Comparative analysis of variations in the critical frequency of the ionospheric F2 layer under different heliogeophysical conditions at the Moscow station

A G Ivannikova¹, N G Kotonayeva¹

¹ Fiodorov Institute of Applied Geophysics, Russian Federation, Moscow, Rostokinskaya str., 9

Abstract. Results of the statistical analysis of variations of critical frequency of a layer of F2 of an ionosphere at various levels of solar and geomagnetic activity are presented by data from the station Moscow from 1957 to 2019. Optimum intervals of division into levels of geomagnetic activity are experimentally found. The need to divide solar activity into low and high in ionospheric research has been proved. The effect of solar and geomagnetic activity on the occurrence of periodic positive and negative deviations of the critical frequency of the ionosphere F2 layer from the median, calculated for 27 previous days in various seasons, is shown. It has been shown that the daily course of deviations at a high level of geomagnetic activity for negative deviations ceases to be pronounced, unlike positive deviations.

1. Introduction
One of the key factors affecting the critical frequency variability of the ionospheric F2 layer are solar and geomagnetic activity [1], [2].

Determining the regularities of the critical frequency variability of the F2 layer is one of the most important issue in solving the problem of forecasting the state of the ionosphere. Despite numerous studies, due to the nontriviality and influence of a large number of difficult to forecast factors, the problem remains unsolved. To solve this issue, various approaches are used: empirical modeling [3], [4], [5], analysis based on data of total electronic content [6], [7], multicomponent model constructions [8], statistical analysis based on oblique data and vertical radiosonde [9], [10]. In this work, the last of the above approaches is used, since it allows the most accurate determination of the relationship between the characteristics of the variability of the critical frequency deviations of the F2 layer of the ionosphere from the median and heliogeophysical conditions of the external environment due to the presence of large samples of accumulated vertical radio sounding data.

In [10], based on the analysis of large data samples from the Moscow station, statistical regularities of variations in the critical frequency of the ionosphere at low and moderate geomagnetic activity were found. However, no division of the data into low and high solar activity was made. The main objective of this work is a comparative analysis of variations in the critical frequency of the F2 layer of the ionosphere under various heliogeophysical conditions at Moscow station based on data obtained from 1957 to 2019 and a search for statistical regularities and their quantitative characteristics for various levels of solar and geomagnetic activity.

To describe the level of geomagnetic activity, we used the effective integral index of geomagnetic activity Apt, which is best correlated with the behavior of the ionosphere. [10] The intervals of geomagnetic activity were selected experimentally, as a result of the study of the diurnal variations of
the deviations of the critical frequency of the F2 layer of the ionosphere from the median calculated for the previous 27 days at Moscow station with different levels of geomagnetic activity. Comparison of graphs with intervals of geomagnetic activity 0 < A<sub>p</sub> ≤ 10, 0 < A<sub>p</sub> ≤ 15 and 0 < A<sub>p</sub> ≤ 20 at low and high solar activity for different seasons, the difference between relative deviations is more than 3%, which means a decrease in accuracy by more than 3% in some cases, with an increase in the interval. This allows us to conclude that an increase in the interval of low geomagnetic activity to 0 < A<sub>p</sub> ≤ 15 is inappropriate due to the loss of accuracy. Therefore, the optimal interval for low geomagnetic activity is 0 < A<sub>p</sub> ≤ 10. It was advisable to choose the upper interval of geomagnetic activity from A<sub>p</sub> ≥ 15, since with an increase in the lower boundary of this interval, the sample size is significantly reduced (for example, in January, at 00 UT at low solar activity for geomagnetic activity with A<sub>p</sub> ≥ 15, the sample size is 224, if the geomagnetic activity A<sub>p</sub> ≥ 20, the sample size will be reduced to 158). If the lower boundary of the interval decreases to 10, even in summer, the accuracy will decrease by 10%.

