Visible and near-infrared airglow structures in the mesosphere and the lower thermosphere observed by space-borne instruments

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Abstract

Visible and near-infrared airglow structures in the mesosphere and the lower thermosphere were investigated using the space-borne instruments in this study. Airglow is the emission of the light from atoms and molecules in the upper atmosphere. Entire structure of the airglow emission has not been detected since the field-of-view (FOV) of the instruments were not wide enough, although atmospheric gravity waves (AGWs) in the mesosphere and the lower thermosphere have been studied via observations of nighttime airglow by the ground-based imagers, rockets and satellites.

Visible and near infrared spectral imager (VISI) of the ISS-IMAP (International Space Station - Ionosphere, Mesosphere, upper Atmosphere and Plasmasphere mapping) mission was developed for the nadir imaging observation of the airglow emission from the International Space Station with wide FOV. Observational targets of VISI were the airglow emissions from oxygen molecules ($\text{O}_2$), hydroxyl radical (OH) around the altitude of 95 km and the emission from atomic oxygen (O) around the altitude of 250 km. These airglow emissions were observed in 762-nm, 730-nm and 630-nm wavelength, respectively. Calibrations and alignments of the imager were carried out before its launch. Noises caused from the electrical interference in the images was subtracted by
using the observational data after launch. Variance in the slit direction which was caused by the difference of slit width was reduced by taking average of the observational data. The relationship between the intensity and the wavelength was re-examined after launch by using the observational data.

Characteristic structures in the airglow emissions were often observed by VISI. Concentric structure in the O$_2$ airglow emission was found in the 762-nm wavelength observation over North America on 1 June, 2013. This is the first observation that the entire structure of the concentric airglow was captured from the space. Spatial scale of this concentric structure was determined to be 1,200 km from the center to the edge. Propagation velocity of the waves in the concentric structure was derived as $125 \pm 62$ m/s from the center to the edge of the structure. This velocity was derived from the difference of the wave fronts positions between the images taken by two FOVs of VISI. The source of the AGWs which made this concentric structure was identified as the convective clouds in the troposphere in this case.

Latitudinal and seasonal variations of the O and the OH airglow intensity were derived from the limb direction observations by the Reimei satellite from March 2008 to January 2011. The peaks of intensity of these emissions were found in the region between $20^\circ$N and $30^\circ$N from the statistical study of three years data. Variation of the intensity and the position of the peak were affected by the atmospheric tides. Relationship between the activity of AGWs in the mesosphere and the lower thermosphere and the lower atmosphere were studied precisely by using the observational data of the nighttime airglow emissions in the nadir direction and the Earth’s limb direction.
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Chapter 1

Introduction

1.1 Airglow emission

Atoms and molecules in the upper atmosphere receive energy from the solar radiation in the daytime. State of these molecules and atoms change into excited state and the excess energy are released as heat and light. Airglow emission observed in the night time is the excess energy release process of the excited species. The main sources of the nighttime airglow are atomic oxygen (O), molecule oxygen (O$_2$) and the hydroxyl radical (OH). Some of the species which cause the airglow emissions are shown in Table 1.1.

The unit "Rayleigh" (R) is used for the intensity of emissions. This is defined as below [Baker et al.(1976)]:

$$1[R] = \frac{10^6}{4\pi} [\text{photons/s/cm}^2/\text{sr}]$$

Intensity of the Milky Way is approximately 1 kR and that of full moon is
Table 1.1: Wavelength, altitude of the emission layer and intensity of airglow emission which can observe from the ground [Leinert et al. (1998)]

<table>
<thead>
<tr>
<th>Species</th>
<th>Wavelength [nm]</th>
<th>Altitude [km]</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>102.6 (Ly $\beta$)</td>
<td>&gt; 1,000</td>
<td>~ 10 R</td>
</tr>
<tr>
<td>H</td>
<td>121.6 (Ly $\alpha$)</td>
<td>&gt; 1,000</td>
<td>3 kR - 34 kR</td>
</tr>
<tr>
<td>O</td>
<td>130.4</td>
<td>250 - 300</td>
<td>~ 40 R</td>
</tr>
<tr>
<td>O</td>
<td>135.6</td>
<td>250 - 300</td>
<td>~ 30 R</td>
</tr>
<tr>
<td>O$_2$</td>
<td>300 - 400</td>
<td>90</td>
<td>8 R/nm</td>
</tr>
<tr>
<td>O</td>
<td>557.7</td>
<td>90</td>
<td>250 R</td>
</tr>
<tr>
<td>Na</td>
<td>589</td>
<td>~ 92</td>
<td>30 R - 100 R</td>
</tr>
<tr>
<td>O</td>
<td>630.0</td>
<td>250 - 300</td>
<td>60 R</td>
</tr>
<tr>
<td>O</td>
<td>636.4</td>
<td>250 - 300</td>
<td>20 R</td>
</tr>
<tr>
<td>H</td>
<td>656.3</td>
<td>&gt; 1,000</td>
<td>4 R - 6 R</td>
</tr>
<tr>
<td>O$_2$</td>
<td>864.5</td>
<td>~ 80</td>
<td>1 kR</td>
</tr>
<tr>
<td>OH</td>
<td>600 - 4,500</td>
<td>85</td>
<td>4.5 MR</td>
</tr>
</tbody>
</table>

Some of the airglow emissions are impossible to observe by the ground-based imagers. It is good to observe from space to observe without the absorption of the Earth’s atmosphere. Spectrum taken by GLO-1 during the STS 53 shuttle mission is indicated in Figure 1.1 [Broadfoot et al. (1999)]. Bright lines and band emissions of O, OH, O$_2$, N, Na are detected in this observation. Oxygen emission in 557.7-nm wavelength and O$_2$ emission in 762-nm wavelength are intense. Emission from atomic oxygen in 630-nm wavelength and OH(8-3) band emission around 730-nm wavelength are observed as emission of 500 - 1,000 R/nm in this case.
1.2 Mechanism of airglow emission

1.2.1 Emission from atomic oxygen

The reactions of the atomic oxygen emission around 630-nm wavelength [Khomich et al.(2008)] are

\[
\begin{align*}
O^+ + O_2 &\rightarrow O_2^+ + O \quad (1.1) \\
O_2^+ + e^- &\rightarrow O + O(^3D) \quad (1.2) \\
O(^1D) &\rightarrow O(^3P_2) + h\nu(630.0 \text{ nm}) \quad (1.3) \\
O(^1D) &\rightarrow O(^3P_1) + h\nu(636.4 \text{ nm}) \quad (1.4) \\
O(^1D) &\rightarrow O(^3P_0) + h\nu(639.2 \text{ nm}) \quad (1.5)
\end{align*}
\]

Oxygen atoms in excited state are produced from the collisions of oxygen...
atoms in the ground state and oxygen molecules. The most intense emission in reactions mentioned above is 630.0-nm and it is about 100 kR at night. Lifetime of the excited state of atomic oxygen O(^1D) is about 134 seconds. These atoms radiate at the altitude around 250 km which is the altitude of the F2 layer.

1.2.2 Emission from OH molecules

The set of reactions of OH molecules are written as below [Khomich et al. (2008)]:

\[
\begin{align*}
H + O_3 & \rightarrow OH(v \leq 9) + O_2, 
 k_1 = 1.4 \times 10^{-10} \exp \left( \frac{-470}{T} \right) \quad (1.6) \\
O + HO_2 & \rightarrow OH(v \leq 6) + O_2, 
 k_2 = 3 \times 10^{-11} \quad (1.7) \\
O + O_2 + M & \rightarrow O_3 + M, 
 k_3 = 6 \times 10^{-34} \left( \frac{300}{T} \right)^{2.3} \quad (1.8) \\
H + O_2 + M & \rightarrow HO_2 + M, 
 k_4 = 5.7 \times 10^{-32} \left( \frac{300}{T} \right)^{1.6} \quad (1.9) \\
OH(v) + O & \rightarrow H + O_2, 
 k_5 = a_5(v) \times 10^{-11}, \quad (1.10)
\end{align*}
\]

\[
a_5(v = 0) = 3.9, \quad a_5(v = 1) = 10.5, \quad a_5(v > 1) = 25
\]

\( T \) is the ambient neutral temperature in Kelvin, and \( k_1, \ldots, k_5 \) are rate coefficient rates. M indicates third species in the reactions such as N\(_2\) or O\(_2\). Emission layer of OH molecules exists around 87 km in altitude. Average intensity of this emission is 1 kR.

1.2.3 Emission from oxygen molecules

Emission from oxygen molecule caused from the transition of the energy level in the molecule:

\[
O_2(b^1\Sigma_g^+) \rightarrow O_2(X^3\Sigma_g^-) \quad (1.11)
\]
Two intense bands are observed in this reaction. 761.9-nm emission which is called (0-0) band is the most intense. Another emission is at 864.5-nm wavelength and called (0-1) band. Oxygen molecular emission in the airglow is difficult to observe by the ground based measurement because of the absorption in the Earth’s atmosphere.

The set of reactions which supposed that O2 emission are as below [Yee et al.(1997)]:

\[
\begin{align*}
O + O + M & \rightarrow O_2^* + M \quad (1.12) \\
O_2^* + O_2 & \rightarrow O_2(1\Sigma) + O_2 \quad (1.13) \\
O_2^* & \rightarrow O_2 + h\nu \quad (1.14) \\
O_2(1\Sigma) + M & \rightarrow O_2 + M, \ M = N_2, O_2, O \quad (1.15) \\
O_2(1\Sigma) & \rightarrow O_2(3\Sigma) + h\nu \quad (1.16)
\end{align*}
\]

Rate coefficients of the three body collision are affected by temperature. Altitude of the emission layer is around 100 km. This corresponds to the altitude of the E layer. Intensity of the O2 airglow emission was observed to be 10 kR in the limb direction by the high-resolution Doppler imager (HRDI) on the Upper Atmosphere Research Satellite [Yee et al.(1997)].

1.3 Airglow observations

1.3.1 Observations from the ground

All-sky imaging from the ground has taken many observational data. This imaging is good in that long term stable observations from the same place are possible despite the fact that the field-of-view (FOV) is limited. Spatial
distribution of the airglow emission and the pattern of varying over the continent have been clarified by using ground-based imagers. For example, there are wavy patterns with 100 km scale and they are moving southwestward. This is so called MSTID (Medium-scale traveling ionospheric disturbance). Some of the emission cannot be observed from the ground because of the absorption by the Earth’s atmosphere.

