
VARIATIONS IN PARAMETERS OF LOW-FREQUENCY SIGNALS ON A MID-LATITUDE RADIO PATH DURING GEOMAGNETIC STORMS CAUSED BY HIGH-SPEED SOLAR WIND STREAMS FROM CORONAL HOLES

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Abstract. Variations in the amplitude and phase of a mid-latitude low-frequency signal from the JJY (40 kHz) transmitter were analyzed during four geomagnetic storms in 2021 and 2025, which were caused by high-speed solar wind streams from coronal holes creating corotating interaction regions. The analysis has shown that nighttime anomalous disturbances in the amplitude and phase were observed for three days during a magnetic storm. The negative amplitude anomalies of the signal ranged from 4.5 to 21 dB; phase anomalies were from 41° to 124°. The sign of the phase anomalies was different on different days. We recorded both positive and negative phase anomalies, as well as wave-like disturbances with a transition from negative to positive anomalies. A statistical relationship was found between

the value of the phase anomaly and the intensity of geomagnetic disturbances. The correlation coefficient with the *Dst* index was -0.39 . The relationship between phase anomalies and the *AE* index is higher; the correlation coefficient in this case was 0.53 . No statistical relationship was observed between geomagnetic activity and the anomaly for the sub-ionospheric signal amplitude.

Keywords: sub-ionospheric radio signals, lower ionosphere, geomagnetic storms, midlatitudes.

INTRODUCTION

Geomagnetic storms are caused by solar wind streams of different types. We can distinguish storms driven by coronal mass ejections (CMEs) and those induced by corotating interaction regions (CIRs). CIRs are formed by the interaction of a fast solar wind stream from coronal holes with a slow solar wind stream [Burlaga, Lepping, 1977; Tsurutani et al., 1995, 2011; Gonzalez et al., 1999]. Due to the solar rotation, they pass by Earth approximately every 27 days, resulting in recurrent magnetic storms caused by high-speed solar wind streams from coronal holes. In this paper, by CIR-driven geomagnetic storms (hereinafter referred to as CIR storms) are meant storms triggered by either a CIR or a high-speed stream, or both at the same time.

Storms caused by CMEs (hereinafter referred to as CME storms) occur mainly during solar maximum due to frequent plasma ejections from the Sun and are often intense and short-term. On the contrary, CIR storms occur more often during the solar cycle descending phase [Richardson et al., 2001] and are usually moderate ($Dst > -100$ nT) and long-term. CIR storms have a long recovery phase during which continuous geomagnetic *AE* activity, induced by Alfvén oscillations within the streams themselves, is observed in the auroral zone

[Belcher, Davis 1971; Tsurutani, Gonzalez, 1987; Tsurutani et al., 2006]. CIR storms, unlike CME storms, rarely have a sudden commencement. Borovsky, Denton [2006] have shown 21 differences between geomagnetic CME and CIR storms.

While CIR storms are weaker than strong CME storms, their cumulative effects in the thermosphere and ionosphere are comparable or even stronger (e.g., [Turner et al., 2009]). In this regard, the characteristics of ionospheric disturbances associated with CIR storms are of particular interest.

Extensive literature has been devoted to examining the response of the ionospheric F-region during geomagnetic storms by measuring the total electron content and to comparing the effects caused by CIR and CME storms [Suvorova et al., 2014; Matamba, Habarulema, 2018; Burešova et al., 2014; Qiu et al., 2015; Abaidoo et al. al, 2025; Dmitriev, 2018]. Less certain are the effects of geomagnetic storms in the lower ionosphere. To study the state of the lower ionosphere, a method of analyzing amplitude and phase variations of VLF/LF (very low frequency and low frequency) subionospheric signals from navigation transmitters in the frequency range 15–50 kHz is currently being used. Waves in this range propagate inside the Earth–ionosphere waveguide and are reflected at an altitude of ~65 km during the day and ~85 km at

night [Clilverd et al., 1999]. Such signals, measured by a receiver, contain information about the reflection region of the ionosphere and its variability [Barr et al., 2000].

Belrose, Thomas [1968], investigating the characteristics of VLF, LF, and decimeter signals in Europe, discovered that the nighttime amplitude of a VLF signal during magnetic storms showed small variations compared to the normal behavior, whereas rapid fluctuations were observed in the signal phase. Kumar, Kumar [2014] found that of seven geomagnetic storms with $Dst < -50$ nT only an intense storm with minimum $Dst = -145$ nT caused a marked decrease in the VLF signal amplitude at low latitudes.

Disturbances in the amplitude and phase of VLF/LF signals were recorded along mid-latitude paths during extreme magnetic storms on April 7, 2000, October 31, 2003 [Peter et al., 2006], and March 17, 2015 [Mondala et al., 2021; Ryakhovskiy et al., 2021; Solovieva et al., 2025]. Anomalous variations in VLF signals at middle and low latitudes were also observed during strong and moderate magnetic storms [Kleimenova et al., 2004; Choudhury et al., 2015; Tatsuta et al., 2015; Nwankwo et al., 2022; Kumar et al., 2023]. However, when moderate geomagnetic storms were analyzed, CME and CIR storms were not considered separately.

