

DEPENDENCE OF OCCURRENCE PROBABILITY OF THE SPORADIC E_s LAYER ON SOLAR ACTIVITY AT DIFFERENT VALUES OF E_s CRITICAL FREQUENCY

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Abstract. The aim of the paper is to study the dependence of the occurrence probability of the sporadic E_s layer on solar activity at different values of the E_s critical frequency. The paper uses data from ionosondes at Irkutsk (52.3° N, 104.3° E), Kaliningrad (54.36° N, 20.12° E), and Novosibirsk (54.84° N, 83.23° E). A new method for correlation analysis of the relationship between the E_s occurrence probability and solar activity has been developed. The method involves calculating the correlation coefficients R between annual average values of the solar activity index $F10.7$ and annual average occurrence probabilities of sporadic E_s layer, whose critical frequency f_oE_s is in the range $f_i \sim f_{i+1}$. As a result of applying the new method, we have found that the correlation coefficients are negative for the f_oE_s ranges

of 1–2 and 2–3 MHz and positive for 4–5 MHz for all three stations; however, the results for $f_oE_s > 5$ MHz differ for different stations. The obtained results are interpreted on the basis of three factors of solar activity influence: 1) increase in photoionization; 2) weakening of the zonal component of the prevailing wind; 3) increase in absorption of radio waves in the underlying layers of the ionosphere.

Keywords: ionosphere; sporadic ionosphere; solar activity; correlation coefficients.

INTRODUCTION

The sporadic E layer (E_s) is a thin plasma layer of metallic and molecular ions formed at E-layer heights from 90 to 130 km. Sometimes E_s becomes denser than the regular E layer, or even denser than the main F2 layer. In such cases, the E_s layer has a significant impact on signal propagation in the F-region and on ionosonde ionograms.

The effect of solar activity on changes in E_s-layer parameters is still an open question. On the one hand, some studies have discovered a high positive correlation between E_s-layer parameters and solar activity indices. On the other hand, there are studies which argue that there is no such a correlation or reveal a negative correlation between E_s-layer parameters and solar activity indices.

Let us review some results of the research on the relationship between solar activity and changes in E_s-layer parameters. Pezzopane et al. [2015] using data from the Rome station (41.8° N, 12.5° E) for 1976–2009 have found a high positive correlation between annual average $F10.7$ and the moving annual average of mean daytime critical frequency (f_oE_s), as well as the blanketing frequency (f_bE_s). Correlation coefficients R were 0.77 for f_oE_s and 0.94 for f_bE_s . For individual solar cycles, R was 0.81–0.94 for f_oE_s and 0.88–0.98 for f_bE_s . Maksyutin et

al. [2001] also established a high positive correlation ($R=0.91$)

between annual average of mean daytime f_oE_s and the sunspot number W for the Moscow station (56° N, 37° E) in 1958–1990, whereas for average f_oE_s they observed a weak negative correlation ($R=-0.19$). Trend removal resulted in an increase in both positive ($R=0.94$) and negative correlations ($R=-0.38$). Zhang et al. [2015], when analyzing data for 1970–2010, discovered a noticeably lower correlation between daytime average f_oE_s and W as compared to [Maksyutin et al., 2001]: $R=0.33$, 0.46, and 0.63 for the stations Hainan (20.00° N, 110.34° E), Lanzhou (36.06° N, 103.87° E), and Syowa (69.00° S, 39.60° E) respectively. The results received by Zhang et al. [2015] for nocturnal average f_oE_s also turned out to be different from the results obtained by Maksyutin et al. [2001]: a high negative correlation ($R=-0.76$) for the Hainan station and a weak positive correlation ($R=0.14$) for the Syowa station. The results of [Niu et al., 2019] differ the most from the results received by Pezzopane et al. [2015] and Maksyutin et al. [2001]. Niu et al. [2019] examined the correlation coefficients R between annual average zonal-mean intensities of E_s and annual average $F10.7$ for various magnetic latitude zones for 2007–2012. The E_s intensity was calculated using COSMIC radio occultation data. For daytime conditions,

R varied from ~ -0.2 ($10\text{--}20^\circ$ S, $20\text{--}30^\circ$ S, $10\text{--}20^\circ$ N) to $\sim +0.5$ ($40\text{--}50^\circ$ S, $0\text{--}10^\circ$ N, $40\text{--}50^\circ$ N) at $R \sim 0$ for $0\text{--}10^\circ$ S and $30\text{--}40^\circ$ N, i.e. without apparent dependence on magnetic latitude. For nighttime conditions, R was negative, varying from ~ -0.2 ($0\text{--}10^\circ$ S and $20\text{--}30^\circ$ N) to ~ -0.6 ($10\text{--}20^\circ$ S and $10\text{--}20^\circ$ N). At the same time, Sivakandan et al. [2023] found a high positive correlation between annual average f_oE_s and W from 1957 to solar cycle 23 and a decrease in the correlation from cycle 24.

