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Key Points:

- We report observations of ELF/VLF conjugated emissions between ground and space at opposite sides of the magnetosphere
- We present Y-shaped features with frequency drift, likely generated by high intensity source
- Spatial gradient of magnetic field affects spectral features of emissions

Supporting Information:

- Supporting Information S1

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Conjugate Observations of Dayside and Nightside VLF Chorus and QP Emissions Between Arase (ERG) and Kannuslehto, Finland

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Abstract We compare for the first time two conjugate events showing simultaneous very low frequency (VLF) wave observations between the same ground station and spacecraft, at different geomagnetic conditions and on opposite sides of the magnetosphere. Waves were observed at Kannuslehto (MLAT = 64.4°N, $L = 5.46$), Finland, and on board Arase (Exploration of energization and Radiation in Geospace, ERG) in the inner magnetosphere. Case 1 on 28 March 2017 shows quasiperiodic (QP) emissions and chorus simultaneously observed on the postmidnight side during the recovery phase of a storm, with sustained high solar wind speed and AE index. Case 2 on 30 November 2017 shows clear one-to-one correspondence of QP elements on the noonside during geomagnetic quiet time ($Dst > 10$ nT and $AE < 100$ nT). We present the characteristics of both cases, focusing on coherence and spatial extent of the waves, electron density, and magnetic field variations. We report that the magnetic field gradient plays a role in the changes of spectral features of the waves.

1. Introduction

Very low frequency (VLF) emissions are naturally occurring magnetospheric plasma waves ($3 \text{ Hz} < f < 30 \text{ kHz}$) propagating in the whistler mode usually generated at or near the geomagnetic equator through resonant cyclotron interactions with energetic electrons (approximately hundreds of kiloelectron volts). As the waves propagate in the magnetosphere, wave-particle interactions result in acceleration or scattering of electrons contributing to the regulation of radiation belt dynamics (e.g., Hayash et al., 2013; Horne et al., 2005; Meredith et al., 2003; Thorne, 2010). Among these types of plasma waves, discrete chorus is one of the most known (Helliwell, 1965). Another type are quasiperiodic (QP) emissions, characterized by a fairly regular periodic modulation of their wave intensity in the order of a few seconds up to several minutes. Although this study presents both chorus and QP observations, it will mainly focus on the characteristics of the latter. QP are classified as Types I and II, depending if they are observed in the presence or absence of geomagnetic pulsations (e.g., Kitamura et al., 1968; Sato & Fukunishi, 1981; Sato et al., 1974). Their link with geomagnetic pulsations suggests that their periodicity is related to modulation by ultra low frequency waves (e.g., Morrison, 1990; Némec et al., 2013; Sato & Fukunishi, 1981; Sato & Matsudo, 1986). For example, Némec et al. (2016) show that the time delay between QP simultaneously detected in space and on the ground is related to azimuthally propagating compressional ultra low frequency waves responsible for the generation of the QP. However, QP observations are not necessarily accompanied by geomagnetic pulsations; thus, another explanation for their generation is related to auto-oscillations of the cyclotron instability of the Earth radiation belts (Trakhtengerts & Rycroft, 2008). Manninen et al. (2013) and Manninen et al. (2014) found that the variations of QP periods, particularly their gradual increment, can be explained by the auto-oscillation regime of the cyclotron instability in the magnetosphere. They also noted that important changes in the periodicity of the QP during substorms could be related to variations in the energetic electron fluxes. Currently, the exact origin and mechanisms behind the periodicity of

QP remain unclear. The present study will contribute with additional and rare observational data from combined ground-space observations to understand the generation processes behind QP emissions, their relationship to chorus and additional information on their magnetospheric propagation.

We present conjugated events between a ground VLF receiver and the Exploration of energization and Radiation in Geospace (ERG), also known as Arase satellite. In this paper, we define a conjugate event as the simultaneous observation of the same wave on the ground and in space, indicating that we are observing waves from the same geomagnetic source (Martinez-Calderon, 2016). This means that in both locations we are observing waves with the same frequency variations and same spectral and temporal features. The ideal case shows clear one-to-one correspondence of the waves. As the waves propagate to the ground and exit the ionosphere, they carry with them information on the plasma parameters and conditions of the region where they were generated. Although by their nature, conjugated events give us significant information on the generation and propagation of waves, up until now they remain rare with only a handful of documented cases (Martinez-Calderon, 2016; Némec et al., 2016; Titova et al., 2015). The novelty of our study is to present two additional singular conjugate events observed during different geomagnetic conditions and at almost opposite sides of the magnetosphere. This study allows us for the first time to compare two conjugate events between the same ground station and satellite, at different geomagnetic conditions (quiet vs. active) and at different magnetospheric locations (morning vs. midnight side). As wave propagation and generation is highly dependent on magnetospheric and ionospheric conditions, we will discuss the differences and similarities found between these two cases. We use electron density variations from ERG and model-based magnetic field variations to explore changes in spectral features. We also discuss the existing link between chorus and QP emissions and parameters that affect wave propagation.

