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Key Points:
- Results of the first SURA-NorSat-1 joint experiment are presented
- Increase in temperature is more substantial than changes in plasma density in high-frequency heating region
- In situ observations detect plasma irregularities down to 200 m at the southern edge of the heated SURA volume

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In Situ Observations of Ionospheric Heating Effects: First Results from a Joint SURA and NorSat-1 Experiment

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Abstract This work presents the first results of measurements of artificial plasma disturbance characteristics using the low-orbit NorSat-1 satellite, which are excited when the ionospheric F2 layer is modified by powerful high-frequency (HF) waves emitted by the SURA heating facility. NorSat-1 carries the multineedle Langmuir probe instrument, which is capable of sampling the electron density at a nominal rate up to 1 kHz. The uniqueness of this experiment lies in the fact that the satellite passes very close to the center of the HF-perturbed magnetic flux tube and in situ observations are first carried out in winter when the absorption is still small in the morning as the Sun is low above the horizon. There are HF-induced plasma temperature and density variations at satellite altitudes of about 580 km. Plasma irregularities are detected by in situ measurements down to 200 m at the southern border of the SURA heating region.

Plain Language Summary The current stage in the development of active experiments includes the use of satellites for sensing plasma disturbances in situ. However, these data can only be obtained if the satellite crosses an HF-perturbed magnetic flux tube, which rests on a region with highly developed turbulence generated near pump wave reflected altitude; in other words, “the satellite has to be in the right place at the right time.” This study presents results related to features of artificial plasma density irregularities at a height of 580 km obtained during the SURA-NorSat-1 active experiment when NorSat-1 passed very close to the center of the HF-perturbed magnetic flux tube. For the first time, in situ measurements were carried out by the satellite with such a high resolution of Langmuir probes in comparison with previous experiments with DEMETER and DMSP. It is shown that there are HF-induced plasma temperature and density variations at satellite altitudes and an increase in temperature is more substantial than changes in plasma density. Plasma irregularities are detected by in situ measurements down to 200 m at the southern border of the SURA heating region. The spatial distribution of artificial plasma disturbances is strongly influenced by the “magnetic zenith” effect.

1. Introduction

Significant local plasma density and temperature disturbances can be caused in the Earth's ionosphere with the help of powerful high-frequency (HF) radio waves directed upward (Frolov, 2017; Grach et al., 2016; Gurevich, 2007; Streltsov et al., 2018). These ionospheric disturbances are relatively short lived (with lifetimes of the order of seconds or to tens of minutes) and do not cause irreversible changes in the plasma. The current stage in the development of active experiments includes the use of satellites for sensing plasma disturbances in situ (Chernyshov et al., 2016, 2020; Streltsov et al., 2018). However, these data can only be obtained if the satellite crosses an HF-perturbed magnetic flux tube, which rests on a region with highly developed turbulence generated near pump wave reflected altitude; in other words, “the satellite has to be in the right place at the right time.”

The scientific literature mentions some successful active experiments including satellites and ground-based tools. For example, the FAST satellite detected ultra low-frequency (ULF) waves injected into the magnetosphere in experiments with heating of the auroral electrojet (Kolesnikova et al., 2002; Robinson et al., 2000). The CASSIOPE/e-POP satellite was used to receive HF waves from the SURA and EISCAT heating facilities in order to study the conversion of the *O*-mode to the *Z*-mode in the *F* region (James et al., 2017). Several experiments were carried out to study the properties of artificial ionospheric turbulence at altitudes of the outer ionosphere (approximately 700 km) using onboard equipment of the French satellite DEMETER which demonstrated the fundamental possibility of forming ducts with excess (up to 40%) plasma density when modifying the F2 region of the ionosphere (Frolov et al., 2016). Experimental evidence of plasma modifications on DEMETER induced by the HAARP heater in which the ion temperature increased considerably were presented in Milikh et al. (2008) and Vartanyan et al. (2012). Besides, DMSP satellites observed ducts over HAARP and SURA with ion outflow (Frolov et al., 2008; Milikh et al., 2010; Vartanyan et al., 2012). Recently, a study that described the first Swarm observations of artificial ionospheric plasma disturbances and field-aligned currents induced by HF heating from the SURA facility (Frolov et al., 2018; Lukianova et al., 2019) was published. Furthermore, using CSES satellite data, it was shown that the power spectrum density of the electric field was larger by an order of magnitude in the region heated by the SURA facility as compared with the background (Zhang et al., 2018).

