Noise Analysis of AHR Spectrometer

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1. Introduction

The noise from Spectrometer can be very confusing. We will categorize different noise and analyze them in this document from spectrometer user point of view.

1.1. Noise when the light input is blocked off

Noise Type	Characteristics	Comments
CCD Dark Current	DC	temperature dependent Pixel variation Can be subtracted.
Readout Noise *Including electronics inside CCD and outside CCD*	AC	CCD Readout circuit design Analog to Digital design Negligible temperature dependency May be reduced by averaging
Leakage Light Noise	DC	Improper enclosure cause light leakage into the spectrometer

Table 1 Noise Sources when the light input is blocked off

CCD Dark current can be subtracted or reduced by temperature cooling. It becomes an issue when the magnitude reaches the signal level. Subtraction does improve the SNR. It is not be big concern if the signal level can reach half of the maximum magnitude with integration time less than 0.5 second at ambient temperature.

The readout noise reduction is critical when design the electronics inside the CCD and off the CCD on the camera board. It is an important factor to consider during detector selection. When designing the camera board, noise reduction is very critical in the design process. Higher analog to digital sampling rate will incur more noise.

1.2. Noise when the light input is blocked off

Addition to noise from Table 1, spectrometers have the following additional noise when there is light input.

Noise Type	Characteristics	Comments
Stray Light	DC	Dependent of input light wavelength Range, and more importantly, the spectrometer design.

Shot Noise	AC	Increase with signal
Pixel Non-Uniformity	Can be corrected by Quadratic Approximation	Linearity Variation

Table 2 Noise Sources when the light input is on

Shot noise and Pixel non-uniformity are determined by the CCD detector. The Stray light is determined by the optical bench design.

Planar Grating design will have higher stray light than Concave system, like the Concavus Spectrometer, due to its simpler light path.

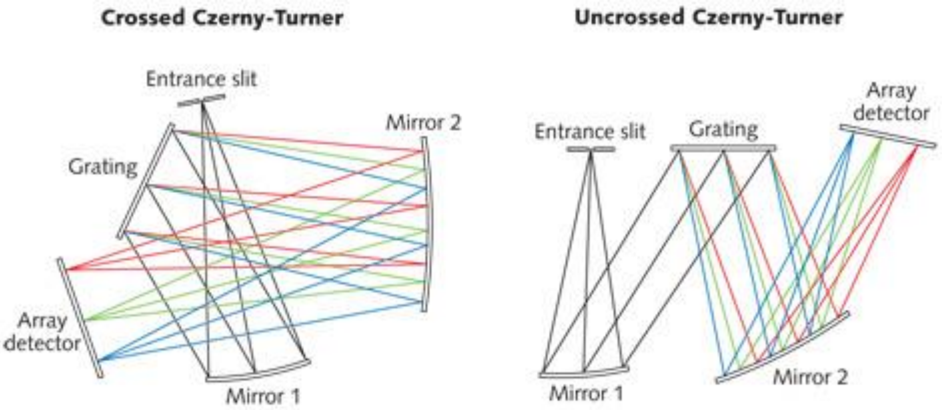

Fig 1. Crossed and Uncrossed (Regular) Czerny-Turner Configuration

For the planar system, two type of configurations are popular, crossed and non-crossed Czerny-Tuner Configuration. Cross ZT may offer more compact design, but has more scattering in front of the CCD, also, it is more difficult to block the unwanted diffraction order due to physical constraint. Uncross ZT has its detector on the side, make it receive less scattering and due to its physical plan, easier to block off unwanted diffraction orders. The difference in stray light can be very significant between these two designs.

AHR series is based on non-symmetrical non-crossed (Regular) Czerny-Tuner Design. When designing Regular CT, one can choose symmetrical or non-symmetrical. In fact, symmetrical CT is a special case. Non-symmetrical configuration was chosen because it can usually generate more optimal design due to its higher order of freedom during the optimization process.

In the following measurement, the measured count is 0-65535 from the 16bit ADC, unless indicated otherwise.