To investigate the effect of solar activity on the E_s occurrence probability (PE_s), Maksyutin et al. [2001] have developed the following method. Annual average occurrence probabilities of E_s with critical frequencies exceeding the threshold values of $PE_s(f_oE_s > f_i)$, $f_i = 3, 4, 5, 6$, and 7 MHz were calculated. Next, the correlation coefficients were worked out between $PE_s(f_oE_s > f_i)$ and annual average sunspot numbers W , i.e. $R(f_oE_s > f_i)$. Applying this method to the data from the stations Moscow (56° N, 37° E), Alma-Ata (43.2° N, 76.9° E), and Irkutsk (52.5° N, 104.0° E) for 1958–1990, Maksyutin, Sherstyukov [2005] received the following results. For all the stations, the highest positive correlation coefficients corresponded to $R(f_oE_s > 3 \text{ MHz})$: 0.86 for the Moscow and Alma-Ata stations and 0.60 for the Irkutsk station. For all the stations, the highest negative correlation coefficients match $R(f_oE_s > 7 \text{ MHz})$: -0.53 for the Moscow station and -0.20 for the Alma-Ata and Irkutsk stations. For all the stations, $R(f_oE_s > f_i)$ decreased monotonously with increasing f_i from the largest positive $R(f_oE_s > 3 \text{ MHz})$ to the largest negative $R(f_oE_s > 7 \text{ MHz})$.

The method described above [Maksyutin et al., 2001] was adopted by Zuo, Wan [2002] to analyze data from the stations Alma-Ata (43.2° N, 76.9° E), Maui (20.8° N, 203.5° E), and Boulder (40° N, 254.7° E); and by Zhang et al., [2015], to analyze data from the Hainan, Lanzhou, and Syowa stations. Unlike [Maksyutin et al., 2001; Maksyutin, Sherstyukov, 2005], Zuo, Wan [2002] and Zhang et al. [2015] carried out the analysis separately for day, night, and all days. As in [Maksyutin, Sherstyukov, 2005], high positive correlation coefficients ($R > 0.6$) were obtained for daytime, except the Syowa station ($R(3 \text{ MHz}) = 0.44$). At the same time, for a number of stations (Hainan, Lanzhou, Maui), the highest positive correlation coefficients R , as opposed to [Maksyutin, Sherstyukov, 2005], were $f_oE_s > 4 \text{ MHz}$. At night, the correlation coefficients were negative for all the stations, except the Syowa station, where $R(f_oE_s > f_i)$ were positive for all f_i . For the Hainan and Lanzhou stations, the highest negative correlation coefficients were $f_oE_s > 7 \text{ MHz}$, as in [Maksyutin, Sherstyukov, 2005]. For the Hainan and Lanzhou stations, the dependence $R(f_oE_s > f_i)$ was different: as f_i increased, the modulus $R(f_oE_s > f_i)$ decreased for the Hainan station and increased for the Lanzhou station.

While the results received by Zuo, Wan [2002] and Zhang et al. [2015] for mid-latitude stations are generally consistent with the patterns found by Maksyutin, Sherstyukov [2005], Pietrella, Bianchi [2009] concluded that the E_s occurrence probability over the Rome station (41.8° N, 12.5° E) weakly depends on solar activity. The conclusion about the insignificant influence of solar activity was drawn from comparison of diurnal and seasonal variations in the E_s occurrence probability with

critical frequencies exceeding the threshold values of $PE_s(f_oE_s > f_i)$, $f_i = 3, 4, 5, 6, 7, 8$, and 9 MHz at minimum and maximum solar activity.

This paper examines the effect of solar activity on the E_s occurrence probability, using the method developed by Maksyutin et al. [2001], and compares the findings with the results of other studies, as well as discusses an alternative method for studying the effect of solar activity on the occurrence probability of the E_s layer.

DATA

The paper is based on data from the following vertical sounding ionosondes: DPS-4, 2003–2023, the Irkutsk station (52.3° N, 104.3° E); Parus-A, 2015–2024, the Kaliningrad station (54.36° N, 20.12° E); automatic ionospheric station (AIS), 1975–1995, Parus, 1995–2023, and a chirp ionosonde, 2023–2024, the Novosibirsk station (54.84° N, 83.23° E).

As a characteristic of the E_s layer, we have taken the annual average E_s occurrence probabilities PE_s in a given range of E_s critical frequencies, representing the ratio of the number of E_s observations in a given range of critical frequencies for a given year to the total number of observations for this year. The choice of the annual interval was dictated by two reasons. First, this interval has been chosen in many previous studies, whose results are compared with ours below. Second, the annual average occurrence probability of E_s depends primarily on solar activity, since the contribution of shorter-period types of activity, such as geomagnetic or meteorological, is suppressed due to the large averaging interval. A similar investigation for shorter intervals (season or month) is of interest and is the subject of a follow-up study.

The analysis method involved calculating the correlation coefficients R between annual average $F10.7$ and annual average occurrence probabilities of the E_s layer in a given range of critical frequencies. As our calculations have shown, for high R the zero-shift correlation is optimal. At low R , the correlation with shift may result in a slight increase in R , but R still remains low; therefore, further we demonstrate the results received at zero shift.