Observations of OH airglow emission in 87 km altitude by OMTI (Optical Mesosphere Thermosphere Imagers) are shown in Figure 1.2. Images in this observation were taken in every 10 minutes. Patterns in OH airglow emission seem to be varied in space and time. The spatial wavelength in these images in the NE-SW direction is estimated to be 15 km [Shiokawa et al. (1999)].
Figure 1.2: Observation of OH band emission from 720-nm to 910-nm wavelengths by OMTI imagers in 1998 [Shiokawa et al. (1999)].
1.3.2 Observations from the space

Another way to observe the airglow emission is in-situ observation near the emission layer. Rockets and satellites are used in this case. It is helpful to understand the vertical structure of the emission layer though it is not suitable for long term observation. Imaging observations using satellites enabled to supplement the observation over the oceans where ground-based imaging cannot be stable.

Rocket experiments are also useful to observe vertical structure of the airglow layers. Observations in Turbulent Oxygen Mixing Experiment (TOMEX) are shown in Figure 1.3. Observational volume emission rates of \( \text{O}_2 \) emission at 762-nm wavelength, \( \text{O} \) emission at 557.7-nm wavelength and \( \text{OH} \) emission at 773.5-nm wavelength are compared with TIME-GCM predictions in each panel. These three profiles have different peak altitudes. Volume emission rates of the emission were varied on a scale of 1 km in the vertical direction in this observation [Hecht et al. (2004)].

Observation of OH airglow emission by Wind Imaging Interferometer (WINDII) on the Upper Atmosphere Research Satellite (UARS) is shown in Figure 1.4. Airglow emissions from 500-nm to 900-nm wavelengths were observed in the Earth’s limb direction. Volume emission rate is defined as the number of photons which cause airglow emission in the unit volume and in the unit time. The physical quantities obtained from limb observations are integrated in the direction of line of sight. Some calculations and assumptions such as the uniformity of the emission rate in the layer are needed to estimate the volume emission rate from the observational data.
Figure 1.3: Observations by photometer of TOMEX. Measured $O_2$ emission at 762-nm wavelength is shown in the top panel, OH emission at 773.5-nm wavelength is shown in the middle panel and $O$ emission at 557.7-nm wavelength is shown in the bottom panel with solid lines. Dotted lines and dashed lines in each figure are the TIME-GCM predictions. [Hecht et al.(2004)]
Figure 1.4: Altitude profile of the OH airglow volume emission rate derived from the WINDII/UARS observation are shown in the panel (A). Standard deviation of the distribution is shown in the panel (B). Observation was made at 734.6-nm wavelength. [Lowe et al.(1996)]
1.4 ISS-IMAP mission

ISS-IMAP (International Space Station - Ionosphere, Mesosphere, upper Atmosphere and Plasmasphere mapping) mission started the observation of the Earth’s upper atmosphere at August 2012. This mission has two independent imagers which are named VISI (Visible and near-infrared spectral imager) and EUVI (Extreme ultraviolet imager). VISI observes airglow emissions in the E region and the F region in the nadir direction. EUVI observes resonant scattering lights from O⁺ and He⁺ in the limb direction of the Earth. These observational instruments are set on the Exposure Facility on the International Space Station (ISS). Both of the observations by VISI and EUVI are made in the nighttime. There are 16 paths for the observation in one Earth day since the daytime and nighttime of ISS is 90 minutes cycle. Observation is planned to be continued for three years.

Speed of ISS is 8 km/s and it flies around the Earth in 90 minutes. Inclination of ISS is 51.6°. The altitude of ISS is between 350 km and 450 km.

VISI observes airglow emissions in the night side region between 51.6°N and 51.6°S. VISI is also able to observe auroral emissions in some part of high latitude region in the geographical coordinates.
Figure 1.5: Observations in 762-nm wavelength by VISI on 1 June 2013. Color indicates the strength of the emission.

1.5 Targets of this thesis

Motion of the atmosphere in the mesosphere and the lower thermosphere (MLT) can be clarified by the observation of the airglow emissions. Horizontal fine structures with the spatial scale of several hundred kilometers have been observed by the ground-based instruments partially. Imaging observations of the entire structure for longer than 2,000 km in the orbital direction were enabled by VISI on ISS. This can be contributed to the elucidation of the horizontal motion of the MLT atmosphere.

Observations of the airglow structure in the nadir direction from the space can clarify the relationship between the structures in the MLT regions and the perturbations in the lower atmosphere. The effects of tropospheric activity on the airglow disturbances in the mesosphere and the lower thermosphere have been previously studied. For example, some concentric airglow structures have been related to the thunder storm activities [Taylor et al.(1988), Sentman et al.(2003)]. However, the entire structure of the concentric distur-
bance in the airglow emission was not clarified from the ground-based observations, because of their narrow FOVs and restrictions due to weather conditions. Concentric structures of the airglow were observed mostly around tropospheric disturbances, which can be the sources of the atmospheric gravity waves (AGWs).

It is also important to understand the vertical distribution of the airglow emission for the understanding of the atmosphere in the MLT region. Latitudinal distribution and the vertical variation of the airglow emissions in the mid-latitude region have not been clarified yet. VISI is good for the observations in the horizontal structures from the space though the altitude distribution of the emission are not clear from the nadir direction observations. The Reimei (INDEX) satellite observed airglow emissions in the limb direction of the Earth for three years. It is able to elucidate the latitudinal distribution in the spatial size of several hundred kilometers and vertical variation of the airglow emissions by analyzing these observational data.

Some of the structures in the airglow emission are affected by the disturbances in the lower atmosphere. VISI on the International Space Station (ISS) has wider range of FOV than ground-based imagers and is able to observe the airglow emissions in the orbital direction up to 8,000 km. Alignments and calibrations of VISI were carried out before the launch. Electrical interference noise and non-uniformity in the slit direction in the observational data taken in the space were calibrated after the launch. These alignments and calibrations of VISI are described in Chapter 2.

Concentric airglow structure was observed by VISI from ISS on 1 June 2013. The source of the AGWs which made the circular shape in the airglow emission
was clarified in this observation. This is the first observation that the entire
concentric structure was captured from the space. Analysis of this event is
described in Chapter 3.

Statistical results of the latitudinal structure of the O and OH airglow, which
is more precise than previous observations, were derived from the limb observa-
tions by the Reimei satellite. Variations among the seasons are also affected by
the atmospheric tides. These analyses are described in Chapter 4.
Chapter 2

Development and calibration of spectral imager

2.1 Visible and near-infrared spectral imager

Visible and near-infrared spectral imager (VISI) observes airglow emissions at three different wavelengths. Outlooking of the imager is shown in Figure 2.1 and sectional view is shown in Figure 2.2.

CCD was set at the end of VISI as seen in Figure 2.2. This CCD sensor has $1,024 \times 1,024$ pixels. Airglow emissions and lights that come into VISI are spectrally dispersed by glittered prism in the optical part and are imaged on CCD.

VISI consists of 48 surfaces of lens. Its size is $450 \, \text{mm} \times 240 \, \text{mm} \times 210 \, \text{mm}$
Figure 2.1: Outlooking of VISI

Figure 2.2: Sectional view of VISI
and its weight is 14.5 kg. VISI has two slit field-of-views (FOVs) pointing 45° forward and backward to nadir along the orbital direction.

VISI was set into MCE (Multi-mission Consolidated Equipment). MCE was launched to ISS in July 2012. The nominal observations started at October 2012 after the initial checkouts. ISS maintains its orbit at altitudes between 350 km and 450 km. Width of the region which VISI can observe is approximately 600 km for OH emission and O₂ emission around 100 km altitude, and approximately 300 km for O emission at 250 km altitude. The spatial resolution of the image is 10 km for OH and O₂ image and 5 km for O emission image in the orbital direction.

Alignment of the optical unit, measurement of line dispersions and calculation of sensitivity based on the ground test were done before the launch. These tasks were done in cooperation with Dr. Sakanoi at Tohoku University [Sakanoi et al. (2011)]. The details are described in Section 2.2. Calibrations for the observational data of VISI were also done after the launch since some parts of the ground test were insufficient. Noise caused from the electrical interference was subtracted and sensitivity was recalibrated with the observational data in the space. The altitude of the the O airglow emission layer and the OH airglow emission layer were estimated from the observational data taken by VISI. These are described in Section 2.3.

Some constants and parameters are necessary for the conversion from count values to Rayleigh which is the unit of intensity of light. Important constants and parameters are expressed in Table 2.1.
Table 2.1: Constants and parameters for VISI optical system

<table>
<thead>
<tr>
<th>Constants and parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude of ISS orbit</td>
<td>400 ± 50 [km]</td>
</tr>
<tr>
<td>Moving speed of ISS</td>
<td>8 [km/s]</td>
</tr>
<tr>
<td>Focal distance of the optical system</td>
<td>5.5 [mm]</td>
</tr>
<tr>
<td>F-value of the optical system</td>
<td>0.96</td>
</tr>
<tr>
<td>Width of slit</td>
<td>13.3 [μm]</td>
</tr>
<tr>
<td>Lateral magnification of the optical system</td>
<td>1</td>
</tr>
<tr>
<td>Size of one CCD pixel</td>
<td>13.3 [μm]</td>
</tr>
<tr>
<td>Directions of FOV pointing</td>
<td>±45°</td>
</tr>
<tr>
<td>Ratio of the FOV illuminance to the axis direction</td>
<td>0.9</td>
</tr>
<tr>
<td>Throughput efficiency of the optical system (630-nm)</td>
<td>0.47</td>
</tr>
<tr>
<td>Throughput efficiency of the optical system (730-nm)</td>
<td>0.51</td>
</tr>
<tr>
<td>Throughput efficiency of the optical system (762-nm)</td>
<td>0.53</td>
</tr>
<tr>
<td>Dark noise at −30°C</td>
<td>0.24 [el/pixel/s]</td>
</tr>
<tr>
<td>Dark noise at −40°C</td>
<td>0.043 [el/pixel/s]</td>
</tr>
<tr>
<td>Read out noise</td>
<td>2 [el/rms]</td>
</tr>
<tr>
<td>Quantum efficiency of CCD</td>
<td>0.92</td>
</tr>
<tr>
<td>Absolute diffraction rate of glittered prism</td>
<td>0.63</td>
</tr>
</tbody>
</table>

2.2 Optical tests before the launch

2.2.1 Alignment of focus

Alignment of VISI was done with 10 μm accuracy since the size of pixels on the CCD is 13 μm × 13 μm. The focus of VISI was adjusted by shifting the distance between the lenses. The adjustment can be done in three directions: 1) the direction of the optical axis, 2) rotating direction in the normal plane to the optical axis and 3) the direction of other two dimensions without the optical axis. He-Ne laser (633-nm wavelength) was used as the light source of this experiment. A beam of He-Ne laser was collimated and diameter of a beam was limited to 10 μm by optical equipments before the beam arrived to VISI. The half-moon shaped optical mask was used to align the focus. The reason why the half-moon shaped mask was used is that the motion of the lenses should
be adjusted to an accuracy of \( \mu \text{m} \). The beam of He-Ne laser was imaged as a
dot in the one pixel on CCD after the alignment. This means the focus of VISI
had aligned correctly with 10 \( \mu \text{m} \) accuracy.

