A case study of correspondence between Pc1 activity and ionospheric irregularities at polar latitudes

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Abstract
A possible driver of precipitation of magnetospheric energetic electrons in the high-latitude atmosphere is represented by electromagnetic ion-cyclotron (EMIC) magnetospheric waves. The precipitating particles produce variations, by collision, in the ionized component of the atmosphere, altering its chemistry and electrical conductivity, with a significant impact on the atmospheric processes. In this framework, it would be significant to find experimental evidence of a correspondence between ionospheric electron density irregularities and the occurrence of Ultra-Low-Frequency (ULF) Pc1 geomagnetic pulsations, i.e., the ground signatures of EMIC waves, at high latitudes. In this work, we face this subject by considering a specific case study occurred on 22 February 2007 during quiet magnetospheric conditions. The study is based on the analysis of simultaneous ULF geomagnetic field and Total Electron Content (TEC) measurements recorded at Mario Zucchelli Station in Antarctica. We show that Pc1 pulsations occur in correspondence to solar wind pressure increases and that, at the same time, the ionosphere is characterized by the presence of ionospheric irregularities. We suggest that a possible link between the Pc1 activity and the ionospheric irregularities may be energetic electron precipitations, driven by EMIC waves generated in the compressed magnetosphere, which produce density variations in the ionized component of the atmosphere.

Keywords: ULF waves, Ionospheric irregularities, Solar wind

Introduction
Ultra-Low-Frequency (ULF) Pc1 waves (f ~ 0.2–5.0 Hz) are known to be generated by the electromagnetic ion-cyclotron (EMIC) resonance in the equatorial magnetospheric regions with unstable, energetic ions, such as ring current and plasma sheet ions during disturbed geomagnetic conditions (Menk 2011). In addition, during geomagnetically quiet periods even modest compressions of the magnetosphere, due to solar wind dynamic pressure increases, can be responsible for magnetospheric plasma instabilities just inside the dayside magnetopause, driving Pc1 waves (Anderson and Hamilton 1993; Engebretson et al. 2002; Usanova et al. 2008, 2012). A statistical study by Park et al. (2016) shows that, during quiet conditions, geosynchronous EMIC waves are mostly triggered by solar wind pressure enhancements, and they occur from morning to afternoon with an occurrence peak around noon.

Such waves are transmitted as Alfven waves along geomagnetic field lines into the auroral ionosphere and then, after being converted into compressional waves, they propagate horizontally in the waveguide represented by the ionosphere, becoming linearly polarized well far from the injection region (Greifinger and Greifinger 1968; Greifinger 1972; Fraser 1975; Fujita and Tamao 1988). Since ionospheric waveguide boundaries are not perfect reflectors, the waves are attenuated when propagating (Manchester 1966); moreover, several studies (Hayashi et al. 1981; Kim et al. 2010, 2011; Regi et al. 2017a) showed that their poleward propagation is more efficient and that these waves can be detected also at polar
latitudes. A statistical study based on experimental measurements from an Antarctic magnetometer array over a very large range of geomagnetic latitudes (−62° to −87°, spanning 2920 km geographically) showed that they propagate from the injection region with power attenuation factors of 10–14 dB/1000 km (Kim et al. 2011). Moreover, the results of a numerical modeling presented by Fedorov et al. (2018) indicate that, at distances smaller than 600 km from the injection point, the wave amplitude decreases by ~1 dB/100 km during nighttime and by ~10 dB/100 km during daytime, while at distances larger than 600 km the nighttime and daytime attenuation rates are approximately the same, ~1 dB/100 km.

Observational evidences show that Pc1 waves are responsible for the relativistic electron precipitation into the high-latitude (60°–70°) ionosphere (Rodger et al. 2008; Clilverd et al. 2010; Blum et al. 2015). Indeed, Pc1 waves can resonate with >1 MeV outer radiation belt electrons and scatter them into the loss cone (Engelbrecht et al. 2008 and references therein). Recent works (Ukhorskiy et al. 2010; Hendry et al. 2017) show evidence of sub-MeV electron precipitations driven by EMIC waves, with electron energies of several hundred keV. Through ionization processes, precipitating electrons can modify both the chemistry and the electric conductivity of the atmosphere, with potential effects on local or even global climate (Mironova et al. 2015). Recent statistical studies have shown significant effects of Pc1 activity on atmospheric properties at stratospheric and tropospheric altitudes in Antarctica (Francia et al. 2015; Regi et al. 2016, 2017b).