RESULTS OF CORRELATION ANALYSIS OF THE OCCURRENCE PROBABILITY OF THE E_s LAYER AND $F10.7$

We have processed the Irkutsk data for 2003–2023, employing the method developed by Maksyutin et al. [2001], i.e. we have calculated annual average E_s occurrence probabilities with critical frequencies exceeding the threshold values of $PE_s(f_oE_s > f_i)$, $f_i = 1, 2, 3, 4, 5, 6$, and 7 MHz . Next, we estimated the correlation coefficients $R(f_oE_s > f_i)$ between $PE_s(f_oE_s > f_i)$ and annual average $F10.7$. As in [Zuo, Wan, 2002; Zhang et al., 2015], the analysis was carried out separately for day (09–15 LT), night (21–03 LT), and all days. Additionally, we computed the annual average E_s occurrence probabilities with blanketing frequencies f_oE_s exceeding the threshold values of $PE_s(f_oE_s > f_i)$, $f_i = 1, 2, 3, 4, 5, 6$, and 7 MHz , for which we also calculated the correlation coefficients

$R(f_b E_s > f_i)$ between $PE_s(f_b E_s > f_i)$ and annual average $F10.7$. Figure 1 plotted $R(f_o E_s > f_i)$ and $R(f_b E_s > f_i)$ as function of f_i for the Irkutsk station for 2003–2023.

The main difference between the results received for the Irkutsk station and the results of previous studies is low positive daytime correlation coefficients with maximum $R(f_o E_s > 4 \text{ MHz}) = 0.18$. In [Maksyutin, Sherstyukov, 2005; Zuo, Wan, 2002; Zhang et al., 2015] for mid-latitude stations, maximum daytime positive R was at least 0.6. Another difference includes the high negative correlation coefficients for daytime with maximum $R(f_o E_s > 5 \text{ MHz}) = -0.62$. In [Maksyutin, Sherstyukov, 2005; Zhang et al., 2015] for mid-latitude stations, maximum daytime negative R was $R(f_o E_s > 7 \text{ MHz}) = -0.53$ for the Moscow station (56° N , 37° E) and $R(f_o E_s > 7 \text{ MHz}) \sim -0.20$ for the remaining stations. Thus, the Irkutsk data showed a decrease in positive and an increase in negative correlation under daytime conditions relative to the results of previous studies. Negative correlation coefficients in the range $-0.42 \div -0.07$ were obtained for the Irkutsk station at night, which matches the range of correlation coefficients for the night period presented by Zuo, Wan [2002] and Zhang et al. [2015], except for the Syowa station (69.00° S , 39.60° E), where a positive correlation was observed at night.

During the transition from $f_o E_s$ to $f_b E_s$, both positive and negative correlations increase for the Irkutsk station: maximum daytime positive $R(f_b E_s > 4 \text{ MHz}) = 0.46$; maximum daytime negative $R(f_b E_s > 6 \text{ MHz}) = -0.73$; night correlation coefficients are within $-0.57 \div -0.30$.

The significant difference between the correlation coefficients for the Irkutsk station and those derived by previous studies was the motivation for comparing R for the Irkutsk station with R for the Kaliningrad and Novosibirsk stations. Figure 2 shows $R(f_o E_s > f_i)$ and $R(f_b E_s > f_i)$ as function of f_i for the Kaliningrad station for 2015–2024.

Unlike the Irkutsk station, the Kaliningrad station has a very high positive correlation coefficient $R(f_o E_s > 4 \text{ MHz}) = 0.92$ under daytime conditions, which exceeds the highest R given in [Maksyutin, Sherstyukov, 2005; Zuo, Wan, 2002; Zhang et al., 2015], except the values for the Maui station (20.8° N , 203.5° E): $R(f_o E_s > 4 \text{ MHz}) = 0.96$. Another difference is that the maximum negative correlation coefficient under daytime conditions for the Kaliningrad station is inherent to $f_o E_s > 1 \text{ MHz}$ (i.e. to all E_s) and is equal to $R(f_o E_s > 1 \text{ MHz}) = -0.47$,

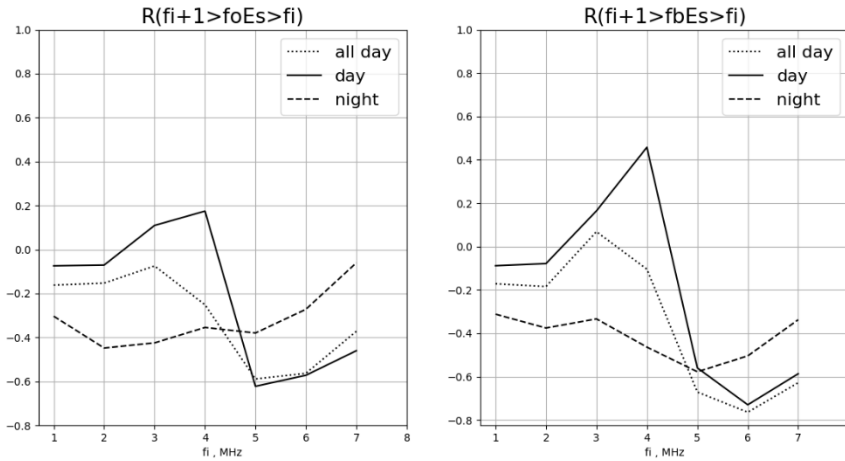


Figure 1. Correlation coefficients between annual average $F10.7$ and occurrence probabilities $P(f_o E_s \geq f_i)$ (left) and $P(f_b E_s \geq f_i)$ (right) for the Irkutsk station for 2003–2023