2.2.2 Measurement of line dispersion

The measurement of line dispersion was held after the alignment of VISI focus.
The relation between the coordinates of CCD and wavelength can be determined
from the line dispersion measurement. The light sources used in this measure-
ment were He-Ne laser and Fe-Ar-Ne lamp. He-Ne laser which was used in focus
alignment emits 633-nm wavelength light. Fe-Ar-Ne lamp emits the light from
570-nm to 850-nm wavelength. The distribution of wavelengths and intensity of
lights emitted from Fe-Ar-Ne lamp are well known by the specification of this
lamp. Position of the image of 633-nm wavelength light from He-Ne laser has
been already known from the focus alignment examination. Figure 2.3 shows
the examples of the obtained image data taken in this measurement.

Photon counts of the CCD pixels are proportional to the intensity of the
light. The wavelengths of light on the CCD pixels were determined from the
output counts for the corresponding images on CCD. The locations of the light
images on the CCD were examined with the two light sources for two FOVs.
The twelve wavelengths of the Fe-Ar-Ne lamp emission and 633-nm emission
of He-Ne laser were used to evaluate the line dispersion. The relation between
wavelength of light and the coordinates on the CCD are shown in Table 2.2.
The origin of CCD coordinate is taken at the edge of the forward FOV. The
coordinate of another edge of the CCD is 1,023.

The line dispersion of the light from the forward FOV is determined to be
Figure 2.3: CCD image of Fe-Ar-Ne lamp light entered. The left panel is the image of the light from the forward FOV and the right panel is the image of the light from the backward FOV. Color indicated the electron counts of each pixel. The beam without diffraction is imaged on the left side of the Forward FOV image.

1.02nm/pixel and 0.90nm/pixel for the light from the backward FOV from this measurement.
Table 2.2: The relation between wavelength of light and the coordinates on the CCD.

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>Coordinates in the forward FOV</th>
<th>Coordinates in the backward FOV</th>
</tr>
</thead>
<tbody>
<tr>
<td>772</td>
<td>0</td>
<td>854</td>
</tr>
<tr>
<td>764</td>
<td>8</td>
<td>864</td>
</tr>
<tr>
<td>750</td>
<td>21</td>
<td>877</td>
</tr>
<tr>
<td>738</td>
<td>32</td>
<td>890</td>
</tr>
<tr>
<td>727</td>
<td>43</td>
<td>902</td>
</tr>
<tr>
<td>706</td>
<td>64</td>
<td>926</td>
</tr>
<tr>
<td>697</td>
<td>74</td>
<td>938</td>
</tr>
<tr>
<td>688</td>
<td>102</td>
<td>969</td>
</tr>
<tr>
<td>660</td>
<td>110</td>
<td>978</td>
</tr>
<tr>
<td>651</td>
<td>119</td>
<td>989</td>
</tr>
<tr>
<td>640</td>
<td>129</td>
<td>1,000</td>
</tr>
<tr>
<td>633</td>
<td>136</td>
<td>1,008</td>
</tr>
<tr>
<td>627</td>
<td>142</td>
<td>1,016</td>
</tr>
</tbody>
</table>

2.2.3 Calibration of sensitivity

The objective of the sensitivity calibration is to find the relation between the intensity of entering light and the output counts of each pixels of CCD. An integration sphere of National Institute of Polar Research was used in this calibration. The strength of the entering light was controlled with the integration sphere.

It is necessary to convert the intensity of the entering light for each pixel to estimate the sensitivity of pixels. Intensity of the entering light was measured in the unit of [W/sr/m²/nm] in this experiment. The energy of photon whose wavelength is \( \lambda [\text{nm}] \) is \( \frac{hc}{\lambda} [\text{J}] \). Here, \( h \) is Planck constant and \( c \) is the speed of light. Number of photons which can be observed in the one second emission of 1[W] light of wavelength \( \lambda [\text{nm}] \) is \( \frac{\lambda}{hc} \). For example, the intensity of the light be \( 5.0 \times 10^{-6} [\text{W/sr/m}^2/\text{nm}] \) for 630-nm radiation, the intensity at 730 nm and 762 nm will be converted as in Table 2.3 using the equation which gives the
intensity of entering light $Q[W/sr/m^2/nm]$:

$$
Q[W/sr/m^2/nm] = Q \times 10^{-4} \times \frac{\lambda}{hc}[\text{photons/sr/cm}^2/s/nm] = \frac{Q\lambda}{hc} \times \frac{4\pi}{10^6} \times \frac{10^4}{4\pi}[\text{photons/sr/cm}^2/s/nm] = \frac{4\pi Q\lambda}{hc} \times 10^{-10}[R/nm] \\
\sim Q\lambda \times 6.3 \times 10^{15}[R/nm]
$$

Table 2.3: The intensity of light used in the sensitivity calibration

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>Intensity [W/sr/m$^2$/nm]</th>
<th>Intensity [R/nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>630</td>
<td>$5.0 \times 10^{-6}$</td>
<td>$2.0 \times 10^{3}$</td>
</tr>
<tr>
<td>730</td>
<td>$6.6 \times 10^{-6}$</td>
<td>$3.0 \times 10^{3}$</td>
</tr>
<tr>
<td>762</td>
<td>$6.8 \times 10^{-6}$</td>
<td>$3.3 \times 10^{3}$</td>
</tr>
</tbody>
</table>

The sensitivity of each pixel $S[\text{el/R/pixel/s}]$ is estimated from the count $C_{\text{exp}}$ obtained from the experiment as equation (2.3).

$$
S = \frac{C_{\text{exp}}G}{D} / \left( \frac{4\pi Q\lambda}{hc} \times 10^{-10} \right)
$$

where $G$ is the gain of CCD output. $G$ is 2 el/bit in the most case of this experiment.

The example of the data taken in this calibration is shown in Figure 2.4. The black dotted line indicates the pixels that 630-nm wavelength emission line are imaged. The intensity of the calibration light was about 200 kR/nm. The exposure time is one second and the gain was 2 el/bit. The plot on the right side of Figure 2.4 is the distribution of the count value of electrons at 630-nm wavelength.
The baseline of electron counts in Figure 2.4 gradually increases from 200 counts to 1,200 counts. This is because surplus charges are collected during the read out from CCD since this experiment was carried out without Peltier electrical cooling. The amount of the surplus charge is proportional to the read out time. The estimation of thermal noise is also the objective of this examination. Value of the calibration light was 2,400 counts after the subtraction of the surplus electrons. The relations between the intensity of the calibration light and the count values were taken for the intensity from $1.0 \times 10^2$ R/nm to $2.0 \times 10^5$ R/nm. Experimental data were taken with 0, 1, 2 and 4 second exposures for the different intensity light.

The sensitivity of pixels at 630-nm, 730-nm and 762-nm radiations are evaluated to be $0.028 \text{ el/R/pixel/s}$, $0.035 \text{ el/R/pixel/s}$ and $0.034 \text{ el/R/pixel/s}$ from these calibration data, respectively. The absolute diffraction rate of the glittered prism in VISI is $D = 0.63$. 

Figure 2.4: Image taken at the calibration test is on the left. Count value of electrons at 630-nm line coordinate are on the right.
2.3 Observational modes of VISI

VISI has three observational modes which are referred to as "Calibration" mode, "Spectral" mode and "Peak" mode. Calibration mode uses the whole sensitive area on CCD. Exposure time in this mode is 2 - 6 seconds. A sample of Calibration mode observation is shown in Figure 2.5. The right side of this figure corresponds to the diffracted image in the forward FOV and the left side is that for the backward FOV. The precise analysis of images taken in this mode is described in the next section.

It is impossible to take all data in Calibration mode during observations because of the restriction of downlink data rate. Spectral mode and Peak mode are used to take much data in observations. Six regions of interest (ROIs) are defined in these modes and data in ROIs are selected from raw observational data. ROIs are now defined for 630-nm, 730-nm and 762-nm wavelengths for each FOVs. The window width of ROI is 12-nm for each ROI.

Data of 12 pixels in the wavelength direction are taken in Spectral mode. Observational data in each ROI are binned only in spatial direction. A sample of Spectral mode observations is shown in Figure 2.6. Spectrum taken by VISI is bent for two pixels in the edge which should be straight in the wavelength direction idealistically. This is because of the limitation of the optical part. Exposure time in this observational mode is 1 - 6 seconds. The number of binning in spatial direction can be chosen from 8, 16 and 32.

It is possible to record continuous data in Peak mode observations. The maximum value and background value in each pixel are recorded, which is shown in Figure 2.7. Binning of data in spatial direction and exposure time are the same as Spectral mode observations. The figures of "Peak value" and "Background
Figure 2.5: Calibration mode observation in 13 August 2012. Color corresponds to the count value.
Figure 2.6: Spectral mode observation at 762-nm wavelength. Top panel is the observation in the forward FOV and the other is that in the backward FOV. The vertical direction of these images correspond to wavelength.

value” can be drawn from Peak mode observational data. The emission in the upper atmosphere can be obtained by the subtraction of background data from peak value data.
Figure 2.7: Peak mode observation at 762-nm wavelength. Left panel is the Peak value figure and right is the Background.
2.4 Calibrations of VISI after the launch

2.4.1 Subtraction of electrical interference noise

Wavy patterns, which are seen in Calibration mode images, are shown in the right half part of Figure 2.5. These patterns were also seen in the ground test before launch and seen in the case without light injection to VISI. This means the wavy patterns are noise and these are caused by electrical part of the imager system.