Thus, the electron precipitation, modulated by the variability of the geomagnetic activity, produces ionospheric electron/ion density variations (often steep gradients), commonly referred as “ionospheric irregularities”.

The high-latitude ionospheric irregular structures are usually hosted in the boundaries of the auroral oval and within the polar cap and, being driven and modulated by the geospace forcing, intensify under disturbed geomagnetic conditions (see, e.g., Spogli et al. 2009; Alfonsi et al. 2011).

The presence of ionospheric irregularities can be revealed by measurements of Total Electron Content (TEC) and in particular by its Rate Of Change (ROT), both derived by Global Navigation Satellite System (GNSS) receivers (see, e.g., Basu et al. 1999).

In this work we investigated the correspondence between long-lasting narrowband Pc1 activity and the occurrence of ionospheric irregularities at high latitude using a case study. To carry out the analysis, ULF geomagnetic field and TEC measurements recorded at the Italian Mario Zucchelli Station (MZS, Terra Nova Bay, Antarctica) were considered.

**Data and analysis methods**

We analyzed Pc1 pulsations measured at MZS (geographic coordinates 74.69°S, 164.12°E, corrected geomagnetic coordinates 80.03°S, 307.74°E; local time (LT) = universal time (UT) + 11, magnetic local time (MLT) = UT−8) during 22 February 2007. We focused our attention on the time interval 02-14 UT (18-06 MLT at MZS, i.e., between the local magnetic evening and the local magnetic morning), excluding hours close to the magnetic noon when the region of interest approaches the polar cusp and measurements are characterized by large broadband fluctuations. The examined time interval was geomagnetically quiet (with the geomagnetic index AE ranging between 10 and 80 nT), so that, in absence of large storm/substorm disturbances, Pc1 wave packets were clearly detectable. Measurements were performed by a search-coil magnetometer, which provides variations of the geomagnetic field in the northward H, eastward D, and vertically downward Z components at a 4 Hz sampling rate. To reduce aliasing, a low-pass filter was applied so that the response at frequencies greater than 1500 mHz was strongly dampened.

Applying the Welch’s method (Welch 1967), we computed the power spectral density (PSD) over 300-s time intervals, using the Hamming window (Elliot 1987) and averaging 100-s sub-intervals overlapping by 50%, with a correspondent frequency resolution of 10 mHz. Spectra were converted using the instrument transfer function from mV^2/Hz to nT^2/Hz. Dynamical spectra were obtained using 300-s non-overlapping spectra.

Moreover, to better identify the pulsation signals, we computed the signal-to-noise ratio $\text{SNR}(f)$ (De Laet et al. 2010; Ponomarenko et al. 2002) for each 300-s interval, as follows:

$$\text{SNR}(f) = \frac{S(f)}{N(f)} = \left[ \frac{S_T(f) - N(f)}{N(f)} \right] = \frac{S_T(f)}{N(f)} - 1,$$

where $S_T(f)$ is the experimental total (signal + noise) power spectrum, $S(f)$ the power spectrum of the unknown signal, and $N(f)$ the background noise; $N(f)$ was estimated by fitting a linear function to the log($S_T$)−log($f$) dependence at the extremes of the 100 mHz–1 Hz frequency range:

$$\log(N) = \alpha \log(f) + \beta.$$

Our method does not reveal impulsive, broadband signals whose power spectra do not emerge significantly from the corresponding noise spectra (Regi et al. 2017a).

A GPS Ionospheric Scintillation TEC monitor (GISTM, Van Dierendonck et al. 1993) receiver,
consisting of a dual-frequency receiver with a low phase noise that is required for monitoring phase scintillation, is installed in MZS since 2006. The GISTM located in MZS has been proven to be strategic in studying the formation and dynamics of the ionospheric irregularities and their effects on GNSS systems (see, e.g., Alfonsi et al. 2011; Spogli et al. 2013; Prikryl et al. 2011, 2015). The GISTM is able to compute the TEC from GPS L1 (1575.42 MHz) and L2 (1227.60 MHz) carrier phase signals. In specific, to measure ionospheric irregularities in a more consistent and reliable way, instead of considering TEC time series, we preferred to use the rate of TEC (ROT = ΔTEC/Δt, Δt = 1 min) time series, which are better suited to highlight small-scale variations of TEC superimposed on a slower and large-scale trend. In addition, the use of ROT allows being safe from unknown biases affecting the TEC determination (see, e.g., Ciraolo et al. 2007; Cesaroni et al. 2015). We selected only time windows for which the elevation angle of the satellite was higher than 30° and the ionospheric pierce point at 350 km was taken within 500 km from the MZS zenith at the same altitude. This procedure minimizes the effects (like multipath) of the environment surrounding the GISTM that may mimic the signatures of the ionospheric irregularities in the sampled signals.

