The Derivation of Sodium Density in the Mesosphere and Lower Thermosphere from the Na Lidar Photon Counting Profiles

Xiaoqi Xi
Utah State University

Follow this and additional works at: https://digitalcommons.usu.edu/etd

Part of the Physics Commons

Recommended Citation

This Thesis is brought to you for free and open access by the Graduate Studies at DigitalCommons@USU. It has been accepted for inclusion in All Graduate Theses and Dissertations by an authorized administrator of DigitalCommons@USU. For more information, please contact digitalcommons@usu.edu.
THE DERIVATION OF SODIUM DENSITY IN THE MESOSPHERE AND LOWER THERMOSPHERE FROM THE NA LIDAR PHOTON COUNTING PROFILES

by

Xiaoqi Xi

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Physics

Approved:

Tao Yuan, Ph.D.                                             Ludger Scherliess, Ph.D.
Major professor                                             Committee Member

Jeong-Young Ji, Ph.D.                                      D. Richard Cutler, Ph.D.
Committee Member                                           Vice Provost of Graduate Studies

UTAH STATE UNIVERSITY

LOGAN, UTAH

2023
Copyright © Xiaoqi Xi 2023

All Rights Reserved
ABSTRACT

The Derivation of Sodium Density in the Mesosphere and Lower Thermosphere from the Na Lidar Photon Counting Profiles

by

Xiaoqi Xi, Master of Science

Utah State University, 2023

Major Professor: Dr. Tao Yuan
Department: Physics

The ground-based Sodium (Na) lidar collects the Na fluorescence photon for the investigation of the Na density in the mesopause region (~80 to 110 km altitude). A conventional algorithm heavily relies on temperature and wind information, which needs a substantial lidar signal level, to precisely derive the Na density in the mesopause region [Kruger et al., 2015]. However, the conventional algorithm's derivation of the Na number density in the higher altitude (above 110 km altitude) falls short due to the low Na lidar echo signals. An innovative algorithm is thus required to utilize the collected Na fluorescence counting data to investigate Na density at the high altitude in the mesosphere and lower thermosphere (MLT). This paper introduces an innovative algorithm and applies it to the Na fluorescence photon counting profiles collected from 2018 to 2021. The data analysis of this paper focuses on the summer (from June to August) and winter (November to January) due to the distinct variations of the mesospheric Na layer in the two seasons.

(28 pages)
The Derivation of Sodium Density in the Mesosphere and Lower Thermosphere from the Na Lidar Photon Counting Profiles
Xiaoqi Xi

Derivation of Sodium (Na) number density from the Na lidar observations requires the in situ temperature and wind information because the absorption cross-section of the Na atom is a function of these dynamic parameters. The Na number density above ~ 110 km altitude was difficult to derive with the conventional algorithm, however. The standard output of the Na number density that utilizes the lidar-measured wind and temperature information falls short at ~ 110 km altitude and above due to the relatively large measurement uncertainties in the two critical parameters (low signal-to-noise ratio). Therefore, an innovative algorithm that may drive the Na number density directly from the Na fluorescence photon counting profiles is required for the Na number density investigation in the aforementioned region. This paper will introduce the innovative algorithm step by step and provide results for the hourly average Na number density and its variations from 2018 to 2021 in summer and winter.
ACKNOWLEDGMENTS

I would like to express my most profound appreciation to my mentor and the chair of my committee, Dr. Tao Yuan, who gave valuable advice in this research. I am also extremely grateful to the USU ground-based Na lidar team under Dr. Yuan’s leadership; their dedicated work provided the data for this study. Additionally, this project would not have been possible without the funding of the Center of Atmospheric and Space Science and the USU Physics Department.

