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Radio-based Sensing of Turbulent, Ionospheric Flow: A Four-dimensional View

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Abstract

This talk will present the results from combining two new and fundamentally different radio-based methods to obtain electrodynamic and spectral measurements of ionospheric turbulence, using the coherent scatter radar ICEBEAR, as well as a CHAIN GPS receiver. We compare the two-point correlation function of coherent echoes in the auroral E-region (its spectrum) to the power spectrum of amplitude scintillations observed in ground-based GPS receivers. We also compare the apparent motion of radar echo clusters to the plasma drift speed derived from GPS signal analysis. Whereas the two methods rely on completely different signals (one spatial and one temporal), they nevertheless produce consistent velocity readings of the flowing ionospheric plasma, as well consistent spectral measurements of the internal structuring of that turbulent flow.

1. Introduction

The ionosphere is a dynamic layer of partially ionized gas that features a prominent large-scale convection cycle at high latitudes, and the extant ionization supports large-scale electrical currents flowing into and out of the ionosphere. During disturbed conditions, the magnetosphere dissipates pent-up energy into the ionosphere, now acting as a resistor. Part of this dissipation (which at times characterizes the ionosphere-magnetosphere coupling) comes in the form of electrostatic plasma turbulence. The swirls, or eddies, in the flowing plasma couple with each-other non-linearly, producing complex and stochastic structures [1, 2] that invariably end up disrupting human signal communication and navigational efforts [3].

With recent hardware and software advances in remote radio-based sensing, we are able to present a comprehensive view of such plasma turbulence, as it unfolds in the nothern hemisphere auroral region. The observational theatre, located in Saskatchewan, Canada, is illustrated in Figure 1a). The ICEBEAR radar and a CHAIN GPS receiver, separated by around 700 km, measure E-region turbulence and overhead GPS scintillations respectively. The two signals (panels b and d) are then further analyzed. As we shall demonstrate, the result constitutes four-dimensional measurements of a turbulent flow of plasma through the observational volume.

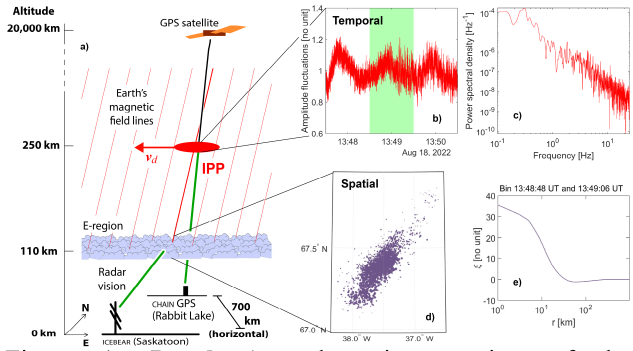

Figure 1: **Panel a):** schematic overview of the measurement situation. ICEBEAR is observing an unstable E-region that in general does not $E \times B$-drift, while the CHAIN GPS receiver is recording stoachistic fluctuations in signal amplitude that took place at a "frozen-in" altitude. **Panel b):** the L2 amplitude fluctuations on the Rabbit Lake CHAIN GPS receiver observed during an extended interval centered on 13:48 UT [4]. **Panel c):** amplitude spectrum of the fluctuations inside the green region in Panel a), calculated using a fast-Fourier transform technique. **Panel d):** an ICEBEAR radar point-cloud plotted in geomagnetic coordinates, consisting of 1950 echoes collected during the 18-second interval following 13:48:48 UT, clustered using the method presented in Ref. [5]. **Panel e):** the two-point correlation function of the point-cloud in panel d), calculated using the method presented in Ref. [6]

2. Method

The spatial part of the signal consist of coherent scatter radar data from ICEBEAR, an experimental radar capable of imaging the distribution of small-scale (3 m) plasma turbulence in 3-dimensions (3D) [7, 8] (Figure 1d–e). Ref. [6] developed a method to correlate the distances between all possible echo pairs, a method that yields spatial powerspectra $P(k)$ [9, 10],

$$P(k) = \int_0^\infty \xi(r) J0(kr)\, r dr, \qquad (1).$$

where ξ is the two-point correlation function assuming statistical anisotropy (Figure 1e), and $J_0(kr)$ are zeroth order Bessel functions of the first kind. Such powerspectra yield spectral information roughly between the scale sizes 750 m and ~ 10^5 m, much larger than the ICEBEAR radar wavelength (3 m). Later, the spectra were demonstrated to match the small-scale structuring of field-aligned electrical currents associated with pulsating aurorae [11].

Next, we shall derive a (spatial) *k*-spectrum from the temporal amplitude fluctuations (Figure 1b) in a CHAIN GPS receiver using phase screen theory [12]. Here, the Fresnel frequency f_F is derived using,

$$fF = \frac{vd}{\lambda F}$$

where v_d is an average F-region drift velocity determined with the aid of the ionosphere free linear combination (IFLC) technique. It is used to remove the refractive component of the signal, leaving behind the diffractive component. The Fresnel frequency f_F is then estimated from the breakpoint or "knee" in the IFLC spectrum [13], assuming a height of 250 km for the frozen-in irregularities. This value is compared to the value of f_F derived from the zero-crossing of the normalized cross-spectrum of the L1-L2 or L1-L5 carrier frequencies [13]. The resulting *k*-spectrum yields spectral information on scales roughly between 5 km and 300 m, with additional spectral information down to 10s-of-meters that is likely affected by noise.