2. Data

To monitor waves on the ground, we use a VLF receiver from the Sodankyla Geophysical Observatory at auroral latitudes in Kannuslehto (KAN, MLAT = 64.4°N, $L = 5.46$), Finland. The receiver is composed of two square loop antennas that measure the magnetic field variations in the east-west and north-south directions, respectively. Data have a sampling frequency of 78.125 kHz. Further details on the system can be found in Manninen (2005). Observations in space were made by the ERG spacecraft launched on December 2016. ERG has an orbital inclination of 31° and an elliptical orbit with an apogee altitude of 5 R_E (Miyoshi et al., 2018). Electric and magnetic field data for ERG are provided by the Plasma Wave Experiment (PWE) (Kasahara et al., 2018). Wave electric and magnetic field spectra are measured by the On-board Frequency Analyzer (OFA) (Matsuda et al., 2018). The instrument measures electric fields from 10 Hz to 20 kHz and magnetic fields from 1 Hz to 20 kHz with 1-s time resolution (132 frequency points) in the nominal mode. Spectrum matrices for wave direction finding analyses are provided by OFA with 8-s time resolution. Cold plasma density is derived from the upper-hybrid resonance frequency by the High-Frequency Analyzer (HFA) with 1-s time resolution (Kumamoto et al., 2018). Magnetic field data are obtained from the fluxgate magnetometer from the Magnetic Field Instrument (Matsuoka et al., 2018). Wave analysis was carried out using the Singular Value Decomposition method (Santolík et al., 2003) and we used PWE/OFA-MATRIX data for the calculations shown in Figures 2 to 5. The ionospheric footprint of ERG was calculated using the IGRF internal model and Tsyganenko (T01) external model (Tsyganenko, 2002). Calculations of magnetic field lines, L shell values, and magnetic field values at the geomagnetic equator were also obtained using the aforementioned models.

3. Observations

3.1. Case 1: 28 March 2017

We report a QP and chorus conjugate event between KAN and ERG on 28 March 2017 from 22:36 to 23:00 UT. Figure 1a shows geomagnetic activity before and after the event (vertical blue lines) which occurred during the recovery phase of a geomagnetic storm, at times of high AE ($400 < AE < 800$ nT) and sustained high speed solar wind (650 km/s). Case 1 happened in the postmidnight sector (00–02 MLT), while ERG was moving southward, away from the magnetic equator (MLAT = 25°) and at $L \sim 5$. Figure 1c shows the northern ionospheric magnetic footprint of ERG (blue line) calculated with T01 to the top of the ionosphere (altitude ~ 100 km) and located approximately 300 km from KAN (red triangle). Figures 2a and 2b show, respectively, the power spectrum density from magnetic field variations at ERG and KAN for 22:30 to 23:10 UT. Local electron half-gyrofrequency was between 5 and 11 kHz, while the equatorial half-gyrofrequency was

Figure 1. Geomagnetic conditions for (a) Case 1 and (b) Case 2. Timings of events are indicated by vertical lines. (c) Location of Kannuslehto ground station (KAN) and magnetic ionospheric footprint of ERG for Case 1 (blue) and 2 (orange). ERG = Exploration of energization and Radiation in Geospace.

