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Ionospheric Irregularities in the Cusp Ionosphere: In situ Observations by NorSat-1 Satellite

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Abstract

Ionospheric irregularities can greatly influence the trans-ionospheric signals due to the scintillation effect, and thus they can affect the satellite-based communication and navigation systems. Due to their practical space weather impacts, it is of great interest to study plasma irregularities and their generation mechanisms. However, our understanding of plasma structuring mechanisms at high latitudes is still not complete partially due to insufficient in situ data at high-resolution. The first Norwegian scientific satellite, NorSat-1, provides a good opportunity to enhance our understanding of the multi-scale features of ionospheric irregularities. Norsat-1 is a polar orbiting microsatellite at ~600 km altitude. NorSat-1 carries the multi-needle Langmuir probe (m-NLP) system, which is capable of collecting currents from four different voltages at a rate up to 1 kHz. The electron density can be derived from the collected currents. Here we present a case study using the m-NLP instrument to characterize small-scale ionospheric plasma structures. NorSat-1 crossed the cusp ionosphere in a noon-midnight orbit. With the support from ground and space-based auroral images, we see that the cusp ionosphere is a region with mesoscale (40-80 km) electron density enhancements that are likely due to pulsed electron precipitations. The density enhancements are associated with significant small-scale irregularities.

1 Introduction

The Earth's ionosphere is often highly turbulent with significant irregularities. When present, ionospheric irregularities can cause problems in receiving trans-ionospheric signals due to the scintillation effect [1]. The cusp ionosphere is the main region where ionospheric irregularities are created through a variety of instability processes [2-5]. It is of practical interest to study the plasma structuring processes in the cusp ionosphere. However, due to a lack of high-resolution in situ measurements of the electron density, the understanding of the plasma processes is incomplete [6].

To better understand the generation processes of small-scale ionospheric irregularities, the University of Oslo has developed the multi-Needle Langmuir Probe (m-NLP) system [7, 8]. The m-NLP system is able to measure the electron density at an unprecedented high resolution (several kHz). The m-NLP system has been successfully tested in several sounding rockets, e.g., the Norwegian Investigations of Cusp Irregularities (ICI) sounding rockets [9]. In addition, the m-NLP system was deployed on a microsatellite, i.e., the first Norwegian satellite (NorSat-1). As such, NorSat-1 provides frequent observations of the high-latitude ionosphere at a high resolution, and it provides valuable data to understand the multi-scale feature of ionospheric irregularities. In this study, we present a case study using m-NLP onboard NorSat-1.

2 Data and Instrument

NorSat-1 was launched on July 14th, 2017. It is a microsatellite with a dimension of 23 cm × 39 cm × 44 cm weighting ~16 kg. Its orbit is nearly sun-synchronous at around 600 km altitude. The m-NLP system onboard NorSat-1 consists of four needle Langmuir probes which are biased to different voltages. The probes collect electron currents, which are sampled at a rate of up to 1 kHz. From the collected currents, the electron density can be derived [7, 8]. In this study, we present a case during the commission phase when the sampling rate was 400 Hz. The detailed technical specification of the m-NLP on board NorSat-1 can be found in Hoang et al. [10].

3 Observations

We present a case on November 24, 2017. Figure 1 shows the background ionospheric condition around the time of interest. Both panels are presented in magnetic latitude/magnetic local time (MLAT/MLT) coordinates, where magnetic noon is to the top and dawn is to the right. NorSat-1 flew in the noon-midnight orbit as shown by the black segment. Fortunately, the Defense Meteorological Satellite Program (DMSP) F17 flew across the Arctic around the same time. F17 carries the Special Sensor Ultraviolet Spectrographic Imager (SSUSI), which takes auroral observations at five wavelengths in the far ultraviolet range (115–180 nm) with high spatial resolution (7–9 km at nadir) by scanning across the track of the orbit every 15 s [11]. Figure 1a shows the auroral emission from N2 Lyman-Birge-Hopfield short filter (LBHS) band (165–180 nm). Though the auroral emission was weak around the cusp region, NorSat-1 should enter the auroral region at ~8:10 UT. The all-sky imager at Ny-Ålesund (NYA) was operated at this time and the field-of-view of the all-sky imager is shown by a circle around Svalbard in Figure 1a. Figure 1b shows the Global Positioning System (GPS) Total Electron Content (TEC) map in a global view. The ionopsheric density was very low (<4 TECU, where 1 TECU = 10^{16} el/m^2) in the Arctic during the current solar minimum.