Active experiments should be conducted when the satellites are located over the heating facility or in the magnetically conjugate ionosphere. It should be noted, however, that joint experiments involving heating facilities and satellites that pass through or over the heating spot in the ionosphere are of a single character and only provide short insights into individual experiments. It is exceedingly rare that the satellite passes through the center or close to the center of the HF-disturbed magnetic flux tube since the orbit and ephemeris of the satellite cannot be changed. In addition, many satellites were not equipped with all the necessary instruments to fully study the characteristics of electromagnetic and plasma disturbances induced at the heights of the outer ionosphere during the operation of heating facilities.

In this paper, we describe results for a joined SURA-NorSat-1 experiment performed on 25 February 2018. The uniqueness of this experiment lies in the fact that the satellite passed very close to the center of the HF-perturbed magnetic flux tube and the NorSat-1 satellite measured in situ ionospheric plasma parameters at a nominal resolution of 1,000 Hz. For comparison, the Langmuir probe instrument on the DEMETER satellite during SURA-DEMETER experiments provided data at a 1-Hz resolution both in survey and in burst modes (Lebreton et al., 2006). Moreover, our experiment was conducted in the local morning hours (more precisely, in the late morning), which is good time for studying artificial irregularities. It should be noted that the daytime ionosphere is characterized by a higher level of photoelectrons, a lower height of the F2 layer maximum, and a higher density of plasma and neutral particles in the ionosphere, while at nighttime, the critical frequencies of the ionospheric F2 layer can vary greatly. Besides, this active experiment was performed under quiet geomagnetic conditions in the midlatitude ionosphere that allows to more accurately assess the effect of artificial HF heating.

2. Results of the Joint SURA-NorSat-1 Experiment

On 14 July 2017, the Norwegian satellite NorSat-1 was launched into a high-inclination (98^{o}), low Earth orbit (~600-km altitude) from Baikonur, Kazakhstan (Eriksen et al., 2019). As part of the payload package, NorSat-1 carries the multineedle Langmuir probe (m-NLP) instrument, which is capable of sampling the electron density at a rate up to 1 kHz, thus offering an unprecedented opportunity to continuously resolve ionospheric plasma density structures down to a few meters.

The m-NLP design uses four cylindrical probes biased at fixed voltages within the electron saturation region. The currents to these four probes can be sampled at a much higher rate since no voltage sweeping is involved, resulting in high-resolution plasma parameter observations. The electron saturation current of a cylindrical probe with a surface area of A, while its radius is much smaller than the Debye shielding distance, is given by the orbital motion limited (OML) theory as

$$I_c(V_p) = -\frac{en_eA}{4}\sqrt{\frac{8k_BT_e}{\pi m_e}\frac{2}{\sqrt{\pi}}}\ \sqrt{1+\frac{e((V_S+V_b)-V_0)}{k_BT_e}} \tag{1}$$

where n_e is the electron density, k_B is Boltzmanns constant, T_e is the electron temperature, e is elementary charge, m_e is the electron mass, V_b is the probe bias, V_S is the satellite floating potential, and V_0 is the plasma potential, assumed to be at 0 V. The measurement method of the m-NLP system handles at least two probes biased at two different fixed voltages to determine the absolute electron density as