2. Contents

3. Revision

3.1. Creation of document 7/16/2014

4. Dark Current

Under no input light, 4ms integration time

Temperature (C)	Dark Current
3.4	188
4.5	188
5.8	190
6.83	195
7.69	202
8.22	209
9.4	218
10.5	236
11.22	246
12.4	280
14.33	324
15.51	365
16.47	395
17.43	444
18.83	485
19.68	517
20.11	542
20.54	563
21.82	615
24.3	725

Table 3 Dark current and temperature

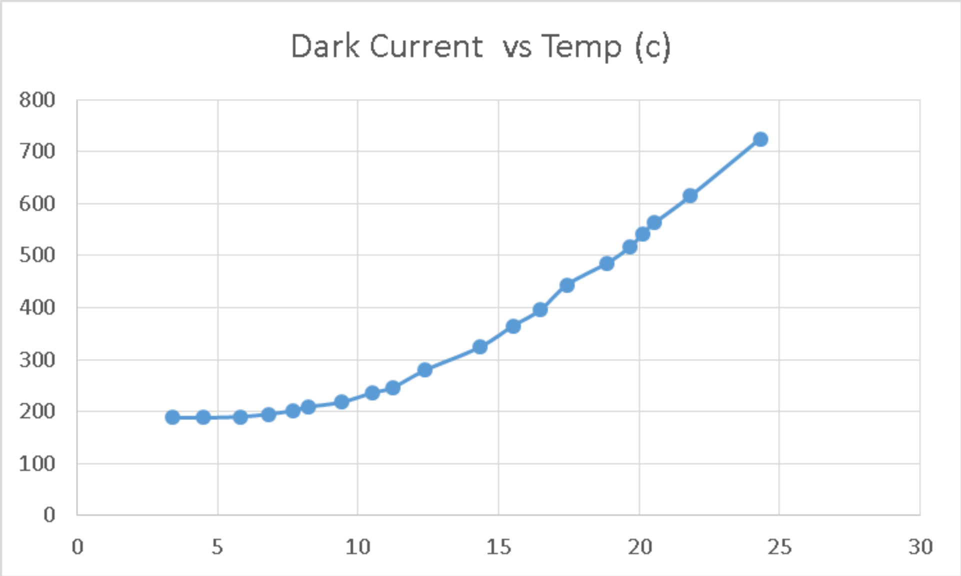

Fig 2. Dark Current vs. Temperature

The level at 0C is adjusted to 180 count level. A good rule of thumb of rule is that the dark current double every 10C.

