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Statistical Scintillation Indices in Polar Ionospheric Climatology

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Abstract

It has been established that polar cap patches are capable of triggering phase scintillation via various convective instabilities such as Gradient Drift, Gravitational Interchange, Current Convective, and Kelvin-Helmholtz Instabilities coupled with turbulent plasma processes in the cold and warm approximation. These multiple instabilities provide a qualitative density peaking mechanism which ultimately leads to the formation of highly dense and coherent nonlinear structures such as polar patches and auroral blobs at high latitudes. It is important to note that the nonlinear evolution of these polar patches/blobs and their associated plasma number density inhomogeneities are primarily controlled by dominant magnetospheric (inertial) or ionospheric (collisional) current systems. Moreover, intense observational studies on the trans-polar movement of these polar patches/blobs and their associated morphology further classify these structures as Type 1 and Type 2 blobs depending upon their density estimates and ionisation sources. In this study, a correlation between inherent polar patches plasma parameters and phase scintillation metrics is discussed in terms of Total Electron Content (TEC) and ROTI measurements at a localised region Ny-Alesund [78.93°N, 11.86°E], Svalbard which is more sensitive to the polar patch mobilisation driven by dayside polar cusp dynamics. Moreover, it is concluded that phase scintillation studied in terms of TEC and ROTI local estimations could be used as proxies for the polar ionosphere.

1 Introduction

Plasma density irregularities drastically affect trans-ionospheric electromagnetic signals and cause rapid fluctuations of the received wave amplitude/ phase signal information, which are often referred to as scintillations [1]. Classical studies on ionospheric scintillations started early in 1946 and thereafter later advancements and subsequent research revealed that ionospheric scintillations frequently occurred in the equatorial region, mid-latitude sectors and at high latitudes.

The European arctic region is frequently monitored through many sophisticated and advanced diagnostics for many decades. It turns out that polar patch/blob convection is guided by the polar sector twin cell potential. High density polar F region plasma density coherent structures called Polar cap patches exit the polar cap into the nighttime aurora and then return to the dayside [2, 3]. Many coordinated campaigns have revealed that phase scintillation estimates are more dominant in this region around magnetic midnight as compared to the daytime scenario [4]. It has been found that GPS (Global Positioning System) phase scintillations dominate over GPS amplitude scintillations in the polar sectors[5, 6]. These polar patches are termed auroral blobs when they exit the polar cap and enter inside the auroral oval.

Further, these blobs could be broadly classified and differentiated into Type I and Type blobs II based upon their convection characteristics and density inhomogeneity scale length. Blob type 1 (BT-1) is the reminiscent or trace related to the high-density islands of polar cap patch material that has been convected to the night-side auroral oval. However, blob type-2 (BT-2) relates to the plasma density enhancement/structure that has been triggered locally by particle precipitation in that localised zone. It turns out that the BT-1 blob dynamics is responsible for the worst scintillation cases.

A number of primary instability mechanisms have been proposed to explain these density irregularity productions at high latitudes, including the background plasma turbulence, the gradient drift instability (GDI), the Kelvin-Helmholtz instability (KHI), or velocity shear-driven instability. Additionally, more complex analyses of these highly dense patch structures have been made by the temperature gradient instability to address the inherent thermal properties of these polar patches. These models also include the current density investigations arising out due to the inclusion of parallel current in the proposed patch/blob convection trajectory analysis [7, 8, 9].

