Investigations of Polar Cap Ionosphere Structures using the Greenland Network (GNET)

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Abstract
TEC values from the Greenland network (GNET), complemented with additional GPS receivers that belong to the Canadian High Arctic Ionospheric Network (CHAIN), and 630.0 nm airglow emissions recorded with an imager located at Qaanaaq in Greenland are used to identify large-scale ionospheric structures produced by the passage of polar cap patches, Sun-aligned arcs, and other type of polar cap aurorae. The TEC measurements presented here are restricted to the month of December 2009. Multiple observations of the structures employing different GPS receivers are used to calculate the velocity of the structures. As the patches move in the anti-sunward direction and the Sun-aligned arcs move in the Dawn-dusk directions, a good differentiation can be performed and identify individual structures associated with patches and arcs. We demonstrate that TEC continuous measurement over Greenland can be used to investigate the appearance, velocity, and evolution of arcs, and patches and relate these measurements to the IMF, other solar wind parameters, satellite (e.g. DMSP) and radar (e.g. SuperDARN) measurements. Our observations indicate that during December 2009, more than 20 patches transit across Greenland, all moving in the anti-sunward direction. Several arcs are also detected within the polar cap that occur mainly when the B_z IMF component is directed north.

1. Introduction

Polar cap patches (PCP) consist of isolated regions within the polar ionosphere containing plasma enhanced by a factor of at least 2 with respect to the surrounding ionosphere. Patches transit across both polar caps mainly when the IMF B_z component is directed southward. They move from noon to midnight displaying horizontal dimensions between 100 and 1000 km [*Buchau et al.*, 1983; *Weber et al.*, 1984]. Patch shapes vary from circular to highly elongated cigar-type forms containing the major axis aligned along the dawn-dusk meridian [*Fukui et al.*, 1992].

Early investigations indicated that the source of the enhanced plasma was in the sub-auroral region and that the plasma entered the polar cap through the dayside following the two-cell convection pattern [*Foster and Doupnik* 1984; *Kelly and Vickrey*, 1984]. However, several other sources of patch plasma have been postulated. *MacDougall and Jayachandran*, [2007] used f_0F_2 values from several stations located in the Canadian Arctic to indicate that density enhancements can be produced by low-energy electron precipitation as the plasma returns from midnight around the dawn convection cell. Cusp/cleft particle precipitation can in some cases form polar cap patches [*Valladares et al.*, 1994, 1998; *Walker et al.*, 1999]. When the IMF is directed northward, cusp precipitation can also form a patch in a stirred lobe cell [*Oksavik et al.*, 2006]. *Bust and Crowley* [2007] combined a trajectory analysis and an assimilation scheme to infer that a sequence of patches observed at Svalbard on December 12, 2001, had been transported toward noon from the morning and afternoon sectors, and conclude that the patch densities originated at 62° geographic latitude. *Valladares et al.* [2014] traced backward in time the location of PCPs to point out the existence of large flows when the PCPs were transiting the cusp region.

Significant progress has been achieved in the last 10 years finding the origin of the patches and the causes of the patchy nature of the density enhancements. The EISCAT and the EISCAT Svalbard radars have confirmed the role of transient magnetic reconnection in bringing plasma into the polar cap and carving patches out of the continuous tongue-of-ionization (TOI) [*Lockwood and Carlson*, 1992; *Carlson et al.*, 2002, 2004, 2006]. *Lorentzen et al.*, [2010] demonstrated that poleward moving auroral forms (PMAF) co-exist with enhanced ionization moving into the polar cap. *Moen et al.*, [2006] used radar and all-sky observations to indicate the role of downward Birkeland current sheets to segment the TOI creating a sequence of patches at latitudes even equatorward of the cusp/cleft region. *Carlson,* [2012] pointed out the role of velocity shears to efficiently separate the continuous TOI in regions of low and high density and simultaneously seed other plasma structuring processes. These studies speak loudly of a growing consensus in which transient magnetic reconnection and processes associated with it can help chop the continuous tongue-of-ionization into isolated islands of enhanced plasma.

Another type of structure commonly seen in the polar cap are the Sun-aligned arcs (S-AA) and the transpolar auroras (theta aurora). These auroral displays are mainly observed when the IMF B_z component is directed northward. The polar cap auroras likely map to the magnetotail and are linked to a particular topology of the tail during northward IMF conditions. However, it is necessary to define how the magnetotail topology in some cases allows the development of transpolar arcs and in other instances favors the occurrence of the weak, but numerous F-region polar cap arcs. To explain the formation of transpolar arcs a few conceptual models have been proposed. *Reiff and Burch* [1985] proposed the reclosure cell model (RCM) and the *Kullen* [2000] discussed the twisted magnetotail model (TMM). These two models are briefly discussed in the following paragraphs.

