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Resolving F-region irregularity spectra using novel incoherent scatter radar methods

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Abstract

Plasma structuring in the high-latitude ionosphere impacts over-the-horizon radio communication and global navigation systems, and are an important space weather effect. Therefore, characterizing the formation and morphology of these structures is critically important. Irregularity spectra are useful for quantifying which plasma structures are abundant in the high-latitude ionosphere, as well as their drivers. From this information it is then possible to forecast the occurrence of irregularities and predict their impact on radio wave propagation. By leveraging phased array incoherent scatter radar (ISR) technology, and using the facts that, cross-field diffusion is slow at scale lengths greater than 10 km, and the magnetic field lines are nearly vertical at high-latitudes, we develop and apply a novel technique for ISR measurements to resolve high-latitude ionospheric irregularity spectra at a higher spatial-temporal resolution than has been previously possible with ground-based instruments. We will motivate the newly developed ISR technique, describe its methodology, and provide results demonstrating its effectiveness. This technique will enable future studies that will directly link high-latitude ionospheric plasma structure drivers to their impact on radio wave propagation.

1 Introduction

Plasma structures form, move, and evolve within the ionosphere, altering radio wave propagation and degrading the performance of critical technologies, such as global navigation satellite systems (GNSS) [1, 2], and over-the-horizon communication systems [3, 4]. In situ measurements from rockets and spacecraft are able to probe the plasma density of these irregularities at a high-resolution (e.g. down to the decameter scale [5, 6]), but they only provide a measurement at a specific time and location. Meanwhile, ground-based instruments are able to monitor a large geographic region over a longer period of time. The Super Dual Auroral Radar Network (SuperDARN), for example, provides excellent global coverage of plasma convection by monitoring the phase velocity of backscatter echoes generated by decameter scale plasma irregularities within the ionosphere [7]. However, SuperDARN can only examine field-aligned irregularities and only at the decameter scale. The performance of this network is also vulnerable to poor radio wave propagation conditions during geomagnetically active periods [8]. On the other hand, incoherent scatter radars (ISRs), which are not as vulnerable to poor radio wave propagation conditions, provide high-resolution plasma density measurements in both time and space over a large geographic region (albeit a smaller region than the coverage a SuperDARN radar provides).

There are several ways in which plasma structuring can be quantified using ISRs. For example, much work has been done using ISRs to examine polar cap patches, which are polar cap plasma density enhancements twice that of the ambient background ionosphere (these are often associated with optical structures, known as airglow patches). These structures have been of particular interest to the space weather community because they are associated with magnetosphere-ionosphere coupling and are often collocated with enhanced electric fields [9], as well as decameter irregularity growth associated with SuperDARN radar backscatter echoes [10]. High-resolution ISR measurements not only allow us to detect patches passing through the ISR field-of-view [11], but allow us to study the different mechanisms by which they can be formed [12] and their morphology [13].

Since the scale-size and occurrence of a plasma density irregularity is linked to its generation mechanism, as well as the dynamics and energy deposition of the high-latitude ionosphere, it is particularly useful to resolve more generally plasma density changes and structures as a function of spatial frequency. Previous studies have demonstrated the effectiveness of using ISR data in developing irregularity spectra. Figure 1 shows one spectrum resolved from Chatanika ISR observations of the midnight sector auroral zone at 350 km altitude [14]. It is similar to those subject to active precipitation in the dayside polar cusp (particularly the peak at 0.02 km^{-1}), indicating that soft electron precipitation is not just an important mechanism in driving dayside irregularities, but in driving irregularities throughout the entire high-latitude ionosphere.

Advances in ISR technology can be leveraged to improve upon previous studies in critical ways. For example, since

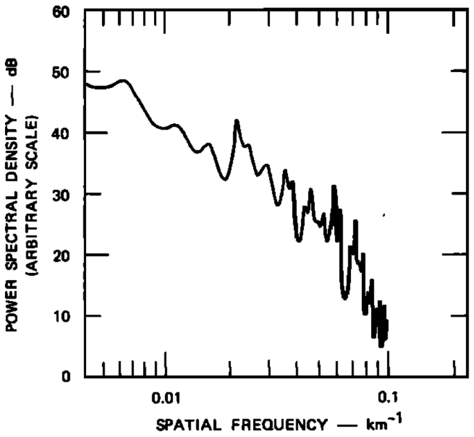

Figure 1. An irregularity spectrum developed using midnight auroral zone Chatanika ISR observations at 350 km altitude [14].

the Chatanika radar dish needed to be steered to resolve parameters from different lines-of-sight, scans could take upwards of 12 minutes to complete [14]. This is problematic given that high-latitude plasma flows can change dramatically within 12 minutes, redistributing plasma structures [15]. However, newer Advanced Modular ISRs (AMISRs) utilize an array of antennae and electronic beam steering to observe multiple directions nearly simultaneously. This modern development vastly improves the spatial-temporal resolution of ISR measurements.

