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Morphology of the spectral resonance structure of the electromagnetic background noise in the range of 0.1–4 Hz at $L = 5.2$

A. G. Yahnin[1], **N. V. Semenova**[1], **A. A. Ostapenko**[1], **J. Kangas**[2], **J. Manninen**[2], **and T. Turunen**[2]

[1]Polar Geophysical Institute, Apatity, 184200, Russia
[2]Sodankylä Geophysical Observatory, Sodankylä, Finland

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Abstract. Continuous observations of fluctuations of the geomagnetic field at Sodankylä Geophysical Observatory ($L = 5.2$) were used for a comprehensive morphological study of the spectral resonance structure (SRS) seen in the background electromagnetic noise in the frequency range of 0.1–4.0 Hz. It is shown that the occurrence rate of SRS is higher in the nighttime than in the daytime. The occurrence rate is higher in winter than in summer. The SRS frequencies and the difference between neighbouring eigenfrequencies (the frequency scale) increase towards nighttime and decrease towards daytime. Both frequency scale and occurrence rate exhibit a clear tendency to decrease from minimum to maximum of the solar activity cycle. It is found that the occurrence rate of SRS decreases when geomagnetic activity increases. The SRS is believed to be a consequence of a resonator for Alfvén waves, which is suggested to exist in the upper ionosphere. According to the theory of the ionospheric Alfvén resonator (IAR), characteristics of SRS crucially depend on electron density in the F-layer maximum, as well as on the altitudinal scale of the density decay above the maximum. We compared the SRS morphological properties with predictions of the IAR theory. The ionospheric parameters needed for calculation were obtained from the ionosphere model (IRI-95), as well as from measurements made with the ionosonde in Sodankylä. We conclude that, indeed, the main morphological properties of SRS are explained on the basis of the IAR theory. The measured parameters of SRS can be used for improving the ionospheric models.

Key words. Ionosphere (auroral ionosphere; wave propagation) – Radio Science (electromagnetic noise and interference)

Correspondence to: A. G. Yahnin
(yahnin@pgi.kolasc.net.ru)

1 Introduction

Altitudinal distribution of the electron density in the upper ionosphere is appropriate for establishing a resonator for the shear Alfvén waves in the range of 0.1–10 Hz. The "walls" of the ionospheric Alfvén resonator (IAR) can be the E-layer and the electron density gradient above the maximum of the F-layer. This concept was approved theoretically (e.g. Polyakov, 1976; Polyakov and Pappoport, 1981; Belyaev et al., 1989b, 1990; Lysak, 1991, 1993), and it stimulated experimental investigations of the resonator effects. As a result of the experimental efforts, Belyaev et al. (1987, 1989a), using ground-based observations of the geomagnetic fluctuations in the ULF range, yielded the discovery of the resonance structures in the spectra of the electromagnetic noise. (The noise is, presumably, due to radiation from distant lightning discharges.) These first observations of the spectral resonant structure (SRS) were carried out at mid-latitudes, but recently, similar structures have also been found in records made in the auroral zone (Belyaev et al., 1999) and at lower latitudes (Bösinger et al., 2002; see also Hickey et al., 1996). The SRS at different latitudes has some common features. Thus, at any latitude the SRS eigenfrequencies exhibit similar diurnal behaviour: they are higher in the nighttime in comparison with those in the daytime. This agrees well with the IAR theory (Belyaev et al., 1987), as it reflects diurnal changes of the ionosphere. But ionosphere at different latitudes exhibits local peculiarities, so one may expect different behaviour of the SRS characteristics at different latitudes. Some differences were indeed observed. For example, the probability to SRS at nighttime in Crete, $L = 1.3$ (Bösinger et al., 2002) is much higher than in Sodankylä, $L = 5.2$ (Semenova et al., 1999).

In spite of a relatively long story of SRS studies (see references above and the special issue of Journal of Atmospheric and Solar-Terrestrial Physics; Vol. 62, No. 4, March 2000), many SRS features have not yet been studied in great detail. Until now, there are only a few papers describing the SRS morphology, where most of them deal with SRS at mid-