It is necessary to subtract wavy noise structure to analyze the emission observed by VISI Calibration mode. The wavy pattern seems to be the same in every observation though conditions such as exposure time or reflection from clouds are different. There were 56 Calibration mode observational data taken from August to December in 2012. Average noise pattern is shown in Figure 2.8. Noise is mainly seen in the forward FOV region though not in the backward FOV. A baseline of the count is determined for the subtraction of the average value in the backward FOV from the count value in the center of the pixels columns.

Count values after the subtraction of the wavy noise structures are 10 - 50 counts around the pixels corresponding to 630-nm, 730-nm and 762-nm wavelength in the both FOVs. Signal to noise ratio is larger than 1.0 since the thermal noise count, which can be detected in the region where light is not imaged on CCD, is less than 1 count.
Figure 2.8: Count values of wavy noise seen in Calibration mode observation.
2.4.2 Sensitivity calibration for observational wavelength

The range of wavelength which can be observed by VISI is determined by using reflection of clouds and auroral emission. Intense light reflected by clouds comes in VISI during the observations if the moon bright area is large enough. The moonlight reflected by clouds can be regarded as white light. The observational image of the reflected light by cloud after the subtraction of the wavy noise is shown in Figure 2.9.

![Image of observational image of reflected light from cloud](image)

Figure 2.9: Calibration mode observational image of the reflected light from cloud. Wavy structured noise is already subtracted.

It was difficult to extract 557.7-nm emission data from airglow emission
data taken by VISI though it is theoretically able to observe. VISI can observe auroral emission in high geomagnetic latitudes. Auroral emission at 557.7-nm wavelength is stronger than that in the airglow emission. Figure 2.10 is the graph of the spectrum of auroral emission observed by VISI. The 557.7-nm emission is recorded with 60 R/nm in the forward FOV in this observation.

![Graph of the spectrum of auroral emission](image)

**Figure 2.10:** Calibration mode observational image of the reflected light from cloud. Wavy structured noise is already subtracted.

Spectrums in 500-nm to 900-nm are recorded in Calibration mode. Average of the spectrum in Calibration mode is shown in Figure 2.11. Main targets of VISI are the emissions from O at 630-nm, OH band around 730-nm and O$_2$ at 31
762-nm wavelengths. ROIs around 630-nm, 730-nm and 762-nm wavelengths are shown with blue, green and pink dashed lines in the figure, respectively. VISI is able to observe Na emission at 589-nm and 557.7-nm emission of atomic oxygen in the forward FOV and 864.5-nm emission from oxygen molecule in the backward FOV. The sensitivity to the emission intensity differs between the forward FOV and the backward FOV as seen in Figure 2.11. The value of the forward FOV data is approximately 20% larger than the value of the backward FOV.

Figure 2.11: Average intensity of airglow emission observed by VISI. ROIs around 630-nm, 730-nm and 762-nm wavelengths are shown with blue, green and pink dashed lines, respectively.
2.4.3 Calibration of the slit direction non-uniformity

Non-uniformity of the sensitivity in the slit direction of VISI was found as the straight bright lines in the spatial direction in observational images. These are seen in Figure 2.9 and Figure 2.12. It was confirmed that there were no extraordinary pixels through various ground tests and after launch. Width of the slit which exists before the optical system of VISI was not uniform and this was the cause of the non-uniformity of the observational image. Appearance of the non-uniformity is different in observational modes since the way of processing and compression of observational data on board is different among Calibration mode and other modes.

An observational image taken in Peak mode is shown on the left side of Figure 2.12. This image is the observation at 762-nm wavelength taken around 05:25 UT on 21 October 2012. Lines can be seen along the ISS orbital direction in the original image. Coordinates of the edge of these high values are always the same. The increases of the count value in these regions are proportional to the intensity of the airglow emission. Non-uniformity seen in the slit direction is reduced by substituting the value calculated from the data near the region where the high values appear. The recalibrated image is shown in the right panel of Figure 2.12.
Figure 2.12: Left panel is the original image in Peak mode. Bright lines in the vertical direction are seen in the left panel. Right panel is the image after the reduction of the non-uniformity.
2.4.4 Altitude calibration of VISI data

The altitude of the emission layer can be determined by focusing a specific structure in the airglow emission. Two FOVs of VISI point 45° angle nadir along the orbital direction. Distance from ISS to the altitude of a specific structure in the emission is derived as the half of the moving distance of ISS from the point where the forward FOV observed the structure to the point where the backward FOV observed the structure. The altitude of the emission layer is obtained by subtracting this distance from the altitude of ISS at the observational time.

Figure 2.13: Observation geometry of two FOVs of VISI. Line of sight of both FOVs are 45° to ISS orbit.

O$_2$ emission layer is observed at 762-nm wavelength and O emission layer is observed at 630-nm wavelength. The altitude of these emission layers has been derived as approximately 95 km and 250 km in prior researches. Observational data taken by VISI at 762-nm and 630-nm with one second exposure are used in this analysis. Spatial resolution in the orbital direction is approximately 12 km in this mode. Resolutions in the slit direction, which is perpendicular to ISS orbital direction, are approximately 10 km and 5 km, respectively.

ISS moves with 8 km/s at the altitude of approximately 400 km. Structures
which move slower than ISS are focused in this method. Correlation was taken between the images taken by both FOVs by shifting the image in the ISS orbital direction. There is a maximum point of the correlation coefficient between both images. This point is regarded as the index of the distance along which ISS moves from the point of the specific structure that was observed by the forward FOV to the point of the structure that was observed by the backward FOV. Through the geometrical shift, the propagating velocity and the altitude variance in the structure can be obtained under the assumption that the altitude of the background emission layer is constant during the VISI observation.

Observational data taken by VISI at 762-nm wavelength from 10:13 - 10:42 UT on 22 May 2014 is shown in Figure 2.16. Upper panel is the observational data in the forward FOV and the lower panel is that in the backward FOV.
Correlation coefficient between the images taken in the forward FOV and the backward FOV is calculated with pixel shifts. The backward FOV image was shifted from -100 pixels to 100 pixels relative to the forward FOV image. Maximum of correlation coefficient was derived as 0.95 when the backward FOV image was shifted 50 pixels to the forward FOV image. Altitude of O$_2$ emission layer in this event was estimated to be 120 km considering that the altitude of ISS was 431 km in this observation.

There are 7,713 observations from September 2012 to July 2014 with one second exposure mode. Distributions of the estimated altitude of emission layers are derived from 630-nm and 762-nm wavelength observational data. Relation between the shifted pixel numbers and maximum correlation coefficient is shown in Figure 2.18 and Figure 2.19.

Most of 762-nm observational data concentrate around 52-pixels shift. This shift corresponds to the altitude of 90 - 110 km. Correlation coefficient distributed around 0.9 which indicates there is little difference between images in the both FOVs.

Two concentrations are seen in the graph for 630-nm wavelength observation. Concentration around 30 pixels in the orbital coordinate corresponds to the altitude of 220 km in this case. This peak expresses the altitude of the O emission layer. Another peak is seen around 70 pixel in the orbital coordinate.
Figure 2.17: Correlation coefficient of the forward FOV image and the backward FOV image with pixel shifts.
Figure 2.18: Relation between shifted pixels and correlation coefficients in 762-nm observations.
Figure 2.19: Relation between shifted pixels and correlation coefficients in 630-nm observations.
This corresponds to the city light on the ground which was observed when airglow emission from atomic oxygen was dark.

2.5 Calibration result of VISI

Line dispersion and sensitivity to the emission intensity were evaluated before the launch. Noises caused by the electrical interference were subtracted by using observational data after launch. Sensitivity of VISI was calibrated and modified by the observational data. Parameters obtained from calibrations are shown in Table 2.4.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line dispersion in the forward FOV</td>
<td>1.02 [nm/pixel]</td>
</tr>
<tr>
<td>Line dispersion in the backward FOV</td>
<td>0.90 [nm/pixel]</td>
</tr>
<tr>
<td>Sensitivity at 630-nm wavelength</td>
<td>0.028 [e]/[R/pixel/s]</td>
</tr>
<tr>
<td>Sensitivity at 730-nm wavelength</td>
<td>0.035 [e]/[R/pixel/s]</td>
</tr>
<tr>
<td>Sensitivity at 762-nm wavelength</td>
<td>0.034 [e]/[R/pixel/s]</td>
</tr>
</tbody>
</table>

2.6 Conclusion of development and calibration of VISI

VISI was developed for the spectrographic observations of the airglow emission from ISS. VISI has two FOVs in the forward and backward in the ISS orbital direction and observes the emissions in the nadir direction. There are three observational modes for VISI, which are referred as "Calibration", "Spectrum" and "Peak" modes. Focus of VISI was aligned and line dispersion was measured before the launch. Sensitivity of the optical system was also calibrated before
launch though it was insufficient because of the lack of CCD cooling system at the ground test. Recalibration after the launch was needed to cover some insufficient part of the ground tests. Electrical interference noise which was conspicuous in Calibration mode was reduced using the observational data after launch. Non-uniformity of the slit direction that was caused from the difference of slit width was remarkable in Peak mode observation. This was reduced by substituting the value calculated from the observational data. Sensitivity of the forward FOV and that of the backward FOV is different for 20%. Difference of the sensitivities between two FOVs were found in the observations from the space. This difference affects the accuracy of the determination of the altitude of emission layers using the VISI observational data.
Chapter 3

Analysis of the concentric structure in $\text{O}_2$ airglow observed by VISI

3.1 Introduction of the circular structure in airglow emissions

Airglow is the emission of light from atoms and molecules in the upper atmosphere. These atoms and molecules release their excess energy that is caused by the solar radiation in the daytime. Atmospheric gravity waves (AGWs) in the mesosphere and the lower thermosphere are studied via the observations of airglow by ground-based and space-borne instruments [Siskind et al.(1991), Shepherd et al.(1993), Hays et al.(1993)]. Variations in airglow emission are
mainly caused by the variations of the number density and the temperature of atoms and molecules in the emission layer. A single all-sky imager with a FOV of several hundred kilometers is insufficient for observing the entire wave structure, which may be larger than 1,000 km [Shiokawa et al.(1999)].