The RCM model uses the hypothesis of anti-parallel merging of *Crooker* [1979] between northward-directed interplanetary field lines and dayside closed and open tail lobe field lines merging at locations poleward of the cusp. The RCM model theorizes that if closed field lines are merged with northward IMF containing $B_z > |B_y|$, a pair of field lines, one connected to the NH and the other to the SH can be opened. The newly opened lines will move tailward and then drape on opposite sides of the magnetotail driven by the tension force. However, these field lines will be forced by the electric field to attract each other and will be able to reconnect and form one reclosure cell in each hemisphere. These cells will have an intruding region containing closed field lines. In one hemisphere the closed field line region will be adjacent to the oval, but in the other hemisphere will be located within the polar cap and flanked at both sides by open field lines. For negative (positive) B_y and merging in the SH, the reclosure cells will be on the dusk (dawn) side in the SH with the closed region near the center of the NH.

The RCM model also indicates that the direction of motion of the transpolar arc and S-AA will be in the direction of B_y in the northern hemisphere. This arc motion is due to the dayside merging process that brings newly opened flux tubes into the polar cap [*Valladares et al.,* 1994b], displacing not only the transpolar arc but the whole reclosure cell as one entity.

The TMM model is based on the observational fact that a nonzero IMF B_y produces a twist of the tail plasma sheet [*Kaymaz et al.*, 1994]. These authors indicated that the sense of tail rotation depends on the sign of B_y. Viewing from the tail toward the Earth, the magnetotail twists clockwise for positive B_y and counter-clockwise for negative B_y. The TMM model relies on an IMF B_y sign change to produce a double rotation of the magnetotail, creating in this way a tail twisted in two opposite directions. The B_y sign reversal affects first the near-Earth region of the magnetotail, producing a twist in a direction opposite to the one prevailing at the far tail, and then for each time step, the new twist rotation will be displaced further tailward. Initially, if B_y is nonzero and steady for tens of minutes, the whole plasma sheet becomes twisted in one direction, mapping to the ionosphere as a widened and poleward-expanded auroral oval. The B_y sign flip affects first the near-Earth tail producing a separation of a bar of closed field lines from the expanded oval. This separation is produced by closed field lines originating in the highly twisted far-tail plasma sheet that bifurcate the near-Earth tail lobes and the polar cap. As the new twisting propagates to the far tail, the closed field line region will move poleward. Eventually, the closed region will reach the opposite side of the auroral oval. The TMM model argues that the closed field line region is the location where the transpolar arc occurs. MHD simulations of the TMM model [*Kullen and Janhunen*, 2004] have in fact corroborated that a bridge of closed field lines can split from the dawn (dusk) edge of the polar cap when $B_y < 0$ ($B_y >$ 0). The simulations predict a time of 50 min for the arc to move from dawn to dusk in the NH. While the direction of the arc motion is identical to the predictions of the RCM model, the simultaneous appearance of transpolar auroras in opposite hemisphere is quite different to the RCM model that postulates a conjugacy dependent on the B_x sign.

This paper presents observations of PCPs and S-AAs using the GNET regional network of GPS receivers located in Greenland. The advantage of a distributed network of GPS receivers over other observational techniques is that they operate continuously and are impervious to sunlight and cloudy sky conditions. The GPS receivers in Greenland were designed and deployed to map the steady vertical velocity field associated with postglacial rebound and to measure elevation changes in the Earth's crust. The CHAIN receivers are dedicated to measuring scintillation levels associated with plasma structuring in the polar and auroral ionospheres. Section 2 of this paper introduces the characteristics of the solar wind that prevailed on December 2009. Section 3 shows selected events of TEC enhancements associated with patches and auroral arcs, the calculation of the patch velocity and a method to discern patch occurrence. In section 4 we discusses the main results of the paper, and outline the conclusions of polar cap structures for the month of 2009.