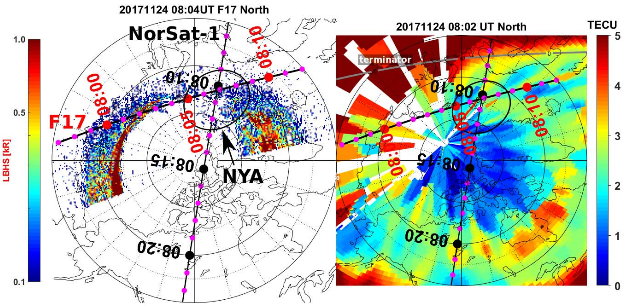

Figure 1. (a) Auroral image from SSUSI onboard DMSP F17. (b) The ground-based GPS TEC map from the Madrigal database. The orbits of F17 in dawn-dusk direction and NorSat-1 in noon-midnight direction are shown by black segments with timestamps annotated. In the right panel, the solar terminator is shown by a grey line.

Figure 2 shows the in situ data from the Special Sensor Magnetometer (SSM) and the Special Sensor J (SSJ) instruments onboard DMSP F17 [12, 13]. The field-aligned currents (FAC) were derived assuming that F17 crossed infinite field-aligned current sheets at normal direction [14]. The two vertical dashed lines indicate the time when F17 crossed the cusp region, which is a region of significant FAC sheets (Figure 2a), soft electron beams (Figure 2d) and ion dispersion (Figure 2e) due to the velocity filtering effect. The word "CPS" (central plasma sheet) in Figure 2d is used to identify the region of closed field line with diffuse and high-energy precipitation.

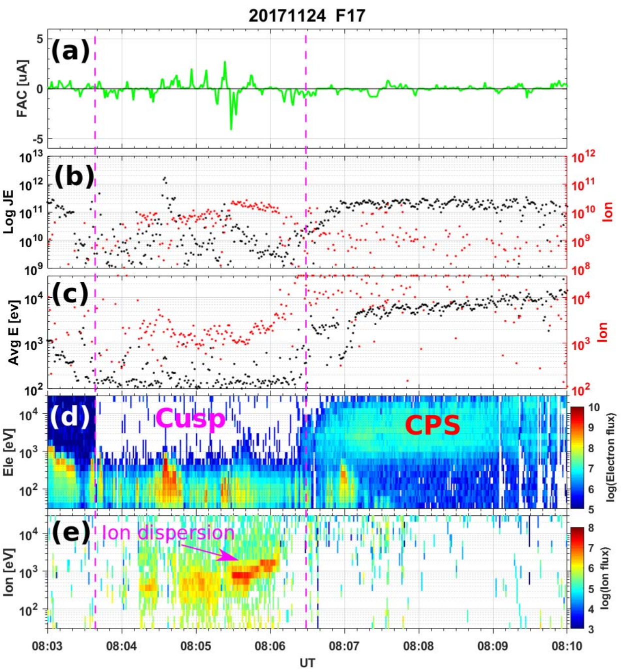

Figure 2. The data from DMSP F17. (a) field-aligned currents, (b) electron (black) and ion (red) energy fluxes, (c) average electron (black) and ion (red) energy levels, (d) electron flux, and (e) ion flux.

The all-sky imager at Ny-Ålesund is sensitive to observe the dayside aurora during deep winter conditions when the Sun is about 10º below the horizon. Figure 3 shows an example of the auroral image taken at 630.0 nm during the time of the NorSat-1 and F17 cusp crossing. The cusp aurora was clearly seen above Svalbard; it is characterized by significant red line aurora (at 630.0 nm) and weak green line aurora (at 557.7 nm, data not shown). F17 crossed the cusp aurora around 8:04-8:07 UT, while NorSat-1 crossed the aurora around 8:10-8:11 UT. Both satellites experienced discrete auroral arcs and this is consistent with the inverted-V like precipitation from the F17 data in Figure 2d.

