September 1999 SI events: Ionospheric response in different MLT sectors

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Abstract

We studied three sudden impulse (SI) events that took place in September 1999 during the International Space Weather Campaign. The three SIs occurred on 15^{th}, 12^{th} and 22^{nd} at 2019, 0400 and 1220 UT, respectively. Clear shocks were observed in the solar wind by ACE, WIND, IMP-8 and GEOTAIL. SuperDARN, Scandinavian Twin Auroral Radar Experiment (STARE) and several magnetometer chains in different magnetic local time sectors were used to monitor ionospheric processes. During the first two events the IMF B_z was positive or weakly negative and only minor ionospheric effects were recorded. During the last event when the IMF B_z turned from positive to negative at the shock front, our instrumentation observed a clear ionospheric response. Propagation and intensification of the pulse was recorded by the dayside magnetometers. Both SuperDARN and STARE lost the signal, which was due to a decrease in the E-field below the threshold value as a consequence of enhanced precipitation. Magnetometers measured Pc 5 type pulsations after the SI, and variations with the same period were present also in the STARE signal-to-noise ratio (SNR).

1 Introduction and data description

Three sudden impulse (SI) events were observed in September 1999 during the International Space Weather Campaign. SIs took place on 15^{th}, 12^{th} and 22^{nd} at 2019, 0400 and 1220 UT according to the ground-based magnetometers.

Solar wind parameters were measured by ACE, WIND, IMP-8 and GEOTAIL. For all three SIs the satellites recorded a shock: a sudden increase in pressure, proton number density, proton temperature, bulk velocity and the total magnitude of IMF.

In this study we used four magnetometer chains operating in the northern hemisphere: IMAGE (Scandinavia), CANOPUS (Canada), GIMA (Alaska) and the

Greenland chain. The sampling rates of the chains are the following: 10s for IMAGE, 5s for CANOPUS, 2s for GIMA and 20s for Greenland. We also used the provisional Dst-index to monitor the activity before and after the SI.

CANOPUS photometer data were available for one event (Sep 12), while the other two events occurred during daylight in Canada. The operating season of the Scandinavian all-sky cameras (*Syrjäsuo et al.* [1998]) had not started yet in September 1999. The whole SuperDARN network was naturally operating during the campaign and running the common mode program (time resolution 2 minutes).

The Scandinavian Twin Auroral Radar Experiment (STARE) consists of two coherent radar stations located in Midtsandan (10.7°E, 63.4°N) in Norway, and in Hankasalmi (26.9°E, 62.3°N) in Finland. The common field-of-view (FOV) of the radars extends roughly from 68°N to 72°N in latitude and from 15°E to 25°E in longitude and covers a geographic area of about 200000 km^2 in the E-region. The radars operate at frequencies 140 MHz and 143.8 MHz, respectively, and are sensitive to E-region irregularities of the scale size of about one meter. The spatial and the temporal resolutions of STARE are about 20 km$\times$20 km and 20 seconds, respectively (*Greenwald et al.* [1978]). STARE data were available for the last event (Sep 22).

In the following sections we describe each SI event separately starting from the solar wind conditions followed by the most important features observed by the ground-based magnetometers and coherent radars.

2 Observations

2.1 Sep 15

In Sep 15 the shock in the solar wind was recorded by ACE (GSE X$\sim$239 R_E, Y$\sim$-32 R_E, Z$\sim$19 R_E), WIND (GSE X$\sim$70 R_E, Y$\sim$-35 R_E, Z$\sim$-3 R_E) and GEOTAIL (GSE X$\sim$0 R_E, Y$\sim$12 R_E, Z$\sim$2 R_E). GEOTAIL was inside the magnetopause and it observed the shock simultaneously with the first magnetometers on the ground, at 2019 UT. According to ACE and WIND the IMF B_z and B_y were both positive on both sides of the shock front but there was a clear increase in the IMF magnitude of about 5 nT.

