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# GPS TEC Variation Affected by the Interhemispheric Conjugate Auroral Activity on 21 September 2009

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***Abstract*****—**This paper observed the interhemispheric conjugate auroral activity occurred on 21 September 2009. The GPS derived ionospheric total electron content (TEC) during a weak substorm interval recorded at interhemispheric conjugate points at Husafell in Iceland and Syowa in Antarctica is investigated to look at their signatures on the auroral features. Selection of all-sky camera (ASC) images and keogram at Tjörnes and Syowa during the interval 00:47:54 – 00:50:14 UT on 21 September 2009 found that the auroral activity had exerted their influence on the GPS TEC as a consequence of varying interplanetary magnetic field (IMF) $B_y$ polarity.

***Keywords*****—**Auroral activity, GPS TEC, Interhemispheric conjugate points, Responses

## I. INTRODUCTION

AURORAL activity as one of the magnetospheric phenomena can be seen from the Earth, mainly at 100–500 km during the whole season in the night time in the polar region. They are commonly visible between 65 to 72 degrees north and south latitudes, which place them in a ring just within the Arctic and Antarctic circles. Obviously, auroras are more frequent and brighter during the intense phase of the solar cycle when the coronal mass ejections increase the intensity of the solar wind, and accelerated along the Earth's geomagnetic field. The electrons captured in the Earth's magnetosphere are basically constrained to move toward the northern and southern hemispheres along the geomagnetic field lines (see Sato et al. [1], [2] for more details).

We need to look at another potential method that aurora's can be used to link between solar activity and terrestrial climate. The upper atmospheric phenomena like auroral activity offer a realistic chance to connecting it occurrence with the parameters in the atmosphere. With argument that the GPS signals through total electron content (TEC) disturbed during aurora's activity communicated with geomagnetic field, so this activity is proposed as a media propagation to pave the way of the coupling process.

It was also proved by many studies (e.g. [3]) that the higher geomagnetic activity (i.e. geomagnetic storms) can disrupt the communication systems as indicated by significant increased of TEC. More specifically, this study is conducted in the perspective of interhemispheric conjugate points. Conjugate points are related to many aspects of the similarities and/or asymmetries of their properties phenomena between the hemispheres which could be strongly affected by solar activity.

This paper aims to identify the response of the interhemispheric conjugate auroral features on the GPS TEC variations. Investigations are carried out during a weak substorm interval recorded at the northern and southern geomagnetic conjugate points at Husafell in Iceland and Syowa in Antarctica on 21 September 2009.

## II. METHODOLOGY

The response of auroral activity on GPS signals is examined through conjugate points between SYOG and HUSA. The primary data used in this study is TEC derived from GPS observations. As well, the work presents the response of solar activity and geomagnetic activity using satellite and ground measurements. The measurement of interplanetary magnetic field (IMF) from Advanced Composition Explorer (ACE) and the record of fluxgate magnetometer from geomagnetic coordinates at Husafell (HUSA: 66.67°N, 338.97°E) in Iceland and Syowa (SYOG: 69.00°S, 39.58°E) in Antarctica are investigated. Motoba et al. [4] has reported the auroral features on 21 September 2009. Based on their features, the investigations on GPS TEC are focused for this date, which covers the period from 20 to 21 September. There was no auroral data recorded at HUSA for that period. Thus in this work, measured auroral at Tjörnes (TJOR: 66.21°N, 343.89°E) was used. TJOR is one bigger station maintained by the National Institute of Polar Research (NIPR) Japan, which is about 300 km northeast of HUSA. At the current status, there is no GPS receiver installed at TJOR. In addition, TJOR and the conjugate point of HUSA are very close to SYOG. The invariant latitude between TJOR and SYOG is about 66.3 degrees. Figure 1 shows the location of observations. Because of no GPS data at TJOR, the GPS derived TEC at Reykjavik (REYK: 64.08°N, 338.43°E) in Iceland under International GNSS Service (IGS) is compared.