2. Solar Wind conditions during the month of December 2009

Figures 1 and 2 show the characteristics of the solar wind during the month of December 2009 measured by the ACE satellite. The IMF B_z values (Figure 1) and the solar wind velocity (Figure 2) for almost every day in December are displayed to study the dependence between the development of structures over Greenland and the characteristics of the solar wind parameters. The yellow color shadings in Figure 1 indicate periods when the IMF B_z is negative. During the month of December 2009, the average F10.7 index was ~75, and quiet magnetic conditions prevailed for each day. The highest K_p index was equal to 3^0, which occurred on December 14, 2009. The solar wind velocity (Figure 2) displays increases above 400 km/s that last for less than 1 day on December 6, 18, 19, and 24, 2009. All 3 components of the IMF show periods of rapid sign fluctuations. However, long periods of steady B_z values exist on December 13 and 14, 2009. On December 13, B_z remains near -3 nT for a period of 18 hours between 06 and 2400 UT. This IMF condition has been mentioned before to support the transit of PCP across the polar cap. On December 14, B_z reaches +5 nT and remains positive for 14 hours, during the time interval between 10 and 24 UT. This conditions are favorable for the observation of S-AAs. The availability of continuous ionospheric observations of polar cap structures over Greenland makes it possible to relate the appearance of PCP or S-AA with the solar wind variability.

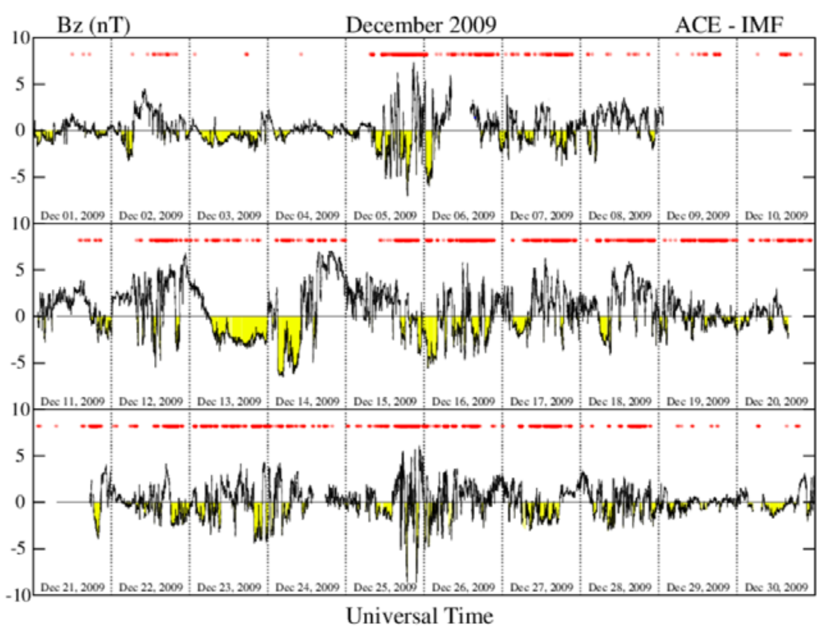

Figure 1. IMF Bz component of the solar wind for the first 30 days of December 2009.

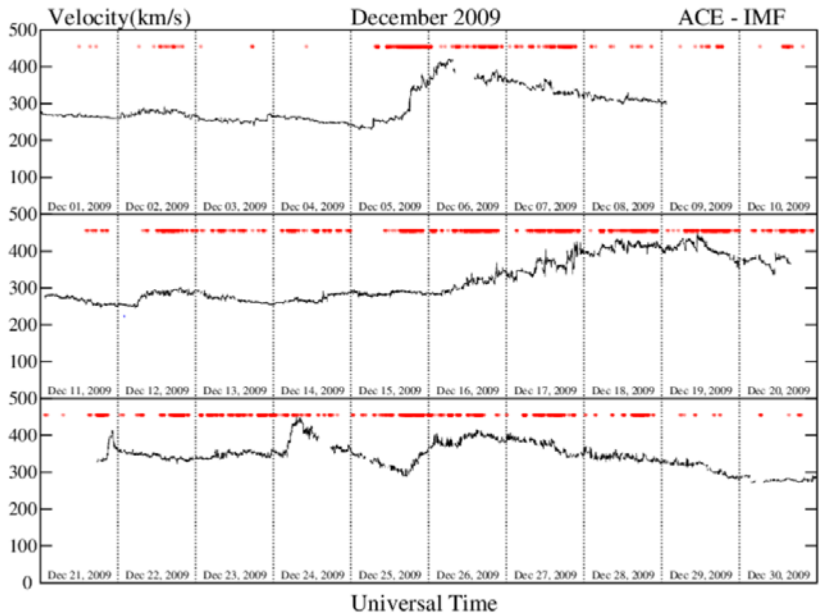

Figure 2. Solar wind velocity measured by the ACE satellite on December 2009. The large red dots on top of the Figure indicate the times when TEC enhancements were detected by the GNET network of GPS receivers in Greenland.

