Monochromatic Pc5 Modulations of the Ionospheric Velocities and TEC and GOES-16 Magnetic Field Associated with Repeated Solar Wind Dynamic Pressure Enhancement

Ram Singh[1], Young-Sook Lee[2], and Yong Ha Kim[2]

[1]Dept. of Astronomy and Space Science, College of Natural Sciences, Chungnam National University Daejeon, South Korea
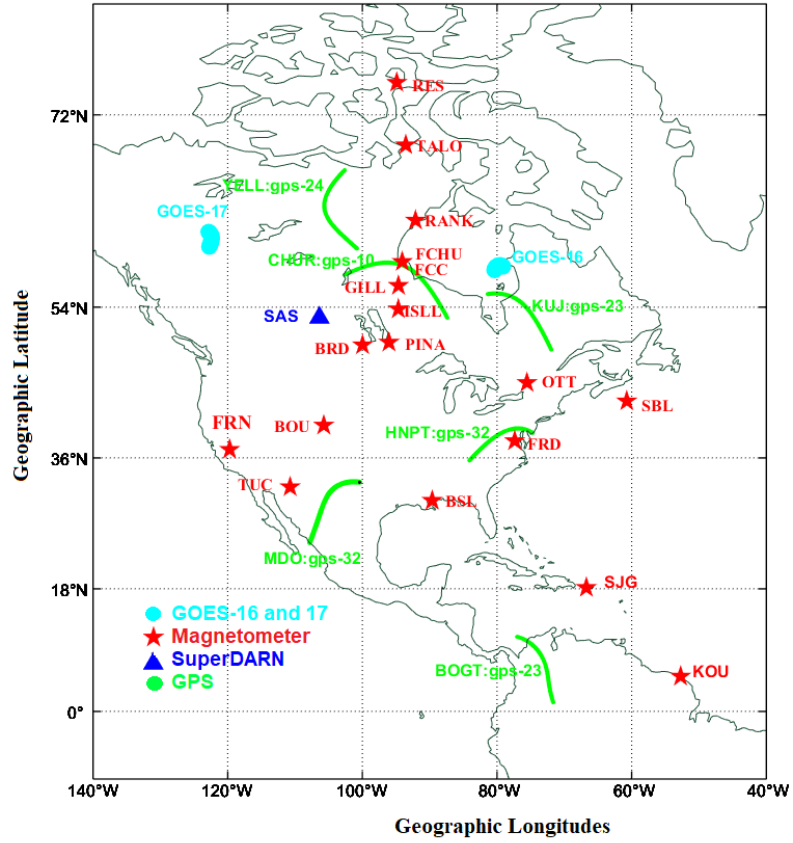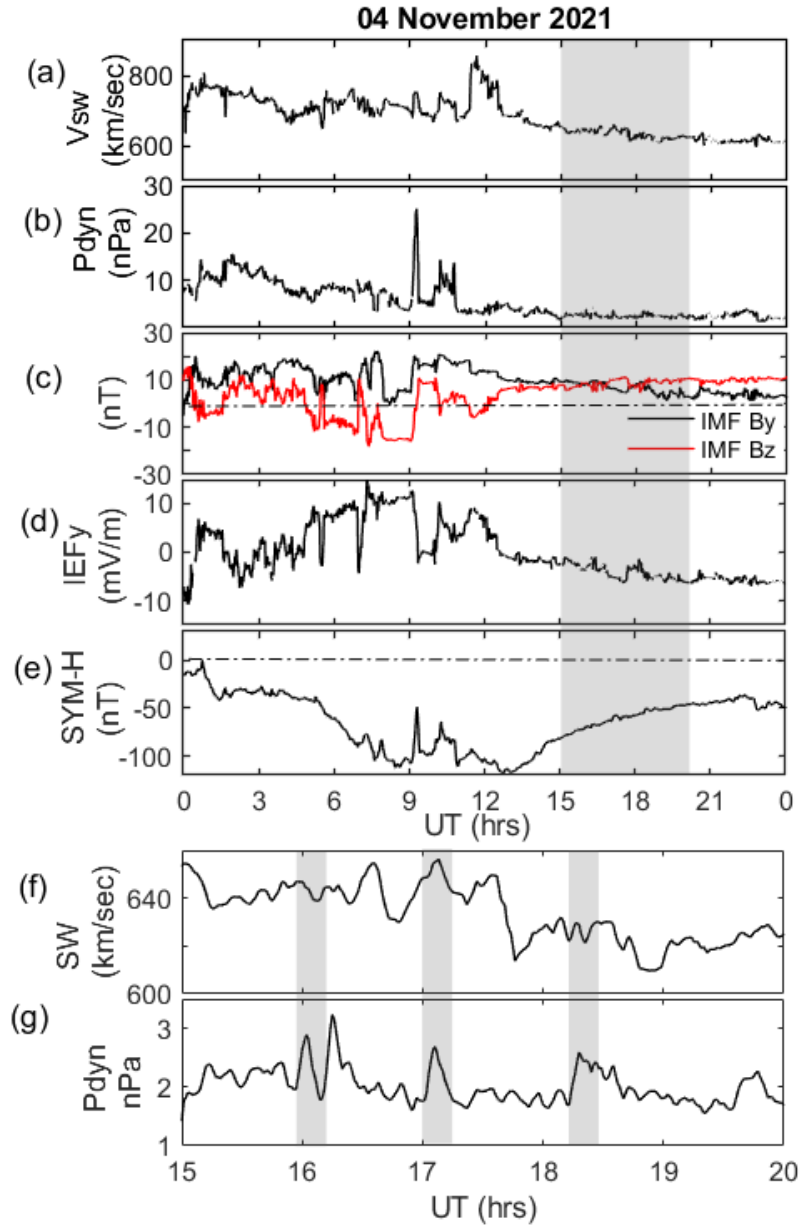[2]Chungnam National University
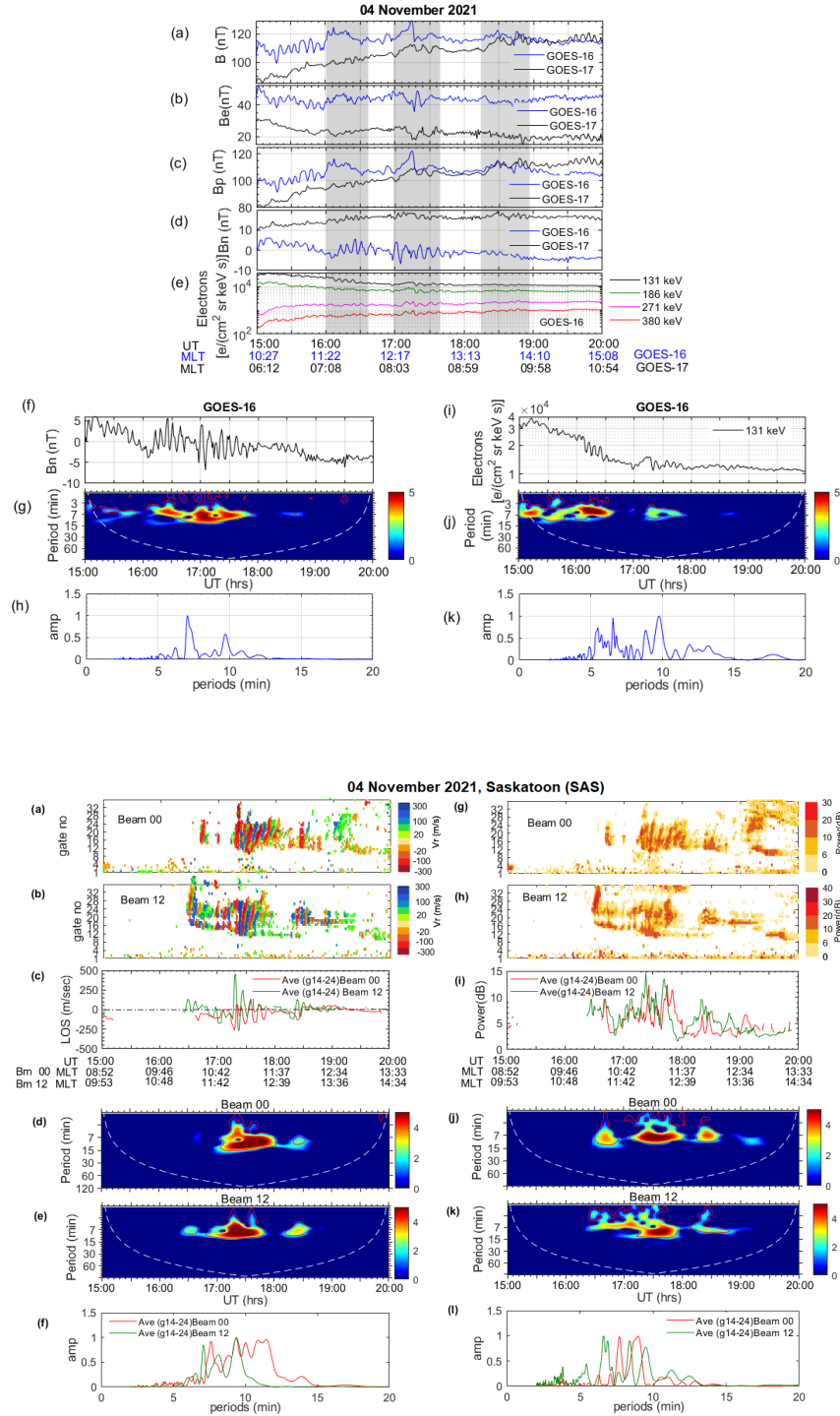
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Abstract

This study presents ultra-low frequency (ULF) Pc5 discrete spectrum simultaneously observed in the magnetosphere and high- to low-latitude ionospheres near noon hours (~10-14 MLT) during the recovery phase of geomagnetic storm on November 4, 2021. During the recovery phase, magnetospheric toroidal mode oscillations (GOES-16 Bn) appeared according to solar wind dynamic pressure enhancements after GOES Bp and Be (poloidal mode) oscillations precede during high solar wind speeds. When Bn oscillates, the ionospheric line-of-sight (LOS) velocity and echo power oscillate at the same discrete frequencies of 1.7 and 2.2 mHz (9.7 and 7.5 min), observed by Super Dual Auroral Radar Network (SuperDARN) at Saskatoon (eastward LOS). The period of negative LOS velocity (away from the radar) for 7.5 min or 9.7 min corresponds to echo power increase. This signifies that both the ionospheric density and poleward convection velocity increase are driven by the periodic forcing of the convection electric field and energetic electron precipitation. The same frequency pulsations have also been observed in the geomagnetic field (H-component) and Global Positioning System (GPS) total electron content (TEC) from high- to low-latitude ionosphere. The oscillation frequency of the H-component is consistently preserved at 1.7 mHz (9.7 min) down to low latitudes. The Pc5 oscillations at high to low latitudes can be attributed to toroidal mode Alfven waves and the compressional mode propagating across magnetic field lines as well as the fast magnetosonic waveguide mode at work by the solar wind dynamic pressure enhancements at high solar wind speeds.

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(a) H-componenet (Northward Magnetic Field) **(b)** FFT (Lomb-Scargle) **(c)** wavelet

(d) H-componenet (Northward Magnetic Field) **(e)** FFT (Lomb-Scargle) **(f)** wavelet

