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Incidence of Alfvenic SC Pulse Onto the Conjugate Ionospheres

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Key Points:

- Interhemispheric properties of Alfvenic pulses with duration less than field line eigenperiod must differ from larger period disturbances
- At high latitudes the amplitude ratio in conjugate ionospheres in general does not correspond directly to either current or voltage regimes
- Interhemispheric asymmetry of SC amplitudes at Greenland and Antarctica magnetometers corresponds qualitatively to the Alfvenic pulse model

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Abstract A circuit analogy for magnetosphere-ionosphere current systems has two extremes: the voltage generator (when the ground magnetic response is proportional to the ionospheric conductance) and the current generator (when the ground magnetic response practically does not depend on the ionospheric conductance). Nonsteady field-aligned currents interact with the ionosphere in a different way depending on the ratio between the driver time scale τ and the Alfven field line eigenperiod T_A. Sudden Commencement (SC) impulses at high latitudes correspond to the situation when $\tau \ll T_A$. This case of Alfven pulses propagating independently away from the equatorial plane is analytically examined with the magnetospheric plasma box model with thin asymmetric conjugate ionospheres. At high latitudes the amplitude ratio in conjugate ionospheres in general does not correspond directly to either the current or voltage regimes. Theoretical predictions are supported by examples of typical SC event observations at conjugate magnetometer sites in Greenland and Antarctica during summer and winter periods.

1. Introduction: Current/Voltage Dichotomy of ULF Disturbances

In models of the magnetosphere-ionosphere electrodynamic drivers it is physically intuitive to use a circuit analogy and distinguish between generators which deliver a fixed current, and those in which the voltage is fixed (Lysak, 1985). Magnetosphere-ionosphere quasi-periodic or transient current systems with time scales about 1–10 min in the ultralow frequency (ULF) band can also be described using an electrical circuit analogy as current or voltage generators (Lysak, 1990). Distinctions between those two regimes can be revealed by analyzing the dependence of the ground magnetic response on the ionospheric conductance. If the magnetospheric driving of field-aligned current (FAC) in/out the ionosphere behaves as a voltage generator, then one expects that the ionospheric current and ground magnetic field must increase upon growth of the ionosphere conductivity. In contrast, if the magnetospheric process behaves as a current generator, one expects current and magnetic field intensities to remain only weakly sensitive to the ionosphere conductivity (Lam & Rodger, 2004; Sibeck et al., 1996).

Regimes of current and voltage generators are determined by the ratio between an internal generator resistance and a load resistance. For a FAC generator, the local ionospheric resistance above an observation site plays the role of a load resistance, whereas the Alfven wave resistance and the resistance of the conjugate ionosphere play the role of an internal source resistance. Oscillatory FACs interact with the ionosphere in a different way depending on the relationship between the driver periodicity τ and the Alfven field line eigenperiod T_A. Two possible situations were examined in Pilipenko et al. (2019): a forced quasi-direct current (quasi-DC) driving of FAC ($\tau \gg T_A$), and resonant excitation of field line oscillations ($\tau \simeq T_A$). They considered a simple "plasma box" model of the magnetosphere with asymmetric conjugate ionospheres driven by an external current located at the magnetospheric equatorial plane and compared the ground magnetic response in both hemispheres. The influence of the conjugate ionosphere conductivity on the internal source resistance makes the interpretation of seasonal variations ambiguous. For example, upon a quasi-DC driving, in the high-conductive hemisphere the ground magnetic response should not depend on the local ionospheric conductivity, which corresponds to a current generator, but in the low-conductive conjugate hemisphere the ground magnetic response is expected to be proportional to the local ionospheric conductance, which corresponds to a voltage generator. Interhemispheric relationships may provide a more

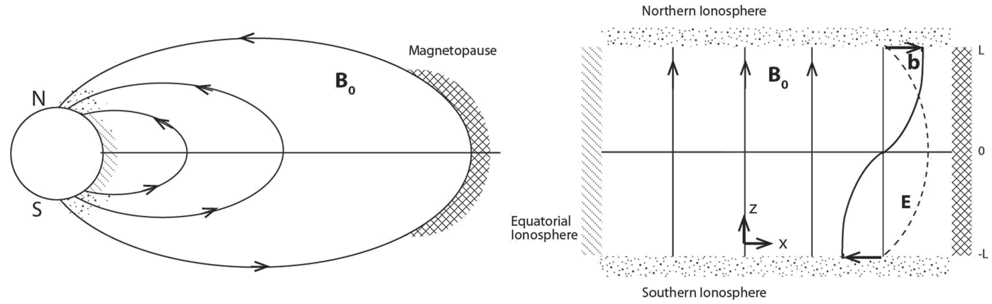

Figure 1. A sketch of the magnetospheric Alfven resonator (left-hand panel). Alfven field line oscillations in a simple "magnetospheric plasma box" model: homogeneous plasma with constant Alfven velocity V_A immersed in a straight magnetic field B_o (right-hand panel). The field lines with length $2L$ are terminated by conjugate Southern (S) and Northern (N) ionospheres. Dashed E line and solid b line denote the disturbance of fundamental field line oscillation.

definitive and straightforward conclusion. For DC-driving, the ratio between the magnetic disturbance amplitudes in conjugate points is expected to be proportional to the ratio of ionospheric conductances, that is, it corresponds to the voltage generator regime.