The Dst-index was increased from -13 nT at 2000 UT to -3 nT at 2100 UT. At the SI time IMAGE was located near magnetic midnight, the Greenland chain around 18 MLT, CANOPUS close to midday and GIMA at about 9 MLT. Both the first and the last SI observation were measured by the Greenland East chain with a time difference of 1 min 47 secs. The STARE and SuperDARN radars measured initially very little backscatter, which did not allow us to draw any conclusions about the scattering conditions.

2.2 Sep 12

ACE (GSE X$\sim$242 $\mathrm{R_E}$, Y$\sim$-32 $\mathrm{R_E}$, Z$\sim$17 $\mathrm{R_E}$), WIND (GSE X$\sim$33 $\mathrm{R_E}$, Y$\sim$-38 $\mathrm{R_E}$, Z$\sim$-4 $\mathrm{R_E}$) , IMP-8 (GSE X$\sim$30 $\mathrm{R_E}$, Y$\sim$-16 $\mathrm{R_E}$, Z$\sim$-25 $\mathrm{R_E}$) and GEOTAIL (GSE X$\sim$13 $\mathrm{R_E}$, Y$\sim$-20 $\mathrm{R_E}$, Z$\sim$-3 $\mathrm{R_E}$) measured a shock shortly after UT–midnight on September 12^{th}. All the satellites were located in the solar wind. The position of WIND and GEOTAIL was very close to the magnetopause and they observed the shock front only a couple of minutes before the first ground-based magnetometers reacted (before 0400 UT). In this case the IMF B_z was weakly negative but peaked to more negative values at the shock front. The IMF B_y decreased to more negative values, too, after the passage of the shock, and the increase in the total IMF was about 6 nT.

The ionospheric Dst-index increased by 22 nT during an hour from the initial value of -4 nT at 0400 UT. At the SI time IMAGE was around 6 MLT, Greenland in the post-midnight sector, CANOPUS in the pre-midnight sector and GIMA around 17 MLT. Poker station in GIMA recorded the SI signature first, 1 min and 23 secs before the last observation by Rankin Inlet in CANOPUS. Again, the time difference was so small that no systematic propagation effect was detectable.

The magnetogram from Gillam station in CANOPUS showed a negative bay of about 130 nT in the ground B_x starting at 0400 UT, i.e. at about 2130 MLT. The magnetometers at the stations next to Gillam hardly reacted. However, the preliminary data from the MPA scanning photometer at Gillam recorded structured emission in both green (557.7 nm) and red (630.0 nm) lines starting from the impulse at 0400 UT. Also the hydrogen line (486.1 nm) emission strengthened remarkably.

Again, STARE and SuperDARN radars measured initially so little backscatter that no SI effect could be seen in those data.

2.3 Sep 22

All the four satellites measured a shock on September 22^{nd} (ACE at GSE X$\sim$235 $\mathrm{R_E}$, Y$\sim$-37 $\mathrm{R_E}$, Z$\sim$12 $\mathrm{R_E}$ and WIND at GSE X$\sim$83 $\mathrm{R_E}$, Y$\sim$-8 $\mathrm{R_E}$, Z$\sim$1 $\mathrm{R_E}$). This time GEOTAIL (GSE X$\sim$9 $\mathrm{R_E}$, Y$\sim$-22 $\mathrm{R_E}$, Z$\sim$-3 $\mathrm{R_E}$) and IMP-8 (GSE X$\sim$-8 $\mathrm{R_E}$, Y$\sim$-34 $\mathrm{R_E}$, Z$\sim$-23 $\mathrm{R_E}$) were close to the magnetopause observing the shock one minute before and one minute after the first magnetometers on the ground (1220 UT). At the shock front the IMF B_z dropped from about +10 nT to -15 nT and stayed negative for almost 5 minutes. The IMF B_y was negative as well decreasing somewhat after the shock and the increase in the IMF magnitude was about 10 nT.

