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IMAGE Observations of "Patchy" Specularly Reflected Whistler Mode Echoes: A New Diagnostic Tool for Large-scale Field-aligned Irregularities

Amani Reddy*(1,2) and Vikas S. Sonwalkar(1)
(1) Department of Electrical Engineering, University of Alaska Fairbanks, Fairbanks, AK, USA, email: areddy1@alaska.edu
(2) Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK, USA

Abstract

Field-aligned irregularities (FAIs) are one of the key indicators of space weather and physical processes that occur due to changing space weather conditions. Whistler mode (WM) radio sounding from the IMAGE satellite has led to observations of "Patchy" specularly reflected (SR) echoes, which provide a new way to measure FAI. Patchy SR echoes result from IMAGE signals (transmitted at different frequencies) propagating in the presence of large-scale FAI and returning to the satellite after reflecting specularly at the Earth's ionosphere boundary. The presence of FAI along the ray paths leads to the deflection of signals over a range of transmitted frequencies, resulting in a "patchy" echo pattern. Using patchy SR echoes observed on 22 October 2005, we demonstrate a raytracing method to determine FAI parameters. Our results indicate that irregularities of 10-100 km scale size at 200 – 1600 km and enhancement of 50-70% along L~ 2.185 explain observed patchy SR echoes. The method demonstrated here for FAI measurements applies to the lightning-generated whistlers (that display a patchy pattern) observed on spacecraft such as Van Allen Probes. Application of this method to patchy echoes/whistlers observed on spacecraft (e.g., IMAGE, DSX, Van Allen Probes) should provide data on ionospheric and magnetospheric plasma density structure not available previously and could be used to build empirical models of FAI that can potentially serve as an indicator of space weather.

1. Introduction

The generation of field-aligned irregularities (FAIs) is an important manifestation of (1) the injection of energy and momentum originating at the sun into the earth's atmosphere, (2) physical processes occurring in the underlying atmosphere, and (3) physical processes occurring in the overlying magnetosphere. FAIs occur at all latitudes, including low- and mid-latitudes, plasmapause, auroral, and polar regions [1-3]. FAIs are generated by various processes, including plasma instabilities, particle precipitation, and plasma drifts occurring in the ionosphere [1]. These plasma processes are enhanced during disturbed solar and geomagnetic conditions, leading to the generation of plasma density structures [4]. Thus, FAIs are key indicators of space weather and physical processes that occur due to changing space weather conditions. FAIs are also important from a practical standpoint because they contribute to the fading of high-frequency trans-ionospheric signals, the degradation of ground-to-satellite communication, and uncertainties in GPS signals [3]. Forecasting and specification of the irregularities that affect radio wave propagation is a major component of space weather programs [5].

In the past, FAIs were obtained mainly from the bottom and topside sounding of the ionosphere using radio waves in the HF range [1, 6] or from in situ satellite measurements using plasma density probes [7], ground-based instruments, including radars, all-sky airglow imager, digisondes, Fabry–Perot interferometer [4], and GPS ground and satellite receivers for TEC measurements [8-10]. Recently, a combination of observations from low altitude (<1000 km) satellites, ground-based radars, and GPS TEC receivers have been used to determine the altitudinal and latitudinal extent of FAIs at ionospheric heights [11].

Whistler mode (WM) waves play an important role in magnetospheric physics and have proved to be a powerful tool for magnetospheric cold and hot plasma diagnostics [12-14]. WM waves are profoundly affected by FAI of wide scale lengths (10 m – 100 km) present in the magnetosphere [15-18]. This makes WM waves a powerful remote sensing tool to detect and measure FAI. The modified structure of WM waves, resulting from FAI influence, has important consequences for wave-particle interactions and radiation belt dynamics. We present a new way to measure FAIs and their altitudinal extent using "patchy" Specularly Reflected (SR) WM echoes observed by Radio Plasma Imager (RPI) on the IMAGE satellite.