However, in previous consideration of the ground magnetic response in conjugate asymmetric ionospheres to magnetospheric FAC only a steady-state solution, comprising both hemispheres, was analyzed. However, there might occur impulsive disturbances at high latitudes that cannot be treated this way, because the condition may exist, when the impulse duration is less than the local field line eigenperiod, $\tau \ll T_A$. Such a disturbance is a sudden commencement (SC) pulse caused by the impact of an interplanetary shock (IS) on the magnetosphere (Nishimura et al., 2016; Pilipenko et al., 2018). Indeed, at high latitudes $T_A \simeq$5–10 min, which can be longer than an SC impulse with $\tau \simeq$1–2 min. When an SC impulse impinges on one of the ionospheres, the conjugate ionosphere does not influence this process. For an adequate treatment of such phenomena, consideration of the nonsteady problem is necessary. Here we try to consider this problem in a very simple model and compare the theoretical predictions with observational results from conjugate high-latitude stations in Antarctica and Greenland.

2. Analytical Solution for Alfvenic Pulse

We consider the plasma box model of the magnetosphere (Figure 1) that mimics the magnetosphere at middle and high latitudes. Magnetospheric straight field lines with length $2L$ are terminated by thin ionospheres with height-integrated Pedersen and Hall conductances Σ_P and Σ_H. The coordinate x corresponds to the earthward radial direction, the z axis is along the magnetospheric magnetic field $\mathbf{B}_0$, and the y axis corresponds to the azimuthal direction (the system is homogeneous in this direction).

Let at some magnetic shell a transient pulse of FAC $j_z(t)$ be excited by an external transverse current $j_x^{(e)}$. The polarization of an external current in the radial direction corresponds to an azimuthally large-scale disturbance (azimuthal component of the wave vector $k_y \rightarrow 0$). The electric field $\mathbf{E}_\perp = \{E_x, E_y\}$ of the disturbance is described by the wave equation

$$(\partial_z^2 - V_A^{-2}\partial_t^2)E_x(t,z) = \mu_0 \partial_t j_x^{(e)}(t,z) \tag{1}$$

The magnetic field disturbance $\mathbf{B} = \{B_x, B_y, B_z\}$ can be found from Maxwell's equations as $\partial_t B_y = -\partial_z E_x$. Equation (1) describes an Alfvenic type disturbance carrying a nonsteady FAC $j_z = \Sigma_A \nabla E_\perp$, where $\Sigma_A = (\mu_o V_A)^{-1}$ is the magnetospheric Alfven conductance determined by the Alfven velocity V_A. The fundamental Alfven wave period in the magnetospheric box model is $T_A = 4L/V_A$. The fundamental eigenmode of the magnetospheric Alfven resonator with highly conductive conjugate ionospheres has a field-aligned structure with an E-field antinode and a B-field node at the magnetospheric equator. In the box model the disturbed B_x components in opposite hemispheres are antiparallel, however, in a realistic geometry they are oriented in the same North-South direction (Figure 1).

The impedance-type boundary conditions at conjugate Northern (N) and Southern (S) ionospheres ($z = \mp L$) are as follows (Newton et al., 1978):

$$B_y = \mp \mu_0 \Sigma_P E_x \tag{2}$$

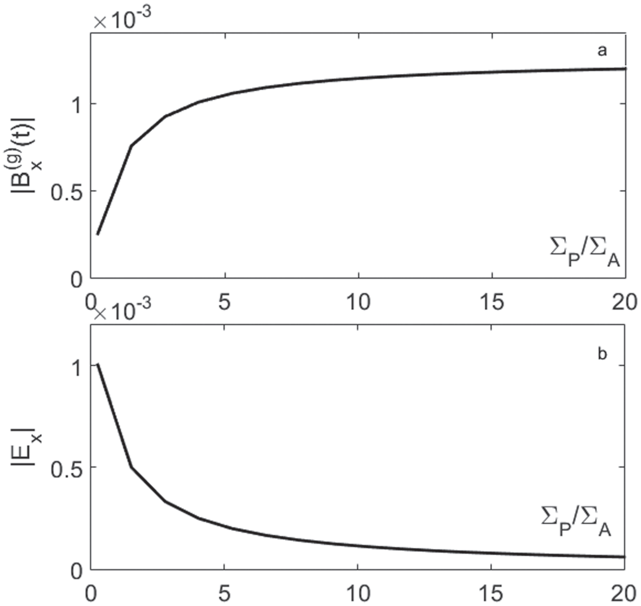

Figure 2. The amplitude of the pulse reaching the ionosphere (at $t \simeq T_A/4$) launched by a source at the magnetospheric equator: (a) ionospheric current and ground magnetic response to the impulse reaching the ionosphere, and (b) electric field, in relation to the normalized conductance Σ_P/Σ_A.

