Energetics and structure of the lower E region associated with sporadic E layer

K.-I. Oyama¹, K. Hibino², T. Abe³, R. Pfaff⁴, T. Yokoyama⁵,* and J. Y. Liu¹

¹Institute of Space Science, National Central University, NO300, Jhongda Rd., Jhongli City, Taoyuan, Taiwan, China
²Faculty of Science, University of Tokyo, Hongo, Bunkyo-Ku, Tokyo, Japan
³Institute of Space and Astronautical Science, JAXA, 3-1-1, Sagamihara, Kanagawa, Japan
⁴NASA Goddard Space Flight Center, Greenbelt, MD, USA
⁵Solar Terrestrial Environment Laboratory, Nagoya University, Aichi, Japan
* now at: Earth and Atmospheric Sciences, Cornell University, Ithaca, NY, USA

Received: 14 January 2008 – Revised: 4 August 2008 – Accepted: 11 August 2008 – Published: 25 September 2008

Abstract. The electron temperature ($T_e$), electron density ($N_e$), and two components of the electric field were measured from the height of 90 km to 150 km by one of the sounding rockets launched during the SEEK-2 campaign. The rocket went through sporadic E layer ($E_s$) at the height of 102 km–109 km during ascent and 99 km–108 km during decent, respectively. The energy density of thermal electrons calculated from $N_e$ and $T_e$ shows the broad maximum in the height range of 100–110 km, and it decreases towards the lower and higher altitudes, which implies that a heat source exists in the height region of 100 km–110 km. A 3-D picture of $E_s$, that was drawn by using $T_e$, $N_e$, and the electric field data, corresponded to the computer simulation; the main structure of $E_s$ is projected to a higher altitude along the magnetic line of force, thus producing irregular structures of $T_e$, $N_e$ and electric field in higher altitude.

Keywords. Ionosphere (Electric fields and currents; Ionospheric irregularities; Mid-latitude ionosphere)

1 Introduction

The SEEK-2 campaign was planned in order to study the sporadic E layer, which accompanies quasi-periodic (QP) echoes with two sounding rockets launched from the Kagoshima Space Center (Geographic location; 131°05′ E, 31°15′ N). The campaign was conducted when two radars were set up at the temporary stations at the north and south of Tanegashima Island (Saito et al., 2005) to observe QP echoes. These were the Lower Thermosphere Profile Radar (130.96° E, 30.38° N); and the Frequency Agile Radar (131.03° E, 30.75° N), respectively. Details of the SEEK-2 campaign and experiment objectives are found in Yamamoto et al. (2005).

One of the rockets, S-310-31, was launched at 23:24 JST on 3 August 2002, containing a glass-sealed Langmuir probe to measure $T_e$ and $N_e$, an impedance probe to measure $N_e$, and an electric field probe.

In the past, $E_s$ was examined mainly by using the height profile of $N_e$, which were obtained by Langmuir probe (Langmuir and Motto-Smith, 1924). Valenzuela et al. (1981) conducted a balloon observation to get the 3-dimensional (3-D) structures by detecting resonance scattering from magnesium ions, which are major ion constituents of $E_s$. However, nobody was successful in drawing a 3-D structure by sounding rockets as well as from ground observations. Furthermore, a study on energetics in the height region of $E_s$ is a difficult task because of the small number of measurements of $T_e$ in $E_s$ layer have been reported in the past and accuracy is difficult. As far as we know, the paper by Schutz et al. (1976) briefly investigated the energetics of $E_s$.

In this paper, we discuss the energetics in the lower E region and attempt to draw 3-dimensional structures of $E_s$ by using $T_e$, $N_e$ and electric field data that were simultaneously obtained by the rocket.