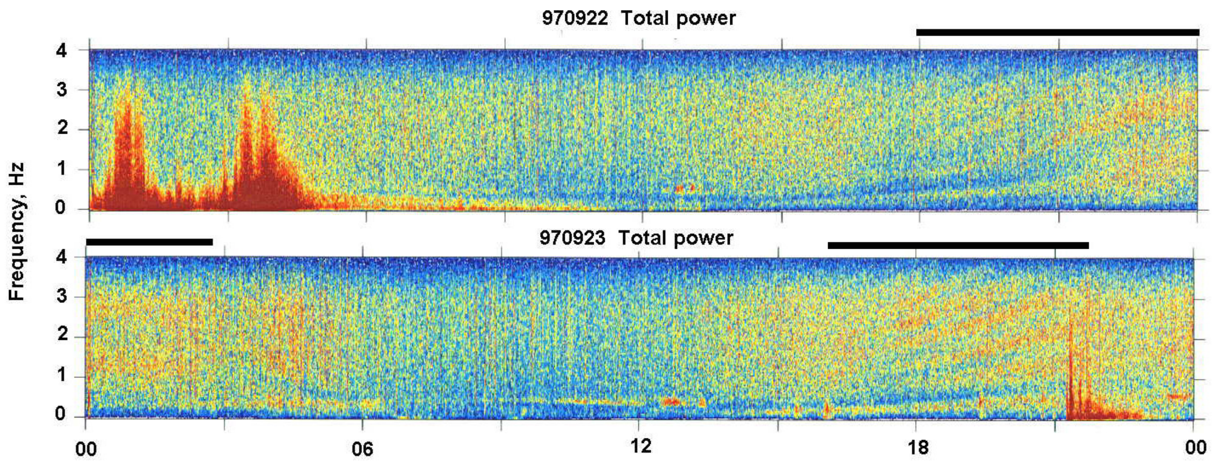

Fig. 1. Examples of the Spectral Resonance Structure observed at Geophysical Observatory Sodankylä (SGO). Spectrograms for two successive days are shown. Intervals of visible SRS are marked by black bars above the spectrograms.

latitudes.

The attempt of morphological study of SRS at high latitude was made only recently by Yahnin et al. (2001). This paper is to expand that study both in morphological aspect and in comparison with predictions of the IAR theory.

Two basic characteristics of SRS can be revealed from the observed spectra. One of them is the occurrence rate (P) of SRS observations. Indeed, the resonant structure can be recognised only if the background noise intensity varies significantly with frequency. Qualitatively, according to the IAR theory, this occurs in the case of a sufficiently large modulation of the reflection coefficient of the ionosphere (sufficiently large resonator quality, Q-value). The modulation amplitude of the magnetic noise intensity depends on parameters of the upper ionosphere, particularly on the plasma density drop between the F-layer maximum and the magnetosphere, the spatial scale of the F-region, as well as the conductivity in the E-region (e.g. Trakhtengerts et al., 2000).

Another SRS characteristic parameter is the frequency interval between neighbouring spectral lines (frequency scale). The IAR eigenfrequencies calculated using a simplified ionosphere model (where the bottom side of the ionosphere is a layer with thickness h, and the electron density exponentially decays in the upper ionosphere with a scale l) are given by the formula (Belyaev et al., 1990): $f_k = \frac{c(k+1/4)}{2n_a(l+h)}$, where n_a is the Alfvén refractive index at the altitude of the F-layer maximum. Thus, the frequency scale

$$\Delta F = \frac{c}{2n_a(l+h)} \qquad (1)$$

depends only on ionosphere parameters ($n_a \propto (M_{eff} * N_{emax})^{1/2}$, where M_{eff} and N_{emax} are effective ion mass and electron density in the F-layer maximum, respectively).

Using the theory by Belyaev et al. (1989b), Demekhov et al. (2000) demonstrated the consistency of the calculated spectra and the observations for two particular cases. Yahnin et al. (2001) compared long-term behaviour of observed and calculated ΔF (using above formula) and also found a good coincidence.

Below we will present the result of our statistical study of the two above-mentioned SRS characteristics (P and ΔF) obtained from observations at Sodankylä Geophysical Observatory (SGO). The observatory is located in the auroral zone ($L \approx 5.2$). We will show that the diurnal, seasonal, and long-term behaviour of SRS occurrence and its frequency interval are in agreement with the predictions of the IAR theory. The IAR characteristics will be considered on the basis of numerical calculations of the reflection coefficient of the top-side ionosphere. The method has been developed by Ostapenko and Polyakov (1990). A similar approach has been used by Vagner (1981) and Prikner and Vagner (1991).