(a) **(b)** **(c)** **(d)**

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High Latitude
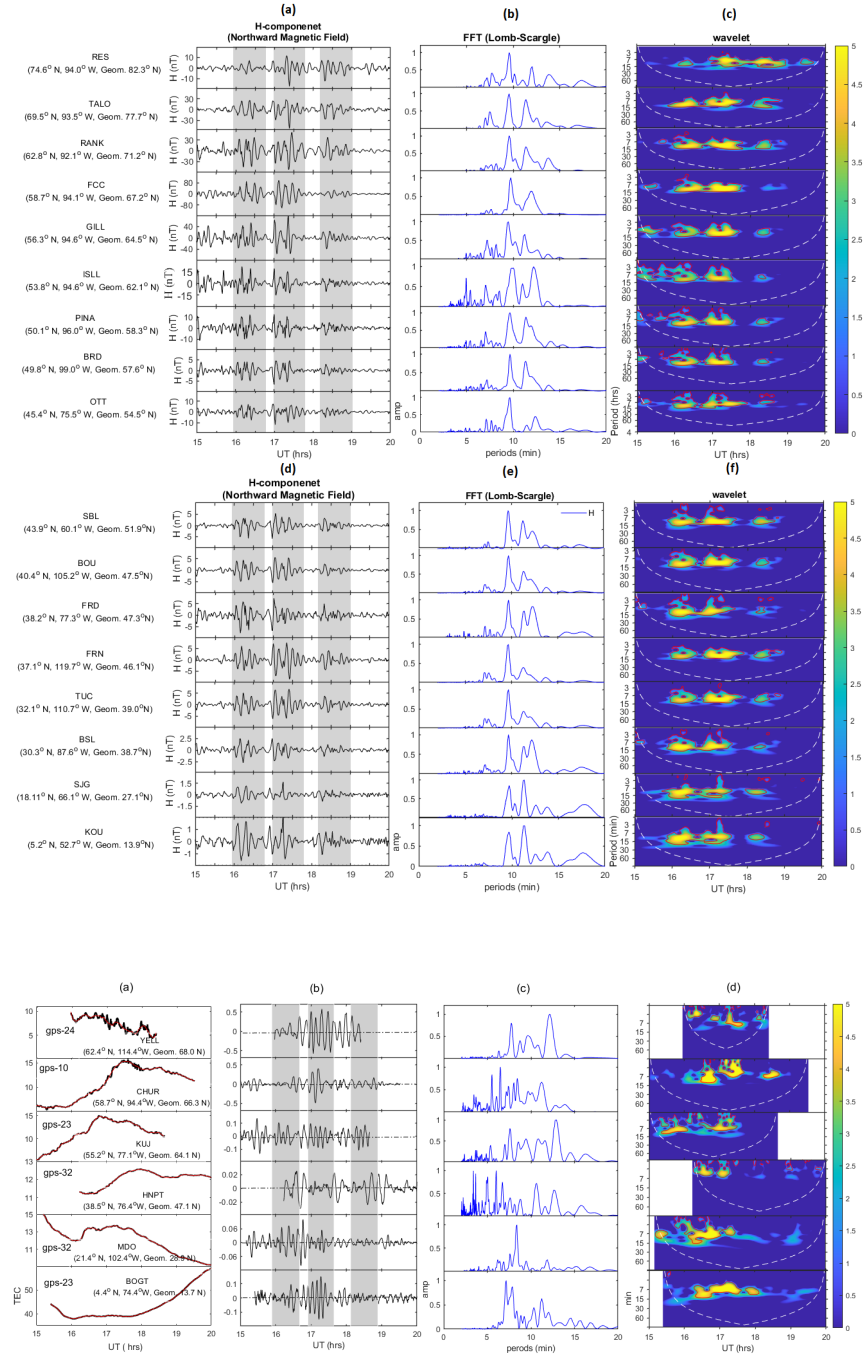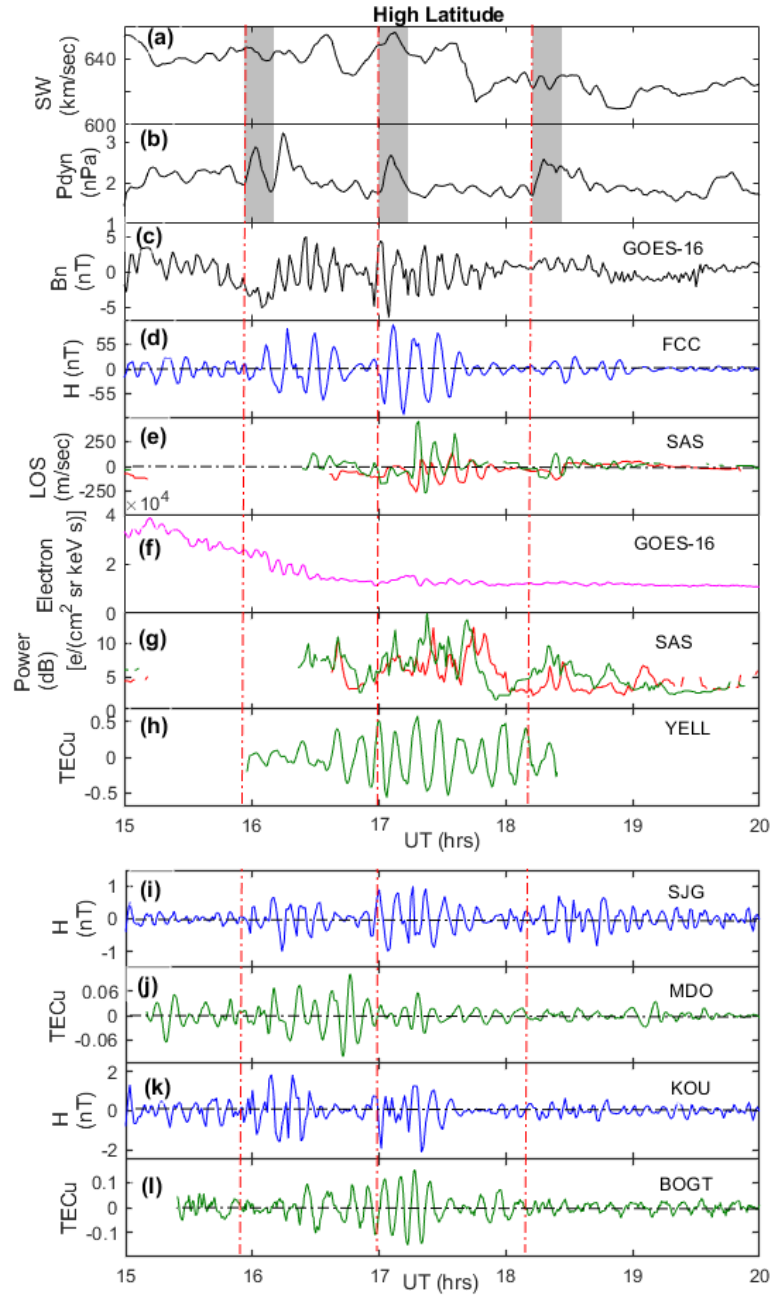
1 **Monochromatic Pc5 Modulations of the Ionospheric Velocities and TEC and GOES-16**

2 **Magnetic Field Associated with Repeated Solar Wind Dynamic Pressure Enhancement**

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4 Ram Singh, Young-Sook Lee, and Yong Ha Kim

5

6 Department of Astronomy and Space Science, Chungnam National University, Daejeon,

7 South Korea

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9 Corresponding author: Ram Singh (email:ramphysics4@gmail.com)

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11 **Key points**

12 1) Simultaneous observations of ultra-low frequency (ULF) Pc5 oscillations in the

13   magnetosphere and high to low-latitude ionosphere

14 2) Dominant Pc5 desecrate frequency (1.7 mHz) retained consistently without significant

15   changes

16 3) A series of three monochromatic oscillations observed in the magnetosphere and

17   ionosphere

18

19 **Abstract**

20 This study presents ultra-low frequency (ULF) Pc5 discrete spectrum simultaneously

21 observed in the magnetosphere and high- to low-latitude ionospheres near noon hours (~10-

22 14 MLT) during the recovery phase of geomagnetic storm on November 4, 2021. During the

23 recovery phase, magnetospheric toroidal mode oscillations (GOES-16 Bn) appeared

24 according to solar wind dynamic pressure enhancements after GOES Bp and Be (poloidal

25 mode) oscillations precede during high solar wind speeds. When Bn oscillates, the

26 ionospheric line-of-sight (LOS) velocity and echo power oscillate at the same discrete

27 frequencies of 1.7 and 2.2 mHz (9.7 and 7.5 min), observed by Super Dual Auroral Radar

28 Network (SuperDARN) at Saskatoon (eastward LOS). The period of negative LOS velocity

29 (away from the radar) for 7.5 min or 9.7 min corresponds to echo power increase. This

30 signifies that both the ionospheric density and poleward convection velocity increase are

31   driven by the periodic forcing of the convection electric field and energetic electron

32   precipitation. The same frequency pulsations have also been observed in the geomagnetic

33   field (H-component) and Global Positioning System (GPS) total electron content (TEC) from

34   high- to low-latitude ionosphere. The oscillation frequency of the H-component is

35   consistently preserved at 1.7 mHz (9.7 min) down to low latitudes. The Pc5 oscillations at

36   high to low latitudes can be attributed to toroidal mode Alfven waves and the compressional

37   mode propagating across magnetic field lines as well as the fast magnetosonic waveguide

38   mode at work by the solar wind dynamic pressure enhancements at high solar wind speeds.

39   **Plain Language Summary**

40   Pc5 ultra-low frequency (ULF) oscillations in the Earth's magnetosphere play an important

41   role in the transfer of energy in the magnetosphere and ionosphere, including solar wind

42   magnetosphere interaction, and coupling with different plasma wave modes and plasma

43   instabilities. This study presents simultaneous observations of Pc5 wave oscillations in the

44   magnetosphere and high to low-latitude ionosphere near noon hours. Three times increase in

45   solar wind dynamic pressure prompted the occurrence of three monochromatic oscillation

46   packets in Bn, high-to-low latitude ground north-south magnetic field (H), SuperDARN LOS

47   velocity and echo power, and GPS TEC (high-low latitudes). The azimuthal eastward

48   component of the magnetic field (poloidal mode (Bn)) and electron flux intensities showed

49   oscillations in the Pc5 discrete spectrum with dominant periodicities of 7.5 and 9.7 min (2.2

50   and 1.7 mHz) in the magnetosphere. The dominant Pc5 discrete frequencies occurring in the

51   magnetosphere and at high latitudes are consistently preserved all the way to low latitudes

52   without significant changes. Magnetic field oscillations active in toroidal field line

53   resonances in the magnetosphere affect oscillations in ionospheric velocity, plasma density,

54   and ground magnetic field at high latitudes.

55   **Keywords**

56   Magnetosphere, ionosphere, Pc5 pulsations, SuperDARN, GPS-TEC, Magnetometer.

57   **1. Introduction**

58   Pc5 ultra-low frequency (ULF, 1.6-6.7 mHz) waves can be used to diagnose several

59   magnetospheric properties, such as the acceleration of auroral electrons, particle scattering,

60   and energization and transport of radiation belt electrons (Samson et al., 1992a; Elkington et

61   al., 1999), as well as ground phenomena, such as geomagnetically induced currents which

62 can cause damage to technological infrastructure (Belakhovsky et al., 2019; Boteler et al.,
63 1998; Yagova et al., 2021). The ULF perturbations in the magnetosphere can be caused by a
64 variety of external (e.g., by the solar wind) or internal (e.g., by the resonance with energetic
65 particles) sources. The external drivers of ULF waves in the magnetosphere include the
66 Kelvin-Helmholtz Instability (KHI) via surface waves, direct solar wind pressure changes,
67 and solar wind discontinuation (Chen & Hasegawa, 1974; Southwood, 1974; Allan et al.,
68 1986; Wright and Rickard, 1995; Mann et al., 1999). The ULF waves detected on the ground
69 are not always the same as those entering the magnetosphere via the solar wind. As waves
70 generated outside the magnetosphere must pass through the magnetopause, wave energy is
71 transformed and amplified by processes occurring within the magnetosphere, such as field
72 line resonance (FLR) and other cavity resonances (Samson et al., 1991; Kivelson et al.,
73 1984; Kivelson and Southwood, 1986; Southwood and Kivelson, 1990).

74 Previous studies have reported pressure pulse-induced FLR at different discrete frequencies
75 of 1.3, 1.9, 2.6, and 3.3 mHz in the Pc5 spectrum which occurred simultaneously at different
76 latitudes (Samson et al., 1991; Ruohoniemi et al., 1991; Walker et al., 1992; Baddeley et
77 al.2007). Baddeley et al. (2007) examined the latitudinal and longitudinal characteristics of
78 Pc5 pulsations with dominant frequencies of 1.7, 2.6, 3.3, 4.2, and 5.4 mHz in the dawn flank
79 induced by a sudden increase in solar wind dynamic pressure.

80 Pc5 wave pulsations can significantly modulate ionospheric and magnetospheric parameters
81 including the electric field, plasma convection velocity, field-aligned current, precipitating
82 electron flux, ionosphere conductance, electron and ion temperatures, and total electron
83 content (TEC) (Lester et al., 2000; Ponomarenko et al., 2001; Sakaguchi et al., 2012;
84 Norouzi-Sedeh et al., 2015; Belakhovsky et al., 2016; Fenrich et al., 2019; Kozyreva et al.,
85 2020). Modern ground-based sounding techniques, such as HF Doppler sounders,
86 SuperDARN radars, trans ionospheric radio wave propagation, and riometers, can detect local
87 variations in ionospheric electron density caused by long-period ULF waves (Fenrich et
88 al., 1995; Ziesolleck et al., 1998; Ponomarenko et al., 2001; Pilipenko et al. 2014a; Watson et
89 al.,2015; Vorontsova et al, 2016; Fenrich et al., 2019; Kozyreva et al., 2020). The GPS-TEC
90 technique can also detect certain types of ULF waves in the ionosphere including the Pc5
91 waves at high latitudes and Pc3-4/Pi2 waves at mid latitudes (Davies & Hartman, 1976;
92 Hamada et al., 2015). The mechanism of TEC modulation by ULF waves is still unknown
93 and challenging for the MHD wave theory. According to Skone and Nicholsons (2006), the

94   relative disturbance of the TEC caused by Pc3 waves compared to quiet times is similar to or

95   even larger than that of the geomagnetic field. At high latitudes, the relative amplitude of

96   TEC variation is larger than that of geomagnetic pulsations (Pilipenko et al., 2014a).

97   Previous studies have shown that the latitudinal structure and azimuthal propagation

98   characteristics of ULF waves can be examined very effectively by using ground

99   magnetometers and the Super Dual Auroral Radar Network (SuperDARN) (Ziesolleck et al.,

100   1998; Ponomarenko et al., 2001; Pilipenko et al. 2014a; Watson et al.,2015; Fenrich et al.,

101   2019; Kozyreva et al., 2020). Kozyreva et al. (2020) showed simultaneous modulations in

102   SuperDARN Doppler velocity, GPS TEC, and ground magnetometer data by ULF waves.

103   They suggested that a sudden increase in solar wind density triggers transient Pc5 pulsations

104   on the morning flank of the magnetosphere in both the geomagnetic field and ionospheric

105   plasma. Pilipenko et al. (2014a) and Watson et al. (2015) demonstrated the ULF waves

106   induced modulations in the ionospheric plasma using ground-based TEC measurements.

107   Baddeley et al. (2007) reported Pc5 wave characteristics in the dawn and dusk flanks. They

108   hypothesized that an abrupt rise in solar wind dynamic pressure could induce a Kelvin-

109   Helmholtz-driven waveguide mode, which would cause a large increase in wave activity and

110   FLR structures.

111   The occurrence of Pc5 pulsations at low and equatorial latitudes has been explained in

112   numerous studies using a variety of processes (Ziesolleck and Chamalaun 1993; Reddy et al.

113   1994; Shinohara et al., 1998; Motoba et al. 2002; Huang 2021). Ziesolleck and Chamalaun

114   (1993) suggested that the spatial characteristics of Pc5 pulsations at low latitudes are

115   consistent with the magnetic ground signatures of global compressional modes or large-scale

116   cavity resonances. Reddy et al. (1993) and Motoba et al. (2002) proposed that in contrast to

117   the effects of directly incoming hydromagnetic waves on the low-latitude ionosphere, electric

118   field oscillations at low and equatorial latitudes were caused by $E \times B$ effects due to

119   ionospheric electric field penetration from high latitudes to the equator.

120   In this study, we present observations of monochromatic Pc5 oscillations in the

121   magnetosphere and high- to low-latitude ionospheres driven by repeated solar wind dynamic

122   pressure enhancements at high solar wind speeds during the recovery phase of strong

123   magnetic storms on November 4, 2021. It is evident that dominant Pc5 discrete frequencies

124   occurring in the magnetosphere and high latitudes are consistently preserved all the way to

125   low latitudes without significant changes. This paper is structured as follows: Section 2

126 outlines the data source analyzed. Section 3 presents the observations and results. The
127 interplanetary and geomagnetic conditions are presented in Section 3.1. Geosynchronous,
128 particle and magnetic field observations (GOES-16 and GOES-17) and ground-based and
129 ionospheric measurements (SuperDARN/Magnetometer/GPS TEC) are presented in sections
130 3.2 and 3.3. Sections 4 and 5 contain the discussion and conclusion, respectively.