~3.3–3.5 kHz, therefore not visible on the figures. From approximately 22:35 UT we see the start of a chorus emission in both locations, and as time moves on we also observe the same frequency changes in the waves. This is more easily seen at the beginning of the emissions following the white line indicating the upper envelope of the emissions observed at KAN in both figures. We consider the observed spectra feature of discrete emission as chorus since it shows rising tones and impulsive bursts while propagating below the local electron half-gyrofrequency (Figure S1 in the supporting information). In the following 20 min, both locations observe two chorus frequency bands at 1 and 0.4 kHz. At ~22:45 UT a third band with QP features appears at ~1.5 kHz lasting approximately 10 min. A better look of these features is given in Figures 3a and 3b, where arrows indicate the approximate location of the three bands for KAN and ERG, respectively. These features are observed at the same time and same frequencies in both ground and space, suggesting that the waves are coming from the same source region. Within the source region where the waves are generated at the equatorial plane, there can be several areas where the waves are generated coherently; in this case we see clear correspondence between elements on the ground and in space. Other waves generated by the same source region but outside of the coherence area can show similar spectral features or frequency changes as shown here. If we look more closely, during this conjugate event we have some instances of one-to-one correspondence but they are not always present (supporting information Figure S2). As both the waves from the same source region and the same coherent area can exit the ionosphere at the same point, they overlap on the ground, making the one-to-one correspondence difficult to match.

Figure 2. Power spectrum density of magnetic field at (a) KAN and (b) ERG and electric field at (c) ERG. (d) Cold plasma density from ERG. (e) Normal wave angle, (f) polarization sense, (g) wave planarity, and (h) Poynting vector from ERG data. (i) Magnetic field deviations from ERG in MFA coordinates. (j) Angle of arrival at KAN, angle between minor axis of polarization ellipse and north-south direction. White line indicates the upper envelope of the emission at KAN and vertical dashed line indicates the approximate end of the conjugated event. ERG = Exploration of energization and Radiation in Geospace; PWE = plasma wave experiment; OFA = On-board Frequency Analyzer.

Figure 3. Power spectrum density of magnetic field at (a) KAN and (b) ERG. (c) Normal wave angle, (d) wave planarity, and (e) Poynting vector from ERG data. (f) Angle of arrival at KAN, angle between minor axis of polarization ellipse and north-south direction. (g) Magnetic field deviations from ERG in MFA coordinates and at (h) SOD magnetometer (35 km from KAN). White and black arrows indicate the three frequency bands of the event. ERG = Exploration of energization and Radiation in Geospace; PWE = plasma wave experiment; OFA = On-board Frequency Analyzer.

After ~23:00 UT, both ERG and KAN keep observing waves but the lack of correspondence in spectral features makes it difficult to verify if they are coming from the same source; thus, we mark this timing as the end of the conjugate event. This timing is indicated by the vertical gray dashed line in Figure 2. After this timing, KAN observes mostly chorus mixed with hiss and some periodic bursts with a periodicity of a few tens of seconds. Meanwhile, onboard ERG the chorus emission transforms into a QP at approximately 23:40 UT. Figure 4a shows the chorus emission at KAN, while Figure 4b shows the QP emission observed by ERG. KAN shows chorus features below 1.5 kHz, while ERG observes a very clear QP below 1 kHz with a periodicity of 12–20 s. This QP continues to be observed by ERG until ~1:00 UT on 29 March 2017.

Figures 4g and 4h show, respectively, magnetic field deviations recorded at ERG and the induction coil magnetometer at Ivalo (IVA), located approximately 100 km north of KAN. These values were calculated by subtracting the 2-min averaged magnetic field from each component: x (positive values toward geographical North), y (positive toward geographical East), and z (positive toward center of the Earth). The black (gray) vertical lines show when the increase of B_y (B_z) corresponds with a QP element. In the first 3 min of this

Figure 4. Power spectrum density of magnetic field at (a) KAN and (b) ERG. (c) Normal wave angle, (d) wave planarity, and (e) Poynting vector from ERG data. (f) Angle of arrival at KAN, angle between minor axis of polarization ellipse and north-south direction. (g) Magnetic field deviations from ERG in MFA coordinates and at (h) SOD magnetometer (35 km from KAN). Black vertical dashed lines are a guide to indicate the correspondence between QP periodicity and pulsations. ERG = Exploration of energization and Radiation in Geospace; PWE = plasma wave experiment; OFA = On-board Frequency Analyzer.

interval we see that some of the pulsations roughly correspond to 2 times the periodicity of the QP. Afterward, this changes to 3 times the periodicity of the QP. We note that even though the pulsations onboard the satellite have a low amplitude (<1 nT), the correspondence with IVA would suggest that this is a Type I QP emission. However, if we look at Figure 3h showing the magnetic field deviations at SOD magnetometer (same format as IVA), 35 km from KAN, we note that there were no similarly coincident pulsations during the conjugated event. Indeed, we found that neither SOD, IVA (not shown), nor ERG (Figures 2i and 3g) detected coincident pulsations between 22:35 and 23:00 UT.