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On the other hand, an interhemispheric conjugate point auroral feature during a weak substorm interval recorded at TJOR-SYOG is investigated using simultaneous all-sky camera (ASC) measurements. Note that a new white light all-sky CCD camera (Watec, WAT-120N+) operates at the rate 30 Hz was installed at TJOR during the September 2009 campaign.

For TEC determination, it is derived from both the pseudorange (code) and the carrier phase at dual-frequencies along the path from satellite to the receiver. There is no denying that the both measurements contain of noise and bias due largely to multiple paths and are subject to cycle slips associated with rapid ionospheric scintillations. Slant TEC (STEC) values quantified from a ground-GPS receiver around the ionospheric pierce point (~350 km for poles, or ~400 km for equator). STEC then converted into Vertical TEC (or TEC for simplicity) by using the modified single-layer model (MSLM) mapping function. To obtain the final precise TEC estimation, the inherent instrumental biases both from the receiver and the satellites were reduced and corrected by using the Differential Code Bias (DCB) obtained from the AIUB Data Center of Bern University, Switzerland. Detail method for calculating absolute TEC by employing a dual-frequency code and phase measurements can be found elsewhere (see e.g. [5], or [6]).

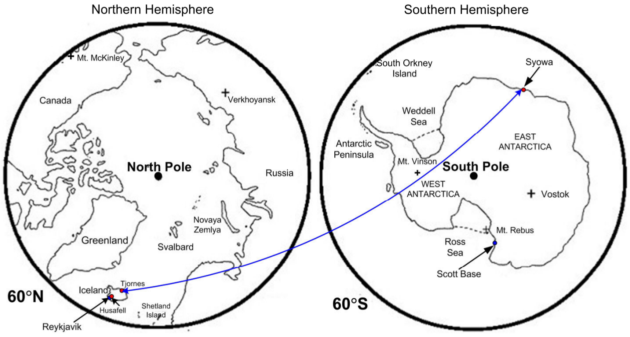

Fig. 1 Geomagnetically conjugate stations between Syowa in Antarctica and Tjörnes in Iceland. Maps are adapted from http://gdl.cdlr.strath.ac.uk/scotia/vserm/vserm0103.htm

## III. Results and Discussions

### A. Solar Wind and Ground Magnetometer Responses

The first graph of Fig. 2 shows the IMF for $B_y$ and $B_z$ components measured from ACE spacecraft, and the last one shows the reading of fluxgate magnetometer for $H$ components measured at SYOG and the conjugate points (HUSA and TJOR). The times from 20:00 UT on 20 September to 06:30 UT on 21 September as indicated by vertical dashed line shows the possible perturbation of the upper atmosphere due to aurora activity occurred at 00:18:12 – 00:50:14 UT on 21 September. Looking at around 20:00 UT on 20 September, the IMF $B_z$ was a negative peak at -3 nT under southward direction. During this time, the IMF $B_y$ polarity is decreasing and reached to a minimum peak of -6 nT at 22:00 UT. At this time, the IMF $B_z$ was opposed to that of $B_y$. At one hour later, the IMF $B_y$ polarity was peaked at 23:00 UT at -1 nT, whereas the IMF $B_z$ is decreasing and reached a minimum peak of -2.8 nT at 24:00 UT. Under southward conditions at 24:00 UT, the IMF $B_z$ together IMF $B_y$ then reached to a positive peak (northward) at 02:00 UT on 21 September with values 8.2 nT and -2.5 nT, respectively. Four hours later before at 06:30 UT, both IMFs are exchange between 4 nT and -6.8 nT and meet at 16:30 UT with opposite variation. After 06:30 UT, the IMF variation was low and fluctuated between ±2 nT. The next day was checked with quiet conditions (not shown). Therefore, one can be noted during the IMF $B_z$ maximum (positive), IMF $B_y$ had a low fluctuation. On the other hand, during the quiet day, both IMFs were in normal conditions with smaller variations.

