Short Term Minutes-timescale Temporal Variation Statistics of Sodium Layer Dynamics

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Abstract

The brightness and height of the sodium laser guide star of adaptive optics could vary significantly due to the temporal dynamics of sodium column density and the mean height of the sodium layer. To measure these dynamics, an independent sodium Lidar is a necessity. Without such an instrument, it is almost impossible to discern the cause of the brightness variation of the laser guide star from the sodium layer’s dynamics or other factors from the laser itself. For applications such as characterizing the performance of sodium laser for sodium laser guide star generation, minutes scale short term statistics of the sodium layers’ abundance and height is extremely helpful for estimating the contribution of sodium layer’s variation to the variation of laser guide star’s brightness. In this paper, we analyzed our previous measurement of sodium layer dynamics that has been gathered in two winters, and presented the temporal variation statistics of sodium column density and mean height within a minute timescale based on our measurements.

Key words: Astronomical instrumentation – Laser guide stars

1. Introduction

Sodium Laser Guide Star (LGS) is becoming an indispensable component for Adaptive Optics (AO) system in recent years. In comparison with natural guide star, the artificially made sodium laser guide star could be projected to anywhere in the sky, and significantly improves the sky coverage of traditional AO system that solely depends on natural guide stars.

However, because the sodium laser guide star is generated by the spontaneous emission of sodium atoms in the mesosphere. The performances of the sodium laser guide star are bond with the variation of the sodium layer which is normally located 90 ~ 110 km above sea level in the atmosphere. The abundance, or column density of sodium atoms in this layer will influence the brightness of sodium LGS, while the variation of the vertical distribution of sodium layer will introduce focal anisoplanatism and change the shape of LGS spot in AO wave front sensor and thus degrade AO system’s wave front sensing performance. It is, therefore, important to measure and study the dynamics of sodium layers on site. For the evaluation of sodium LGS performance in the long-term and large geological scale, data from remote sensing satellites have been published by several sources such as Fan et al. (2007), Fussen (2004), Fussen et al. (2010), Langowski et al. (2017). High cadence sodium dynamics measurements on-site have also been conducted and reported in a number of articles Kwon et al. (1988), Gong et al. (2002), Hickson & Pfommer (2010), Jiao et al. (2014). However, the focus of these articles is mainly either on the overall trends of the absolute value of sodium abundance on a long timescale or on the sporadic behaviors of the sodium layer. For relatively short term applications such as characterizing the performance of sodium laser for generating sodium laser guide star, which normally takes a few minutes for each test, one needs to answer the question of how much percentage of sodium column density would change within minutes timescale because the variation in these photometric results includes not only the results of the laser but also from the short dynamic change of the sodium layer.

In this paper, we attempt to use previous measurements gathered at Gao-Mei-Gu Observatory in two winters to find this answer, or at least provide a possible hint of the scale of the variation of sodium column density and sodium layer’s mean height that could help similar LGS experiments evaluating laser’s performances.

In Section 2, we will present data that we have gathered on site, and the criteria by which certain data are chosen to do...
statistics. In Section 3, we will describe the method we used for statistics and show the results. In Section 4, the conclusion is given based on our current results.

2. Data

Gao-Mei-Gu observatory is located in Yunnan, China. Its latitude and longitude are 26°42’32”N,100°01’51”E respectively. A sodium fluorescence lidar developed by the University of Science and Technology of China was deployed at the site for monitoring the variations of column density and mean height of the sodium layer Xue et al. (2013). The transmitter of the lidar was a tunable pulsed dye laser. The pulse energy of the laser is 60 mJ. The laser’s repetition rate and wavelength are 20 Hz and 532 nm. The central wavelength of the dye laser was first tuned to 589 nm sodium D2 line with a sodium vapor cell, and further fine tuning was achieved by maximizing the backscattered photon return from atmospheric sodium layer. The projection direction of the laser is in the zenith. A 1.8 m diameter telescope Rao et al. (2010) was used for collecting photons returned from the sodium layer. The collected photons were passed through a narrow band interference filter before they were finally detected by a photomultiplier tube. The time bin length of the lidar is 100 μs which corresponds to a range bin length of 150 m. The number of accumulated laser shots for obtaining each lidar photocount profile was adjusted so that for every minute we had approximately 30 measurements for column density and mean height of the sodium layer unless the returned signal was very strong so that we could shorten the accumulation time and having more measurements per minute. The main specifications of the USTC lidar system are listed in Table 1.

Observation of the sodium layer was conducted separately in two phases in 2013. The first phase was from late February to the end of March. The second phase started from late October and ended by late November. A total of 19 nights’ data were collected. Figure 1 presented the data availability for all measurements. During the first phase, the weather condition is not favorable. The continuity and density of data for the first phase was therefore not on par with the second phase as shown in Figure 1. Due to this reason, further statistical analysis for the sodium layer’s dynamics was based only on data obtained in the second phase, which included 10 nights of data. Figure 2 showed these measurements for both the sodium column density and the sodium layer’s mean height.

Because that the sodium Lidar would drop bad values if the signal to noise ratio was low and also that some of the occasional spikes could be contributed by the sporadic behaviors of the sodium layer that could actually happen during a laser guide star, all data produced by the Lidar were included in our statistics.