The effects of tropospheric activity on airglow disturbances in the upper atmosphere have been previously studied. The circular structures of OH airglow disturbances, which have been interpreted to be caused by convective clouds, were partly observed by ground-based imagers [Yue et al.(2009)]. Some concentric airglow structures have been related to thunder storm activities [Taylor et al.(1988), Sentman et al.(2003)]. A concentric gravity wave structure centered over a typhoon was observed by a ground-based imager in Japan [Suzuki et al.(2007)]. However, the entire structure of the concentric disturbance was not clarified from the ground-based observations, because of their narrow FOVs and restrictions due to weather conditions. Concentric structures of the airglow were observed mostly around tropospheric disturbances, which can be the sources of AGWs. The observations of these structures near AGW sources by ground-based imagers are difficult because their FOVs are covered by clouds. Therefore, the sources of these concentric structures can be identified by observations from space, which can observe the airglow over clouds.

The entire image of a concentric airglow structure was first observed on 1 June 2013, by the spectral imager on ISS. The horizontal dimension of this concentric structure was 1,200 km, which is larger than the FOV range of the ground-based imagers.
3.2 Observation and results

A concentric airglow emission event at the 762-nm wavelength was observed on 1 June 2013 by VISI.

VISI was installed on July 2012, on the Exposure Facility of the Japanese Experiment Module on ISS at an orbit of approximately 400 km altitude. VISI observes the airglow in the nadir direction on the night side with two FOVs facing 45° in the forward and backward of the orbital direction [Sakanoi et al. (2011)]. The FOVs of VISI are approximately 600 km wide at an altitude of 100 km perpendicular to the ISS orbit. The spatial resolution of VISI is approximately 10 km at the same altitude. The observational mode that records the peak values and the background values of emissions was used in this observation. Airglow emissions continuously observed by VISI are 630-nm O, 762-nm O₂ emission, and OH(8-3) band emission at approximately 730-nm [Sakanoi et al. (2011)]. These images were recorded at sampling intervals of 1.8 seconds, which corresponds to a horizontal resolution of approximately 15 km.

An event observed over the North American continent on 1 June 2013, is the focus of this chapter. The observational period was from 04:33:44 UT to 04:49:01 UT on 1 June 2013. Observational images of O₂ emission at 762-nm captured by VISI are shown in Figure 3.1. The 762-nm airglow emission from O₂ exists around an altitude of approximately 95 km. The upper and lower panels in Figure 3.1 are observational images recorded by the forward and backward FOV of VISI, respectively. The horizontal axis in Figure 3.1 corresponds to the direction of the ISS velocity. The vertical axis is the direction of the slit of VISI. The ISS moved from left to right, as shown in Figure 3.1. The geographic coordinates shown in Figure 3.1 represent the positions of the
center pixels of the images with the assumption that the emission layer exists at an altitude of 95 km. The green color in the figure indicates the 762-nm emission in the intensity range of 1,000 R to 7,000 R. The strongest emission in this observation was 7,897 R. Emission in the region between the equator and 20°N was approximately 1,000 R. The intensity observed by the backward FOV was weaker than that of the forward FOV. This difference would be caused by an inaccuracy in instrument calibration. Red lines in the figure indicate the positions of the data at the times shown in UT. The ISS was positioned 6.1°S, 135.6°W at the start and 38.1°N, 96.5°W at the end of this observation at an altitude of 410 km.

![Figure 3.1: Images of the 762-nm observation by VISI. Upper and lower panels are the forward and backward FOV images, respectively. Images are plotted in the 1,000 - 7,000 R range. It is assumed that the emission layer altitude is 95 km. A concentric structure of the airglow emission is observed from 04:44 UT to 04:49 UT.](image)

No light from the moon was visible in this area. Reflection of the O₂ airglow emission by clouds at the 762-nm wavelength were absorbed by the Earth’s atmosphere. Most of the emission of city lights on the ground were also absorbed by the Earth’s atmosphere, although some in the image were strong and appeared as white pixels. Cosmic rays that struck the CCD pixels also appear
as white pixels in the observational image. Intense emissions of the O_2 airglow appeared between 20°N and 40°N. Intense emission was observed from 04:42 UT to 04:47 UT by the forward FOV of VISI. A wavy structure appeared at approximately 04:44 UT when the location of the center pixel of the forward FOV was at 29.9°N, 106.9°W. This wavy structure, observed for five minutes until the end of this observation at 04:49 UT, was concentric with the center near 35°N, 95°W. This structure was also observed in the backward FOV of VISI, although the entire image of the concentric structure was not captured by the backward FOV because the VISI observation ended at dawn.

Figure 3.2: High-pass filtered observational data of VISI’s forward FOV. Data obtained near Oklahoma, United States, is plotted under the assumption that the emission layer exists at an altitude of 95 km. The unit of intensity is Rayleigh. Red lines in the figure indicate wave fronts in the concentric structure. The star in the figure indicates the estimated center of the structure.

The remainder of this chapter mainly investigates the image of the forward
FOV. High-pass filtered data with a cut-off wavelength of 700 km is shown in Figure 3.2. The geographic coordinates of Figure 3.2 are 110°W to 90°W longitude and 25°N to 45°N latitude. The center of concentric structure was estimated under the assumption that wave fronts are circular and that the structure has a single center. The estimated position of the center was at 35.3°N, 95.0°W which is represented by a star in Figure 3.2. Red circles indicate wave fronts from the estimated center; the smallest radius is 260 km. Some circular wave fronts were observed in a region closer than 260 km to the estimated center. The centers of these circular wave fronts appeared to differ; those inside the smallest circle in Figure 3.2 were in the region of 94°W to 96°W longitude and 34°N to 36°N latitude.

The high-pass filtered data on the line 35.3°N, 95.0°W, which is the estimated center, to 25°N, 108°W is shown in Figure 3.3. This line runs southwestward and is parallel to the ISS trajectory. The fluctuations from 0 km to 700 km correspond to the concentric structure in Figure 3.2. The average intensity of the peak-to-peak amplitude of the fluctuation was approximately 1,000 R, which approximately represents a 20% fluctuation of the background airglow intensity. The amplitude of fluctuation was nearly constant in the range of 0 - 1,200 km, and the dominant wavelength of this structure was 40 - 80 km.

The propagation speed was estimated from the spatial difference between the forward and backward FOVs of VISI. The difference of one pixel size corresponds to 9.8 km at an altitude of 95 km. The interval of the observation by the forward and backward FOVs was 78 seconds at an altitude of 95 km. The difference of the concentric wave fronts between forward and backward FOVs was one or zero pixels in the radial direction from the center. The propaga-
Figure 3.3: Variation of intensity from the center of the circular structure. The horizontal axis indicates the distance from the center of the concentric structure and the vertical axis indicates fluctuation from the average intensity. The base line is taken from 35.3°N, 95.0°W to 25°N, 108°W parallel to ISS orbit. Spectrum of these wave components are shown in the lower panel.
The propagation speed derived from the difference between the two FOVs was 130 - 160 m/s, which is consistent with the phase velocity observed by previous studies [Shiokawa et al.(1999), Yue et al.(2013)].

3.3 Discussion

3.3.1 Observation by VISI

Concentric waves in the O$_2$ airglow emission were observed in the range of 1,200 km radius from the center at approximately 04:40 UT on 1 June 2013. The width of the central region was 260 km in diameter with a dominant wavelength of 80 km. Its amplitude was 20% of the background intensity near the center and was nearly almost constant in a 1,200 km radius from the center. The propagation speed of waves in the concentric structure was estimated to be 125 ± 62 m/s.

The duration time of the concentric structure was estimated from the propagation speed and the distance from the center to the edge of the structure. At a constant speed, the propagation time of waves from the center to the edge at 1,200 km was estimated to be 3.5 ± 1.7 hours. These results indicate that the concentric structure was created after 23:20 UT on 31 May, which is the time evaluated from the slowest speed of propagation.

A decrease in intensity was not observed as waves of 80-km wavelength propagated to 1,200 km. It is interpreted from this constant amplitude that waves were ducted near the emission layer. A numerical simulation based on the event observed in Brazil showed the duct propagation of AGW at an altitude
of 90 km for a distance of 1,000 km \cite{Vadas2009a}.

To identify the source of the concentric structure, the infrared observation of tropospheric clouds provided by the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) was compared with that of the airglow emission by VISI. No clouds were observed before 23:00 UT on 31 May in the $3^\circ \times 3^\circ$ region near 35.3°N, 95.0°W which is the center of the concentric structure. A tornado occurred on 31 May from 23:03 UT to 23:43 UT near 35.5°N, 98.0°W as reported by the National Oceanic and Atmospheric Administration (NOAA), approximately. This was five hours prior to the observation of the concentric structure by VISI. Super cells that were observed as clouds with high altitude tops existed for five hours in the $3^\circ \times 3^\circ$ region near 35.5°N, 98.0°W after the tornado disappeared.

Observation of clouds at 04:00 UT on 1 June 2013, and the observation of the airglow by VISI are plotted in Figure 3.4. The range of this map is 25°N to 45°N latitude and 110°W to 90°W longitude, which is the same as that shown in Figure 3.2. The clouds are plotted according to VISI observation in the upper panel of Figure 3.4. Color in the figure indicates the temperature of the cloud top in 203 - 313 K range. VISI observation is plotted in green at the position under the assumption that the emission layer existed at an altitude of 95 km. The center of the concentric structure is represented by the blue star in the figure, and wave fronts are represented by red circles in the lower panel of Figure 3.4. The intervals of these circles were 80 - 100 km in the radial direction, which corresponds to the dominant wavelength of this concentric structure. Clouds with top temperatures of approximately 215 K were observed at approximately 35.3°N, 95.0°W, which is the center position of
Figure 3.4: Infrared image of clouds recorded at 04:00 UT on 1 June 2013. Temperature of clouds is indicated by contour. The frame of the region of VISI observation is shown as a green rectangle. Red circles indicate wave fronts observed by VISI.
the concentric structure. Many circular wave fronts of the airglow were observed inside the central region, which correspond to the inside of the smallest circle in the lower panel of Figure 3.4. Multiple centers of circular waves appeared to exist inside of the central region. Ripples of the airglow intensity variation can be generated when multiple sources exist nearby [Vadas et al.(2012)]. Several clouds with high altitude cloud tops under the region of multiple circular wave fronts of the airglow were observed by VISI. The sources of these circular wave fronts appeared to exist inside a diameter of 260 km from the center. Super cells, which correspond to clouds with high altitude cloud tops near 35.3°N, 95.0°W, are believed to be the source of AGWs that generate the concentric structure in the airglow emission outside the region. The dominant 80-km wavelength in this concentric structure is consistent with that of the airglow structure caused by thunder storms [Vadas et al.(2012), Yue et al.(2013)].