The Dst changed from about -5 nT at 1200 UT to about 18 nT at 1300 UT. During this SI, IMAGE was located near 15 MLT, Greenland around midday and CANOPUS and GIMA in the post-midnight sector. The magnetometer that measured this SI first was Brorfelde, the Greenland chain station in Denmark. Brorfelde locates at lower latitudes than any other station we used, and at the SI time, 1220 UT, it was on the dayside at about 13 MLT. The latest pulse observation was recorded by Gakova station in GIMA ($\sim$ 0130 MLT), 4 minutes and 22 seconds later. This time delay is almost twice as long as in the two previous cases.

A more detailed study revealed two correlations. Including only the (36) magnetometers on the dayside we found a correlation between the corrected geomagnetic latitude (CGMLAT) of the magnetometer station and the SI observation time at the same station, with a correlation coefficient of 0.71 (Figure 1). In addition, there was a correlation between the SI related pulse peak-to-peak amplitude (nT) and the observation time, with the correlation coefficient of 0.72 (Figure 2). In the latter analysis we took into account only the clearest pulses on the dayside (30 altogether).

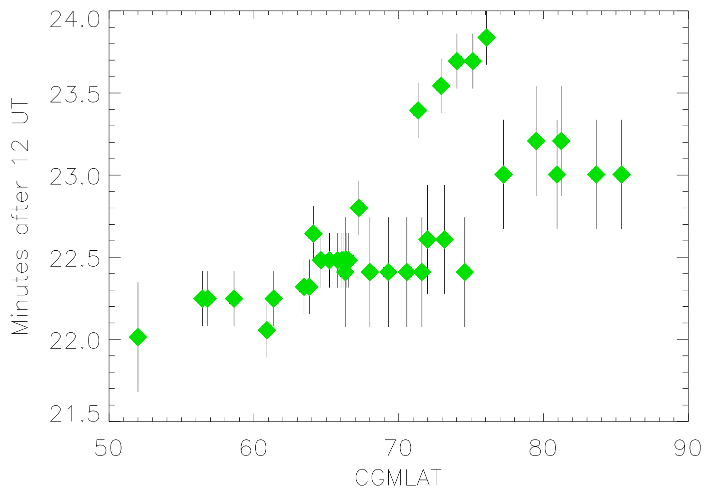

Figure 1: SI observation time versus corrected geomagnetic latitude (CGMLAT) of the magnetometer station. Length of the error bras is twice the sampling interval of the data. Correlation coefficient between these parameters 0.71 .

Northern hemispheric SuperDARN radars detected a strong decrease in backscattered power 4 minutes after the SI (see Figure 3). After another 4 minutes the signal strengthened again almost to its initial level. The same effect was found also in the signal-to-noise ratio (SNR) of the STARE radar, especially in the recordings of the Norwegian radar which looks more parallel to the ionospheric convection. Three minutes after the SI the radar began to lose the echo (see Figure 4), first from lower

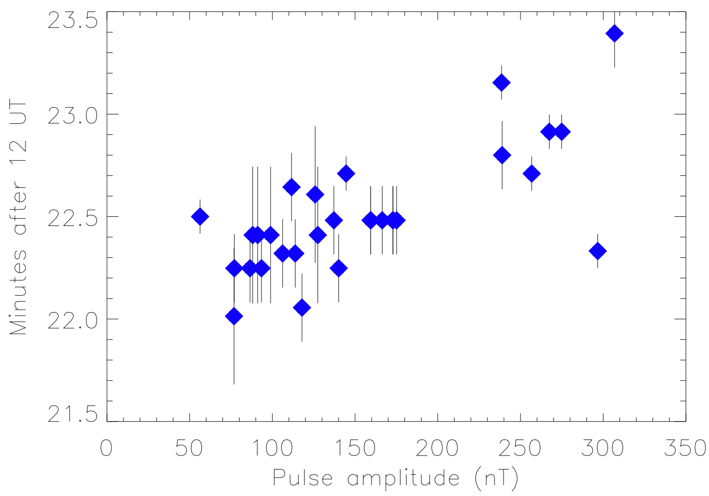

Figure 2: SI observation time as a function of the pulse amplitude (nT). Correlation coefficient of the data is 0.72 and the length of the error bars is twice the sampling interval.

latitude ranges (68–70°), and one minute later also from the northern edge ($\sim 72°$) of the FOV.

