853								0
2087	2087	23.922									0
2097	2088	24.924	35.366								0
2097	2088	24.775									0
2111	2088	25.521	36.174								

Result

signal	offset	std_dev	delta-std	signal-offset	average_signal-offset	total noise	shot+rd	read(DN)	FPN	sig_shot	offset_correction
2292	2088	32.776	46.31	194	194	32.7765	32.74612	25.8	1.410993	20.16601	10
2292	2088	32.777		194							10
2496	2088	39.729	55.851	398	397.5	39.781	39.49262	25.8	4.781303	29.90029	10
2495	2088	39.833		397							10
3703	2088	65.913	91.78	1605	1605	65.9065	64.89826	25.8	11.48401	59.54951	10
3703	2088	65.9		1605							10



Use Logarithmic Axes

Glossary

- PRNU (Photo Response Non Uniformity)

Revision History

- 23 Jan 2012: initial release of part 1
- 24 Jan 2012: Goals page inserted as p4. revisions to PP 6, 9, 14, glossary added at end re-release of part 1