A Comparative Study of the Electron Density Estimated with MF Radar DAE Method and Cosmic Noise Absorption at Poker Flat, Alaska

KAWAMURA Seiji, MORI Hirotaka, and MURAYAMA Yasuhiro

The method to estimate electron density from partial reflection of medium or high frequency radio waves from the ionospheric D-region was proposed in 1950s and established in 1970s. This method, which is applied for MF radar observations, is called Differential Absorption Experiment (DAE), and is now used without significant improvements though many years have passed. In this paper, we compare the electron density from MF radar and Cosmic Noise Absorption (CNA) from imaging riometer, both instruments are installed at Poker Frat, Alaska. The accuracy and validity of electron density estimated with the MF radar are discussed.

Keywords
MF radar, Electron density, Differential absorption experiment, Cosmic noise absorption, Ionospheric D region

1 Introduction

The ionospheric D region (altitudes of 60–90 km) is the lowest layer of the ionosphere, where atoms or molecules are partially ionized. This region is also referred to as the “mesosphere and lower thermosphere” (MLT) because the region includes the boundary between the mesosphere and thermosphere, which are defined by temperature gradient. In recent years, studies on the ionospheric D region have increased, reflecting the many questions that remain to be resolved in terms of wind velocity variations and the chemical reactions of ionization within this region.

Observation rockets have been used since the early days of measurements of the ionospheric D region. However, while rockets offer the advantage of direct observation, they are costly to launch, preventing frequent observation and rendering continuous observation nearly impossible. The MF (medium frequency) radar is now widely adopted as a relatively cost-efficient and effective method for conducting continuous observation of winds in the ionospheric D region[1].

In addition to wind measurements, the MF radar is also capable of estimating the electron density of the ionospheric D region. This method of electron density estimation using medium- to high-frequency radio waves is known as the “differential absorption experiment” (DAE), and was first proposed in the 1950s[2]. Although numerous studies were carried out and some progress was made on this method through 1970s, limitations in hardware technologies and scientific knowledge of the time brought an end to development, and interest in the method subsided. Validation studies on the method have yet to be carried out to this day.

The electron density of the ionospheric D region is among the significant parameters closely associated with the chemical processes involving ions in this region. In the present study, electron density measured by the MF radar installed at Poker Flat Research Range in Alaska is compared to the cosmic noise absorption (CNA) data collected by an imaging riometer (also installed at the same facility), with a view to the establishment of a reliable method of electron density estimation using the MF radar. The CNA data measured by the imaging riometer represent the degree of absorption of cosmic noise by electrons as it passes through the ionospheric D region, and so the CNA value can be considered an indicator of electron density in the D region[3]. Thus it becomes possible to discuss the validity of electron density estimation made using the MF radar DAE method by comparing the results of MF radar observations with the CNA value.

2 Electron density estimation method using MF radar

This section will introduce the procedures of the differential absorption experiment (DAE) for electron density estimation. The radio waves in the plasma propagate in two modes: O (ordinary radio wave) mode and X (extraordinary radio wave) mode, classified based on the direction of polarization. The DAE makes use of the difference between the two modes in the degree of reduction in the amplitude of radio waves propagating through the ionosphere.

Let us assume a case in which radio waves are emitted in the zenith direction, and those reflected at altitude h are received back on the ground. When the amplitude of the electric field is A and the coefficients of reflection and absorption at a certain altitude are R and k, respectively, the amplitude ratio of the radio waves in the two modes may be expressed as follows, using subscripts O and X for the 2 modes.

$$\frac{A_x}{A_o} = \frac{R_x}{R_o}\exp\left(-2\int_0^h (k_x - k_o)\,dh\right) \qquad (1)$$

Note that the coefficient of absorption $k = \omega\beta/c$ when the refractive index $n = \alpha - i\beta$ (where ω is the angular frequency of the radio wave and c is the speed of light). By taking the logarithm for both sides of Eq. (1) and differentiating them in the altitudinal direction, the equation for electron density $N(h)$ at altitude h can be obtained.

$$N(h) = \frac{\dfrac{d}{dh}\left(\ln\dfrac{R_x}{R_o}\right) - \dfrac{d}{dh}\left(\ln\dfrac{A_x}{A_o}\right)}{\dfrac{2(k_x - k_o)}{N}} \qquad (2)$$

The value that can be obtained by observation is A_x/A_o, in the second term in the numerator on the right-hand side of Eq. (2), and the values of R_x/R_o as well as those in the denominator may be obtained from theoretical calculations of the refractive index[4]. The calculation assumes that electron-neutral collision frequency is proportional to atmospheric pressure; here the CIRA−86 model[5] is adopted with respect to pressure. The IGRF model[6] is used for the geomagnetic field. The denominator in Eq. (2) contains the parameter N, which represents electron density, but since it is known that the value of the denominator in the altitude range targeted by this method is nearly constant[2], N is considered to take a constant value.