The outline of this paper is as follows. We first describe the instrumentation of the Langmuir probe and the electric field probe. We then introduce the data in detail. We further discuss the energetics of E region associated with $E_s$ by using the data that has been analyzed. Finally, we speculate what the 3-D structure of $E_s$ is, by using the height profiles of $T_e$, $N_e$, and electric field.
the probe voltage of 0 V and 2.5 V, respectively, for the whole rocket trajectory versus time. The time and altitude of the rocket are marked, respectively, at the bottom and top of the figure from the cut on the glass tube 60 s after the rocket launch. The altitude of the rocket at 60 s after the launch is 70 km. The data is plotted every 0.25 s and 0.125 s for electrons and ion currents, respectively. As Fig. 1 shows, negative current starts appearing from approximately 73 s. At 78 s, the whole measurement system, including current and differential amplifiers, is calibrated. During the time period of 87–92.5 s, the probe current reveals large ion current, which reaches approximately −0.1 μA. Expanded v-i current characteristic curves show that the potential of the rocket, with respect to the ambient plasma, drops lower than −2.5 V. As the maximum sweep voltage of the probe is 2.5 V, \( N_e \) is not available from the electron current.

The rocket reaches the maximum height of 152 km at 193 s after the launch. During the descent, the most dense \( E_s \) layer is detected at 297 s. The \( T_e \) and \( N_e \) are obtained by semi-log-plotted electron current, which is derived when the ion current is subtracted from the v-i characteristic curve. Since the subtraction of ion current from the v-i current characteristic curve influences the evaluation of the electron temperature, we have developed the human-computer interactive program, which allows us to choose the most probable linear line to the ion current region. Each curve is examined manually and then, finally, the electron current is obtained. The electron current is plotted on a semi-logarithmic scale (logarithmic current versus probe voltage) and only one line, which fits best, is chosen. Finally, the electron temperature is calculated from the slope. This time and energy-consuming procedure is repeated for all v-i curves, both for ascent and descent of the rocket.

## 3 Results

### 3.1 Overview of height profiles of \( T_e \) and \( N_e \)

Figure 2 shows a height profile of \( N_e \), calculated from a DC Langmuir probe for ascent (left panel), and descent (right panel) of the rocket. \( N_e \) in the height range of 100–105 km is not shown here, as the detailed discussion on the \( T_e \), in the \( E_s \) layer, is treated in another paper (Oyama et al., 2008). \( N_e \) below the height of 105 km, which is used in Sect. 3.3 to discuss energetics, is obtained by normalizing the electron current that was measured by using the fixed bias spherical probe, with ionosonde. Thus, the \( N_e \) data obtained corresponds with data obtained with an impedance probe onboard the same rocket.

At the height of 127 km, \( N_e \) starts to fall at 128 km and peaks at 129 km, and then decreases at the height of 129.5 km. Similar features are also found in the electron current obtained with a fixed-bias spherical Langmuir probe (see...
Fig. 2. Height profile of electron density for ascent (left) and descent (right). Data below the height of 106 km during up leg was not available by a glass-sealed Langmuir probe.

Fig. 3, Oyama et al., 2008). The height profile during descent indicates a small $E_s$ at the height of 100–107 km.

Figure 3 shows a height profile of $T_e$ for ascent (left) and descent (right). Neutral temperature, which is calculated from a MSIS-86 model, is also included (Hedin, 1987). It is noted that $T_e$ around the heights of 100 km, is much higher than modelled neutral temperature.

Heights, which show an unusual feature, are marked as 1, 2, 3, 4, 5, and 6 in Fig. 3. First irregular feature appears at the height of 127.5 km (at the height 1) with a strong jump of $T_e$ to 2500 K. At the heights of 139 km and 149.5 km which correspond to the heights 2, and 3, respectively, small spikes of $T_e$ are recognized. At the height of 152 km marked as 4, a small and sharp increase of $T_e$ exists. In addition to these 4 height regions, $T_e$ is found to increase up to about 1400 K at the heights of 119 km–126 km.

During descent, two peaks of $T_e$ are found at the heights of 133 km and 120 km (marked as 5, and 6), respectively. In the height region below 95 km, $T_e$ scatters and is not reliable because the measurement is done in the disturbed wake and the rocket surrounding is heated by aerodynamics.

3.2 Detail structure of $N_e$, $T_e$ and electric field

Figures 4, 5, and 6 provide the fine structures of $N_e$, $T_e$, and the electric field at 6 points, which are mentioned in Sect. 3.1.

