Investigating the effects of photomultiplier Nonlinearity in the Purple Crow Lidar

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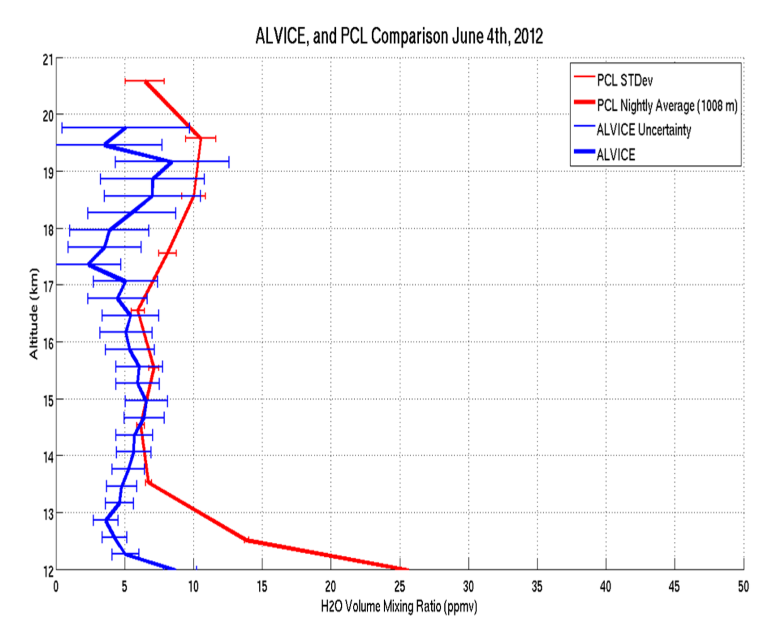
Background: ALVICE comparison

In Spring 2012, the Purple Crow Lidar (PCL) participated in a water vapor comparison with the NASA/GSFC ALVICE (Atmospheric Laboratory for Validation, Interagency Collaboration, and Education) lidar. Analysis showed that the PCL water vapor mixing ratio measurements were consistently higher than ALVICE [5].

Water vapor mixing ratio: $\boldsymbol{w} \propto \frac{\boldsymbol{N}_{\text{water vapor}}}{\boldsymbol{N}_{\text{nitrogen}}}$

Perhaps there is paralysis in one of the photo detector channels. We want to characterize the tube so we can accurately gauge its response to signal pulses.



Digital Paralysis and Deadtime

Digital paralysis occurs at high photocount rates when the detector cannot distinguish between overlapping pulses, resulting in a loss of measured counts with respect to actual counts. The time during which the system cannot distinguish between adjacent pulses is called deadtime.

Deadtime Correction:

$$N = S\exp(-S\tau_d)$$

N = Observed count rate
S = True count rate
τ_d =Deadtime

It is difficult to express the true count rate analytically, requiring clever methods for solving. To further complicate matters, the deadtime value itself varies, though is generally around 4ns in our system.