Studies show that the effects detected in VLF/LF signals during magnetic storms can be different for signals with different frequencies, as well as for paths at different latitudes with varying lengths and orientations relative to the magnetic field. In this paper, we analyze phase and amplitude variations of an LF signal (40 kHz) on the mid-latitude radio path in the Far East during several geomagnetic CIR storms. In the previous paper [Solovieva et al., 2025], we have examined the effects

occurring along this path in the main phase of strong and extreme geomagnetic CME storms during the period 2000–2024.

1. DATA IN USE

The paper is based on data from continuous monitoring of the Japan—Kamchatka mid-latitude radio path (2220 km, $f = 40$ kHz). The JJY transmitter is located in Fukushima Prefecture ($\varphi = 37.37^\circ$ N, $\lambda = 140.85^\circ$ E); the receiver, in Petropavlovsk-Kamchatsky ($\varphi = 53.15^\circ$ N, $\lambda = 158.91^\circ$ E). The UltraMSK receiver [http://ultramsk.com/] measures both amplitude (in dB) and phase (in degrees) with a sampling frequency of 96 kHz. Long-term variations are analyzed using data with subsequent 20-s averaging. The JJY transmitter broadcasts standard time signals and ensures a stable signal phase.

Daytime propagation of VLF/LF signals is stable, whereas their nighttime propagation is less stable. The night-time ionosphere is not only more variable than the daytime one, but also supports a larger number of modes in the Earth–ionosphere waveguide, which leads to more complex mode interference. As a result, the amplitudes and phases of received signals are more sensitive to ionospheric variations at night than during the day [Thomson et al., 2007]. Accordingly, the LF signal was analyzed at night. The night interval was determined from the daily variation of signals and did not include terminator regions due to large variations in signal amplitudes and phases in these regions (Figure 1, at the top). Difference values of the signal characteristics were calculated as the difference between current and monthly average values (Figure 1, at the bottom).

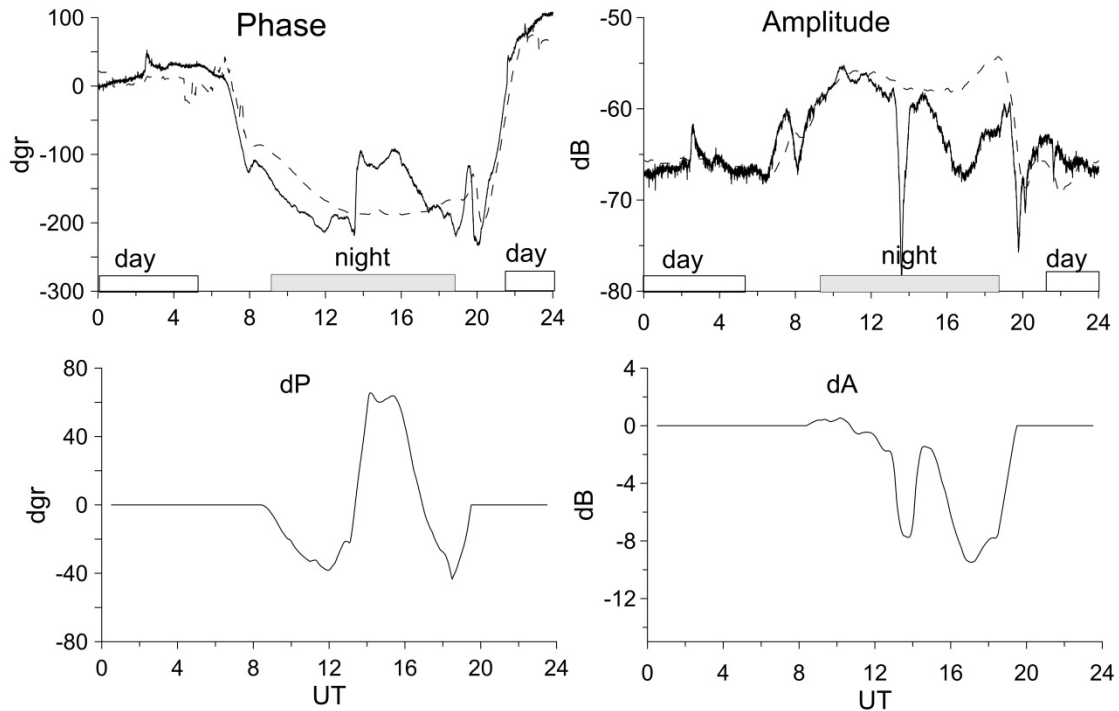


Figure 1. The top panels illustrate the determination of the night and day intervals for the disturbed day on March 12, 2025: the dashed line indicates monthly averages of the amplitude (on the right) and phase (on the left) of an LF signal; the solid line, their current values. The bottom panels show the difference values of the amplitude (dA , right) and phase (dP , left) of the signal at night, smoothed by a 1-hour running window

