Rocket Observation of Electron Density Irregularities in the Lower *E* Region

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Local ionospheric electron density irregularities in the scale size of 3 m to 300 m have been measured on the ascending path from 74 km to 93 km by a fix biased Langmuir probe on board the S-310-16 sounding rocket. The rocket was launched at 22:40:00 on February 1, 1986 from Kagoshima Space Center in Japan. It is found from frequency analysis of the data that the spectral index of the irregularities is 0.9 to 1.8 and the irregularity amplitude is 1 to 15%. The altitude where the amplitude reaches its maximum is 88 km.

The generation mechanism of these irregularities is explained by the neutral turbulence theory, which indicates that the spectral index is $5/3$ and has been confirmed by a chemical release experiment using rockets over India to be valid up to about 110 km.

From frequency analysis of the data observed during the descent in the lower *E* region, we have found that the rocket-wake effect becomes larger when the probe is situated near the edge of the rocket-wake, and that this is also the case even when the rocket-wake effect does not clearly appear in the DC current signal which approximately changes in proportion to the electron density, where the probe is completely situated inside the rocket-wake region.

1. Introduction

Observations of ionospheric electron density irregularities have been carried out by sounding rockets both in the equatorial *E*-region and the middle latitude ionosphere. The observed results by the K-9M-44 rocket have made it clear that the spectral index of the density irregularities at the height from 91 km to 113 km is 2.2 to 4.1, the irregularity amplitude is 1 to 5%, the altitude where the amplitude reaches its maximum is 92 km to 95 km and the vertical gradient in the electron density profile is positive. The generation mechanism of the electron density irregularities in the ionospheric *E-F* region is explained by the theories of the cross field instability or the neutral turbulence. The spectral index theoretically deduced from the cross field instability is 3. The rocket observations over India have shown that the spectral index of the density irregularities is 2 to 4 and the irregularity amplitude is 1 to 20%. The density irregularities have been observed only when the density profile is positive height gradient. The generation mechanism of the electron density irregularities observed by the K-9M-44 sounding rocket is explained by the cross field

instability theory.

Our experiment was planned to examine the possibility of the irregularities being generated by neutral turbulence in the ionosphere. The ionospheric electron density irregularities in the scale size of 3 m to 300 m and the electron density height profile have been measured by a constant biased Langmuir probe on board the S-310-16 rocket launched from Kagoshima Space Center.

2. Outline of the Observation

The S-310-16 rocket was launched at 22:40:00 (JST) on February 1, 1986 from the Kagoshima Space Center (31.2°N, 131.1°E) and after 445 seconds landed on the sea at a distance of 239.8 km with 29.4°N, 132.3°E. The altitude, distance, latitude and longitude at the apogee of this rocket at 223.1 sec are 200.6 km, 105.8 km, 30.3°N and 131.4°E, respectively.

A fix biased Langmuir probe was installed to observe the electron density profile and irregularity by measuring the probe current from the space plasma. The BeCu cylindrical probe with a diameter of about 10 mm and a length of about 1 m stuck out as a sensor from the rocket surface to the plasma. The electron density and irregularity were deduced from the DC saturation current and its AC component, respectively. The probe was biased at 5 volts with respect to the rocket (WATANABE and OBAYASHI, 1984). Figure 1 shows the block diagram of the electron density and irregularity detector. The irregularity signal was transmitted to the ground receiver through the IRIG telemetry channel No. 15. The observation was carried out from 60 to 385 sec after the probe extension at 47 sec. The telemetry channel was switched to the physical instrument side at 46 sec after launch.

We observed the ionospheric *E* layer from 100.3 km (75 sec) to 119.7 km (90 sec) during the ascent and from 114.7 km (360 sec) to 101.6 km (370 sec) during the descent. The *E* layer has a peak density of $2\sim3\times10^4\text{ cm}^{-3}$ and shows a complex multi-layer structure (WATANABE *et al.*, 1986). The *E-F* valley was also observed in

Fig. 1. Block diagram of a constant biased Langmuir probe circuit for measuring the ionospheric electron density and electron density irregularity. A cylindrical BeCu probe with a diameter of 10 mm and a length of 1000 mm is installed. The condenser is $1\text{ }\mu\text{F}$ and the input resistance of the AC amplifier is $390\text{ k}\Omega$.

the height region from 125 km to 170 km; the minimum electron density of the valley was 600 cm^{-3} during ascent and 3000 cm^{-3} during descent. The rocket wake-effect appeared during descent and the data were affected by the spin modulation effect. The spin rate of this rocket was 0.86 sec. The DC current signal during descent was slightly smaller than that of ascent because of the rocket-wake effect.