Since the selected intervals do not overlap, it was necessary to select several more intervals to increase the accuracy of the studies. It has been experimentally established that the optimal interval is 5 < A<sub>p</sub> ≤ 20, at which the sample sizes are about 450.

To describe solar activity, the Wolf number is used, which reflects the number of sunspots. The moments of time at which the Wolf number W ≥ 70 are taken for high solar activity, and those at which the Wolf number W < 70 are taken as low.

To create the necessary samples, we analyzed the observation data of the critical frequency f<sub>oF2</sub> at the Moscow station for the period 1957 to 2019. Each measured value was assigned a median value for 27 days (13 days before and 13 days after obtaining a specific value). From this volume, only those obtained on the days when the necessary conditions for the levels of solar and geomagnetic activity described above were fulfilled were selected. The values of the quantile levels are considered α = 0.05; 0.03 with negative deviations from the median, and α = 0.95; 0.97 with positive deviations from the median. The sample under study was grouped by month, data from a specific ionospheric observation point Moscow, equipped with a vertical radiosonde ionosonde, were used for the analysis.

The study was divided into three parts:
- study of samples at a low level of solar activity for different levels of geomagnetic activity;
- study of samples at a low level of geomagnetic activity for different levels of solar activity;
- study of samples with a high level of geomagnetic activity for different levels of solar activity.

2. Low solar activity

In figure 1 shows the values of the diurnal variations of the distribution quantiles of 3% in different seasons.

In December, positive disturbances of up to 90% are observed with high geomagnetic activity from 6 to 11 UT; with an average level of geomagnetic activity, disturbances in the same period are 55%.

The maximum negative and positive deviations under calm conditions are observed before dawn. For negative deviations, it reaches the 55% level.

At a high level of geomagnetic activity from 0 to 12 UT, both positive and negative deviations have approximately the same level, of the order of 30%, after 12, negative deviations are greater and amount to about 50%, while positive deviations are of the order of 30%. The daily variation of the quantiles of positive and negative deviations at an average and low level of geomagnetic activity has practically the same shape and a difference in values of the order of 5-10% at all times, except for the moment of disturbance from 6 to 11 UT, when the difference in values is 30%.
Figure 1. Diurnal variation of quantiles of deviations of the current values of foF2 from the median level of 0.03 and 0.97 in different months with low solar activity and different levels of geomagnetic activity. The figure shows: solid line - high geomagnetic activity. The large dotted line is moderate geomagnetic activity. Small dotted line - low geomagnetic activity.

In June, the maximum of positive deviations is observed from 19 to 0 UT. With a high level of geomagnetic activity, deviations during this period increase by 20-30% compared to daily values, with a low level by 5-10%. With high geomagnetic activity, positive deviations are greater than negative ones and are at the level of 30-50%, while negative ones are at the level of about 20%. The diurnal variation of the quantiles of positive and negative deviations at all levels of geomagnetic activity has almost the same shape. The difference in the values of positive deviations is about 5-10% between low and medium levels of geomagnetic activity and 10-20% between medium and high levels.

In March, with a high level of geomagnetic activity, disturbances are observed in the area of positive deviations, with amplitudes of 92% at 9 UT and 90% at 11 UT. However, when comparing the 5% and 3% quantiles for a high level of geomagnetic activity, it was revealed that at 5% these disturbances significantly (up to 45%) decrease in amplitude.

Also, with a high level of geomagnetic activity, positive deviations are at the level of about 40%, while negative ones are at the level of 20-30%. The maximum positive deviations are observed before sunrise and after sunset.

In September, with a high level of geomagnetic activity, the maximum of positive deviations, as in June, is observed at 20 UT (up to 56%); however, in contrast to June, immediately after this the level of deviations drops to 40%. The minimum of positive deviations is observed at 15 UT. Both positive and negative deviations have approximately the same level throughout the day, from 20 to 40%, excluding the maximum.