We also used 1-min values of the solar wind dynamic pressure and AE index from the OMNIWeb database (http://cdaweb.gsfc.nasa.gov/).

**Experimental results**

**The pulsation event**

Figure 1 reports the dynamical spectrum and $\text{SNR}(f)$ of the total horizontal magnetic field (upper and middle panels) and the AE index and solar wind dynamic pressure (bottom panel) between 0200 and 1400 UT on 22 February 2007. A significant Pc1 pulsations activity is present between 0200 and 1300 UT, i.e., during the local afternoon and premidnight sector; it is characterized by an $\text{SNR}(f)$ greater than 3 (~0.5 in the log scale), corresponding to a noise lower than 25% of the total signal (black contours in the dynamical spectrum and yellow–red colors in the dynamical $\text{SNR}(f)$). Such activity is distributed in the 200–300 mHz frequency band especially between 0200 and 0330 UT while, in the time interval 0330–1300 UT, it appears to be more as monochromatic wave packets in the same frequency band. In addition to the Pc1 activity, impulsive, broadband wave power (associated to irregular PiB pulsations) is observed in the dynamical spectrum right after 0630, 0700 and 0900 UT, in correspondence with small AE increases; it is characterized by an $\text{SNR}(f)$ much lower than 3.

Pc1 activity roughly corresponds to an enhanced solar wind dynamic pressure, suggesting that the Pc1 pulsations could represent the ground signatures of EMIC waves generated just inside the magnetopause by magnetosphere compressions. Due to the horizontal propagation in the ionosphere, from the ground-based observations only it is not possible to identify the L value corresponding to the wave injection region into the ionosphere (Lessard et al. 2019). Nevertheless, the observed pulsation frequency can provide some indication. For this purpose, we compared the observed pulsation frequency with the equatorial cyclotron frequency of O+$^+$, He+$^+$ and H+$^+$ at the subsolar point for different L values, based on the T96 model (Tsyganenko and Stern 1996). Figure 1 shows that the pulsation activity appears at frequencies between the dashed curves superimposed on the dynamical spectrum and $\text{SNR}(f)$, which correspond to the He+$^+$ gyrofrequencies at $L = 9.5$ (lower curve) and $L = 7.5$ (upper curve); this suggests a possible injection region located between geomagnetic latitudes 68°S and 71°S.

To characterize the observed pulsations, we computed the magnitude squared coherence $\gamma^2$ between H and D components and applied the polarization...
analysis by Fowler et al. (1967). Figure 2 shows that the coherence is high ($\gamma^2 > 0.6$) in correspondence to Pc1 signals detected in Fig. 1, indicating fluctuations at the same frequencies in both components. The corresponding polarization ratio $\rho$ (i.e., the ratio between the polarized and total energy of the horizontal signal) is high ($\rho > 0.7$) and the ellipticity $\epsilon$ (i.e., the ratio between the minor and major axis of the polarization ellipse) is close to zero (i.e., $|\epsilon| \leq 0.2$) indicating linearly polarized pulsations. This feature is expected for pulsations propagating in the ionospheric waveguide well past from the injection region (Greifinger 1972). Two examples of coherent, linearly polarized pulsations are presented in the two upper panels of Fig. 2 during two 4-min intervals just after ~04 UT and ~12 UT, respectively; both reveal clear waveforms in both horizontal components.

The ionospheric irregularities

To examine the possible effects on ionospheric conditions, we analyzed ROT data. Upper and lower panels on the left side of Fig. 3 respectively show the time series (smoothed over 15-min) of the geomagnetic field fluctuation power, integrated in the 200–300 mHz frequency band characterized by significant, linear polarized Pc1 signals (see Figs. 1 and 2), and the ROT time series, as recorded from different satellites in the field of view of MZS. The right side of the figure shows corresponding ionospheric pierce points of satellites, assumed located at an altitude of 350 km. A good correspondence can be noted between Pc1 power enhancements and intense ROT fluctuations (ROT $\geq 1$ TECu/min); at the same UT, similar fluctuations are observed by satellites with close ionospheric pierce points.
To better examine such correspondence, we computed, for each satellite, a moving variance over 5-min interval with a step size of 5 min (i.e., without overlap); then, for each interval, we averaged the variances corresponding to satellites observing intense ROT fluctuations, applying a smoothing over 15 min. The average variance represents a measurement of the ionospheric activity and can be compared with the Pc1 pulsation power, as shown in Fig. 4 (upper panel) where the two quantities show a similar long-term trend and a general correspondence. We also computed the correlation coefficient between the ROT variance and the pulsation power and found a value of 0.74 (0.76 considering only the time intervals characterized by an SNR(f) greater than 3, black thick line). To speculate about the nature of the ionospheric irregularities highlighted by ROT variations, we investigated also the phase ($\sigma_\phi$) and amplitude ($S^4$) scintillation indices for every satellite-receiver link, defined as (Fremouw et al. 1978).