I would like to extend my sincere thanks to Dr. Scherliess and Dr. Ji. They provided valuable advice that helped me to improve my research. I am also grateful to my family for their moral support during the time I was working on this research. I can not imagine how I would finish this research without all of you.
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>iii</td>
</tr>
<tr>
<td>Public Abstraction</td>
<td>iv</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>v</td>
</tr>
<tr>
<td>List Of Figures</td>
<td>vi</td>
</tr>
<tr>
<td>Chapter 1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Chapter 2 Instrument</td>
<td>3</td>
</tr>
<tr>
<td>Chapter 3 Algorithm</td>
<td>5</td>
</tr>
<tr>
<td>1. Background Removal</td>
<td>5</td>
</tr>
<tr>
<td>2. Data Normalization</td>
<td>6</td>
</tr>
<tr>
<td>3. Determine and Remove Bad Data</td>
<td>8</td>
</tr>
<tr>
<td>4. Deriving Factors and Applying Them to Normalized Data</td>
<td>11</td>
</tr>
<tr>
<td>Chapter 4 Results</td>
<td>14</td>
</tr>
<tr>
<td>1. Summer Na Density Variations in Target Region</td>
<td>14</td>
</tr>
<tr>
<td>2. Winter Na Density Variations in Target Region</td>
<td>15</td>
</tr>
<tr>
<td>Chapter 5 Discussion</td>
<td>17</td>
</tr>
<tr>
<td>Chapter 6 Conclusion</td>
<td>19</td>
</tr>
<tr>
<td>Reference</td>
<td>21</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1 The major parts of the Na Lidar. ................................................................. 3

Figure 2 The converting factors before and after the Rayleigh definition correction. The x-axis represents the days of the summer, the y-axis represents the hours for each night, and the colorbars represent the value of the factors. ........................ 8

Figure 3 The visible bad data in the linear scale, the x-axis presents the time from 4:00 (located at 1) to 9:00 (located at 6) UT time................................................................. 9

Figure 4 One photon counting profile on a linear scale (left) and a log10 scale (right). .................................................................................................................................. 10

Figure 5 Normalized data after bad data removal........................................................... 10

Figure 6 The examples of the variations of the hourly comparison result (conversion factors) of a summer night (left) and a winter night (right). ......................... 12

Figure 7 The hourly Na number density variations in the unit of #/cm3 are derived from the new algorithm, based on averaging the normalized Na lidar fluorescence photon counting profiles for winter (left) and summer (right) between 2018 and 2021 at USU. .................................................................................................................... 13

Figure 8 The diurnal mean Na density in count per cubic meter. The Na density in the upper mesosphere increases during winter and decreases during summer, which is contrary to the Na density variations in the target region in this study............ 15
Chapter 1 Introduction

The ground-based Na lidar sends out photons with a specific wavelength (589.159 nm) that excites the Na atoms in the mesosphere and lower thermosphere (MLT) region and collects the Na fluorescence photons emitted by the excited Na atoms [Kruger et al., 2015]. These Na atoms, along with the other metallic atoms, such as Fe, Ca, K, etc., are deposited into the upper atmosphere after the ablations of the meteors [Plane et al., 2015]. The temperature and wind velocity observations by the lidar are achieved by measuring the thermal broadening and the Doppler shift of the Na fluorescence spectrum, respectively, with respect to the reference frequency (the D2a transition line in the Na resonance spectrum). Theoretically, a Na fluorescence cross-section, which is a function of the in situ temperature and wind velocity, is required to precisely derive the Na density [Kruger et al., 2015]. Based on the Na lidar equation (equation 1), the lidar echo signals are directly proportional to Na number density and the number of photons emitted by the lidar transmitter. However, assuming constant laser power, at high altitudes (above ~ 110 km altitude), the low Na density may not be able to generate high enough echoes to provide accurate temperature and wind velocity results, causing large uncertainties in these critical parameters. Thus, the inaccuracy of this information can lead to questionable, sometimes unrealistic Na number density values at these high altitudes. There have been many observations and investigations of the Na layer extension up into the thermosphere, where the lidar signal level is relatively weak [Plane et al., 2015]. Therefore, an innovative algorithm is demanded to derive the Na number density in the ~105 to 130 km altitude, which will hereby be referred to as the target region. The innovative algorithm provides a solution for various scientific investigations related to the high altitude region Na density variations without the knowledge of the in situ temperature and wind velocity.
\[ N(r) = B + \eta \cdot T_{12} \cdot \frac{EL}{h\nu} \cdot \Delta r \cdot (\rho a \cdot \sigma 1) \cdot T_2 \cdot \frac{Ar}{r^2} \] (1)

Equation 1 presents the relationship between the Na lidar photon count received by the lidar in the detective range \((r - \Delta r/2, r + \Delta r/2)\) and other important elements that decide the lidar signal level. \(N(r)\) represents the photon count received by the Na lidar. \(B\) represents the photon count induced by background noises, including sky background and electronic noise. \(\eta\) is the optical efficiency of the lidar transmitter, such as the reflectivities of the mirrors that guide the lidar laser beams in different directions. \(T_{12}\) is the two-way transmittance between the lower edge of the Na layer and Na lidar. \(EL\) represents the power of the laser. The term \((h\nu)\) represents the energy for each photon. \(\Delta r\) is the bin’s altitude. \(\rho a\) represents Na density. \(\sigma 1\) represents the temperature and wind cross-section. \(T_2\) is the two-way transmittance of the Na layer. \(Ar\) is the area of the lidar receiving mirror. The \(r\) is the range of each bin relative to the lidar station.