Let the driving current be localized at the magnetospheric equatorial plane ($z = 0$), namely, $j_x^{(e)}(z) = I_e(t)\delta(z)$. Integrating the basic Maxwell's equations across the region occupied by a driver, the conditions on a jump $\{...\} = ...(z = 0 + 0) - ...(z = 0 - 0)$ of transverse magnetic and electric fields can be obtained

$$\{E_x\}|_{z=0} = 0, \quad \{B_y\}|_{z=0} = -\mu_0 I_e(t). \tag{3}$$

We consider a short impulse with duration τ much less than the Alfven wave eigenperiod T_A of a field line under consideration, $\tau \ll T_A$. In this case, after excitation Alfvenic pulses start to propagate independently without attenuation toward Northern and Southern hemispheres away from the magnetospheric equatorial plane. At $t < T_A/4$ only incident (i) pulses can be seen in both hemispheres above the ionospheres. In this case they are described as follows from the wave equation (1)

$$B_y^{(i)}(t,z) = \frac{\mu_0}{2}\begin{cases} I_e(t + z/V_A) & \text{at } z < 0 \\ -I_e(t - z/V_A) & \text{at } z > 0 \end{cases}$$
$$E_x^{(i)}(t,z) = \frac{-1}{2\Sigma_A}\begin{cases} I_e(t + z/V_A) & \text{at } z < 0 \\ I_e(t - z/V_A) & \text{at } z > 0 \end{cases} \tag{4}$$

The incident pulses are reflected from the ionospheres. Their reflection coefficient R is determined by the ratio between the ionospheric Pedersen conductance and wave conductance, $\bar{\Sigma}_P = \Sigma_P/\Sigma_A$, as follows:

$$R = (\bar{\Sigma}_P - 1)/(\bar{\Sigma}_P + 1) \tag{5}$$

The Alfvenic pulses reflected (r) from the ionospheres can be presented as follows:

$$B_y^{(r)}(t,z) = \frac{\mu_0}{2}[-R^{(S)}I_e(t - \frac{z+2L}{V_A}) + R^{(N)}I_e(t + \frac{z-2L}{V_A})]$$
$$E_x^{(r)}(t,z) = -\frac{1}{2\Sigma_A}[R^{(S)}I_e(t - \frac{z+2L}{V_A}) + R^{(N)}I_e(t + \frac{z-2L}{V_A})] \tag{6}$$

We consider the structure around the ionosphere ($z \simeq \pm L$) formed by incident (4) and reflected (6) pulses. At $t < (3/2)T_A$ one can find the total field in the ionosphere (either Northern or Southern)

$$B_y(t) = \pm\frac{\mu_0}{2}(1 + R)I_e(t - L/V_A), \ \ E_x(t) = \frac{-1}{2\Sigma_A}(1 - R)I_e(t - L/V_A). \tag{7}$$

Here the upper/lower sign corresponds to z=−/+L. Substitution into these equations of R from (5) results in

$$B_y(t) = \pm\mu_0\frac{\bar{\Sigma}_P}{\bar{\Sigma}_P + 1}I_e(t - L/V_A), \ \ E_x(t) = \frac{-1}{\Sigma_A(\bar{\Sigma}_P + 1)}I_e(t - L/V_A). \tag{8}$$

Now we estimate the ground magnetic response. Using the electric field from (8) the magnetic disturbance $B_g \equiv B_x$ on the Earth's surface produced by the large-scale ($kh \ll 1$, k is the spatial harmonic wave number) Hall current $J_y = -\Sigma_H E_x$ at altitude h is as follows:

$$B_g = \pm\mu_0\frac{\bar{\Sigma}_H}{\bar{\Sigma}_P + 1}I_e(t - L/V_A) \tag{9}$$

where $\bar{\Sigma}_H = \Sigma_H/\Sigma_A$. Figure 2 shows the dependence on the normalized conductance $\bar{\Sigma}_P$ of the ionospheric current and ground magnetic (upper panel) and electric (bottom panel) field responses to the magnetospheric Alfvenic pulse. In respect to the magnitude of the ionospheric conductance, the dependence of the ground response changes from a voltage generator regime (nearly linear growth with $\bar{\Sigma}_P$) to a current regime (weak dependence on $\bar{\Sigma}_P$).

From the relationship (9) the following predictions stem for the seasonal variation. Under a low-conductive ionosphere (e.g., a nightside station), when $\overline{\Sigma}_P \ll 1$, upon the growth of the conductance the ionospheric current and ground magnetic response must linearly increase (i.e., the voltage generator regime) $B_g \propto \Sigma_H/\Sigma_A$. At the same time, under a highly conductive ionosphere (e.g., a dayside station), when $\overline{\Sigma}_P \gg 1$, the ionospheric current and ground magnetic response must change weakly upon increase of conductivity (i.e., the current generator regime), $B_g \propto \Sigma_H/\Sigma_P$. Note that the Alfven conductance is usually assumed constant throughout the magnetosphere, $\Sigma_A^{(N)} \simeq \Sigma_A^{(S)} \simeq 1$ S.