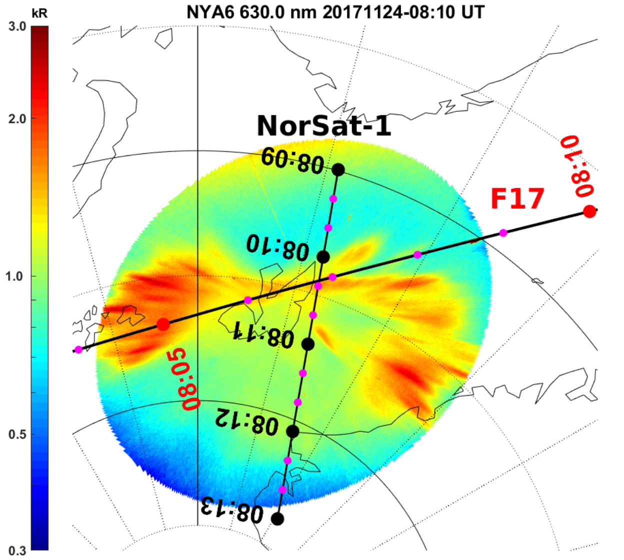

Figure 3. An auroral image at the 630.0 nm wavelength (red line) from the all-sky imager at Ny-Ålesund (imager # NYA6). The orbits of F17 and NorSat-1 are presented as black segments.

The raw electron density (Ne) data, the spectrogram [15] and density fluctuations as quantified by the RMS (root mean square) of Ne at spatial scales (100 m and 500 m) are presented in Figure 4. The two vertical lines are drawn mainly according to the location of the auroral boundaries as estimated from Figure 3, as well as according to the magnitude of the density fluctuations. The electron density in the cusp ionosphere is characterized by density enhancements of scales at 5-10 s. By using the satellite speed of 7.9 km/s, these correspond to spatial scales of 40-80 km. These density enhancements are likely due to beams of electron precipitation as observed by F17. Smaller scale fluctuations are clearly visible within these density enhancements. The density fluctuations are observed both on the edges and in the center of the density enhancements. This is different from the observation by the ICI-2 sounding rocket by Moen et al. where small-scale irregularities are mainly observed on the trailing side of density gradients [9]. The density fluctuations are also observed in the polar cap poleward of the cusp aurora. However, the polar cap structures are generally lacking the mesoscale density enhancements due to a lack of particle precipitation. The spectrogram clearly shows this feature, i.e., in the cusp, the irregularities are clearly enhanced from 0.1-1 Hz (1-10 s). Both in the cusp and polar cap, the irregularities are observed up to 10-100 Hz (i.e., 790-79 m). Recently the scintillation of GPS signals at L band are of special interest for our modern society. The GPS amplitude scintillations are caused by irregularities at ~400 m. In Figure 4c, we plot the density fluctuations at 100 m and 500 m, respectively. The density fluctuations are clearly visible in the cusp and polar cap, with a more enhanced level in the cusp. This is consistent with the recent scintillation observations [3].

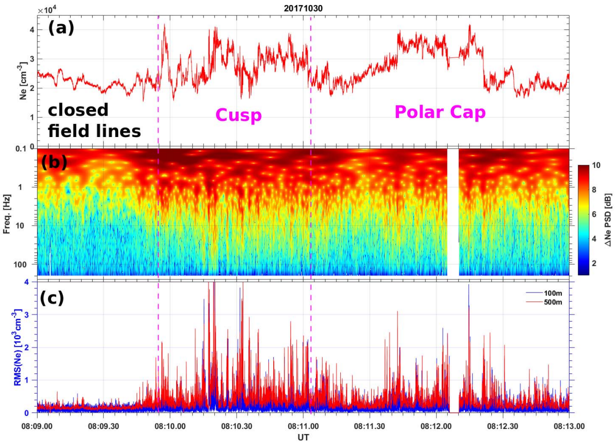

Figure 4. (a) Electron density data derived from m-NLP on board NorSat-1. (b) Spectrogram of the electron density. (c) Electron density fluctuations quantified by the RMS (root mean square).

4 Summary and Conclusion

We have presented the first high-resolution (400 Hz) in situ observations of the cusp ionosphere using the m-NLP instrument on board the NorSat-1 Satellite. Due to the coupling of the solar wind-magnetosphere-ionosphere, the cusp region is characterized by significant FAC sheets and beams of soft electron precipitations. Though at the topside ionosphere (~600 km), NorSat-1 observed significant density enhancements in the cusp, which are likely caused by beams of electron precipitation. Smaller-scale irregularities down to below 100 m are observed to be associated with the density enhancements. While at a lower level, the polar cap is also associated with clear electron density fluctuations. These small-scale irregularities can exert on the trans-ionospheric radio signals and cause detrimental impact on the applications that use GPS signals.

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