The $N_e$, $T_e$ and electric field at three points 1, 2, and 3 are shown in three panels of Fig. 4. The numbers that are attached to each panel correspond to the points shown in Fig. 3.

As the bottom panel of Fig. 4 shows, $N_e$ decreases at the height of 128 km and increases at the height of 128.8 km.

As in the case of sporadic E layer at the 100–110 km, which was discussed in another paper (Oyama et al., 2008), $T_e$ shows anti-correlation with $N_e$. At the height of 127.7 km where $N_e$ shows the minimum, $T_e$ shows the maximum, and is 1000 K higher than that of ambient plasma at 126 km. The value is nearly 2 times of that at the height of 126 km. At the height of 128.8 km where $N_e$ shows the maximum, $T_e$ reduces. Inverse relation between $N_e$ and $T_e$ implies a heat source in the ionospheric E region even at night.

The electric field changes from southwest to east at the height of 126 km as the height changes from 125 km to 128 km, and shows the peak value of 8–9 mV/m at the height of 127.3 km. Difference in height exists between the peak of $T_e$, $N_e$ minimum, and peak of the electric field.

In the middle panel of Fig. 4, $N_e$, $T_e$ and electric field at the point 2 are shown. Nearly the same features as those at point 1 can be found, although they are not clear as point 1. $N_e$ gradually reduces from 135 km, and takes the minimum at the height of 138.5 km. After $N_e$ shows a small peak at 139.5 km, it gradually reduces toward the height of 143 km. $T_e$ slightly increases from 135 km and takes a small peak at 138.5 km, then shows a lower value at 139.5 km. In the same way as at point 1, inverse relationship is again found between $T_e$ and $N_e$. The electric field rapidly changes its direction from southwest to east in the height region of 137–139 km, and above that height the direction changes slowly toward southwest. The magnitude of the electric field shows the peak of 3.5 mV/m at 139 km. The height appears to correspond to the $T_e$ maximum and $N_e$ minimum.
Fig. 3. Height profiles of electron temperature for ascent (left) and descent (right). Numbers indicated as 1–6 are the height regions which we discuss in Figs. 4, 5, and 6. Neutral temperature calculated from the MSIS-86 model is also indicated by a solid line. Scale for \( T_e \) is also applied to the neutral temperature.

The top panel of Fig. 4 shows the \( N_e, T_e \) and electric field at point 3. \( N_e \) gradually reduces from 148 km toward 149.5 km, takes the minimum at the height of 149.7 km. Between the height of 150–150.5 km, \( N_e \) appears to show a higher value that at 151 km; a small \( N_e \) peak exists at 150.5 km. \( T_e \) shows gradual increase toward 149.5 km, and the peak at 149.7 km. Peak \( T_e \) at 149.7 km is 2 times of \( T_e \) at the height of 148 km. At the height of 150.5 km, \( T_e \) appears to be the minimum. Again, as in the case of points 1, and 2, \( N_e \) and \( T_e \) show the inverse relation at point 3 as well. The electric field changes its direction from southwest to northeast in the height range of 146–148 km and from northeast to southwest at the height of 150 km. The peak intensity of the electric field, 7.5 mV/m is observed at the height of 149.6 km. This height appears to be different from the \( N_e \) minimum, and \( T_e \) maximum heights by about 0.1–0.2 km.

In Fig. 5, the same parameters are plotted for point 4. As this region is around the rocket apogee and the rocket height does not change so rapidly, the data is plotted versus time after the rocket launch at the left side of the figure and corresponding heights at the right. \( N_e \) gradually reduces from 185 s, and shows the minimum at 195 s. Between 200–205 s, \( N_e \) shows the broad peak. After the broad peak, \( N_e \) gradually reduces. \( T_e \) gradually decreases towards 193 s and shows the peak at 195 s. At 200 s and 205 s, \( T_e \) indicates small humps. The inverse correlation between \( N_e \) and \( T_e \) is seen at 195 s, and at 200–205 s. During 185–210 s, the electric field changes the direction from southwest, northeast, and then to northwest. The maximum intensity of the electric field of 4.7 mV/m appears at 201 s. However, this peak does not coincide with the \( T_e \) peak and \( N_e \) minimum at 195 s. It appears to agree with \( T_e \) peak, and \( N_e \) dip at 200 s.