Let us compare the ground magnetic response in the Northern and Southern Hemispheres. From (9) it follows that in the box-model coordinates

$$\frac{B_g^{(N)}}{B_g^{(S)}} = -\frac{\bar{\Sigma}_H^{(N)}}{\bar{\Sigma}_H^{(S)}}\frac{\bar{\Sigma}_P^{(S)}+1}{\bar{\Sigma}_P^{(N)}+1} \tag{10}$$

In general, this relationship does not correspond directly to either the current or voltage regimes. Only in a special case, for example, when $\bar{\Sigma}^{(N)} \simeq \bar{\Sigma}^{(S)} \gg 1$, the ratio (10) does not depend on conductivity $B_g^{(N)}/B_g^{(S)} \simeq (\bar{\Sigma}_H^{(N)}/\bar{\Sigma}_P^{(N)})(\bar{\Sigma}_P^{(S)}/\bar{\Sigma}_H^{(S)})$; that is, it corresponds to the current generator regime.

3. Comparison of Theoretical Predictions With Results of Low-Latitude Observations of SCs

The current/voltage generator paradigm was regularly tested with observations at conjugate points or with examination of seasonal effects for different types of ULF transients and waves: traveling convection vortices (TCV; Lam & Rodger, 2004), and Pc3-5 waves (Obana et al., 2005). Similar studies were conducted for SC/SI events. Here we compare the published results of conjugate observations of SCs conducted at low latitudes with the above theoretical predictions.

An SC is a complicated large-scale transient response of the magnetosphere-ionosphere system to an interplanetary shock. It consists of a magnetic field compression transported to the ground by a fast compressional mode wave and a global vortex-like disturbance produced by a FAC system at the magnetopause. The SC-associated compression of the magnetosphere can excite damped Psc5 pulsations in the magnetosphere localized at a latitudinally narrow resonant magnetic shell where $\tau \simeq T_A$ (Samsonov et al., 2011). Beyond this narrow region, no periodic resonant response to SC pulse is observed. Thus, the SC main impulse is a transient FAC stimulated by an interplanetary shock and predominantly it corresponds either to the condition $\tau \gg T_A$ (at low latitudes, where $T_A < 1$ min) or $\tau \ll T_A$ (at high latitudes, where $T_A \simeq$ 5–10 min). Formally, low-latitude observations are to be treated as an example of a quasi-DC excitation.

Studies at low latitudes revealed an interhemispheric difference in SC: their amplitude was significantly larger in the summer hemisphere than in the winter one (Yumoto et al., 1996). Shinbori et al. (2012) examined the seasonal variations of the SC main impulse and suggested that it is intensified by increased ionospheric conductivity during the summer. The size of the diurnal variation tended to increase significantly during the summer, compared with that during the winter. Judging from the seasonal and interhemispheric variations of SCs at low-latitudes, it may be concluded that the SC in this region is caused by a voltage generator rather than a current generator. Thus, the observed strong dependence on conductance corresponds to the regime of a voltage generator, natural for a nonresonant quasi-DC disturbance (Pilipenko et al., 2019).

However, in contrast to low latitudes, for an SC pulse at high latitudes the inverse condition exists, when the impulse duration $\tau \ll T_A$. Examples of such events recorded at Antarctica and Greenland are considered here from the view of the current/voltage dichotomy.

4. Conjugate SC Pulses at High Latitudes

To present examples of typical SC at high latitudes, we use data from the Antarctica-Greenland conjugate magnetometer arrays. Virginia Tech (http://mist.nianet.org) deployed a ground network equipped with an autonomous adaptive low-power instrument platform (AAL-PIP) with a sampling cadence of 1 s in Antarctica, magnetically conjugate to the Greenland West coastal magnetometer chain along the Λ ~40° magnetic meridian.

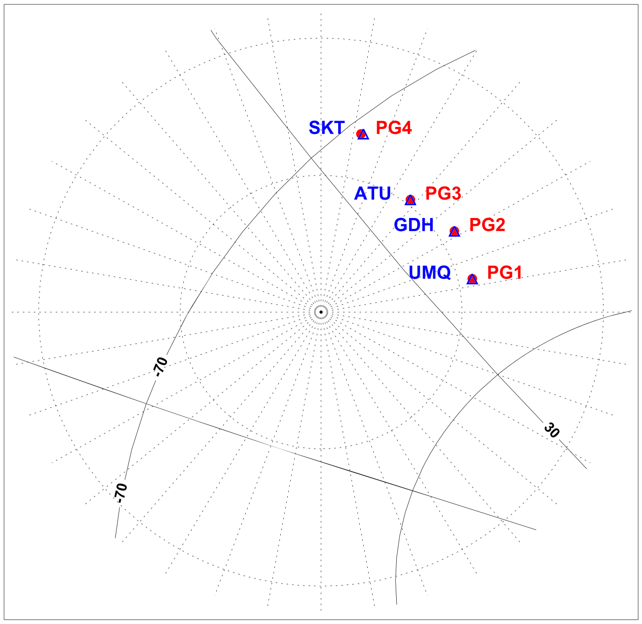

Figure 3. Map of Antarctica with locations of AAL-PIP stations and conjugate points of West Coastal Greenland Array stations. Geomagnetic and geographic coordinates are shown with solid and dashed lines.