In Figure 5 we compare the sum of SNR at latitudes 69°, 70° and 71° to the B_x from the Sørøya magnetometer station (located in the central region of the STARE FOV). The sum was calculated over all longitudes (from 15° to 25°) and one minute in time. The SI related pulse as well as the pulsations after it were recorded both by the magnetometer (upper panel) and the radar (lower panel). Some longer period ($\sim$10 minutes) fluctuations were also measured by the CUTLASS Iceland radar in the beams north of the STARE FOV (between 73° and 75°).

The decrease in the backscattered signal power is seen 4 minutes after the SI in CUTLASS Iceland's beam 8 (Figure 6). But this effect is even clearer in the SuperDARN parameter plot, in Figure 3, where all the northern radars are included.

3 Summary and conclusions

We studied three SI events, on 15th (IMF $B_z > 0$), 12th (IMF B_z weakly < 0) and 22nd (IMF B_z strongly < 0) in September 1999, which occurred at 2019, 0400 and 1220 UT respectively. We used ACE, WIND, IMP-8 and GEOTAIL to identify the shock in the solar wind, and ground-based magnetometers and coherent radars to

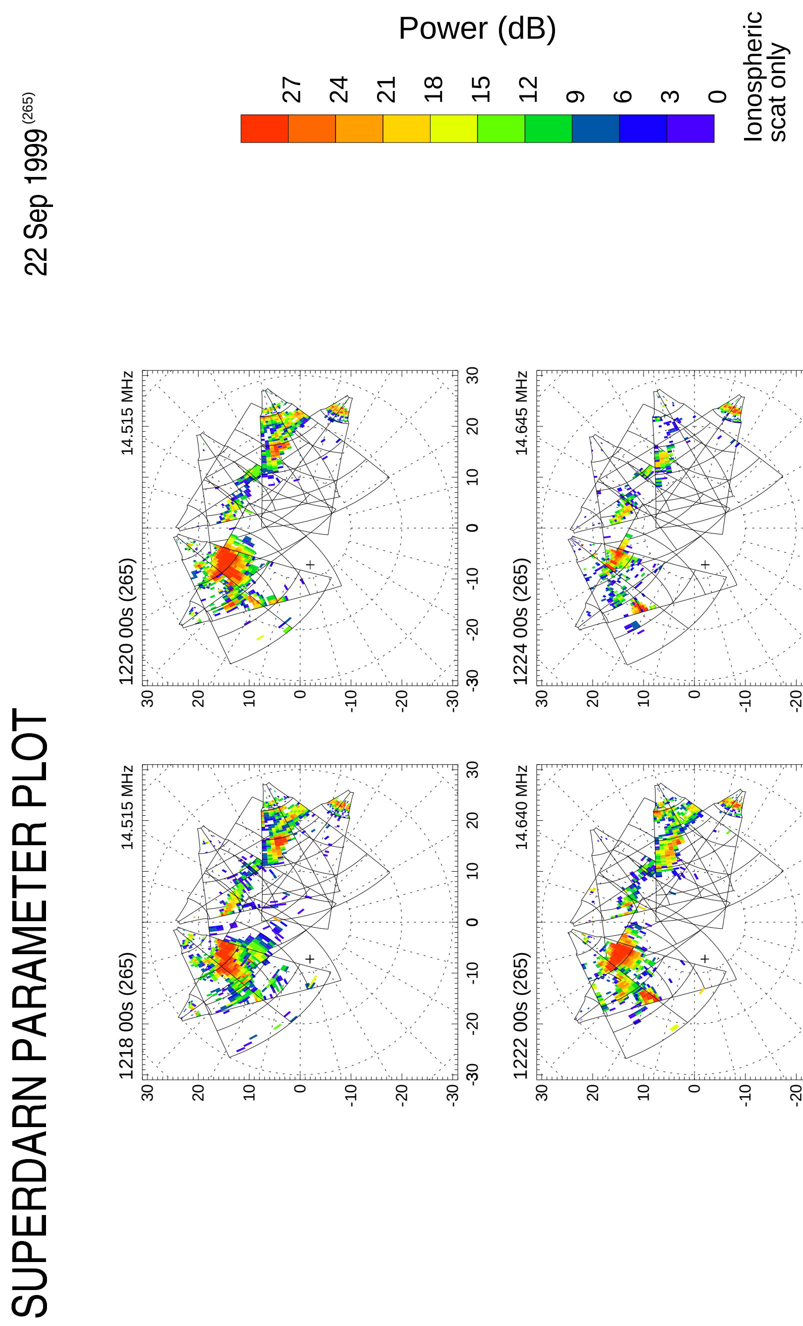

Figure 3: Power from the northern hemispheric SuperDARN radars. Plots from two minutes before (top left), at the SI time (top right), two minutes after (bottom left) and four minutes after (bottom right).

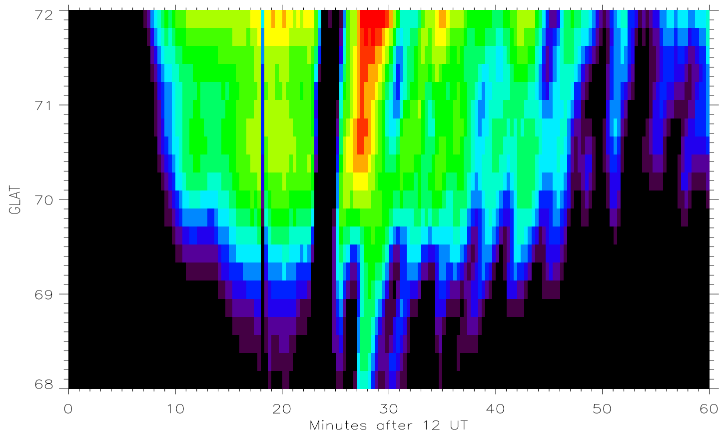

Figure 4: Signal-to-noise ratio from the STARE Norway radar as a function of geographic latitude and time in minutes after 12 UT.

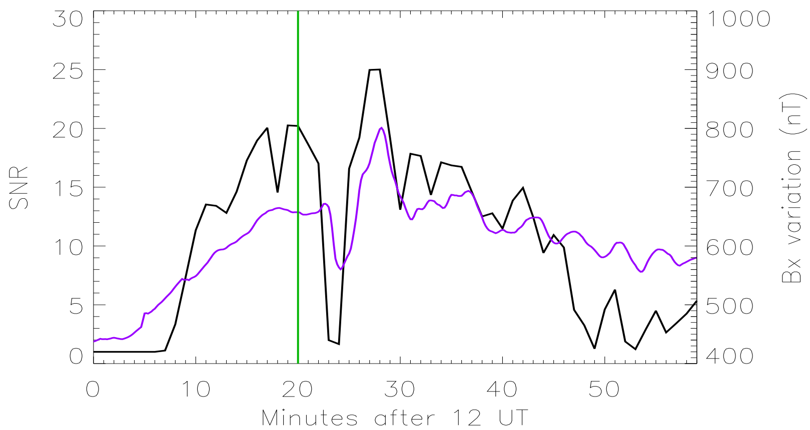

Figure 5: B_x variation at Sørøya station (purple) and summed SNR from the STARE Norway radar (black) around SI observation time, 1220 UT (green vertical line).