Figure 2d shows the variations of background electron density obtained from HFA. We note that during the conjugate event the density decreased. At the time that the third frequency chorus band appeared showing some periodic elements ($\sim 22:48$ UT), ERG also detects density variations. Although the emission is no longer the same at KAN, ERG shows very clear periodicity from $\sim 23:40$ onward. We could consider a relationship between the spectral features and the density; however, spectral features of the waves are determined at the source. ERG is located off equator away from the source region, changes in the local density measured by ERG do not necessarily reflect changes of density at the source and would most likely affect wave propagation and not spectral features.

As expected from whistler mode waves, they are strongly right-handed (Figure 2d). They show high planarity (Figure 2e) except for $f < 1$ kHz between 22:48 and 23:02 UT. Figure 2d shows that waves are propagating almost field aligned, particularly for frequencies >1 kHz where the planarity is high. Before 22:50 UT, lower frequencies are mildly oblique, close to $30\text{--}40^\circ$ but this discrepancy could be due to low planarity values indicating that the single plane wave approximation is no longer valid. A closer view shown in Figures 3c and 3d shows that some regions of low planarity have more oblique angles, but this is not the case for some values close to 2 kHz. From these observations we could conclude that the waves were propagating field aligned with angles $<30^\circ$, suggesting that the waves were propagating ducted to the ground. However, the low planarity values also mean that we are observing a mixture of waves propagating at different wave normal angles, suggesting that if the waves were propagating field aligned, we would expect the planarity to be high. Figure 2h, showing the Poynting vector angle, indicates that the waves were moving southward away from the magnetic equator for $f > 0.8$ kHz. At lower frequencies, the Poynting vector is directed northward; however, the planarity values are also low (below 0.5). While Figure 3e shows clearly that regions of high planarity are where the Poynting flux is directed southward, for lower frequencies, the northward Poynting flux direction seems to be dominant. We can infer the direction of arrival of the waves to the ground station using the angle between the minor axis of the polarization ellipse and the north-south direction with an ambiguity of 180° (0° or 180° indicates the north-south direction). Figure 2j shows that the angle of arrival from KAN was between 140° and 180° , suggesting that the waves could have come from either the north-east or the south-west directions. As seen in Figure 1c, the footprint of ERG was located south-west from KAN which is in agreement with the likely location of the ionospheric exit point.

3.2. Case 2: 30 November 2017

Case 2 was observed on 30 November 2017 from 09:30 to 10:20 UT during geomagnetic quiet times. Figure 1b shows that *SYM-H* values were stable (>-20 nT), and even though there were a few substorms at the time of the event (red vertical lines), we generally had *AE* < 100 nT. Case 2 was on the dayside (11 to 13 MLT), almost on the opposite side of the magnetosphere from Case 1. ERG was northward of the equator but approximately at the same MLAT ($+25^\circ$) and similar *L* shells. Figure 1c shows that the ionospheric magnetic footprint of ERG (orange line) was closer to KAN but remained in the same area as Case 1, southward of the station. As shown in Figure 5i, ERG detected no significant magnetic pulsations that correspond to the QP periodicity. On the ground, SOD, IVA, and TAR (58.26°N , 26.46°E) detected magnetic pulsations with a similar order of periodicity from 2 to 4 min depending on the station. However, we could not find any correspondence between these pulsations and the intensity variations of the QP; therefore, we have classified this as a Type II event.

Figure 5b shows the power spectrum density at KAN, while Figures 5a and 5c show, respectively, magnetic and electric fields at ERG for a snapshot of the event. The local electron half-gyrofrequency was between 6 and 15 kHz, while the equatorial half-gyrofrequency was around 5.2 kHz and they are thus both well above the analyzed frequency range. Comparing the waves from both locations we easily see a clear one-to-one correspondence of all QP elements. This was the case for the entirety of the event that lasted ~ 50 min. The emission abruptly stops from $\sim 10:17$ UT in the magnetic field observations at ERG as shown

Figure 5. Case 2 in the same format as Figure 2.