After analyzing the charts for each month, the following points can be highlighted:

1) In all months, positive deviations are greater with high geomagnetic activity. From April to September, the difference between the deviations at low and high levels of geomagnetic activity is
about 20% from 0 to 17-18 UT and about 40% from 18 to 0 UT. In the remaining months, the difference in deviation values is about 5-10%.

2) Negative deviations in all months in the daytime are greater with high geomagnetic activity and less with low geomagnetic activity. At night, the opposite is true. In the daytime, the difference is usually less than at night and is up to 10-15%, at night in some months the difference between the deviations reaches 20-25% (October-January).

3) In all seasons, except for winter, with low geomagnetic activity, negative deviations have a pronounced diurnal variation, decreasing during the day and increasing at night. Negative deviations with high geomagnetic activity do not have a pronounced diurnal variation.

4) Positive deviations have a diurnal variation at both high and low geomagnetic activity, which is influenced by the moments of sunrise and sunset. This is especially pronounced in the summer period, when, with the setting of the Sun at a high level of geomagnetic activity, an increase in positive deviations by 40% occurs.

5) In all seasons, except for winter, with a high level of geomagnetic activity, positive deviations are greater than negative ones. In winter, negative deviations are slightly greater than positive ones.

3. Low geomagnetic activity
In figure 2 shows the values of the diurnal variations of the distribution quantiles of 3% in different seasons.

![Figure 2](image)

**Figure 2.** Diurnal variation of quantiles of deviations of the current foF2 values from the median in different months at low geomagnetic activity and different levels of solar activity. The figure shows: large dotted line - quantiles of levels 0.03 and 0.97 for high solar activity. Solid line - quantiles of levels 0.05 and 0.95 for high solar activity. Small dotted line - quantiles of levels 0.03 and 0.97 for low solar activity.

In December, negative deviations have two maximums, reaching 328% and 416%, at 8 and 10 UT, respectively. When considering the quantiles of 5%, it can be seen that the amplitude of the deviations at 8 UT decreases to 60%, and at 10 UT it remains at a high level - 384%. The rest of the time,
negative deviations at low and high solar activity have a difference of no more than 10%. The same discrepancy is observed in the positive region at all times, except for the interval from 7 to 10 UT. At this time interval, an increase in deviations up to 100% is observed. When comparing the quantiles of 3% and 5%, it can be seen that the amplitude of the largest positive disturbance remains practically unchanged. The minimum of both positive and negative deviations is observed before and after the maximum disturbances - at 6 and 11 UT. Negative deviations throughout the day are more than positive ones by 30% (they have levels of the order of 50 and 20%, respectively).

In June, no strong disturbances are observed even with a high level of solar activity. The diurnal variation of positive deviations at high solar activity remains approximately at the same level, about 17%, slightly decreasing by 5% from 0 to 3 UT. Thus, in the daytime, deviations at high solar activity exceed the deviations at low solar activity by 5%, and at night - on the contrary, which is achieved mainly due to an increase in deviations at low solar activity at night.

The diurnal variation of negative deviations at high solar activity is pronounced and in shape repeats the diurnal variation of negative deviations at low solar activity. From 0 to 9 UT, negative deviations are greater than positive ones by 10-15%.

In March, the discrepancy between the diurnal variations at high solar activity and low solar activity for positive deviations is up to 4% (deviations at high solar activity are greater), except for the time from 6 to 11 UT, at which a positive disturbance similar to December is observed up to 100% at high solar activity.

Negative deviations at night at high solar activity are 10-13% less than at low solar activity, from 13 to 19 UT - vice versa. From 10 to 13 UT, the diurnal variations coincide, and from 7 to 10 UT, an increase in the amplitude up to 232% is observed.

When comparing the quantiles of 3% and 5%, it can be seen that the amplitude of the largest positive disturbance remains practically unchanged, except for 10 UT, where it drops to 55%. The amplitude of the negative disturbance from 7 to 10 UT becomes equal to the level of deviations at low solar activity. The invariability of the positive disturbance with a change in the negative one indicates that they have a different nature and thus, in this case, a positive disturbance and a negative disturbance are observed separately, but the presence of two-phase disturbances cannot be ruled out either.