3.3.2 Comparison with TEC observation

Global positioning system-total electron content (GPS-TEC) observed by ground-based receivers were investigated to study the altitude range in which AGWs propagated in the vertical direction. Data of ground-based GPS receivers in North America were used. The horizontal structure of TEC perturbation was studied by 20-minutes detrended data of the DRAWING-TEC project (http://seg-web.nict.go.jp/GPS/DRAWING-TEC/) of Japan’s National Institute of Information and Communications Technology (NICT).

Concentric structures in TEC were clearly observed from 23:30 UT on 31 May 2013 to 01:30 UT on 1 June 2013. The center of the TEC concentric structure was near 35.5°N, 98.0°W, which is the position that the tornado existed
Figure 3.5: TEC observation by GPS receivers in the U. S. at 23:50 UT on 31 May 2013 and at 01:00 UT on 1 June 2013. 20-minutes detrended data of the DRAWING-TEC project is used.
from 23:03 UT to 23:53 UT on 31 May. The radius of the TEC concentric structure was 1,500 km at 01:00 UT, which was larger than that of the concentric structure observed by VISI. The amplitude of TEC perturbation was large in the northeast direction and was small in the northwest. The dominant wavelength of the TEC concentric structure was 150 km, which is longer than that in the airglow observation. The propagation speed was estimated to be 160 - 180 m/s, which is faster than that of the wave fronts in the airglow concentric structure observed by VISI. Enhancement of TEC was caused by a geomagnetic storm from 01:30 UT on 1 June, with a minimum value of the Dst index -119 nT at 09:00 UT on 1 June. TEC concentric structures were not clearly observed after 01:30 UT. It is interpreted that AGWs generated in the troposphere propagated in the altitude of 300 km and generated the concentric structure in TEC. AGWs that generated the TEC concentric structure differed from those that generated the airglow concentric structure because the wavelength and propagating velocity differed. This result is consistent with the AGW theory that TEC concentric structures with longer wavelengths propagate faster than airglow concentric structures with shorter wavelengths.

The start time of the airglow concentric structure was estimated between 23:20 UT on 31 May and 03:00 UT on 1 June, which was calculated from the propagation speed of AGWs in the concentric structure. If the airglow concentric structure had started before 01:30 UT, the concentric structure of the airglow and that of the TEC would have simultaneously existed. The dominant wavelength of the airglow concentric structure was 80 km, which is shorter than that of the TEC concentric structure. The short wavelength in the airglow concentric structure can be interpreted as a secondary wave generated by wave
breaking. This mechanism is shown in Figure 3.6. The TEC concentric structure could have existed after 01:30 UT, although it was not observed in this case because of the geomagnetic storm. Furthermore, the TEC concentric structure produced by a different tornado endured for seven hours over North America [Nishioka et al.(2013)].

![Figure 3.6: Schematic figure of AGW propagation from the troposphere.](image)

The propagation from the lower atmosphere was also detected in the Tohoku earthquake case by GPS-TEC observation [Tsugawa et al.(2011), Matsumura et al.(2011)]. Input time of source and the way of propagation are different in these two cases. Earthquake gives the energy at a moment from a single source and the energy propagates vertically upward. Tornado observed in this case was lasted for 40 minutes and there are several sources of input. The propagation was made conically from the source since the spatial size of the center of airglow structure is larger than the source size. Resonance of four minutes period in the neutral atmosphere was estimated to be lasted from the input to the observational time. This resonance can affect the $O_2$ temperature and number density as the emission source. Circular pattern was not clearly seen in the image of 630-nm $O$ emission at the altitude of approximately 250 km.
3.4 Conclusion of this event analysis

The entire structure of a concentric airglow emission in the mesosphere was first observed by the ISS/IMAP-VISI. An image of the O$_2$ airglow emission obtained at the 762-nm wavelength was used in this study. A concentric structure was reported in the observation of 1 June 2013. The distance from the center to the edge of this concentric emission was approximately 1,200 km, and the dominant horizontal wavelength was 80 km. The average amplitude near the source was 1,000 R, which is 20% of the background. Attenuation was not apparent in this event. The center of the concentric structure was near the high altitude top clouds that existed at the time of the VISI observation. Multiple wave fronts were observed near the center of the concentric structure. The duration time of the AGW source was estimated from the entire concentric airglow structure. The concentric structure without attenuation was estimated to be made by horizontal propagation of AGWs for 3.5 hours in the radial direction from the center. Multiple wave fronts near the center appeared to be generated from different points in highly convective clouds. It is supposed that the concentric structure observed in this event was created from highly convective clouds and that AGWs horizontally propagated with little damping.
Chapter 4

Statistical study of airglow latitudinal structure observed by the Reimei satellite

4.1 Introduction of the airglow observations by satellites

Airglow emissions have been observed by various instruments. Imagers on the ground, rockets and satellites are used for the measuring of the airglow emissions. Horizontal structures with several hundred kilometer scale are observed by ground-based imager network [Shiokawa et al. (2009)]. These structures are
affected by the atmospheric gravity waves around the emission layers. Vertical structures of the airglow emissions are observed by rocket measurements and the satellites \cite{Lowe1996, Yee1997, deMenezes2008}. Distribution of volume emission rate (VER) of the OH airglow was obtained from the observations by Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) on the TIMED (Thermosphere Ionosphere Mesosphere Energetics Dynamics) satellite \cite{Marsh2006} though its spatial resolution was not enough. Wind Imaging Interferometer (WINDII) on the Upper Atmosphere Research Satellite (UARS) had also observed the airglow emissions in the Earth’s limb direction \cite{Shepherd1993}. Some part of the relation between the neutral wind and the emission intensity of the airglow is revealed by the observations by WINDII \cite{Russel2003, Russel2005}. There are few observations and analyses by the imaging camera on the satellite which clarified the seasonal variation or spatial distribution of the airglow emissions.

Results of the analyses of observations by Multi-spectral Auroral Camera (MAC) on the Reimei (INDEX) satellite are described in this chapter. MAC observed the airglow emission in the Earth’s limb direction from March 2008 to January 2011. Targets are the emission from the atomic oxygen (O) observed at 557.7-nm wavelength and the emission from the hydroxyl molecules (OH) observed at 670-nm wavelength.

4.2 The Reimei satellite

The Reimei satellite, also known as the INDEX satellite, was launched in August 2005 \cite{Saito2007}. The initial objective of this satellite was the observa-
tion of fine structures of aurora in the polar region. The orbit of the Reimei satellite is a polar orbit with 100 minutes period. This orbit is fixed in 00:50 - 12:50 local time (LT) plane.

Multi-spectral Auroral Camera (MAC) is boarded on the Reimei satellite. The picture of MAC is shown in Figure 4.1. This imager observes emissions of aurora and airglow with three different wavelengths, simultaneously. The wavelengths are 427.8-nm, 557.7-nm and 670-nm. They correspond to the emission of N$_2^+$, O and N$_2$, respectively [Obuchi et al.(2008)].

The energy spectrum analyzer (ESA) boarded on the Reimei satellite had trouble in 2008, and became unable to observe the precipitation of electron. Observations of airglow emission in the mid-latitude region by the Reimei satellite have been conducted from 2008 to 2011. The airglow observations by the
Reimei satellite are operated for three times a day in average. The operations with this frequency started from October 2008. There are approximately 1,100 limb observations by Reimei/MAC from March 2008 to January 2011.

The objective of this study is to clarify the latitudinal structures and seasonal variation of the airglow emissions in the mid-latitude region. The data obtained from the limb observations by MAC at 557.7-nm and 670-nm wavelengths are used in this study.

There are two modes of the optical observation by the Reimei satellite. One is the mode for the simultaneous observation of optical imaging and particle measurements. This mode is not used in the airglow limb observations. Another is the mode to observe the altitude distribution of emissions of aurora and airglow while MAC points at the limb direction of the Earth. CCD with 1,024 pixels × 1,024 pixels is used for MAC. Data obtained by the airglow limb observation is binned in 64 pixels × 64 pixels because the data are spatially averaged for 16 pixels × 16 pixels on board [Obuchi et al.(2008)].

The line-of-sight of Reimei/MAC points at the 100 km altitude region at 2,000 km distant from the satellite position when the satellite observes the airglow emission in the Earth’s limb direction. The field-of-view (FOV) of the observation is 128 km × 128 km around the tangential point, and the temporal resolution is one second. The Reimei satellite observes the airglow emission from the whole longitudinal extent though the region is limited from 15°N to 45°N in latitude.

Examples of observational image taken by Reimei/MAC are shown in Figure 4.2. Limb direction observation of the O airglow is shown in the upper panel and the observation of the OH airglow is shown in the lower panel of Figure 4.2.
Altitude of the O airglow emission layer was 10 km higher than that of the OH airglow emission layer in this observation. It is difficult to derive the absolute altitude of the emission layer because there are some biases in the attitude data of the satellite.

Figure 4.2: Airglow emissions observed by MAC on the Reimei satellite. O airglow is shown in the upper panel and OH airglow is shown in the lower panel. Blue dotted line indicates 39°N and orange dotted line indicates 36°N in the panels.

4.3 Estimation of volume emission rate

Reimei/MAC obtains the value integration of the airglow emission along its line-of-sight. It is necessary to solve an inverse problem to derive the volume emission rate, the emission in unit time and unit volume, at each altitude. The assumptions as below were applied to derive the volume emission rate of the airglow from Reimei/MAC imaging observations:
• Each emission layer has 5 km thickness.

• Volume emission rate is uniform in the emission layer.

• The emission less than 0.1 kR is regarded as noise.

Figure 4.3: Illustration showing the assumptions for the derivation of volume emission rate from the MAC observational data.