2. Observations and Interpretation of "Patchy" SR Echoes

Radio sounding using the RPI instrument on the IMAGE satellite has led to remote sensing of magnetospheric field-aligned electron and ion densities, locations of FAI, and ducts. The RPI transmitted 3.2 ms pulses in 3 kHz – 3 MHz frequency range, permitting radio sounding of the magnetosphere in all four cold plasma wave modes close to electron characteristic frequencies: free space R-X and L-O modes, Z mode (fast and slow), and whistler mode [19]. Echoes (RPI signals propagating into the magnetosphere and returning to the satellite) were

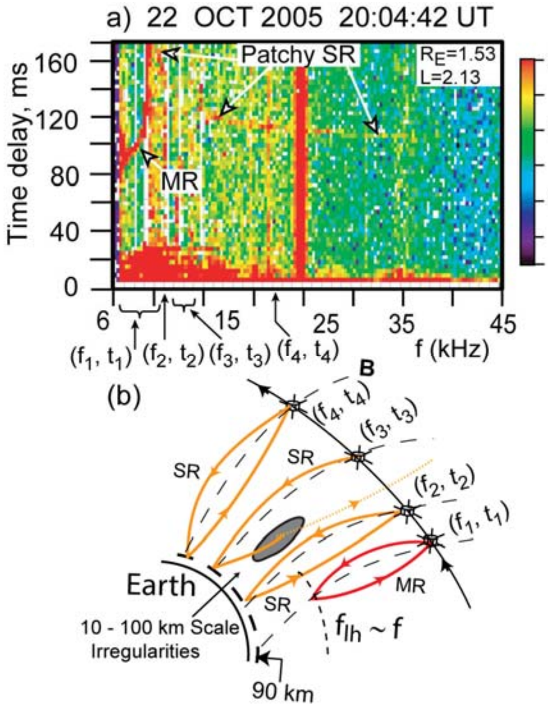

Figure 1. (a) An example showing MR and patchy SR echoes observed when IMAGE was at ~3400 km altitude [Adapted from 14]. (b) Schematic of the satellite along an orbit and generation of MR echoes at time t_1 and frequency f_1, SR echoes later at time t_2 and frequency f_2 and at time t_4 and frequency f_4, and no SR echoes at time t_3 and frequency f_3 due to deflection of RPI signals by large-scale FAIs.

observed in all four modes. Radio sounding in WM has led to observations of SR and magnetospherically reflected (MR) echoes. Both SR and MR echoes propagate very close to the geomagnetic field lines. Therefore, the observed dispersion of SR and MR echoes can be used to obtain measurements of field-aligned electron density (N_e) and ion (Ni: H^+, O^+, He^+) densities profiles from the satellite altitude (~5000 km) down to 90 km [18]. Specular reflection of RPI WM signals from the Earth-ionosphere boundary at 90 km permitted measurement below the F2 peak, and the magnetospheric reflection of WM signals at an altitude level where the wave frequency equals local lower hybrid frequency (f_{lh}) permitted measurement of both N_e and N_i. In addition to N_e and N_i, the dispersion of these echoes can be used to estimate the location and scale sizes of FAIs [18]. In this paper, we demonstrate a method to obtain the scale sizes and location of large-scale FAIs using "patchy" SR echoes observed on the IMAGE satellite.

Figure 1a shows a plasmagram of MR echoes (<10 kHz) and patchy SR echoes (>10 kHz) received by the X - antenna on IMAGE (altitude =3404 km, λ_m= 31.9° N, L = 2:13, and MLT= 11.2) on 22 October 2005. Figure 1b schematically shows the generation mechanism of these echoes. The SR echoes observed on 22 October 2005 are considered patchy because of the absence of SR echoes at a few frequencies. SR echoes are observed at frequencies ranging from 10.2 to 11.4 kHz and 14.7 to 33.3 kHz. The conspicuous gaps between 11.4 and 14.7 kHz may be

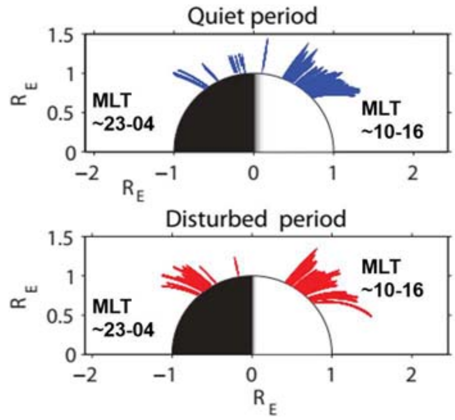

Figure 2. Estimated locations of large-scale irregularities during geomagnetically quiet and disturbed periods.

attributed to the deflection of the ray paths at these frequencies due to the presence of FAIs [20] (Figure 1b ray paths at f3, t3). 1. A survey of all the WM echoes during the August to December 2005 period revealed that almost all the SR echoes observed on IMAGE were patchy. The patchy SR echoes were observed at all latitudes and MLTs and during both quiet and disturbed geomagnetic conditions, indicating the presence of large-scale FAIs at all latitudes and under all geomagnetic conditions.

