Impact of Solar Flares on HF Radio Communication at High Latitude

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***Abstract*—An increase in the solar magnetic field gives rise to the number of visible sunspots in the Earth facing side of the Sun. This tends to impact the Earth's magnetic field. Occurrence of a geomagnetic storm depends on the interaction of magnetic fields of both the Sun (captured in solar wind) and the Earth. The energy of the sun is given out in the form of high-speed solar wind, solar flares, coronal mass ejections (CMEs), solar uV light and energetic particles (MeV). The effect of such geomagnetic storms is borne by the trans-ionospheric message carrying signal and affects both satellite navigation and radio communication systems on Earth. Moreover, the ionosphere, being a refractive and dispersive medium, adds as a source of error to the message signal. Thus, it becomes important to study the effect of space weather activities on GNSS signal and try to overcome its impact. This paper studies the impact of one such solar storm in the mid-high latitude region during the winter solstice of 2015 on GPS and high-frequency airplane communication. A case study of an event that occurred in Stockholm, Sweden on the 4 November 2015 has been investigated using the geomagnetic and satellite geometric parameters, and the total electron content (TEC) variation in the ionosphere. The analysis undertaken in this paper demonstrates the importance of understanding the serious threats solar activity poses to GNSS and its related applications on Earth, which can have rippling effects on industries which are evidently reliable on space technology.**

***Keywords*—Global Navigation Satellite systems (GNSS), Solar storm, Total Electron Content (TEC), trans-ionospheric communication**

I. INTRODUCTION

Reliance on global Navigation Satellite Systems (GNSS) (such as GPS, GLONASS, Galileo, BeiDou) for a wide range of high-accuracy and critical safety-of-life applications has been ever increasing with the uproar of new and robust satellite-based navigation systems. It becomes a challenge and a necessity, both to deliver the solution with ease in availability, reliability and accuracy. GNSS signals are sent from over 20,000 km above the surface of the Earth undergo several phenomena in space which degrades the quality of the signal before it even reaches Earth. These are mostly owed as the *Space-weather effects*. Space weather is a term, which is used to define the environmental conditions in the Earths magnetosphere, ionosphere and thermosphere as a result of physical processes which begin at the Sun and conclusively affect the activities in space and on Earth. In the process of signal transmission and reception in order to determine one's position on earth, the signal sustains various atmospheric and space weather effects. A signal bears the wrath of solar radio bursts, geomagnetic and solar radiation storms and sub-storms which tend to degrade its accuracy [1]. The major space weather effects are directly linked to optical or radio or X-ray interferences and degradation of solar energetic particles, hazards due to space particles and other ionospheric perturbations. Other significant effects include ionospheric scintillation, attenuation, polarisation loss, Doppler shift, phase and/or amplitude scintillation etc [2]. Extensive research has been going on to mitigate the ionospheric effects for many life safety critical applications on Earth.

An intense, sudden and rapid burst of radiation leading to variation in brightness in the Sun's corona is termed as a solar flare. A solar flare occurs with sudden release of magnetic energy from sunspots. They are observed as bright events of the sun, which affect the Earth only when they occur on the sun facing side of it and last typically from minutes to a few hours. Solar flares were first recorded on 1st September' 1859 when two scientists, who were independently observing sunspots, came across a high powered beam of white light emerging from it, which came to be later known as solar flares [3] [4]. Solar flares generally occur in the active region of sunspots, which are highly concentrated areas of strong magnetic field in the coronal area of the Sun. Solar flares are highly likely to occur when the number of sunspots observed increases during the solar maximum [5].

During solar minimum, the active regions of the Suns corona get weaker in intensity and thus the sunspots. Solar flares are solar systems most energetic explosions whose radiations take about 8 minutes to reach the Earth, ionising the Earths ionosphere during its travel. They are capable of temporarily altering the Earth's upper atmosphere leading to disruptions in signal transmission. Changes in the electron density distribution alter the propagation medium and affect the long distance radio signals. By the time they traverse the ionosphere and are received at the ground-based stations, they are either induced with positioning errors, cycle slips or are completely lost. High solar energetic particle induces radio bursts, geomagnetic storms and sub-storms, and turbulences in ionospheric electron density. The rapid random time derivative of ionospheric irregularities cause rapid and random phase and/ or intensity fluctuation to the received signals called scintillation. Moderate to strong scintillation causes malfunctioning of GNSS receivers and related application devices on the Earth [6].