Assumptions for the derivation of volume emission rate from the observational data are illustrated in Figure 4.3. "The $N$-th layer" is defined as the $N$-th layer from the layer in the highest altitude, 650km. $D_N$ and $V_N$ are defined as the observed emission data of the $N$-th emission layer and the volume emission rate of the $N$-th layer, respectively. $l_{Nm}$ is the length of the line-of-sight in the $m$-th layer to obtain $D_N$.

$D_1$, the observed emission from the first layer, is determined only from the volume emission rate of the first layer, $V_1$. $V_1$ is determined as:

\[
V_1 = \frac{D_1}{l_{11}}
\]  

(4.1)
$D_2$ is the integration value of the first layer emission, $V_1$, and the second layer emission, $V_2$. $D_2$ is expressed as follows:

$$D_2 = V_1 l_{21} + V_2 l_{22} \quad (4.2)$$

$V_2$ is determined by Equation (4.3) because the volume emission rate of the first layer, $V_1$ is already determined by Equation (4.1):

$$V_2 = \frac{D_2 - V_1 l_{21}}{l_{22}} \quad (4.3)$$

The volume emission rate of the third layer $V_3$, and more generally the $N$-th layer $V_N$ is determined as follows:

$$V_3 = D_3 - V_1 l_{31} - V_2 l_{32} \quad (4.4)$$

$$V_N = \frac{D_N - \sum_{k=1}^{N-1} V_k l_{nk}}{l_{NN}} \quad (4.5)$$

The volume emission rate of the airglow were derived from the upper layer to the lower layer by using this algorithm. The volume emission rate were derived for every five kilometers from Reimei/MAC observations.

4.4 Area of the limb observation by Reimei/MAC

The limb observation data obtained by Reimei/MAC from March 2008 to January 2011 are used in this study.

1,034 values at 557.7-nm wavelength and 1,062 values at 670-nm wavelength were collected during a period from March 2008 to January 2011. The difference
in the number of the obtained values is caused by the operation of the satellite. The airglow observation by Reimei/MAC was restricted to the region between 15°N and 45°N.

The area where observations were made during this time period is shown in Figure 4.4. The map in the upper panel shows the distribution of the O airglow observations and the map in the lower panel shows the distribution of the OH airglow observations by the Reimei satellite. The resolution of the grid is 5° × 5°. The color scale on the map indicates the number of the airglow observations by the Reimei satellite in the grids. White colored area indicates the area in which there were no observation by the satellite, and colored area indicates the area in which there were observations by the Reimei satellite. The maximum number of the observations, i.e., 52 was obtained in the region from 145°E to 150°E in longitude and from 35°N to 40°N in latitude.

Figure 4.4: Area of the limb observation by the Reimei/MAC. The figure in the upper panel is the area where 557.7-nm wavelength observations were made and the lower panel indicates where 670-nm observations were made.

It is seen that there are more observations above Japan than the other area
in Figure 4.4. This is caused by the satellite operations which were intended to compare the Reimei observations with simultaneous ground-based observations in Japan.

### 4.5 Latitudinal profile of airglow emissions observed by Reimei satellite

Volume emission rate of the airglow in each observation was derived from the observational data obtained by the Reimei satellite. The method of the data analysis in this study consists of three steps: 1) peak search, 2) altitude correction and 3) derivation of the volume emission rate.

The peak of the emission which is thought to be the airglow emission was always found in each observational data although there are several noise emissions in images, and altitude biases. The emission peak between 25 km altitude and 115 km altitude in each observational data were selected. The emission peaks in the wide altitude range were searched since the altitude biases caused by the satellite attitude errors are usually larger than 10 km and less than 50 km. The emission peaks determined by this procedure were assumed to be at 95 km altitude for the O airglow observations and at 85 km altitude for the OH airglow observations. Volume emission rate was derived with the method described in Section 4.3.

Data were averaged in four seasons which are March - May (Spring), June - August (Summer), September - November (Autumn) and December - February (Winter) since the major components of the upper atmosphere change among seasons.
4.5.1 O airglow

Latitudinal variations of the O airglow are shown in Figure 4.5. The average of 232 data for spring, 225 data for summer, 270 data for autumn and 178 data for winter are taken. Data for spring, summer, autumn and winter are shown in red, green, gray and blue lines in Figure 4.5, respectively.

Figure 4.5: Latitudinal profile of the O airglow emission. Data for spring, summer, autumn and winter are shown in red, green, gray and blue lines.

The value of volume emission rate is from 500 photons/cc/s to 1,500 photons/cc/s in spring, summer and autumn. Volume emission rate is smaller than 500 photons/cc/s in winter. There is a tendency that volume emission rate
decreases in the lower latitude in spring, summer and winter. A peak having approximately 1,500 photons/cc/s was observed around 35°N in autumn. The calculation of the volume emission rate using the MSISE-90 model showed the tendency that volume emission rate increases in the equatorial direction. The observation by the WINDII/UARS also showed the tendency of volume emission rate increasing in the equatorial direction. The average from the observational result by the Reimei satellite is different from the model estimation and earlier observations. Comparison of the model calculation and the observations by Reimei/MAC will be discussed in the later section.

4.5.2 OH airglow

Latitudinal variations of the OH airglow are shown in Figure 4.6. The average of 262 data for spring, 227 data for summer, 264 data for autumn and 172 data for winter are taken. Data for spring, summer, autumn and winter are shown in red, green, gray and blue lines in Figure 4.6, respectively.

The values of volume emission rate derived from the observational data by the Reimei satellite are less than 500 photons/cc/s in spring and winter. The volume emission rate is more than 1,000 photons/cc/s in some parts of the observations in summer and autumn. The peak of the volume emission are observed conspicuously in the region from 40°N to 35°N in autumn and winter. The difference of the volume emission rate at the peak from the value at other latitude is approximately 200 photons/cc/s. This is much smaller than the decrease observed in the O airglow and is different from the monotonous variation of O airglow volume emission rate. The details will be discussed in the later section.
Figure 4.6: Latitudinal profile of the OH airglow emission. Data for spring, summer, autumn and winter are shown in red, green, gray and blue lines.
4.6 Longitudinal profile of airglow emission observed by Reimei satellite

Airglow observations by the Reimei satellite were grouped in the following six regions with 45 degrees width in longitudes: 90°W - 45°W, 45°W - 0°, 0° - 45°E, 45°E - 90°E, 90°E - 135°E and 135°E - 180°. Most of observations were made in the region between 90°E and 180° in longitude.

4.6.1 O airglow

Latitudinal variations of the O airglow emission are shown in Figure 4.7. Seasonal dependences are also shown in the figure. Red, green, autumn and blue lines indicate the average variance in spring, summer, autumn and winter, respectively.

Peaks of volume emission rate were observed between 20°N and 30°N in every region. Average of the volume emission rate was derived as 600 photons/cc/s in 90°E and 180° where most observational paths had existed. Variation of volume emission rate among seasons was the largest in the region between 0° and 90°E. The amount of variation was several hundred photons/cc/s in 45°E and 90°E region.
Figure 4.7: Latitudinal variation of the O airglow emission for six different longitudinal regions. Lines in each panel indicate seasonal variation.
4.6.2 OH airglow

Latitudinal variations of the OH airglow emission are shown in Figure 4.8, which are the same as Figure 4.7.

Peaks of volume emission rate were observed around 30°N in every region. These peaks were found in the north of the O airglow emissions. Average of the volume emission rate was derived as 300 photons/cc/s in 90°E and 180° where most observational paths had existed. Volume emission rate was smaller than that of the O airglow emission in the same region, especially between 90°W and 0° in spring.
Figure 4.8: Latitudinal variation of the OH airglow emission for six different longitudinal regions. Lines in each panel indicate seasonal variation.
4.7 Discussions about the statistical analysis of the Reimei observations

4.7.1 The mechanism of variation of emission rate of atomic oxygen

557.7-nm emission of atomic oxygen is produced by the photochemical reaction expressed as below:

\[ O + O + O \rightarrow O_2^* + O(^1S_0) \]  \hspace{1cm} (4.6)

This photochemical reaction contains the detailed process which includes the arbitrary third body, M [Khomich et al.(2008)].

\[ O + O + O \rightarrow O_2^* + M \quad \alpha_{O_2}, \]
\[ O_2^* + N_2 \rightarrow O_2 + N_2 \quad \beta_{N_2}, \]
\[ O_2^* + O_2 \rightarrow O_2 + O_2 \quad \beta_{O_2}, \]
\[ O_2^* + O \rightarrow O_2 + O \quad \beta_{O}, \]
\[ O_2^* \rightarrow O_2 + h\nu \quad A^*, \]
\[ O(^1S_0) \rightarrow O(^1D_2) + h\nu(557.7\text{nm}) \quad A_{557.7}, \]
\[ O(^1S_0) \rightarrow O(^3P_1) + h\nu(297.2\text{nm}) \quad A_{297.2}, \]
\[ O(^1S_0) + O_2 \rightarrow O + O_2 \quad \beta_{O_2}, \]
\[ O(^1S_0) + O \rightarrow O + O \quad \beta_{O} \]

\( \alpha \) are the rates of production of the excited components and \( \beta \) are their deac-
tivation rates in collisions. $A_{557.7}$, $A_{297.2}$ and $A^*$ are the probabilities of the radiation transitions. The volume emission rate of atomic oxygen $Q$ [photons/cm$^3$/s] is expressed as Equation (4.7) by using coefficients $\alpha$, $\beta$ and $A$:

$$ Q = \frac{A_{557.7} \cdot \alpha_O \cdot \alpha_{O_2}[O][M]}{(A_{557.7} + A_{297.2} + \beta_{O_2}[O_2] + \beta_O)(A^* + \beta_{O_2}^*[O_2] + \beta_{N_2}^*[N_2] + (\alpha_O + \beta_O^*)[O])} $$

\begin{align*}
A_{557.7} & = 1.215 [s^{-1}], \\
A_{297.2} & = 0.076 [s^{-1}], \\
A^* & = 3 [s^{-1}], \\
\alpha_O & = 1 \times 10^{-12} [cm^3 \cdot s^{-1}], \\
\alpha_{O_2} & = 5.5 \times 10^{-33} (200/T) \cdot 2 [cm^3 \cdot s^{-1}], \\
\beta_O & = 5.0 \times 10^{-11} \exp(-305/T) [cm^3 \cdot s^{-1}], \\
\beta_{O_2} & = 4.3 \times 10^{-12} \exp(-865/T) [cm^3 \cdot s^{-1}], \\
\alpha_O + \beta_O^* & = 5.9 \times 10^{-12} [cm^3 \cdot s^{-1}], \\
\beta_{O_2}^* & = 3 \times 10^{-14} [cm^3 \cdot s^{-1}], \\
\beta_{N_2}^* & = 4.7 \times 10^{-9} (200/T)^2 \exp(-1506/T) [cm^3 \cdot s^{-1}]
\end{align*}

Some of these coefficients depend on the temperature, $T$. The deactivation of excited atomic oxygen and oxygen molecules are usually neglected because of the small amount. There is an indication that variance of temperature on the ground is not associated with the variation of the intensity of the emission of the atomic oxygen [McDade et al. (1986)]. Volume emission rate of atomic oxygen mainly depends on the number density of the emission source.
4.7.2 The mechanism of variation of emission rate of OH airglow

OH airglow emission is determined by the concentration of ozone produced by the recombination of atomic oxygen and losses by the reaction with atomic hydrogen. The concentration of ozone is expressed by the following equation [Marsh et al.(2006)].

\[
\begin{aligned}
[O_3] &= \frac{k_{O+O_2+M}[O][O_2][M]}{k_{H+O_3}[H]} \\
\end{aligned}
\] (4.8)

The production rate of OH is expressed as follows:

\[
P = k_{H+O_3}[H][O_3]
\] (4.9)

These concentrations are observed by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER). Figure 4.9 shows the volume emission rate observed by SABER instrument averaged over spring of 2002.

