

# GLUING LIDAR SIGNALS DETECTED IN ANALOG-TO-DIGITAL AND PHOTON COUNTING MODES

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## ABSTRACT

Lidar is one of the most effective tools for atmospheric remote sensing. For a ground-based lidar system, the backscattered light usually has large dynamic range. Photon-counting mode has the capability to measure weak signal from high altitude, while Analog-to-Digital mode with better linearity is good at measuring strong signal at low altitude. In some lidar systems, atmospheric return signal is measured in both Analog-to-Digital and Photon Counting modes and combined into an entire profile by using a gluing algorithm. A method for gluing atmospheric return signal is developed and tested. For the Photon Counting signal, the saturation characteristics are analyzed to calculate the coefficients for correction. Then the Analog-to-Digital and Photon Counting signals are glued by a weighted average process. Results show the glued signal is reliable at both low and high altitudes.

## 1. INTRODUCTION

Photoelectric detection is an important issue in the receiving subsystem of lidar. Since the dynamic range of received signal is usually very large for a ground-based lidar, both Analog-to-Digital (AD) mode and photon counting (PC) mode are used to cover the whole dynamic range in many systems. For near-field signal, AD can convert analog voltage signal into digital signal with good linearity, but it cannot efficiently detect weak signal from far-field. On the contrary, PC mode can properly detect the far-field signal by counting the pulses generated by single photon. However, the intensity of near-field signal can easily exceed the maximum counting rate of PC, which results in saturation of photon counting rate. In that case, nonlinear error introduced from pulse pile-up appears [1]. Therefore, AD and PC can detect the near-field and far-field signal separately and two data streams should be combined into one signal profile before further processing.

The gluing algorithm is one of the essential issues to be considered for improving measurement

accuracy of various atmospheric parameters [2-5]. One method is to find regressions coefficient from two measurement modes to convert AD data to PC data and replace the saturated PC data with the converted AD data [6]. The other method is to calculate the variance of the data with Poisson's distribution to determine coefficients between AD and PC data [7]. In addition, Newsom et al., pointed that PC data should be the independent variable in linear regression calculation between AD data and PC data [6]. This method is also used in this paper. However, there is still some space to improve the gluing algorithm. Firstly, since the solar background light has influence on the selection of gluing region, it should not be subtracted from the return signal before applying the gluing process. Secondly, the non-linear relationship of AD and PC data calculated by curve-fitting is useful to determine the gluing region and perform the correction.

This paper develops a new gluing method to solve the problems mentioned above. Firstly, the relationship between original data of AD and PC is analyzed and the linear region is calculated. Secondly, the unit of AD data is converted into photon counting rates and is used to correct the saturated PC data according to the relationship obtained by curve-fitting. At last, the gluing signal is calculated by the weighted average method.

## 2. METHODOLOGY

In lidar system, PMT (photomultiplier tube) is illustrated by backscattered light and outputs analog voltage signal which is converted into digital signal by AD converter or into photon counts by photon counter. The process of gluing AD and PC data is shown in Fig. 1. The glued signal is calculated from the converted AD and PC data by linear-fitting and curve-fitting method.

The original AD data and PC data are compared and shown in Fig. 2. It shows that, when the PC value is less than about 100, there is a good linear relationship between PC and AD data, which means that the measured PC and AD value are

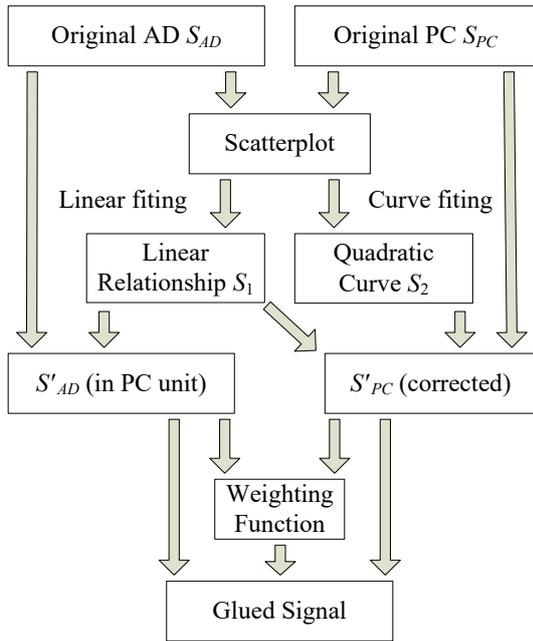


Fig. 1 Flow chart of gluing PC data and AD data

both correct. However, when the PC value is more than 200, there is obvious non-linear relationship between AD and PC data which is in saturated state. As shown in Fig. 2, the black curve is the result by curve fitting method, which is expressed as