The construction of three AMISR radars in the past 15 years is also an advantage. An AMISR radar at Poker Flat, Alaska - PFISR (Poker Flat ISR), and two AMISR radars at Resolute Bay, Canada - RISR-N and -C (Resolute Bay ISR North and Canada, respectively) can provide insight into ionospheric plasma structuring spanning from the sub-auroral to polar-cap region, whereas previous work focused primarily on the auroral region [14]. More recent studies have established that polar cap structures significantly impact radio wave propagation, dayside-nightside magnetosphere-ionosphere coupling, and coupling between the auroral region and polar cap [16]. However, the mechanisms that trigger polar cap structures and their signatures (such as enhanced flows and field-aligned current structures) are still not well understood. These open questions are an ideal target for an irregularity spectral analysis technique.

Given the variety of magnetospheric regions that map to the sub-auroral, auroral, and polar cap ionosphere, each with differing drivers and plasma density generation mechanisms, comparing irregularity spectra computed from RISR-N and -C to those from PFISR have the potential of significantly advancing our understanding of plasma dynamics in the high-latitude terrestrial ionosphere, and their connection to solar dynamics and radio wave propagation. The goal of this work is to use ISR observations to quantify the irregularity spectra of the high-latitude ionosphere

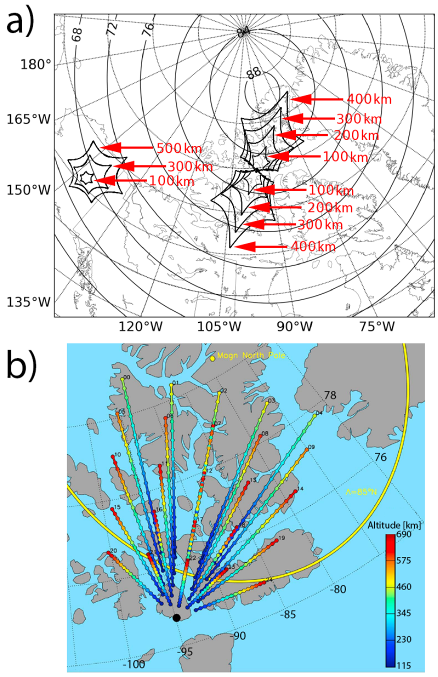

Figure 2. a) Field-of-view for the high-latitude AMISR facilities at a variety of altitudes. b) The RISR-N beam layout for a 25 beam WorldDay55m mode [17].

with precise and uniquely capable techniques. In the next section, we will discuss the methodology and instruments being used in this project.

2 Methodology

2.1 AMISR Instruments

The field-of-view of each of the three high-latitude AMISR facilities is shown in Figure 2, along with one example of how RISR-N's sampling points can be spread in space. RISR-N and RISR-C are located deep in the northern polar-cap - with RISR-N pointing northward and RISR-C pointing southward. RISR-N has been operating since 2009 while RISR-C has been operating since late 2015. Meanwhile, PFISR is positioned to observe auroral and subauroral regions, depending on geomagnetic activity, and has been operational since late 2007.

Despite the fact that some AMISR experimental modes have a large number of beams configured in a tightly packed sampling grid, they cannot provide an irregularity spectrum as finely resolved at 350 km altitude as the 10 km scale provided by the Chatanika ISR along a fixed magnetic meridian [14]. Along a given beam, an AMISR has a range resolution of approximately 24 km (50 km when ambiguity is considered) and a ~1-2 minute time resolution. Between 340 km and 360 km altitude, the smallest spatial distance achievable by a 25 beam "*WorldDay55m*" mode (shown in Figure 2, executed on RISR-N March 9 2010) is 120 km, a much coarser resolution than what the Chatanika experiment provided. Even a 52 beam "*Imaginglp*" mode (executed on RISR-N/-C April 4 2018) has an approximate scale of 20 km near 350 km altitude.