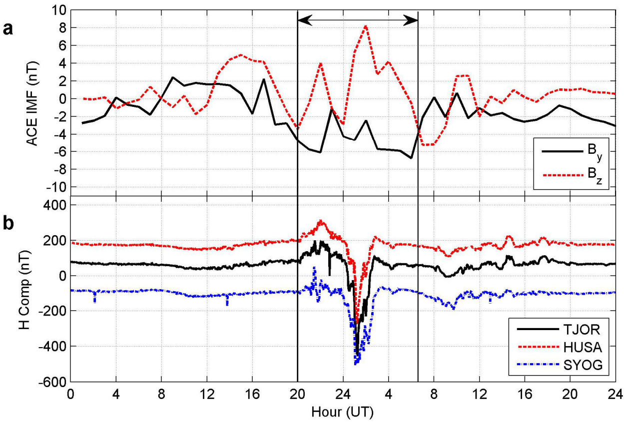

Fig. 2 IMF for $B_y$ and $B_z$ components (a) ACE spacecraft and (b) geomagnetic activity of $H$ component at TJOR, HUSA and SYOG for the period from 20 to 21 September 2009. The interval between the vertical solid lines is an indication of perturbation

In Fig. 2b, the geomagnetic $H$ components at TJOR (solid), HUSA (dash), and SYOG (grey) are presented. The time resolution of the ground magnetometer data is one minute. As shown in the figure, the unnatural irregular signals were started seen only in the $H$ component at TJOR during the interval 22:00 – 24:00 UT. The $H$ component at TJOR showed a suddenly dropped (digression) to 0 nT at around 23:00 UT, when IMF $B_y$ peaked at -1 nT. The other $H$ component for SYOG and HUSA was undetectable. After that, the direction of geomagnetic $H$ components at all stations showed locally downward (westward electrojet at higher latitudes). Just one hour and 20 minutes after the negative peak in $H$ components (at the onset of TJOR), dropped peak to about -500 nT was seen together at all stations, indicated that substorm or storm was occurred. The gradual decrease in the geomagnetic $H$ components caused by the southward IMF of -10 nT or less implies that a substorm growth phase was developed. The rapid small decreased of about -100 nT in ~5 minutes is regarded as a signature of the developing of a negative peak (or westward electrojet). SYOG was developed a negative peak earlier at 01:02 UT (-506.4 nT) than with TJOR at 01:15 UT (-455.4 nT) on 21 September, whereas at HUSA, the negative peak (-271.2 nT) was developed at 01:12 UT. At all stations, the negative peak onsets (00:24 – 02:20 UT) in the geomagnetic $H$ component were coincided with the appearance of the dynamical auroral activity over TJOR and from 00:59 to 01:42 UT over HUSA, which will be presented in Section B

### *B. Conjugate Auroral Activity*

Figure 3 presents the selected image pairs from the ASC images at TJOR and SYOG exposed after the negative peak onset at 00:47:54 – 00:50:14 UT intervals. Note that the original auroral data at TJOR-SYOG conjugate points were sampled every 10 s. The exposed of this interval was due to the phase development of a weak substorm in the late stage between 00:43 and 00:53 UT. To identify a clearly of spiral-like auroras, α and β marked in the image is presented for observed aurora at TJOR, while the counterparts at SYOG are marked by α' and β'. In another note, four east-west aligned spiral-like auroral arcs moving eastward in both ASC field of views (FOVs) and each of them had a similar form between TJOR and SYOG. However, only the third and fourth spiral-like auroral arcs were expected to have the conjugate point of SYOG mapped onto the TJOR. The spiral-like auroras at TJOR at 00:47:54 UT (Fig. 3a) shown moved eastward without a major structure change. At SYOG, a part of the trailing spiral-like aurora (β') began to appear at the westward edge of the ASC FOV at 00:48:44 UT (Fig. 3b). Similar to the leading spiral-like aurora at TJOR, the counterpart at SYOG also moved eastward and then reached the SYOG zenith at 00:49:24 UT (Fig. 3c, bottom). At 00:49:44 UT (Fig. 3d), the leading spiral-like aurora passed out of the ASC FOV at TJOR, whereas the trailing one (β) approached the zenith. At 00:50:14 UT (Fig. 3e, top), seen similar spiral-like aurora at TJOR, and a part of the trailing spiral-like aurora (β') at SYOG appear near the westward of the ASC FOV.