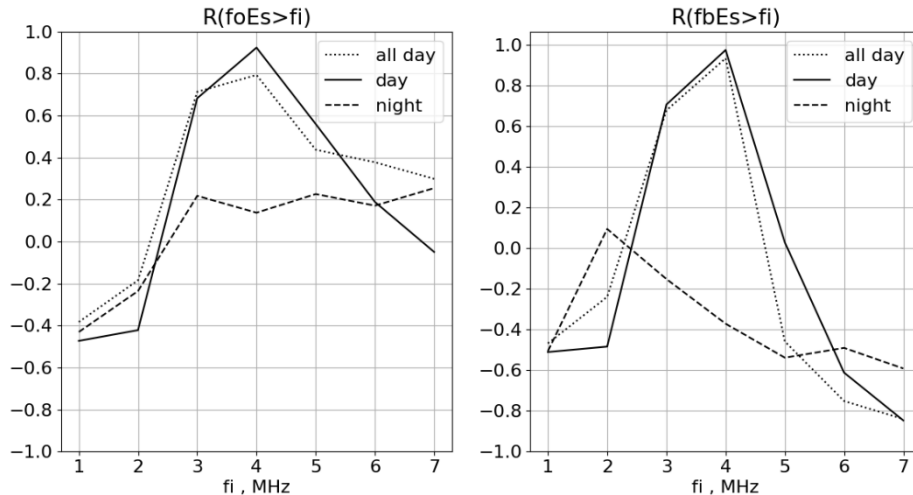


Figure 2. The same as in Figure 1, but for the Kaliningrad station for 2015–2024

whereas for the Irkutsk station $R(f_o E_s > 1 \text{ MHz}) = -0.07$. In the range $f_o E_s > 7 \div 8 \text{ MHz}$, there are low negative daytime correlation coefficients: $R(f_o E_s > 8 \text{ MHz}) = -0.15$, which differs from R in the similar range of $f_o E_s$ for the Irkutsk station and is close to the results received in [Maksyutin, Sherstyukov, 2005; Zhang et al., 2015], except R for the Moscow station (56° N , 37° E): $R(f_o E_s > 7 \text{ MHz}) = -0.53$. At night at the Kaliningrad station there is a positive correlation for $f_i \geq 3 \text{ MHz}$, which differs from the behavior of the correlation coefficients both for the Irkutsk station and for the stations whose results are reported in [Zuo, Wan, 2002; Zhang et al., 2015], except the high-latitude Syowa station (69.00° S , 39.60° E), where a positive correlation was also recorded at night.

As for the Irkutsk station, there is an increase in both positive and negative correlations for the Kaliningrad station during the transition from $f_o E_s$ to $f_i E_s$. For daytime, maximum positive R for $f_i = 4 \text{ MHz}$ rises slightly — from 0.92 to 0.98, whereas the maximum negative value changes significantly: from -0.15 to -0.85 . The correlation coefficients for the night period for $f_i E_s$ are largely negative and reach $R(f_i E_s > 7 \text{ MHz}) = -0.59$, which is close to the results for the Irkutsk station: $R(f_o E_s > 5 \text{ MHz}) = -0.57$.

During the initial analysis, we took data from the Novosibirsk station, which spanned the same time interval (2015–2024) as data from the Kaliningrad station. Calculations showed that all correlation coefficients turned out to be negative in the range $\sim -0.4 \div -0.8$.

To verify this unexpected result, we analyzed the Novosibirsk station data for the AIS operating period, i.e. for 1975–1990. The results are presented in Figure 3. The correlation coefficients $R(f_o E_s > f_i)$ as function of f_i proved to be generally close to similar dependences obtained from the Kaliningrad station data. In the range $f_i \geq 3 \text{ MHz}$, the behavior of the correlation coefficients for daytime as function of f_i for the Novosibirsk and Kaliningrad stations is similar. Both stations are characterized by a high positive correlation for $f_i = 4 \text{ MHz}$: $R(f_o E_s > 4 \text{ MHz}) = 0.94$ for the Novosibirsk station and 0.92 for the Kaliningrad station. As f_i goes up, the correlation coefficient goes down, remaining positive for the Novosibirsk station and reaching small negative values

for the Kaliningrad station. At $f_i < 3 \text{ MHz}$, the daytime correlation coefficient is negative for the Kaliningrad station ($\sim -0.5 \div -0.4$) and positive for the Novosibirsk station ($\sim -0.2 \div 0.3$). In this frequency range, the R values for the Irkutsk station are intermediate between those for the Novosibirsk and Kaliningrad stations.

In our opinion, the reason for the negative correlations for the Novosibirsk station data in 2015–2024 is that the E_s occurrence probabilities during minimum solar activity (2018–2020, minima of cycles 24 and 25) are higher than during maximum solar activity (2014–2015, maximum of cycle 24). Analysis of the Irkutsk station data for 2015–2024 has not revealed any fundamental differences from the results for 2003–2023, and therefore we omit the results of the Irkutsk station data analysis for 2015–2024 in this paper.