For estimating the TEC from GPS observations, the ionosphere was approximated by a spherical shell at a fixed height of 350 km above Earth's surface. Total Electron Content (TEC), defined as the total number of electrons along a slant path from the satellite to receiver, helps in analysing the state of the ionosphere, based on the ionospheric single shell model [7] [8]. The absolute slant TEC (STEC) values derived from the carrier phase delays and pseudoranges of the GPS signals (L1 = 1.575 GHz and L2 = 1.228 GHz) are then converted to absolute VTEC using a mapping function as shown below:

$$VTEC = \frac{STEC}{S(E)} \tag{1}$$

$$S(E) = \frac{1}{cos(z)} = \left[1 - \left(\frac{R_E \times cos(E)}{R_E + h_m}\right)^2\right]^{-0.5} \tag{2}$$

Here R_E is the mean radius of the Earth in km, h_m is ionosphere (effective) height above the Earth's surface, z is the zenith angle and E is the satellite elevation angle in degrees at ionospheric pierce point (IPP) which is estimated from the satellite elevation angle [9]. The rapid enhance and depletion of TEC shows strong correlation with ionospheric scintillation, which ultimately causes significant positioning errors on Earth. Space weather events such as these are included as a part of UKs National Risk Assessment (NRA) and affect various GNSS associated applications such as cellular, emergency and HF communications, ground and avionic technology, aircraft passenger and crew safety, terrestrial mobile networks and electricity grids to name a few [10]. This paper aims to study the effects of one such event that caused air traffic and emergency landing of aircrafts in the high-latitude region of Europe. The geomagnetic conditions have been studied by examining the geomagnetic indices and their impact on TEC and amplitude scintillation. The role of elevation angle and the satellite geometric parameters have also been discussed in detail in the following sections.

II. METHODOLOGY

To investigate the response of the storm, two storm periods of the solar cycle 24, which occurred in the same week of November 2015 with varying intensities have been selected. GPS data is available from the EUREF and IGS network has been used in estimating the TEC and amplitude scintillation (S4) fluctuations over the days. An open-source program software has also been used in estimating the variances in the satellite geometry due to positioning errors. These storms which prevailed on the 3 and 4 November 2015 were amongst the top 20 geomagnetic storms of that year [11]. Among these, the one on 4 November put the air traffic on a standstill in Sweden.

A. Geomagnetic condition

To study the impact of the solar storm at mid-high latitude, we analysed the GNSS data at Maartsbo, Sweden (geographic co-ordinates 60.59°N, 17.25°E and geomagnetic co-ordinates 59.04°N, 106.42°E), the nearest EUREF station to Stockholm, Sweden, where the actual incident occurred. The solar storm interfered with the air traffic control radar systems leading to delays in various flights inbound and outbound to multiple airports in/from Sweden for about 3 hours. This case is a real-time example of an event when solar activity posed a serious threat to GNSS receivers on Earth, to the aviation industry in this particular case. The details of the solar parameters, which describe the intensity of the storm, are presented in Table 1 below:

III. RESULTS AND DISCUSSION

A. The solar storm of 3rd November'2015

A high-speed solar wind buffeted the Earth's magnetic field on 3 Nov 2015 caused a G1 minor geomagnetic storm around the poles. Its impact was comparatively less during the early hours due to the mismatch between the solar and Earth's magnetic field. It, however, exacerbated during the late evening hours continuing to the early hours of 4 Nov 2015. Earth facing sunspot AR2445 erupted a long duration solar flare measuring M3.7 at its peak at 13:52 UT. This almost coincides with the time when airport interruptions in Sweden were reported, during which the solar wind and the southward component of Bz reached a maximum peak [11]. Fortunately, much of the eruptions hurled back towards the Sun, which prevented it from being a far worse storm condition.

TABLE I SOLAR PARAMETERS

Days	*Solar Parameters*				
	Solar wind	*Sunspot*	*Solar flare*	*Btotal*	*Bz(S)*
03/11/2015	684.4 km/sec	94	C5, C5	5.1 nT	0.7 nT
03/11/2015	570.4 km/sec	95	C1, M3	7.1 nT	0.7 nT

A massive solar flare geomagnetic storm continued from the late hours of 3 November 2015, disturbed the Earth's magnetic field on the next day which affected the radar installations in southern Sweden and caused R1-Minor Radio Blackout. Fig. 1 and Fig. 2 show the DST and Kp index variation for the two days respectively. The storm on 3 Nov commenced into its initial phase at 07:50 UT and underwent a sudden decline in the DST immediately afterwards during the mid-day hours. Before observing a rise in the Kp values again from 18:30 UT, the storm had reached into its recovery phase for a brief period of time. The impact of the storm persisted into the day hours of 4 Nov, which recorded an increased Kp and negative DST of -59nT for most part of the day. Solar wind also reached its peak to 570.4 km/sec and the sunspot number increased to 95 (Table 1).