3. TEC enhancements detected using the GNET network

The location of the GPS receivers that operated in Greenland (GNET) in December 2009 and in the Canadian Arctic (CHAIN) are displayed in Figure 3. This Figure shows a total of 55 receivers belonging to GNET and 8 additional receivers that are part of the CHAIN network in Canada. The presence of patches or arcs are discerned by using an analysis software that automatically identifies TEC enhancements and structures [*Seemala and Valladares*, 2010]. This method consists of calculating the TEC daily variability by individually fitting a 4th order polynomial to the TEC trace for each GPS satellite pass and for each station of the GNET and CHAIN networks. The fitted TEC curves are then subtracted from the corresponding measured TEC values. When the TEC difference is above a certain threshold that is commonly set to +0.40 TEC units, a possible TEC enhancement is marked. A second TEC fitting is conducted for each TEC trace excluding the times when TEC enhancements were detected in the first pass. The second step guarantees a better determination of the unperturbed daily variability. The final step searches for the starting and ending times of the enhancements by examining small changes in the time derivative of the TEC curves and times when TEC is above 0.02 TEC units. This analysis code was applied to the TEC values derived from each GPS satellite pass, for each station of Figure 3, and for each day of December 2009.

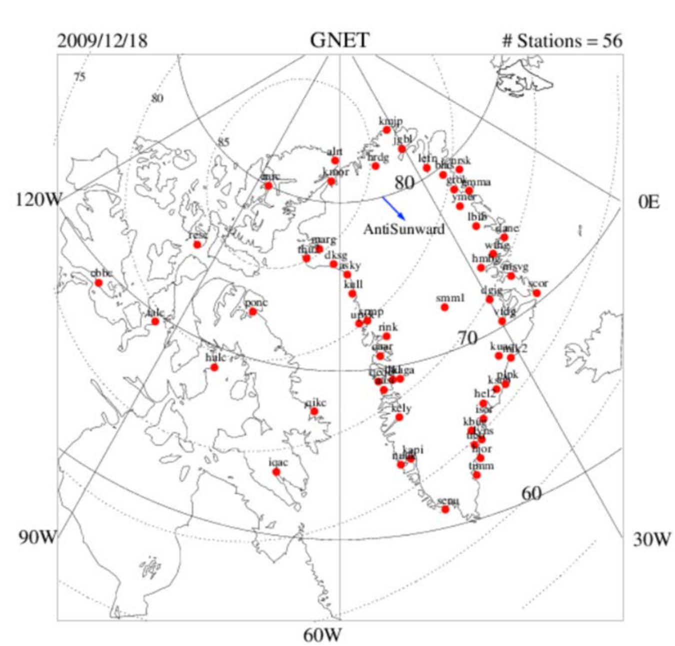

Figure 3. Location of GPS receivers considered in this study. Note the direction of the antisunward angle indicated near the top of the image.

3.1 TEC enhancements associated with PCPs

The background colors of both panels of Figure 4 display the TEC values for December 16, 2009, between 0250-0300 and 0300-0310 UT. The TEC values have been filled up by interpolating the TEC values measured by all the GPS receivers. Note that the average TEC values measured near local midnight is less than 10 TEC units. These 2 panels also present black dots and thick lines to indicate the locations where TEC enhancements are detected at magnetic latitudes below 74°. TEC enhancements, observed at latitudes above 74°, are depicted using red dots and segments. The arrows that start near the red dots represent the motion of the plasma structures. These values are calculated using the TEC enhancements detected by adjacent receivers and using a cross correlation algorithm to estimate the time delays of patches arriving at the stations. This method is similar to the one used by *Valladares and Sheehan* [2016], and *Valladares et al.* [2017] applied to calculate the phase velocity of traveling ionospheric disturbances.