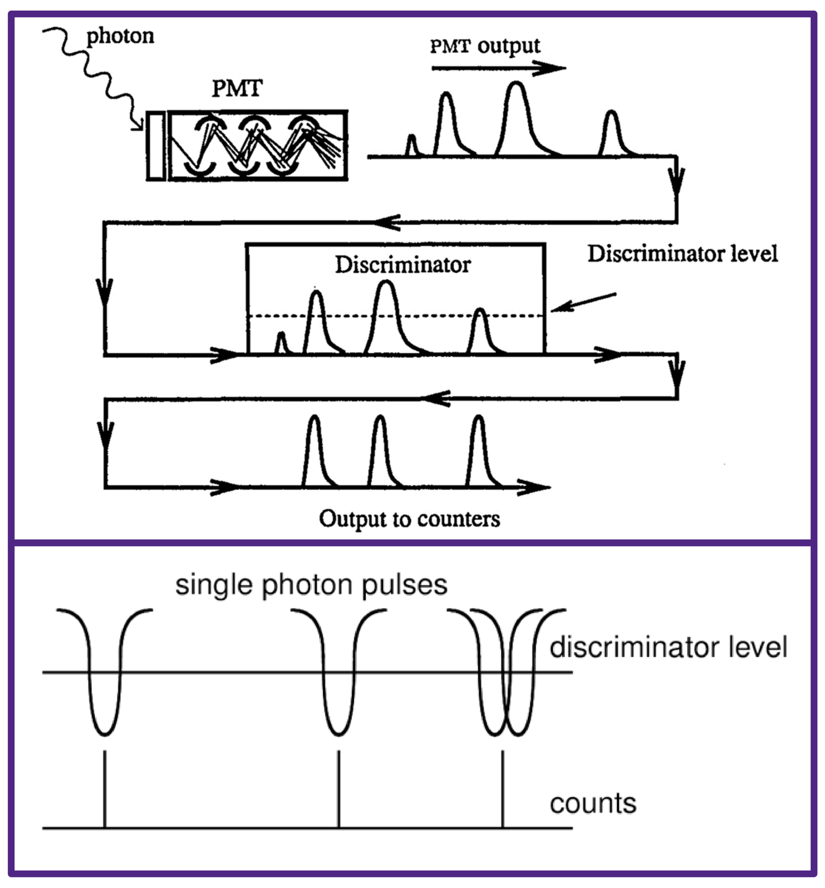


Figure 1

Fig. 1: (top) Illustration of photon counting, in which photons enter a photomultipler tube (PMT), generating photocount pulses [2]. A discriminator is set to filter out noise. (bottom) If photon pulses overlap such that the they cannot be distinguished from one another, they are counted as one count, leading to count loss [3].

Data Processing

- Define range to correct (cut off nonlinear low heights and noisy upper heights)
- Coadd counts into larger height bins (to increase signal to noise ratio)
- Subtract Background and AC offset (analog only)
- Normalize other channels to Digital High Rayleigh

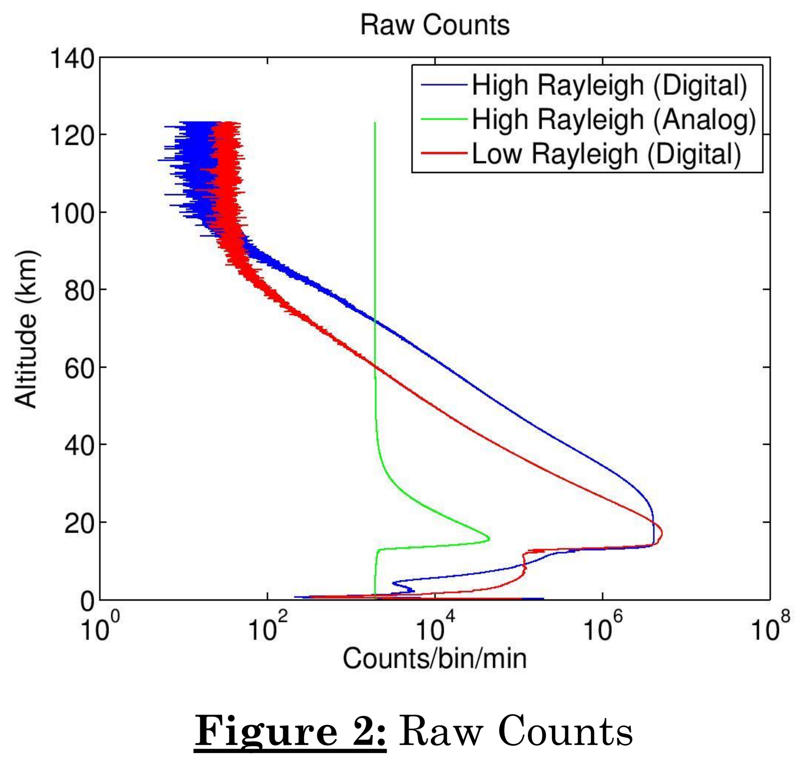


Figure 2: Raw Counts

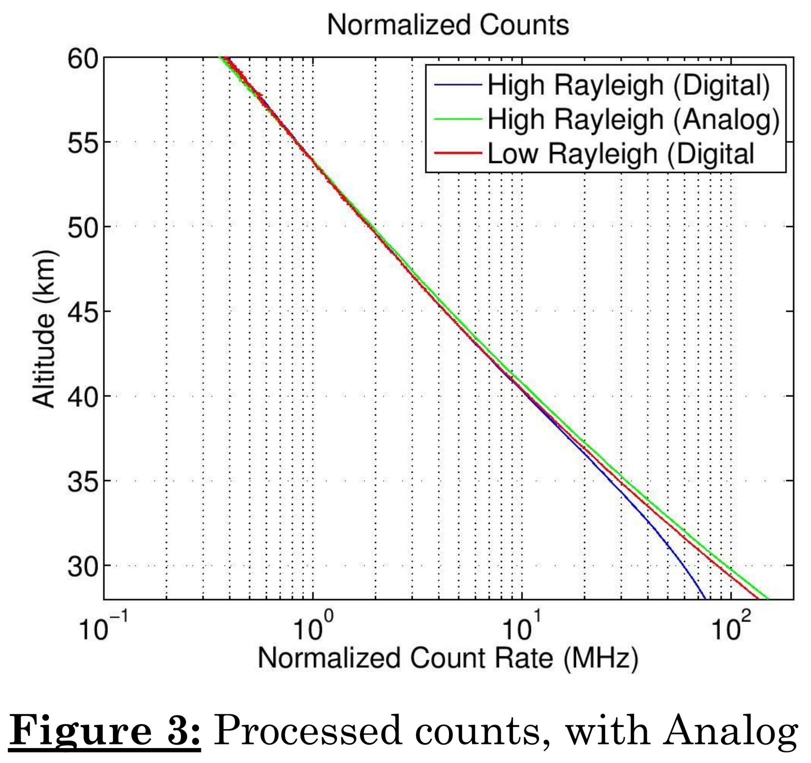


Figure 3: Processed counts, with Analog High Rayleigh and Low Rayleigh normalized to Digital High Rayleigh. Note how Digital High Rayleigh deviates from linearity below 35km.