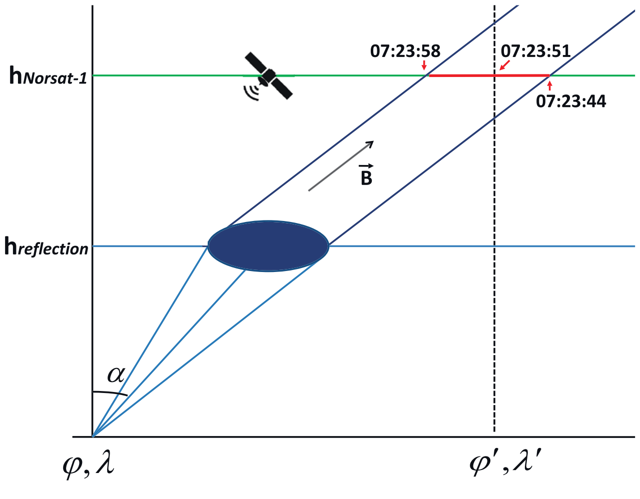

Figure 1. The scheme of the joint experiment SURA-Norsat-1 (not to scale). Here, $\varphi = 56.15°$N and $\lambda = 46.1°$E are geographical coordinates of the SURA heater; $\varphi' = 54.72°$N and $\lambda' = 45.8°$E are geographic coordinates of geomagnetic tube center at satellite orbit height $h_{Norsat-1} = 580$ km; $h_{reflection} = 205$ km is pump wave reflection height; $\alpha = 12°$ is antenna pattern tilt to the south. The red bold line is the satellite flight over a heating region with a radius of 50 km. Minimal distance between NorSat-1 and center of the HF-disturbed magnetic flux tube due to SURA's work is near 6 km at 07:23:51 UT.

$$n_e = \frac{1}{KA}\sqrt{\frac{\Delta(I_c^2)}{\Delta V_b}} \quad (2)$$

where K is a constant given by $(e^{3/2}/\pi)\sqrt{2/m_e}$, $\Delta(I_c^2)$ is the difference in the square of the collected currents, and ΔV_b is the difference in the probe biases (Jacobsen et al., 2010). A key feature of the m-NLP technique is an ability to determine the electron density without the need to know the plasma potential or electron temperature.

Under the assumption that the plasma potential is 0, we can also look at the ratio of the squared currents collected by two probes biased at fixed but different voltages V_b relative to the spacecraft potential V_S

$$R = \frac{I_p^2(V_{b1})}{I_p^2(V_{b2})} = \frac{1 + \frac{e(V_S + V_{b1})}{k_B T_e}}{1 + \frac{e(V_S + V_{b2})}{k_B T_e}} \quad (3)$$

From this expression (3), we can derive the electron temperature as in units of eV

$$\frac{k_B T_e}{e} = \frac{R(V_S + V_{b2}) - (V_S + V_{b1})}{1 - R} \quad (4)$$

In this expression, the spacecraft potential is also unknown; however, from previous experience, a reasonable estimate for V_S can be used in order to estimate the electron temperature.

The SURA heating facility which was used in this experiments on ionospheric modification by high-power HF radio waves is located near Vasilsursk, 120 km east of Nizhny Novgorod (the geographic coordinates 56.15°N, 46.1°E) (Frolov, 2017). The experiments performed previously at the SURA midlatitude heating facility on modification of the ionospheric F2 layers by high-power HF radio waves with the ordinary (O) polarization have demonstrated that if the pump wave frequency was somewhat below the F2 layer critical frequency, f_{0F2}, then intensive artificial ionospheric turbulence was generated in the ionospheric plasma (Erukhimov et al., 1987; Gurevich, 2007, 1978; Streltsov et al., 2018).