$$\sigma_\phi = \sqrt{\langle \phi_{\text{detr}}^2 \rangle - \langle \phi_{\text{detr}} \rangle^2} \quad S^4 = \sqrt{\langle SI^2 \rangle - \langle SI \rangle^2 / \langle SI \rangle^2}$$

where $SI$ is the received signal intensity, $\phi_{\text{detr}}$ is the detrended GPS L1 signal phase and $\langle \cdots \rangle$ indicates the time average over a defined window, set to 1 min. A sampling rate of 50 Hz allows getting scintillation indices based on 3000 samples. Even though the recent literature has highlighted how the phase detrending is a delicate issue (see, e.g., McCaffrey and Jayachandran 2019 and reference therein), here we follow the standard recommendations by Van Dierendonck et al. (1993) and detrending is accomplished by means of a sixth-order Butterworth filter with a 0.1 Hz cutoff frequency. Applying this phase detrending scheme, enhancements of $\sigma_\phi$ may include both refractive, mainly due to large-scale irregularities, and diffractive effects, due to small-scale irregularities, while enhancements of $S^4$ are always due only to diffractive effects on the GNSS signals (see, e.g., McCaffrey and Jayachandran 2019; De Franceschi et al. 2019). The separation between small- and large-scale irregularities is given by the Fresnel’s filtering mechanism (Yeh and Liu 1982). Thus by comparing the time profile of both scintillation indices, the nature of the irregularities triggering the observed scintillation pattern can be drawn, in terms of involved spatial scales.

The time profile of 1-min scintillation indices $\sigma_\phi$ and $S^4$ during 22 February 2007 is reported in the middle and bottom panels of Fig. 4, respectively. Different colors represent different satellites in the field of view of MZS. Since no significant enhancements of $S^4$ are found corresponding to those of $\sigma_\phi$ and according to the above-mentioned phase detrending procedure, the time profiles indicate that phase fluctuations are purely refractive, i.e.,
mainly triggered by irregularities having a typical scale size larger than the Fresnel's length for GNSS signals, of the order of few hundreds of meters. The 5-min averaged $\sigma_\phi$ (smoothed over 15-min; solid line in the middle panel) well follows the Pc1 power and ROT variance (the correlation coefficients are 0.60 and 0.70, respectively). At the same time, the 5-min averages of $S_4$ (solid line in the bottom panel) poorly correspond to the Pc1 power and the ROT variance (the correlation coefficients are 0.18 and 0.36, respectively).

Therefore, since ROT is derived from TEC measurements and TEC is derived from a phase difference, the fluctuations found in $\sigma_\phi$ are strictly linked to ROT ones. Moreover, the observed correspondence between the phase scintillation index and the Pc1 power represents the evidence that EMIC waves can lead to ionospheric irregularities causing phase scintillations.
Discussion

We present a comparative study of ULF geomagnetic fluctuations and TEC variations measured at the high-latitude station MZS on 22 February 2007. For the first time to our knowledge, we report evidence of a correspondence between an enhanced Pc1 pulsation power and the presence of ionospheric irregularities.

In specific, we examined the occurrence of ROT fluctuations as an indicative of ionospheric irregularities. The results show that, when a significant Pc1 activity is observed at MZS, also the ROT time series exhibits intense fluctuations, indicating the presence of electron density gradients, well related to enhancements of the Pc1 power. A possible link between the Pc1 activity and the ionospheric irregularities is represented by the energetic electron precipitation which, driven by EMIC waves, might produce ionization through the atmospheric layers. An additional, interesting result is the close correspondence between the Pc1 activity and ROT fluctuations and the phase scintillation index; such correspondence suggests that EMIC waves can produce ionospheric irregularities, with typical scale sizes above few hundreds of meters, causing phase scintillations.