2 Event details and Data

With the prime motivation of scintillation analysis in the polar latitudes, global and local plasma parameters responsible for the evolution and decay of the polar patches have been compared and correlated with vital statistical scintillation indices in the climatology study at

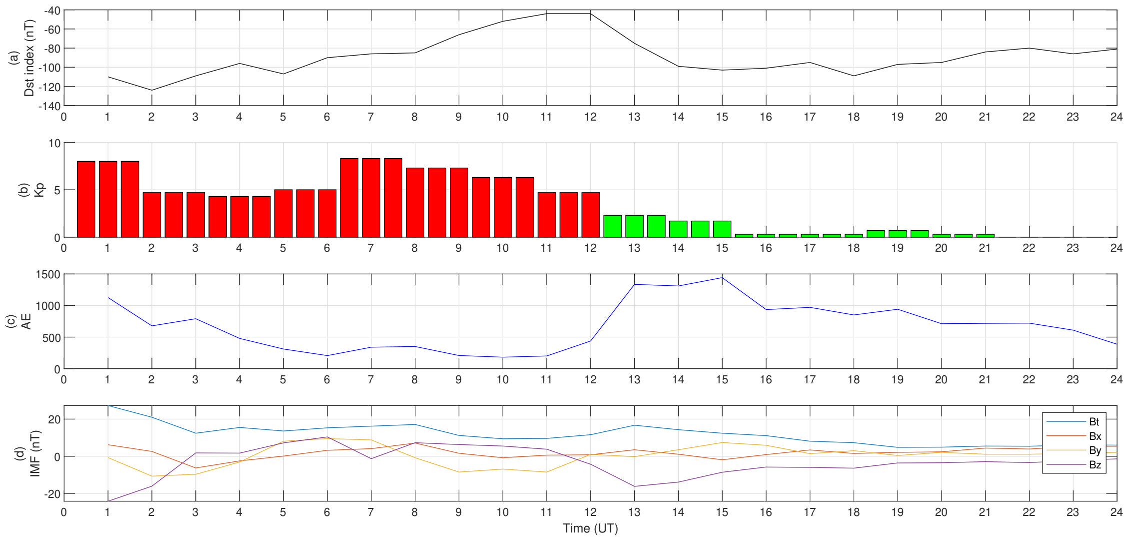

Figure 1. Hourly (a) Dst; (b) K_p; (c) AE; (d) IMF indices for 8 Sep 2017 at NY-ALESUND

Ny-Alesund, Svalbard. The scintillation model has been analysed using global geomagnetic data and correlated in terms of ROTI measurements and global magnetic indices. The storm of 8 Sep 2017 was marked by two CMEs hitting the Earth's magnetosphere with an X9.3 CME, that emerged over the Sun's northeastern limb leading to a strong G-3 class in the late hours of 7 Sep/2300 UT whose effect continued until about 0300UT the next morning and a severe G-4 class at mid-day on 8 Sep. It hit the Earth stronger than expected, making 8 Sep one of the highest geomagnetic storms of 2017 and the solar cycle 24. Their corresponding effects in the form of global indices on the polar region has been observed.

The ionospheric response to the disturbed day of 8 Sep 2017 in the polar region has been analysed by using data from 3 sources:

Geomagnetic indices: Comprising of Dst index, K_p, Auroral Electroject (AE) index. Available at https://omniweb.gsfc.nasa.gov/ow.html

Interplanetary Magnetic Field (IMF) data: Helps in understanding the interaction of the Sun with the Earth's magnetosphere. Data used in this study consists of the total strength of IMF (B_t), x- and y- components B_x and B_y, and the southward (downward) component of the IMF B_z. Available at https://omniweb.gsfc.nasa.gov/ow.html

TEC and ROTI: Used to understand ionospheric irregularities. It is calculated using GNSS data available at https://www.igs.org/data/

3 Results

3.1 Global parameters

The typical polar ionospheric parameters used in characterising the polar patch scenario are as follows:

$$n_0 = 10^{11}\ m^{-3}$$
$$B_0 = 0.5\ G$$
$$T_e, T_i = 1000^0 k$$
$$\frac{\Omega_e}{\nu_{ei}} \sim \frac{\Omega_i}{\nu_{in}} \sim 10^2$$
$$\varepsilon_n^{-1} = L_N \sim 5X10^4\ m$$
$$l_s \sim 3X10^6\ m$$
$$V_{0\perp x} \sim 2X10^2\ m/\sec$$
$$V_{0z} \sim 6X10^4\ m/\sec$$
$$E_{0x} \sim 10\ mv/m$$
$$j_{0\|} = 8\ \mu\ amp\ m^{-2}$$
$$Blob\,Velocity = 200\ m/s$$