2 Data

Since June, 1995 a permanent digital registration of ULF magnetic field variations has been established in SGO. The data are routinely treated to produce daily spectrograms (dynamic Fourier spectra). These spectrograms often show the presence of the resonant structures in the background noise, which will be the subject of this study. Due to the characteristics of the instrument, the frequency range of detection is from 0.1 up to 4 Hz. Figure 1 presents an example of a set of daily spectrograms. Even a quick look at the spectrograms makes clear the main features of the diurnal variation of SRS. Both the SRS frequencies and the frequency interval increase towards nighttime and decrease towards daytime. The SRS is more prominent during nighttime. Below we present this and other morphological features on the basis of a statistical analysis. For the statistical study we divided every day into eight 3-h intervals, and determined whether or not SRS was observed during every such interval. This counting was used for the determination of the occurrence probability $P = N_0/N_t$, where N_0 is the number of the 3-h intervals when SRS was

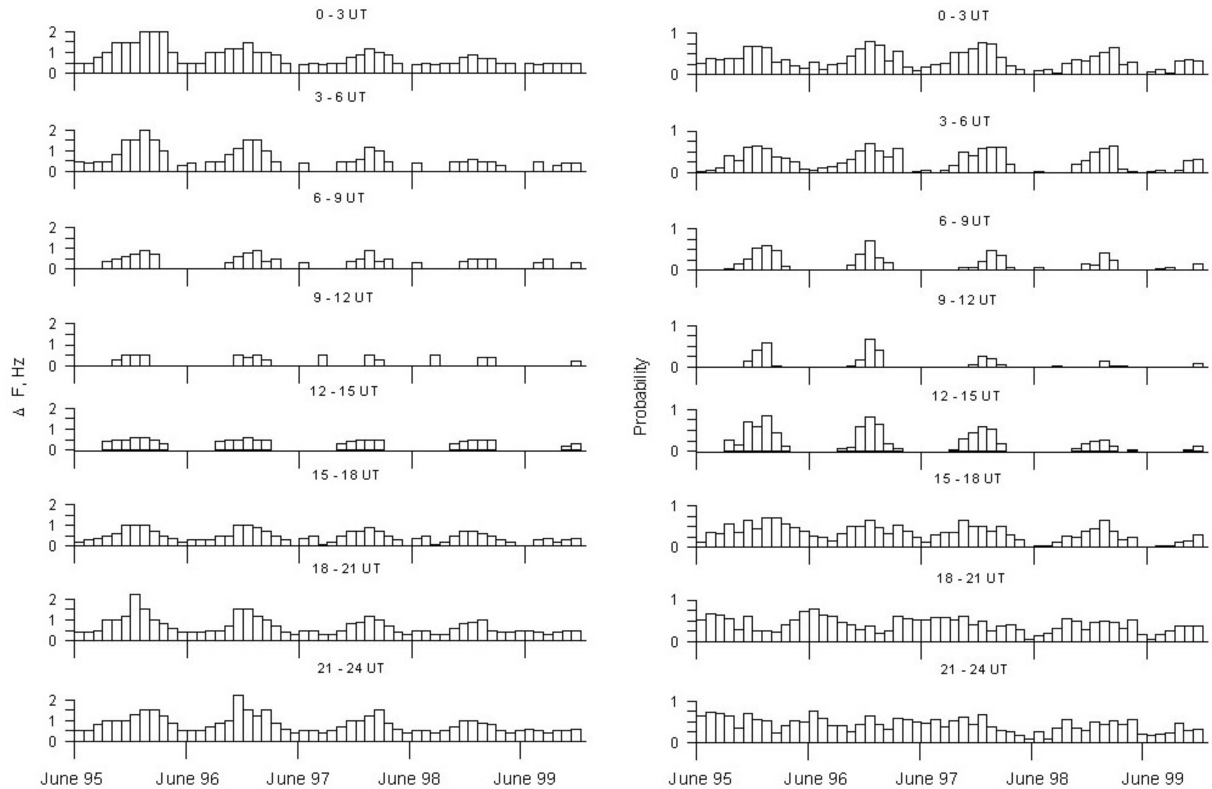

Fig. 2. **(a)** Monthly median values of SRS frequency scale observed in SGO during 1995–1999. **(b)** Monthly occurrence rate of SRS observations in SGO during 1995–1999. Each panel corresponds to a 3-h interval of UT. Note that magnetic local time in SGO is UT+2.

observed, and N_t is the total number of analysed intervals. If SRS was observed, we determined (for the middle of the interval) the frequencies, at which the background noise had maximum and minimum, and a frequency scale (ΔF) between the visible structures.

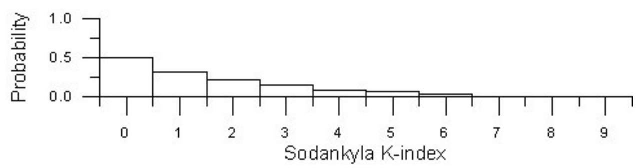

Fig. 3. Occurrence rate of SRS observations in SGO depending on the local K-index.