131

132 **2. Observational information and data sets**

133 We used datasets obtained from the American longitudinal region. The solar wind and
134 geomagnetic condition data at 1-minute cadence were obtained from CDAWEB
135 (http://cdaeb.gsfc.nasa.gov), measured by the Advanced Composition Explorer (ACE)
136 satellite, which monitors the interplanetary medium conditions near the L1 point. Ground-
137 based magnetic field data were obtained from the SuperMAG magnetometer network
138 (http://supermag.jhuapl.edu) and the Canadian Array for Real-time Investigations of
139 Magnetic Activity (CARISMA) (https://www.carisma.ca/carisma), and their site locations are
140 shown in Figure 1. The space-based geomagnetic field data and energetic electron fluxes
141 were analyzed from the fluxgate magnetometer and energetic particle sensor mounted on
142 GOES-16 and GOES-17, respectively. The satellite footpoints GOES-16 (Geog./Geom.):
143 58.2ºN, 79.4ºW/67.68ºN, 9.8ºW; and GOES-17 (Geog./Geom.): 61.5ºN, 123.7ºW/66.3ºN,
144 67.6ºW) are indicated in Figure 1. The GOES-16/-17 magnetic field components and electron
145 flux data at 1 min cadence were obtained from https://www.ngdc.noaa.gov/stp/satellite/goes-
146 r.html. We examined the HF SuperDARN radar data from Saskatoon (Geog: 52.1ºN,
147 106.6ºW, Geom: 60.8ºN, 40.8ºW), which is set up for the eastward field of view and reserved
148 for the observation of the high-latitude ionosphere. SuperDARN data can be downloaded
149 from the site https://ergsc.isee.nagoya-u.ac.jp./, a ground measurement repository created for
150 the About Exploration of energization and Radiation in Geospace "ARASE" (ERG) mission.
151 The SuperDARN radar has a field of view with 15 beams in azimuth and 75 range gates with
152 a width of 45 km, starting at a distance of 180 km distance in the extension of the oblique
153 geometry. GPS TEC data with a 30 s resolution from an array of GPS receivers in American
154 longitudes were taken from ftp://cddis.gsfc.nasa.gov/pub/gps/data, and the site location is
155 shown in Figure 1.

156 **3. Observational Results**

157   In this section, we present the discrete frequency spectra in the ULF Pc5 band detected in

158   various datasets obtained for the magnetospheric and ionospheric (high- to low-latitudes)

159   observations during the recovery phase of the magnetic storm on November 4, 2021.

160   **3.1 Interplanetary magnetic field and geomagnetic conditions**

161   The main effects of solar wind and interplanetary magnetic field on Earth's magnetosphere

162   and ionosphere are demonstrated here. To specify time intervals for the analysis, the solar

163   wind and geomagnetic conditions for November 4, 2021, are presented in Figure 2. Figure 2

164   shows, from top to bottom, the (a) change in solar wind velocity (Vsw), (b) solar wind

165   dynamic pressure (Pdyn), (c) y- and z-components of the interplanetary magnetic field (IMF:

166   By and Bz in black and red); (d) the interplanetary electric field (IEF Ey) calculated from Ey

167    $= -\text{Vsw} \times \text{Bz}$, (e) Sym-H, and (f-g) an enlarged view of Vsw and Pdyn between 1500-2000

168   UT. The time interval from 1500-2000 UT is indicated with a grey shade because discrete

169   frequencies of the Pc5 wave band occurred simultaneously in the magnetosphere and

170   ionosphere. The geomagnetic storm that started from 23 UT on November 3, 2021, is

171   considered to be recovering at ~1300 UT with SYM-H of -120 nT. During the main phase,

172   the geomagnetic activity and interplanetary magnetic field conditions exhibited strong

173   disturbances, whereas monotonic disturbances were observed during the recovery phase.

174   Both IMF Bz and By were positive and nearly stable between 1500-2000 UT. The solar wind

175   velocity varied between 600-700 km/s, and solar wind dynamic pressure was approximately

176   2-4 nPa during the period of 1500-2000 UT (shaded area). The solar wind dynamic pressure

177   experienced repeated enhancements around 1600, 1700, and 1820 UT in high solar wind

178   speed environments, in spite of the small magnitudes as shown in Figure 1f-1g (grey shaded

179   areas). The Auroral electrojet indices (AE, AL, AU) did not indicate any substorm activity

180   between 1500-2000 UT, and their maximum values were less than ~200 nT (not shown here).

181   **3.2 Geosynchronous particle and magnetic field observations (GOES-16 and GOES-17)**

182   GOES-16 and -17 satellites orbiting in a geostationary orbit have positions of 80ºW and

183   ~120ºW, respectively, as shown in Figure 1. A notable interval from 1500-2000 UT

184   corresponds to 1027-1508 MLT and 0612-1054 MLT for GOES-16 and -17, respectively.

185   Figure 3 demonstrates (a-d) the magnetic field of the (a) total value (Bt); (b-d) Be (e is

186   directed radially inward), Bp (p is parallel to the Earth's spin axis), and Bn (n is the

187   azimuthally Earth's spin axis) components as measured by GOES-16 (blue line) and GOES-

188   17 (black line); and (e) GOES-16 electron fluxes plotted for the four energy channels ~131,
189   186, 271, and 380 keV. It is notable that at the 1600 UT boundary, the GOES-16 magnetic
190   field oscillation mode significantly changed from poloidal (including compressional) to the
191   toroidal mode, such that noticeable oscillations of the Bp and Be components were transited
192   to amplified Bn oscillations.

193   In addition, the amplified oscillations were observed for the GOES-16 electron flux from
194   1600-1800 UT (Figure 3e), corresponding to near noon time, however not to the dawn sector
195   (GOES-17 located), as tick-labeled in MLT. Significantly smaller amplitude oscillations of
196   Bn were also observed in GOES-17 at the same time (Figure 3d), indicating that GOES-17
197   was farther from the source region of the oscillations than GOES-16.

198   To determine the oscillation frequency of Bn and the electron flux, Figure 3 (g-h and j-k)
199   depicts a periodic analysis using Morlet wavelet analysis (Torrence and Compo., 1998) and
200   the Lomb-Scargle (LS) method (Lomb, 1976). Figures 3f and 3i display the temporal
201   variations in the magnetic Bn and electron flux (at 131 keV), respectively; the middle panels
202   (g and j) display the wavelet spectrogram analysis, and the bottom panels (h and k) display
203   the LS periodogram. For the periodogram analysis of the Pc5 frequency band, the long-term
204   low-frequency region was removed using the third-order Savitzky-Golay smoothing
205   algorithm (Savitzky & Golay 1964). Wavelet analyses of Bn (Figure 3g) and electron flux
206   (Figure 3j) demonstrated spectral power enhancement in a narrow band (5-10 min) of ULF
207   Pc5 waves. This spectral power enhancement lasted for more than 2 hours. The LS analysis
208   reveals dominant discrete periodicities at 7 and 9.8 min (2.4 mHz and 1.8 mHz) in Bn (Figure
209   3h) and at 5.5-6.5 min and 9-9.8 min in the electron flux (Figure 3k).

210   **3.3 Ground-based ionospheric measurements (SuperDARN/Magnetometer/ GPS TEC)**

211   Figure 4 shows measurements of the Saskatoon (SAS) SuperDARN HF radar at a high
212   latitude in the northern hemisphere (Geog/Geom: $52.16°$ N, $106.63°$ W/$60.88°$ N, $40.88°$ W)
213   between 1500-2000 UT. The left panel represents the line of sight (LOS) Doppler velocities
214   with positive (blue) velocity when approaching the radar and negative (red) velocity when
215   away from the radar, and (the right panel) for echo power (dB) derived from beam numbers
216   (bm) of 0 and 12. Clear oscillations appear in both (a-b) LOS velocities and (g-h) echo power
217   from bm 0-12 (not all beams shown here) in the range gates of 12-28 that are corresponding
218   to 675-1395 km slant range and Geog./Geom. latitude of $57-63°$N/$65-71°$N at a time interval

219   1720-1740 UT. Figures 4c and 4i exhibit average values of echo power and LOS velocity

220   from gates 14 to 24 for bm 0 (red) and 12 (green). The magnetic local time (MLT) is taken

221   into consideration at the average locations for range gates 14-24 for bm 0 and 12 (Geog:

222   60°N, -95°W; and 60°N, -85°W, respectively).

223   The wavelet spectrum of the average power and LOS velocity is displayed in Figures 4d-e

224   and 4j-k, in which common dominant periods are found to be 7-10 min (1.67-2.4 mHz) from

225   the enhanced spectral power for LOS velocity and echo power between 1630 and 1800 UT

226   (10:15-11:37 MLT for bm 00, 11:16-12:40 MLT for bm 12). A Lomb-Scargle periodogram

227   analysis was performed for the mean values over the gates of 14-24 of bm 0 and 12, as shown

228   in Figures 4f and 4l. The results of the periodic signature common here are at 7 and 9 min

229   (2.4 mHz and 1.8 mHz) for the LOS rate and at ~9 min for the echo power. The SAS radar's

230   LOS velocity and echo power allowed us to observe discrete frequencies of 1.8 and 2.4 mHz

231   in the Pc5 wave band, identical to the magnetometer Bn component of GOES-16. This may

232   be due to the field of view (bm 12) of the SuperDARN SAS radar, which specifically targets

233   a common area, the GOES-16 footprint.

234   The Pc5 wave oscillations were mostly observed before and after the local noon local in the

235   magnetometer observations. Figure 5 shows the meridional profile of the magnetometer data

236   for the American sector. In Figures 5a and 5d, the northward magnetic field (H-component)

237   variations are presented from high to low latitudes in the northern hemisphere at the time

238   interval of 1500-2000 UT. The locations of the sites are listed in Table 1. Using the Savitzky-

239   Golay smoothing algorithm, the third-order fit line in the H variations was used to eliminate

240   low-frequency components. Figure 5 shows the quasi-monochromatic pulsations. Periodic

241   oscillations were observed three times at approximately 1600, 1700, and 1810 UT (gray

242   shades) from high to low latitudes, corresponding to three times the pressure enhancement as

243   shown in Figure 2g. Smaller oscillations up to lower latitudes were present throughout the

244   entire period and large-amplitude oscillations dominated between 1700 UT and 1740 UT.

245   Figures 5b and 5e show periodogram analysis for H component. Here, two major

246   periodicities appear consistently, mainly at 9.5 and 11.2 min (~1.7 and 1.4 mHz) in the Pc5

247   frequency band along the longitudinal sector (8-12 MLT). In particular, it is noticeable that

248   the periodicity of 9.5 minutes is maintained without shifting from 80°N to 14°N. Here

249   discrete spectrum frequencies (1.4 and 1.7 mHz) can be identified near the FLR frequencies

250   (1.3 and 1.9 mHz) (Samson et al., 1991, 1992; Harrold and Samson, 1992). Wavelet analysis

251   of the H component revealed power spectrum enhancement between 1600 and 1900 UT

252 (Figures 5c and 5f), which was centered in the periodic range between 7-12 min (2.3-1.3

253 mHz). The wavelet power spectra also show that three amplitude enhancements occurred at

254 1600, 1700, and 1810 UT with each lasting approximately ~50 min.

255 Figure 6a shows the vertical TEC variations from high to low latitudes at selected GPS

256 locations across the American longitudinal sector. Figure 6a (leftmost column) shows the

257 GPS TEC variations from high to low latitudes in the following order: YELL (GPS-24:

258 62.4°N, 115.4°W), CHUR (GPS-10: 58.7°N, 94.4°W), KUJ (GPS-23: 55.2°N, 77.1°W),

259 HNPT (GPS-32: 38.5°N, 76.4°W), MDO (GPS-32: 21.4°N, 102.4°W), and BOGT (GPS-23:

260 4.4°N, 74.4°W). The TEC variations and polynomial fits obtained using the third-order

261 Savitzky-Golay algorithm are plotted in black and red, respectively. A periodogram analysis

262 of TEC residual, after the long-term trend was subtracted by the polynomial fit, was

263 performed to examine the small-scale fluctuations. The residual TEC is shown in Figure 6b.

264 Figure 6c shows periodogram analysis results of a common dominant periodicity at 8-9 min

265 (1.8-2.0 mHz) over the high-low latitudes, and for high latitudes (55°- 62°N) longer periods

266 of 11-12 min (1.4-1.5-mHz) also appear. The wavelet power spectrum clearly shows the

267 dominant frequencies in the band of the Pc5 ULF waves between 1600-1800 UT except at the

268 mid-latitude station of the HNPT. The wavelet power spectrum also clearly shows dominant

269 periodicities of 5-15 min (3.3-1.1 mHz) between 1600-1800 UT.

270

271 Figure 7 shows a direct comparison of (a, b) solar wind conditions (Vsw, Pdyn), (c, f)

272 magnetospheric and (d-e, g-h, i-l) ionospheric Pc5 oscillations: (c-d) oscillations of the

273 azimuthal component (Bn) of the magnetic field at GOES-16 and the northward magnetic

274 field component (H) at FCC; (e) LOS velocity average between gates 14-24 for beams 00

275 (red); and 12 (green); and (f-h) the variations of GOES-16 electron flux, SuperDARN power,

276 and GPS TEC (at YELL); (i and k) ground H component at SJG and KOU; and (j and l) GPS

277 TEC at MDO and BOGT. Here, it is remarkable that three wave packets are noticeable in the

278 Bn and ground H components from high to -low latitudes, as well as in SAS LOS and echo

279 power with a time delay, and TEC with corresponding to three repeating Pdyn enhancements

280 at ~1600, ~1700, and ~1800 UT (indicated with grey shades). The ULF wave activity and

281 amplitude enhancement of ionospheric and magnetospheric oscillations appear to be

282 significantly linked to pressure pulse enhancements. In the modulated ionospheric and

283 magnetospheric parameters, a strong common periodicity is found as 7.6 and 9.7 min (2.1 and

284 1.7 mHz).

4. Discussion

This section discusses the observations presented in the previous section and attempts to make case for an observational link between wave activity in the magnetosphere and ionosphere. The common periodicities of 7.5 and 9.7 min (2.2 and 1.7 mHz) in the eastward component of the GOES-16 magnetic field (Bn), electron flux intensities, magnetometer data, SupeDARN, and GPS TEC were observed during the magnetic storm's recovery phase on November 4, 2021. These oscillations evident ns were most noticeable in the geomagnetic field and ionospheric density and, which occurred simultaneously from high to low latitudes.

4.1 Pc5 pulsations at high latitude in H- component, GPS TEC, and SuperDARN radar

Several studies have been conducted on Pc5 pulsations and have shown distinctive characteristics for each type of oscillation (Ruohoniemi et al., 1991; Walker et al., 1992; Harrold and Samson, 1992; Lester et al., 2000; Ponomarenko et al., 2001; Sakaguchi et al., 2012; Norouzi-Sedeh et al., 2015; Belakhovsky et al., 2016; Fenrich et al., 2019; Kozyreva et al., 2020). Pc5 pulsations can be generated by the Kelvin-Helmholz instability at magnetospheric boundaries as of standing Alfven waves in a tube with FLRs. FLRs are magnetospheric magnetic perturbations in the azimuthal direction of toroidal mode waves. The FLR signatures in the magnetometer data can be seen in the magnetic north-south or H component owing to the rotational effect of the ionosphere or Hall currents. However, poloidal mode waves are characterized by magnetic field perturbations in the radial direction, which induce perturbations in the magnetic east-west or D component (Hughes, 1983; Chen and Hasegawa, 1991).