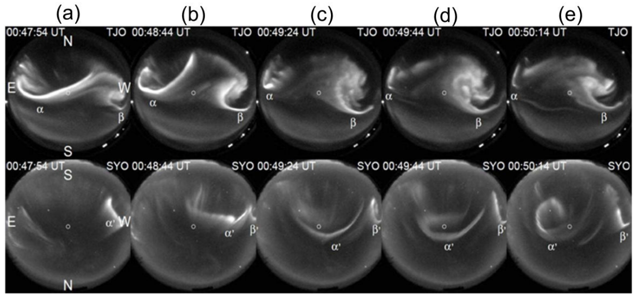

Fig. 3 Auroral activity during the interval 00:47:54 – 00:50:14 adopted from Motoba et al. [4]. The zenith of TJOR and SYOG are shown by white circles. The top and bottom sides are polweward and equatorward, respectively. The left and right between TJOR and SYOG are reversal for westward and eastward. The first and the second spiral-like aurora arcs are labeled α and β at TJOR (α' and β' at SYOG), respectively

### *C. Linkage between TEC and Auroral Activity*

The dynamics of upper atmospheric response to auroral activity is represented by temporal TEC variation. Figure 4 presents TEC variation from 20:00 UT on 20 September to 04:00 UT on 21 September at SYOG, HUSA and REYK stations in one-minute average. In the figure, there was lacking GPS data recorded (20:40 ~ 21:10 UT) for stations in Iceland, while the TEC variation with grey background is an indication of it enhanced due to auroral activity. Referring to that background (00:05 ~ 01:15 UT), the TEC showed increased peak with SYOG and REYK occurred at an almost similar time (at ~00:35 UT), while HUSA was late about 10 minutes. REYK is located at lower geomagnetic latitudes than HUSA and SYOG, and therefore, TEC variations at both stations precede the TEC variation at HUSA and SYOG. Clearly at SYOG, the TEC was seen with five peaks fluctuated between 5 and 8.2 TECU. The HUSA and REYK were seen only one and two peaks, respectively. From these characteristics showed that the TEC will have a response on the stations that to have a conjugate point. In general, the TEC variation for all stations observed was shown a similar pattern. One can be noted that the daily TEC pattern during low sun activity or not under geophysical disturbance was shown closely in a diurnal pattern.

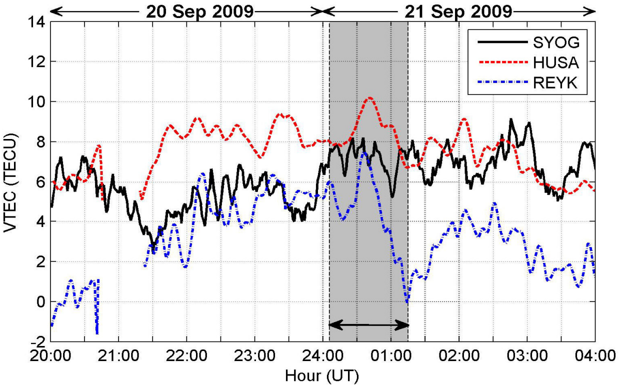

Fig. 4 Vertical TEC variations in one-minute average at SYOG, HUSA and REYK stations for the interval from 20:00 UT on 20 September to 04:00 UT on 21 September. The grey background shows an indication of a weak substorm