Figure 6 shows the expanded height profiles of points 5 (upper panel), and 6 (lower panel). \( N_e \) shows a faint minimum at 134.5 km, and shows a peak at 135.4 km. Above 135.5 km, \( N_e \) shows a constant value of 1500 els/cm\(^3\), indicates a small peak at 137 km, and gradually increases towards 139 km. Features, which appeared at points 1, 2, 3, and 4, are not clear at point 5. That is, \( T_e \) minimum, which is supposed to appear at the \( N_e \) maximum at 135.5 km, is not clear. The direction of the electric field gradually changes from west at 133 km to northwest at 136 km. Above the 136 km, the direction suddenly recovers to a westerly direction. The peak of the electric field is not observable. The behavior of the electric field is different from the cases 1, 2, 3, and 4. At point 6, \( N_e \) gradually reduces towards 116.5 km, shows a peak at 118.2 km, and takes a minimum at 118.3 km. Above the height of 118.3 km, \( N_e \) gradually increases towards 124 km. \( T_e \) shows the broad maximum at 116 km, takes the minimum value at 118 km, and again illustrates the peak at 118.5 km. Above 118.5 km, \( T_e \) reduces toward 124 km.

The electric field shows an abrupt change in the direction from 115 km, points virtually east at 116.2 km, and stays in a southerly direction above 118 km.
3.3 Energetics in the lower E region

Figure 7 shows energy densities of thermal electrons during ascent (left panel) and descent (right panel), that are calculated as \( N_e \times kT_e \), where \( k \) is Boltzmann constant.

In the ascent, minimum of energy density appears at the height of 107 km, where \( N_e \) shows the lowest. After the peak, which appears at the height of 109 km, the energy density gradually reduces with a small minimum at the height of 117 km. Above the height of 123 km, the energy density illustrates a small negative height gradient (or constant) up to the maximum altitude.

In the descent, below the height of 100 km, the value may not be accurate, because \( T_e \) is estimated higher than the true value due to the aerodynamic heating as we mentioned in Sect. 3. The profile shows a peak at the height of 102.2 km, and the second small peak at the height of 106 km, respectively. A small minimum is shown at the height of 108 km. Towards the height of 152 km, the energy density slowly reduces.

We conclude from Fig. 7 that (1) energy density in the height range of 100–110 km is higher than in other heights, and (2) it reduces towards both higher and lower altitudes.
Table 1. Electron temperature, electron density, and electric field (peak value is referred to the value below the peak).

| Region | Deviation of three parameters (height) | Electron temperature | Electron density | Electric field |
|--------|---------------------------------------|----------------------|------------------|----------------|
| 1      | +100% (127.7 km)                      | −10% (128.0 km)      | 5–9 mV/m (127.3 km) |
| 2      | −30% (128.8 km)                       | +60% (128.8 km)      | No peak |
| 3      | +10% (138.9 km)                       | −10% (136.4 km)      | No peak |
| 4      | +10% (151.9 km)                       | −10% (136.4 km)      | 4.5 mV/m (151.6 km) |
| 5      | +10% (136.4 km)                       | −10% (136.4 km)      | No Peak |
| 6      | +50% (119.0 km)                       | −20% (118.8 km)      | No peak |

Fig. 7. Energy density of thermal electrons calculated from $N_e$ and $T_e$. Note the small negative and positive height gradients, extending from the height of about 105 km to the higher and lower heights, respectively, which suggests the existence of some heat source around 105 km.

from 100–110 km. This fact seems to suggest that heat source is confined to a height region where $E_s$ appears.

3.4 Spatial structure of $E_s$

We speculate the 3-D structure of $E_s$ by using $T_e$, $N_e$ and electric field data, which were shown in Figs. 3, 4, and 5. We try to discuss our result by referring the result of computer simulation conducted by Yokoyama et al. (2003). The assumptions for the computer simulation are 1) Rod like $E_s$ extends east-west direction at the height of 100 km, 2) Magnetic line of force has 45 degrees with respect to the ground, pointing from south to north, 3) Neutral wind blows from north to south with the maximum speed of 70 m/s around the height of 100 km, and 4) No external electric field is applied.