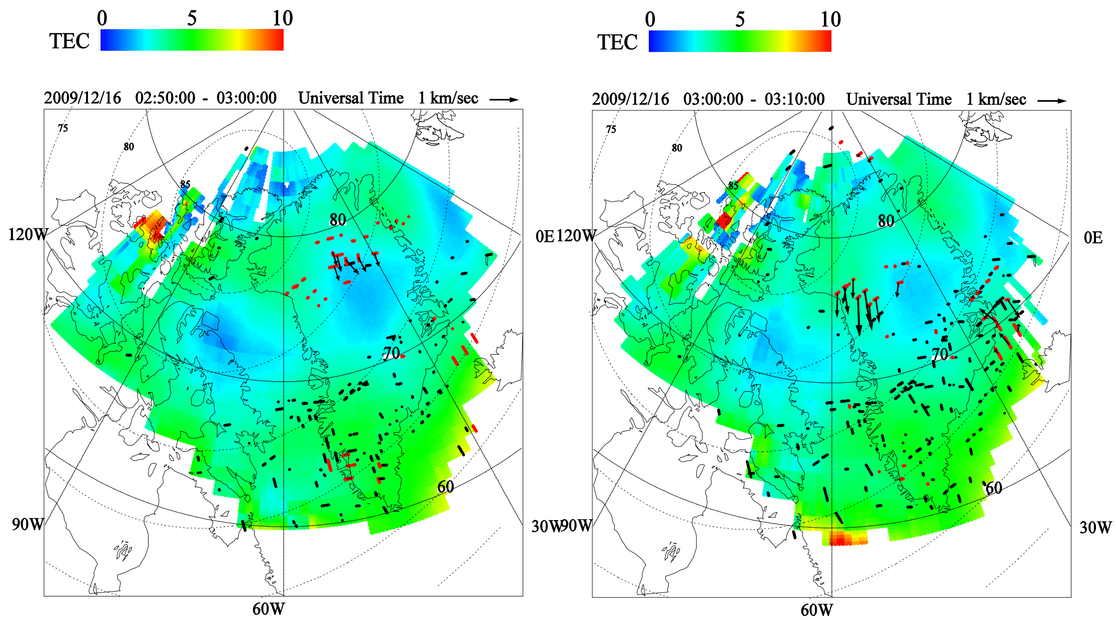

Figure 4. TEC enhancements plotted over TEC values. Each of the large black dots represent a detection of a TEC enhancement. The large red dots correspond also to TEC enhancements, but they are observed at magnetic latitudes above 74°.

During quiet magnetic conditions, the poleward boundary of the auroral oval is located at an average magnetic latitude near 74°. The detection of polar cap patches and arcs is based on this experimental principle and the fact that TEC enhancements seen below 74° are aligned parallel to lines of equal magnetic latitude. These TEC enhancements correspond to auroral arcs and are not considered in this study.

Figure 5 shows the TEC perturbations (TECP) enhancements derived using the signals from the GPS satellite 2 recorded at 7 stations. These stations are located in the northern part of Greenland (see red dots in the right panel). These TECP values are derived by removing the daily TEC variability using a polynomial fitting as described above [*Valladares and Hei*, 2011]. It is evident that all the TECP traces in Figure 5a have a high degree of coherence. Visual inspection indicates a positive delay for most of the adjacent traces. The stations are originally arranged according to their latitude and starting with the most northward station at the top and then progressing toward the most southern station at the bottom. It is known that patches travel in an anti-sunward direction. Therefore, the PCPs propagated from station to station in a slant path in an approximate SW direction. Then, the plotting of the TECP traces was not arranged from north to south, but in a direction that has a slant angle of 119° counter-clockwise from North.

The latitude, longitude and the 4-letter name of the station is printed on the right margin of the plot. Figure 5c shows the cross correlation functions obtained after correlating the TECP traces for each set of two adjacent stations. The short vertical red segments indicate the time delay between the stations. Figure 5d presents the results of the velocity analysis. The small open circles have been color coded to represent the time delay gathered in the correlation analysis with red meaning longer delays, and blue circles pointing out delays close to zero. The small vector at the center of the circles indicates the magnitude and direction of motion of the PCPs. It is found a phase velocity equal to 427 ± 75 m/s that is directed 98° west from North.