In September, in the positive region there are disturbances up to 97% from 6 to 10 UT, and at 12 to 13 UT the deviations at high solar activity are greater than at low solar activity by 10%. When comparing the quantiles of 3 and 5%, it can be seen that the diurnal variation remains unchanged and is characteristic of the deviations of this period.

Negative deviations at high SA throughout the day do not differ in values with deviations at low solar activity by more than 5%, not counting the period from 6 to 8 UT, when the difference is up to 20%.

4. High geomagnetic activity

In figure 3 shows the values of the diurnal variations of the distribution quantiles of 3% in different seasons.

In December, in the positive region, there is a disturbance of up to 98% at both levels of solar activity from 7 to 11 UT at high solar activity and from 7 to 10 UT at low solar activity, which suggests that the nature of this disturbance is more dependent on geomagnetic activity than from the sun. In the trinity region at 9 UT, there is a disturbance, the amplitude of which reaches 470%. When considering the 5% quantiles, it can be seen that this disturbance is typical for this period. The minima of both negative and positive deviations are observed before and after large disturbances - at 6 and 11 UT, respectively.

In June, negative deviations are unstable, but it can be seen that deviations with high solar activity are higher in the daytime (about 20%) and lower at night (about 10%). The largest difference between deviations at high and low solar activity is present at 20 UT and is 21%. Diurnal variations of deviations at low and high solar activity have a similar shape. When considering the 5% quantiles, it
can be seen that the daily variation of positive deviations for 3 and 5% practically does not differ, and for negative deviations it has a significant difference, in particular, at 5 UT the difference is 19%, which indicates that negative deviations in this period can have many random small disturbances throughout the day.

The level of positive deviations (22-40%) in this period is almost twice as high as the negative (25-33%).

In March, from 6 to 12 UT, an increase in deviations with high solar activity up to 97% is observed. At 9 and 11 UT, the deviations reach a maximum at both levels of solar activity. It can be assumed that these disturbances are more dependent on the level of geomagnetic activity than on the level of solar activity. The diurnal variation of negative deviations at high solar activity coincides with the diurnal variation at low solar activity in all cases except for the period from 7 to 10 UT, in which a significant increase in deviations is observed, up to 466% and the period from 15 to 17 UT, where the discrepancy between the deviations is 15-20% (deviations at high solar activity are greater).

![Figure 3](image)

**Figure 3.** Diurnal variation of quantiles of deviations of current foF2 values from the median in different months at high geomagnetic activity and different levels of solar activity. The figure shows: large dotted line - quantiles of levels 0.03 and 0.97 for high solar activity. Solid line - quantiles of levels 0.05 and 0.95 for high solar activity. Small dotted line - quantiles of levels 0.03 and 0.97 for low solar activity.

When considering the 5% quantiles, it can be seen that for high solar activity the amplitudes of both positive and negative disturbances change weakly, the other values of the diurnal variation also remain completely unchanged.

In September, positive deviations throughout the day are greater at high SA by 20-23% than at low SA. From 7 to 11, there is an increase in positive deviations up to 90%.

In negative deviations in September, a burst is observed from 7 to 9 UT with a high SA of up to 212%; however, the graph with 5% quantiles shows that the amplitude of this disturbance decreases to 90%. Also, positive disturbances persist only at 8-9 UT, and at other times they remain at a level of about 40%.
After analyzing the graphs for each month for low and high solar activity, the following points can be highlighted:

1) In the summer period, significant disturbances with a high level of solar activity can occur with a very low probability - they are absent on the graphs of the quantiles of deviations of the 3% level. The daily moves of the 3% quantiles are at levels of the order of 30-60% for the positive area and 20-30% for the negative.