In our observations, oscillations in the magnetic H-component in the magnetometer data could be linked to toroidal mode waves (Bn) or FLRs induced by the solar wind dynamic pressure because magnetic field perturbations between 1600-1900 UT in the magnetosphere are only seen in the azimuthal component (Bn), not in Be or Bp (Figure 3). Additionally, toroidal mode waves are responsible for the simultaneously observed common periods of 7.5 and 9.5 min (2.2 and 1.7 mHz) in the Bn and H components, respectively. Previous studies have reported that Pc5 pulsations with discrete frequencies of 1.3, 1.9, 2.6, 3.4, and 4.2 mHz have been observed from high-latitude ground-based magnetometers triggered by FLRs or driven by magnetospheric waveguide modes (Samson et al., 1991, 1992; Harrold and Samson, 1992; Ruohoniemi et al., 1991). Wright and Rickard (1995) suggested that magnetospheric

316   waveguide modes can be excited by solar wind turbulence at the magnetopause to produce

317   pulsation. According to their studies, running pulses generated by the solar wind, which are

318   predicted to be features of Kelvin-Helmholtz surface waves, can produce magnetopause

319   ripples, waveguide modes, and FLRs with phase velocities equal to the speed of the running

320   pulse. The three-wave packets of PC5 pulsations observed in GOES-16 Bn and the electron

321   flux, H (high-low latitude), SuperDARN LOS velocity and echo power, and TEC

322   observations, can be the result of FLR due to repeated pressure intensification.

323   In poloidal modes, the wave electric field oscillates azimuthally while the wave magnetic

324   field oscillates radially; conversely, in toroidal mode, the wave electric field is radially

325   polarized while the wave magnetic field and velocity perturbations are azimuthally polarized

326   (Hudson et al., 2004). Toroidal waves are more efficiently coupled to compressional

327   disturbances at larger azimuthal scales than poloidal waves (Radoski, 1967). The toroidal Pc5

328   pulsations can be excited by the KHI at the magnetopause stimulated by high solar wind

329   speed and/or the dynamic pressure enhancements, followed by the propagation of a fast

330   magnetosonic wave deep into the magnetosphere and the generation of FLRs. Some of this

331   energy is transformed into standing Alfven waves along field lines when a fast magnetosonic

332   wave travels deep into the magnetosphere; the SuperDARN and ground-based

333   magnetometers can detect these standing Alfvenic waves (Fenrich et al., 1995; Sung et al.,

334   2006; Harrold and Samson, 1992; Lester et al., 2000; Ponomarenko et al., 2001). When

335   pulsations occur on the magnetic field lines elongated from the magnetosphere to the

336   ionosphere, the associated pulsating E field causes the local bulk ionosphere to move with an

337   E×B drift, which can be monitored by SuperDARN HF radar. The field-aligned irregularities

338   at ionospheric heights also experience this force and travel at varying velocities. This

339   movement manifested as a periodic variation in the LOS velocity as recorded by SuperDARN.

340   The ionospheric velocity oscillations observed by the SAS radar as shown in Figure 4a-c are

341   linked to toroidal mode waves, as the compressional disturbance can modulate the Alfven

342   wave magnetic field and velocity perturbations in the azimuthal directions. As a result, the

343   high latitude ionospheric convection electric field and $E \times B$ flow drift can be modulated. The

344   changes of the electric field may be magnified by fast magnetosonic standing Alfven waves

345   moving along the field lines, so that the azimuthal component (Bn) and LOS velocity were

346   observed to have common periods of 7.5 and 9.5 min (2.2 and 1.7 mHz). The oscillation

347   pattern with three wave packets was also clearly visible in the LOS velocity and Bn

348   corresponding to the repeated pressure enhancement at 1600, 1700, and 1820 UT. In addition,

349   the convection maps in the northern hemisphere (not shown here) were repeatedly enlarged

350   and contracted along with the LOS velocity oscillations and echo power. Positive line-of-

351   sight velocity was observed toward the radar as the dusk (dawn) convection cell expanded

352   (contracted), and negative ionospheric velocity was observed as the dusk (dawn) cell

353   contracted (expanded) during that time. As demonstrated in the SuperDARN beam 0 data

354   oscillations, the period of negative LOS velocity (away from the radar) for 7.5 min or 9.7 min

355   corresponded to the echo power increase. As the SAS radar beam 0 looks toward the

356   magnetic north pole, negative velocity increase signified the increase in the poleward

357   (antisunward) convection velocity near noon. As a result, we can surmise that the ionospheric

358   density increases during the enhanced convection electric field. Pc5 pulsation can

359   periodically drive the convection electric field, resulting in the transfer of the magnetospheric

360   electron flux into the ionosphere by precipitation along the magnetic field line.

361   According to Watson et al. (2015), the ULF modulation of energetic electron precipitation

362   may lead to additional periodic ionization of the lower ionosphere, resulting in periodic TEC

363   variations that are much more significant than variations in the geomagnetic field. The theory

364   of Alfven wave interaction with the thin ionospheric layer can also be used to interpret the

365   simultaneous periodic variations in ionospheric plasma velocity and geomagnetic field.

366   Belakhovsky (2016) examined the TEC modulation by magnetospheric Alfven waves and

367   proposed that several possible mechanisms, including periodic plasma heating, convection

368   across a steep gradient, and field-aligned electron transport, could work simultaneously. In

369   some cases, magnetospheric precipitating energetic electron fluxes that are modulated by Pc5

370   pulsations can also efficiently modulate the ionospheric density (Sarris et al., 2007; Pilipenko

371   et al., 2014a, 2014b). In our observations, ionospheric density observed with the proxy of

372   SuperDARN radar echo power and GPS TEC exhibited periodic oscillations similar to those

373   of energetic electron flux at common periodicities of 7.5 and 9.7 min (2.2 and 1.5 mHz) as

374   shown in Figure 4g-l, 6, and 3i-k, respectively. The interaction of electromagnetic

375   hydrodynamic (MHD) waves with the ionosphere can cause ionospheric density modulation.

376   This is evident from the observation of Bn, electron flux, LOS, and H-component oscillating

377   with the same period. Correspondingly, the same mechanism can be expected to cause the

378   TEC modulations via Pc5 waves.

379   **4.2 Pc5 pulsations at low latitude in H component and GPS TEC**

380   The ULF pulsations in the ionosphere are typically a combination of Alfven and

381 compressional fast magnetosonic (FMS) waves. Numerous ground, satellite, and radar
382 observations at high latitudes have demonstrated that Pc5 waves in the ionosphere are
383 primarily composed of Alfven waves (Wright and Rickard., 1995; Samson et al. 1991; Sung
384 et al., 2006; Harrold & Samson, 1992; Lester et al., 2000; Mathie & Mann., 2000; Pilipenko
385 et al. 2014a, 2014b). Pilipenko et al. (2014a) reported that ULF modulation effects can be
386 observed not only at auroral latitudes but also at low latitudes. The transmission of Pc5 waves
387 to lower and equatorial latitudes is most likely explained by a non-Alfvenic mechanism, such
388 as the cavity or MHD waveguide modes. Previous studies suggested the fast magnetosonic
389 waveguide mode for TEC modulations in ULF Pc5 waves at the middle and low latitudes
390 (Marin et al., 2014; Belakhovsky., 2016; Vorontsova et al, 2016).

391 Vorontsova et al. (2016) presented a combined study of TEC and magnetometer observations
392 at the low latitude and provided crucial details regarding the physical mechanism of Pc5
393 pulsations. They suggested that the TEC modulations at low latitudes were caused by plasma
394 compression via the fast magnetosonic mode. As the FMS waveguide mode arrives in the
395 low-latitude ionosphere, it provokes periodic modulation of the TEC and the magnetic field
396 response on the ground. From our observations, periodic oscillations of the TEC and
397 magnetic field H component at low latitudes can be explained by a scenario that the FMS
398 waveguide mode enters the low latitude ionosphere, causing periodic oscillations with
399 periods of 7.5 and 9.7 minutes (2.2 and 1.7 mHz) as shown in Figure 5. The FMS waveguide
400 mode could be induced by impulses in dynamic pressure during high solar wind speed
401 (Figure 7). Pc5 pulsations have been observed at equatorial and low latitudes, and several
402 studies have investigated and provided different explanations for their occurrence (Ziesolleck
403 and Chamalaun 1993; Reddy et al. 1994; Shinohara et al., 1998; Motoba et al. 2002; Huang
404 2021). Ziesolleck and Chamalaun (1993) examined the spatial characteristics of the Pc5
405 pulsations associated with large-scale cavity resonances, global compressional modes, and
406 direct incoming hydromagnetic waves at lower latitudes. In contrast to the effects of directly
407 incoming hydromagnetic waves at lower latitudes, electric field penetration from high
408 latitudes to the equator can be responsible for electric field oscillations in the ExB at lower
409 latitudes (Reddy et al. 1994; Shinohara et al., 1998; Motoba et al. 2002). As the geomagnetic
410 and interplanetary conditions were quiet and of small magnitude during our observations, we
411 assumed that the possibility of penetration of the electric field was relatively low. The
412 presented results lend more credence to sudden impulses in the dynamic pressure and solar
413 wind velocity dependent mechanism.

5. Conclusion

We investigated the monochromatic Pc5 pulsations observed in magnetosphere and ionosphere in the noon (10-14 MLT, 1600-1900 UT) on November 4, 2021, during the recovery phase of the magnetic storm. The events were synchronized with repeated dynamic pressure enhancements during high solar wind speeds, but without significant interplanetary magnetic field activity remained in positive By and positive Bz. Observations from GOES-16, the ground magnetometers, SuperDARN, and GPS-TEC measurements consistently revealed common ULF Pc5 discrete frequency oscillations in the magnetosphere and high-to-low latitude ionosphere.

The main findings of this study are:

1. In the magnetosphere and high-to-low latitude ionospheres, periods of 7.5 and 9.7 min (2.2 and 1.7 mHz) were simultaneously observed in GOES-16 azimuthal component of magnetic field (Bn) and electron flux for the magnetosphere, H component, SuperDARN LOS velocity and echo power, and GPS TEC for the high-to-low ionospheres, in the noon sector of 10-14 MLT.

2. A series of three monochromatic oscillation packets occurred commonly in Bn, high-to-low latitude ground H-component (north-south), SuperDARN LOS velocity and echo power, and GPS-TEC (high-low latitudes) by three times small enhancements of solar wind dynamic pressure during high solar wind speeds.

3. From SuperDARN (bm 0) data oscillations, the period of negative LOS velocity (away from the radar) for 7.5 min and 9.7 min corresponded to echo power increase. This signifies that the ionospheric density increases during the enhancement of poleward convection velocity caused by the enhanced convection electric field.

4. Notably, the dominant Pc5 discrete frequency of 1.7 mHz observed in the magnetosphere (Bn) and high latitudes (H) remained persistent to low latitudes without change.

5. The amplified modulation of the GOES-16 Bn component signifies the magnetic field oscillation active in toroidal field line resonance in the magnetosphere, which can affect the oscillations of the H component, SuperDARN LOS velocity and echo power, and GPS TEC at high latitudes based on observations of their oscillations at the same discrete frequency.

6. Pc5 oscillations in radar power (dB) and TEC at high latitudes can be caused by magnetospheric Alfven waves, field-aligned transport, and periodic magnetospheric electron precipitation.

7. The oscillations in the TEC and H components are attributed to the fast magnetosonic (FMS) waveguide mode.

In summary, multiple observations reveal common oscillations of ULF Pc5 discrete frequencies at 2.2 and 1.7 mHz in the magnetosphere and high-to-low latitude ionosphere. Enhancement of solar wind dynamic pressure during high solar wind speeds can induce toroidal mode FLR modulation in the magnetosphere. The modulation of the ionospheric density, convection velocity, and TEC in the Pc5 frequency at high latitudes can be attributed to the FLR effect, and the Pc5 modulations of H-component and TEC in the low latitudes ionosphere are likely caused by the cavity mode and fast magnetosonic (FMS) waveguide.

Data Availability Statement

OMNI data are available at https://spdf.gsfc.nasa.gov/pub/data/omni/high_res_omni/.
SuperDARN cdf formatted data are available https://ergsc.isee.nagoya-u.ac.jp/data/ergsc/ground/radar/sd/fitacf/. GOES satellites and GPS TEC data can be found at https://www.ngdc.noaa.gov/stp/satellite/ and https://cddis.nasa.gov/pub/gps/data. The magnetometer data are available from the SuperMAG magnetometer network (http://supermag.jhuapl.edu) and the Canadian Array for Real-time Investigations of Magnetic Activity (CARISMA) (https://www.carisma.ca/carisma).

References

475   Allan, W., S. P. White, and E. M. Poulter (1986), Impulse-excited hydromagnetic cavity and

476   field line resonances in the magnetosphere, Planet. Space Sci., 34, 371.

477   Baddeley, L. J., Yeoman, T. K., McWilliams, K. A., & Wright, D. M. (2007). Global Pc5

478   wave activity observed using SuperDARN radars and ground magnetometers during an

479   extended period of northward IMF. Planetary and Space Science, **55**, 792– 808.

480   Belakhovsky, V., Pilipenko, V., Engebretson, M., Sakharov, Y., & Selivanov, V. (2019).

481   Impulsive disturbances of the geomagnetic field as a cause of induced currents of electric

482   power lines. Journal of Space Weather and Space Climate, 9, A18.

483   Belakhovsky, V., Pilipenko, V., Murr, D. et al. (2016). Modulation of the ionosphere by Pc5

484   waves observed simultaneously by GPS/TEC and EISCAT. Earth Planet Sp 68, 102.

485   Boteler, D. H., Pirjola, R. J., & Nevanlinna, H. (1998). The effects of geomagnetic

486   disturbances on electrical systems at the Earth's surface. Adv. Space Res., 22(1), 17–27.

487   Chen, L., & Hasegawa, A. (1974). A theory of long-period magnetic pulsations: 1. Steady-

488   state excitation of field line resonance. J. Geophys. Res., 79(7), 1024–1032.

489   Davies, K., Hartman, G.K. (1976). Short-period fluctuations in total columnar electron

490   content. J. Geophys. Res. 81, 3431–3434.

491   Elkington, S. R., M. K. Hudson, and A. A. Chan (1999). Acceleration of relativistic electrons

492   via drift-resonant interaction with toroidal-mode Pc5 ULF oscillations, Geophys. Res. Lett.,

493   26, 3273.