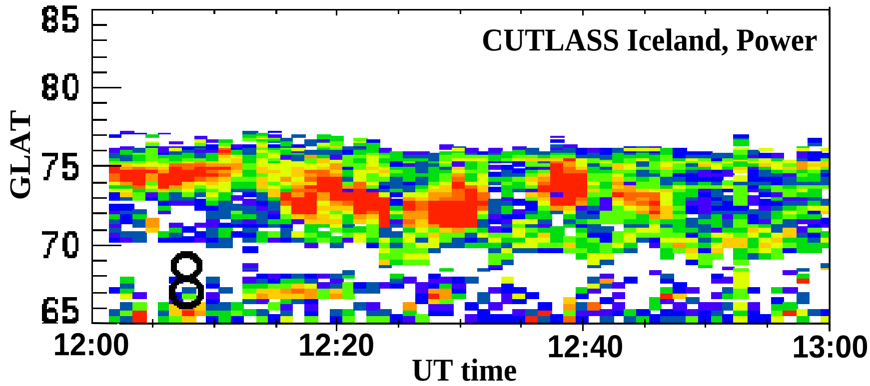

Figure 6: Periodic fluctuations in power from the beam 8 of the CUTLASS Iceland radar.

investigate the ionospheric response.

The ionospheric effects, depending on the IMF B_z (and IMF B_y) condition, were different: the stronger negative B_z the more pronounced effects in ground-based data. During the first two events minor responses were observed while in the last case the radars lost the signal for about 5 minutes and the strong pulse in B_x was clearly delayed and strengthened from lower to higher latitudes. IMAGE recorded some magnetic pulsations after each of the three SIs.

The pressure pulse at the magnetopause changes the location of the magnetopause currents, which immediately (with the speed of light) contributes to the variation of the ground magnetic field. Furthermore, the IMF B_z positive case (Sep 15) gives a pure compression of the magnetosphere which propagates rapidly as a magnetosonic wave through the whole ionosphere. Thus, there are no remarkable delays in the response. The IMF B_z slightly negative (Sep 12) causes a pseudo-breakup or a small substorm (seen at Gillam) when a small amount of solar wind energy enters the magnetosphere. Finally, when the IMF B_z is strongly negative (Sep 22) the solar wind energy has a free access to the magnetosphere. Thus, in addition to the compression which takes immediate effect, there is an Alfvén wave travelling to the ionosphere along the field lines. Different travel times of the Alfvén waves along the field lines with different lengths cause the time delay towards higher latitudes. A significant delay from dayside to nightside was also measured. In addition to these two delays we observed the growth of the pulse with an increasing time delay. Thus, the observed pulse grows towards the higher latitudes, which indicates that the outermost field lines feel the strongest impulse.

As the loss in backscattered signal was detected both by SuperDARN and STARE we believe that it was caused by a change in precipitation. When compressing the magnetosphere the pressure pulse also forces the magnetopause currents to increase, and thus feeds stronger field-aligned currents to the ionosphere. The precipitating electrons enhance the ionospheric conductivity and hence, decrease the E-field, which then drops below the radar threshold value (for STARE $\sim$ 17 mV/m).

The period of pulsations in the magnetogram and STARE SNR was 3-7 minutes which is in the period range of Pc 5. These pulsations are often related to field line resonances (FLR). This finding may suggest that the observed shock generates an FLR but this needs to be confirmed by a more detailed data analysis.

For the future projects the magnetograms should be investigated further in order to see if there are phase shifts of the pulse evident for travelling convection vortices. Equivalent convection patterns could be calculated from the magnetograms in order to study the small scale changes of the convection due to SIs [*Engebretson et al.* 1999]. Some wintertime events will be needed to study the optical SI signatures properly using both photometers and all-sky cameras. Also, these observations should be compared to a SI model by *Araki et al.* [1994].

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