AURORAL IONOSPHERE PLASMA TURBULENCE TRANSPORT COEFFICIENT: DIRECT OBSERVATIONS FROM RADAR COHERENT BACKSCATTERING

R. André[1], **D. Grésillon**[2], C. Hanuise[3] and J.-P. Villain[1]

[1]*LPCE/CNRS, 3A Av. de la Recherche Scientifique 45071 Orléans cedex 2, France*
[2]*PMI, Ecole Polytechnique, 91128 Palaiseau, France*
[3]*LSEET/Université de Toulon, BP132, 83957 La Garde cedex, France*

Abstract

The plasma transport coefficient in the auroral turbulent ionosphere is systematically measured by the SuperDARN network. The measurement principle and technique are described and validated. High values of the diffusion coefficient are found and discussed.

1. Introduction

Observations of the auroral ionosphere by coherent radar backscattering provide information on the electron density volume fluctuations and motion across the magnetic field lines. Observations are now routinely obtained by the SuperDARN radar network over the arctic polar region, providing not only the echo intensity and Doppler velocities but also the echo time correlation function. The later contains information on the microscale plasma motion which are worth using. To this purpose, we devised a model based on the hypothesis of fluctuations being made not of progressive waves but of irregular convective motion. This model is presented here, as well as the results it provides from the SuperDARN data.

2. Plasma motion and collective scattering signal time correlation

Scattering of an electromagnetic wave is known to provide a space Fourier transform of the elementary scatterers space distribution [1]. The scattered electromagnetic wave is amplitude modulated by the complex signal s(t)

$$s(t) \ = \ \int_V e^{-i\vec{k}.\vec{r}} \, \delta n(\vec{r},t) \, dr^3 \tag{1}$$

where the effective analyzing scattering wavevector $\vec{k}$ is the vector difference between the scattered- and the incident- electromagnetic wavevectors. For coherent scattering conditions, the scattering wavelength is much longer than the Debye length and observations are concentrated on slow time scales (much longer than the plasma period). This implies the plasma scattering elements to be the dressed ions and the density δn in Eq. (1) is the ion density. The signal time modulation is related to the ion fluctuating density field evolution. We wish to establish which kind of plasma properties can be obtained from the scattered signal analysis. This is possible if we hypothesize the space-time fluctuation evolution to result only from the plasma convection, i.e., density irregularities are assumed to be convected at the local flow velocity. This is how most of the neutral turbulent gas fluctuations behave, and furthermore, it is compatible with

MHD plasma dynamics. The signal time correlation function is the averaged product of two signal values (such as in Eq. (1)) obtained at two different times. Using mass conservation, the autocorrelation function can be shown to be [2]

$$< s(t).s(t+\tau) > \; = \; S(\vec{k}) \;. \; < e^{i\vec{k}.\vec{\Delta}(\tau)} > \;. \; e^{i\vec{k}.\vec{V_0}\tau} \tag{2}$$

where $S(\vec{k})$ is the so-called "form factor", made from the square density space Fourier transform. It quantifies the plasma space distribution irregularity. $\vec{\Delta}(\tau)$ is the plasma displacement in a time τ, in the plasma reference frame. The second term in Eq. (2) is the statistical "characteristics" of this plasma displacement probability distribution: it depends on time through the turbulent transport motion. The third term in Eq. (2) is the steady Doppler shift component. Displacement $\vec{\Delta}(\tau)$ is a lagrangian variable. Its probability distribution over a large enough observation volume can be assumed to be gaussian and its characteristic function is

$$< e^{i\vec{k}.\vec{\Delta}(\tau)} > \; = \; e^{-\frac{1}{2} <(\vec{k}.\vec{\Delta}(\tau))^2>}, \tag{3}$$

where $\Delta^2(\tau)$ is obtained from an integral of the lagrangian velocity $\delta\vec{v}$ correlation function $R_L(t)$,

$$\Delta^2(\tau) \; = \; 2.\tau \; < \delta\vec{v}.\delta\vec{v} > \int_0^\tau \; (\tau - t) \; R_L(t) \; dt. \tag{4}$$