5. Readout Noise

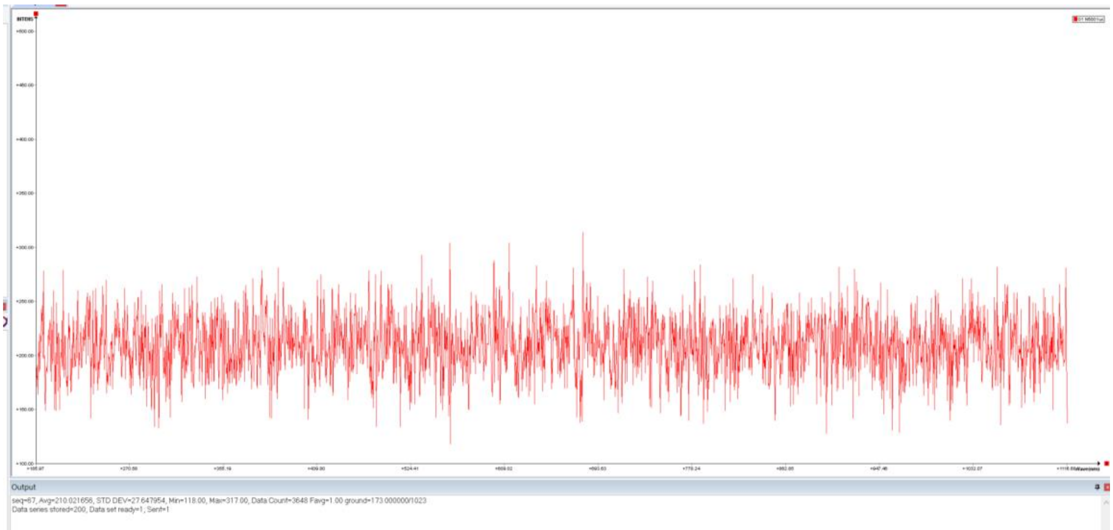

Fig 3. No Averaging, 5ms, RMS 27.6

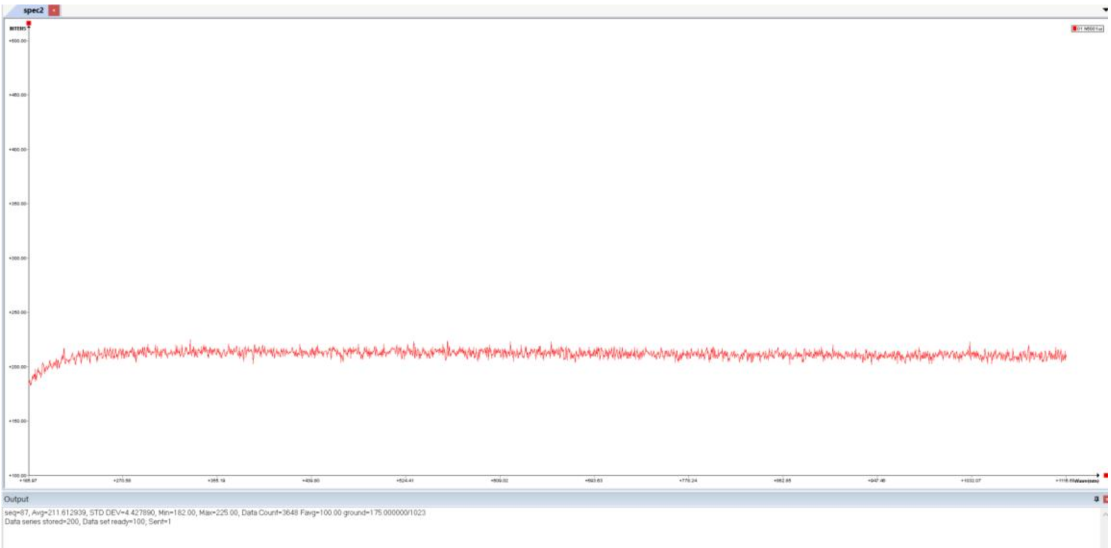

Fig 3. 100 Firmware Averaging, 5ms, RMS 4.4

The readout noise is dependent on the CCD sensor and camera design. The noise from the camera design has to be minimized so the readout noise is mainly due to the CCD sensor. Averaging helps greatly. AHR has averaging feature built-in inside the firmware.

5.1. Dynamic Range

In common definition,

Dynamic Range=Full range of signal/readout noise rms

In this case, Full range = 65535,

DR= 65535/27.6=2374 No averaging

DR= 65535/4.4=14894 Averaging of 100 samples

DR is a good measurement of the CCD sensor noise and camera circuit design.

6. Leakage Light Noise

Due to improper spectrometer design, light can enter the optical bench from places other than the fiber connector. This can be tested with a flashlight. A well made spectrometer should not have spectrum change when a flashlight points at any place on the spectrometer other than the fiber connector.

7. Stray Light

As other noise source is more correlated to the quality of CCD detector, stray light noise is purely influenced by the optical bench. Therefore, it is a good representation of the quality of optical bench itself. Resolution is the most advertised attribute in fiber spectrometers. But stray light probably has more impact in most measurement since it directly influence the SN.

Stray light is directly proportional to the total light energy inside the system. When comparing Stray light in different spectrometers, the light entering the optical system has to be identical.

For example, if you use a tungsten lamp and white LED lamp to measure the stray light. You set the maximum close to saturation. Tungsten lamp setup will generate higher stray light than white LED because tungsten lamp has broader spectrum and higher photon counts.

There are many ways to measure the stray light. We will describe three ways and present the results.

7.1. Use Tungsten halogen lamp to measure stray light

Tungsten halogen lamp does not emit signal below 300nm, to measure the spectrum under 300nm is a simple way to measure stray light. It is a good effective tool to compare the stray light of spectrometers.

1 Connect Tungsten Halogen lamp to the spectrometer with an optical fiber. Set the integration time so the maximum of the spectrum is a little under saturation. In this case, it is 150us and firmware averaging set to 100.