2) At low geomagnetic activity, significant negative disturbances, the amplitude of which is 100-260%, at a high level of solar activity, mainly at 7-10 UT from October to March, appear less likely than in November and December. In November and December, the amplitude of such disturbances reaches 400%. With high geomagnetic activity, these disturbances are present from September to April (amplitudes 318-548%), in September with an amplitude of 212% and less likely than in other months.

3) Significant (up to 100%) positive disturbances at a high level of solar activity at 6-7-10-12 UT with low geomagnetic activity arise from August to May (in August with a lower probability), as well as at high geomagnetic activity (with a lower probability in May).

4) At low geomagnetic activity, the level of negative and positive deviations for high solar activity is approximately the same, or negative deviations are greater by 5%. With high geomagnetic activity for high solar activity in the period from March to September, the level of positive deviations is almost twice as high as the negative, especially from 18 to 00 UT, in other periods is approximately the same.

5) The shape of the diurnal variations in most cases coincides with low and high solar activity.

6) At 8 UT in November, a significant (from 250 to 375% in different cases) negative deviation is observed for all heliogeophysical conditions, except for completely calm ones. In December, at 8 UT, the same positive deviation is observed, with amplitudes from 55% (with average geomagnetic activity and low solar activity) to 97% with high geomagnetic activity and solar activity.

7) From April to August, with high geomagnetic activity, an increase in deviations by 30% is observed from 16 to 18 UT for both high and low solar activity. Moreover, the difference between the deviations themselves for high and low solar activity can be 10-20% at these moments (with high solar activity, the deviations are greater).

5. Conclusion
As a result of a comparative analysis of variations in the critical frequency of the F2 layer of the ionosphere under various heliogeophysical conditions at Moscow station, the following conclusions can be drawn:

1) High solar activity with low geomagnetic activity in a greater number of cases (all months except June-August) leads to strong disturbances of the ionosphere, which also depends on the season than high geomagnetic activity with low solar activity (February, March, November, December) ... In addition to the presence of turbulent geophysical conditions, the presence of these disturbances also depends on the season.

2) Ionospheric storms characteristic of equinox periods occur during periods of high solar activity and almost never occur during periods of low solar activity, regardless of the level of geomagnetic activity:
   - High geomagnetic activity, high solar activity, September, from 7 to 11 UT an increase in the amplitude of positive deviations to 89%, negative from 7 to 9 UT to 212%
   - High geomagnetic activity, high solar activity, March, from 6 to 12 UT an increase in the amplitude of positive deviations to 97%, negative from 7 to 10 UT to 466%
   - Low geomagnetic activity, high solar activity, September, from 6 to 10 UT an increase in the amplitude of positive deviations to 97%.
   - Low geomagnetic activity, high solar activity, March, from 6 to 11 UT an increase in the amplitude of positive deviations to 97%, negative from 7 to 10 UT to 232%.
3) Under calm geophysical conditions, significant disturbances in the ionosphere are not observed in any months except October. In October 7-8 UT, a positive disturbance with an amplitude of 77% is observed.

4) Negative deviations at high geomagnetic activity do not have such a pronounced daily variation as at low geomagnetic activity for both low and high solar activity, which is due to a large number of insignificant (with an amplitude of 5-10%) disturbances. When considering the 5% quantiles, the diurnal variations appear smoother.

5) Positive deviations have a diurnal variation at both high and low GA, which is influenced by the moments of sunrise and sunset, especially in the summer, when positive deviations increase with sunset.

6) The variability in the behavior of the ionosphere of the ionosphere differs significantly at different levels of solar activity at both low and high geomagnetic activity. The differences mainly consist in the presence of significant deviations at high solar activity, up to 100% in the positive region and up to 500% in the negative region in the morning from 6 to 12 in all seasons except summer. In the summer period, differences are also present, but up to 20%.

7) Significant, up to 60-100% positive disturbances have a greater dependence only on solar activity than negative ones, which have a dependence on solar activity and geomagnetic activity.

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