The value of volume emission rate observed by SABER was \(10^4 - 10^5\) photons/cc/s. The volume emission rate observed by the Reimei satellite was smaller than the observation by SABER. This is because of the difference of the wavelength and the band filter used for OH airglow. The width of the band filter used for Reimei/MAC observation of the OH airglow was 38.23 nm [Obuchi et al.(2008)]. SABER observes infrared emissions between 1.27 \(\mu\)m and 15.2 \(\mu\)m. This is much wider band used in the Reimei satellite observation.
Figure 4.9: SABER OH Meinel 2.0 μm volume emission rates. The unit of volume emission rate is $10^5$ photons/cc/s. [Marsh et al.(2006)]

### 4.7.3 Accuracy of the Reimei observation

Volume emission rate observed by Reimei/MAC is larger than the previous observations. This was caused by degradation of the sensitivity of the observational instruments. The Reimei satellite launched and started observation in August 2005. The beginning of the airglow limb observation is in March 2008. There are about three years from the launch to the beginning of limb observations. The sensitivity of the CCD on the satellite would be declined than that measured before launch.

Another cause of over-estimation of volume emission rate may be the assumption of the emission layer. The assumption put at the process of calculation is that there are uniform emission layer with 5 km thickness. The thickness of the emission layers observed by WINDII is about 6 - 9 km thickness [Lowe et al.(1996)]. The thickness of the emission layers observed by the
Reimei satellite were about 10 km for the most of the observations.

4.7.4 Estimation of the airglow emission with models

Volume emission rate of atomic oxygen calculated with the MSISE-90 model for each season is shown in Figure 4.10. Figure 4.10 shows the volume emission rate of atomic oxygen on the vernal equinox (Day of Year: DOY 080), the summer solstice (DOY 172), the autumnal equinox (DOY 266) and the winter solstice (DOY 355). Number densities of the upper atmospheric components such as He, O, N\textsubscript{2}, O\textsubscript{2}, Ar and H are calculated with the MSISE-90 model [Hedin(1991)]. The region where volume emission rates were calculated is 30°N to 45°N in latitude and 120°E to 150°E in longitude. Universal time is set at 17:00 UT, 02:00 LT over Japan. The local time of observational area when MAC is directed into the east is about 02:00 LT though the orbit of the Reimei satellite is fixed around 00:50 LT.

It is found that the volume emission rate gets larger at lower latitudes during summer and at higher latitudes during winter. There was no clear increase nor decrease trend of volume emission rate in spring and autumn. The peak values of volume emission rate are about 150 photons/cc/s in every season.

The value of volume emission rate derived from the Reimei satellite observations are about 500 photons/cc/s in every season. These are about three times larger than that of the estimation using the MSISE-90 model. The volume emission rate derived from the Reimei observation has declining tendency in south in every season. This tendency is consistent with the model calculation in winter though it is inconsistent in the other seasons. These differences would be caused by the variation of the upper atmosphere and the atmospheric tide.
Figure 4.10: Volume emission rate of atomic oxygen calculated from the MSISE-90 model. The unit of volume emission rate is [photons/cm$^3$/sec]. Each panels show volume emission rate on vernal equinox, summer solstice, winter solstice and autumnal equinox in clockwise from the topside panel on the left.
4.7.5 Effects of atmospheric tides

The atmospheric tides affect the mesosphere where the peaks of the airglow emissions appear. This result is shown by the calculation of O and OH airglow by the TIME-GCM model [Zhang et al.(2001)].

Figure 4.11: Comparison of volume emission rate of O airglow (March). The left panel is the result without atmospheric tide and on the right panel is the result with the atmospheric tide. [Zhang et al.(2001)]

Figure 4.11 shows the zonal average of volume emission rate of O airglow in March [Zhang et al.(2001)]. The left panel shows the simulation result without the atmospheric tide and the right panel shows the result with atmospheric tide. The differences between these two panels are the position of the peak of the airglow emission and the value of the volume emission rate. The result without the atmospheric tide shows that there is a single peak around −20° in latitude. The value of the volume emission rate is more than 250 photons/cc/s. The result with the atmospheric tide shows that there are two peaks around −30° and +30° in latitude. The values of volume emission rate of these peaks
are about 150 photons/cc/s. The atmospheric tides play a role to diffuse the peak of volume emission rate in the latitudinal direction. The peaks are at 30°N and 30°S in this simulation. The value of volume emission rate around 35°N is about 100 photons/cc/s and the value increases in south.

Figure 4.12: Comparison of volume emission rate of OH airglow (March). The figure on the left is without atmospheric tide and on the right is with the atmospheric tide. [Zhang et al.(2001)]

Figure 4.12 shows the result of simulated volume emission rate of the OH airglow in March. The left panel shows the result without the tide and the right panel shows the result with the tide. The volume emission rate reaches 450 photons/cc/s in the calculation result without the atmospheric tide. The result with the atmospheric tide shows that the volume emission rate reaches 640 photons/cc/s and that the emission layer stretches to the lower altitude. It is seen that the atmospheric tides affect the vertical structure of the OH airglow and the intensity of the emission is increased.
4.8 Conclusion of analysis of the airglow latitudinal structure

Airglow emissions from atomic oxygens and OH molecules were observed by Multi-spectral Auroral Camera on the Reimei satellite from March 2008 to January 2011. Approximately 1,100 values of limb directional observation of airglow were collected by MAC in the three years. Observational regions were limited in the northern hemisphere because of the operation of the satellite. Latitudinal variations in the intensity of O airglow and OH airglow were found from the statistical analysis. The peak of the volume emission rate existed between $20^\circ$N and $30^\circ$N. Value of volume emission rate was 500 - 1,000 photons/cc/s for the O airglow observed at 557.7-nm wavelength, and was 200 - 500 photons/cc/s for the OH airglow observed at 670-nm wavelength. Latitudinal variances of emissions also differed among seasons. Volume emission rate of the O airglow was the largest in spring and that of the OH airglow was the largest in autumn. Intensity of airglow emission observed by MAC was larger from previous observations and the model simulation result. This difference was caused from the density of emission sources in the layer which was affected by atmospheric tides.
Chapter 5

Conclusions

Observations of the airglow emissions are made by ground-based imagers, rockets and satellites. Ground-based imagers have some difficulties to observe the structures in the airglow emission caused by the tropospheric disturbance because of the narrow FOVs and restrictions due to weather conditions. Observations from the space is free from these restrictions and able to have wider FOVs.

VISI was developed for the airglow observation from the International Space Station. VISI has two field-of-views, and observes airglow to the nadir direction. Calibrations of the optical system were carried out before the launch, and some modifications are added to the calibration results by using observational data which was taken after launch. Altitudes of the O airglow and the OH airglow emission layers were estimated from the observational data taken by VISI as the part of data calibration.

A concentric structure in the O$_2$ airglow emission was observed by VISI on 1 June, 2013. This was the first case that the whole structure of 1,200 km was
fully observed by single imager. This structure can interpreted to be caused by the atmospheric gravity waves (AGWs) from convective clouds after tornado. AGWs were propagated upward from the troposphere to the altitude of the airglow emission layer. AGWs were ducted in the horizontal direction around the emission layer and lasted for two to five hours until the VISI observation. The VISI observation was also able to determine the altitude of the emission layer since VISI has two field-of-views.

Latitudinal structures of airglow emission were analyzed using the Reimei (INDEX) satellite. A peak in the airglow emission intensity was found to be around 30°N by the Reimei satellite observation. This peak was produced from the variation of the density and the temperature of the emission source in the upper atmosphere. Variations in the density and temperature were thought to be caused by atmospheric tides.

Structures in the airglow emissions are affected by AGWs around the emission layers. The mesosphere and the lower thermosphere are affected by the AGWs from the lower atmosphere such as the troposphere and the stratosphere. The concentric structure in the O2 airglow emission found by VISI was the first observation in which the source of AGWs in the troposphere was identified from the space. Variances of the emission intensity were also observed from the space. The Reimei satellite observation clarified seasonal and latitudinal variations of the airglow emission which were caused by the atmospheric tides.

VISI enabled the observation of the entire structure of the airglow emission in the MLT region. It was able to take correspondence between the cause of the airglow structure and the source in the troposphere by nadir directional observation from the space. Propagation of the AGWs of 80 km wavelength
in the concentric airglow structure was observed by VISI. This propagation was estimated to be existed for 3.5 ± 1.7 hours from the distance and the velocity observed by VISI. Horizontal motions for more than 1,000 km was firstly observed and the duration time of the structure which was caused by the perturbations in the lower thermosphere was estimated from the space-borne observation. Latitudinal structure and vertical distribution of the O airglow and the OH airglow was partially clarified by the Reimei satellite observation. The spatial scale observed by this satellite was several hundred kilometers. It was found that variations with this spatial scale was affected by the atmospheric tides from the statistical study of the Reimei satellite limb direction observations.
List of papers


This thesis is based on the paper [1] and [2].
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