2 Turn off the lamp, and save the dark current spectrum and use that for subtraction. (Use as Dark, and enable Use Dark) Now new reading should be at zero dc level.

3 Turn on the lamp, notice the DC level below 300nm increase from 0 to roughly 85, that is stray light. 85/65535=0.15%

4 We perform the same test on Concavus System, and the stray light in the magnitude of 30. 30/65535=0.05%

Fig. 4. Stray light from Tungsten Halogen Lamp. ~85 counts

One can also use Hg-Ar calibration lamp to measure the baseline increase as stray light measurement. However, the total light energy from Hg-Ar lamp is much weaker than Tungsten Halogen lamp, therefore, it is not as good a measurement, but a good sanity check.

7.2. *Use Filter or Solutions to measure the stray light*

There are solutions that are used as industrial calibration standards for measuring stray light. The issue is that their range is from 200nm to 390nm and that might be outside the range of the spectrometer. These are preferred method if stray light below 390nm is needed.

Material	Cut-off	Concentration
Sodium Nitrite	390 nm	5% aqueous
Potassium Iodide	260 nm	1% aqueous
Sodium Iodide	260 nm	1% aqueous
Lithium Carbonate	227 nm	Saturated aqueous
Sodium Chloride	205 nm	1% aqueous
Potassium Chloride	200 nm	1.2% aqueous

One can also use common Schott Optical Glass filters. For example, RG610 is a long pass filter with cutoff at 610nm. It is suitable for VIS stray light measurement. You have to be careful with glass filter if input light has UV components as some glass filters emit florescence that can be mistaken as stray light.

One can also use thin-film optical filters. But user needs to be mindful of the entrance angle as the filter characteristics is dependent on it.

7.3. *Tungsten Halogen lamp and 3mm thick RG610 optical glass filter*

1 Connect Tungsten Halogen lamp to the spectrometer with an optical fiber. Set the integration time so the maximum of the spectrum is a little under saturation. In this case, it is 150us and firmware averaging set to 100.

2 Turn off the lamp, and save the dark current spectrum and use that for subtraction. (Use as Dark, and enable Use Dark) Now new reading should be at zero dc level.

3 Place RG610 Filter in the light path before light enters the spectrometer. Turn on the lamp, notice the DC level below 500nm increase from 0 to roughly 70, that is stray light.

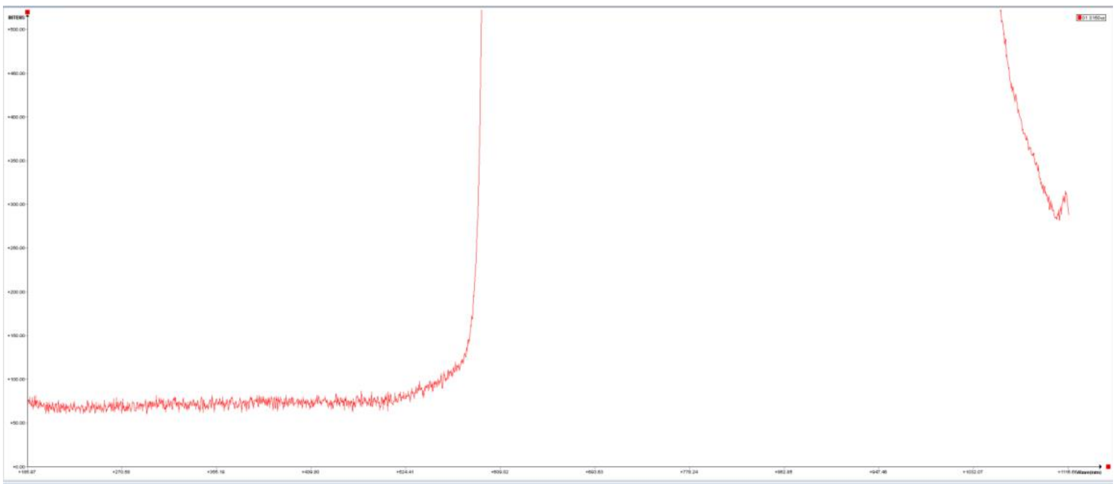

Fig. 5. Stray light from Tungsten Halogen Lamp & 3mm RG610 Filter. ~70 counts

The stray light is less than measurement from 7.1 because the filter cut off a percentage of the total light energy going into the system. The stray light is related to the random scattering of light inside the system, and the scattering light intensity is directly proportional to the total light energy in the system. Also, one can compare the cutoff transition to study the stray light property.