Since WM waves propagate close to the field lines, measuring frequencies at which echoes are absent and obtaining the L-shell of the satellite when those frequencies were transmitted gives the field lines along which large-scale FAIs may be present. We selected a two-month period (08 August 2005 to 07 October 2005) that included geomagnetically quiet time ($Kp < 3^+$, Dst > -20 nT) and disturbed periods ($Kp > 3^+$, Dst < -50 nT). Based on the frequency gaps and the satellite location (L-shell) corresponding to the gaps, we determined the L-shells along which FAI may be present. Figure 2 shows the estimated locations of FAIs during the quiet (top panel) and disturbed period (bottom panel). On the day side, the difference in the occurrence of FAIs during storm time relative to quiet time was marginal. On the night side, an increase in FAI occurrence at mid-latitudes was noticeable during disturbed periods relative to quiet time, confirming that FAIs respond to geomagnetic storms [8].

3. Raytracing Results

Assuming WM wave propagation in a smooth magnetosphere, using radio sounding inversion method, Sonwalkar et al. [17] analyzed MR and SR echoes shown in Figure 1a to obtain field-aligned electron and ion densities profiles (see Figure 9 in [18]) in the L-shell range 2.11 to 2.24 (L-shells traversed by MR and SR echo ray paths) on 22 October 2005. The measurements of N_e along these L-shells were extrapolated to construct the 2-dimensional electron density map shown in Figure 3a. Using Stanford 2-D raytracer [18], we perform raytracing simulations in a magnetosphere containing a large-scale FAI to explain the patchy SR echoes shown in Figure 1a.

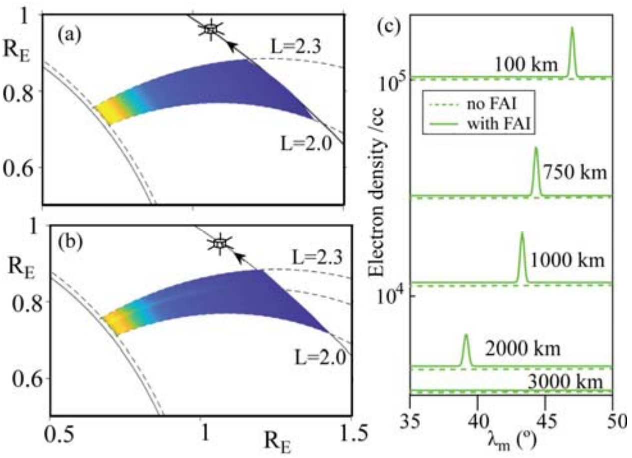

Figure 3. A 2-D map of the electron density constructed from the measurements of field-aligned electron density from the WM radio sounding along the IMAGE orbit on 22 Oct 2005, assuming RPI signal propagation in a smooth magnetosphere (a) and in a magnetosphere with FAI (b). (c) The latitudinal variation of N_e at different altitudes. The ray tracing density model assumes no latitudinal variation in electron density; therefore, in a smooth magnetosphere, N_e remains constant at a given altitude.

The raytracing simulation of patchy SR echoes involved an iterative procedure. The first step was determining FAI's probable location and scale size based on the raytracing simulations performed in a smooth magnetosphere (Figure 3a). Figure 4a, the top panel, shows three ray paths of SR WM waves at 12 kHz and 15 kHz, two rays passing on either side of the satellite and one ray passing through the satellite. The ray paths returning to the satellite at these frequencies span L-shells from approximately 2.13 to 2.2, indicating a possible FAI L-shell width (ΔL) of less than 0.07. The widest excursion of ray paths at these frequencies occurred at ~800 km altitude, suggesting that the FAI is within an altitude range of ~500 km to 1000 km.

Consistent with the raytracing results discussed above, an initial density model with typical FAI parameters is constructed. Raytracing calculations were performed to simulate SR echo ray paths in the 11.4 to 15 kHz frequency range. If the simulated ray paths in the 11.7 to 14.4 kHz frequency range return to the satellite, the location and scale size of the FAI are adjusted until ray paths at desired frequencies are deflected and do not reach the satellite.