3 Diurnal, seasonal, and long-term behaviour of the SRS characteristics

We calculated the monthly median values of ΔF from June 1995 until December 1999. The result for every 3-h UT interval subset is shown in Fig. 2a. A similar plot was made for monthly values of P (Fig. 2b). These figures illustrate the basic features of the SRS morphology: diurnal behaviour, seasonal dependence, and solar cycle variations. Let us consider the diurnal variation. From Fig. 2 it is clearly seen that for night hours (18:00–21:00, 21:00–24:00, 00:00–03:00 UT), ΔF is higher than that for day hours. For example, for January 1996, the ΔF is ~2 Hz at 00:00–03:00 UT and ~0.7 Hz at 12:00–15:00 UT. This is more prominent in winter than in summer. There is very clear dependence of ΔF on the season; for every UT interval ΔF is larger in winter than in summer. Seasonal variations are more pronounced for night hours; they are stronger for the years close to the minimum of solar activity (1995–1996).

The occurrence rate of SRS exhibits a similar behaviour. On average, it is higher at night hours, in wintertime, and during years of solar activity minimum. Such behaviour is typical for each time interval, except for the intervals 18:00–21:00 and 21:00–24:00 UT. At that time, in contrast to the average behaviour, the occurrence rate in winter is smaller than in summer during 1995–1996. We will discuss this anomaly later.

4 Dependence on geomagnetic activity

Examination of the bulk of the data reveals that SRS is rarely observed during pronounced broad-band ULF activity, which is connected to geomagnetic disturbances (e.g. pulsations PiB, PiC). The result of a statistical investigation of the dependence of the SRS occurrence on the level of geomagnetic activity (characterized by the local K-index) is presented in

Fig. 3. (The local K-index characterises the amplitude of the geomagnetic field variations at the given station within a three-hour interval.) The figure (constructed using the whole data set) shows that when the geomagnetic activity increases, the occurrence rate of SRS decreases. This holds not only for the whole data set, but also for every yearly subset (not shown).

5 Comparison of observations with predictions of the IAR theory

As it has been mentioned, SRS in the range of 0.1–10 Hz is commonly interpreted as a result of the IAR. According to the theory, SRS is due to the resonant nature of the ionosphere reflection coefficient, which is the ratio of the reflected magnetic field magnitude to the magnitude of the incident Alfvén wave.

We calculated the ionosphere reflection coefficient using the full-wave analysis method by Ostapenko and Polyakov (1990). The method allows one to calculate the reflection coefficient of the upper ionosphere based on computing the wave amplitude at any altitude. The calculations require knowledge of the altitudinal profile of the ionospheric electron and ion densities. Due to the lack of measurements of these parameters, the calculation has been done using the IRI-95 model. Figure 4a shows the electron density profiles (according to IRI-95) above the site with coordinates of SGO for mid-winter and mid-summer conditions in 1995 and 1999. (Note that the year 1995 is close to a minimum, and the year 1999 is close to a maximum of the solar activity.) All profiles are taken for 00:00–03:00 UT. The calculated reflection coefficients are shown in Fig. 4b. They exhibit clear resonant structure, but the features of the structure vary significantly depending on season and year. Namely, the modulation depth for the year of the solar activity minimum is larger. This means that the probability of observing the structure on the ground should be larger as well (see discussion in Trakhtengerts et al., 2000; Belyaev et al., 2000). From Fig. 4b one can also infer a seasonal dependence. Indeed, the modulation depth in winter is larger than in summer. From Fig. 4b it is clear that a larger difference between neighbouring minima of the reflection coefficient (ΔF) is expected in 1995, and a smaller one in 1999. The difference between winter and summer is also evident. Thus, the tendencies evident from the calculations based on the IAR theory presented in Fig. 4b are in a good qualitative agreement with the SRS morphology.

An important element of the above consideration is the use of the IRI model. In spite of the usefulness and advantages of this model, the imperfection of the IRI model is well known. In particular, at the high latitudes it may reproduce the ionosphere parameters with significant errors. To illustrate this fact, we compared the electron densities obtained from the ionosonde observations with those calculated from the IRI model (Figs. 5a and b). To estimate N_{emax}, we used the SGO ionosonde measurements of the critical frequency *fo*F2. (This frequency is the maximum ordinary mode radio wave frequency capable of reflection from the F2-region of the ionosphere; this is proportional to the square root of the maximum electron density.) Figure 5a shows N_{emax} calculated from the median values of *fo*F2 for every month within eight 3-h intervals of UT. Figure 5b demonstrates the maximal density in the F-layer revealed by the IRI model. The discrepancy is clearly seen.