7.4. Monochromator Scanning

Above tests have limitation where it cuts off a large portion of the spectrum(LPF). To study the stray light thoroughly, one needs to input monochromatic light at each wavelength and observe its stray light. A programmable scanning monochromator is used for that purpose in our laboratory. We couple the monochromatic light into the spectrometer. We increase the integration time to saturate the signal. The wavelength is continuously scanned from 200 to 1100nm. And we observe the stray light during the scanning process. We use this tool as verification tool to make sure there is no noticeable stray light.

Measurement Setup	Stray Light %
Tungsten lamp	0.15% AHR02 0.05% HR02
RG610 Filter + Tungsten Lamp	0.1%

8. Shot Noise

We take a Tungsten Halogen lamp spectrum and save it as Dark and subtract it from subsequent readings.

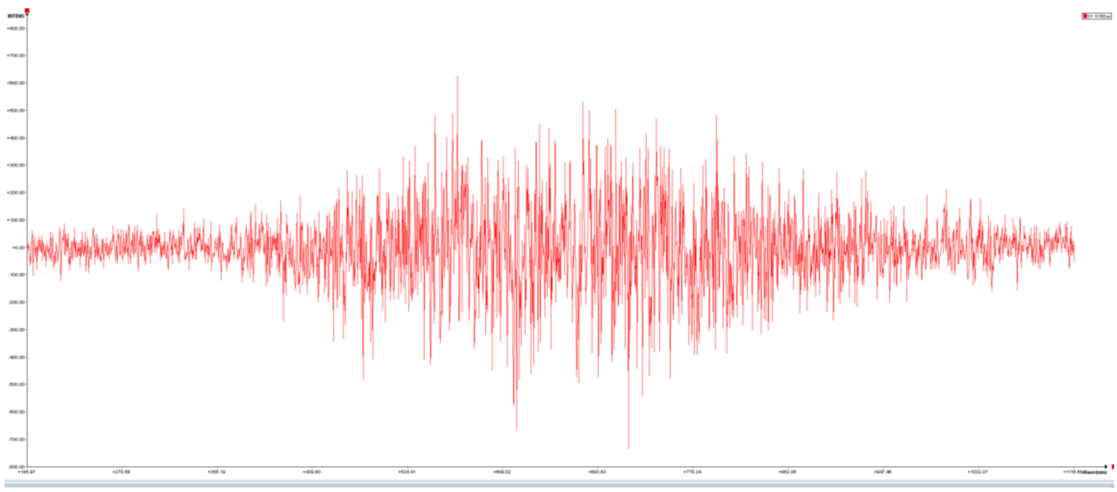

Fig. 6. Shot Noise

The noise increase with signal intensity.

SNR measurement:

1. Tungsten lamp, No Averaging at 9 different pixels. Integration Time=65us

   Pixel 1400, avg=35168.232000, stddev=140.822975 SNR=249.733625

   Pixel 1500, avg=42452.607000, stddev=141.003286 SNR=301.075303

   Pixel 1600, avg=51428.019000, stddev=163.166616 SNR=315.187139

   Pixel 1700, avg=53530.075000, stddev=151.900827 SNR=352.401471

   Pixel 1800, avg=56577.750000, stddev=154.048439 SNR=367.272466

   Pixel 1900, avg=55398.996000, stddev=164.835294 SNR=336.086980

   Pixel 2000, avg=57549.169000, stddev=151.430012 SNR=380.038067

   Pixel 2100, avg=64802.726000, stddev=153.942648 SNR=420.953691

   Pixel 2200, avg=58477.762000, stddev=163.588818 SNR=357.467966

2. Tungsten lamp, Averaging=10 at 9 different pixels. Integration Time=57us

   Pixel 1400, avg=35143.409908, stddev=27.725078 SNR=1267.567581

   Pixel 1500, avg=42436.867907, stddev=28.410132 SNR=1493.723037

   Pixel 1600, avg=51422.176662, stddev=34.715253 SNR=1481.256001

   Pixel 1700, avg=53510.173061, stddev=33.048530 SNR=1619.139294

   Pixel 1800, avg=56573.884100, stddev=34.244635 SNR=1652.051021

   Pixel 1900, avg=55390.527110, stddev=35.157382 SNR=1575.502028

   Pixel 2000, avg=57611.498674, stddev=39.583242 SNR=1455.451757

   Pixel 2100, avg=64840.579443, stddev=31.275777 SNR=2073.188435

   Pixel 2200, avg=58525.627404, stddev=35.816466 SNR=1634.042503

9. Pixel Non-Uniformity

Pixel non-uniformity is a CCD parameter. The software can measure the linearity of nine pixels.

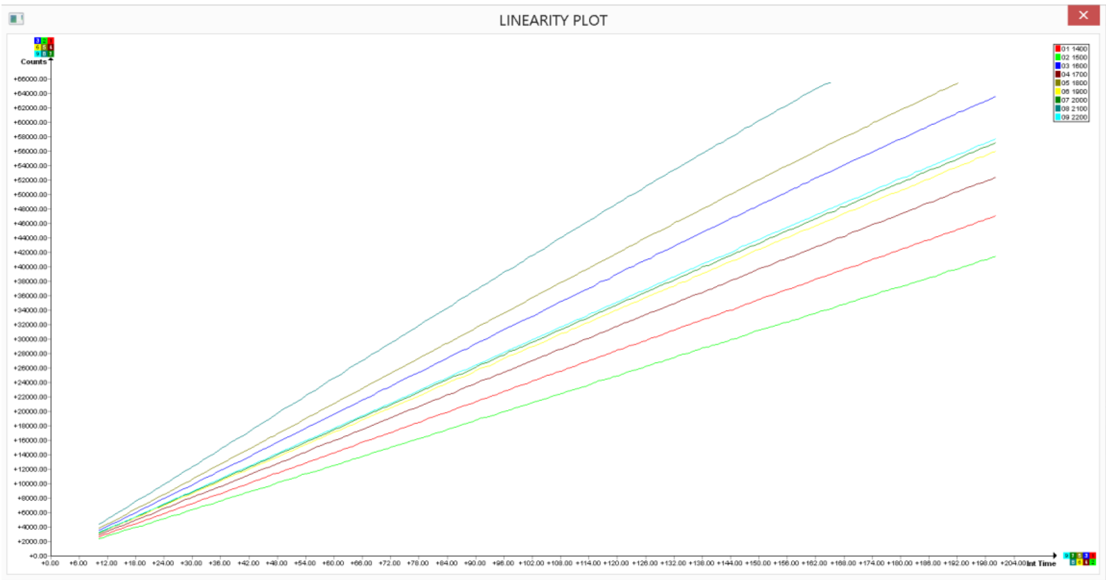

Fig. 6. Linearity Plot of Nine Pixels

Each pixel has different response slope (sensitivity) with respect to integration time. It is due to its difference in responsivity to different wavelength.

If we only care about the linearity of the curve, but not the slope for each pixel. We normalize the curve by divide it by itself from its interpolated linear fit. We get Fig. 7. We see the linearity error is less than 2%. If we want to correct that, we can then do a polynomial fit and straighten the curve, we get Fig. 8. Around 0.01-0.02 deviation.