3. Observation of the Irregularity

The raw data observed during the ascent are shown in Fig. 2. The DC high gain signal, DC low gain signal and AC irregularity signal are shown in the upper, middle and lower columns, respectively. The electron density irregularity appears from about 58 sec after the probe extension at 47 sec. The DC high gain signal in the upper column begins to saturate at about 90 km. At that moment, the DC low gain signal in the middle column begins to exhibit the E region multi-layer, the E-F valley and the maximum height region. Figure 3 is the AC irregularity signal from 47 to 48 sec, when the probe extends. The abscissa is flight time from 47 to 48 sec and the ordinate is probe current from $0.2 \mu\text{A}$ to $-0.2 \mu\text{A}$. The upper pictures presented in Figs. 4 to 7 have the same ordinate as Fig. 3. The extension of the probe has started at exactly 47.26 sec and after that the cyclic noise due to the probe vibration appears, as denoted by arrows. The irregularity signal before the probe extension and after the vibration exhibits a normal character without any instrumental noise. The irregularity signals from 47 sec to 71 sec, 340 sec to 360 sec and from 370 sec to

Fig. 2. Raw data observed during the ascent. The DC high gain signal, DC low gain signal and AC irregularity signal are shown in the upper, middle and lower columns, respectively. The density irregularity appears from about 58 sec after the probe extension at 47 sec.

Fig. 3. AC irregularity signal from 47 to 48 sec when the probe extends. The abscissa is flight time from 47 to 48 sec and the ordinate is irregularity strength. The upper pictures presented in Figs. 4 to 7 have the same ordinate as Fig. 3. The probe extension starts exactly at 47.26 sec and after that the cyclic noise due to the probe vibration appears, as denoted by arrows. The irregularity signal before the probe extension and after this vibration exhibits a normal character without any instrumental noise.

385 sec have been frequency-analyzed. The abscissa in the spectrum, shown later in Figs. 4 to 7, corresponds to the wavelength of the irregularity by using the rocket velocity on the assumption that the propagation velocity of the density irregularities is much slower than the rocket speed (ITO *et al.*, 1975). Consequently, the wave number of the density irregularity (k) is proportional to the frequency of the irregularity signal. The frequency 5 to 500 Hz corresponds to the wavelength 300 m to 3 m by considering the rocket speed of 1.5 km/sec. The spectral index of the irregularities is used to examine characteristics of the electron density irregularities. The spectral index of the irregularities (z) is defined as follows. It is determined from the gradient of $N(k)$ plotted logarithmically.

$$[n_1^2] = \int N(k) dk \quad (1)$$

$$N(k) \propto k^{-z} \quad (2)$$

where n_1 is local electron number density and $N(k)$ is the irregularity component with k , respectively.

4. Analysis of the Irregularity

4.1 Result-1

4.1.1. At 68 sec during the ascent

The raw data of the electron density irregularities (upper column) and the frequency-analyzed data (lower) at 68 sec, at the height of 90.5 km are shown in Fig. 4. Obviously, the electron density irregularities have been observed in the FM telemetry signal at the IRIG channel No. 15 in the upper figure. The ratio of the electron density irregularities to the background electron density ($\Delta N_e/N_e$) is 5.4 to 7.7%. The irregularity amplitude during the ascent is 1 to 15%. The spectral index of the density irregularities (z) determined from the gradient of frequency spectrum in

Fig. 4. The density irregularities and the frequency-analyzed data from 68 sec to 69 sec. The irregularities are observed in the upper FM telemetry signal of the IRIG channel No. 15. The abscissa is flight time from 68 to 69 sec and the ordinate is irregularity strength. The spectral index of the density irregularities (z) is determined from the gradient of the frequency spectrum with the ordinate of $\log(\Delta i/i)$ and the frequency abscissa. The frequency 5 to 500 Hz corresponds to wavelength 300 m to 3 m considering the rocket speed of about 1.5 km/sec. Lower pictures presented in Figs. 5 to 7 have the same abscissa and ordinate as Fig. 4. The height is 90.5 km, N_e is 2300 cm^{-3} , the irregularity amplitude is 5.4 to 7.7% and the spectral index is 1.0 to 1.4.

the lower graph is 1.0 to 1.4. Though the contamination effect of the probe surface should be taken into account when the DC probe method is used, it is usually difficult to estimate this quantitatively. So, we only examine it qualitatively. Since the noise component in the higher frequency region of the spectrum becomes slightly larger because of the surface contamination of the probe, the true gradient should be adjusted to be steeper, and accordingly the spectral index tends to be larger.