3 Observation and data

The measuring instruments used in the present study are the MF radar[7] and the imaging riometer[3] installed at Poker Flat Research Range (N 65.1°, W 147.5°) and operated jointly by NICT and the University of Alaska, Fairbanks.

The specifications of the Poker Flat MF radar are presented in Table 1. The center frequency of this radar is 2.43 MHz. Since it uses a 27-μm pulse, its altitudinal resolution is approximately 4 km. (Data is acquired at 2-km intervals for oversampling.) As observation is

Table 1 Main specifications of the Poker Flat MF radar

Site (Lat., Long.)	Poker Flat, Alaska (65.1 N, 147.5 W)
Frequency	2.43 MHz
Bandwidth	60 kHz
Peak Power	50 kW
Pulse duration	27 μs
Time resolution	3 min. (5 min. since Aug. ’04)
Range resolution	4 km
Sampling interval	2 km
Antenna	4 cross-dipoles (for Tx and Rx)

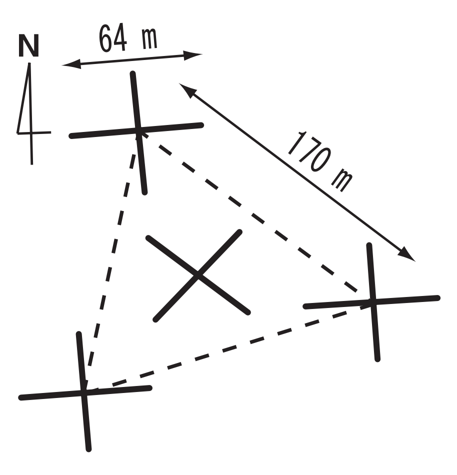

Fig. 1 Antenna arrangement of the Poker Flat MF radar

alternated between 2-minute Full Correlation Analysis (FCA) wind observation and 1-minute DAE electron density observation, the obtained data has a time resolution of 3 minutes. (Since a 2-minute meteor observation was added in August 2004, the time resolution since then has been 5 minutes.) It may be seen from Fig. 1 that the four cross dipoles have been set at the apexes and the center of an equilateral triangle with sides measuring 170 m. For FCA wind observation, the correlations between each receiving channel are calculated to estimate wind velocity. For electron density observation, the O- and X-mode radio waves are transmitted alternately by switching the direction of the circular polarization wave using the cross dipoles to determine the amplitude ratio; the received signals for each channel are combined for this calculation.

Figure 2 presents the data for Nov. 6, 1998 as an example of MF radar observation. From top to bottom, the panels show the diurnal variations in the received signal powers for the O mode, that for the X mode, and estimated electron density, respectively. The horizontal axis represents time in Universal Time (UT); local Alaska time (AKST) may be obtained by subtracting 9 hours from UT. It can be seen from the figure that the X mode is more strongly affected by absorption by electrons compared to the O mode and therefore displays lower signal power. In the example given in Fig. 2, the electron density is estimated to take a maximum value of several hundred electrons/cm^3. It is known that in the ionospheric D region, the chemical process of ionization differs from day to night. This is why a difference is observed in the altitudinal power distribution at night (in this example, around 2－17 UT) and daytime observation data. During the nighttime, electron density at low altitudes is barely observable. In contrast, electron density is notable at altitudes as high as 60 km in the daytime. Figure 3 presents, as an example, the vertical profile (1-hour averaged value) of the data shown in Fig. 2 at 14 UT. From right to left, the panels represent X-mode power, O-mode power, amplitude ratio for the two modes, and the estimated electron density, respectively.

The imaging riometer is a passive device for receiving cosmic noise at a frequency of 38.2 MHz using 256 phased-array cross-dipole antennas. When precipitation of high-energy particles into the earth’s atmosphere is induced by magnetospheric substorms with geomagnetic disturbances, the collision between the particles and the atmosphere increases the electron density near the ionospheric D region. Particles with higher energies can penetrate deeper into the atmosphere, so the altitude at which electron density increases depends on the energy of the particle. Since cosmic noise is absorbed by the electrons in this region, cosmic noise absorption (CNA) will be observed as a relative reduction in the cosmic noise level during such phenomena.