$$E = \sum_{i=0}^m E_i^2 = \sum_{i=0}^m [S_2(x_i) - y_i]^2, \quad (1)$$

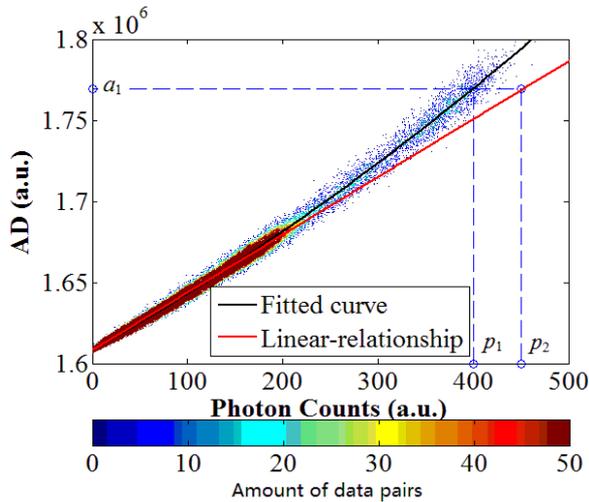


Fig. 2. Scatterplot of PC data and AD data. Red line is the linear-relationship between AD and PC data, black curve is the fitted curve, and colored points represent the amount of data pairs.

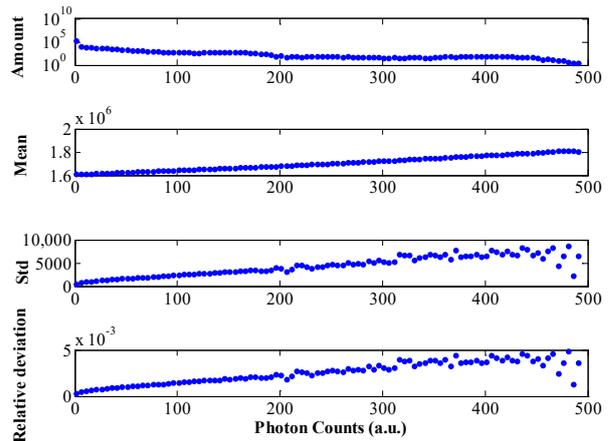


Fig. 3. Analysis of PC and AD data showing the amount of data pairs, mean, standard deviation and relative deviation in corresponding bin of photon counts from top to bottom.

$$S_2(x) = ax^2 + bx + c, \quad (2)$$

where  $S_2(x)$  is the expression of quadratic curve,  $y_i$  is the data before fitting,  $E$  is the total residual.  $a$ ,  $b$ ,  $c$  are the coefficients of the quadratic curve. The solution of  $S_2$  can be obtained by minimizing the total residual  $E$ .

To find a good linear region between AD and PC data, the PC axis is divided into photon counts bins to calculate the amount of data pairs, mean, standard deviation, the relative deviation (ratio of standard deviation and mean) in each bin. As shown in Fig. 3, the relative deviation increases with PC value. The linear region is determined by the threshold of the relative deviation, which is selected to be about 0.003. The data within this region is used for fitting linear relationship shown by the red line in Fig. 2. The linear fitting method is expressed as

$$E = \sum_{i=0}^m E_i^2 = \sum_{i=0}^m [S_1(x_i) - y_i]^2, \quad (3)$$

$$S_1(x) = ax + b, \quad (4)$$

where  $S_1(x)$  is the expression of linear relationship,  $y_i$  is the data before fitting,  $E$  is the total residual.  $a$  and  $b$  are the slope and offset of the line. The solution of  $S_1$  can be obtained by minimizing the total residual  $E$ .

An example of the process of gluing method is shown in Fig. 2. In the first step, for any PC value  $p_1$ , the corresponding AD value  $a_1$  can be

calculated according to the fitted curve shown by the black curve in Fig. 2, which can correct the saturated PC data. In the second step, to convert the AD data into PC unit,  $p_2$  is calculated from the AD value  $a_1$  according to the linear relationship shown by the red line in Fig. 2. These two steps carry out the correction of PC data. As shown in Fig. 2, when original PC value is about 400, the corrected PC value is about 450, corresponding to a saturation amount of about 13%. When PC value is beyond 400, the saturation amount is more than 13%. To convert any original AD data to PC unit, just the second step is needed.

Finally, the gluing signal is calculated by weighted average method expressed as

$$S_{Glued} = (1 - W)S'_{PC} + WS'_{AD}, \quad (5)$$

$$W = \begin{cases} 0, (S'_{PC} \leq C_{\min}) \\ \frac{S'_{PC} - C_{\min}}{C_{\max} - C_{\min}}, (C_{\min} < S'_{PC} < C_{\max}), \\ 1, (S'_{PC} \geq C_{\max}) \end{cases} \quad (6)$$

where  $S_{Glued}$  is the glued data,  $S'_{PC}$  is the corrected PC data,  $S'_{AD}$  is the converted AD data,  $W$  is weighting function,  $C_{\max}$  and  $C_{\min}$  are the maximum and minimum value in the gluing region, respectively.