in Figure 4a (rightmost purple horizontal line). QP elements are still very clearly visible on the electric field data (panel c) for an additional 15 min, as well as in KAN (panel b). This disappearance also corresponds with the lowest density value detected by ERG (Figure 4d). Similarly, at 10:10 UT, a marked decrease of the intensity on the magnetic field at ERG (in particular for frequencies <2 kHz) corresponds to a consequential drop of the local cold plasma density (leftmost purple horizontal line). Unlike Case 1, the changes in density are not accompanied by changes in the spectral characteristics but clearly affect wave intensity. Sudden drops of density are concurrent with sudden decrease of the magnetic field intensity with at least one order of magnitude. We note that overall the period of the QP increases with the density, changing from 50

to 150 s, while the density slowly decreases by one order of magnitude approximately. However, the significant drops of density do not seem to instantly translate to sudden changes in the periodicity. From wave analysis we found the waves to be strongly right-hand polarized (Figure 4f). Planarity is much lower than for Case 1, remaining relatively low (~ 0.4) for most of the event. However, up until 10:10 UT, and between 1 and 3 kHz, planarity can be considered as moderately high. For these intervals, the wave vector is mostly field aligned, close to 20° (Figure 5e) suggesting that the waves could have propagated ducted and their Poynting vector indicates they propagated northward away from the magnetic equator (Figure 4h). We note, however, that between 10:00 and 10:10 UT for frequencies below 2 kHz the wave normal angle becomes more oblique reaching values up to 40° . Discrepancies in the wave normal angle outside of these intervals can be explained by the low planarity values. The angle of arrival at KAN is close to 90° suggesting that the waves are coming from either eastward or westward from the station. Figure 1 shows that the footprint of ERG was moving from the south-east to the south of KAN putting the location of the ionospheric point likely westward of these positions.

Additionally, both KAN and ERG detect Y-shaped structures which have not been previously reported on ground-based data; an example of such features is shown here at $\sim 09:47$ and $09:54$ UT (pink horizontal lines). These structures were not accompanied by density changes or visible changes in the wave properties. In addition, between $09:58$ and $10:15$ UT and at frequencies of 3–4 kHz, there are some fainter periodic elements present in the data from KAN. These elements are not immediately visible on ERG data, even when changing the color scale. However, a trace that could correspond to one of these faint elements can be seen on the electric field data at $10:14$ UT.

4. Discussion

4.1. General Properties

This study presents two rare conjugate events between the ground and space, the first one in the postmidnight sector during geomagnetically active times and the second on the dayside during quiescent times. In both cases presented here, the ionospheric footprint of ERG stays within the same area southwest of KAN (less than 300 km from each other). We expected wave propagation in the magnetosphere to be affected by the different geomagnetic conditions; however, this does not seem to have been the case here. The location of the ionospheric wave exit point in a similar area could signify that the geographical location is significant for the exit point. Martinez-Calderon et al. (2015) studied the ionospheric exit point of simultaneously ground-observed chorus waves using two VLF receivers in Canada at similar latitudes. They found that, even though the three cases were under different conditions, the waves were exiting the ionosphere at similar points, suggesting a preferential path from the magnetosphere to the ground. However, these are not statistically significant results and a more thorough study of the location of the ionospheric point with more cases should be considered. Additional conjugated events between KAN and ERG currently under study show that the footprint of ERG is usually located south or south-westward of KAN. On the other hand, we also note that there is at least one case reported by Demekhov, Manninen, Santolík, and Titova (2017) of a chorus conjugated event between KAN and RBSP-B where the footprint of the spacecraft was located southeast from KAN. This shows that additional thorough analysis of how the waves propagate to the ground is necessary. To better understand the differences between these cases, further discussion on this point, including ray tracing, will be the subject of a separate paper.

Case 1 occurred during active geomagnetic conditions; wave activity was relatively high. Several VLF receivers located in Canada at similar L shells as KAN observed multiple QP emissions throughout the day. They were usually observed while the stations stayed on the dayside (06–13 MLT) except for KAN which observed QP throughout the day (00–20 MLT). At the start of the conjunction between KAN and ERG, the footprints of both Van Allen Probes were located $\sim 3,300$ – $5,000$ km westward of the ground station and moving rapidly eastward. Neither satellite detected any similar emissions to those observed by ERG. We note however that at $22:30$ UT, when the RBSPs were closest to KAN, RBSP-B observed some periodic bursts that did not have the same periodicity as those observed by KAN or ERG. When the conjunction between ERG and KAN was over, both RBSPs were in the same hemisphere but with a 12-hr MLT difference from KAN, near the VLF receiver of Athabasca (MLAT = 61.2° N, $L = 4.3$). The latter observed clear QP emissions with different characteristics ending at 23 UT. These results suggest that wave activity was high during the conjunction interval with several QP emissions being generated at the time.