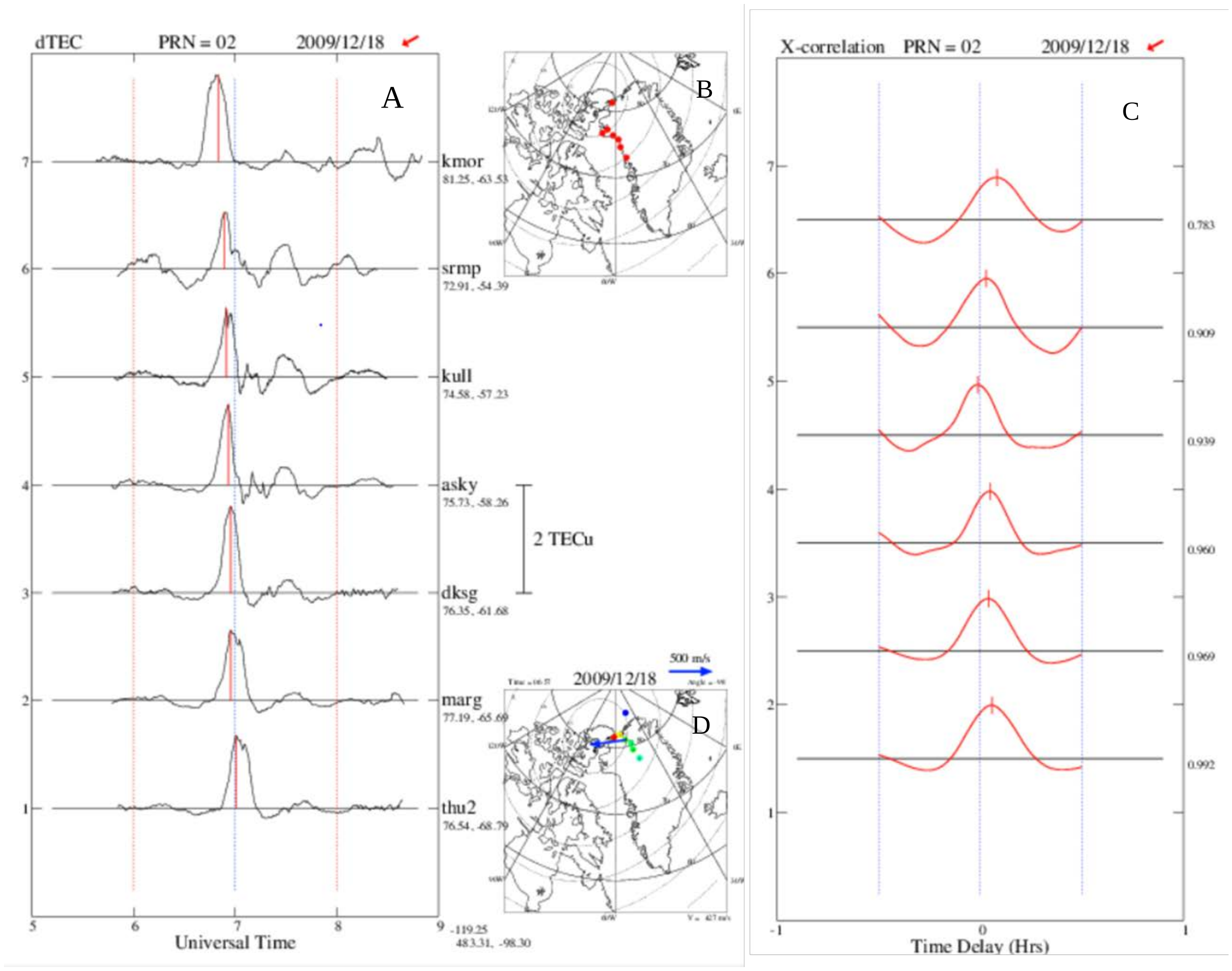

Figure 5. TEC perturbation curves and cross correlation functions for the patches of December 18, 2009.

3.2 TEC enhancements associated with S-AAs.

This section presents observations of polar cap arcs conducted with the imager that is installed in Qaanaaq, Greenland (77.47° N 69.27° W, ~86° magnetic latitude, 0310 UT midnight magnetic local time), and the GPS receivers that belong to the GNET network. Due to the imager location in a very high magnetic latitude, any arc that is observed will be residing within the polar cap. Figure 6 shows a series of 630.0 nm airglow/aurora images recorded between 19:11 and 19:38 UT on December 18, 2009. Date and time information is printed at the bottom side of the images. During this season, the imager was operating with a one-minute cadence time. At the beginning of the observations (19:11 UT), the sunward direction is toward geographic southwest and the dawn-dusk meridian almost aligned to the northwest-southeast axis. Each panel of Figure 6 displays a series of three and sometimes five elongated arcs that are extending toward the Sun, but move, for this particular instance, toward dawn. During this day the polar cap arcs, also named Sun-aligned arcs, initiated at Qaanaaq near 14:30 UT, persisted for several hours and were observed at this station until 24:00 UT.