In summary, Figure 1 provides an overview of the temporal (panels b, c) and spatial (panels d, e) signals from which we derive a comprehensive spectral characterization of the turbulent, ionospheric flow. Both the signals yield an independent measurement of drift speeds and the internal structure of the turbulent flow. Remarkably, the two datasets deliver highly consistent results.

3 Results

Figure 2 shows the result of the composite analysis described in the previous section. Panel a) shows an overview of the various ICEBEAR echo point clouds observed during 13:47 UT–13:56 UT (grey points), a spatio-temporal average vector field derived from the echo cluster motions (red arrows), and the ionospheric pierce point (IPP) whose amplitude fluctuations were observed and analyzed during the interval. Figure 2b) presents the two spectra, along with information about the turbulent decay in power. The rate at which power specteral density decays with increasing wavenumber tend to follow a power-law [15, 2, 16],

$$P(k) \propto k^{-\alpha},$$

where k denotes wavenumber ($k = 2\pi/L$, L being spatial scale), and α is a positive constant. In auroral plasma turbulence, such power decay, or 'cascade', often feature 'break-points' occurring on spatial scales between 1000 m – 5000 m [17, 18, 19] and between 30 m – 300 m [20, 21, 16, 22]. Such break-points often mark the onset of *energy injection* [21, 23, 18].

During the event under study, the two spectra (black and red lines in Figure 2b) measure a remarkably similar value of α; 3.32 and 3.35, for wavenumbers around 1 km. In addition, we observe a prominent spectral break-points at around 5 km and at the Fresnel-scale at around 300 m.

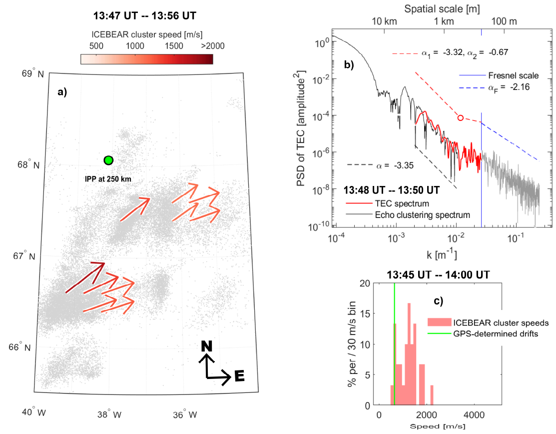

Figure 2: Comprehensive overview of the conjugate observations made during the minor amplitude scintillation event in Figure 1. **Panel a)** shows ICEBEAR cluster velocities calculated using the method presented in Ref. [5], velocities that measure the ionospheric electric field [14]. **Panel b)** compares the ICEBEAR clustering spectrum (black) with the GPS amplitude spectrum (red) observed during the event. **Panel c)** compares the distribution of ICEBEAR cluster speeds (red histogram) with the average drift speed derived from the IFLC spectrum (vertical green line) [13].

Panel c) compares the distribution of ICEBEAR speeds observed during an extended interval (13:45 UT–14:00 UT) to the GPS-derived average F-region drift speed. The distribution of ICEBEAR cluster speeds (red histogram) is consistent with the average F-region drifts derived from a cross-correlation analysis of different frequencies.

4 Discussion

In Figure 2, the ionospheric pierce-point, the point at which the observed CHAIN GPS amplitude disturbances are believed to take place, is necessarily "frozen into" the geomagnetic field [13], whereas the ICEBEAR radar data stem from plasma in the E-region which explicitly does not $E \times B$-drift. The latter, however, closely follows the ionospheric electric field, in effect bypassing the retarding action of ion-neutral collisions that has hitherto kep E-region radars from measuring electric fields [5, 14, 24]. The two signals then produce a matching spatial spectrum (Figure 2b) as well as consistent velocity measurements (Figure 2c). This is a strong indication that the GPS amplitude fluctuations did in fact take place at a "frozen-in" altitude of ionosphere, and that the turbulence which produced those amplitude fluctuations are *mapping down to the E-region* through the field-perpendicular organization of magnetic field-tubes. The mapping is consistent with theoretical predictions (see, e.g., Figure B1 in Ref. [23]) and observations [19], and is also consistent with recent studies that show how field-aligned current filamentation carries a clear signature of E-region turbulence [6, 11].

Given that the CHAIN GPS receiver is observing "frozen-in" turbulence, we conclude that the tentative result of the present investigation constitutes a completely novel approach to understanding *turbulent flows* of ionospheric plasma, with a method that simultaneously characterizes the flow speed, direction, and internal, turbulent structure. The break-points in Figure 2b) at around 5 km and 300 m may indicate the action of plasma instabilities in shaping the internal structure of the flow, disrupting the otherwise steep decay in power.

While *in-situ* observations of such turbulent structuring can measure spatio-temporal turbulence as it appears projected onto a one-dimensional line, our method is privy to the full spatio-temporal ("4D") turbulent signal. Such a comprehensive view of auroral plasma turbulence is highly sought-after, and the ground-based suite of instrumentation that we present here will surely play a significant role in future investigations that seek to incorporate the non-linear aspect of the ionosphere-magnetosphere coupling.

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