In the joint experiment SURA-NorSat-1, during measurements to create artificial plasma disturbances in the Earth's ionosphere, the SURA operated during a time interval $T =$ 07:05:00–07:23:55 UT (10:05:00–10:23:55 local [Moscow] time) for the flight of the NorSat-1 over the heating facility (see Figure 1 where the scheme of the joint experiment SURA-Norsat-1 is presented), which is sufficient for the development of artificial ionospheric turbulence. It is worth noting that the in situ observations were first carried out in February, when the absorption is still small in the morning because the Sun is low above the horizon. The SURA operated in continuous wave (CW) mode at a pump wave frequency 4,544 Hz ($f_{0F2} =$ 4.6 MHz), the effective radiated power of the pump wave was 30 MW and the reflection height of a powerful radio wave was about 205 km (this is a fairly low height, which means that the late morning ionosphere is close in characteristics to the daytime one). The HF beam was inclined to the south of vertical by 12° to realize the conditions of the "magnetic zenith" near the height of interaction of a powerful HF radio wave with an ionospheric plasma. On vertical sounding ionograms for an ionosonde placed near the SURA heating facility, the excitation of a spread F was detected during the ionosphere heating. The values of geomagnetic indices during measurements were $\Sigma Kp = 7^-$ and AE near 0, that is, our experiment was carried out under quiet geomagnetic conditions. $T^* =$ 07:23:51 UT was the time of the closest approach of the satellite to the center of the HF-disturbed magnetic flux tube, which was of ~6 km. It should be mentioned that it is an extremely rare case during joint experiments of heating facilities and satellites. A part of NorSat-1 orbit when distance between the satellite and the heating center was less than 50 km is painted red in Figure 1. It corresponds to the time interval $T =$ 07:23:44 ÷ 07:23:58 UT.

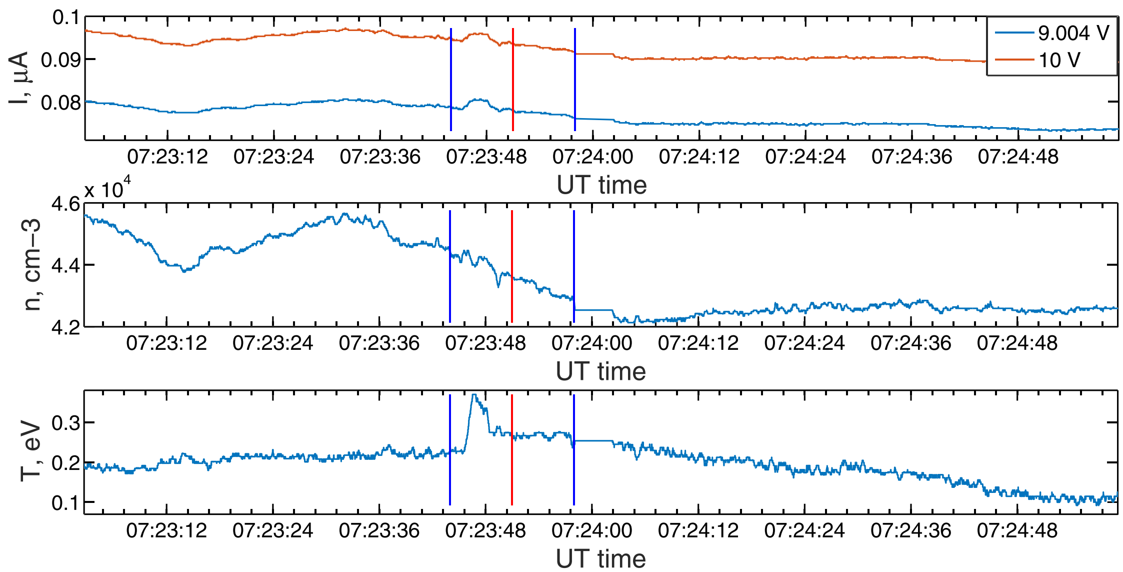

Figure 2. Currents (top panel), electron density (middle panel), and temperature parameter for electrons (bottom panel) estimated from currents to the probes on NorSat-1.