ALTERNATIVE METHOD FOR CORRELATION ANALYSIS OF PE_s AND $F10.7$. RESULTS AND DISCUSSION

Based on the research results [Chavdarov et al., 1975; Maksyutin et al., 2001; Maksyutin and Sherstyukov, 2005; Pezzopane et al., 2015], we can identify three main factors affecting the occurrence probability of the sporadic layer at different levels of solar activity. The first factor is an increase in photoionization with increasing solar activity, which leads to a rise in electron and molecular ion densities in the regular E layer. The second factor is a change of wind shear in a solar cycle. The third factor is an increase in absorption of short radio waves with increasing solar activity. The first factor primarily affects layers consisting of molecular ions with relatively low critical frequencies $f_o E_s$ (the threshold value has not been determined), the occurrence probability of such layers increases with increasing solar activity. The third factor influences layers with low critical frequencies $f_o E_s$ (the threshold value depends on the ionosonde potential), reducing the probability of their observation with increasing solar activity. Thus, the occurrence probability of the layers consisting of molecular ions with low critical frequencies $f_o E_s$ depends on the competing influence of the first and

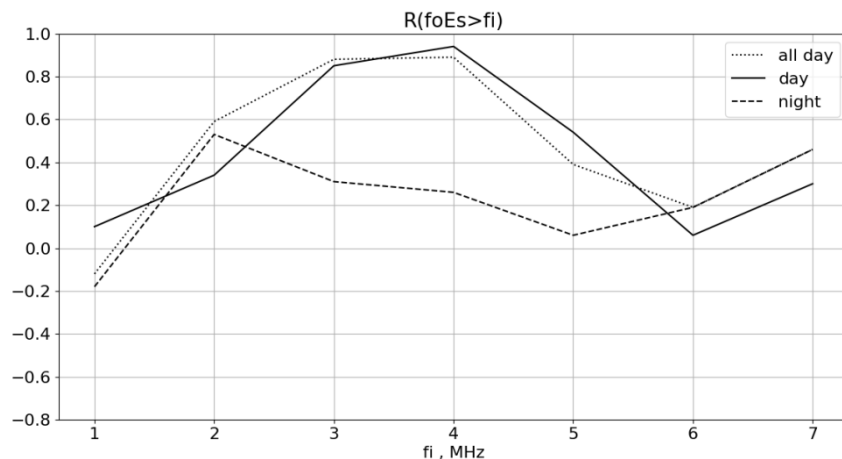


Figure 3. Correlation coefficients between annual average $F10.7$ and $P(f_o E_s > f_i)$ for the Novosibirsk station for 1975–1990

third factors. The second factor affects all layers. According to [Maksyutin et al., 2001; Maksyutin, Sherstyukov, 2005], this factor is dominant for intense layers composed of metal ions with high critical frequencies f_oE_s (photoionization has little effect on the metal ion density). It is this factor that Maksyutin et al. [2001] used to explain the negative correlation of the occurrence probability of intense layers with solar activity. The negative correlation between the occurrence probability of intense layers and solar activity can be attributed to a decrease in the zonal component of the prevailing wind with increasing solar activity. Mind that, according to [Pezzopane et al., 2015], as solar activity ramps up the metal ion density and the amplitude of the semidiurnal tide rise, i.e. there should not be a negative correlation.

The contribution of various factors both increasing and decreasing the E_s occurrence probability stimulated the development of an alternative method for correlation analysis of the occurrence probability of the sporadic layer and the solar activity index. An alternative to the integral estimate [Maksyutin et al., 2001] is a differential estimate, i.e. the calculation of the correlation coefficients R between annual average $F10.7$ and annual average occurrence probabilities of the E_s layer whose critical frequency f_oE_s is within $f_i \div f_{i+1}(P(f_{i+1} > f_oE_s \geq f_i))$. Similar calculations were performed for $P(f_{i+1} > f_bE_s \geq f_i)$. Figure 4 shows the correlation coefficients $R(f_{i+1} > f_oE_s \geq f_i)$ and $R(f_{i+1} > f_bE_s \geq f_i)$ as function of f_i for the Irkutsk station for 2003–2023.

Let us consider the daytime conditions. For f_oE_s 1–2 and 2–3 MHz, correlation coefficients are negative (–0.32 and –0.34), which is due to the dominance of the third factor (a decrease in PE_s with increasing absorption). The highest positive correlation is observed for f_oE_s 4–5 MHz ($R=0.78$), which implies a significant dominance of the first factor (a rise in PE_s with increasing photoionization). For f_oE_s 5–6 and 6–7 MHz, correlation coefficients become negative (–0.51 and –0.57), which may be due to the dominance of the second factor (a fall in PE_s with a change of wind shear in a solar cycle). At night, correlation coefficients are negative for

all f_oE_s , a maximum is observed for f_oE_s 6–7 MHz ($R=-0.58$). This fact may be related to the increasing influence of the second factor as f_oE_s goes up. As in the integral estimate, when passing from f_oE_s to f_bE_s , both positive and negative correlations ramp up: daytime maximum positive $R(5 > f_bE_s > 4 \text{ MHz})=0.89$; nighttime maximum negative $R(7 > f_bE_s > 6 \text{ MHz})=-0.65$.

Figure 5 depicts the correlation coefficients $R(f_{i+1} > f_oE_s \geq f_i)$ and $R(f_{i+1} > f_bE_s \geq f_i)$ as function of f_i for the Kaliningrad station for 2015–2024.

Under daytime conditions, as for the Irkutsk station, the correlation coefficients are negative (–0.67 and –0.78) for f_oE_s 1–2 and 2–3 MHz, and the highest positive correlation is recorded for f_oE_s 4–5 MHz ($R=0.92$). Accordingly, the data can be explained by the consistent dominance of the third and first factors. A fundamental difference in the behavior of the correlation coefficients is observed for the ranges with $f_oE_s > 5$ MHz. For the Irkutsk station, the correlation is negative; and for the Kaliningrad station, the correlation decreases as f_i increases, while remaining positive. Such behavior of R can be interpreted as a consistent decrease in the influence of the first factor and an increase or persistence of the second.