As shown by *Monin and Yaglom* [3], $R_L(t)$ can be assumed to be an exponential decay

$$R_L \; = \; e^{-\frac{t}{T_L}} \tag{5}$$

In which case,

$$\Delta^2(\tau) \; = \; 2.D.T_L \; (\frac{\tau}{T_L} \; + e^{-\frac{\tau}{T_L}} \; - \; 1) \tag{6}$$

where the lagrangian correlation time T_L and the diffusion coefficient D (in the direction of $\vec{k}$) are defined as

$$T_L \; = \; \int_0^\infty \; R_L(\tau) \; d\tau \tag{7}$$

$$D \; = \; < \delta\vec{v}.\delta\vec{v} > T_L \tag{8}$$

Then measurements of the temporal dependence of the complex signal autocorrelation function amplitude can be compared to Eq. (6) to check if the convective motion hypothesis appropriately predicts the experimental result. If it does, a numerical best fit of these measurements provides a determination of the plasma turbulent diffusion coefficient, and of the autocorrelation integral time scale.

3. Measurement of turbulent transport in the auroral ionosphere

SuperDARN is a network of coherent radar over the northern and southern polar regions, aimed at observation of the solar wind forcing on ionospheric convection. Collective backscattering is used to determine the plasma velocity (in a plane perpendicular to the magnetic field) by Doppler shift. A multipulse transmission and detection scheme leads to the determination of the complex autocorrelation function. Radar frequencies are ranging between 9 and 14 MHz, thus the probed irregularity wavelength is of the order of 15 m, much greater than Debye length ($\lambda_D \approx 1cm$), and greater than ion Larmor radius ($\rho_{ci} \approx 3m$). A typical example of a signal correlation is shown in Figure 1 as a series of black dots. The analytical characteristic function (Eq. (3) and (6)) that best fits these results is shown as the full line: it is obtained with a turbulent diffusion coefficient of 314 m^2/s and a correlation time of 13.5 ms.

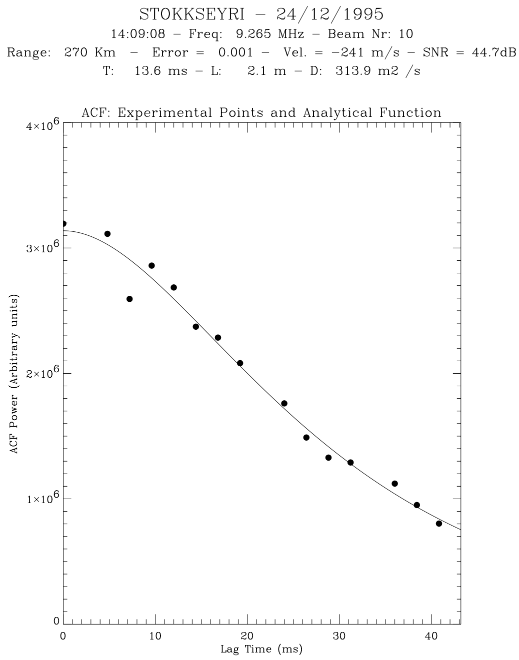

Figure 1.

As a first check of this method, the turbulent diffusion coefficient thus obtained should be independent of the radar frequency. It is not possible to probe the same plasma position and state simultaneously by two radar beams of different frequency since the e.m. ray trajectories are different.

But it is possible to look at a large number of measurements and form histograms of the obtained diffusion coefficients at two radar frequencies. This is shown in Figure 2. The two different radar frequencies are 9 and 12MHz (analyzing wavelengths are 16.7 and 12.5 m resp.). The two distributions clearly show different characteristics. The one obtained at 9 MHz (red/gray area) is maximum for a diffusion coefficient of 400 m^2/s and displays a large width (200 m^2/s), whereas the 12 MHz histogram (blue/black area) is maximum at 100 m^2/s with a smaller width (50 m^2/s). Thus, changing the effective wavelength by a factor of 1.3 leads to an increase of the measured diffusion coefficient by a factor of 4. Using other radar frequency channels, it is found that distributions obtained for radar frequency comprised between 11 and 14 MHz are nearly identical to the one at 12 MHz.