As stated above, the NorSat-1 satellite passed under conditions of a late morning ionosphere at an altitude of 580 km in the south-to-north direction very close to the center of the HF-disturbed magnetic flux tube. The time of the maximum approach of the satellite to the magnetic flux tube was $T^* =$ 07:23:51 UT. The lower altitudes, 400–500 km, are of particular interest because they conform to the transition from the region where the generation of the most intensive plasma heating takes place and the most intensive artificial ionospheric turbulence are observed, to the region where the HF-disturbed plasma spreads from the ionosphere F2 region to the outer ionosphere and magnetosphere. No observational data on the properties of plasma turbulence induced by the high-power HF pumping at this altitudinal range existed except for the recent first results obtained during joint experiments using Swarm (Frolov et al., 2018; Lukianova et al., 2019).

In Figure 2, measurements of the NorSat-1 Langmuir probes are shown. On the top panel of Figure 2, currents of Langmuir probes (LP) are presented. Only measurements of two probes are plotted here: one is probe with biased 9-V potential (blue curve) and another one with biased 10 V (red curve). It is clearly seen that currents collected by two probes have very similar behavior and the current of second probe is higher than first one due to higher biased potential. In Figure 2 in all panels, red vertical lines mark time when distance between satellite and the center of the HF-perturbed magnetic flux tube was the least (less than 6 km). Blue vertical lines are times when distance was 50 km from the center of HF-disturbed magnetic flux tube region for the SURA-tube geometry owing to the operation of SURA. It is seen from the electric current measurements that the current values increase in the heating spot. This means that density or/and temperature increases in this case. On the middle panel (see Figure 2), calculated density using known LP currents is shown. Note that density is calculated under the assumption that theory of small cylindrical probe is correct. In that case, electron density is proportional to $\sqrt{\Delta I^2/\Delta V}$ (Hoang et al., 2018). Figure 2 shows density variations of about 2%, the largest ones at the edges of the region with increased temperature at the height of the satellite NorSat-1. The probe currents mainly increase by electron temperature increasing in the heating region.

As outlined above, in the electron saturation region of the LP voltage-current characteristic, we cannot calculate the electron temperature precisely. Although the absolute electron temperature cannot be derived without knowledge of the platform potential according to the theory of Langmuir probes, the absolute change in temperature can be calculated. Therefore, below we use the less rigorous term "temperature parameter" instead of the concept of temperature.

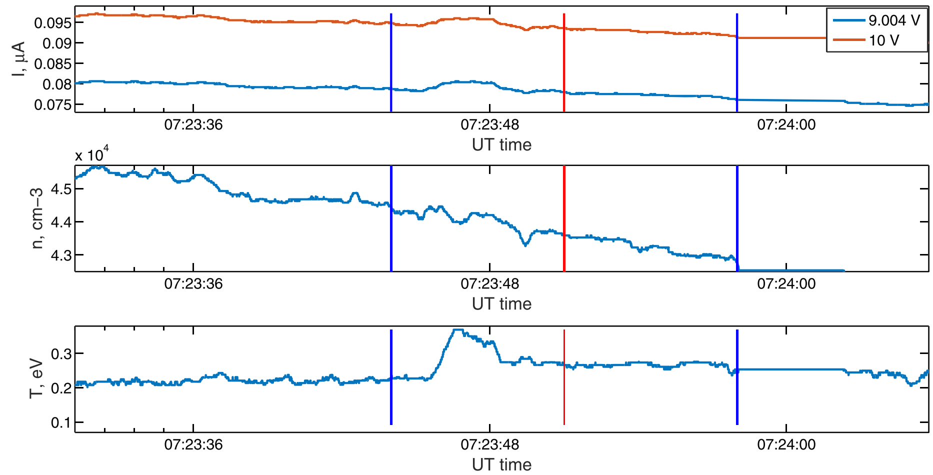

Figure 3. Enlargement version of Figure 2 (currents [top panel], electron density [middle panel], and temperature parameter [bottom panel]).