494   Fenrich, F. R., Gillies, D. M., Donovan, E., & Knudsen, D. (2019). Flow velocity and field

495   aligned current associated with field line resonance: SuperDARN measurements. Journal of

496   Geophysical Research: Space Physics, 124, 4889–4904.

497   Fenrich, F. R., J. C. Samson, G. Sofko, and R. A. Greenwald (1995). ULF high- and low-m

498   field line resonances observed with the Super Dual Auroral Radar Network, J. Geophys. Res.,

499   100, 21,535–21,548, doi:10.1029/95JA02024.

500   Hamada, A.M., Mahrous, A.M., Fathy, I., Ghamry, E., Groves, K., Yumoto, K. (2015). TEC

501   variations during geomagnetic storm/substorm with Pc5/Pi2 pulsation signature. Adv. Space

502   Res. 55, 2534–2542.

503   Harrold, B. G., and J. C. Samson (1992), Standing ULF modes of the magnetosphere: A

504   theory, Geophys. Res. Lett., 19, 1811. Hughes, W. J. (1974). The effect of the atmosphere

505   and ionosphere on long period magnetospheric micropulsations. Planetary and Space

506   Science, 22(8), 1157– 1172.

507   Harrold, B. G., and J. C. Samson (1992). Standing ULF modes of the magnetosphere: A

508 theory, Geophys. Res. Lett., 19, 1811.

509 Huang, C.-S. (2021). Global Pc5 pulsations from the polar cap to the equator: Wave
510 characteristics, phase variations, disturbance current system, and signal transmission. J.
511 Geophys. Res., 126, e2020JA029093.

512 Hudson, M. K., R. E. Denton, M. R. Lessard, E. G. Miftakhova, and R. R. Anderson (2004).
513 A study of Pc-5 ULF oscillations, Ann. Geophy., 22, 289.

514 Jacobs, J. A., Kato, Y., Matsushita, S., & Troitskaya, V. A. (1964). Classification of
515 geomagnetic micropulsations. J. Geophys. Res., 69(1), 180–181.

516 Kivelson, M., Pu, Z. (1984). The Kelvin-Helmholtz instability on the magnetopause.
517 Planetary and Space Science 32, 1335–1341.

518 Kivelson, M.G., Southwood, D.J. (1986). Coupling of global magnetospheric MHD
519 eigenmodes to field line resonances. Journal of Geophysical Research 91, 4345–4351.

520 Kozyreva, O. V., Pilipenko, V. A., Bland, E. C., Baddeley, L. J., & Zakharov, V.
521 I. (2020). Periodic modulation of the upper ionosphere by ULF waves as observed
522 simultaneously by SuperDARN radars and GPS/TEC technique. Journal of Geophysical
523 Research: Space Physics, 125, e2020JA028032.

524 Lester, M., Davies, J. A., & Yeoman, T. K. (2000). The ionospheric response during an
525 interval of Pc5 ULF wave activity. Annales Geophysicae, 18, 257–261

526 Lomb, N. R. (1976). Least-squares frequency analysis of unequally spaced data, Astrophys.
527 Space Sci., 39, 447–462.

528 Mann, I. R., A. N. Wright, K. J. Mills, and V. M. Nakariakov (1999). Excitation of
529 magnetospheric waveguide modes by magnetosheath flows, J. Geophys. Res., 104, 333.

530 Marin J, Pilipenko V, Kozyreva O, Stepanova M, Engebretson M, Vega P, Zesta E. (2014).
531 Global Pc5 pulsations during strong magnetic storms: excitation mechanisms and
532 equatorward expansion. Ann Geophys 32:319–331.

533 Mathie, R. A., and I. R. Mann (2000). Observations of Pc5 field line resonance azimuthal
534 phase speeds: A diagnostic of their excitation mechanism, J. Geophys. Res., 105, 10,713.

535 Motoba, T., Kikuchi, T., Lühr, H. et al., (2002). Global Pc5 caused by a DP 2-type
536 ionospheric current system. J. Geophys. Res., 107(A2).

537 Norouzi-Sedeh, L., Waters, C. L., & Menk, F. W. (2015). Survey of ULF wave signatures
538 seen in the Tasman International Geospace Environment Radars data. Journal of Geophysical
539 Research: Space Physics, 120, 949–963.

540 Pilipenko V, Belakhovsky V, Kozlovsky A, Fedorov E, Kauristie, K. (2014b). ULF wave

modulation of the ionospheric parameters: radar and magnetometer observations. J Atmos Sol-Terr Phys 108:68–76.

Pilipenko, V., Belakhovsky, V., Murr, D., Fedorov, E., Engebretson, M. (2014a). Modulation of total electron content by ULF Pc5 waves. J. Geophys. Res. 119, 4358–4369.

Ponomarenko, P. V., Waters, C. L., Sciffer, M. D., & Fraser, B. J. (2001). Spatial structure of ULF waves: Comparison of magnetometer and Super Dual Auroral Radar Network data. Journal of Geophysical Research, 106, 10,509–10,517.

Radoski, H. R. (1967). A note on oscillating field lines, J. Geophys. Res., 72(1).

Reddy, C. A., Ravindran, S., Viswanathan, K. S. et al. (1994). Observations of Pc5 micropulsation-related electric field oscillations in the equatorial ionosphere. Ann. Geophys, 12, 565–573.

Ruohoniemi, J. M., R. A. Greenwald, K. B. Baker, and J. C. Samson (1991). HF radar observations of Pc 5 field line resonances in the midnight/early morning MLT sector, Geophys. Res. Lett., 96, 15,697.

Sakaguchi, K., Nagatsuma, T., Ogawa, T., Obara, T., & Troshichev, O. A. (2012). Ionospheric Pc5 plasma oscillations observed by the King Salmon HF radar and their comparison with geomagnetic pulsations on the ground and in geostationary orbit. Journal of Geophysical Research, 117, A03218.

Samson, J. C. et al., (1991) Magnetometer and radar observations of MHD cavity modes in the Earth's magnetosphere, Can. J. Phys., **69**, 929–937.

Samson, J. C., B. G. Harrold, J. M. Ruohoniemi, and A. D. M. Walker (1992). Field line resonances associated with MHD waveguides in the magnetosphere, Geophys. Res. Lett., 19, 441-444.

Sarris, T.E., Loto'aniu, T.M., Li, X., and Singer, H.J. (2007). Observations at geosynchronous orbit of a persistent Pc5 geomagnetic pulsation and energetic electron flux modulations, Ann. Geophysicae, 2007, vol. 25, pp. 1653-1667.

Savitzky, A., & Golay, M. J. E. (1964). Smoothing and differentiation of data by simplified least squares procedures. Analytical Chemistry,36, 1627–1639.

Shinohara, M., Yumoto, K., Hosen, N., Yoshikawa, A., Tachihara, H., Saka, O. et al. (1998). Wave characteristics of geomagnetic pulsations across the dip equator. J. Geophys. Res., 103(A6), 11745–11754.

Skone, C., Nicholson, N. (2006). Detection and mitigation of geomagnetic pulsation effects using GPS. In: ION GNSS 2006, Session D3, Fort Worth, Texas.

574   Southwood, D. J. (1974). Some features of field line resonances in the magnetosphere, Planet.

575   Space Sci., 22, 483.

576   Southwood, D. J., and M. G. Kivelson (1990). The magnetohydrodynamic response of the

577   magnetospheric cavity to changes in solar wind pressure, J. Geophys. Res., 95(A3), 2301 –

578   2309.

579   Sung, SK., Kim, KH., Lee, DH. et al., (2006). Simultaneous ground-based and satellite

580   observations of Pc5 geomagnetic pulsations: A case study using multipoint

581   measurements. Earth Planet Sp 58, 873–883.

582   Torrence, C., & Compo, G. P. (1998). A practical guide to wavelet analysis. Bulletin of the

583   American Meteorological Society, 79, 61–78.

584   Vorontsova E, Pilipenko V, Fedorov E, Sinha A. K, Vichare, G. (2016). Modulation of total

585   electron content by global Pc5 waves at low latitudes. Adv Space Res 57:309–319.

586   Walker, A.D.M., Ruohoniemi, J.M., Baker, K.B., Greenwald, R.A., Samson, J.C. (1992),

587   Spatial and temporal behavior of ULF pulsations observed by the Goose Bay HF radar.

588   Journal of Geophysical Research, 12187–12202.

589   Watson C, Jayachandran PT, Singer HJ, Redmon RJ, Danskin D. (2015). Large amplitude

590   GPS TEC variations associated with Pc5–6 magnetic field variations observed on the ground

591   and at geosynchronous orbit. J Geophys Res. doi:10.1002/2015JA021517.

592   Wright, A. N., and G. J. Rickard (1995). ULF pulsations driven by magnetopause motions:

593   Azimuthal phase characteristics, J. Geophys. Res., 101, 24,991.

594   Yagova, N. V., Pilipenko, V. A., Sakharov, Y. A., & Selivanov, V. N. (2021). Spatial scale of

595   geomagnetic Pc5/Pi3 pulsations as a factor of their efficiency in the generation of

596   geomagnetically induced currents. Earth Planets and Space, 73(1), 88.

597   Ziesolleck, C. W. S., & Chamalaun, F. H. (1993). A two-dimensional array study of low-

598   latitude PC 5 geomagnetic pulsations. J. Geophys. Res., 98 (A8), 13703–13713.

599   Ziesolleck, C. W. S., Fenrich, F. R., Samson, J. C., & McDiarmid, D. R. (1998). Pc5 field

600   line resonance frequencies and structure observed by SuperDARN and CANOPUS. Journal

601   of Geophysical Research, 103(A6), 11,771–11,785.

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605   **Figure**

606   **Figure 1.** Site map for GPS TEC, ground magnetometers, SuperDARN SAS, and magnetic

607   footprints of the GOES-16 and GOES-17 satellites**.**

608   **Figure 2.** Solar wind and geomagnetic conditions for 04th November 2021. (a) Solar wind

609   speed (Vsw, km/s), (b) solar wind dynamic pressure (Pdyn, nPa), (c) IMF By (black) and Bz

610   (red) in nT, (d) IEFy (mV/m), and (e) SYM-H (nT). (f-g) Enlarged views of high solar wind

611   speeds (Vsw) and three times enhancements of Pdyn, matched with the gray-shaded region

612   from 1600-1900 UT.

613   **Figure 3.** (a-e) Magnetic field and electron flux observations from the GOES-16 (blue) and

614   GOES-17 (black) geosynchronous satellite and the Pc5 pulsation analysis for GOES-16: (a)

615   Bt (total magnetic field), (b) Be (earthward or radial), (c) Bp (azimuthally eastward), (d) Bn

616   (parallel to the earth spin axis), and (e) electron flux intensities in the energy channels ~131,

617   186, 271, 380 keV. For GOES-16 (f, i) Bn and electron flux, (g, j) wavelet power spectrum

618   and (h, j) Lomb-Scargle periodogram, respectively. The grey-shaded regions indicate three

619   times the Pdyn enhancements and PC5 pulsations observed.

620   **Figures 4.** (a-b) SuperDARN SAS site line-of-sight (LOS) velocity for beams 00 and 12, (c)

621   average LOS velocity over gates 14 to 24 (red and green line for beams 00 and 12), (d-e)

622   wavelet power spectrum of the LOS average, and (f) the periodogram. The right panels from

623   g-l are the equivalent panels (a-f) except for the echo power.

624   **Figure 5.** (a) Pc5 analysis for ground magnetometers located in the American longitudinal

625   sector: (left) residual after applying Savitzky and Golay algorithm, (middle) periodogram,

626   and (right) wavelet spectrogram for (a-c) high latitudes and (d-f) low latitudes.

627   **Figures 6.** Pc5 analysis for TEC obtained from the GPS sites (numbers) of YELL (GPS-24),

628   CHUR (GPS-10), KUJ (GPS-32), HNPT (GPS-32), MDO (GPS-32), and BOGT (GPS-23)

629   located in the American longitudinal sector: the (a) VTEC (black) and the fitted (red) with

630   Savitzky and Golay algorithm, (b) residual of TEC (c) periodogram, and (d) wavelet

631   spectrogram.

632   **Figures 7** Comparison among solar wind condition and magnetospheric and ionospheric

633   parameters: (a) solar wind velocity (Vsw), (b) solar wind dynamics pressure (Pdyn), (c)

634   GOES-16 magnetic field (Bn), (d) H-component at FCC, (e) average LOS velocity (bm 00

635   (red) and 12 (green)), (f) GOES-16 electron flux at 131 keV, (g) average power for beams 0

636   (red) and 12 (green), and (h) TEC at YELL including high-latitude sites; for low latitude (i, k)

637   H component and (j, l) TEC oscillations. Pressure pulse enhancements are indicated with

638   gray-shaded regions (a-b).

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649 **Table 1** List of magnetometer and GPS TEC stations used in the analysis and their

650 geographical and geomagnetical coordinates.