Here, the basic notations typical to the polar ionospheric parameters are: n_0 is the ambient plasma number density, $B_0 = 0.5$ is the ambient magnetic field, T_e is the equilibrium electron temperature, T_i is the equilibrium ion temperature, Ω_i is the ion gyrofrequency, Ω_e is the electron gyrofrequency, ν_{ei} is the electron to ion species collision frequency, ν_{in} is the ion to neutral species collision frequency, L_N is the density inhomogeneity scale length of the polar cusp region, l_s is the magnetic shear scale length, E_{0x} is the equilibrium electric field arising due to the perpendicular flow, $j_0 \|$ is the equilibrium current arising due to the parallel flow in the polar cusp region. $V_{0\perp x}$ is the equilibrium plasma drift in the perpendicular direction, V_{0z} is the equilibrium plasma drift in the parallel direction [7]. The resultant equilibrium plasma drifts deduced from the ambient perpendicular and parallel dynamics imparts the finite velocity to the plasma patch/blob. It turns out that the convection dynamics of these high density patches/blobs are controlled by the resultant equilibrium plasma drifts.

Fig. 1 shows the global parameters of geomagnetic data. These help in assessing the quality and intensity of a storm. The Dst value (a) subsided to reach its minimum at 0200 UT and underwent a declining phase again from 1200 UT.