On the bottom panel in Figure 2, calculated temperature parameter for electrons is shown. It is evident that changes in probe currents occur due to an increase in temperature in the HF-perturbed magnetic flux tube. In the time interval 07:23–07:25UT, no other artificial signal variations were recorded. It is worth emphasizing that the temperature parameter values on the ordinate axis in Figure 2 (bottom panel) are not accurate (it depends on spacecraft potential) and the main thing here is that there are significant temperature variations.

In order to observe in detail the heating effect in the ionosphere during the operation of SURA, for the sake of clarity, Figure 3 shows an enlarged zone for HF heating region. It is well seen in Figure 3 (middle and bottom panels) that the maximum of the temperature parameter T_e coincides with the minimum of the plasma density N_e. The temperature parameter for electrons rises, and this corresponds to the results obtained in the article where the temperature changes were detected according to the low-orbit Swarm satellite (Frolov et al., 2018). It is worth noting that Swarm data showed that strong temperature variations and weak density variations were recorded at 500 km, while during active experiments with the DEMETER satellite (height of the satellite 660–710 km), the density variations were larger than the temperature variations (Frolov et al., 2016). The temperature parameter, estimated from the probe currents installed on NorSat-1, shows that on the southern boundary of the SURA heated volume, T_e increased substantially. Unfortunately, as mentioned above, since the exact temperature is not determined, we can only say that changes in the temperature parameter are significant (and ones are higher than plasma density variations), but we cannot accurately determine how many percent relative to the average level. From the results of measuring the plasma density N_e, one can see the appearance of its artificial variations with the average value 2–3%. The size of the region with enhanced temperature parameter for electrons is ~20 km. Most likely, this size depends on the effective radiation power P_{eff} of the pump wave. In this experiment, it was relatively low ($P_{eff} =$ 30 MW); however, even in this case, we see noticeable effects of artificial plasma heating in the Earth's ionosphere. Note that 20 km corresponds to the spot size of the “magnetic zenith” region (Frolov, 2017).

At the heights of the outer ionosphere, the duct formation with an increased plasma density inside the HF-perturbed magnetic flux tube, which rests on the HF-disturbed ionospheric volume with strong artificial ionospheric turbulence, was most likely observed. The formation of strong ducts is observed normally in the night ionosphere at pump wave powers greater than 45–50 MW. It should be mentioned that we do not see explicitly the formation of a density duct in the present study. Perhaps, this is due to the fact that the active experiment was carried out in the late morning (normally, the daytime ducts were weaker than those in the nighttime using the HAARP and SURA facilities Frolov et al., 2016; Vartanyan et al., 2012), there was a small pump wave power, and the pump wave frequency was almost equal to the critical frequency f_{0F2}. Note that the effects of the interaction of the irregularities were studied near to and far from the heating source in

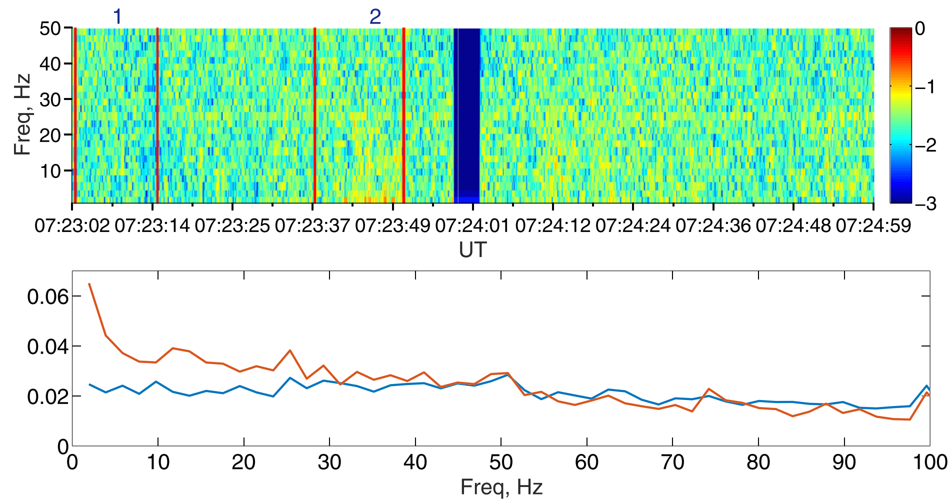

Figure 4. (top panel) FFT of probe current with 10 V biased and (bottom panel) two power spectra averaged over region 1 (blue line) and 2 (red line).