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Station name	Station CODE	Geographic (Latitude)	Geographic (Longitude)	Geomagnetic (Latitude)	Geomagnetic (Longitude)
Magnetometers					
Resolute	RES	74.5° N	94.8° W	82.3° N	47.2° W
Taloyoak	TALO	69.5° N	93.5° W	77.7° N	35.1° W
Rankin Inlet	RANK	62.8° N	92.1° W	71.2° N	28.3° W
Fort Churchill	FCC	58.7° N	94.0° W	67.0° N	29.2° W
Gillam	GILL	56.3° N	94.6° W	64.5° N	29.0° W
Island Lake	ISLL	53.8° N	94.6° W	62.1° N	28.2° W
Pinawa	PINA	50.1° N	96.0° W	58.3° N	29.1° W
Brandon	BRD	49.8° N	99.9° W	57.6° N	33.7° W
Ottawa	OTT	45.4° N	75.5° W	54.5° N	3.5° W
Sable Island	SBL	43.9° N	60.1° W	51.9° N	15.1° W
Boulder	BOU	40.4° N	105.2° W	47.5° N	37.4° W
Fredericksburg	FRD	38.2° N	77.3° W	47.1° N	5.0° W
Fresno	FRN	37.1° N	119.7° W	42.9° N	52.2° W
Tucson	TUC	32.1° N	87.6° W	39.0° N	16.0° W
Stennis Space Center	BSL	30.3° N	110.7° W	38.8° N	41.5° W
San Juan	SJG	18.1° N	66.1° W	27.1° N	7.1° W
Kourou	KOU	5.2° N	52.7° W	13.9° N	21.2° W
GPS TEC Receivers					
Yellowknife	YELL	62.4° N	114.4° W	68.1° N	56.5° W
CHURCHILL	CHUR	58.7° N	94.4° W	66.3° N	28.8° W
Kuujjuarapik	KUJ	55.2° N	77.4° W	64.1° N	5.7° W
Cambridge	HNPT	38.5° N	76.4° W	47.1° N	3.8° W
Fort Davis	MDO	21.4° N	102.4° W	28.23° N	31.5° W
Bogota	BOGT	4.4° N	74.4° W	13.7° N	1.3° W

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671 Figure 1

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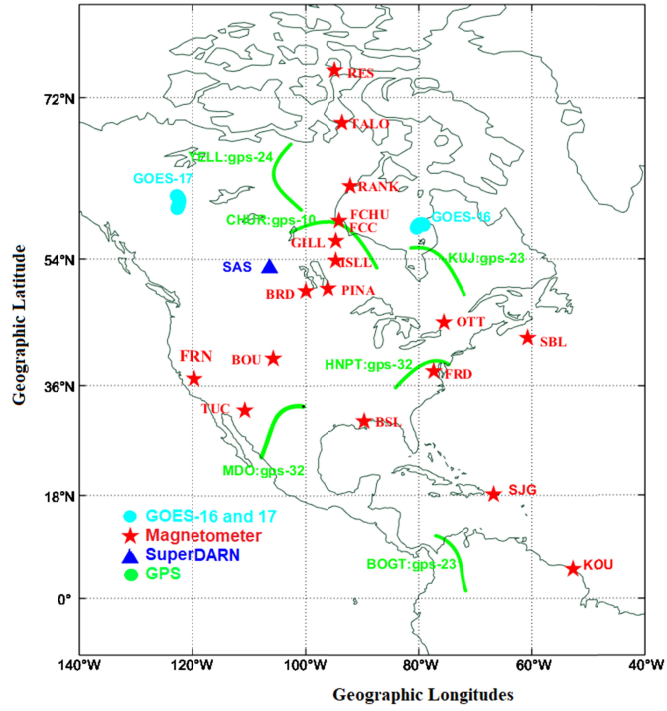
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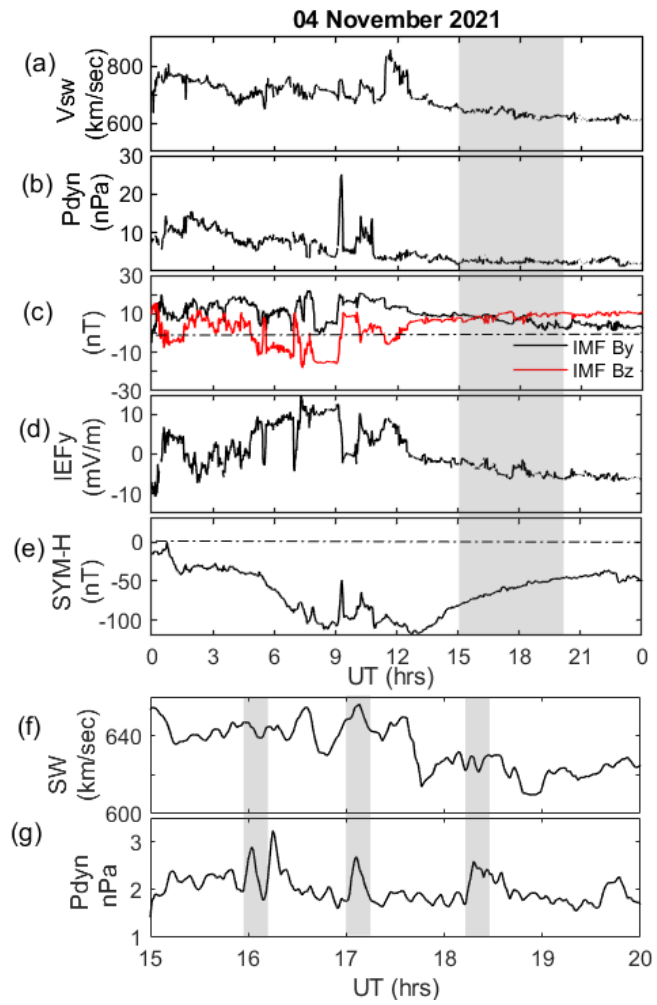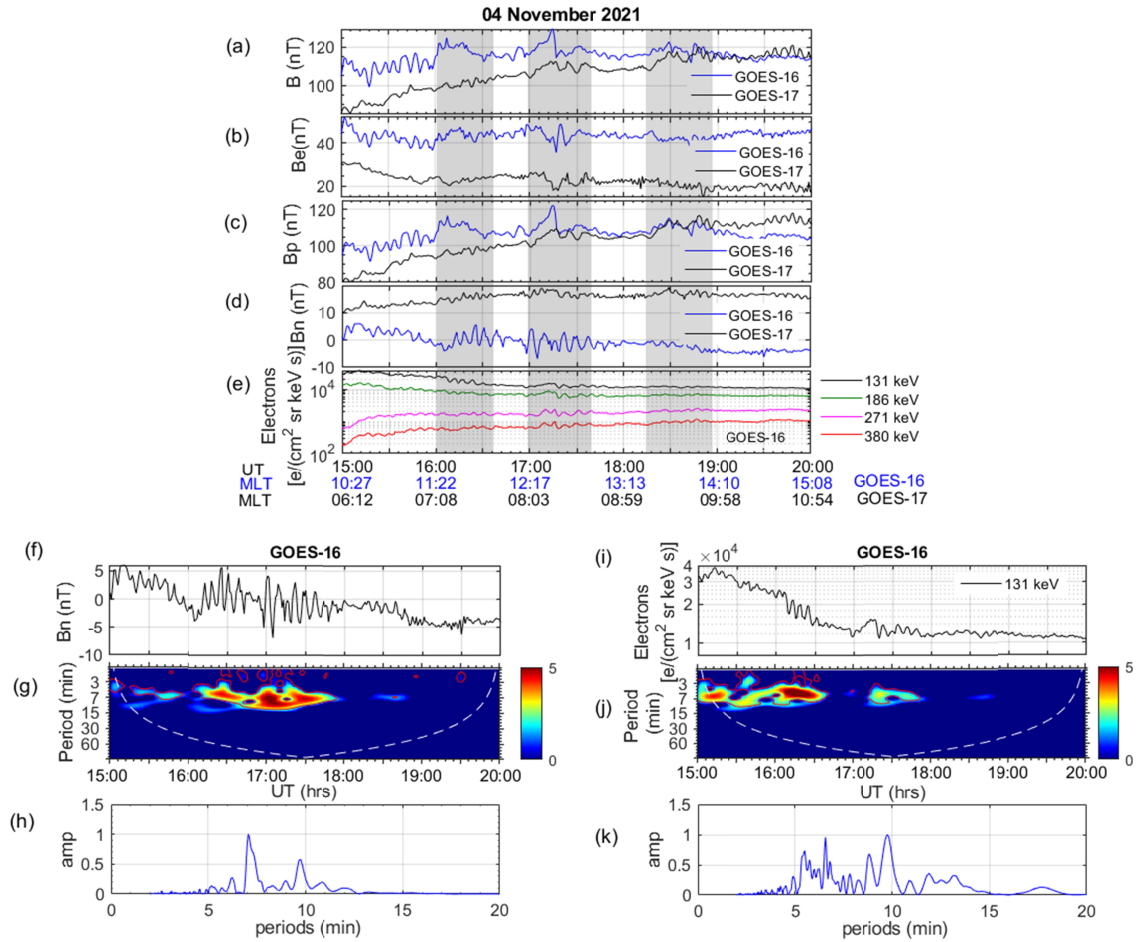
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Figure 2

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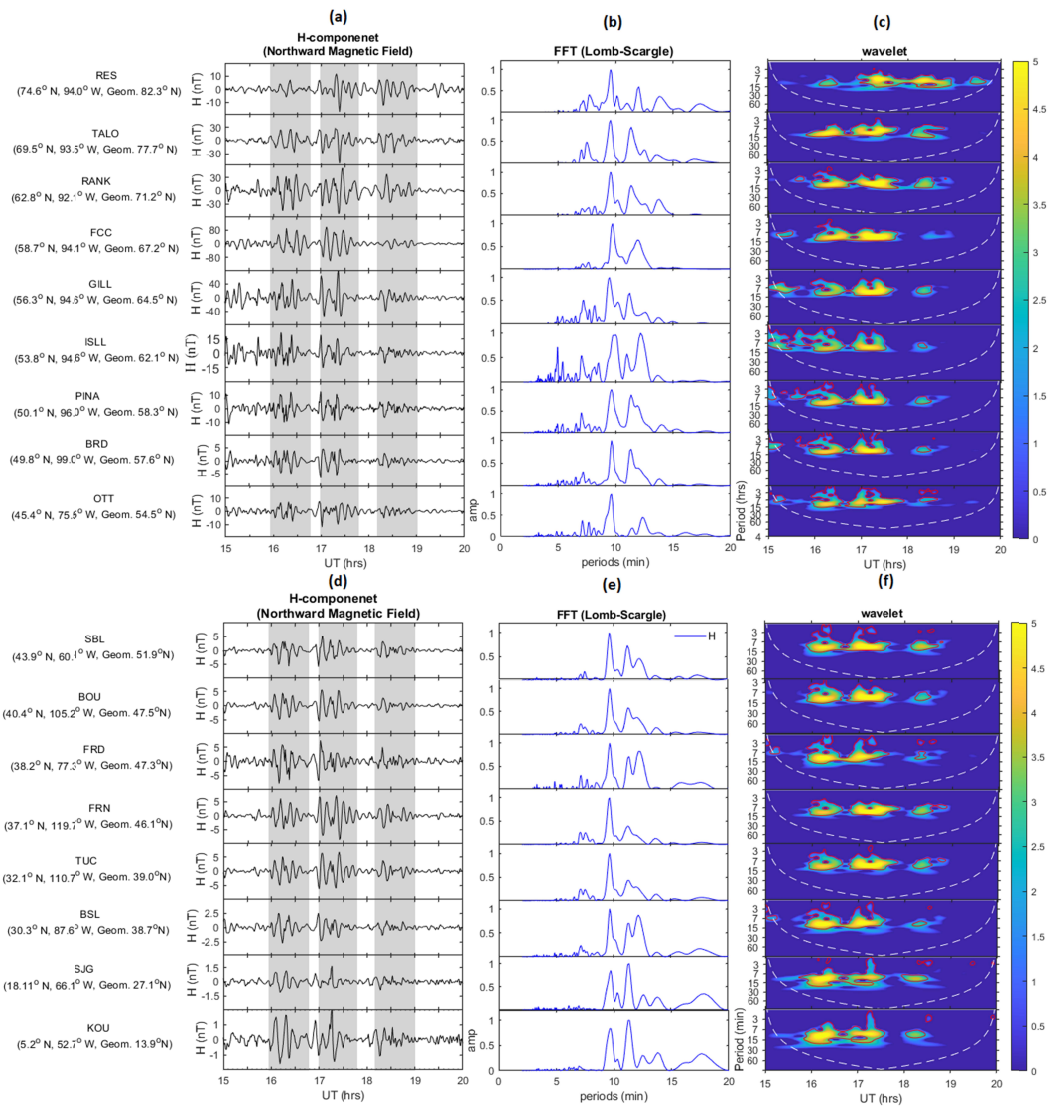702

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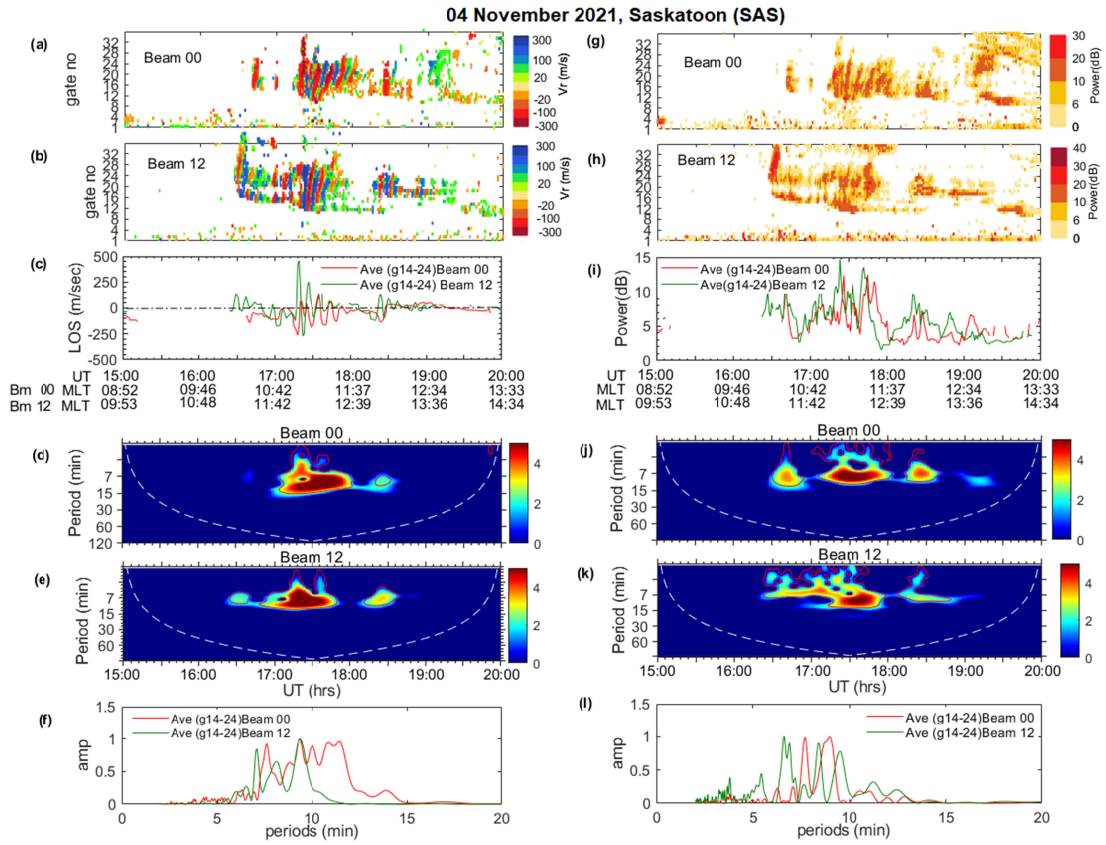
Figure 3

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04 November 2021, Saskatoon (SAS)