The 2-D structure of $N_e$ and electric field around $E_s$ resulting from the computer simulation is shown in Fig. 8, where $N_e$ and the electric field are uniform in the direction vertical to the paper. The figure shows the followings.

The polarization of the electric field is produced at the boundary of rod-like $E_s$ where strong gradient of $N_e$ exists. As a result, a region of high $N_e$ appears in the rod-like structure at the upstream of neutral wind. Inside the high-density region, plasma irregularities appear and the electric field is northward (opposite to the neutral wind direction). Low $N_e$ region is produced in the downstream of neutral wind. In the background, which is far from the rod-like structures at 100 km, the electric field prevails in a southerly direction, which is the same direction as the neutral wind. In Figs. 4, and 5, the directions of electric field inferred from the computer simulation by Yokoyama et al. (2003), which shows the
Table 2. Comparison between observed features and those of model structure proposed by Yokoyama et al. (2004).

| Parameters | Model* | Region 1 | Region 2 | Region 3 | Region 4 |
|------------|--------|----------|----------|----------|----------|
| Direction of neutral wind | SW | SSW | SSW | SSW | SSW |
| Variation of electric field | SW | SW (125 km) | SW (135 km) | SW (145 km) | SW (150 km) |
| → NE | → E (128 km) | → E (138 km) | → NE (149 km) | → NE (151 km) |
| → SW | → SE (142 km) | → S (142 km) | → SW (150 km) | → NW (151.5 km) |
| Variation pattern of $N_e$ | Dec* | −10% | −3% | −15% | −9% |
| | → Inc* | → +60% | |

* SW, SSW, and NE: Southwest, Southsouth West, and Northeast

Variation of electric field: from lower altitude to higher altitude

Dec. and Inc for $N_e$: decrease and increase.

Direction changes by 180° at the density perturbed region, are superimposed on the observed values. It is noted that the directions of the electric field measured at points 1, 2, and 3, agrees with the theoretical result.

The simulation suggests that a sheet-like structure extends along the magnetic filed line from the original rod shaped $E_s$.

We presume from the measurements of $N_e$, $T_e$ and electric field that rod-like structure extends southeast/northwest with southwest neutral wind as shown in Fig. 9. Larsen et al. (2005) measured neutral wind by using TMA ejected from the rocket S-310-32, 15 min after the launch of S-310-31. The zonal and meridional winds are 10 m/s westerly and 40 m/s southerly at the height of 100 km, and reach 50 m/s and 80 m/s at 103 km, respectively. At the height of 105 km and 108 km, meridional wind becomes zero m/s. Between these heights the wind shows 50 m/s southerly at 106.3 km. Zonal wind shows 0 m/s at the height of 106.3 km and the velocity reaches 80 m/s westerly at the height of 108 km. On an average, the direction of neutral wind is between south and southwest.

Under the influence of the neutral wind, a sheet structure extending southeast/northwest along the geomagnetic line of force, is considered to be generated. The structure originates from the rod-like structure at the height of ~105 km. $N_e$ becomes lower at the southwest side and higher at the northeast side. The electric field inside the sheet is in a northeasterly direction and in other places the electric field should be in a southwesterly direction.

These features correspond to the result of Yokoyama et al. (2003), which is rotated at 45 degrees in the horizontal plane. It is presumed that the rocket went through the field-aligned sheet structure, which we described above. Then the behavior of the electric field, and electron density with respect to the height generally agrees with the features, which are derived from the computer simulation as we summarize in Table 2. The directions of theoretical electric field were already shown in Figs. 4 and 5. The spacing of two rod-like structures at $E_s$ height is 13–14 km, which we can presume from the features observed at points 1, 2, 3, and 4.