This paper introduces this innovative algorithm that calculates the Na number density in the target region based on the Na lidar photon-counting profiles in section 2. The results are shown and compared with standard Na density outputs derived by the conventional lidar algorithm in the mesopause region in section 3. The data in this paper is based on the USU Na lidar observations from July 2018 to January 2021. We included the data from 4:00 UT time to 9:00 UT time for summer and the data from 2:00 am to 11:00 UT time for winter. When the large aperture Rayleigh lidar receivers, ~ 5 m² receiving area, are utilized to receive Na lidar signal. This study focuses on the distinct Na density variations in the winter and summer in the lower thermosphere above 110 km altitude.
Chapter 2 Instrument

In this study, the Na lidar located in USU collected and recorded all photon counting profiles for derivation. The procedure of generating the photon counting profiles can be broken down into two steps:

Step 1: Sending laser shots with a specific wavelength to the target region.

Step 2: Collecting and counting fluorescence photons.

The USU Na lidar system contains two main parts following the procedure steps. The seed laser, amplifying laser, and directing mirrors emit the laser with a particular wavelength to the target region; the receiving mirrors and photon receivers collect photons; and the photon magnifier tube (PMT) and electric counting card read the collected photon and give the accurate count number.

The logical relationship between the major parts of the Na lidar is presented in figure 1.

Figure 1 The major parts of the Na Lidar.
The laser system contains two core devices which are the seed laser and the amplifying laser. The seed laser generates a laser beam with a precise wavelength, of 589.159 nm. The laser beam with this wavelength excites the Na atoms in the MLT region, and when the excited Na atoms return to the ground state, the fluorescence photons are released. Because the Na atoms are well mixed with the atmospheric molecules in the upper atmosphere, their behaviors reflect the atmospheric conditions there.

The receiver of the Lidar system contains three main devices: the mirror or telescope to collect the returning Na echoes (photons); the Photo-Multiplier-Tube (PMT) that converts these photons to electronic pulses; and the electric counting card embedded in the data-taking computer to count these pulses for each altitude. The mirror or telescope is aligned to the lidar laser beam, which points to the target region, collecting and focusing the Na fluorescence photons into the attached optic fiber. The fiber, then, guides the photons to the PMT. A counting card counts the electric pulses coming out of the PMT, and the outputs are saved in the data-taking computer. Note that the efficiency of the PMT is ~ 30-40%, meaning only a fraction of the collected photons can be counted.
Chapter 3 Algorithm

The most critical step of this innovative algorithm is to create the Na fluorescence photon counts variations over time for each altitude, hereby referred to as normalized data, which are directly proportional to the geophysical variations of the Na number density in the MLT region.

Assuming the linear relationship between the Na lidar fluorescence photon counts and the Na density in the MLT region [Plane et al., 2015], a robust factor has to be determined by the ratio between standard Na density outputs and the normalized data, so that the derived normalized Na photon counts can be converted to the Na number density. As shown in equation (1), three major factors affect the Na photon counting signals: background (including the electronic noise of the lidar detector and sky background) and the lidar laser power fluctuations during the lidar observation. Accordingly, the derivation of the Na density in the target region from the Na fluorescence photon counting profiles requires four steps:

Step 1: The background removal,

Step 2: The laser fluctuations and the telescope-laser alignment normalization based on Rayleigh scattering signal strength from low altitudes,

Step 3: Determine and remove the bad data of low signal-to-noise ratio

Step 4: Compare the normalized data (photon counting profiles with background removal and low altitude Rayleigh scattering signal normalization) to the standard outputs at 85 to 105 km altitude (The region with the most accurate Na density derived by conventional algorithm) to determine the conversion factor.

Step 5: Apply this factor to the photon counting profiles in the target region to study the Na variations in this region.