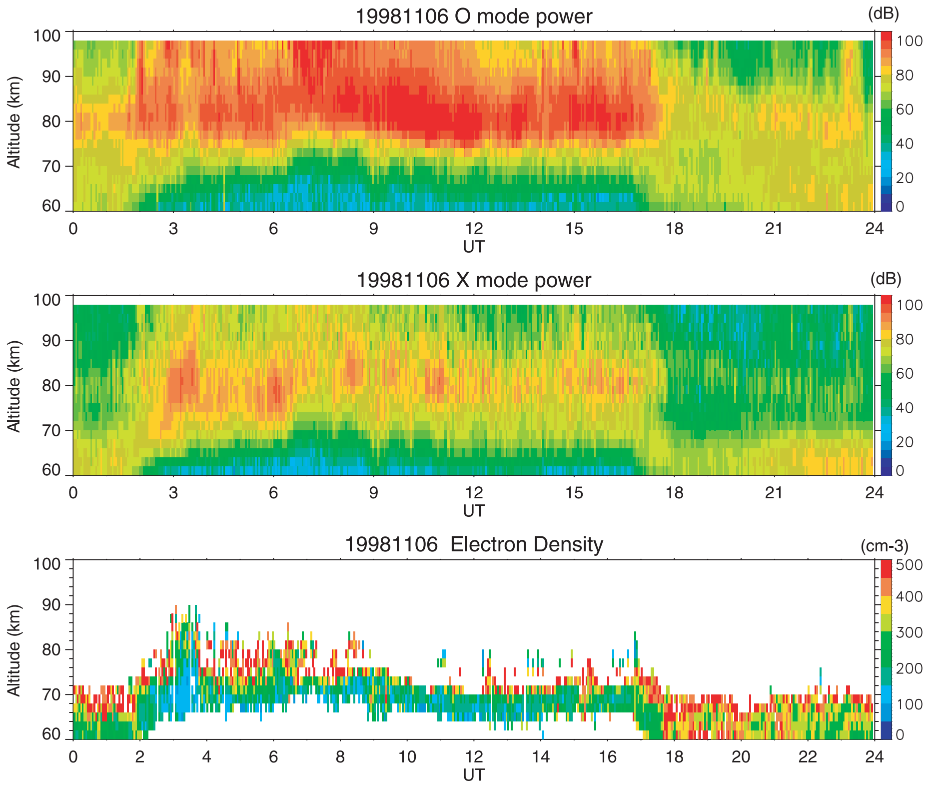

Fig.2 *Example of electron density observation by MF radar (Nov. 6, 1998)*

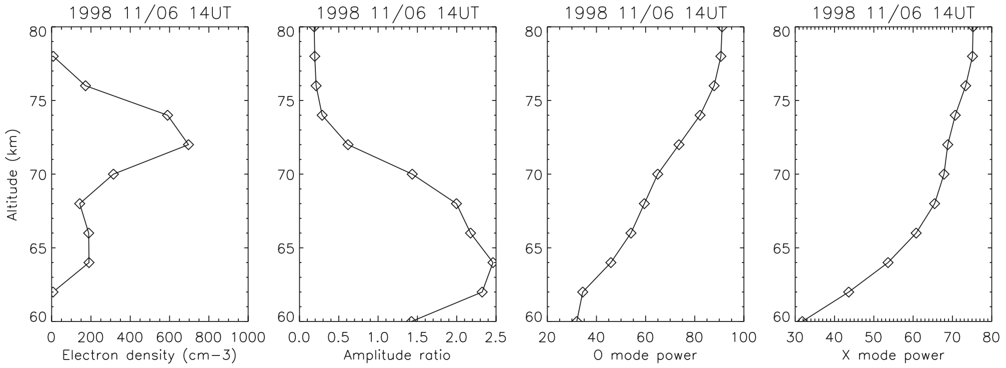

Fig.3 *Example of observation at 14 UT Nov. 6, 1998 (1-hour averaged value)*

Thus, CNA may be regarded as an indicator of electron density in the ionospheric D region. In the present study, the 1-minute averaged value obtained by averaging only the beam near the zenith is used as data for the imaging riometer, in order to enable comparison with the MF radar data, in which only the zenith direction is observed.