Contrary to R for the Irkutsk station, there are both negative and positive correlations for the Kaliningrad station at night. The maximum negative correlation coefficient is typical for f_oE_s 1–2 MHz ($R=-0.70$); and the largest positive value, for f_oE_s 3–4 MHz ($R=0.45$). For $f_oE_s > 4$ MHz, the correlation is insignificant (R varies from –0.15 to +0.14). The high negative correlation for f_oE_s 1–2 MHz may be linked to the third factor (a decrease in PE_s with an increase in absorption). The insignificant correlation for $f_oE_s > 4$ MHz can be attributed to the absence of any significant effect of all three factors: absorption has no effect due to sufficiently large values of f_oE_s , there is no photoionization at night, and wind shear does not change in a solar cycle.

When passing from f_oE_s to f_bE_s , the positive correlation increases for daytime conditions: $R(5 > f_bE_s > 4 \text{ MHz})=0.99$, and there is also a strong negative correlation for f_oE_s 7–8 MHz ($R=-0.74$). The nighttime correlation coeffi-

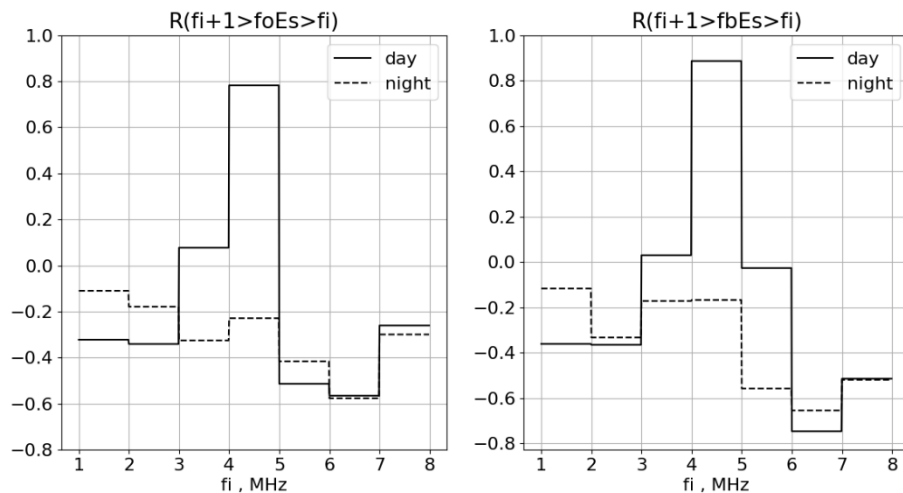


Figure 4. Correlation coefficients between annual average $F10.7$ and $P(f_{i+1} > f_oE_s \geq f_i)$ (left) and $P(f_{i+1} > f_bE_s \geq f_i)$ (right) for the Irkutsk station for 2003–2023

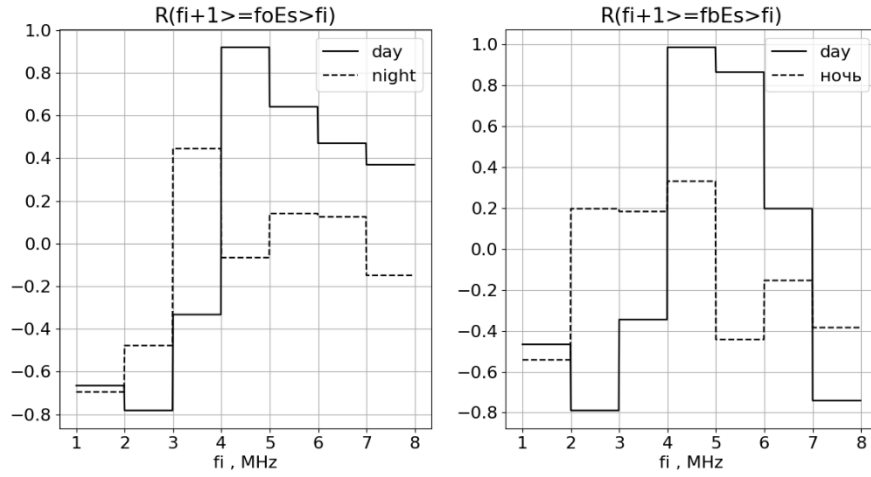


Figure 5. Correlation coefficients between annual average $F10.7$ and $P(f_{i+1} > f_o E_s \geq f_i)$ (left) and $P(f_{i+1} > f_b E_s \geq f_i)$ (right) for the Kaliningrad station for 2015–2024