It was during this time that the blackout of the airplanes from the radar screens at about 14:30 UT was observed which lasted for more than an hour. Airports in Stockholm and Gothenburg were severely affected as no flights were allowed to take off which resulted in over a dozen delays. The halt of flights also disrupted the schedule of other neighbouring airports, mainly Copenhagen, to where the flights from Sweden were expected.

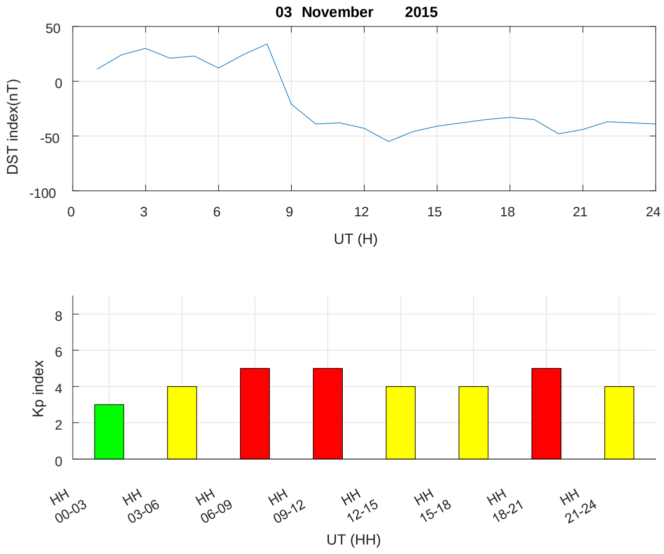

Fig. 1. DST and Kp index variation on 3 Nov 2015

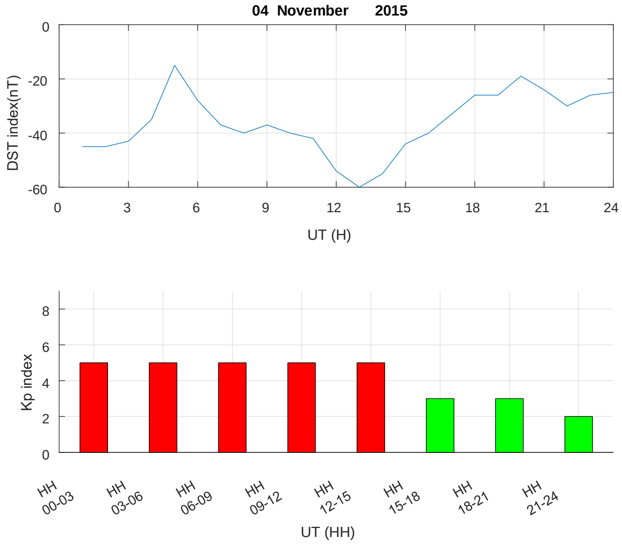

Fig. 2. DST and Kp index variation on 4 Nov 2015

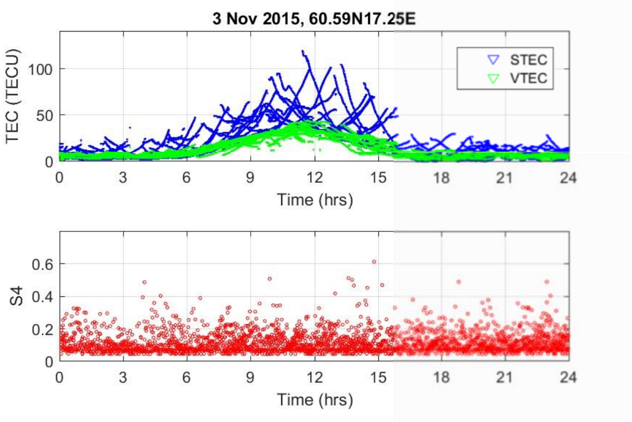

Fig. 3. TEC and S4 index variation on 3 Nov 2015

The air traffic problems started at the most intense phase of the radio storm and followed right on the heels of a minor geomagnetic storm caused by the high-speed stream of a coronal hole. The effect continued until a week after when a coronal mass ejection (CME) was produced by the M3.7 solar flare and caused a moderate (Kp = 6) geomagnetic storm during the first half of 7 November. In addition, there were storms recorded in continuation with them until the 10 Nov 2015, it, being a more massive one than these. It has been further analysed by studying the TEC content, both STEC and VTEC for the two days. The TEC variation as shown in Fig. 3 and Fig. 4, follow the same trend that the DST and Kp index depicted in the figures above. Fig. 3 observes a sudden TEC enhancement from 08:30 - 13:30 UT, as does the Kp and negative DST relative to the same day. Fig. 4 also suggests strong stormy conditions by displaying the behaviour of TEC depletion.