To resolve this, we will take advantage of the fact that the dominant transport mechanism parallel to the magnetic field between 200 km and 400 km altitude is diffusion [18, 19, 20], and at the scale-sizes resolved by AMISRs the cross-field diffusion can be considered negligible. Since the magnetic field is essentially vertical at high-latitudes, we can make the assumption that the irregularity spectrum maps vertically along the magnetic field lines between 200 and 400 km. Thus, to first order, vertical changes in this region are only the result of scale height effects, which can be corrected for using an empirical model. By correcting for scale height, all of the AMISR sampling points in this altitude range can be used to infer the irregularity spectra at any given altitude within that range; that is, each sample can be mapped vertically along a field line. Thus, all of the sampling points can be mapped to the same altitude. This will allow for the density of sampling points at a given altitude to increase, providing a more highly resolved irregularity spectrum. This technique allows us to probe irregularities at a 10 km resolution, and allows us to use a wider variety of AMISR datasets for this study (tens of thousands of hours worth of data).

Initial results compensating for the scale-height effect for a single beam are shown in Figure 3. Here, Figure 3a shows RISR-N plasma density observations made using a single beam at an azimuth of 26° and an elevation angle of 55°. After correcting for scale height changes (adjusting the plasma density to its magnitude at 350 km), Figures 3b and 3c show the resolved spectra before and during a plasma density enhancement. A series of power law fits are shown, and are consistent with previous results [14]. Overall the spectrum increases as the plasma density increases, except near 2.2e-2 km^{-1}, which remains somewhat unchanged and shows an apparent dip. Sharp spectral structures such as these indicate the presence of a physical mechanism altering the irregularity scale-sizes. However, in this particular case, this feature may be the result of restricting our observations by using measurements from a single beam between 200 km and 400 km altitude. Our next step will be to resolve spectra that incorporate multiple beams simultaneously. This will improve our spectral resolution, and allow us to achieve comparable resolutions to Figure 1 over a wider region.

2.2 Validation using Swarm

It is possible to verify the irregularity spectra resolved with ISR measurements with those from spacecraft measurements, such as the Swarm constellation. Launched in 2013, the Swarm spacecraft are three identical spacecraft travelling in a polar orbit with a periodicity of approximately 1.5 hours. Swarm A and C are flying nearly side-by-side at an altitude of 460 km, while Swarm B is at 530 km. The orbital tracks of each spacecraft frequently intersect the PFISR and RISR-N/-C fields-of-view. Each spacecraft has two Langmuir probes, sampling at 2 Hz [21]. Although there are other similar spacecraft that currently orbit the Earth (e.g. Defense Meteorological Satellite Program, DMSP), only the Swarm spacecraft directly measure the plasma density at altitudes probed with ISR observations, making them particularly desirable.

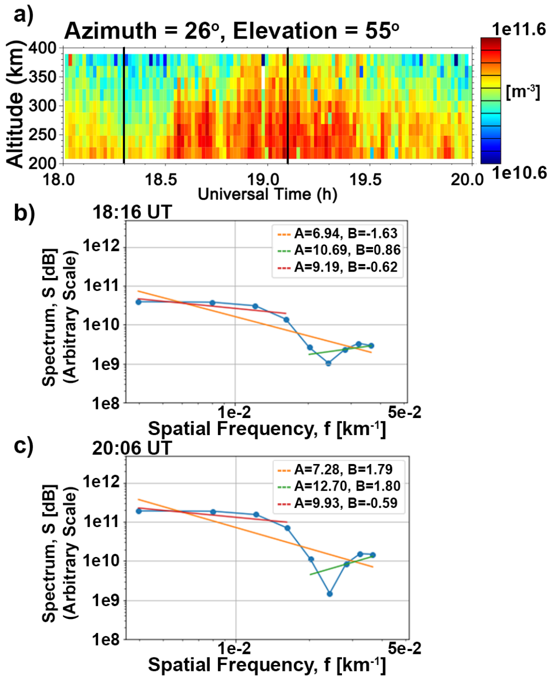

Figure 3. a) RISR-N September 12 2014 plasma density observations. b) and c) Irregularity spectra at 18:16 UT and 20:06 UT (respectively, indicated by the black lines in Panel a). Different power law fits are shown (orange is for the entire spectrum, green is between 0.02 km^{-1} and 0.05 km^{-1}, and red is less than 0.02^{-1}), where: $S = 10^A + f^B$.

3 Summary

Using novel ISR techniques and observation methods, high-latitude irregularities that disrupt radio propagation can be resolved at a finer spatiotemporal resolution than has been previously possible with ground-based observations (at 10 km scales). These measurements are used to compute irregularity spectra, which can then be used to find the typical spatial-scales, temporal-scales, and locations of irregularities in the high-latitude ionosphere. This will allow us to identify irregularity generation mechanisms and provide new knowledge into polar cap dynamics, space weather effects, and solar driving of the ionosphere.

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