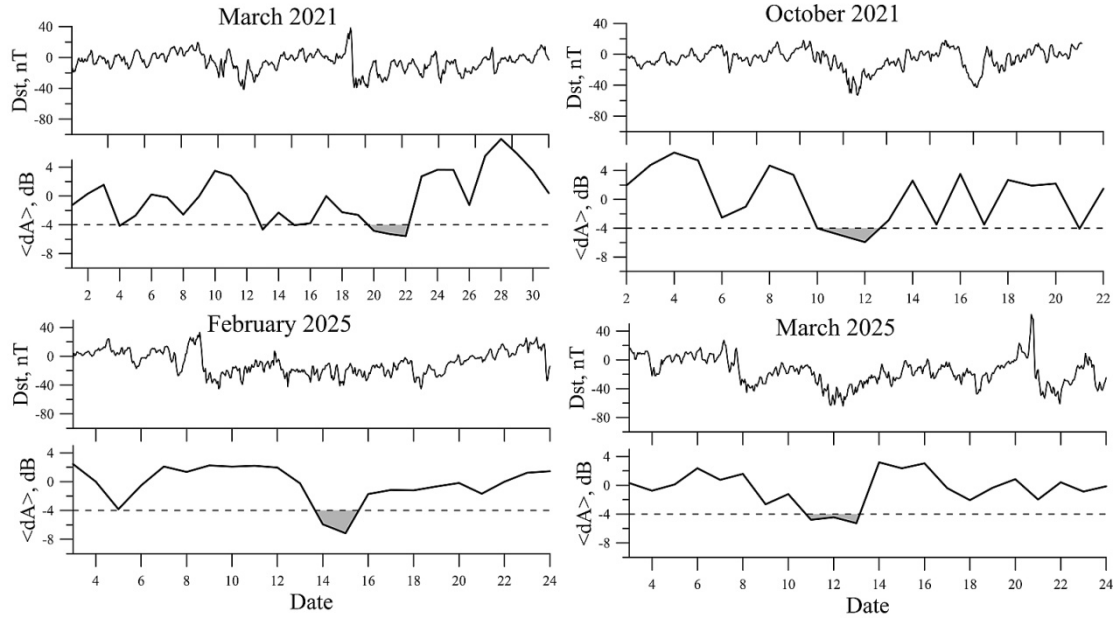


Figure 2. Variations in the Dst index and the night average difference amplitude ($\langle dA \rangle$, dB relative to $1 \mu V/m$) of a JJY signal for four analysis periods. The dashed line is the -2σ level; shaded areas denote a decrease below this level; along the X-axis are the days of the month

Data on Dst variations was taken from the Kyoto WDC (World Data Center) website [<https://wdc.kugi.kyoto-u.ac.jp/dstdir/>]. One-hour values of the solar wind velocity and AE were obtained from the OMNI database [<https://omniweb.gsfc.nasa.gov/form/dx1.html>]. Data on high-energy electron fluxes (5 min) was borrowed from the database of the geostationary satellite GOES 16 [<https://data.ngdc.noaa.gov/platforms/solar-space-observing-satellites/goes/goes16/l2/data/>]. Information on coronal holes was gained from the STAR (Solar Terrestrial Activity Report) website [http://www.solen.info/solar/old_reports/].

2. ANALYSIS RESULTS

We have analyzed four geomagnetic storms caused by high-speed streams from coronal holes: for two storms during weak solar activity on March 20–23 and October 10–14, 2021, and for two storms during the declining phase of solar activity on February 9–15 and March 9–13, 2025. The monthly average number of sunspots was 21.7 in March 2021, 45.2 in October 2021, 154.6 in February 2025, 140 in March 2025.

Figure 2 plots the Dst index and the overnight average difference amplitude of the JJY signal for the four periods of interest. The dashed line in the amplitude plot indicates the -2σ level. The signal amplitude is seen to decrease below the -2σ level during CIR storms for three days.

Let us take a closer look at the storms selected for analysis.

Geomagnetic storm on March 20–23, 2021

The storm was caused by a high-speed stream from coronal hole CH1000, which crossed the central solar meridian on March 17–19.

Figure 3 illustrates variations in the solar wind velocity, Dst , AE, high-energy electron fluxes (according

to GOES data), and nighttime difference amplitudes and phases of the JJY signal with 5-min smoothing over the period March 17–23, 2021.

The day before the start of the storm on March 19, high-energy electron fluxes appeared (about $280000 \text{ (cm}^2 \text{ sr keV s)}^{-1}$) and a negative amplitude anomaly of the JJY signal was observed. The deviation of the amplitude of the current signal, smoothed by the 1-hr running window from the monthly average, was -13 dB . A method was adopted which can calculate the average value for the current point and its neighboring points in the given data window. The window is shifted by one value on the time scale. This smoothing was applied in order to remove large short-term outliers (see Figure 1).