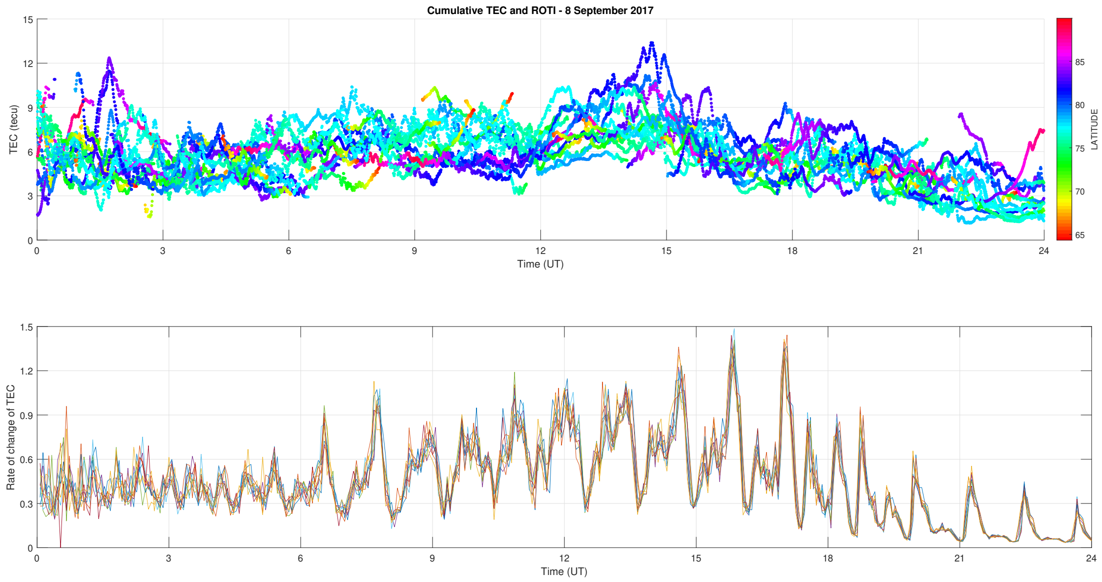

Figure 2. Top: Cumulative TEC over the 24-hr; Bottom: 2-D ROTI for 8 Sep 2017

A CME arising from a sunspot region that is close to the centre of the Earth-facing solar disk is capable of producing aurora when it reaches the Earth. For the first half of the day, observed $K_p \geq 4$ (b). $K_p = 4$ strengthens the chances of auroral activity at high latitudes whereas, at middle and low latitudes, a higher K_p will be needed to achieve auroral spotting. An important parameter observed is the AE index which indicates the overall disturbance activity of the electrojets. It is the difference between the eastward and westward electrojets in the auroral region, i.e. $AE = AU - AL$. From (c), an increased level of AE was observed. AE began with a swift rise at 1100 UT and then sharply increased to attain about 1500nT at 1500UT; after which it started subsiding slowly, marking the exit of CME. AE index is a quantitative and qualitative representation of the ionospheric and magnetic disturbances below and within the auroral oval and is used to understand the coupling between the interplanetary magnetic field and the earth's magnetosphere. B_t represents the combined magnetic field strength in the north-south, east-west, and towards and away-from-Sun directions. (d) shows an enhanced B_t of 20+nT during the early and mid-day hours. This is correlated by a negative/southward B_z during the same hours, indicating a connection with the Earth's magnetosphere. B_z is another important parameter that helps in understanding auroral activity.

3.2 TEC, ROTI and Scintillation indices

Periods of solar activity that cause changes in the near-Earth environment should correspond with the TEC enhancements and depletions. To affirm and understand this, ionospheric irregularities causing GPS scintillation at high latitudes are often studied in the context of storm events [10]. Fig. 2 (top) shows the cumulative TEC from all visible PRNs, latitude wise. It indicates the presence of electron density irregularities dominated in the region of 75° and above. TEC enhancements of the order of ≥ 9 tecu were observed in 75° region at about 0200 UT, with fewer spottings in the 80° region. Midnight behaviour of TEC enhancement is owed to substorm behaviour and charged particle precipitation. The magnetic reconnection enables the transfer of energy leading to high variational TEC in the polar regions. After mid-day the pattern changed as prominence increased in the 80° region with TEC rising to 14tecu. This can be explained by the drifting of charged particles from the nightside due to ionopsheric currents. These irregularities are a function of time and geographical location and are higher due convecting plasma dominated by the presence of large-scale(200–1000 km) clouds of high-density plasma and F region patches [11].

Previous studies have concluded ROTI to be good indicators for the presence of ionospheric irregularities even though their individual magnitudes can differ. The correlation between ROTI and scintillation indices varies with geographical location and latitudes, however, a stronger correlation exists between ROTI and σ_ϕ over ROTI and S_4 due to ionospheric plasma structures and high speed plasma convection in the polar region. ROTI $\geq$ 0.5 tecu indicates the presence of ionospheric irregularities at scale lengths of a few kilometers [12]. Fig. 2 (bottom) demonstrates consistent ROTI oscillations in the range of 0.3-0.5 tecu in the mid-night sector indicating moderate to strong geomagnetic activity due to magnetic reconnection of charged particles. The mid-day phase of the storm observed ROTI peaks at 1.5tecu which can be attributed to R1 and R2 currents that circle the auroral oval as they precipitate in the dawn-noon sector. In terms of σ_ϕ, scintillation is characterised as 0.1< weak <0.25 rad, 0.25<moderate<0.5 rad or >0.5 strong wrt ROTI, indicating that TEC and ROTI estimates at polar/auroral latitudes exhibit a statistically significant relationship and could be used as scintillation proxies [13] [14].

4 Conclusion

For both scientific understanding and practically monitoring space weather conditions, it is crucial to identify the actual sources and drivers leading to the strong scintillation estimates. Ny-Ålesund is ideally located to observe GPS scintillations modulated by the ionosphere cusp dynamics and is important for velocity shear and magnetic shear induced effects on polar patches. This paper observes the typical classification of scintillation occurrences suggesting strong GPS phase scintillation in relation to TEC and ROTI, signifying that TEC enhancements and strong ROTI oscillations indicate storm behaviour in polar regions and supports the argument of work. Further, the relative generative mechanism for the density structures such as polar cap patches, blobs Type I and Type II, have to be understood in terms of their origin from the tongue of ionisation and auroral particle precipitation.

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