The Greenland Coastal Array operated by the Technical University of Denmark (https://www.space.dtu.dk) is equipped with three-axes linear-core fluxgate magnetometers which run fully automatically and are optimized for long-term stability. Ten-second data are available for the period under study. The sensor axes of both AAL-PIP and Greenland stations are oriented along local magnetic north ($H \equiv B_x$), local magnetic east ($E \equiv B_y$) and vertical down (Z).

Figure 3 shows the locations in Antarctica of the selected AAL-PIP stations and the geomagnetic conjugate points of their counterparts in Greenland, and Table 1 gives their coordinates.

We have selected SC events on a quiet background during summer and winter. We have determined from conjugate station data the ratio between amplitudes of conjugate pulses $B_x^{(N)}/B_x^{(S)}$ at conjugate pairs of stations.

The different position of the north and south magnetic poles with respect to the Earth rotation axis creates a hemispheric asymmetric solar illumination of the northern and southern high-latitude zones. Because of the substantial shift of geographic and geomagnetic poles, the ionospheric properties in conjugate points are hard to predict. Because of the lack of direct information about the ionospheric conductivities, one has to use information from statistical empirical models. Here, the height-integrated (80–1,000 km) ionosphertic conductivities have been estimated using the online resource of Kyoto University (http://wdc.kugi.kyoto-u.ac.jp/ionocond/sigcal), based on the IRI-2016 model (Bilitza & Reinisch, 2008). The energetic electron precipitation, not accounted for in the IRI model, can modify the actual ionospheric conductance, especially in the region of the auroral oval. To avoid the ambiguity caused by the auroral electron precipitation, for the events under consideration we have checked the relative position of our stations and the auroral diffuse precipitation caused by energetic (0.1–30 keV) electrons predicted by the OVATION-prime (OP) model (Newell et al., 2014). The OP model is an auroral precipitation model parameterized by solar wind driving, developed using energetic particle measurements from the low-orbiting Defense Meteorological Satellite Program satellite. A SC impulse can trigger sporadic precipitation of energetic electrons (Rosenberg et al., 1980) and soft electrons (Pilipenko et al., 2018), which may locally modify ionospheric conductance and the upper ionosphere density, consequently. However, these observations have shown that such precipitation is not strong enough to modify considerably the dayside ionospheric global parameters.

There is an additional factor that may obscure the observed relationship between the ground magnetic response and the ionospheric conductance, which should be taken into account. Though the model considered here is homogeneous, in reality the plasma distribution along a field line is inhomogeneous: the plasma density N_e in the upper ionosphere at the sunlit end of a field line probably should be higher than at

Table 1
*VITMO Model (*https://omniweb.gsfc.nasa.gov/vitmo/cgm_vitmo.html*) for Epoch 2015*

Station code	Geo. Lat	Geo. Long.	CGM Lat.	CGM Long.	Conjugate Geo. Lat.	Conjugate Geo. Long.
PG1	−84.50	77.20	−77.26	37.33		
UMQ	78.45	38.12	70.68	307.87	−84.50	77.20
PG2	−84.42	57.95	−75.53	39.05		
GDH	69.25	306.47	74.69	37.72	−84.42	57.96
PG3	−84.81	37.63	−73.43	35.95		
ATU	67.93	306.43	69.25	306.47	−84.81	37.63
PG4	−83.34	12.25	−71.08	36.13		
SKT	65.42	307.10	70.77	36.24	−83.32	12.97