715   Figure 4

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(a)　　　　(b)　　　　(c)　　　　(d)
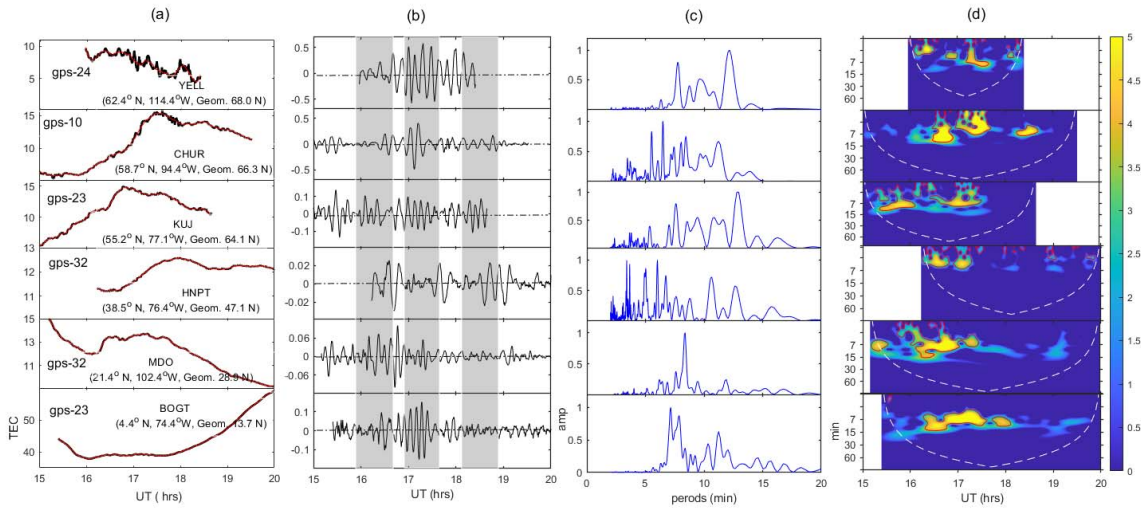
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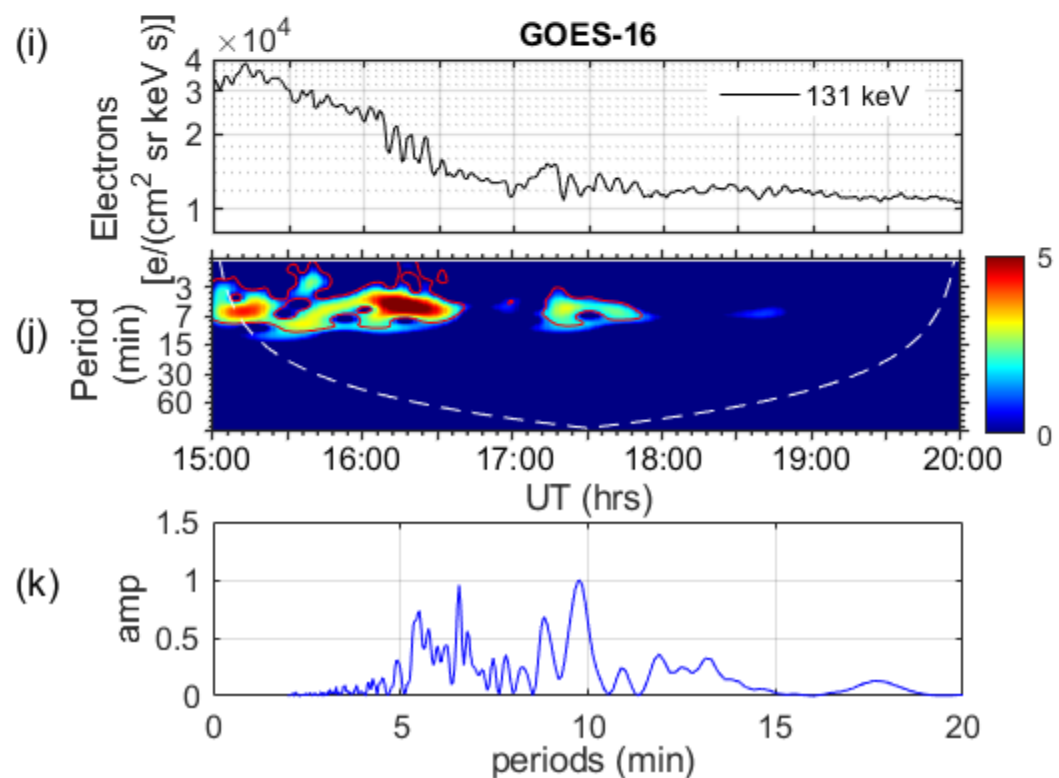
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Figure 7

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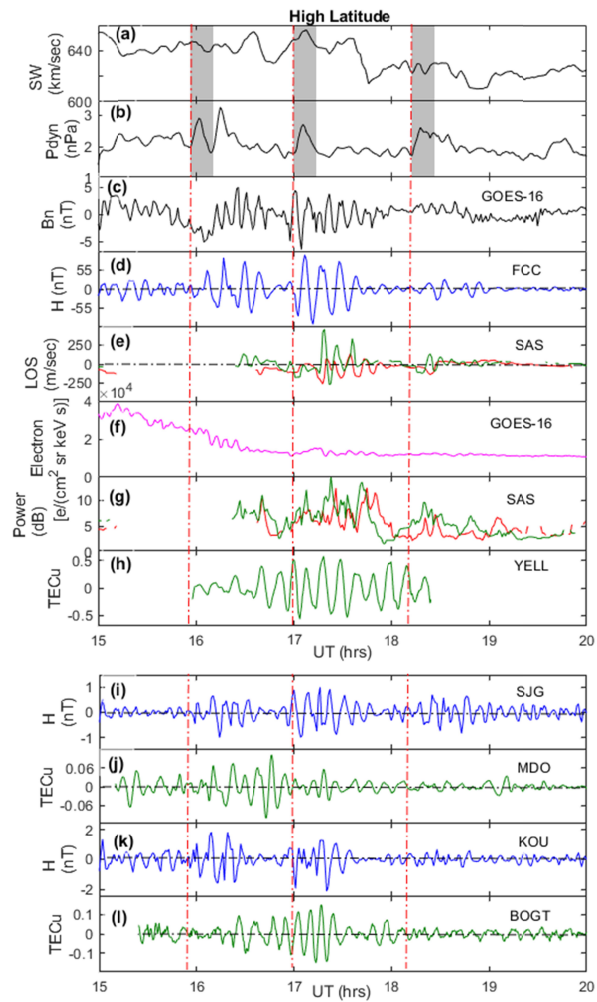
Figure 1.
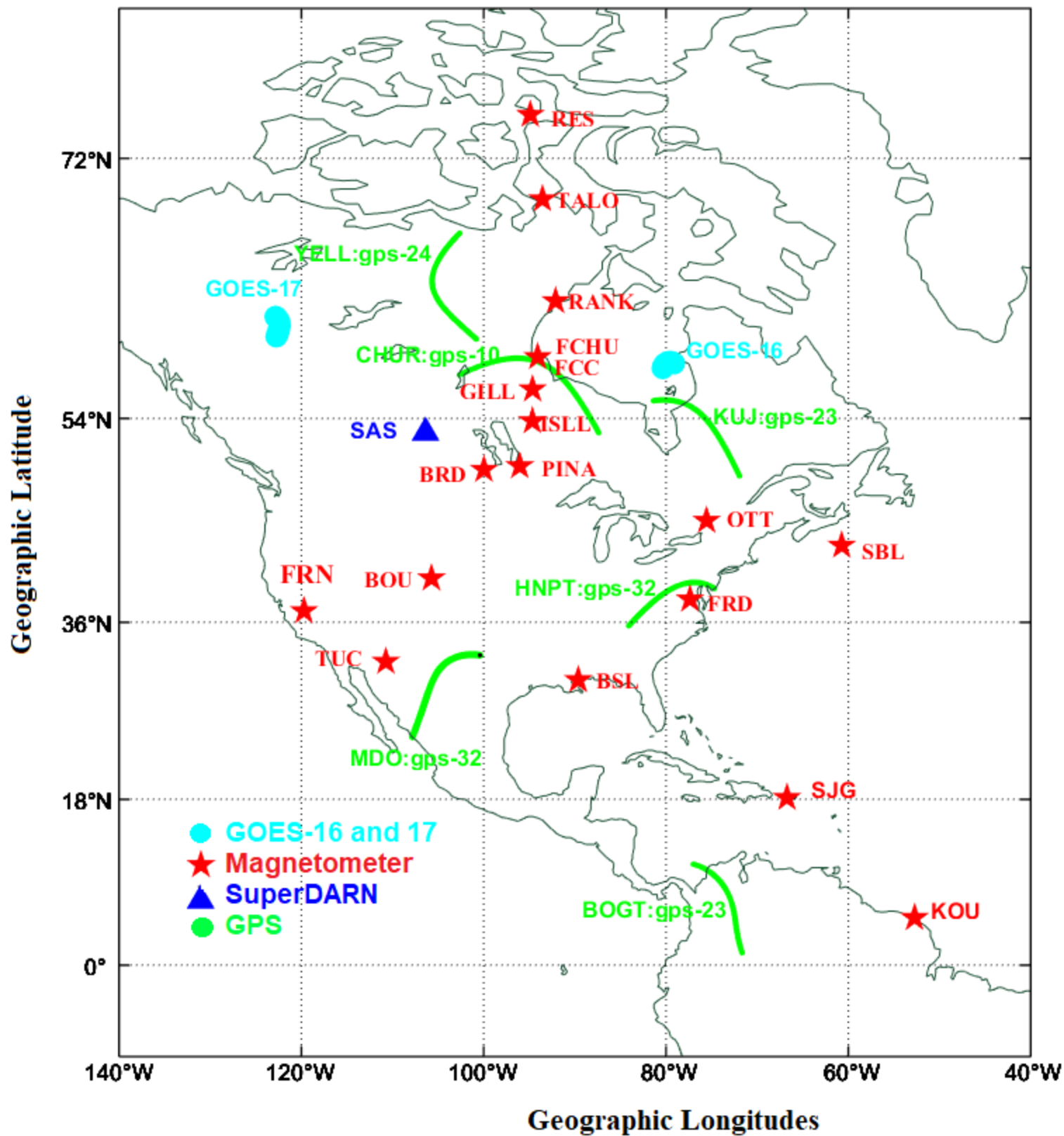
Figure 2.

04 November 2021

(a) V_{SW} (km/sec)

(b) P_{dyn} (nPa)

(c) (nT) — IMF By, IMF Bz

(d) IEFy (mV/m)

(e) SYM-H (nT)

UT (hrs)

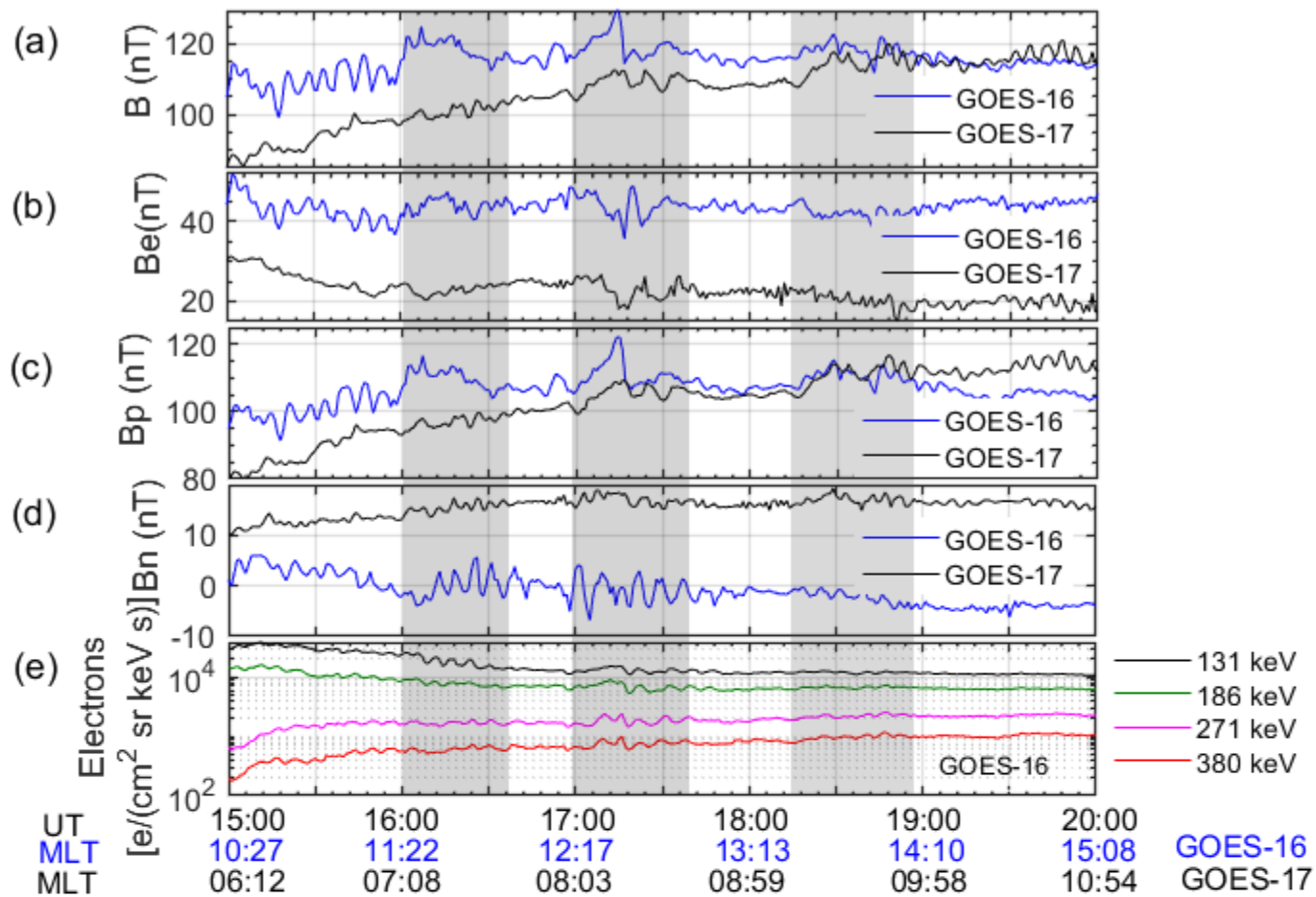(f) SW (km/sec)