4.1.2. At 70 sec during the ascent

The raw data of the electron density irregularities (upper column) and the frequency-analyzed data (lower) at 70 sec, where the background electron density is $3 \times 10^3 \text{ cm}^{-3}$ and the height is 93.4 km, are shown in Fig. 5. It is obvious from the upper graph that large irregularities have been observed when the probe is situated near the rocket-wake region, which appears as the electron-density depression. The spin of the rocket is 1.16 Hz. The electron-density depression due to the rocket-wake usually appears once in one spin time. The minimum region at about 70.49 sec in the upper graph may correspond to the central region of the rocket-wake. The

Fig. 5. The irregularities and frequency spectrum from 70 to 71 sec. The large irregularities are observed when the probe is located near a rocket-wake region. In this case, a clear peak appears at about 200 Hz in the frequency spectrum and a second harmonic is also observed. The height is 93.4 km, N_e is $3 \times 10^3 \text{ cm}^{-3}$, the irregularity amplitude is $\sim 13.5\%$ and the spectral index is 1.2 to 1.8.

irregularity amplitude reaches 13.5%. The DC high gain signal approaches the saturation level between 70 sec and 70.38 sec and saturates between 70.8 sec and 71 sec. The electron density irregularities as observed from 70.38 sec to 70.8 sec might have been observed at both these periods if the DC amplifier had been perfectly designed. Frequency-analysis is carried out by using the data from 70 to 71 sec, because it is confirmed that the same value of the spectral index is obtained both when the data from 70.38 sec to 70.8 sec are used and when the data from 70 sec to 71 sec are analyzed; in this case, the frequency-analyzed signal level at the low frequency region slightly increases for its saturated signal. When the rocket-wake effect appears, a peak appears at about 200 Hz in the frequency spectrum. The second harmonic has also been observed. The spectral index in the wavelength region from 15 m to 400 m is 1.2 to 1.8.

4.1.3. At 346 sec during the descent

The electron density irregularities (upper) and the frequency-analyzed spectrum (lower) at 346 sec are shown in Fig. 6. It is found from the upper graph that the raw

Fig. 6. The irregularities and the frequency spectrum from 346 to 347 sec. The data is clearly affected by two serial rocket wakes. A large noise enhancement is observed in the frequency range over 200 Hz of the frequency spectrum. N_e is $3 \times 10^3 \text{ cm}^{-3}$, the height is 131.4 km, the irregularity amplitude is $\sim 11.6\%$ and the spectral index is not deduced because of the rocket-wake effect.

data has been clearly affected by two serial rocket wakes, shown as two minus ravines. In these cases, large noise enhancement appears in the frequency range over 200 Hz in the frequency spectrum. This noise due to the rocket wake has been continually observed on the whole descending path. At 346 sec when the height is 131.4 km, the electron density is $3 \times 10^3 \text{ cm}^{-3}$ and the irregularity amplitude is $\sim 11.6\%$. This altitude region is the bottom of the so-called *E-F* valley. The spectral index is not deduced because the rocket-wake effect is so large. It may be nearly the same value as that during the ascent.

4.1.4. At 382 sec during the descent

The electron density irregularities (upper) and the frequency-analyzed spectrum (lower) at 382 sec are shown in Fig. 7. It is found from the upper graph that the raw data seem to be scarcely affected by the wake effect, but that a large noise increment due to the rocket-wake appears over 200 Hz in the frequency spectrum. As the probe is entirely situated inside the rocket-wake, the electron-density depression does not

Fig. 7. The irregularities and the frequency spectrum from 382 to 383 sec. The upper data is almost unaffected by the wake effect, but a large noise increment appearing at 200 Hz in the frequency spectrum may be due to the rocket-wake. The height is 84.7 km, N_e is about 110 cm^{-3} , the irregularity amplitude is $\sim 15\%$ and the spectral index can not be deduced because of the rocket-wake effect.

appear during one rocket-spin time. Nevertheless, the frequency spectrum has a large noise increment due to the rocket-wake over 200 Hz. When we determine the ionospheric electron density, we should consider the effect of the rocket-wake during the descent and the probe contamination, which will have a large influence on the observed data. At 382 sec when the height is 84.7 km, the electron density is about 110 cm^{-3} and the irregularity amplitude is $\sim 15\%$.