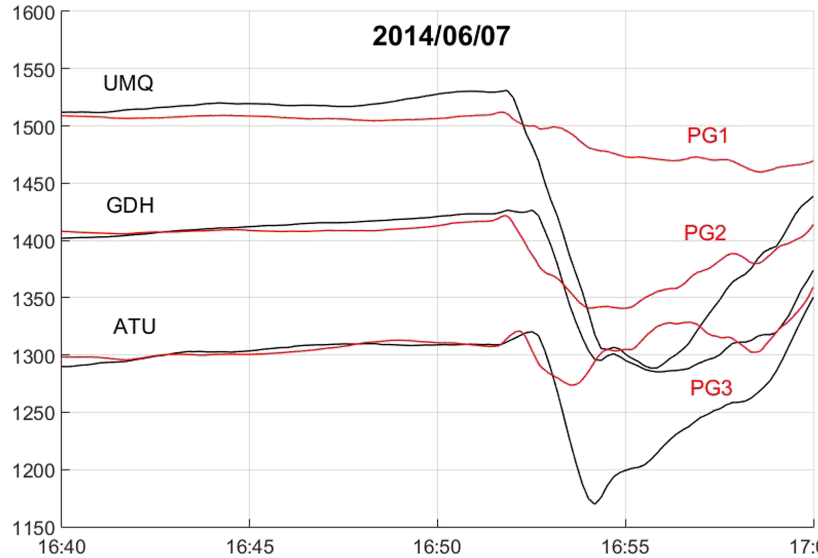

Figure 4. Magnetograms from Antarctic and Greenland conjugate pairs of stations during a Northern summer SC event that occurred on 7 June 2014, 17 UT.

the dark end. As a result, the Alfven wave conductance, $\Sigma_A \propto \sqrt{N_e}$, must be higher at the sunlit end. Thus, the contrast in the ratio Σ_P/Σ_A, which determines the reflection condition and ground response, is to be less distinct between (N) and (S) ionospheres. Here, as a proxy of plasma density in the upper ionosphere N_e the total electron content (TEC) maps from GPS receivers has been used (http://vt.superdarn.org).

We compare magnetic records from conjugate pairs of stations where SC pulses are most intense and evident in Antarctica and Greenland: UMQ-PG1, GDH-PG2, ATU-PG3, and SKT-PG4. The magnetospheric Alfven conductance is supposed not to differ considerably throughout the magnetosphere, $\Sigma_A^{(N)} \simeq \Sigma_A^{(S)} \simeq 1$ S.

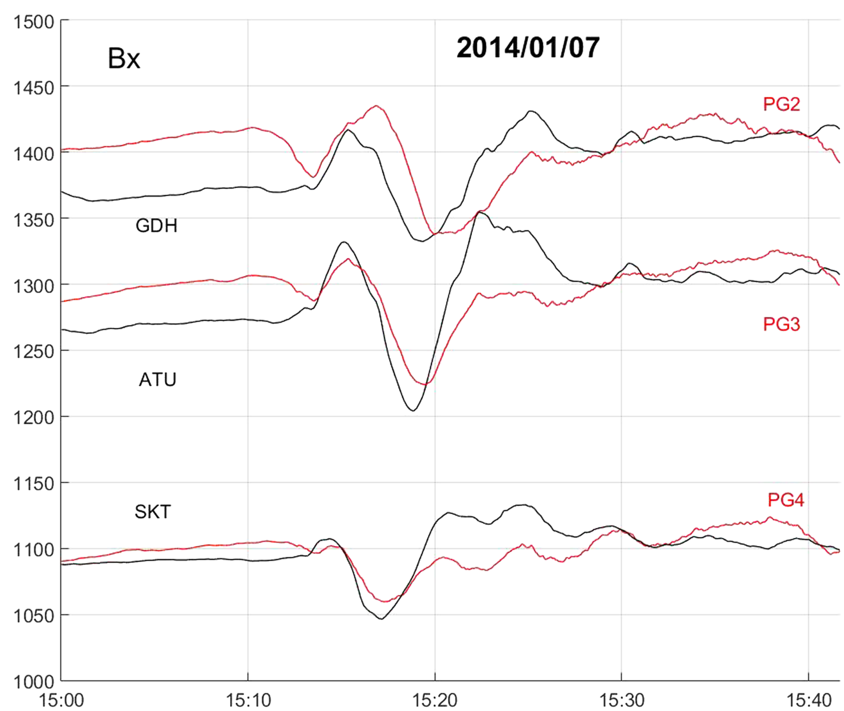

Figure 5. Magnetograms from Antarctic and Greenland conjugate pairs of stations during on Northern winter SC event occurred on 7 January 2014, 15 UT.