3. Method and Results

In this analysis, we only focused on the variation of sodium dynamics in short term minute timescale. For typical sodium laser guide star tests such as measuring the brightness variation against different changing laser parameters like output power level, polarization or modulation depth of $D_{2b}$ re-pumping, etc., the duration of such a single test is normally in the range of 5–20 minutes. The relationship between the brightness or the photon flux $\Phi$ of sodium laser guide star and the sodium column density $C_{Na}$ can be described with Equation (1), where $L$ is the mean height of the atmospheric sodium layer, $P$ is the laser power, $T$ is the atmospheric transparency, $\theta$ is the laser launch zenith angle, and $X = 1/(\sec(\theta))$.

$$\Phi = \frac{S_x \cdot P \cdot (T)^X \cdot C_{Na} \cdot X}{L^2}.$$  \hspace{1cm} (1)

The variation of photon flux due to the change of height $\Delta L$ and sodium column density $\Delta C$ can then be described as,

$$\frac{\partial \Phi}{\partial C} / \Phi = \frac{\Delta C}{C} \approx \frac{\Delta C}{C},$$

$$\frac{\partial \Phi}{\partial L} / \Phi = -\frac{2 \Delta L}{L} \approx -\frac{2 \Delta L}{L}.$$  \hspace{1cm} (2)

Therefore, in order to isolate the variation of brightness of the sodium laser guide star from the variation of sodium layers dynamics for such tests, we need to analyze the statistics of sodium column density and the mean height of the sodium layer within a corresponding time duration.

A moving time window with a window size of fixed duration of $\Delta T$ were used for picking out the data set for statistics calculation. This time window was then applied from the beginning of each night’s data, and was shifted for every measurement after mean and standard deviation (STD) for the
previous set were calculated until the right side of the window reached the last measurement of the day.

The ratio of standard deviation $\sigma_i$ to mean value $\mu_i$ for each data set $i$ would represent the relative variation of sodium layer within $\Delta T$ at the time of the data set $i$. The Cumulative Distribution Function (CDF) of this ratio for each night would indicate the possibility that the column density or the mean height changed by a certain percentage within $\Delta T$ during that

Figure 1. The sodium lidar’s night time data availability. X-axis is the date of the measurement. Y-axis is the UTC time for every half hour. Different colors in the grids represent the amount of data gathered during half-hour period.

Figure 2. Data for sodium column density (a) and sodium layer’s mean height (b) gathered during the second phase. Coloring for different dates are the same in both figures.
night. Figure 3 shows the 10 minutes statistics of sodium column density for each night, and Figure 4 shows the 10 minutes statistics for sodium layer height.

With this method, we could analyze for each of these 10 nights, the possibility that the percentage of variation is lower than a certain level within a different duration of time. For our laser
testing scenario, we arbitrarily set this level to 10% for column density and 0.5% for sodium layer height according to our laser characterization test requirements. Statistics results with different time windows as shown in Figures 3 and 4 could also be provided on request which could be used to derive probability with other levels.

Figure 5 shows the results of these statistics for both sodium column density (left) and sodium layer’s mean height (right).

4. Conclusion

The motivation of this paper is to help sodium laser guide star performance test to determine a suitable time duration for a single test set so that even without a LIDAR one could claim if the brightness variation of sodium laser guide star is due to sodium layer or laser with a certain confidence. Therefore, based on our previous measurements, we analyzed the minute timescale statistics of sodium column density and sodium layer’s mean height considering such test sets are normally in the range of 5–20 minutes.

Figure 5 shows the approximate possibilities of sodium column density and sodium layer’s mean height to be within the given range aggregating all 10 nights’ statistic results. As shown in the figure, with a larger time window, the confidence for claiming the variation of column density or mean height to be within 10% or 0.5% is lower, and the scattering is also worsening which represents differences in sodium dynamics between these 10 nights. If the duration is limited within 10 minutes, there is a high probability (>90%) that the ratio of sodium column density’s STD to mean value is less than 10%. For the mean height of the layer, not only the variation is small with a ratio of STD/mean less than 0.5%, but also for a duration of less than 10 minutes, the probability to have a small variation is also high. If the time window extends to a longer time, the confidence to have such claims, especially for column density drops obviously. As can be noted in the same figure, the sodium layer’s mean height appears to be more sensitive to vary in time, opposite to the sodium column density which seems to achieve a plateau in the variability of 20% after the 12 minutes mark. This could largely be contributed by the
different short-term physics that caused the variation of sodium column density and the variation of the layer’s mean height. For sodium column density, the variation is normally caused by sporadic meteors ablating through the atmosphere that creating small concentrations of different amounts of sodium atoms in the layer. Trails of these meteors would also partially affect the sodium layer’s mean height, while at the same time, strong varying traversal wind can also play a very important role as indicated by Kane & Gardner (1993). With the lack of data for wind profile, we could not tell for certain which one has more influence over the layer’s mean height variation for now.

Equation (2) shows that the variation of brightness of the sodium laser guide star is in a linear relationship with variations of column density and mean height. However, comparing these two factors of sodium layer with the aforementioned results, the influence of column density on the brightness of sodium laser guide star is much more significant than mean height.

In light of these, for sodium laser guide star performance test without the aid of LIDAR, if the laser guide star’s brightness is expected to be changed higher than 10% with a changing parameter of the laser, a test set with a duration shorter than 10 minutes would be sufficient. The test duration needs to be shorter if the precision requirement is more stringent.

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