Simultaneously, the GPS receivers of GNET and CHAIN networks that are located inside the polar cap observed several TEC enhancements. These density/TEC enhancements are produced by the electron precipitation that typically accompanies the polar cap arcs and produce the airglow features that are displayed in Figure 6. These TEC enhancements display a short temporal duration and last no more than 10 minutes in average due to the slim cross section of the arcs and their motion (~100 m/s) perpendicular to their alignment. In addition, on December 18, 2009, the TEC enhancements show a succession of several peaks associated with the passage of several polar cap arcs. This series of TEC enhancements are in accord with the multiplicity of the polar cap arcs seen in Figure 6. Figure 7 was built arranging the TECP traces from the most northwest station toward the southeast. Only stations that showed a good degree of coherence (larger than 0.7) were included in this analysis. It is known that polar cap arcs move toward dawn or dusk [*Valladares et al.*, 1994]. At the time of the observations, the direction toward dusk is ~135° clockwise from North (southeast). The negative delay that the adjacent traces indicate that the S-AAs were, in fact, moving toward dawn.

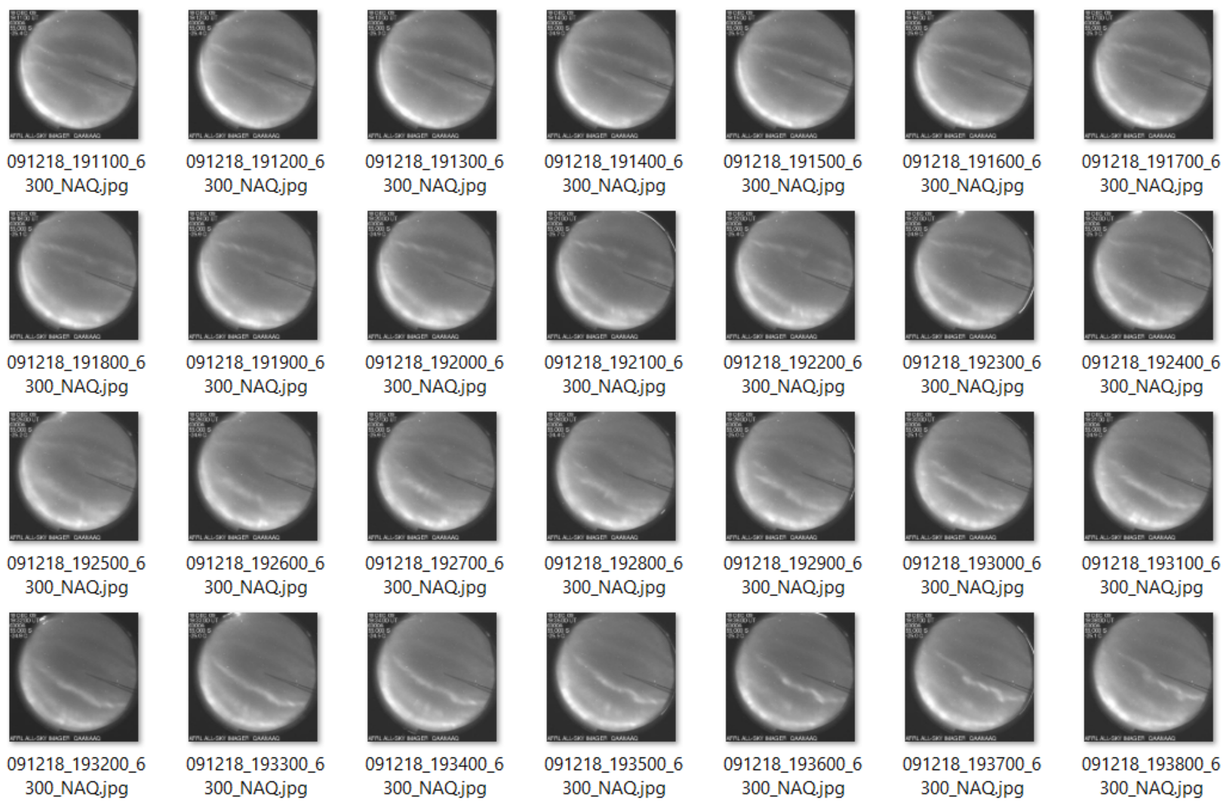

Figure 6. Set of images observed at Qaanaaq using red lime emissions (630.0 nm). Several Sun-aligned arcs are displayed in the series of images moving toward the northwest direction.