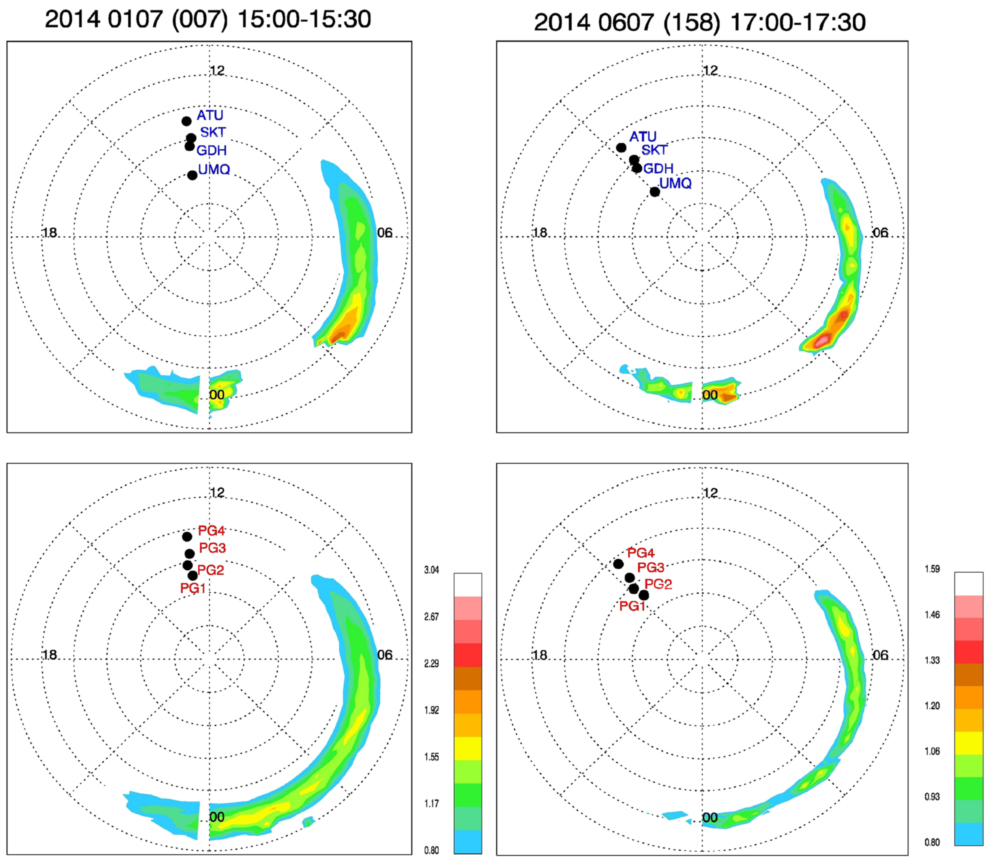

Figure 6. The location of Greenland (blue codes) and Antarctic (red codes) stations and diffuse auroral oval derived from the OP model during the SC events that occurred on 7 January 2014, 15 UT (left-hand panel) and on 7 June 2014, 17 UT (right-hand panel).

4.1. Northern Summer Event

First, we consider the typical Northern summer event on 7 June 2014, 17 UT (Figure 4). For the central PG3 station in Southern Hemisphere the ionospheric conductances estimated with the use of IRI-2016 model are as follows: $\Sigma_P^{(S)} \simeq 0.2$ S and $\Sigma_H^{(S)} \simeq 0.2$ S. For the conjugate station ATU in the Northern Hemisphere the ionospheric conductances are as follows: $\Sigma_P^{(N)} \simeq 6.8$ S and $\Sigma_H^{(N)} \simeq 8.8$ S. Therefore, it is reasonable to assume that $\bar{\Sigma}_P^{(N)} \gg 1$ and $\bar{\Sigma}_P^{(S)} \ll 1$. According to the SuperDARN TEC maps, for the 7 June 2014 event (1650–1655 UT), the TEC in Northern Hemisphere is around 15 TECu, while in the Southern Hemisphere it is below 5 TECu. Then, (10) gives us

$$\frac{B_g^{(N)}}{B_g^{(S)}} = \frac{\bar{\Sigma}_H^{(N)}}{\bar{\Sigma}_H^{(S)}} \frac{1}{\bar{\Sigma}_P^{(N)}} \simeq 6.5 \tag{11}$$

The asymmetry of $\Sigma_A^{(N)}/\Sigma_A^{(S)} \simeq \sqrt{TEC^{(N)}/TEC^{(S)}} \simeq 1.7$ decreases this estimate down to ~ 3.8. This prediction matches surprisingly well the observed ratio between magnetic responses in conjugate ionospheres: for the ATU-PG3 pair the ratio is ~ 3.8.

4.2. Northern Winter Event

As another typical situation, let us consider the Northern winter event that occurred on 7 January 2014, 15 UT (Figure 5). For the central PG3 station in the Southern Hemisphere $\Sigma_P^{(S)} \simeq 5.0$ S and $\Sigma_H^{(S)} \simeq 6.0$ S. For the conjugate station ATU in the Northern hemisphere $\Sigma_P^{(N)} \simeq 2.4$ S, and $\Sigma_H^{(N)} \simeq 2.1$ S. In this event, the contrast between the Northern and Southern conductances is not so strong. For the 7 January 2014 event (1520–1525 UT), based on very sparse observations in Greenland and Antarctica, TEC in the Northern Hemisphere is $\sim$12 TECu, while in the Southern Hemisphere TEC is $\sim$15 TECu. Then, (10) gives us

$$\frac{B_g^{(N)}}{B_g^{(S)}} = \frac{\bar{\Sigma}_H^{(N)}}{\bar{\Sigma}_H^{(S)}} \frac{\bar{\Sigma}_P^{(S)}}{\bar{\Sigma}_P^{(N)} + 1} \simeq 0.5 \tag{12}$$

The correction for the asymmetry of $\Sigma_A^{(N)}/\Sigma_A^{(S)} \simeq \sqrt{TEC^{(N)}/TEC^{(S)}} \simeq 0.9$ does not modify this estimate noticeably. Thus, the model predicts that by the order of magnitude the amplitudes of pulses in conjugate ionospheres are to be about the same. The observed amplitudes of the SC pulse at station pairs GDH-PG2, ATU-PG3, and SKT-PG4 are indeed about the same within 15%.