1. Background Removal
This study defines the average photon counts per bin from 200 to 240 km altitude as the background signal level for each lidar bin. Typically, the Na layer exists in the MLT region between ~ 70 to 120 km altitudes [Kruger et al., 2015]. Studies have shown that atmospheric waves may dynamically lift the Na layer to ~ 150 km altitude during summertime [Cai et al., 2017]. Therefore, this study has chosen 200 km in altitude as the background noise derivation starting point, where no Na fluorescence signals exist. Furthermore, the USU Na lidar records the returning photon counts bin-by-bin, with each bin range between each bin is 150 m. Thus, the background derivation has 266 photon measurements for each minute. The average background signal level of each bin between 200 and 240 km is calculated and, then, subtracted from the signals within each bin, resulting in noise-free Na signal profiles.

2. Data Normalization

Equation 2 presents the procedure of the aforementioned Rayleigh normalization procedure. Same as equation (1), \( N(r) \) represents again the normalized data in each bin (see Equation 1), \( D \) represents the original photon counting within each lidar bin, \( B \) represents the averaged background noise level per bin, and \( R \) represents the Rayleigh scattering factor, which is discussed in details in this section.

\[
N(r) = \frac{(D-B)}{R}
\]  

(2)

If the lidar beam perfectly aligns with the mirror, the lidar laser power is directly proportional to the lidar return signal (see equation 1). Thus, the Na lidar signal variations induced by the lidar laser power fluctuations need to be neutralized in the data processing. There is another element that decides the received Na echoes, however: the alignment between the lidar laser beam and the receiving telescope. Because of the relatively small field of view and long-range (over 100 km), a slight misalignment between the two can induce a considerable drop in the receiving Na
signal level. The Rayleigh signals of the Na lidar are generated by the Rayleigh scattering of the laser by the air molecules and are also directly proportional to the lidar laser power, assuming the atmospheric density in the stratosphere changes can be ignored. Because the atmospheric density decreases exponentially, the Rayleigh signals in the Na lidar echoes drop considerably above ~50 km. They are becoming at the same level of background noise as altitude increases. In the stratosphere between ~20 and 50 km, where the Rayleigh signals are strong, they are sensitive to the laser power fluctuations and the alignment between the lidar receiver direction and the laser point direction. Thus, using the Rayleigh signals in the Na lidar echoes properly, we can neutralize the aforementioned two factors that are not related to the Na number density geophysical variations.

In this study, we define the average photon count from the 25 to 40 km altitude range for most photon-counting profiles as the normalization factor to remove the Na signal fluctuations by the two aforementioned issues. As mentioned earlier, the lidar echoes are strong in the lower atmosphere due to high atmospheric density. Typically, below 25 km, the Rayleigh signal becomes too strong for the Photon Multiplier Tube (PMT) to respond linearly and, thus, the Na lidar is designed to receive the lidar returning signals only above ~25 km, above which the linearity between the lidar signals and the PMT response are assumed. There are exceptions in 2019/2020 summer, during which the Na lidar laser power was concentrated on a single zenith beam instead of the standard setup, where three beams pointed in different directions. This change induced much stronger Rayleigh scattering signals than usual, and during this time, the PMT in the Na lidar system responds to the Rayleigh signal below ~35 km non-linearly. Such nonlinearity due to strong Rayleigh scattering caused non-geophysical fluctuations in the Na density outputs and larger than usual Na number density (see equation 2) when the algorithm is
applied. Therefore, the Rayleigh normalization range for those nights’ experiments requires a modification that takes the average value from a higher altitude range, 35 to 45 km altitude, where the Rayleigh signal is weaker than that within the standard Rayleigh range. This adjustment addresses this nonlinearity issue, generating more consistent results. Figure 2 gives the Na number density conversion factors before and after the Rayleigh signal definition correction. As the figure shows, the factor variations decrease significantly after the upgrading in the Rayleigh normalization range.

Figure 2 The converting factors before and after the Rayleigh definition correction. The x-axis represents the days of the summer, the y-axis represents the hours for each night, and the colorbars represent the value of the factors.

3. Determine and Remove Bad Data

During the lidar operations, several issues may result in bad data being recorded. The most common incidents are the seed laser frequency drifting and cloudy weather. The drifting of the laser wavelength leaves unreliable photon counting results since the fluorescence cross-section is frequency-dependent. The current lidar system requires the operator to manually lock the laser at
the desired frequency (Na D2a transition line) once the drift is spotted, and the occurrence of the drifting, although rare, is unpredictable. Another major bad data source is the cloudy weather during the lidar observation, which is impossible to eliminate. Due to the nature of the laser frequency drifting and cloudy weather incidents, some data are inevitable affected by these circumstances and labeled as “bad data”. The only way to get a reliable result from the normalized data is to identify and remove the bad data.