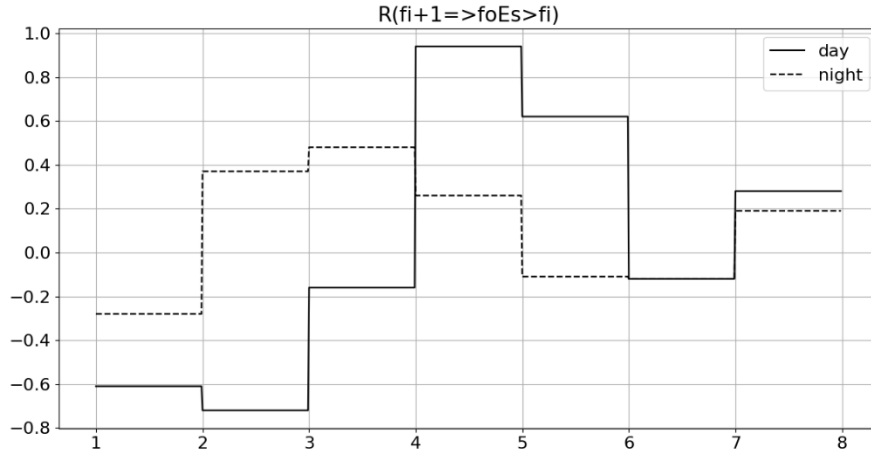


Figure 6. Correlation coefficients between annual average $F10.7$ and $P(f_{i+1} > f_o E_s \geq f_i)$ for the Novosibirsk station for 1975–1990

coefficients for $f_o E_s$ are both negative ($R(2 > f_o E_s > 1 \text{ MHz}) = -0.54$ and $R(6 > f_o E_s > 5 \text{ MHz}) = -0.44$) and positive ($R(5 > f_o E_s > 4 \text{ MHz}) = 0.33$).

Figure 6 shows the correlation coefficients $R(f_{i+1} > f_o E_s \geq f_i)$ as function of f_i for the Novosibirsk station for 1975–1990.

Under daytime conditions, the behavior of $R(f_{i+1} > f_o E_s \geq f_i)$ as function of f_i for the Novosibirsk and Kaliningrad stations is similar, except $f_o E_s$ 6–7 MHz: $R = 0.12$ for the Novosibirsk station and $R = +0.47$ for the Kaliningrad station. At night, both negative and positive correlations are observed for the Novosibirsk and Kaliningrad stations. The correlation coefficients in the range $f_o E_s$ 1–2 MHz differ most widely: $R = -0.28$ for the Novosibirsk station and $R = -0.70$ for the Kaliningrad station. Values of the correlation shift toward positive for $f_o E_s > 4 \text{ MHz}$ also differ markedly: R varies from -0.12 to $+0.26$ for the Novosibirsk station and from -0.15 to $+0.14$ for the Kaliningrad station.

Similar behavior of $R(f_{i+1} > f_o E_s \geq f_i)$ as function of f_i for the Novosibirsk and Kaliningrad stations for daytime conditions allows us to apply the same interpretation. For $f_o E_s < 3 \text{ MHz}$, the third factor dominates (a decrease in PE_s with an increase in absorption). For $f_o E_s$ 4–5 MHz, the first factor dominates (an increase in PE_s

with increasing photoionization). As $f_o E_s$ continues to ramp up, the influence of the first factor decreases. At night, the first factor has no effect of any kind, and the influence of the third factor is different: a high negative correlation in $f_o E_s$ 1–2 MHz for the Kaliningrad station and a weak negative correlation for the Novosibirsk station. The main difference between the behavior of the correlation coefficients $R(f_{i+1} > f_o E_s \geq f_i)$ for these stations and the behavior of R for the Irkutsk station is the absence or weak influence of the second factor (a decrease in PE_s with a change in wind shear in a solar cycle) on the E_s occurrence probability at these stations.

The difference between the correlation coefficients for the Irkutsk station and the correlation coefficients for the Novosibirsk and Kaliningrad stations has no apparent explanation. The fact that different stations have significantly different negative correlation coefficients was established by Maksyutin, Sherstyukov [2005], but the authors did not provide any explanation for it. Interestingly, negative correlation coefficients can differ substantially for the same station in choosing different time intervals for analysis.

Figure 7 plots the correlation coefficients $R(f_{i+1} > f_o E_s \geq f_i)$ and $R(f_{i+1} > f_b E_s \geq f_i)$ as function of f_i for the Novosibirsk station for 1996–2009.

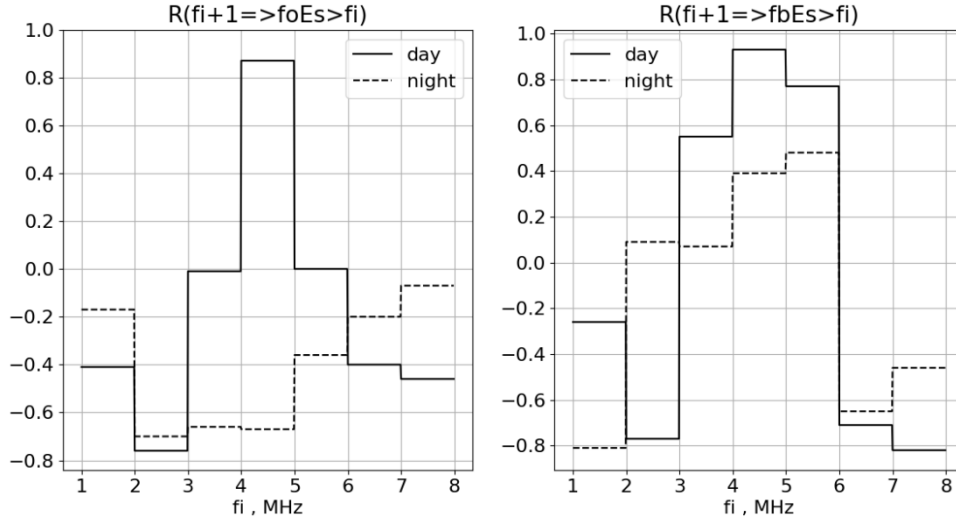


Figure 7. Correlation coefficients between annual average $F10.7$ and $P(f_{i+1} > f_o E_s \geq f_i)$ (left) and between $F10.7$ and $P(f_{i+1} > f_b E_s \geq f_i)$ (right) for the Novosibirsk station for 1996–2009