The phase deviation from the monthly average was $+40^\circ$ at the beginning of the night and -56° at the end of the night. Note that disturbances in the JJY signal were also observed on March 17 and 18, which might have been related to the preparation of an M7 earthquake with an epicenter in the range of sensitivity of the subionospheric signal propagation path. In addition, on March 17 high-energy electron fluxes appeared and AE increased to $\sim 550 \text{ nT}$, which might have caused abnormal, albeit short-term, disturbances in the amplitude and phase of the JJY signal. On March 20, Dst dropped to -45 nT , the solar wind velocity rose to $\sim 650 \text{ km/s}$, AE increased to 800 nT ; high-energy electron fluxes, to $510000 \text{ (cm}^2 \text{ sr keV s)}^{-1}$. The amplitude anomaly on this day was -15 dB . Phase disturbances had different signs: $+72^\circ$ at the beginning of the night and -83° at the end. On March 21, Dst was -33 nT , AE increased to $\sim 900 \text{ nT}$; and electron fluxes, to $590000 \text{ (cm}^2 \text{ sr keV s)}^{-1}$. The solar wind velocity remained approximately the same as on March 20. Deviation of the signal amplitude, smoothed by the 1-hr window, from monthly averages was -21 dB ; the phase, $+98^\circ/-47^\circ$. On March 22 and 23, minimum Dst was about -20 nT , AE decreased signifi-

cantly, the electron flux and solar wind velocity also went down. The amplitude anomaly was -21 dB on March 22 and -12 dB on March 23; and the phase anomaly was $+60^\circ$ and -41° respectively. Sizes of the anomalies were determined from the maximum deviation of the signal characteristics, smoothed by the 1-hr running window, from monthly averages.

Geomagnetic storm on October 10–14, 2021

The storm was caused by a high-speed stream from coronal hole CH1036, which reached the central solar meridian on October 9.

The *Dst* index dropped to -29 nT by the end of October 10 (Figure 4). On the same day, high-energy electron fluxes of ~ 230000 ($\text{cm}^2 \text{ sr keV s}^{-1}$) were recorded; substorm *AE* was 600 nT. On that day, a negative anomaly of 17 dB was observed in the JJY signal amplitude; and a positive anomaly of 124 dB, in its phase. The next day, *Dst* continued to fall, the electron flux and *AE* remained at the level of the previous day, and the solar wind velocity increased to ~ 400 km/s. The amplitude anomaly was -9 dB; the phase anomaly, $+61^\circ$.

On October 12, the storm developed under the influ-

ence of both the high-speed stream from the coronal hole and the interplanetary inhomogeneity created by the coronal mass ejection. *Dst* reached a minimum of -65 nT, the solar wind velocity rose to almost 500 km/s, *AE* increased to 1200 nT; and electron fluxes, to ~ 600000 ($\text{cm}^2 \text{ sr keV s}^{-1}$). The amplitude anomaly on that day was -14 dB; the phase anomaly, $+112^\circ$.

Geomagnetic storm on February 9–15, 2025

The storm was caused by high-speed solar wind streams from coronal holes CH1269 and CH1270, which crossed the central meridian from February 6 to 13.

On February 9, *Dst* was -37 nT, *AE* increased to 700 nT, the solar wind velocity went up to 660 km/s, and the electron flux was weak (Figure 5). The JJY signal remained undisturbed on that day. The next day, *Dst* dropped to a minimum of -45 nT, in the next two days it rose to -22 nT, *AE* and the solar wind velocity remained approximately at the same level for these three days; the electron flux was 470000 ($\text{cm}^2 \text{ sr keV s}^{-1}$) on February 10 and 230000 ($\text{cm}^2 \text{ sr keV s}^{-1}$) on February 12. There were no variations in the JJY signal at this time.