We developed a method to determine the bad data by following three steps: visualize and examine data by linear scale, visualize and examine data on a log10 scale, and examine the signal-noise ratio. Figure 3 presents an example of visible bad data on a linear scale. We can easily spot an overwhelming noise occurring from the fourth to the sixth hour.

Figure 3 The visible bad data in the linear scale, the x-axis presents the time from 4:00 (located at 1) to 9:00 (located at 6) UT time.
After removing the linear scale visible bad data, we found some bad data were not visible on the linear scale (presented in Figure 4). Thus, we visualized photon signals in both linear and log10 scales.

![Figure 4 One photon counting profile on a linear scale (left) and a log10 scale (right).](image)

At last, we reviewed the signal-noise ratio and decided that if the value is below 10, the profile will be treated as bad data. The bad-data-free normalized data is presented in figure 5.

![Figure 5 Normalized data after bad data removal](image)
4. Deriving Factors and Applying Them to Normalized Data

As we mentioned earlier, for each altitude, a ratio between the normalized Na data and the Na density value generated from the standard output provides a conversion factor that can directly convert the normalized Na data to Na density. In other words, the ratio between the standard Na density output and the normalized data generates one factor for each bin. These bin-by-bin factors can then convert the normalized data to Na density throughout the target region. In the end, the average factor for each bin is, then, calculated and applied for all the altitudes. On the other hand, the consistency of the bin-by-bin elements in the mesopause verifies the accuracy of the innovative algorithm. Figure 6 shows examples of the factor’s variations vs. altitude for each hour during a summer night and a winter night. The figure shows good consistency of the conversion factor between ~85 km and 95 km for both summer and winter, where the Na lidar signals are strong. Below ~ 85 km and above ~ 110 km, as we mentioned before, the temperature and wind information has large uncertainty due to the sudden drop of the Na signal, leading to questionable Na density values generated by the standard algorithm. In addition, the hourly factors in summer demonstrate much better consistency near and above ~ 100 km than those in the winter night. This behavior is currently not understood and is worth further investigation. It may be related to the very large temperature gradient in the winter above 100 km, where the atmospheric temperature increases from ~ 180 K near 100 km to ~ 300 K near 115 km altitude. In summer, however, the temperature gradient is much less: the same temperature increase occurs between ~ 85 km and 115 km altitude range, about half of the gradient in wintertime.
It is worth noting that, based on the classic Na chemistry theory [Plane et al., 2015], the NaHCO₃ in the upper mesosphere is the primary reservoir for the metallic Na atoms in the upper atmosphere, while the Na⁺ becomes the dominant reservoir above ~ 100 km. The conversion of NaHCO₃ to atomic Na involves several temperature-dependent chemical reactions, and the transformation accelerates as temperature rises. On the other hand, the neutralization of Na⁺ involves chemical reactions that are slightly anti-correlated to the in situ temperature.

Considering the dramatic seasonal change of temperature in the mesopause region [Yuan et al., 2008], separating the conversion factor calculation by seasons is necessary for this algorithm. For example, the atmospheric temperature near 85 km is ~ 160 K in the summer but above 200 K in the winter. Such distinct seasonal variation generates significantly different atomic Na production rates in the upper mesosphere and, thus, could lead to various Na conversion factors. However, we found the average seasonal value of bin-by-bin factors, derived from the lidar data between 2018 and 2021, are ~ 2600 +/- 600 for summer and ~ 2300 +/- 400 for winter, which, considering the uncertainties, implicates a similar conversion factor working for all seasons. Nonetheless, the above two factors are applied to their individual season in this investigation.
We apply the summer and winter seasonal factors to the normalized Na data in summer and winter, respectively, and the innovative algorithm delivers robust and reliable results of Na density in the target region. Figure 7 illustrates the Na number density variations during the night in universal time (7 hours ahead of the local solar time) within the target region for winter and summer.