Fortunately, the IRI model gives us an opportunity to adapt the model result to some observable parameters. In further calculations, we used the IRI model adapted to observations of the electron density in the F-layer maximum (N_{emax}), as shown in Fig. 5a. Thus, we obtained the profiles of the ionospheric parameters needed for the reflection coefficient calculations. In turn, the calculated ionosphere reflection coefficients similar to those presented in Fig. 4b were used to reveal the frequency scale ΔF within every 3-h interval for the middle day of every month during 1995–1999. The calculated values of ΔF are shown in Fig. 6. (Some gaps in the plot are due to the lack of *fo*F2 measurements.) Quantitatively, the calculated frequency scale exhibits diurnal, seasonal, and long-term variations similar to those observed (Fig. 2a), but values of the parameter may sometimes differ significantly. More likely, this fact means that the problems with the IRI model are not solely due to an incorrect prediction of the maximum electron density in the F-region. Evidently, the upper part of the ionosphere (above the F-layer maximum), which cannot be probed by ionosonde, is also reproduced poorly by the model.

6 Summary and discussion

We studied the morphological properties of the spectral resonance structure in the background electromagnetic noise in the frequency range 0.1–4.0 Hz, as observed at Sodankylä Geophysical Observatory, which is situated in the auroral zone, $L = 5.2$. It was shown that:

1. Both the SRS occurrence rate and the SRS frequency scale exhibit a clear diurnal variation. Both values are highest in the night hours;

2. There is a clear dependence on season. Both the occurrence rate and the frequency interval are higher in winter than in summer (with some exception for the occurrence rate at 18:00–24:00 UT in 1995–1997);

3. The long-term behaviour of the two parameters exhibits a tendency to become smaller from the years of solar minimum to the years of solar maximum;

4. The occurrence rate of SRS decreases when geomagnetic activity increases.

Similar diurnal variations of ΔF were found by Bösinger et al. (2002) at low latitude, by Belyaev et al. (1989a) at middle latitude and by Belyaev et al. (1999) and Semenova et