For both events we have checked the relative position of the diffuse auroral oval with the use of the OP model of the auroral particle precipitation (http://sd-www.jhuapl.edu/Aurora/ovation/) and location of stations. As evident from Figure 6, the stations during events under consideration were situated far from the auroral electron precipitation regions, so the particle precipitation does not modify the ionospheric conductance.

5. Discussion

The considered simple plasma box model can provide only qualitative predictions. Despite the simplicity of the model, the resulting theoretical conclusions have provided a qualitatively correct explanation of the interhemispheric properties of SC pulses. For example, the conception of an Alfvenic pulse oscillating between conjugate ionospheres was previously used to interpret Pi2 pulsation observations (Maltsev et al., 1974). Besides the model deficiency, a comparison of SC responses in conjugate points has additional complications that will be discussed further.

A TCV pulse can be mistaken for a bi-polar SC pulse. The difference between them becomes evident at near-equatorial stations: A global SC is clearly evident at near-equatorial stations, whereas localized TCV is absent. The two events described in the previous section are indeed SC events based on inspection of low-latitude stations.

There are a few additional factors that may obscure the observed relationship between the ground magnetic response and the ionospheric conductance (Hartinger et al., 2017). The primary deficiency is the lack of direct information about the ionospheric conductivities, which require us to use information from the statistical IRI model (Bilitza & Reinisch, 2008). Another issue is that though the model considered here is homogeneous, in reality the plasma distribution along a field line is inhomogeneous. This factor can modify somewhat the reflection coefficient, because it is determined not by the ionospheric conductance but by the contrast between the ionospheric and Alfven conductance $\Sigma_A \propto \sqrt{N_e}$. This may partly equalize the ground response in conjugate ionospheres. As a proxy of N_e in the upper ionosphere we have used TEC data. However, to take into account adequately an inhomogeneous plasma and magnetic field distribution along a field line a numerical modeling of Alfvenic pulse propagation is necessary.

The energetic electron precipitation, not accounted for by the IRI model, tends to reduce hemispheric conductivity asymmetries produced by solar illumination. A typical ratio of summer to winter conductivities outside the auroral oval is more than an order of magnitude, whereas inside the oval it can be roughly just a factor of 2. A special examination with the OP model of the auroral particle precipitation has shown that both SC events occur in the dayside ionosphere, far from the auroral oval. Therefore, these factors will not change the basic results of the SC amplitude comparison in conjugate ionospheres.

Another complication is related to the asymmetry of the initial impact of the shock (Oliveira & Raeder, 2014). For standing mode excitation the position of a driver with respect to a node of a standing mode might be important. However, for an impulsive disturbance, such as an SC, the location of the driver with respect to the ionospheres is likely not significant, because we expect the impulse attenuation upon field-aligned propagation can be neglected. In the two present cases, the shock hit at a ∼45° angle with respect to the magnetic equator, which is a typical situation. We suppose that shock inclination should not have a significant effect on the amplitude of the initial high-latitude ground magnetic response, but it may result in a time difference between SC impulse onsets in opposite hemispheres. The SC signatures presented here are nearly in-phase at conjugate stations, which indicates nearly simultaneous arrival of Alfvenic pulses.

Here we have presented two typical events under contrasting seasonal conditions. Surely, an extensive statistical study is necessary to verify the predictions of the theoretical model developed here. The theoretical model itself is very simple, and its conclusions should be validated with more advanced magnetohydrodynamics (MHD) modeling. In turn, this work suggests that global MHD simulations seeking to predict ground magnetic perturbations should accurately specify not just the ionospheric conductivity but also the driver time scale τ and field line eigenperiod, T_A. As we have shown, the relationship between these parameters determines how the ground magnetic perturbation depends on the ionospheric conductivity. Even if a global

MHD simulation accurately specifies the ionospheric conductivity, it will inaccurately predict the ground magnetic response if these two parameters are not specified correctly.

6. Conclusion

The conclusions made here are valid for a short pulse when a conjugate ionosphere does not influence the pulse interaction with the ionosphere of interest. The presented study completes together with Pilipenko et al. (2019) the consideration of ULF wave and transient interactions with the ionosphere and its dependence on the ionospheric conductance from the view of the current-voltage dichotomy. At low latitudes, the SC can be considered as driven by a quasi-DC source, and its properties must correspond to the voltage generator regime. At high latitudes, the SC pulse amplitude in the general case does not correspond either to the current or voltage generator. Even the simplified model presented here indicates that besides the ionospheric conductances there are several additional factors that should be taken into account to resolve the current-voltage dichotomy: the driver duration, eigenperiod of Alfven field line oscillations, and plasma distribution along a field line.

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