Fig. 9. Spatial structure of $E_s$, which is speculated from the measurement of $T_e$, $N_e$, and electric field. Numbers 1, 2, 3, and 4 correspond the heights, 128 km, 139 km, 149 km and 151 km which are mentioned in Figs. 3, 4, and 5. Distance between two rods, which is presumed from the rocket measurements, is 13–14 km at the height of 105 km.

4 Conclusions

We studied energetics and spatial structure of nighttime sporadic E layer in mid latitude by using $N_e$, $T_e$ and electric
field data, which have been measured simultaneously on the same rocket. Good correlation between steep increase of $T_e$, $N_e$, and variation of electric field intensity seems to imply that there is additional heating source, which might be related to the sporadic E layer. The heat source which raises background $T_e$ higher than neutral temperature in the lower E region (100–130 km) is still not identified.

We also tried to draw a 3-D picture of $E_s$, by using $N_e$, $T_e$, and electric field data by referring the computer simulation proposed by Yokoyama et al. (2003). The behavior of $N_e$ and electric field show quantitative agreement between model and observation, although the agreement is not complete.

We showed here that a well prepared $T_e$ measurement could give useful information to understand structure and energetics of $E_s$.

Acknowledgements. The authors express their sincere thanks to the rocket launch crews of the Institute of Space and Astronautical Science for their successful operation. They also express their gratitude to all government institutions and fishery Unions for their supports.

Topical Editor M. Pinnock thanks H. S. S. Sinha and another anonymous referee for their help in evaluating this paper.

References

Hedin, A.: MSIS-86 thermospheric model, J. Geophys. Res., 92(A5), 4649–4662, 1987.

Langmuir, I. and Motto-Smith, H.: Studies of electric discharges in gases at low pressures Part I–V, General Electric Rev., 28, 449–455, 538–548, 616–623, 762–771, 810–820, 1924.

Larsen, M. F., Yamamoto, M., Fukao, S., Tsunoda, R. T., and Saito, A.: Observation of neutral winds, wind shears, and wave structure during a sporadic-E/QP event, Ann. Geophys., 23, 2369–2375, 2005, http://www.ann-geophys.net/23/2369/2005/.

Oyama, K.-I. and Hirao, K.: Application of a glass sealed Langmuir probe to ionosphere study, Rev. Sci. Instr., 47, 101–107, 1976.

Oyama, K.-I., Abe, T., Mori, H., and Liu, J. Y.: Electron temperature in nighttime sporadic E layer at mid-latitude, Ann. Geophys., 26, 533–541, 2008, http://www.ann-geophys.net/26/533/2008/.

Pfaff, R., Freudenreich, H., Yokoyama, T., Yamamoto, M., Fukao, S., Mori, H., Otsuki, S., and Iwagami, N.: Electric field measurements of DC and long wavelength structures associated with sporadic-E layers and QP radar echoes, Ann. Geophys., 23, 2319–2334, 2005, http://www.ann-geophys.net/23/2319/2005/.

Saito, S., Yamamoto, M., Fukao, S., Marumoto, M., and Tsunoda, R. T.: Radar observations of field-aligned plasma irregularities in the SEEK-2 campaign, Ann. Geophys., 23, 2307–2318, 2005, http://www.ann-geophys.net/23/2307/2005/.

Schutz, S. R. and Smith, L. G.: Electron temperature measurements in mid-latitude Sporadic E layers, J. Geophys. Res., 81, 3214–3220, 1976.

Valenzuela, A., Bauer, O., and Haerendel, G.: Balloon observation of ionospheric magnesium ions, J. Atmos. Terr. Phys., 43, 785–788, 1981.

Yamamoto, M., Fukao, S., Tsunoda, R. T., Pfaff, R., and Hayakawa, H.: SEEK-2 (Sporadic-E Experiment over Kyushu 2) – Project Outline, and Significance, Ann. Geophys., 23, 2295–2305, 2005, http://www.ann-geophys.net/23/2295/2005/.

Yokoyama, T., Yamamoto, M., and Fukao, S.: Computer simulation of polarization electric field as a source of midlatitude field-aligned irregularities, J. Geophys. Res., 108(A2), 1054(SIA2), doi:10.1029/2002JA009513, 2003.