Method 1: Manually finding deadtime

The analog channel does not measure discrete photocounts, so it is immune to digital paralysis. Thus, the analog count can be considered true count rates.

Inserting the digital and analog count rates into the deadtime correction equation as observed and true count rates, we can reverse engineer a lookup table to get a value for deadtime.

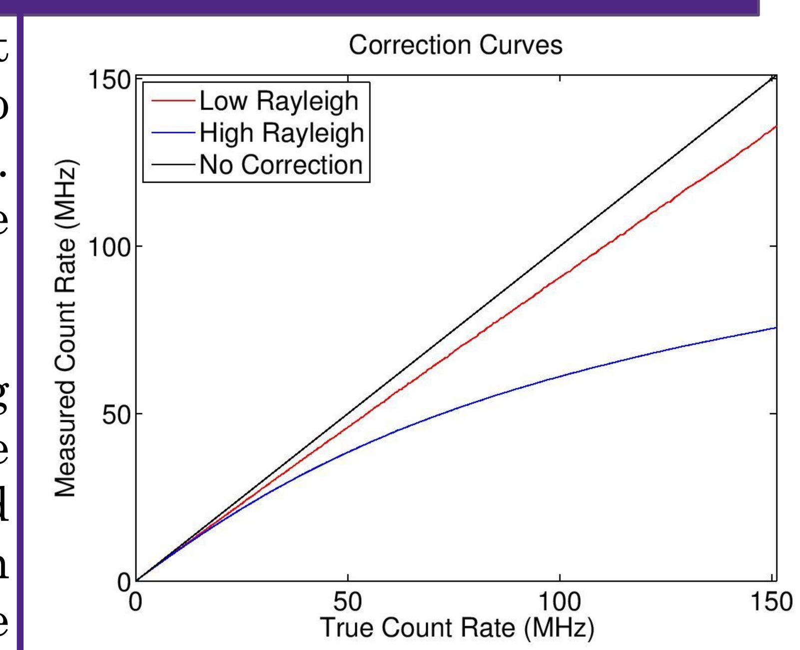


Figure 4

Fig. 4: Ratios of digital to analog counts. The black line represents no digital paralysis or loss of counts (when True=Observed counts). For Low Rayleigh (red line), there is a small deadtime causing a slight loss of measured counts (relative to true counts). For High Rayleigh, the deadtime is larger, resulting in a greater loss of measured counts and noticeably nonlinear relation.

Method 2: Optimal Estimation

Optimal estimation method (OEM) provides an efficient way to solve nonlinear problems, in which an unknown quantity (e.g. true counts) can be calculated from a known quantity (observed counts). Its power lies in the use of Bayes' statistics, where an *a priori* guess (estimate of what the actual value might be based on prior knowledge) for the unknown quantity is given. Bayes' theorem is then used to update the probability density function associated with the a priori guess and generate an answer.
The necessary content is housed in the cost function [4]:

$$c = [y - F(\boldsymbol{x})]^T S_y^{-1}[y - F(\boldsymbol{x})] + [\boldsymbol{x} - x_a]^T S_a^{-1}[\boldsymbol{x} - x_a]$$

y = measurement (observed counts)
F = Forward model (deadtime correction equation)
S_y =Measurement covariance
x_a =A priori guess (4ns)
S_a =A priori covariance
$\boldsymbol{x}$ = Solution (actual deadtime)

Minimizing the cost function and solving for $\boldsymbol{x}$ via the Gauss-Newton algorithm gives:

$$x = x_a + \left(S_a^{-1} + K^T S_y^{-1} K\right)^T K^T S_y^{-1}(y - F(x_a))$$

Conclusions

Deadtime Values (ns)

Date	5/23	5/24	5/25	5/26	5/28
Method 1	5.49	4.88	4.38	6.44	4.81
Method 2	5.89	4.58	5.00	7.11	4.80

Why do the values change so much from day-to-day and between the two methods?

Future Work
- More meticulous/systematic processing of data
- Process simulated lidar returns (analog variance not required)
- Extend survey to other channels (Nitrogen, Water vapor) and examine effects on water vapor mixing ratio
- Examine possible system fluorescence

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Sponsored by:

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