laboratory experiments on modeling ionospheric heating (Aidakina et al., 2018, 2018a). It was shown that near the heating sources, the irregularities had the form of a set of channels with reduced plasma density and a transient process with a positive density perturbation was observed at a large distance from the heating sources.

Note that the center of the region with the maximum disturbances is shifted to the south from the point of the maximum approach (~30 km). As seen from Figure 2 or 3, the temperature parameter is higher on the southern edge of the heating region and the environment there is more turbulized compared with the northern edge due to the “magnetic zenith” effect (Gurevich, 2018a). The “magnetic zenith” effect lies in the fact that when the F2 region of the ionosphere is modified, the strongest perturbations of the ionospheric plasma are observed when the powerful radio wave of *O*-polarization propagates along the lines of the geomagnetic field in the region of its interaction with the magnetized ionospheric plasma. It was found that the “magnetic zenith” effect is the result of a strong nonlinear plasma structuring process and an anomalously high heating of electrons, accompanied by the generation of plasma density irregularities stretched along the magnetic field (Kosch et al., 2000; Gurevich, 2007; Rietveld et al., 2003). Interestingly, observations of artificial optical emission of atomic oxygen red line, along with perturbations of slant total electron content, were presented in Grach et al. (2018), and it was demonstrated that the area occupied by airglow patches was located in the southern part of the SURA antenna pattern and the brightest patches were located near the magnetic zenith. The NorSat-1 measurements confirmed that maximum heating takes place at the southern edge of the HF-disturbed magnetic flux tube.

To study features of HF-induced ionospheric irregularities registered in the HF-disturbed magnetic flux tube, fast Fourier transform (FFT) of measured currents was performed. In Figure 4 (top panel), one can see FFT of probe's current with 10-V bias, on which the calculated spectral power is color coded. It should be mentioned that in the region marked by number 2, intensity of plasma irregularities increases. In Figure 4 (bottom panel), we compare two power spectra averaged over regions 1 (blue line) and 2 (red line). It is seen that the spectrum in region 1 (the area when the satellite was outside of the heating spot) has lower power in comparison with averaged spectrum of region 2 when it was inside of heating spot with maximum artificial disturbances. Such a difference is manifested for frequencies up to 40 Hz with the strongest difference up to 5 Hz. FFT shows that increasing current fluctuations with frequency up to 40 Hz appear in the south boundary of the SURA heating region as inferred from Figure 4. The latter means that the characteristic spatial scale of irregularities l reaches down to ~200 m (given the sensitivity limit of the instrument), as $l = v/f$, where v is the velocity of the satellite (~7.5 km/s) and f is determined from FFT, that is, with the strongest artificial density variations of about of ~200 m. The experiment with NorSat-1 confirms the development of artificial ionospheric plasma irregularities. Langmuir probes installed on board NorSat-1 have

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registered the heating effect (variations of temperature parameter for electrons and plasma density). Langmuir probes provide valid changes in the temperature parameter estimated from the values of probe currents and fixed voltage on the board of the NorSat-1 satellite.