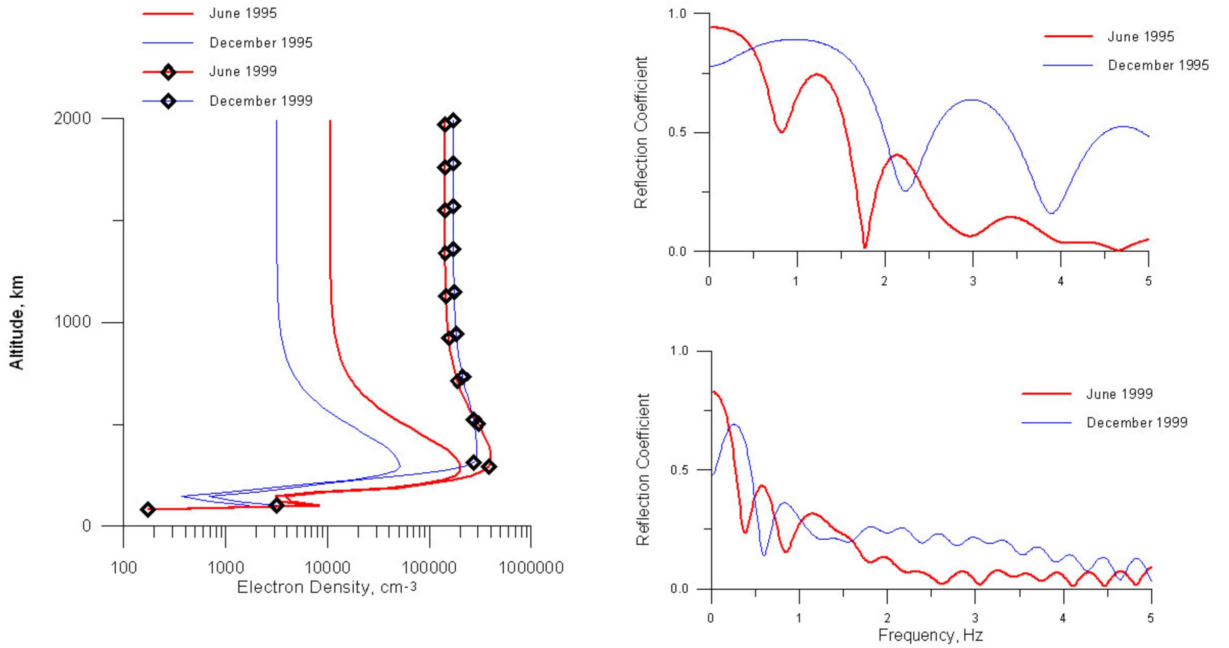

Fig. 4. **(a)** Altitude profiles of the ionospheric electron density above Sodankylä according to the IRI-95 model for summer and winter conditions during solar minimum (1995) and maximum (1999). **(b)** Reflection coefficient of ionosphere as a function of frequency for summer and winter conditions during solar minimum (1995) and maximum (1999). The calculation has been done using the "full wave" algorithm by Ostapenko and Polyakov (1990) taking into account the ionosphere density profiles shown in Fig. 4a.

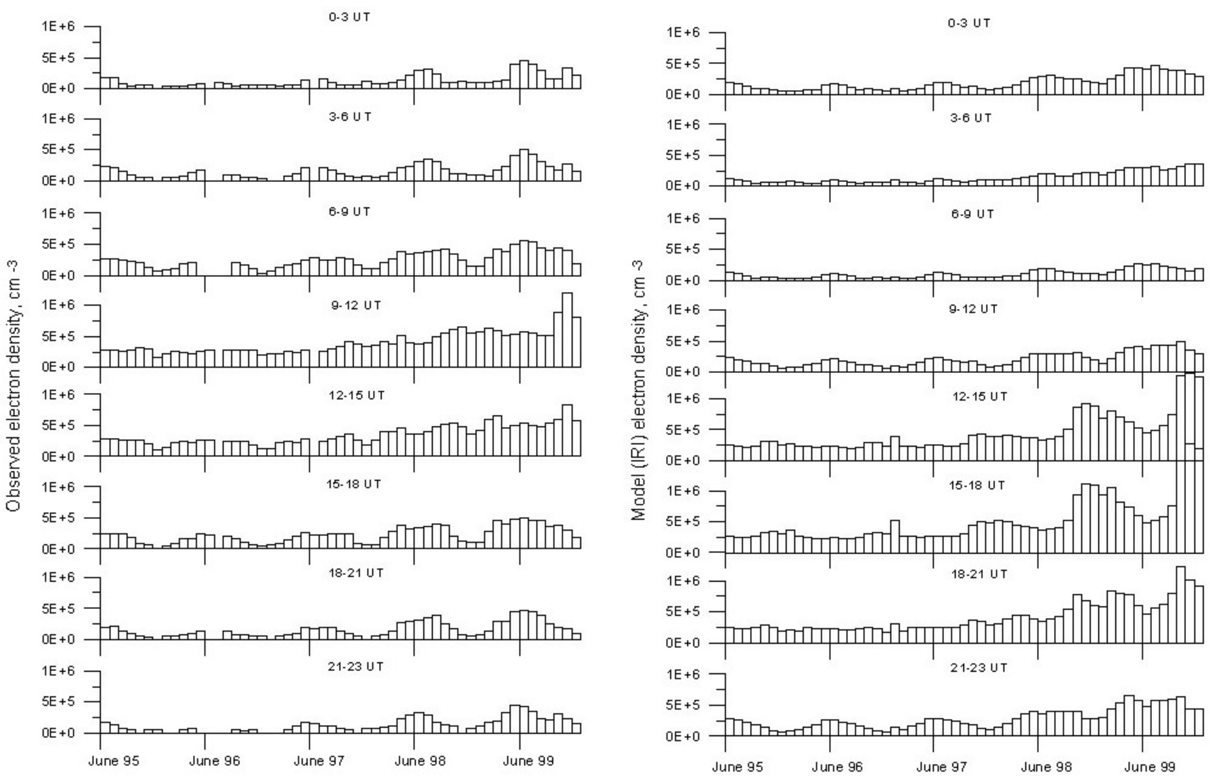

Fig. 5. **(a)** Electron density in the maximum of the F-layer (N_{emax}) obtained from monthly median values of *fo*F2 measured by ionosonde in SGO within 3-h intervals during 1995–1999. **(b)** Electron density in the maximum of the F-layer (N_{emax}) above Sodankylä according to the IRI model for the middle of every 3-h interval of the middle day of every month during 1995–1999.