*Figure 7* The hourly Na number density variations in the unit of #/cm$^3$ are derived from the new algorithm, based on averaging the normalized Na lidar fluorescence photon counting profiles for winter (left) and summer (right) between 2018 and 2021 at USU.
Chapter 4 Results

This study focuses on Na number density and its hour-by-hour variations in the target region of the lower thermosphere. Figure 7 presents the average value of the Na number density variations throughout the night during the summer and winter generated by this algorithm. We reviewed the results and found several notable variations in the Na density variations. Here, the deviations below the scale of 1/cm³ are treated as insignificant and will not be discussed in this section. Neither are some anomalies, such as the two variations located at the top left and top right in figure 3 winter section, which are not statistically significant.

1. Summer Na Density Variations in Target Region

During summer, the abundant Na density between 110 and 115 km is high; the average Na density value from 5:00 to 9:00 UT time in this region is ~20/cm³. In fact, it is higher than that during the winter, which is discussed later. This phenomenon is likely caused by an adiabatic expansion driven by the gravity wave that transports the Na atoms from the upper mesosphere upward. We will discuss this transportation more in section 4 of this chapter. The Na density around ~110 km altitude increases between 4:00 am to 6:00 UT time, when the hourly Na density average value increases from ~25/cm³ to 32/cm³. It is getting stable after UT 6:00.

There is another profound Na density variation that occurred between ~120 to 130 km altitude from 4:00 to 7:00 UT time. The Na number density decreases slightly from 4:00 to 5:00 UT between ~122 to 127 km altitude from ~5/cm³ to ~4/cm³. However, from 5:00 to 7:00 UT, the Na density hourly average value between ~122 to 130 km altitude increases slightly from ~4/cm³ to 6/cm³, and the Na density remains stable in this area for the rest of the night. We haven’t uncovered the underline mechanism generating such Na density variations between ~120 to 130
km altitude from 4:00 to 7:00 UT. Further investigations, some numerical model simulations focusing on the dynamics and chemistry in that area, are needed.

2. Winter Na Density Variations in Target Region

The Na density pattern in winter differs significantly from its summer behavior in the target region. The average Na density value from 5:00 to 9:00 UT time is \( \sim 13 \text{ /cm}^3 \), which is only \( \sim 61.5 \% \) of the Na density for summer at the same altitude. The most profound Na density variation is that contrary to the seasonal variation in the upper mesosphere (see figure 7) [Yuan et al., 2012], which shows a considerably larger Na number density in winter than that in summer, the hourly average Na density value between \( \sim 110 \) to \( 115 \) km altitude is significantly reduced, compared with the summer time. However, above \( \sim 115 \) km, the Na abundance is again higher in winter than in summer.

![Figure 8](image.png)

*Figure 8 The diurnal mean Na density in count per cubic meter. The Na density in the upper mesosphere increases during winter and decreases during summer, which is contrary to the Na density variations in the target region in this study.*

There are also distinguishable temporal variations of winter Na density. For example, the Na density increases from 7:00 to 10:00 UT above \( \sim 113 \) km altitude. The hourly average Na density
from ~ 113 km to 130 km altitude increases from ~ 9 /cm$^3$ to 12 /cm$^3$ between 7:00 to 10:00 UT. The scale of the number density variation in this process is small, but the altitude range of this process is relatively wide. We also spotted a secondary Na density increase occurring between ~ 113 and 121 km altitude. The secondary Na density increasing covers less altitude range, and starts fading after 10 UT. The first phase of secondary Na density variations starts at 9:00 UT time and ends at 10:00 UT. The hourly average Na density increases from ~ 11 /cm$^3$ to 13 /cm$^3$ in the beginning phase of secondary Na density variation. The second phase of the secondary Na variation occurred at ~ 118 km to 121 km altitude.

Contrary to the first phase, the Na density decreases from ~ 13 /cm$^3$ to 12 /cm$^3$. Again, the underline mechanisms behind Na density variations and the secondary Na density variations are beyond the scope of this study. However, we speculate that these Na density variations may be caused by temperature-dependent chemical reactions at high altitudes, where a substantially vertical temperature gradient exists. But this hypothesis requires further numerical investigation.
Chapter 5 Discussion