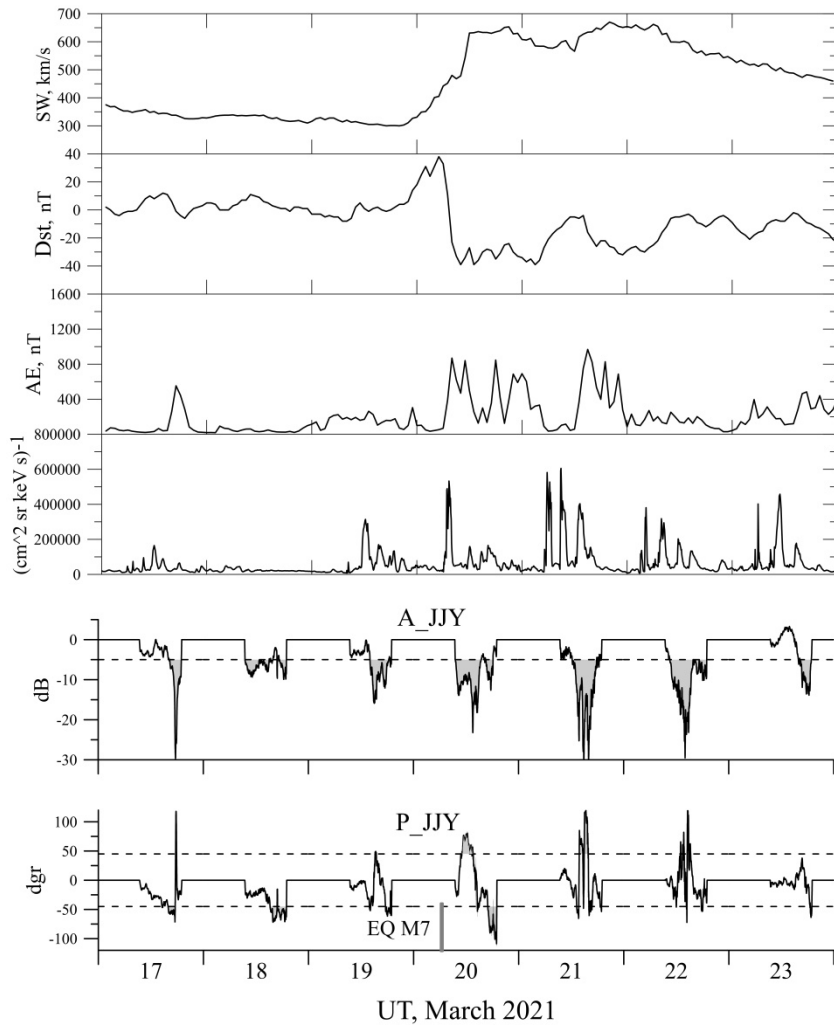


Figure 3. From top to bottom: the solar wind velocity, *Dst*, *AE*, high-energy electron fluxes on the GOES satellite (50–4000 keV), the night difference amplitude (*dA*) and phase (*dP*) of the JJY signal (with 5-min smoothing). The dashed line in the amplitude plot denotes the level -2σ ; in the phase plot, $\pm 2\sigma$. Shaded areas show a decrease below the -2σ level and an excess of the 2σ level