Figure 6. Magnitude of the magnetic field as a function of height along the field line from the geomagnetic equator, calculated by T01 and normalized by the local electron gyrofrequency for (a) Case 1 and (c) Case 2. Fitted parabolic curve for (b) Case 1 and (d) Case 2.

Using the timings of conjugated observations and assuming the simplest propagation scenario, we projected the field line from ERG to the geomagnetic equator. If we assume that the waves propagated directly, without reflection, from the source region to the satellite and then to the ground, we can estimate the maximum longitudinal size of the flux tube in which the waves were observed and possibly generated. For Case 1, from 22:36 to 23 UT, the tube extends from $L = 4.6$ to 5.1 with IGRF or $L = 5.0$ to 5.6 taking into account T01. For Case 2, from 09:30 to 10:20 UT the flux tube would extend from $L = 3.7$ to 5.1 (both models). For this event, the QP continues to be observed at KAN until 12:30 UT, simply suggesting that the satellite left the propagating flux tube. Titova et al. (2015) found that for active times, the location of the source region of QP emissions was at $L = 3.9$ – 4.2 which corresponds to a flux tube of approximately $0.3 L$ shells in width. While in our case the estimated source location is at higher L shells, the width of the propagation tube shows similar values with the simplest approach. The difference can be explained by the location of the satellite, away

Figure 7. Parabolic coefficient as a function of time for (b) Case 1 and (d) Case 2. Changes in spectral features correspond to changes in magnetic field gradient shown in the spectrograms from ERG (a) Case 1 and (c) Case 2.

from the source region ($MLAT = 25^\circ$), which leads to an overestimation of the size of the equatorial source. Comparing the size of the flux tube in the two cases presented in this study, a first approach would suggest that during quiet times the size of the flux tube would be larger than during active times. We also note that previous studies have shown that QP emissions can be observed in regions that are much larger than the source region (Némec et al., 2018; Titova et al., 2015). Lyubchich et al. (2017) calculated the growth rate of the QP emission in the case presented by Titova et al., 2015. They confirmed the location of the source region and found that the generation in this case necessitated ducted propagation. Therefore, to properly understand how geomagnetic conditions influence the location and size of the source and propagating flux tube, as well as their relative size to each other, we need to consider a much larger number of conjugated events.

4.2. Changes in Spectral Features

We found that spectral features of VLF waves seemed to be linked to electron density variations (Case 1, Figure 2) during geomagnetic active times but not during quiet times (Case 2, Figure 5). Cold plasma density can influence wave intensity on the magnetic field variations (Figures 5c and 5d). However, since local-measured density does not necessarily reflect changes in the density at the source region, this seems an unlikely scenario to explain the changes in spectral features. We suggest that these variations are related to other parameters. Previous studies have related spectral changes in whistler mode chorus emissions to changes in the spatial magnetic field gradient (Kato & Omura, 2013). We propose to investigate if this can be a factor in our observations.

From ERG's position in the magnetosphere, we calculated the magnetic field line to the ionosphere on the opposite hemisphere and determined the geomagnetic equator (location on the field line where the radial magnetic field component reverses sign automatically detected by the Tsyanenko model procedure). We obtain the height along the field line $\pm 25^\circ$ from the equator, along with its associated magnetic field. The validity of the magnetic field values is given by the ratio between the theoretical model result and observations by ERG at the starting point of the field line. These ratios are 0.91 to 1.02 for Case 1 and 0.99 to 1.01 for Case 2, in good agreement. Results from the T01 model are shown in Figures 6a and 6c for Cases 1 and 2, respectively. We plotted the magnetic field as a function of h^* which corresponds to the distance from the magnetic equator along the field line, normalized by the speed of light c and equatorial electron gyrofrequency Ω_{e0} . Since the spatial scales of both wavelength and field line length change depending on the magnitude of the background magnetic field, this normalization allows us to compare observation results measured in locations of different background magnetic fields. This normalization also represents a characteristic length that can allow to easily compare with simulation results. Each dot corresponds to a point in the field line automatically calculated by the T01 routine. Each colored line represents the field line every 10 min, from the start and end time indicated in the figures. We made a polynomial fit, $f(h) = ah^2 + bh + c$, for