### 3. RESULTS

The lidar system [8-10] developed by Ocean University of China (OUC) is used to acquire data for testing the proposed gluing method. Specifications of the lidar are shown in Tab. 1. Atmospheric signal was measured on January 17, 2015 from 20:08 to 20:12 when the weather was

Tab. 1 Specifications of the lidar system

Parameters	Specifications
Wavelength	532 nm
Repetition rates	100 Hz
Pulse energy	0.12J
Pulse duration	10ns
Linewidth	100MHz
Spectrum purity	> 99.9%
Analog-to-Digital converters	400MHz 14bit
Photon counters	400MHz

cloudy. Data of every 100 pulses (about a second) is saved in a data file and a scatterplot of all data pairs is shown in Fig. 2.

After subtracting background, the AD, PC and glued data is shown in Fig. 4. The signal shows a cloud layer at altitude of about 4.7km, which accords with weather condition. Fig. 4(b)(c)(d) show the details at different altitudes. As shown in Fig. 4(a) the saturation of PC signal is obvious when the data is beyond 300. As shown in Fig. 4(c) and (d), the glued signal is consistent with AD, and PC data. However, it is shown in Fig. 4(b) that the PC is saturated and the glued signal corrects the saturation.

Fig. 5 shows the deviation of AD and PC data compared to the glued data. The difference between PC data, AD data and glued data is obviously at the height of about 1km, especially the absolute deviation of PC data due to saturation. However, absolute deviation of AD data is much smaller than PC data because AD data becomes noisy in the case of weak signal with small

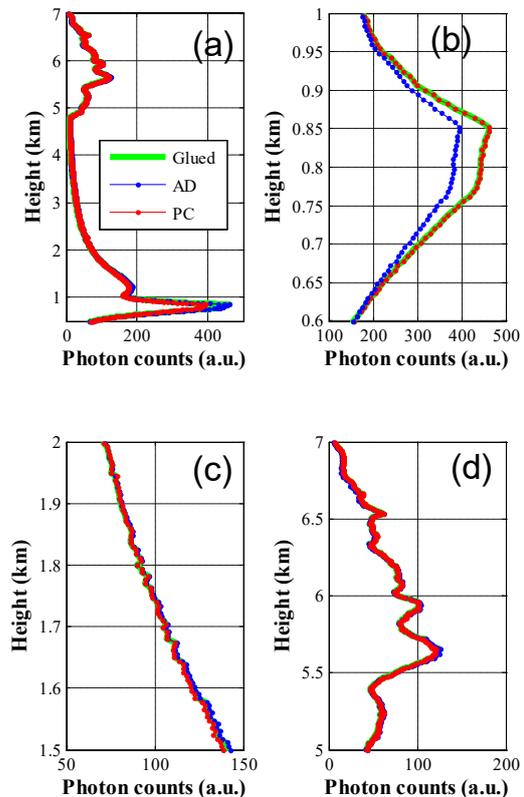


Fig. 4 Signals after background subtraction in the height of (a) 0.5km to 7km, (b) 0.6km to 1km, (c) 1.5km to 2km and (d) 5km to 7km.

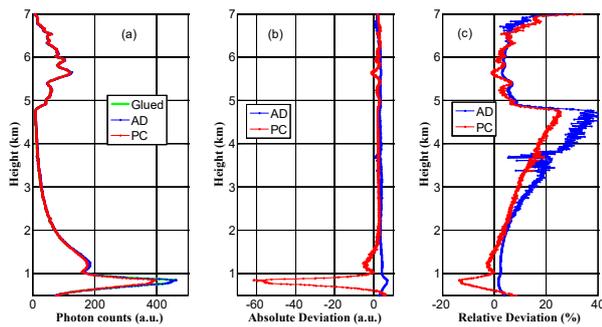


Fig. 5 Deviation of AD and PC data compared to the glued data. (a) glued data, AD data and PC data, (b) absolute deviation of AD (AD data minus glued data) and PC (PC data minus glued data), (c) relative deviation (absolute deviation divided by glued data) of AD and PC.

absolute value. In addition, relative deviation increases below cloud layer. However, in the cloud region at the height of 5km to 7km, relative deviation decreases.

#### 4. CONCLUSIONS

A gluing method is proposed and tested in this paper. Original AD data and PC data are used to calculate the relationship by curve-fitting and to correct PC data. A linear region is determined to obtain a linear relationship to change AD data to PC unit. Finally, the glued signal is calculated by weighted average. Results show the gluing method can correct the saturated PC data. Comparison in cloud region indicates that strong signal keeps the reliability after gluing. This method can be used for gluing PC data and AD data in lidar systems for measuring various atmospheric parameters.

#### ACKNOWLEDGEMENT

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