Alongside in Fig. 3 and Fig. 4 depicted is the variation in the amplitude scintillation (S4). S4 is an index dependent on the intensity of the GNSS signal and fluctuations in it concur to low signal power, thereby making the signal tracking very difficult.

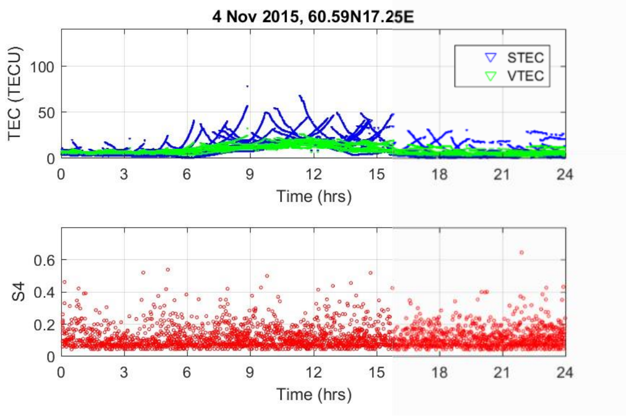

Fig. 4. TEC and S4 index variation on 4 Nov 2015

Although amplitude scintillation is usually associated with equatorial and mid-latitudes, the small scale irregularities in the F-region of the ionosphere produce amplitude fluctuations which can hinder navigation and communication systems in the very high frequency (VHF) ranges [12]. It is thus, a prevalent phenomenon in the mid-high latitudes, as can be seen from the sufficient amount of scintillation activity recorded on both days.

To analyse the TEC enhancement and depletion, the mean TEC of the quiet days of November 2015 has been plotted against the top five intense storm days of the same month in Fig. 5. While the peak of mean TEC for Nov reached as high as 14.3 tecu, a clear enhancement in TEC was observed for 3 November 2015 when the mean TEC peak was around 34 tecu (more than the double of the average of quiet days). Relatively a depression in the TEC trend was observed for the other storm days. It can thus be concluded that effect of solar storms on TEC also has a positive and negative effect, i.e. TEC enhancement and TEC depletion. This helps us to study the impacts of a solar event with respect to the concentration of ionospheric irregularities and plasma instabilities in the medium of radio signal propagation.

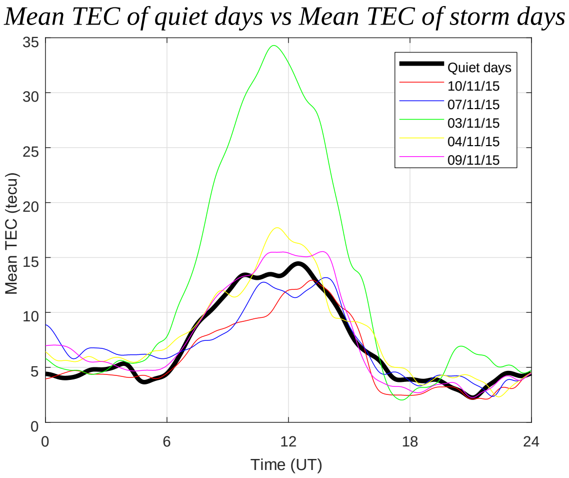

Fig. 5. Mean TEC vs TEC for disturbed days

The distribution of satellites above an observer's horizon contributes to GPS positioning accuracy to a great extent. The geometric strength of the visible satellites at one point of time is studied using dilution of precision (DOP). A high DOP does not necessarily cause GPS positioning error but the uncertainty of the GPS position is increased by the DOP factor [6]. A summary of the geometric parameters, horizontal DOP, vertical DOP, position DOP and the geometric DOP w.r.t to the visible satellites (NSAT) has been summarised in Table II which helps to analyse the uncertainty in the GPS position observed on both storm days considered in this paper.