Variation of auroral activity can be monitored by keogram as depicted in Fig. 5. The keograms profiles at TJOR and SYOG for the interval from 21:00 UT on 20 September to 04:00 UT on 21 September 2009 is presented. Each meridian keogram is made by cutting in the north-south (south-north for SYOG) section through the zenith on 10 s sampling ASC images. Bright stripes are an indication of auroral activity over almost the complete FOV. The intervals X and Y marked in figure (00:47:54 – 00:50:14 UT) correspond to the auroral time intervals of Fig. 3. Unfortunately, after 01:30 UT, we could not saw the northern footprint of SYOG because of data lacking in both ASC FOVs. In addition, it is found that the northern footprint of SYOG dramatically moving during the substorm development. By comparing Figs. 5 and 3, the keograms at TJOR and SYOG of the conjugate auroras in the late stage of the substorm (after 00:45 UT) shows similar features. The time sequence of the conjugate auroral features also corresponded well with that of the *H* component variations. Therefore, the possible persuade of auroral activity communicated via solar wind on the ionospheric TEC can be explained as follows.

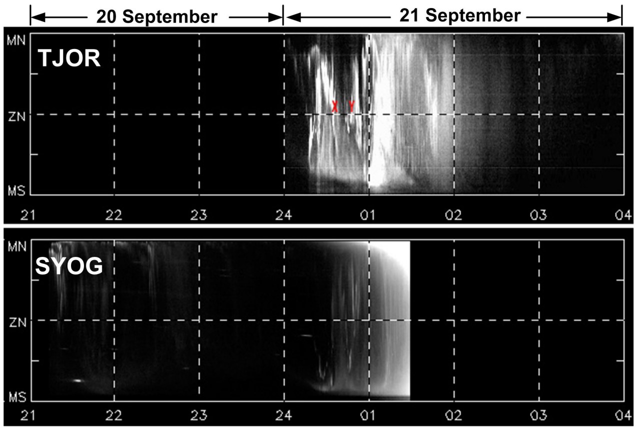

Fig. 5 North-south meridian auroral keogram at TJOR and SYOG during the interval from 21:00 UT on 20 September to 04:00 UT on 21 September

From the dynamics of spiral-like aurora arcs at selected ASC images between TJOR and SYOG, and from the magnetic *H* variation at TJOR, it can be seen that TEC variation has increased and peaked at 10 and 20 minutes later for REYK and HUSA (northern hemisphere) to about 7.5 and 10.2 TECU, respectively. At this time, a weak substorm was intensified development from 00:15 to 02:40 UT on 21 September. However, the selected ASC images in Fig. 3 were just a short part of the full story. The auroral activities at TJOR was seen started from 00:07:11 UT (see Fig. 5). On the other hand, small enhancements in the TEC values around the same time at 01:10 UT on 21 September from keogram profile at TJOR had been found. In addition, fluctuated TEC at all stations starting from 21:30 to 23:30 UT on 20 September (see Fig. 4) correspond well with keogram profile in Fig. 5. Thus, TEC enhancement during a weak substorm can be understood by the enhancement of electron density in the E- and F-regions created by the precipitating auroral electrons associated with the auroral activity. In another meaning, an increasing the density of an incident energetic particles in the atmosphere (shown by TEC), and a major change in the conductivity from the ionospheric E-region to the upper atmosphere with the effects of auroral activity and to explain deeply its physical mechanism is a great challenge to a further investigation.

## IV. CONCLUSION

This paper successfully identifies the response of GPS TEC during a weak substorm on the auroral activity for the first time using GPS data. The investigation of interhemispheric conjugate auroral features at TJOR and SYOG occurred on 21 September 2009 at conjugate stations found that the conjugate auroral features corresponded well with the magnetic *H* component and TEC variation. Based on a detailed comparison of both ASC images with time-dependent TEC variation during the interval 00:47:54 – 00:50:14 UT, the northern geomagnetic footprint of SYOG was displaced poleward of TJOR by up to 3 degrees or more in the initial stage of substorm developments. With this drift, we observed that the TEC peaked during the period of perturbation has a time difference to other stations caused by auroral poleward expansion develops from lower latitudes to higher latitudes. We highlight that the dynamic motion of the auroral activity on the conjugate points has affected the GPS TEC as a consequence of varying IMF $B_y$ polarity. Therefore, if the huge auroral take place in the polar region communicated via solar wind, the effects can also be monitored by GPS technique.

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