Various attempts have been made to provide analytical explanations for the presence of small-scale plasma structures in the heating region in earlier studies. The famous sounding rocket experiment (Kelley et al., 1995) at Arecibo revealed that the spatial distributions of fully developed irregularities were over a wide range of characteristic scales between meters to a few kilometers. It was shown that kilometer-scale patches contained small-scale filaments associated with deep density depletions and that the filaments were bunched at 50- to 500-m scales. In Franz et al. (1999), observations using Langmuir probes in the rocket experiment made it possible to determine that the spectrum of relative density fluctuations had two breaks and was in agreement with the results of radar backscattering. The excitation of striations and nonlinear structuring at Arecibo is much more difficult than in mid- and high-latitude ionosphere and source of electron heating might be attributed to Langmuir waves generated with the development of a striction type parametric instability (Grach et al., 2016). In our joint experiment, we confirm the presence of plasma density irregularities on a scale of hundreds of meters by in situ observations although it must be taken into account that the development of small-scale artificial structures may differ, since the conditions in the midlatitude ionosphere (SURA) and in the low-latitude ionosphere (Arecibo) can be distinct. The small-scale, meters to tens of meters, artificial irregularities have been attributed to the thermal parametric instability (Grach et al., 1978; Basu et al., 1997) or the parametric decay of the heater wave to frequencies near the ion cyclotron frequency (Keskinen et al., 1995). As a result of the development of parametric instability, together with the generation of upper hybrid plasma waves, small-scale irregularities elongated along the geomagnetic field are formed with a reduced plasma density. Note that the development of a parametric instability is possible only when the ionosphere is modified by *O*-mode high-power radio waves. Also, self-focusing instability of the beam of high-power radio waves and subsequent nonlinear effects may be responsible for the occurrence of plasma irregularities > 100 m (Gurevich, 1978). The "magnetic zenith" effect and nonlinear plasma structuring as a result of self-focusing of the pump wave into plasma regions filled with small-scale artificial ionospheric irregularities elongated along the geomagnetic field leads to an increase in the generation of irregularities with scales from hundred meters to a kilometer (Frolov, 2017; Gurevich, 2007). In the work of Bolotin et al. (2017), ionosonde signals were used for aspect scattering from irregularities of 50–200 m, and it was supposed that these irregularities appear most likely as the nonlinear cascade over the turbulence spectrum (Erukhimov et al., 1987).

3. Summary

The study presents results related to features of artificial plasma density irregularities at height $h \approx 580$ km obtained during the SURA-NorSat-1 active experiment when NorSat-1 passed very close to the center of the HF-perturbed magnetic flux tube. The uniqueness of this active experiment lies in the fact that the joint satellite experiment was first conducted in the winter time (February) in the morning hours, when the ionosphere is sunlit, but there is weak absorption since the Sun is low above the horizon. This region is transitional from the region of the ionosphere near the pump wave reflection height to the outer ionosphere. At the height of reflection of the pump wave, there is a resonant interaction of a powerful *O*-polarization radio wave with plasma of the F2 region. That is accompanied by the generation of intensive artificial ionospheric turbulence, including plasma irregularities with different scale lengths. The strong heating of electrons in this region results in the formation of a plasma density depletion which acts as a focusing lens which focuses high-power HF radio waves that was predicted analytically (Bliokh & Bryukhovetskiy, 1970) and confirmed experimentally (Frolov, 2017).

The main results obtained in the framework of the joint Sura-NorSat-1 experiment are as follows:

- For the first time, in situ measurements were carried out by the satellite with such a high resolution of Langmuir probes in comparison with previous experiments with DEMETER and DMSP.
- Confirmation of the theory that the maximum development of artificial ionospheric turbulence is at the southern edge of the HF-disturbed magnetic flux tube due to the "magnetic zenith" effect.
- An increase in temperature is more substantial than changes in plasma density at the satellite altitude. The size of the region is rather narrow and has a size about 20 km.

- At the same time as temperature parameter increases, plasma irregularities appear up to 40 Hz (with the strongest difference up to 5 Hz) at the southern border, which means that the characteristic spatial scale of these irregularities reaches down to ∼200 m at a given instrument sensitivity.
- Langmuir probes (m-NLP) can, in general, provide adequate variations of temperature parameter for electrons calculated from the values of currents and assuming fixed probe potential.

Data Availability Statement

The NorSat-1 data are publicly available at http://tid.uio.no/plasma/norsat/.

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