In addition to the satellite visibility and geometric dilution of precision, the signal quality is the most important aspect of the GPS positioning accuracy. Previous researches have simulated the signal-to-noise ratio (SNR) with respect to their respective elevation angles with and without considering multipath [13]. GPS receivers experience loss of lock when the SNR is degraded by reducing below a particular threshold value. This is generally a result of amplitude scintillation [14]. Fig. 6 shows the Signal to Noise ratio of all PRNs on 3 and 4 November with respect to their elevation angles. It is used as an approach to mitigate the noises from multipath and low elevation angles to indicate better positioning accuracy. As observed, better SNR was observed at higher elevation diminishing the impact of low-level irregularities.

Such type of an event has earlier been recorded in October 2003, when a CME caused a Japanese satellite failure, delimited GPS accuracy, led the polar region flights to get diverted and caused power outages in parts of Europe and Africa [15] [16]. Another relatively small solar event in January 2005 deteriorated the HF radio communications of transpolar airline travel, resulting in the rerouting of dozens of flights.

TABLE II SATELLITE GEOMETRY OBSERVED FOR 24 HOURS EACH DAY

Days	*Mean of the Geometric parameters*				
	NSAT	*GDOP*	*PDOP*	*HDOP*	*VDOP*
3rd Nov 2015	9.707	6.161	5.196	3.088	4.058
4th Nov 2015	9.737	5.405	4.577	2.928	3.824
7th Nov 2015	9.949	4.144	3.53	2.312	2.604

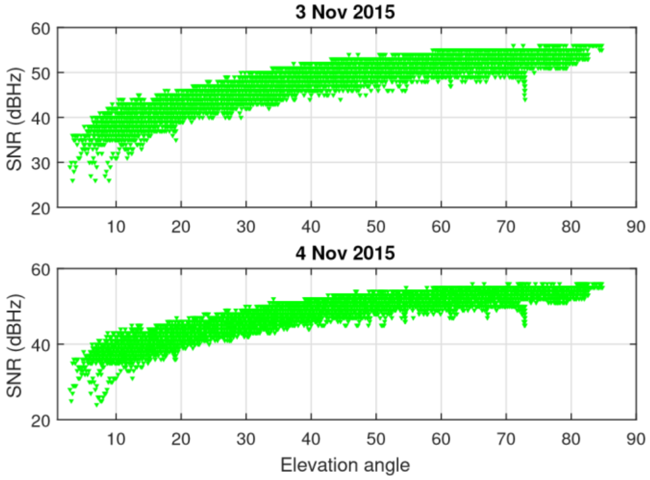

Fig. 6. Elevation angle vs SNR for 3 and 4 Nov 2015

IV. CONCLUSION

Minor geomagnetic storms are capable of affecting satellite operations, power grid functioning, migratory animals, and at higher levels, even auroras visibility at high latitude. Reliability on GNSS systems is on a rise and will continue to as long as the scientific arena is expanding. Trans-ionospheric communication of radio waves from the transmitter to user is affected by the ionosphere which is highly variable and dynamic in both space and time. Ionospheric disturbances, capable of causing range errors, rapid phase and amplitude fluctuations (radio scintillation) degrade the system accuracy, reliability and positioning. This dependence on positioning systems is hindered by space weather effects and cause a long-term effect for users on Earth.

In this paper, we investigated the G-1 geomagnetic storm of 3 and 4 November 2015, which knocked off the air traffic control in Sweden. Rapid enhancements and depletions in the TEC (validated above) have found to be well correlated with the already existing data of the geomagnetic parameters, i.e. Kp and DST index variation and solar parameters indicating the presence of a moderate storm. Significant disturbances in the TEC have been used as a parameter to study the impact of space-based storms on Earth's navigation and trans-ionospheric communication systems. A strong TEC enhancement and/or depletion also demonstrates the effects on the satellite geometry. An increase in the DOP parameters thus decreased the positional accuracy by reducing the number of satellites locked or cycle slips, thereby recording incorrect positional data or missing it to record completely. The degradation in the DOP implies that the GPS receiver performance is greatly affected under storm conditions and the measurements thus become quite unreliable.

An early warning, in this case, could have mitigated the economic and financial loss that followed and would have made the users well prepared for the event.

Ionosphere's vulnerability to the impacts of a space weather events is very high and in turn massively affects users on Earth. Thus it becomes imperative for researchers to study and analyse these effects and compare them using both practical and theoretical statistics. Forecasting the ionosphere's response to such events can be used to issue early warnings and mitigate the losses caused by the space weather. The inspection of severe storms that have occurred in the past in different geographical areas can be used to asses the varying impacts and how to mitigate its impact by using ionospheric scintillation modelling and forecasting in near real-time.

V. ACKNOWLEDGMENT

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