Although a geomagnetically quiet day was examined, we observed Pc1 fluctuations at MZS. Coherent, linearly polarized pulsations occurred at the Pc1 lower frequencies, i.e., between 200 and 300 mHz, approximately in correspondence to increases of the solar wind pressure. With regard to this, Engebretson et al. (2002) found that, at high latitudes, a major part of Pc1 events is associated with magnetosphere compressions and undisturbed magnetospheric conditions. The waves, generated by the magnetospheric compressions near the equatorial plane and just inside the magnetopause, are observed mostly at L-shell between 8 and 10 (corresponding respectively to geomagnetic latitudes of ~69° and ~72°; Usanova et al. 2012). They can be detected even at the boundaries of the polar cap since they can propagate along the outermost closed field lines into the ionosphere and then in the ionospheric waveguide, more efficiently in the poleward direction (Kim et al. 2010, 2011; Regi et al. 2017a). Considering a wave power attenuation of ~10 dB/1000 km during the propagation in the waveguide (Kim et al. 2011), we believe that waves may be observed over a distance of the order of thousands of kilometers. Thus, the Pc1 waves observed in the present study at MZS could be injected into the ionosphere at a somewhat lower latitude (we tentatively estimated 71°–68°S). On this regard, the availability of simultaneous magnetic measurements (only the D component was available) at Concordia station (DMC, Dome C, Antarctica, geographic coordinates 75.11°S, 123.40°E; corrected geomagnetic coordinates 88.83°S, 55.62°E; LT = UT + 8, MLT = UT − 1, at a distance of ~1200 km from MZS) allows us to examine if such waves are observed also at a higher geomagnetic latitude station, located at approximately the same geographic latitude but at a different longitude. Figure 5 shows the dynamical spectrum and SNR(f) of the D component at DMC and the coherence between the D components at MZS and DMC. Significant signals are detected also at DMC, corresponding in frequency and time to those of MZS; moreover, the high coherence (>0.8) indicates a clear relationship between magnetic field fluctuations at the two stations. This result indicates that the two stations, at a distance of a thousand of kilometers, observe waves that propagated, maybe along different paths, in the ionospheric waveguide from the same injection region at a lower geomagnetic latitude.

In this context, we found useful to analyze search-coil data from the Finnish pulsation magnetometer array (MLT − UT + 2, LT − UT + 2). Figure 6 shows the dynamical spectra of the total horizontal component at Barentsburg (BAR, L = 15.8), Kilpisjärvi (KIL, L = 6.2), Ivalo (IVA, L = 5.9), Sodankyla (SOD, L = 5.4), Rovaniemi (ROV, L = 5.1), Oulu (OUL, L = 4.6) and Nurmijärvi (NUR, L = 3.4). Besides higher frequency features, the figure shows that a narrowband signal in the range 200–300 mHz, as the one observed at MZS, clearly emerges from ~0830 UT (i.e. 0630 LT) when stations enter the dayside sector. The pulsation power is high at L ~ 5–6, attenuates at BAR, at polar latitudes, while almost disappears at the subauroral station NUR. The comparison between stations at L = 5–6 shows that the power integrated between 200 and 300 mHz maximizes at KIL and decreases with decreasing L value, indicating that the power peak corresponds to a latitude greater than 66.2°S. This result is consistent with our suggestion that waves propagate from the equatorial region just inside the magnetopause, where they are generated, along the outer closed magnetic field lines up to the auroral ionosphere, both southward and northward; from the injection region into the ionosphere they propagate in the waveguide and are observed also at polar latitudes. In particular, the comparison of the spectra at BAR and MZS (Fig. 7) shows a close correspondence between 0800 and 1300 UT, indicating that the waves can be observed in both hemispheres at stations located in open field line regions.

The observed correspondence between Pc1 power enhancements and the occurrence of ionosphere irregularities may be tentatively interpreted in terms of two different scenarios:

1. A causal relationship between the magnetospheric electron precipitation, due to Pc1 events, and ionospheric electron density variations and irregularities;
2. Direct effects of the variable electromagnetic fields of waves on ionospheric electrons.