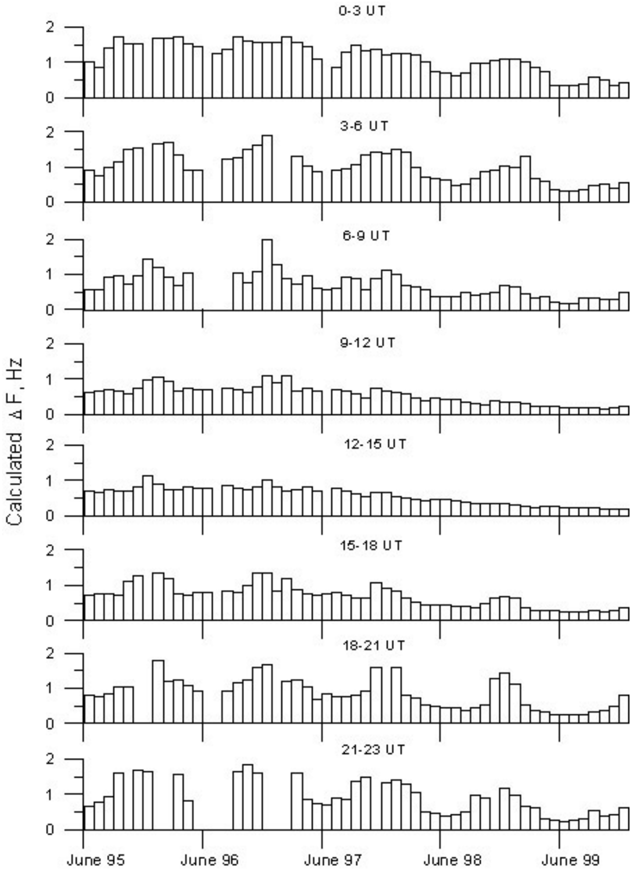

Fig. 6. Values of the SRS frequency scale during 1995–1999 calculated on the basis of the IAR theory using the IRI model adapted to the values of N_{emax} shown in Fig. 5a.

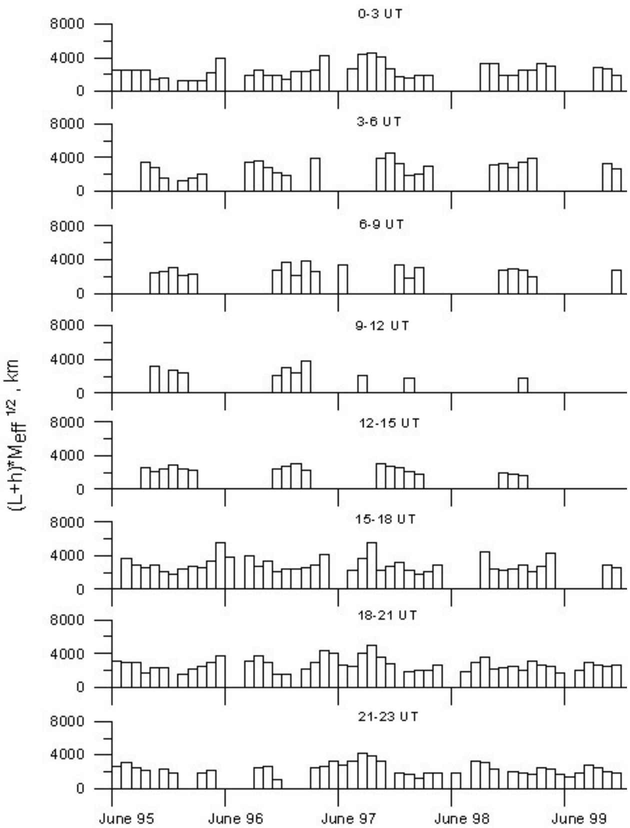

Fig. 7. The long-term variations of the parameter L, characterising the upper ionosphere electron density decay, inferred from the SRS frequency scale and ionosonde *fo*F2 measurements made in SGO.

al. (1999) in the auroral zone. The diurnal behaviour is explained on the basis of the IAR theory as a result of diurnal changes in the upper ionosphere. Demekhov et al. (2000) did a quantitative modelling of the diurnal changes in ΔF and obtained a good correspondence with observations.

The seasonal dependence has not been noted in the past literature. As to the variations during the solar cycle, Belyaev et al. (2000) have found a similar behaviour, as reported here, of the occurrence rate in mid-latitudes on the basis of 10 years of observations. Note that Belyaev et al. (2000) could not resolve the seasonal variation because the observations were very scanty (sometimes only a few days per year). The solar cycle variation of the SRS occurrence rate was explained by Trakhtengerts et al. (2000) on the basis of the IAR theory by consideration of the modulation depth of the ionosphere reflection coefficient for solar minimum and maximum conditions. As shown in the previous section, both seasonal and solar cycle dependence of the frequency interval are also in a good qualitative agreement with the predictions of the theory.