4. Discussion and Conclusions

We have presented multi-instrumented (GPS, imager and solar wind) measurements associated with polar cap patches and polar cap arcs that developed during the month of December 2009. This analysis was carried out for TEC data collected only during one month. It is demonstrated here that the TEC data can be used to study the morphology of patches and sun-aligned arcs. A more comprehensive study will follow and will include TEC data for several years. It is expected that this study will be able to reveal which is the dominant mechanism that produces the polar cap patches. However, this study should include velocity information gathered with the SuperDARN radars and likely concurrent DMSP's velocity and temperature measurements. The TEC data have also been used to identify arcs in the polar cap and differentiate their features from the signatures of patches using the motion of the TEC structures. Then, it is required for the analysis software to include a precise determination of the motion of the TEC enhancements. It is also expected that future studies will be conducted to decipher the proper IMF and solar wind conditions that favor the formation of arcs and control the dawn-dusk motion across the polar cap. Consequently, the continuous and permanent availability of TEC data is necessary to succeed on these two projects.

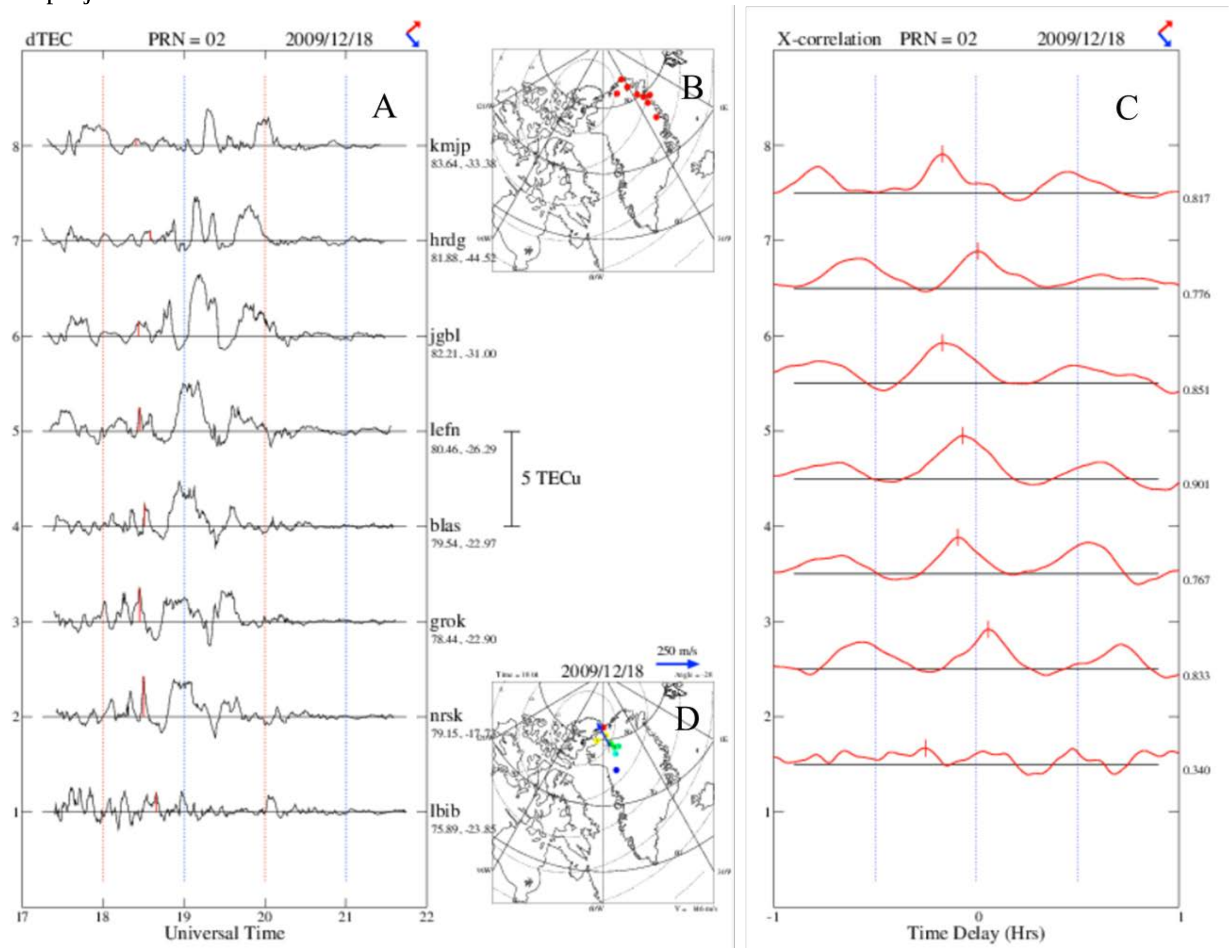

Figure 7. TEC perturbation curves and cross correlation functions for S-AAs observed between 17 and 22 UT on December 18, 2009.