Routine observations alternating between FCA and DAE have been carried out by the Poker Flat MF radar since Oct. 1998. The imaging riometer started its observations in Oct. 1995, and stopped for the period from Aug. 1999 to Oct. 2002. In the present study we will employ the data acquired for the 286-day period between Oct. 19, 1998 and Jul. 31, 1999, as both data were available during this period.

4 Results

Figure 4 shows seasonal variations in 24-

hour-averaged electron density for an altitude range of 60–80 km and 24-hour-averaged CNA. The top and middle panels show electron density measured by the MF radar and CNA measured by the imaging riometer, respectively, and error bars represent the standard deviations in the averages. In the bottom panel, these results are superimposed, along with the addition of the Ap index, which is an index for geomagnetic disturbance activity (green line). In order to make the variations in the data more comprehensible, five-day running averages are performed for each data. Since the three values are represented in different units, only the patterns of variations are considered in the lower panel. There is clearly a strong positive correlation between CNA (blue line) and the Ap index (green line). The CNA occurred due to the increase in electron density caused by the collision between neutrals and high-energy particle precipitation associated with a geomagnetic disturbance. The strong positive correlation between CNA and the Ap index indicates that the above cause-and-effect relationship is firmly established and thus that CNA may be regarded as a parameter representing electron density in this altitude region. However, it should be noted that CNA is an indicator of absorption integrated in the altitudinal direction, and gives us no information on the height distribution of absorption. A comparison between variations in CNA (blue line) and electron density (red line) also shows that the two are

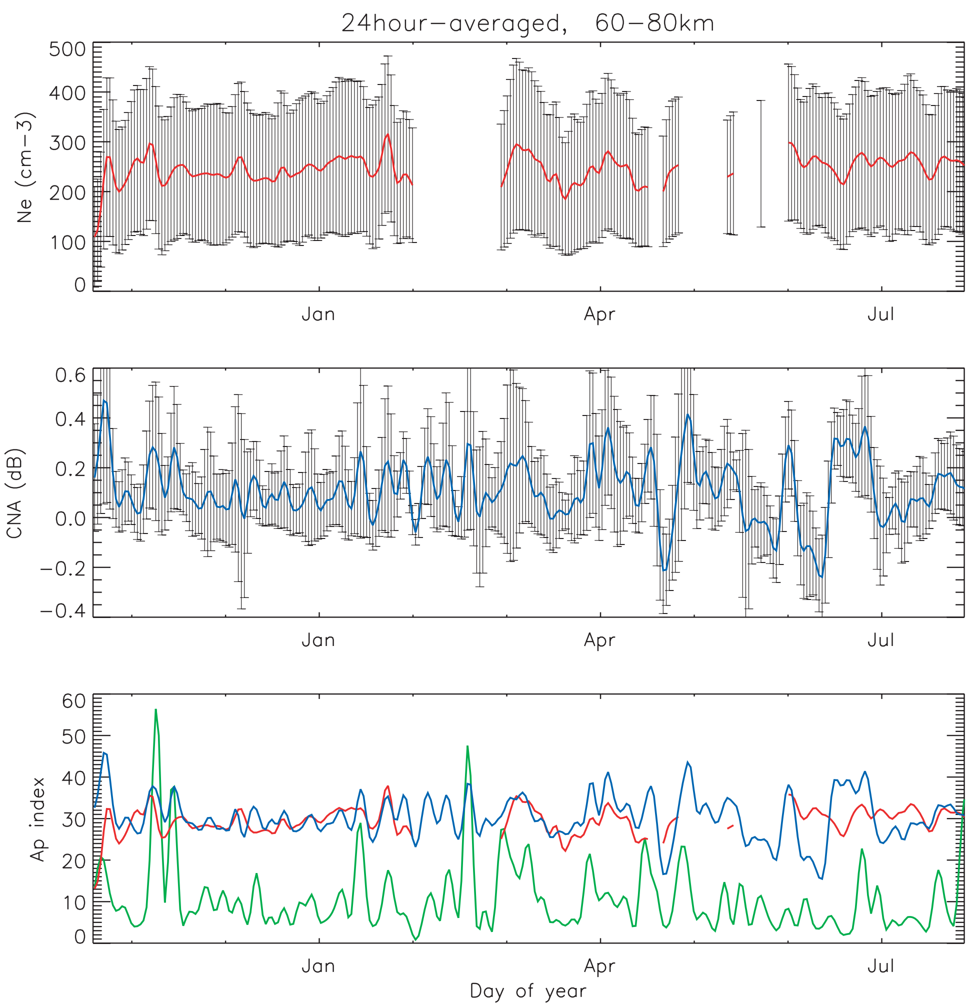

Fig.4 Comparison of long-term variations in electron density (red line), CNA (blue line), and Ap index (green line) (averaged over 24 hours and 60–80 km altitude)