Figure 3b shows the 2-D electron density map constructed from the measured field-aligned electron density along MR and SR echo ray paths. The electron density map includes an FAI along L=2.185 with ΔL=0.02L, $\Delta N_e/N_e$=70%, in the ~100 to 1600 km altitude range. These FAI parameters are consistent with past measurements of ionospheric irregularities at mid-latitudes [1, 4]. The raytracing density model assumes no latitudinal variation in N_e. Figure 3c shows the latitudinal extent of FAI at different altitudes. Note that the FAI disappears at 3000 km. Figure 4 bottom panel shows the simulated ray paths at f=12 kHz and f=15 kHz using the density model shown in figure 3b.

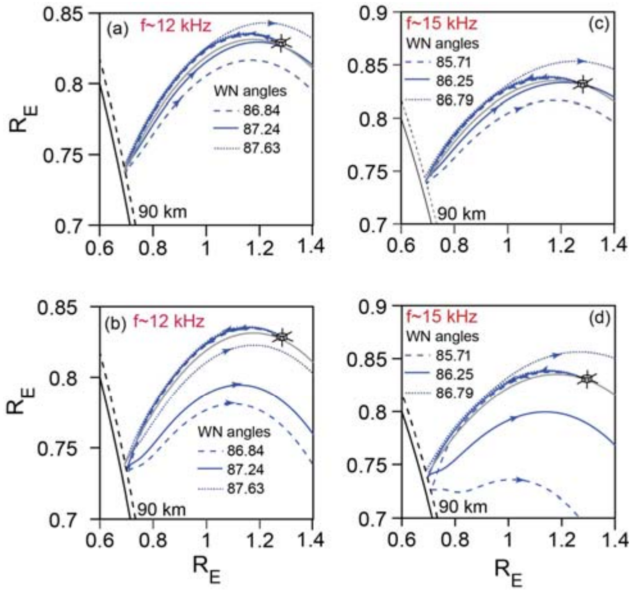

Figure 4. Ray paths of WM waves propagating in a smooth magnetosphere (top panel) and in the presence of FAI (bottom panel) at f=12 12 kHz (a, b) and at f=15 kHz (c, d).

The ray paths at f=12 kHz propagate towards L-shells lower than the satellite, leading to no SR echo at 12 kHz (figure 4b), whereas the ray paths at f=15 kHz propagate on both sides of the satellite (towards higher and lower L-shells) leading to an SR echo. Thus, we demonstrated that patchy echoes can be explained by large-scale irregularities at ionospheric altitudes deflecting RPI signals. The dispersion of patchy echoes could be used for remote sensing ionospheric FAIs, including their location, scale size, width, enhancement factor, and attitudinal extent. Furthermore, analysis of patchy echoes observed along the satellite orbit permits 2-D imaging of the magnetosphere with FAI.

4. Summary, Discussion and Conclusions

Analysis of patchy MR and SR echoes observed on IMAGE permits simultaneous measurements of FAI, electron density, and ion density profiles along field lines. Results from the analysis of patchy SR echoes on 22 Oct 2005 indicate that irregularities of 10-100 km scale size at ~100 – 1500 km and enhancement of 50-70% along L~ 2.185 explain the observed echo features. These measurements of irregularities are consistent with those measured in the past.

The method presented here applies to patchy SR and MR echoes observed on other spacecraft (e.g., DSX) and to lightning generated MR and SR whistlers [Sonwalkar and Reddy, 2024] (that display a patchy pattern) seen on spacecraft such as Van Allen Probes. Furthermore, analysis of patchy echoes/whistlers observed along a satellite orbit can used to obtain 2-D images of the magnetosphere with FAI. Such an analysis should provide measurements on ionospheric and magnetospheric plasma density structures that were not available previously. These measurements can lead to empirical models of FAI that can potentially serve as an indicator of space weather.

Most plasma structures at middle latitudes are largely due to the presence of large- and medium-scale perturbations that propagate through the region and are produced by neutral winds in the lower thermosphere that transport plasma parallel to the magnetic field. Therefore, knowledge of field-aligned electron and ion densities is critical to understanding the generation, sustenance, and decay mechanisms of FAI. Raytracing analysis of patchy SR and MR echoes provides information on FAI and field-aligned electron and ion density profiles. Such information combined with physics-based model simulations such as SAMI2 [21] should provide a new understanding of the physical processes and mechanisms important to generating irregularities.

6. Acknowledgements

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