each field line shown in Figures 6b and 6d for Cases 1 and 2, respectively. The quality of this fit is illustrated in Figure S3 in supporting information, where we show the fit over the T01 points for selected field lines. To see more clearly how the spatial magnetic field gradient changes in time, we have plotted the parabolic coefficient (a) as a function of time (Figure 6) using both IGRF (purple) and T01 (blue dots) models. We note that results were also calculated using the T04s model; however, as they were very similar to those of T01 we have decided to omit them from the figures. Here we use the magnitude of the coefficient to simply visualize the spatial gradient of the background magnetic field, as we are more interested in the variations of the coefficient in time and not its value.

For Case 2, where the emission is purely QP, the parabolic coefficient increases moderately but steadily (Figure 7b). The results from both models are similar since we are in quiet geomagnetic conditions. Though some changes in periodicity are observed (the period increases three times), the emission remains quasi-periodic with no significant spectral changes, as illustrated by two short intervals taken at different timings shown in Figures 7e and 7f. On the other hand, for Case 1 the parabolic coefficient starts gradually increasing until $\sim 23:40$ UT at which point it rises much faster (Figure 6a). Case 1 showed changes in the spectral properties, from chorus to QP. These changes are somewhat gradual, sometimes overlapping, but from $\sim 23:45$ UT the emission becomes distinctly QP (vertical dashed line). We see clearly that before and after the rapid increase in the parabolic coefficient, the spectral features change accordingly as shown in Figures 7c and 7d. The IGRF and T01 models are stationary in time; thus, we take into account that the spatial distribution of the magnetic field does not change in time. In Case 1, at the beginning of the event from 22:30 to $\sim 23:45$ UT, we observe chorus and low parabolic coefficients (0.05–0.03), while afterward we observe QP and high parabolic coefficients (0.03–0.10). Increasing parabolic coefficients means that the gradient of the magnetic field is going from low to high values. In the time interval where we observe changes from chorus to QP, we are in a substorm recovery phase with negative IMF B_z , thus we can expect tailward stretching. This means that the magnetic field changes from a dipolarization configuration to stretching of the field lines and as such from low to large values of magnetic field gradient. In Case 2, the steady parabolic coefficient suggests that the magnetic field gradient did not change much during the event. In this case we observe only QP.

Previously, Trakhtengerts (1999) suggested that the inhomogeneity parameter plays a key role for chorus generation threshold, while Katoh and Omura (2013) has suggested that changes in the magnetic field gradient at the equator control changes in the waves characteristics for chorus and hiss-like emissions. More recently, Ozaki et al. (2015) linked the changes in temporal features of chorus emissions and pulsating aurora to enhancement in chorus from small geomagnetic field inhomogeneities. We suggest that a similar procedure is responsible for the changes from chorus to QP shown in Case 1. Katoh and Omura (2013) suggested that, with the same initial velocity distribution of energetic electrons assumed at the equator, hiss-like emissions are generated in the smaller inhomogeneity regions and that distinct chorus elements appear in the larger inhomogeneity regions. Therefore, in the large inhomogeneity case, the wave generation is not continuous but occurs sporadically only when the wave amplitude exceeds a threshold level. We can apply a similar reasoning to Case 1 in which for smaller magnetic field gradients, there is a large number of wave elements whose distribution in time shows some quasiperiodicity within a few seconds (Figure 7c; also found in simulations by Demekhov, Taubenschuss, & Santolík, 2017). On the other hand, in regions of large magnetic field gradient, we expect a larger threshold for the generation of wave elements; thus, the intensity of the triggering wave should be high. The generation of the wave elements would no longer have a short periodicity but would require a much larger periodic impulse, releasing all the elements within the order of minutes, thus generating QP. We could assume that the same kind of particles with a specific velocity distribution existed alongside regions of low and high magnetic field gradient, as the anisotropy generates waves from the particle population, the region of low gradient produces chorus features while the region of high gradient more QP features. The important difference between Cases 1 and 2 is not the value of the gradient itself but the changes in the gradient. When we have larger changes of the gradient, we have changes in the spectral features, but just the fact that we have a large gradient value does not automatically mean that QP will be generated. Currently, we are unable to determine the mechanism responsible for the timing when the amplitude exceeds the threshold. Here we assume that the same kind of energetic electrons is in the wave source region, but we can consider the variation of particles in the same gradient. The variation of particles would be another factor controlling spectral property. We also need to consider the different time scales of chorus and QP elements and that of the change of magnetic field gradient revealed here. Further

observational results should be investigated by carrying out statistical surveys with a much larger number of conjugated events.