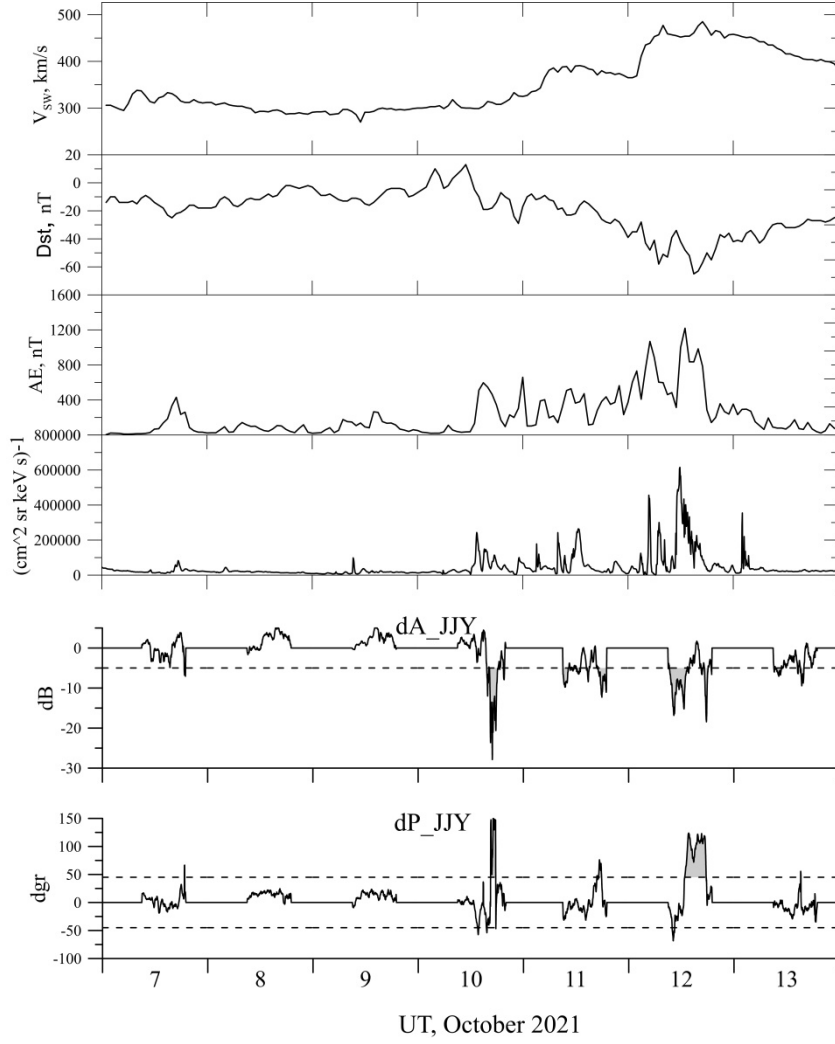


Figure 4. The same as in Figure 3 but for October 2021

The electron flux began to increase on February 13 and reached $870000 \text{ (cm}^2 \text{ sr keV s)}^{-1}$ on February 15. On these days, abnormal variations in the LF signal occurred. The deviation of the amplitude smoothed by the 1-hr running window was -5 dB on February 13, -9 dB on February 14, and -11 dB on February 15. Phase deviations were $+52^\circ$ on February 13; wave-like phase disturbances from $+53^\circ$ to -55° were recorded on February 14; and a negative anomaly of 67° , on February 15.

Geomagnetic storm on March 9–13, 2025

This storm, like the previous one, is associated with coronal hole CH1270. On March 9, the solar wind velocity was as high as 650 km/h , Dst decreased to -51 nT , AE increased to 980 nT , and electron fluxes reached almost $1000000 \text{ (cm}^2 \text{ sr keV s)}^{-1}$ (Figure 6). On that day, a negative anomaly of 9 dB was observed in the amplitude of the JJY signal (in the 1-hr running window), and there was also a negative anomaly of 63° in its phase.

On March 10, Dst increased, whereas AE and electron fluxes decreased. On that day, the JJY signal remained undisturbed. On March 11, there was a negative anomaly of 6 dB in the signal amplitude, phase disturbances were within the standard deviation; on March 12, Dst was -62 nT ; AE , $\sim 1000 \text{ nT}$; electron fluxes,

$\sim 800000 \text{ (cm}^2 \text{ sr keV s)}^{-1}$; and the solar wind velocity, $\sim 510 \text{ km/s}$. Approximately the same values were recorded the next day. The amplitude anomaly was -10 dB on March 12 and -12 dB on March 13; the phase anomaly, $+63^\circ$ and -70° respectively.

Figure 7 shows the dependence of the amplitude and phase anomalies of the JJY signal for 15 disturbed days during four storms (see Table) on daily minimum Dst and daily maximum AE . Since the phase anomalies had variable signs, we used maximum absolute values. No statistical relationship was found between Dst and the signal amplitude anomaly size. The correlation coefficient was close to zero. The correlation coefficient of phase anomalies with Dst was -0.39 . The signal phase proved to be more sensitive to AE : the correlation coefficient was 0.53 , whereas for amplitude the correlation coefficient with AE was only -0.13 .

3. DISCUSSION

We analyzed the behavior of the amplitude and phase of the JJY signal (40 kHz) along the mid-latitude wave path during four CIR-driven geomagnetic storms. If we compare the results with those obtained for strong CME storms [Solovieva et al., 2025], the following features can be noted.