fairly consistent with each other. Therefore, it may be said that the time variation of the height integrated electron density estimated by MF radar reflects actual electron density variations, at least for long-term variations.

Even if we change the time or altitude range over which the values are averaged, the electron density and CNA generally display a relatively strong positive correlation. Figures 5 and 6 show two examples in which the range for averaging was narrowed down for the same data as in Fig. 4. In both, the time-wise average is limited to the daytime (9-15 LT). In Fig. 5, the electron density is averaged over relatively low altitudes in the range of 60-64 km, while in Fig. 6, it is averaged over relatively higher altitudes of 76-80 km. In both figures, the standard deviations (error bar in top and middle panels) have become smaller by narrowing the range compared to Fig. 4. Based on a comparison of electron density averaged for the low-altitude range, CNA, and the Ap index in the bottom of Fig. 5, we see that the CNA and Ap index still display good correlation, as in Fig. 4, and that a significantly strong positive correlation is observed between electron density and CNA variations. Thus it indicates that electron density at low altitudes measured by the MF radar is well represented the actual electron density variations at low altitudes. On the other hand, the relationship between electron density averaged over high altitudes and CNA shown in Fig. 6 is quite different, and the elec-

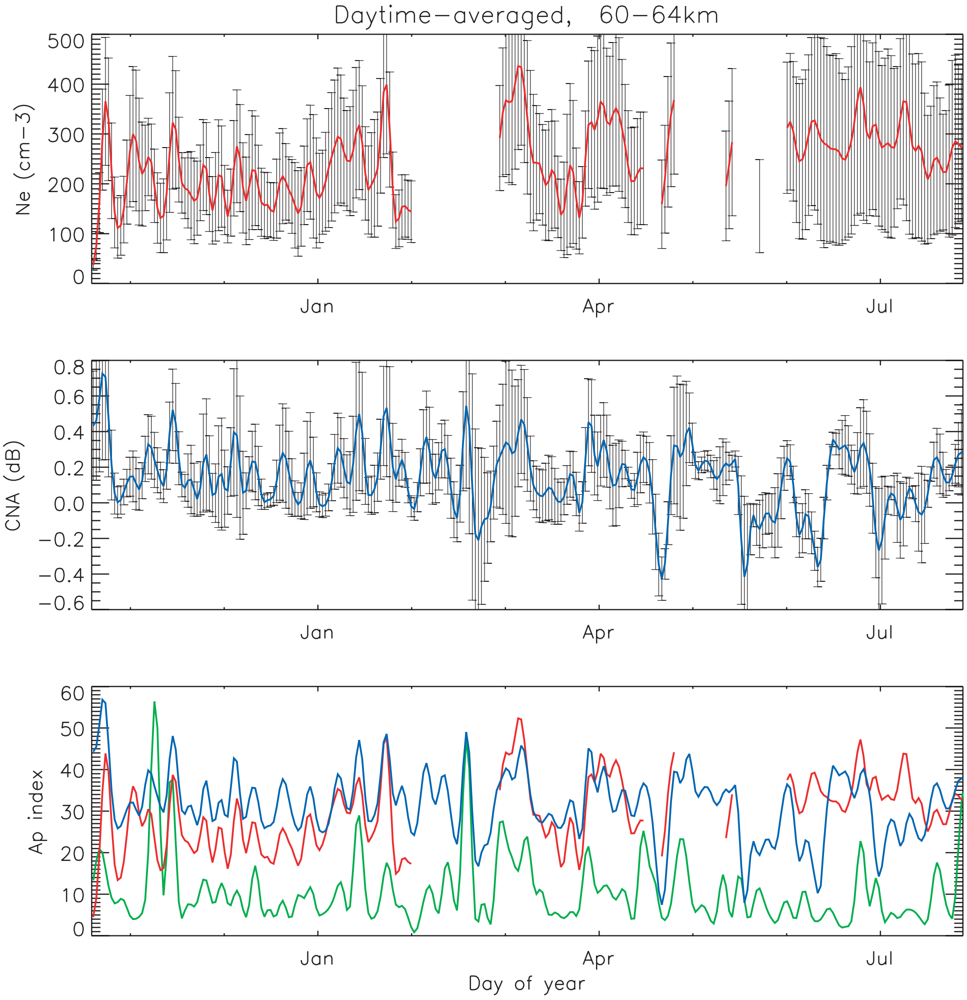

Fig.5 *Comparison of long-term variations in electron density (red line), CNA (blue line), and Ap index (green line) (averaged over daytime and 60–64 km altitude)*

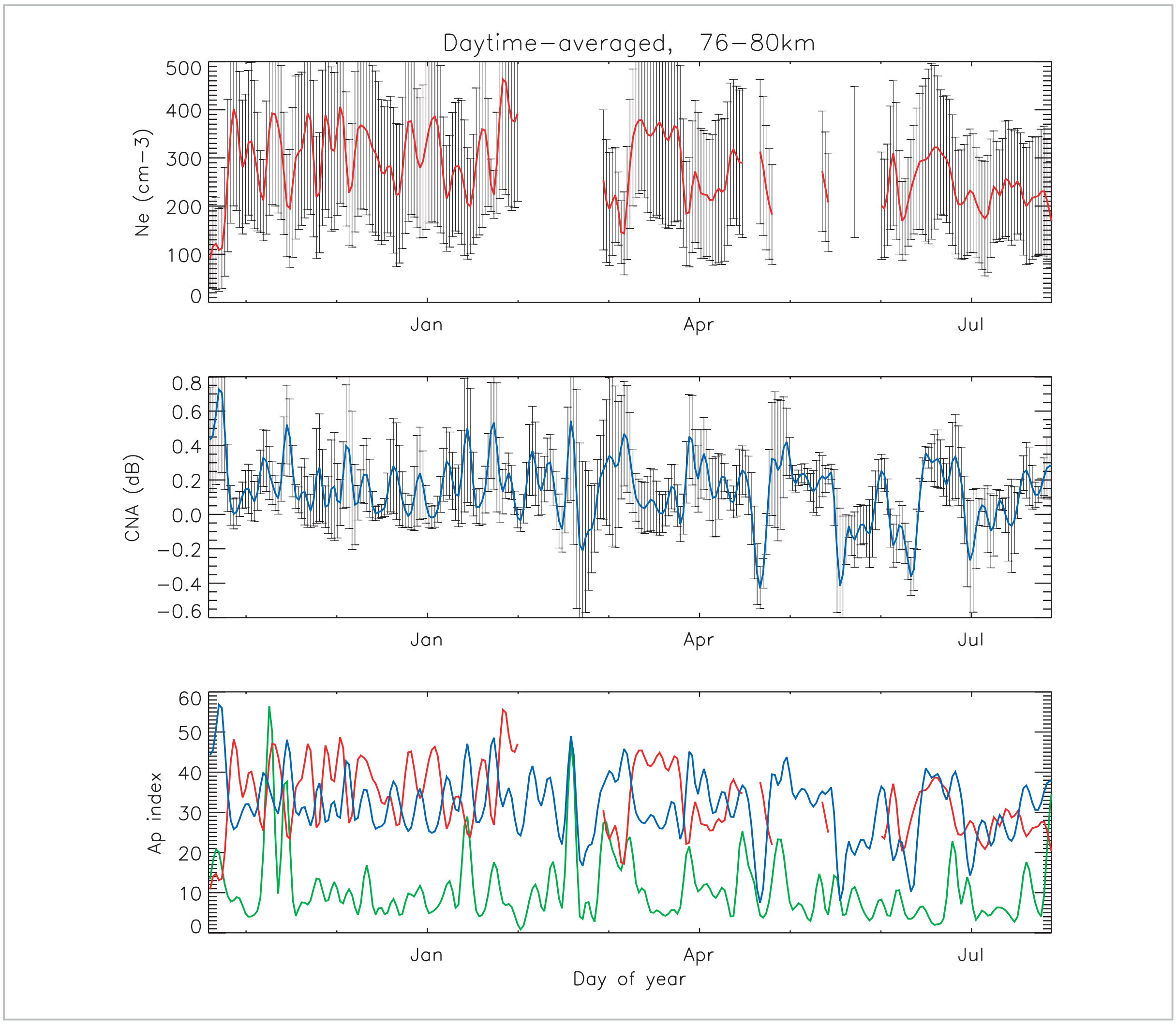

Fig.6 Comparison of long-term variations in electron density (red line), CNA (blue line), and Ap index (green line) (averaged over daytime and 76–80 km altitude)

tron density and CNA variations display an inverse correlation throughout the observation period.