This qualitative agreement confirms the suggestion by Belyaev et al. (1989b) that the SRS frequency scale can possibly be used for the estimate of the upper ionosphere parameters. The SRS observations, along with the ionosonde measurements, enable us to estimate the parameter which characterises the scale of the electron density decrease above the F-layer maximum. Thus, we determined the value $L = (l + h) * (M_{eff})^{1/2}$ according to Eq. (1) by using ΔF and N_{emax} from Figs. 2a and 5a, respectively. The result presenting the long-term variation of L is shown in Fig. 7. For this figure those values of ΔF were taken which were obtained with a probability of the SRS observation exceeding the threshold of 10% (see Fig. 2b). This fact, as well as the lack of the *fo*F2 observations during some intervals, explains the gaps in Fig. 7. It is interesting to compare these characteristics with that estimated from the IRI model. Of course, the model electron density profile differs from the simplified one applied for derivation of the Eq. (1). As a proxy for the sum $(l + h)$ we take l_0, which is the characteristic scale of the electron density altitude decay above the F-layer maximum. To obtain l_0 we approximated the model profile by an exponent, which provides the model electron density values in two points: at the maximum of F-layer and at an altitude of 1500 km. The long-term behaviour of the $l_0 * (M_{eff})^{1/2}$ for interval 18:00–21:00 UT is shown in Fig. 8. (M_{eff} – the effective mass of ions in the F-layer maximum – is determined here from the IRI model.) Comparing the quantities

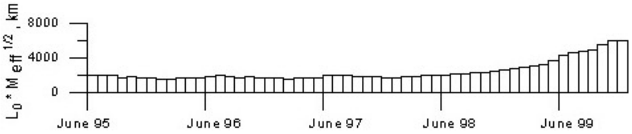

Fig. 8. The long-term variations of the upper ionosphere electron density decay inferred from the IRI model. The decay estimation was done for the middle of the 18:00–21:00 UT interval of the middle day of every month during 1995–1999.

$l_0 * (M_{eff})^{1/2}$ and $(l+h))*(M_{eff})^{1/2}$, which are revealed, respectively, from the ionosphere model (Fig. 8) and observations (Fig. 7), one can see a significant difference. The parameter revealed from observations is more variable with season. This seems to be natural, keeping in mind polar night and day conditions during northern winter and summer, respectively. The model parameter is rather stable during 1995–1998, and it increases unrealistically in 1999. The overestimation of the top-side ionosphere electron density for the high solar activity conditions was noted, for example, by Radicella and Leitinger (2001). We believe that the account of the observed SRS characteristics can help in improving the existing ionosphere models, although the applicability of the SRS-related estimates still needs a direct verification (e.g. by comparison with the EISCAT measurements).

The IAR theory also explains the influence of the geomagnetic activity on the SRS occurrence. Indeed, increasing the geomagnetic activity means an enhancement of the particle precipitation, which, in turn, increases the conductance in the E-region. According to the theory, the modulation depth of the SRS decreases when the conductivity in the E-region increases (see Trakhtengerts et al., 2000, their formula 2).

The exceptional behaviour of the occurrence rate during two intervals (18:00–21:00 and 21:00–24:00 UT) is puzzling. Although we cannot yet explain this anomaly unambiguously, we would like to note that one possible reason might be the influence of the geomagnetic activity, which, for night hours in winter 1995–1996 and 1996–1997, was rather strong. Another reason might be the fact that the SRS eigenfrequencies increase very rapidly to the night hours for the years close to the solar cycle minimum. This could result in the loss of statistics for those SRS cases, whose eigenfrequencies are above the upper frequency limit used in the present study.

7 Conclusion

We performed a morphological study of the electromagnetic noise SRS observed at an auroral zone station. We showed that the SRS diurnal behaviour found at mid-latitudes is also present in the auroral zone data. At the same time our study revealed new SRS properties. These are the seasonal variations in the frequency scale and the occurrence rate of SRS, the solar cycle variation in the frequency scale, and dependence on local geomagnetic activity. We demonstrated that these morphological properties of SRS agree with predictions by the IAR theory. Finally, we confirmed that observations of SRS could be used for estimation of the upper ionosphere parameters and for improving the existing ionosphere models.

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