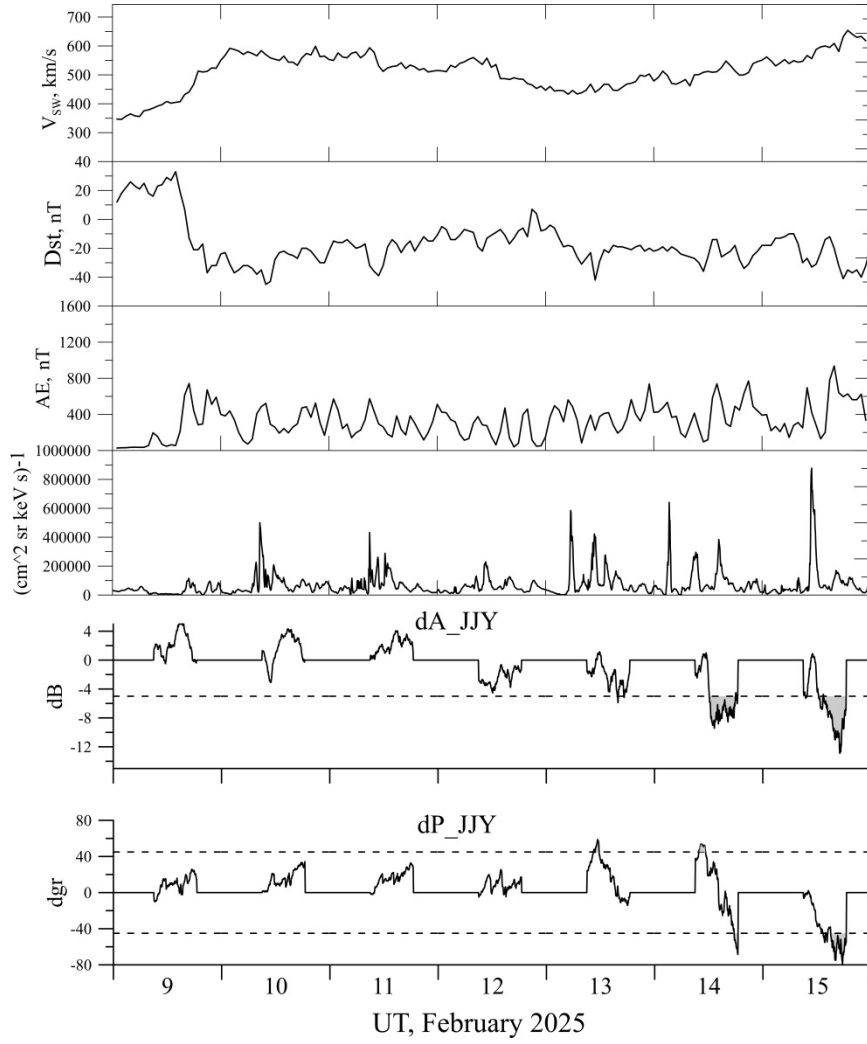


Figure 5. The same as in Figure 3 but for February 2025

Maximum deviations of JJY signal amplitude and phase,
smoothed by the 1-hr running window,
from monthly averages

Date	max AE, nT	min Dst, nT	ΔA , dB	ΔP , deg.
Mar. 20, 2021	800	-45	-15	72/-83
Mar. 21, 2021	910	-33	-21	98/-47
Mar. 22, 2021	130	-24	-21	60
Mar. 23, 2021	430	-19	-12	-41
Oct. 10, 2021	600	-29	-17	124
Oct. 11, 2021	500	-33	-9	61
Oct. 12, 2021	1200	-65	-14	112
Feb. 13, 2025	450	-42	-5	52
Feb. 14, 2025	700	-36	-9	53/-55
Feb. 15, 2025	870	-41	-11	-67
Mar. 09, 2025	980	-42	-9	-63
Mar. 10, 2025	400	-28	-4.5	-41
Mar. 11, 2025	430	-19	-6	26
Mar. 12, 2025	1000	-62	-10	63
Mar. 13, 2025	850	-66	-12	-70