(g) P_{dyn} nPa

UT (hrs)
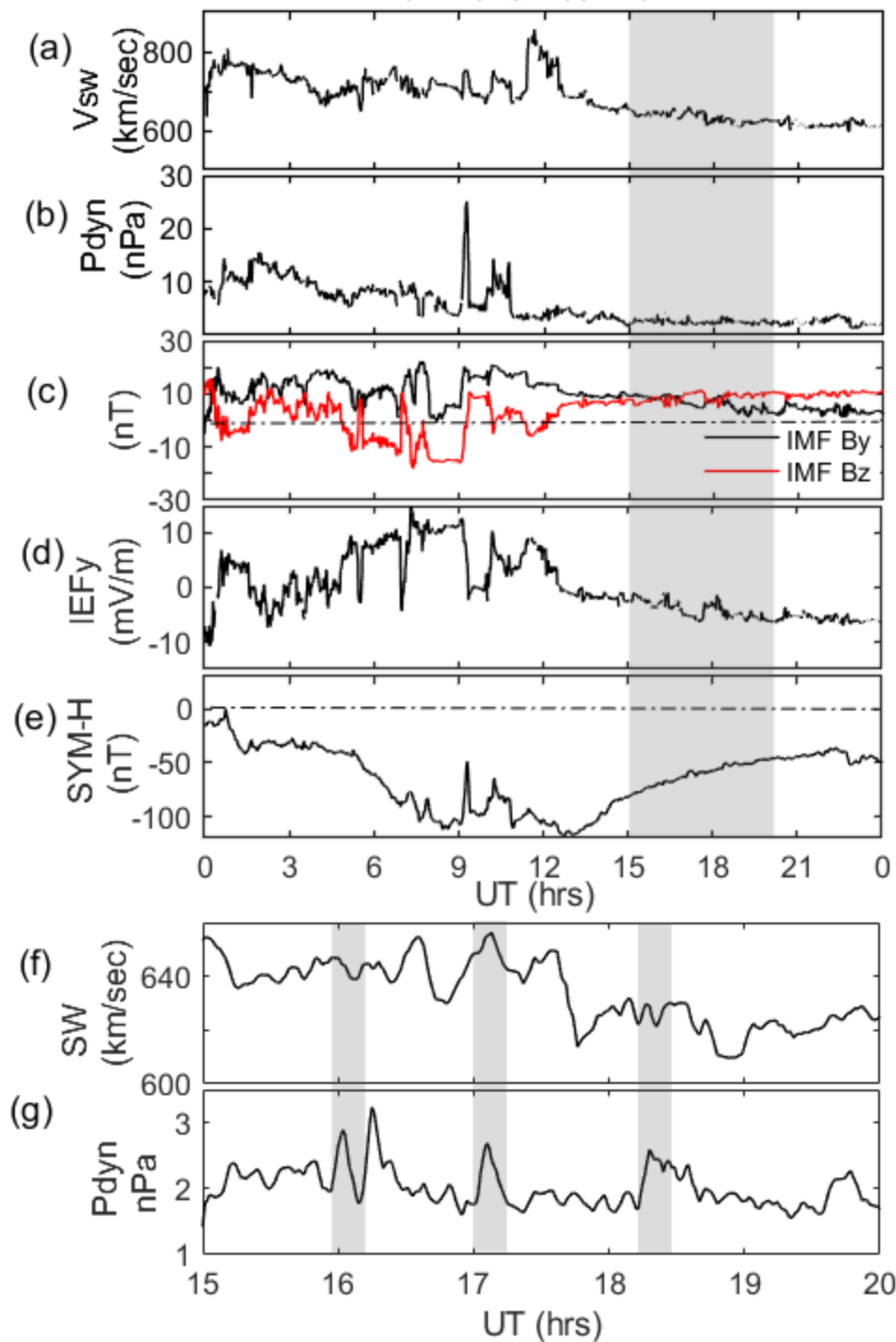
Figure 3.

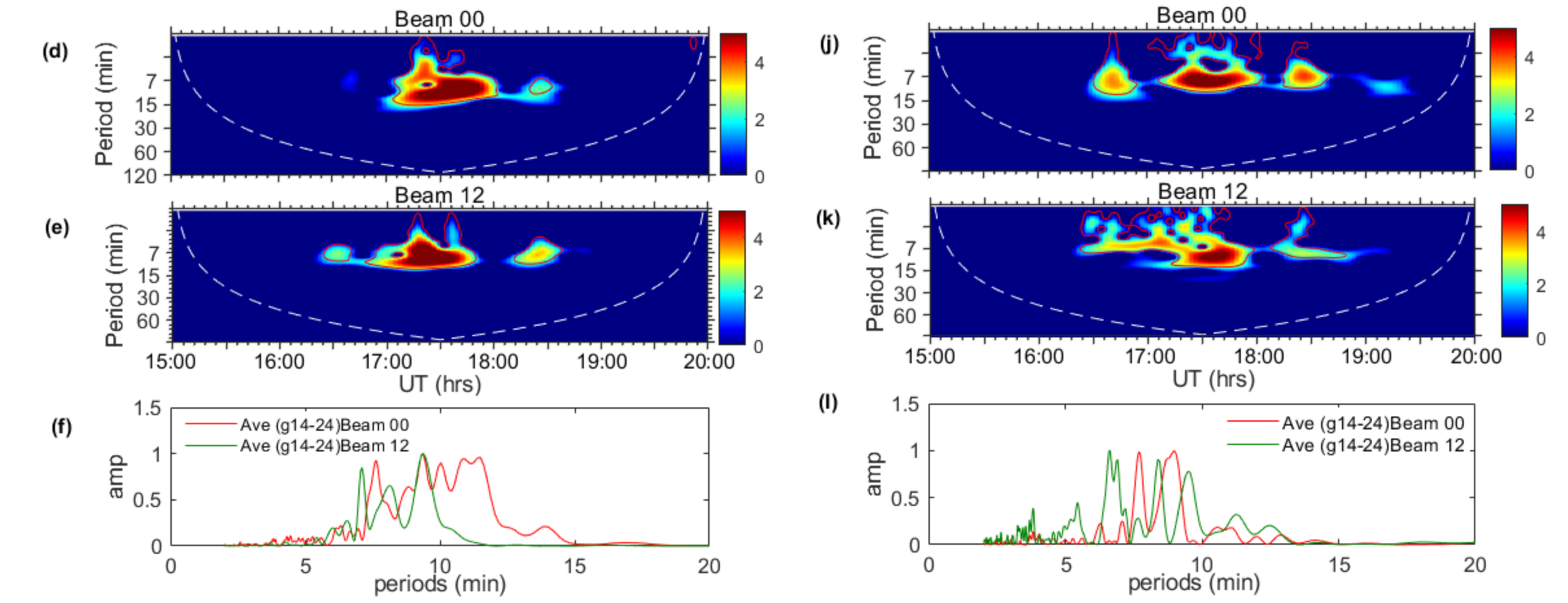# 04 November 2021
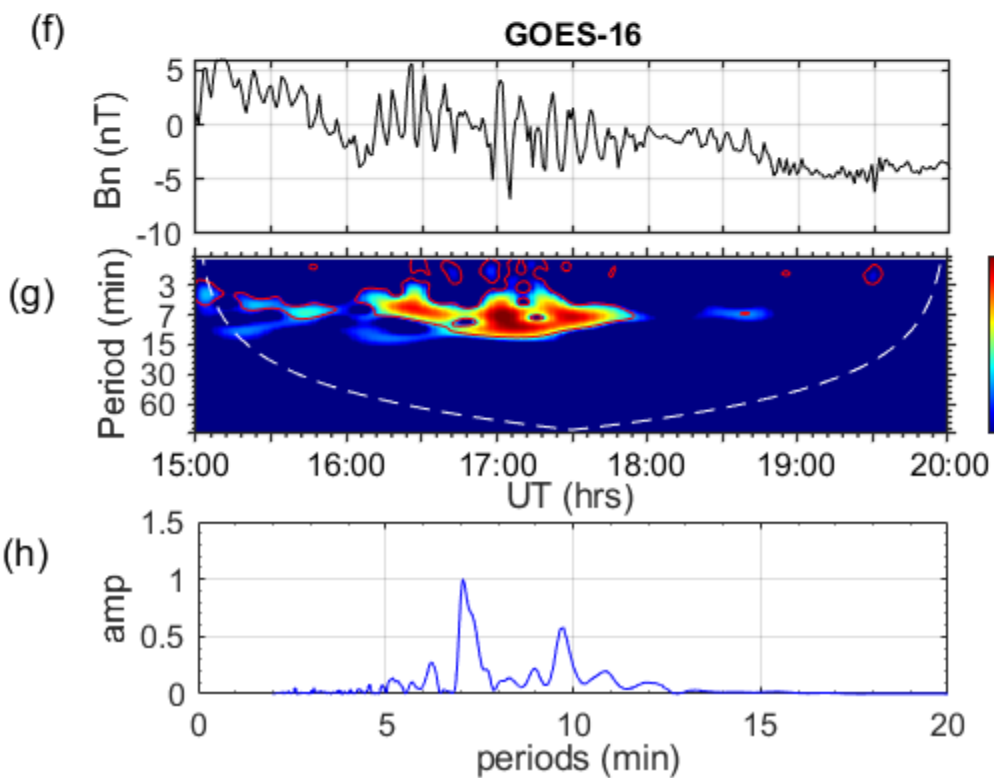
Figure 4.

04 November 2021, Saskatoon (SAS)

Figure 5.

(a) H-componenet (Northward Magnetic Field)

(b) FFT (Lomb-Scargle)

(c) wavelet

RES (74.6° N, 94.0° W, Geom. 82.3° N)
TALO (69.5° N, 93.5° W, Geom. 77.7° N)
RANK (62.8° N, 92.1° W, Geom. 71.2° N)
FCC (58.7° N, 94.1° W, Geom. 67.2° N)
GILL (56.3° N, 94.6° W, Geom. 64.5° N)
ISLL (53.8° N, 94.6° W, Geom. 62.1° N)
PINA (50.1° N, 96.0° W, Geom. 58.3° N)
BRD (49.8° N, 99.0° W, Geom. 57.6° N)
OTT (45.4° N, 75.5° W, Geom. 54.5° N)

(d) H-componenet (Northward Magnetic Field)

(e) FFT (Lomb-Scargle)

(f) wavelet

SBL (43.9° N, 60.1° W, Geom. 51.9°N)
BOU (40.4° N, 105.2° W, Geom. 47.5°N)
FRD (38.2° N, 77.3° W, Geom. 47.3°N)
FRN (37.1° N, 119.7° W, Geom. 46.1°N)
TUC (32.1° N, 110.7° W, Geom. 39.0°N)
BSL (30.3° N, 87.6° W, Geom. 38.7°N)
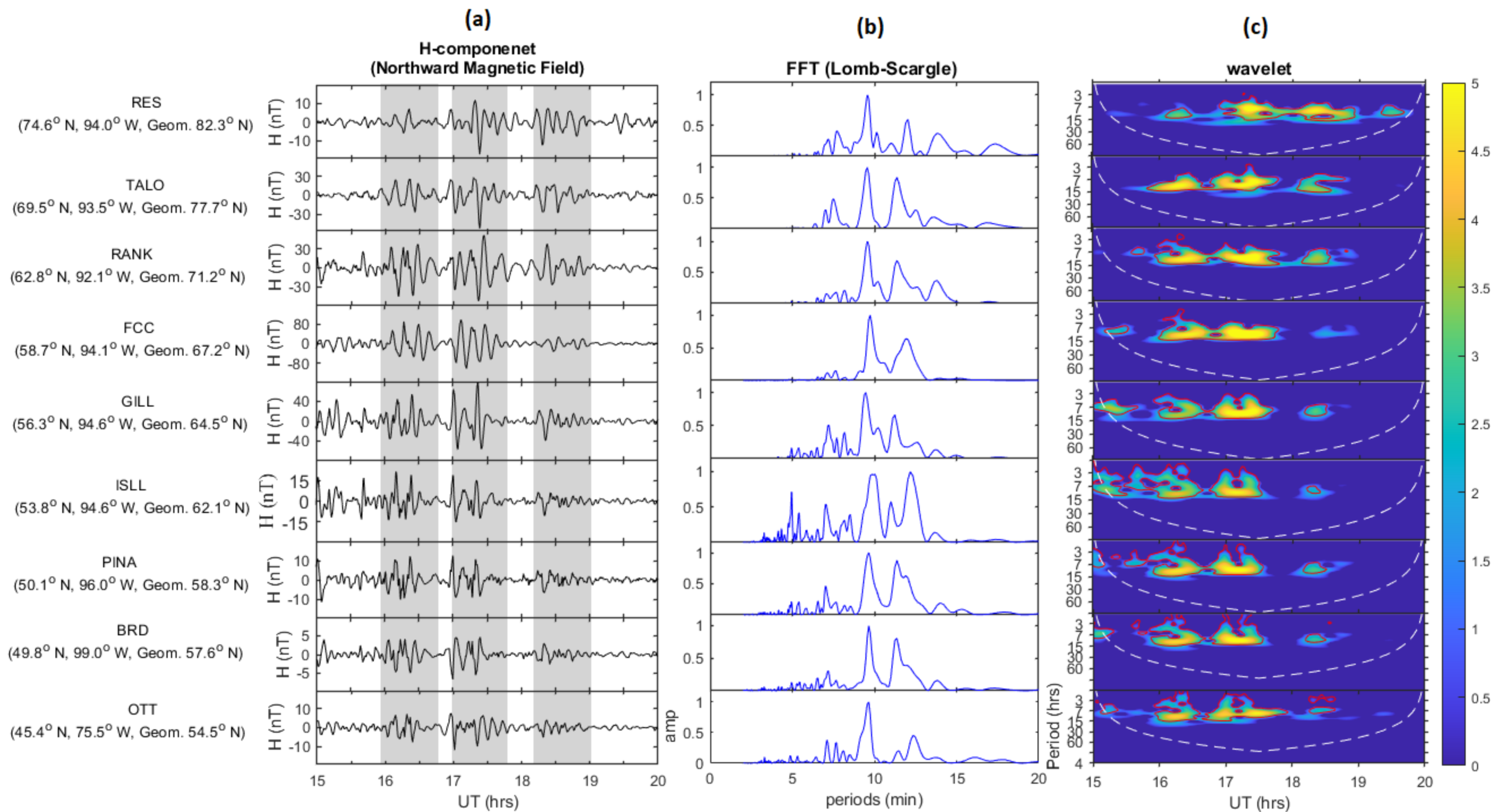SJG (18.11° N, 66.1° W, Geom. 27.1°N)
KOU (5.2° N, 52.7° W, Geom. 13.9°N)

Figure 6.

(a)   (b)   (c)   (d)

gps-24   YELL (62.4° N, 114.4°W, Geom. 68.0 N)

gps-10   CHUR (58.7° N, 94.4°W, Geom. 66.3 N)

gps-23   KUJ (55.2° N, 77.1°W, Geom. 64.1 N)

gps-32   HNPT (38.5° N, 76.4°W, Geom. 47.1 N)

gps-32   MDO (21.4° N, 102.4°W, Geom. 28.9 N)

gps-23   BOGT (4.4° N, 74.4°W, Geom. 13.7 N)

Figure 7.

High Latitude