The innovative algorithm derives the high altitude hourly Na density night-time variations in summer and winter. Based on the results presented in figure 7, the Na density in summer is more abundant than in winter between ~ 110 km and 115 km, which may provide enough lidar signal to derive temperature and wind information [Liu et al., 2016 and; Yuan et al., 2021]. Plane addressed this difference in 2015 as the contribution from the atmospheric gravity wave, a combination effect on the atmospheric mean flow that generates the upward flow in the MLT during the summertime but a downward flow during the winter. The gravity waves originated in the troposphere, and it combines the impact of the orographic forcing, the wind shear, cumulonimbus cloud formation, and the cyclonic fronts [Plane et al., 2015]. The stratosphere filters some energy and momentum, but a significant portion of the short wave can travel to the upper mesosphere. The wave travels upward through the mesosphere, and it becomes unstable and eventually breaks due to the decreasing pressure and increasing wave amplitudes. This procedure releases both the energy and the momentum in the MLT region, which drags the zonal wind and creates a meridional flow towards the winter pole in the middle and upper mesosphere [Plane et al., 2015]. This dynamic phenomenon, the upward and southward flow, causes an adiabatic expansion in the Na layer in the summer MLT region, which simultaneously reduces the temperature through the adiabatic process.

The increasing Na density near 110 km altitude in summer may also associate with the secondary Na layer that mainly occurs in the first half of the summer night. This secondary layer is believed to be closely associated with the sporadic E layer [Yuan et al., 2014]. The secondary Na layer occurs between ~ 100 to 104 km altitude from 5:00 to 7:00 UT time. On the other hand, the results of this study present the average Na number density trending in the whole summer and
winter instead of a particular month, so it may not be able to provide a clear image of the secondary Na layer impact. However, Cai et al. [2017] did a comprehensive numerical simulation of the Na density variations in this altitude range. They concluded that dynamic transport might play an important role, while the contributions from the Na ion-chemistry may be insignificant.

Another notable phenomenon is that the background noise changes dynamically during certain hours. We examined the hourly average background noise each night and spotted the background noise decreasing at dusk. The hypothesis of the background dropping we came up with is that sunlight may still be a factor in Na production due to the photolysis [Yuan et al., 2019] at a higher altitude after sunset in the troposphere. The ground-based Na lidar usually starts operating right after sunset to protect the light-sensitive instrument. Note that once the sunset is on the horizon, the sunlight may still radiate into the air at higher altitudes. At this moment, we are not able to draw this conclusion due to the lack of numerical investigation to support this hypothesis yet. However, considering the timing and the consistency of the background noise decrease revealed in this study, the hypothesis could be pretty convincing in explaining the phenomenon.
Chapter 6 Conclusion

The innovative algorithm introduced in this paper provides a method to improve the Na number density calculation near the edge of the mesospheric Na layer where the Na number density is low. By applying the background noise removal and the data normalization through the lidar Rayleigh signals, we derive a potent factor that can convert the normalized Na lidar photon counting signals to the Na number density. We apply this factor to the normalized data to derive the Na density in the altitude range of ~ 110 km - 130 km, where the Na density is several orders of magnitude lower than the peak of the Na layer ~ 90 km. The innovative algorithm may compensate for the significant drawback of the conventional algorithm in the low Na density region, where the necessary temperature and wind results have substantial uncertainties. The calculations of Na density between 70 to 90 km altitude also encounter the same difficulty as the conventional algorithm. The innovative algorithm may also improve the questionable Na density results caused by the low Na density between ~ 70 to 85 km altitude.

The USU ground-based Na lidar record the photon counting profiles minute-by-minute. The innovative algorithm derives the Na density directly from those photon-counting profiles. Therefore, the minute-by-minute Na density trending can be derived from the photon-counting profiles. This procedure can provide more detailed, high temporal, and spatial Na density variations than the hour-by-hour standard outputs.

In this study, since the Na density calculation is highly sensitive to the Rayleigh normalization process, an issue with the Rayleigh normalization range occurred due to the nonlinear response of the PMT to the strong Rayleigh signal during some summer nights. This nonlinear response from the PMT may lead to questionable Na density variations. Thus, for the nights when the lidar converged all its laser power to the vertical channel, we redefined the Rayleigh range from the
standard 25 km - 45 km altitude to 35 km - 45 km altitude with weaker Rayleigh signals to conduct this normalization process. This modification provides more precise and consistent results of the Na density in the target region than before.

In this research, several nights’ data were abandoned due to insufficient data of an entire hour or more; only full nights of the lidar observations were selected. We look forward to refining the innovative algorithm with a more subtle data-selecting method to utilize all the data from these nights. A primitive idea of the correction method is focusing on data for each hour in the entire season, which may expand the data pool and derive more precise results of the Na density in the target region.