Figure 7 presents an example of a comparison between the diurnal variations in electron density and CNA on Mar. 9, 1999. The top panel shows the time-height variations in electron density and the middle panel shows the time variations in electron density averaged over an altitude range of 60‑80 km. The bottom panel presents the diurnal variations in CNA. Even at the small time scales of the diurnal variations, variations in electron density and CNA display notable positive correlation. Although electron density is observed at different altitudes during the day and at night, increases in electron density — taking place at

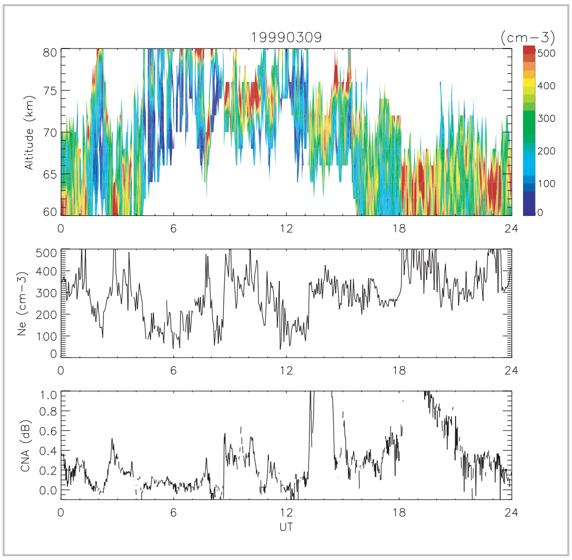

Fig.7 Comparison of diurnal variations in electron density and CNA (Mar. 9, 1999)

low altitudes during the daytime and at high altitudes during the nighttime — are at both times accompanied by a corresponding increase in CNA.

5 Conclusions

The differential absorption experiment (DAE) method to estimate the electron density of the ionospheric D region was proposed in 1950s and developed until 1970s. But validation studies on this method have yet to be carried out to this day. In this study we performed a comparative study on electron density estimated using an MF radar and CNA obtained by an imaging riometer at Poker Flat, Alaska, USA for the purpose of verifying the DAE method. Electron density from the MF radar and CNA from the imaging riometer showed relatively high positive correlations both for long-term and diurnal variations. In particular, the long-term variations in daytime electron density averaged over a low altitudinal range (60‒64 km) showed an especially strong positive correlation with daytime CNA, which indicates that the value of electron density estimated by the MF radar DAE method closely reflects actual electron density.

On the other hand, comparison between long-term variations of electron density averaged over the higher altitude range (76‒80 km) and CNA showed that the two displayed an inverse correlation. This inverse correlation is difficult to interpret physically and may indicate that it is still needed to reinvestigate the DAE electron density estimation method. One potential explanation for the inverse correlation is a possible limit to the altitudes at which the conditions assumed in the DAE [Eq. (2)] are applicable. Since the beam width of the Poker Flat MF radar is relatively wide, the possibility may exist of contamination by echoes from different altitudes due to beam spreading. The principle of MF radar observation assumes partial reflection from the layered atmosphere, but in reality, echoes may also be caused by other radio-scattering mechanisms such as turbulence[8]. In order to carry out more quantitative studies in the future, simulations on radio wave propagation through plasma (such as by Full Wave calculation) will be important.

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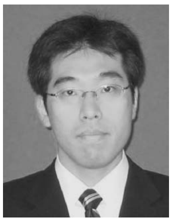

KAWAMURA Seiji, *Ph.D.*

Researcher, Environment Sensing and Network Group, Applied Electromagnetic Research Center

Atmospheric Physics, Radar Engineering

MURAYAMA Yasuhiro, *Dr. Eng.*

Planning Manager, Strategic Planning Office, Strategic Planning Department

Dynamics in the Thermosphere and Mesosphere

MORI Hirotaka, *Dr. Sci.*

Key Technology Research Supporting Group, Key Technology Research Promotion Department

Upper Atmosphere Dynamics