Regarding the first mechanism, it is worth highlighting that TEC variations refer to the whole satellite-receiver path, including also low altitudes. The MeV electrons involved in EMIC wave activity deposit most of their energy below 60 km (Turunen et al. 2008). On the other hand, recent studies have shown experimental evidence that lower energy (200–300 keV) EMIC-driven electron precipitation not only is possible (Clilverd et al. 2015; Rodger et al. 2015) but also predominant (Hendry et al. 2017). Such precipitation would influence more effectively ionospheric altitudes of 100–120 km (Turunen et al. 2008). The hypothesis of a causal relationship presents a criticality in that the electron precipitation (with a latitudinal and longitudinal width of 2–3° and 3 h magnetic local time, respectively, Clilverd et al. 2015) and the corresponding ionospheric effects should occur close to the Pc1 injection region, which is not above MZS. However, we remark that the region investigated by the ROT analysis is not restricted above the station, but it extends over a radius of about 500 km around it, where the effects of the electron precipitation could still be measured.

To check the second hypothesis, that is the interpretation of the correspondence of ionospheric irregularities with the Pc1 wave activity in terms of the direct effects of the variable electromagnetic fields of waves on ionospheric electrons, we made a spectral analysis of the high-resolution time series of ROT (i.e., $\Delta$TEC/$\Delta$t, $\Delta$t = 1 s).

The corresponding dynamical spectrum, shown in Fig. 8, reveals only weak and sporadic correspondences with the Pc1 dynamical spectrum and undefined evidence of oscillations at the same frequencies (200–300 mHz) of the observed Pc1 waves (see Fig. 1, upper panel). It is worth noting that, in a recent study, Watson et al. (2016) found a clear link between TEC fluctuations and geomagnetic field fluctuations in a frequency range much lower (6.7–22 mHz) than that analyzed in our study (0.2–1 Hz).

**Summary and conclusions**

We examined a Pc1 event observed at a high-latitude station during geomagnetic quiet conditions, with the aim at looking for possible correspondences with the
The pulsation activity is enhanced in correspondence to solar wind dynamical pressure increases;  
2. Pulsations of equal frequency are simultaneously observed at polar and auroral geomagnetic latitudes; 
3. Correspondence is found between the Pc1 pulsation activity and the occurrence of ionospheric irregularities, as clearly showed by the analysis of ROT fluctuations.

The study clearly shows that signatures of EMIC waves, driven by increased solar wind pressure, can be observed also at polar latitudes, simultaneously in both hemispheres, due to their propagation in the ionospheric waveguide. Such waves, generated just inside the magnetopause, propagate through the magnetosphere and transmit as Alfven waves along geomagnetic field lines.
up to the auroral ionosphere. They can produce the precipitation of magnetospheric energetic electrons into the atmosphere, causing electron/ion density variations as measured by TEC fluctuations.

We believe that the observations of this work, although present a very interesting result, should be substantiated by further investigations, based on a number of events and additional data (satellite and/or riometer data) to be fully explained.

Abbreviations
BAR: Barentsburg; DMC: Dome C; EMIC: Electromagnetic ion-cyclotron; IVA: Ivalo; KIL: Kilpisjarvi; LT: Local time; MLT: Magnetic local time; MZS: Mario Zucchelli station; NUR: Nurmijarvi; OUL: Oulu; PSD: Power spectral density; ROT: Rate of TEC; ROV: Rovaniemi; SOD: Sodankyla; S4: Amplitude scintillation index; σφ: Phase scintillation index; TEC: Total electron content; ULF: Ultra-low frequency; UT: Universal time.

Acknowledgements
This research activity was supported by the Italian PNRA (Programma Nazionale di Ricerche in Antartide, PnR2013/B2.09). The authors also thank PNRA for GNSS data. The authors acknowledge J.H. King and N. Papathribili at NASA and CDAWeb for solar wind data (http://cdaweb.gsfc.nasa.gov).
Authors’ contributions
PF, MR and MDL made the ULF and TEC analysis, interpreted the results and were the major contributors in writing the manuscript. MP, CC and LS prepared the TEC time series. TR provided the Finnish pulsation magnetometer data. All participating authors contributed to the discussions. All authors read and approved the final manuscript.

Funding
The research activity of M. Regi was in part supported by the Consorzio “Area di Ricerca in Astrogeofisica”.

Availability of data and materials
Measurements of the magnetic field fluctuations at Terra Nova Bay and Dome C can be requested to M. De Lauretis at the following e-mail address: marcello.delauretis@aquila.infn.it. TEC data can be requested to M. Pezzopane and C. Cesaroni at the following e-mail addresses: michael.pezzopane@ingv.it and claudio.cesaroni@ingv.it. The Finnish pulsation magnetometer data are available by request from Sodankylä Geophysical Observatory at https://www.argo.fi/Data/archive.php.

Competing interests
The authors declare that they have no competing interests.

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Received: 28 November 2019 Accepted: 24 April 2020 Published online: 07 May 2020

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