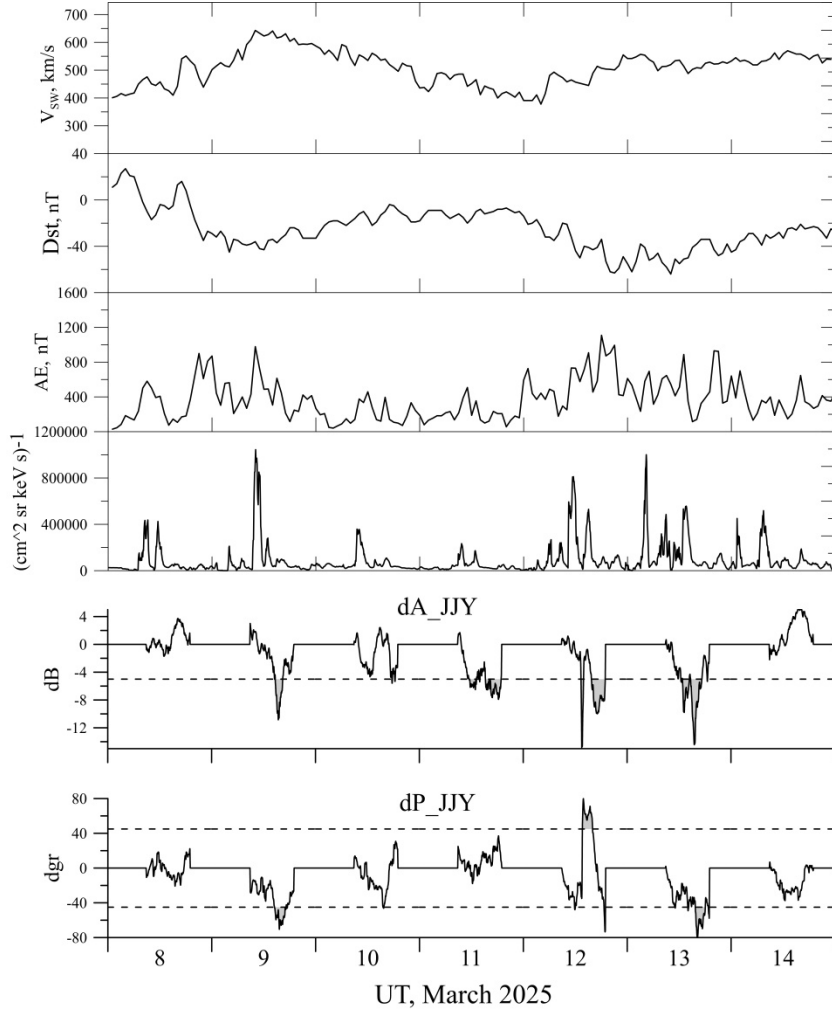


Figure 6. The same as in Figure 3 but for March 2025

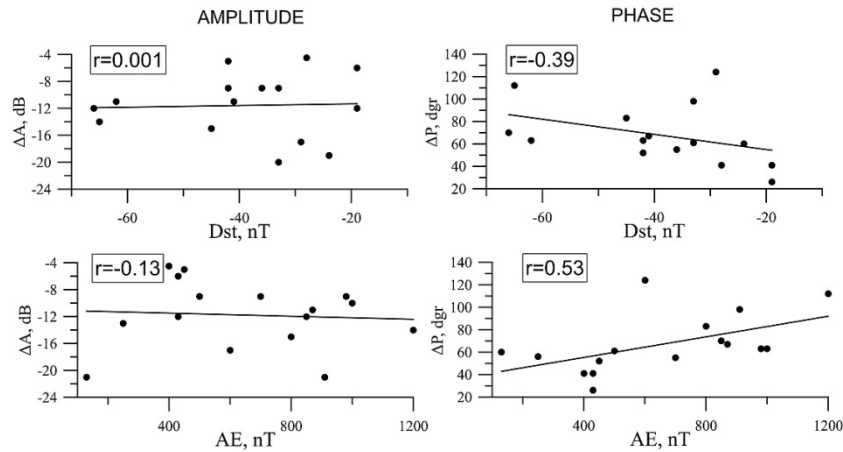


Figure 7. Amplitude (left) and absolute phase (right) anomalies plotted as function of daily minimum *Dst* (top) and daily maximum *AE* (bottom); r is the correlation coefficient

Anomalous amplitude and phase disturbances during CIR storms considered were observed for 3–5 days, whereas during strong and extreme geomagnetic CME storms the disturbances were recorded for only one day, except for the March 17, 2015 storm.

The effects in VLF/LF signals along mid- and low-latitude radio paths were found only for those strong and extreme CME storms whose sudden commencements and main phases occurred at a local night. The

effects were recorded in 7 of 12 cases (58 %) for low-latitude paths [Kumar et al., 2023] and in 16 of 20 cases (80 %) for mid-latitude JJY signal propagation paths. The CIR storms considered in this paper do not have a sudden commencement, and the time of day does not affect the appearance or absence of the effects.

While CIR storms are much weaker than CME storms, their effect on the JJY signal characteristics turned out to be somewhat stronger than that of CME

storms. The average size of the JJY signal amplitude anomaly during CIR storms, calculated for 15 disturbed days (see Table), was -11.3 dB; the abnormal deviation of the JJY signal amplitude from monthly averages during strong and extreme CME storms (16 events), -9.5 dB [Solovieva et al., 2025]. For the signal phase, the average absolute anomaly sizes were 67° for CIR storms and 57° for CME storms.

In the case of both strong CME storms (16 disturbed days) and magnetic CIR storms (15 disturbed days), no statistical relationship was found between the geomagnetic activity level and the JJY signal amplitude anomaly size. The phase appeared to be more sensitive. The correlation coefficient between *Dst* and the absolute size of phase anomalies was 0.25 for CME storms and -0.39 for CIR storms. For CIR storms, a statistical relationship was found between the JJY signal anomalies and *AE*. The correlation coefficient for the amplitude was -0.13 ; for the phase, 0.53. In the case of strong CME storms, there is no correlation with *AE* for either the JJY signal amplitude or its phase: for both characteristics, the correlation coefficient was ~ 0.05 .

The JJY signal phase anomalies in the case of strong and extreme CME storms were always negative, except for the March 17, 2015 storm (the so-called St. Patrick's Day storms), when phase anomalies had different signs. On March 17, there was a negative anomaly of 52° at the beginning of the night and a positive anomaly of 108° at the end of the night. On the next two days, the anomalies were positive (121° and 70°); and on March 20, a negative anomaly of 58° was recorded. In the case of CIR storms, the JJY signal phase anomalies had different signs. Three of 15 disturbed days had wave phase anomalies when the sign changed from plus to minus, six had positive anomalies, and five had negative ones. In one case, the deviation of the phase value, smoothed by the 1-hr running window, did not exceed the 2σ level, whereas an abnormal deviation from averages was observed in the amplitude.

CONCLUSIONS

Analysis of features of the subionospheric propagation of long-wave signals in midlatitudes during four CIR-driven geomagnetic storms has shown that anomalous signal amplitude and phase disturbances lasted for 3–5 days.

Negative amplitude anomalies of the signal ranged from 4.5 to 21 dB; and phase ones, from 41° to 124° . The sign of the phase anomalies was different on different days. Both positive and negative phase anomalies were observed, as well as wave-like phase disturbances with a transition from positive to negative values. A weak statistical relationship was found between the size of the signal phase anomaly and the intensity of geomagnetic disturbances. The correlation coefficient with *Dst* was 0.39. The dependence of phase anomalies on *AE* with a correlation coefficient of 0.53 is more significant. For the LF signal amplitude, no relationship was revealed between the geomagnetic activity level and the anomaly size.

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