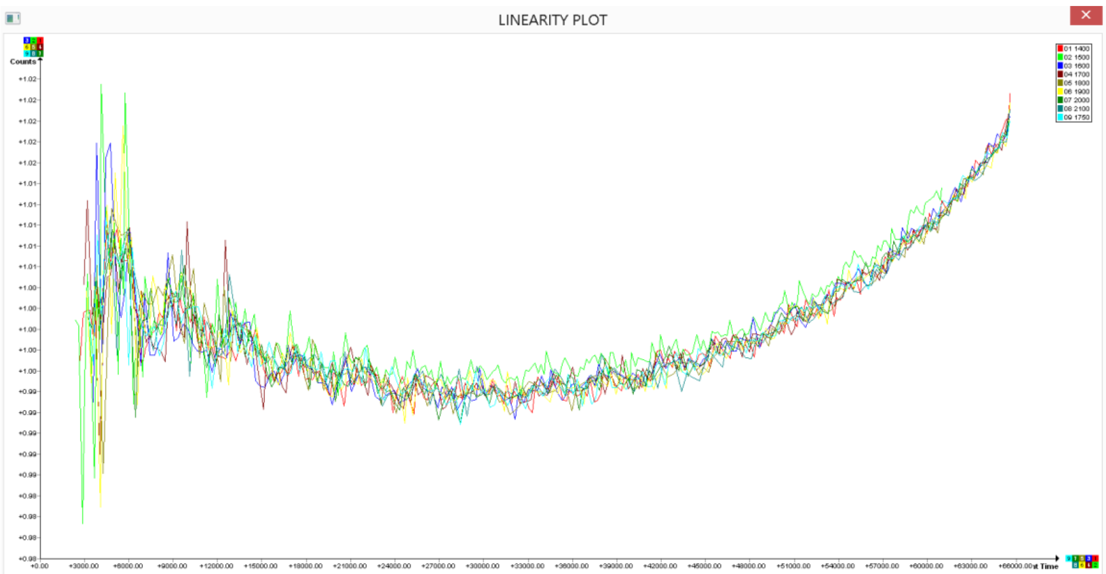

Fig. 7. Normalized Linearity Plot of Nine Pixels

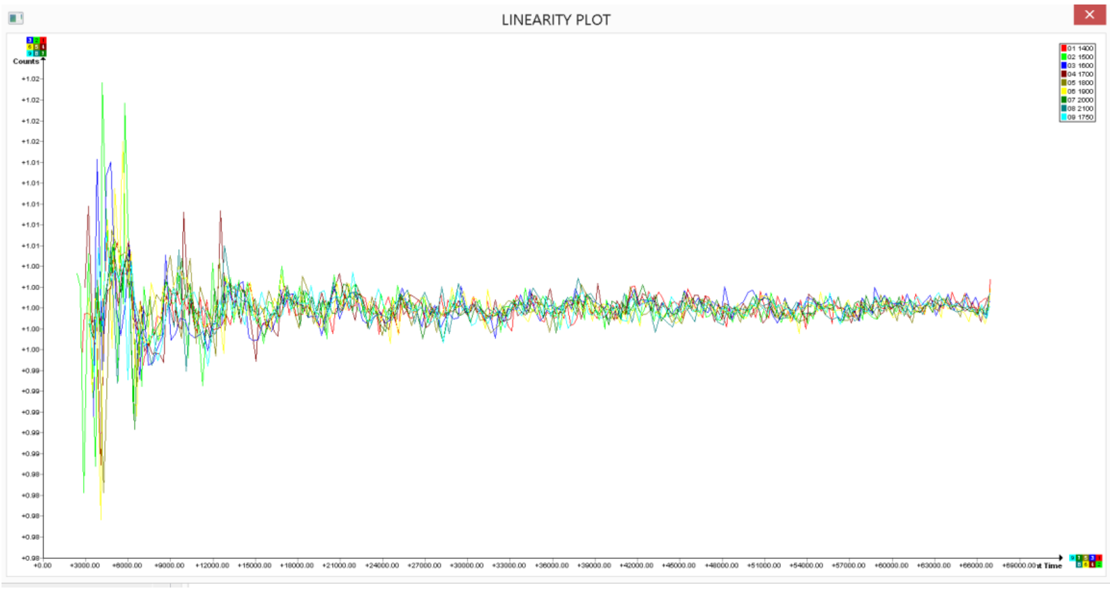

Fig. 8. Corrected Linearity Plot of Nine Pixels

10. CONCLUSION

We analyzed all the noise sources in AHR spectrometer. Aside from CCD detector noise, the stray light and camera board ADC noise are the challenge for spectrometer designer. In AHR system, we showed that we can keep the TCD1304DG CCD readout noise below 30rms without averaging. And keep stray light under 100 counts in Tungsten Halogen lamp test.

Note we can keep the stray light under 30 counts in Tungsten Halogen lamp test for Concavus System.