Figures 5c and 5d show that for Case 2 the decrease of wave intensity corresponds to an abrupt decrease of density, suggesting that if the electron background density reaches a certain threshold, the wave disappears entirely. In comparison, the electric field remains mostly unaffected, although there is some decrease of intensity after 10:20 UT. Density variations can affect the refractive index that controls the ratio between the electric and magnetic field components of the waves. As the density increases, the refractive index becomes larger and thus the electric to magnetic field ratio decreases. If there are no changes in the electric field, the decreasing E/B ratio means that the magnetic component must decrease which is what ERG observes in this case. We could estimate the refractive index as well as the E/B ratio changes as a function of the electron density; however, at this time, the calibration of the electric fields has not been fixed. The sensitivity of the electric sensor is a function of electric density and temperature, meaning the measured electric intensity and phase varies depending on the plasma environment. Because the derived electric field is currently converted into the absolute value using a fixed calibration table (in vacuum), it is difficult to compare the E/B ratio measured in different electron density regions. Thus, we are unable to qualitatively discuss density dependence of E/B ratio using the present version data. Since the ground emission remains unchanged, we can also attribute these changes to propagation characteristics of the wave. As only ERG observed the modulation of the wave intensity related to the decrease of density along the satellite's path, this could indicate that at that time the spacecraft might have been observing waves generated somewhere else, possibly close to its location.

A feature that is neither related to density nor magnetic field changes are the Y-shaped structures (pink lines, Figure 4). These structures are seen at least 3 times during the whole event. If these emissions were only seen on the ground, then it could indicate two overlapping QP with different periodicity. At KAN this could translate as two emissions showing different angles of arrival; however, Figure 5j shows that this is not the case and at least the waves are seen coming from similar directions. In addition, these Y-shaped structures are also seen on ERG and, as their frequency does not change during propagation, we can only assume that these features are related to changes at the source region. The change of the frequency sweep rate from one element to the other was reported in Pasmanik et al. (2004), where they modeled QP generation regimes in the magnetospheric cyclotron maser considering the properties of the energetic particle source. When they considered the case of drift losses with an anisotropic source with a rather high intensity, they found that spikes with two different shapes were generated. Compared to the first spike, the second shape had a faster frequency shift, lower wave amplitude, and its generation started after the first spike faded. These are similar characteristics to those presented by the Y-shaped structures in this paper. Pasmanik et al. (2004) then suggested that after the end of the first spike, even a small addition of anisotropic electrons by the source would result in a secondary spike, with simultaneous generation in a wide frequency band thus resulting in the different shape. This could be a possible mechanism behind the Y-shaped structures. We should also mention that the fainter elements seen at KAN preceding the main QP events could represent the right side of the Y-shaped emissions, which could become less intense in time. After a time, these elements would not propagate to ERG, explaining why they are not visible in Figure 5a. Further discussion on the propagation properties of these waves is necessary to make further conclusions and will be the subject of a separate paper.

5. Summary

In summary, comparing two conjugated ELF/VLF events at different geomagnetic activities and locations in the magnetosphere we found the following.

1. In our two cases, the footprint of ERG was located in the same area southward of KAN. One explanation could be that the waves likely exited the ionosphere at similar points, and this exit point is largely independent on geomagnetic conditions. We tentatively discuss the size of the flux tube and found that it could be affected by the conditions of the magnetosphere. However, additional cases must be studied in order to find if there is a relationship between geomagnetic conditions and MLT and the ionospheric point.
2. Changes in the spatial magnetic field gradient are related to changes in spectral features of the VLF emissions observed here. In cases of larger magnetic field gradient waves show QP-like characteristics, while for smaller gradient they are chorus like.

3. Y-shaped emissions are unrelated to changes in the magnetic field or the background plasma density. We believe that the first branch is a QP element generated by a high intensity source. Then, a rather small addition of anisotropic electrons would generate a secondary spike in a wider frequency band, appearing with a different spectral shape as the secondary arm of the Y-shaped emission.

Further study on these characteristics, in particular how the waves propagated to the ground, will be taken into account studying additional conjugated events between KAN and ERG in a future paper.

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