Figure 7 shows that under daytime conditions at large values of $f_o E_s$ and $f_b E_s$ the correlation coefficients reach rather large negative values: $R(8 > f_o E_s > 7 \text{ MHz}) = -0.48$ and $R(8 > f_b E_s > 7 \text{ MHz}) = -0.82$. Thus, under daytime conditions, the behavior of the correlation coefficients $R(f_{i+1} > f_o E_s \geq f_i)$ as function of f_i for the Novosibirsk station for 1996–2009 is closer to the behavior of R for the Irkutsk station than to the behavior of R for the Kaliningrad station.

Comparing the correlation coefficients for $f_o E_s$ and $f_b E_s$ has revealed that both positive and negative correlations increase during the transition from $f_o E_s$ to $f_b E_s$. The increase in the positive correlation is consistent with the conclusions drawn by Pezzopane et al. [2015] that $f_b E_s$ is better suited than $f_o E_s$ for identifying the effect of solar activity on the E_s layer, because $f_b E_s$, determined by the E_s -layer density, is more closely linked to photoionization than $f_o E_s$. The reason for the increased negative correlation remains unclear.

The difference between the results of the Novosibirsk data analysis for different time intervals has no apparent explanation, as well as the difference of the correlation coefficients for the Irkutsk station for 2003–2023 and the Novosibirsk station for 1996–2009 from the correlation coefficients for the Kaliningrad station for 2015–2024 and the Novosibirsk station for 1975–1990. We would conjecture that the difference is related to the type of ionosonde (analog station in 1975–1995 and digital ionosonde in 1995–2023); in any case, this version was discussed in [Laštovička et al., 2012]. It is paradoxical that the closest correlation coefficients are inherent in the data collected: 1) at different stations; 2) using ionosondes of various types; and 3) for different time intervals (data from the Kaliningrad station for 2015–2024 and from the Novosibirsk station for 1975–1990).

CONCLUSION

The main result of this study is the development of an alternative method for correlation analysis of the occurrence probability of the sporadic layer and the solar activity index. The method involves calculating

correlation coefficients R between the annual average solar activity index $F10.7$ and annual average occurrence probabilities of the E_s layer whose critical frequency $f_o E_s$ is within $f_i - f_{i+1}$ ($P(f_{i+1} > f_o E_s \geq f_i)$).

Applying the method to the data from the Irkutsk, Kaliningrad, and Novosibirsk stations allowed us to propose the following interpretation of the results received for daytime conditions. For $f_o E_s$ 1–2 and 2–3 MHz, the correlation coefficients are negative, which can be attributed to an increase in absorption with increasing solar activity, and hence to a decrease in the E_s occurrence probability. The highest positive correlation is observed for $f_o E_s$ 4–5 MHz, which may be due to the dominant effect of increasing photoionization with increasing solar activity on the rise in the occurrence probability of the E_s layer. These patterns are common to the three stations.

For $f_o E_s > 5 \text{ MHz}$, we have established differences in the behavior of the correlation coefficients for the stations considered. For the data from the Irkutsk station for 2003–2023 and from the Novosibirsk station for 1996–2009, sufficiently high negative correlation coefficients were obtained, which may be explained by a decrease in the E_s occurrence probability due to changes in wind shear in a solar cycle. According to [Maksyutin et al., 2001; Maksyutin, Sherstyukov, 2005], this factor is dominant for intense layers consisting of metal ions with high critical frequencies $f_o E_s$, assuming that photoionization has little effect on the metal ion density. For the data from the Kaliningrad station for 2015–2024 and from the Novosibirsk station for 1975–1990, the correlation decreases with increasing boundaries of $f_o E_s$, while remaining positive. This behavior of the correlation coefficients for daytime conditions can be interpreted as a consistent decrease in the role of photoionization with an increase in $f_o E_s$ if there is no change (or a slight change) in the wind shear in a solar cycle. For nighttime conditions, the above interpretation is maintained provided that there is no photoionization.

The difference of the correlation coefficients for the Ir-

kutsk station for 2003–2023 and the Novosibirsk station for 1996–2009 from the correlation coefficients for the Kaliningrad station for 2015–2024 and the Novosibirsk station for 1975–1990 has no apparent explanation. The fact that different stations have significantly different negative correlation coefficients was established in [Maksyutin, Sherstyukov, 2005], but the authors did not provide any explanation for it.

Comparing the correlation coefficients for f_oE_s and f_bE_s has revealed that both positive and negative correlations increase during the transition from f_oE_s to f_bE_s . The increase in the positive correlation is consistent with the conclusions drawn by Pezzopane et al. [2015] that f_bE_s is better suited than f_oE_s for identifying the effect of solar activity on the E_s layer, since the blanketing frequency f_bE_s , determined by the E_s -layer density, is more closely related to photoionization than f_oE_s .

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