4.2 Result-2

4.2.1. Dynamic spectrum during the ascent

The dynamic spectrum of the electron density irregularities on the ascending path is shown in Fig. 8. The signal intensity at 47 sec when the probe extends is very high. The density irregularities appears from about 58 sec. A small peak due to the rocket wake is observed at about 200 Hz. This peak appears just after the probe extension at the place where the background electron density is still low, even though the peak level is small. The irregularity amplitude reaches its maximum at 66 sec after launch when the altitude is 88 km.

4.2.2. Dynamic spectrum during the descent

The dynamic spectrum of the electron density irregularities on the descending path is shown in Fig. 9. The signal intensity is higher than that of the ascending path but the signal intensity decreases with the time lapse. The noise signal at about 200 Hz gradually becomes a wide band signal.

Fig. 8. The dynamic spectrum during the ascent. The abscissa is flight time and the ordinate is frequency. The signal intensity at 47 sec when the probe extends is strong. The density irregularities appear from about 58 sec. The slight peak due to the rocket-wake is observed at about 200 Hz. This peak appears just after the probe extension at the place where the background electron density is low, though the peak level is low. The irregularity amplitude reaches its maximum at 66 sec after launch when the altitude is 88 km.

Fig. 9. The dynamic spectrum during the descent. The abscissa is flight time and the ordinate is frequency. The signal intensity is higher than that of ascending path. The signal intensity decreases with the time lapse. The noise signal at about 200 Hz gradually becomes a wide-band signal.

5. Analysis of the Wake Disturbance

Frequency-analyzed spectra of the density irregularities from 47 sec to 71 sec during the ascending path are shown in Fig. 10. The abscissa is 1 to 500 Hz, the same scale of Figs. 4 to 7. It is found that the frequency at the noise peak around 200 Hz, which appears when the probe is located near the edge of the rocket-wake, changes periodically. The peak appears with a periodic time of about 3 sec. Even though the peak level is low, this small peak is due to the rocket-wake and appears just after the probe extension at the place where the background electron density is low. A second peak is sometimes observed at the second harmonic frequency. The small enhancement at about 200 Hz in the frequency spectrum is explained by a kind of electron density turbulence due to the density disturbance at the edge of the rocket-wake. Noisy wide-band peaks appear in the high-frequency region of the frequency spectrum during the descent. It is hard to avoid the rocket-wake effect in the probe method. These wake disturbances have the following characteristics.

- 1) When the probe approaches the edge of the rocket wake, electron density irregularities are observed and a large noise peak appears around 200 Hz in the frequency spectrum.
- 2) This peak around 200 Hz changes periodically.
- 3) The peak appears with a period of about 3 seconds.
- 4) The peak appears even when the background electron density is low just after the probe extension, although the peak level is low.

Fig. 10. The frequency spectrum of the electron density irregularities. The frequency at the noise peak around 200 Hz in the high frequency region of the spectrum changes periodically. The peak appears with a periodic time of about 3 sec. The peak appears even when the background electron density is low after probe extension, though the peak level is low. A second peak is sometimes observed at the second harmonic frequency.

- 5) A second peak is sometimes observed at the second harmonic frequency.
- 6) Wide-band noisy peaks are occasionally observed in the high frequency region of the frequency spectrum during the descent.
- 7) The large noise peaks are observed over about 200 Hz in the frequency spectrum even though the electron irregularity signal is hardly affected by the wake effect at the low altitude during the descent, because the probe is wholly situated inside the rocket-wake region.

8) The relations between the time and frequency variations of the peak at 200 Hz and the velocity and attitude of the rocket, the probe situation, the intensity and angle of the geomagnetic field line and so on are important subjects to be studied separately.

6. Characteristics at the Probe Extension

The top spectrum in the Fig. 10 is obtained by analyzing the data at 47 sec in Fig. 3 when the probe extends. A large peak appearing at about 13 Hz in the frequency spectrum is generated by cyclic noise due to probe vibration after probe extension at 47.26 sec. The electron density irregularity is very small where the background electron density is low just after the probe extension. Therefore, the analyzed signal level in the frequency spectrum is also low. Because the level during probe vibration is higher than that just after probe extension, the signal intensity during probe vibration is correspondingly darker than that just after probe extension in the dynamic spectrum, as shown in Fig. 8. In order to observe the ionospheric electron density, the impedance probe measures the frequency spectrum of an equivalent capacitance of the BeCu probe by detecting an unbalanced component at the capacitance bridge. The electron density is deduced from various resonance frequencies: the upper-hybrid resonance frequency, plasma resonance frequency, sheath resonance frequency and modified plasma resonance frequency, and the ion sheath capacitance around the probe surface. It is difficult to discover the vibration characteristics during the probe vibration by analyzing the time variation of the frequency spectrum of the equivalent probe capacitance. This is the first time that characteristics during probe vibration after extension has been clarified by analyzing the time variation of the probe current from the plasma.