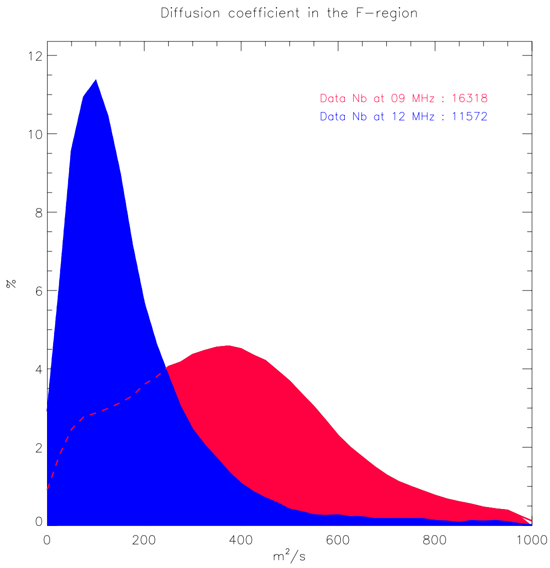

Figure 2.

The diffusion coefficients obtained with a high frequency radar (above 11 MHz) are of the order of 100 m^2/s. This is of the order of the Bohm diffusion coefficient which could apply to a turbulent plasma in the collisionless F-region, where it is estimated to be 125 m^2/s. It is also of the order of the microscopic ion cross B-field diffusion coefficient in the collisional E-region where this coefficient reaches its maximum value. But for lower radar frequencies, this numericaly obtained "best fit diffusion coefficient" is found to behave abnormally. It increases when the radar frequency decreases down to the typical ionospheric plasma frequency (7 MHz). This strongly suggests a deterioration of the radar beam coherence due to the ionospheric irregularities effects on propagation. This effect is stronger as the radar frequency comes closer to the plasma frequency, whereby the spectrum width increases and also, consequently, the measured diffusion coefficient. In addition, it should increase with the radar wave propagation path length. This is what is found in Figure 3. This figure shows two families of 2-dimensional isocontours of the "best fit diffusion coefficient" values occurence frequency distribution, obtained as a function of the echo distance. To this purpose, over 100,000 time correlation functions have been analyzed. The distributions are plotted for radar frequencies of 9 (red/greyline) and 12 MHz (blue/black line). For short propagation distances, both distributions are close to each other. At 12 MHz, the "best fit diffusion coefficient" is distance independent while at 9 MHz it is linearly increasing with the propagation length. These findings support that our model provides an accurate diffusion coefficient determination at high radar frequencies and that a systematic bias is added by propagation in large optical index fluctuations at lower radar frequencies.

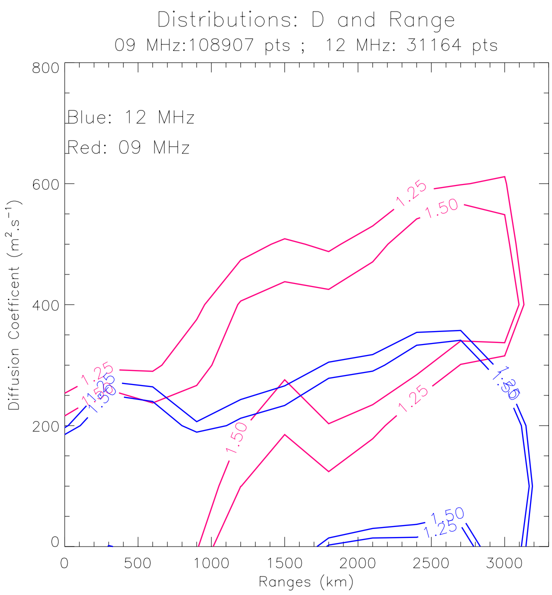

Figure 3.

4. Conclusion

Coherent radar backscattering signal time correlation functions show features that are consistent with a model of scattering out of plasma turbulence convected density fluctuations. A continuous monitoring of the auroral ionospheric plasma diffusion coefficient is possible, provided the radar frequency is above 1.6 the mean plasma frequency. New insights into the ionosphere plasma physics are open. The similarity between the observed plasma diffusion coefficients and the expected maximum collisional microscopic ion cross-B diffusion coefficient is probably significant.

References

[1] I.H. Hutchinson: Principles of plasma diagnostics. Cambridge university press, Cambridge (1987), Chap. 7.

[2] J-P. Villain, R. André, C. Hanuise and D. Grésillon: Observation of the high latitude ionosphere by HF radars. Interpretation in terms of collective wave scattering and characterization of the turbulence. J. of Atmospheric and Terrestrial Physics (*special issue: Electromagnetic Scattering from Gases And Plasmas (ESGAP)*, Aussois, France, March 1994, Vol. 58, No 8/9, pp. 943-958 (1996)

[3] A.S. Monin and A.M. Yaglom: Statistical Fluid Mechanics. Vol. 1, MIT Press, 1971