7. Characteristics of the Spectral Index

The height profile of the spectral index of the density irregularity is shown in Fig. 11. The spectral index is 0.9 to 1.9 in the height region from 74 km to 93 km. The spectral index observed by the K-9M-44 sounding rocket is 2.2 to 4.1 at the height from 91 km to 113 km and is 1.0 to 1.4 above the height of 183 km (ITO *et al.*, 1975). The generation mechanism of the electron density irregularities in the ionospheric *E* region is explained by the theories of cross-field instability or neutral turbulence. The theoretical spectral index of the neutral turbulence in the lower *E* region is $5/3$. This value has been confirmed by a chemical release experiment using rockets over India by Zimmerman. The neutral turbulence theory is valid up to about 110 km. It is applicable to both cases at the positive and negative height gradients of the electron density profile (ZIMMERMAN and TROWBRIDGE, 1973; ZIMMERMAN, 1976). The theoretical spectral index deduced from the cross-field instability is 3 and the theoretical irregularity amplitude is 30 to 50% (SATO and TSUDA, 1967; TSUDA *et al.*, 1969). The rocket observations in the equatorial *E* region over India by Prakash have discovered that the spectral index of the density irregularities is 2 to 4 and the irregularity amplitude is 1 to 20%; but the density irregularities are only observed when the density profile has a positive height gradient (PRAKASH *et al.*, 1970, 1971a, 1971b). It has been confirmed by the K-9M-

Fig. 11. The height profile of the spectral index. The spectral index is 0.9 to 1.9 in the height region from 74 km to 93 km as shown by bars. The spectral index observed by the K-9M-44 sounding rocket is 2.2 to 4.1 at the height from 91 km to 113 km and is 1.0 to 1.4 over the height of 183 km, as shown by rectangular boxes with half shadows.

44 experiment in the middle latitude E region over Japan that the spectral index of the density irregularities at the height from 91 km to 113 km is 2.2 to 4.1, the irregularity amplitude is 1 to 5% and the height where the amplitude reaches its maximum is from 92 km to 95 km (ITO *et al.*, 1975). From the present S-310-16 rocket experiment, intended to measure the electron density irregularity in the scale size of 3 m to 300 m by a fix biased Langmuir probe at middle latitude, the spectral index of the irregularities is 0.9 to 1.8, irregularity amplitude is 1 to 15% during the ascent from 74 km to 93 km and the height where the amplitude reaches its maximum is 88 km.

8. Conclusions

1) The spectral index of 0.9 to 1.8 is lower than the theoretical index of 3 in the case of the cross field instability and the measured index of 2 to 4 by previous rocket experiments over India and Japan.

2) The spectral index of 0.9 to 1.8 is close to the theoretical index of $5/3$, which is deduced from the neutral turbulence theory. The value more closely

approaches $5/3$ when the contamination effect of the probe surface is taken into account.

3) The irregularity amplitude of 1 to 15% is not so different from the theoretical amplitude of 30 to 50% deduced from the cross field instability and the previous measured values of 1 to 20% in the equatorial *E* region and 1 to 5% in the middle latitude *E* region.

4) The irregularity observed from 74 km to 93 km does not contradict the neutral turbulence theory, because the neutral turbulence theory is valid up to 110 km. The spectral index of the density irregularity supports the neutral turbulence theory.

5) The density irregularity observed at the positive height gradient of the electron density profile in the lower *E* region may be explained by the cross field instability and/or the neutral turbulence theory. However, the measured spectral index of the irregularity favors the neutral turbulence theory.

6) The height of 88 km where the irregularity amplitude reaches its maximum compares well with that of the foregoing observations.

7) The density irregularity observed in the lower *E* region from 74 km to 93 km is explained by the neutral turbulence theory.

8) A complicated multi-layer structure have been observed from 100.3 to 119.7 km during the ascent. However, the electron density irregularity has not been observed in these height regions because of the saturated DC high gain signal. If the height distribution of the electron density from 74 km to 119.7 km is interpreted to be the sporadic *E* layer, it may be possible that the irregularity is excited by the plasma disturbance which can be generated in the *Es* layer (ECKLUND *et al.*, 1981). Besides the neutral turbulence, some kinds of plasma turbulence may be superposed, since the high frequency spectral component above 100 Hz exceeds the $f^{-5/3}$ power spectrum.

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