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FIRST VHF RADAR OBSERVATION OF MIDLATITUDE F-REGION FIELD-ALIGNED IRREGULARITIES

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Abstract. We describe the first midlatitude F-region VHF radar observations of small-scale Field-Aligned Irregularities (FAI). Looking northward at ~ 34° elevation the locus of perpendicularity with the geomagnetic field B remains inside the radar beam, such that FAI can be observed, at radar ranges from 350 to over 800 km or F region altitudes from 200 to 500 km, approximately. The preliminary results presented here show the large-scale (> 20 km) configuration of small-scale (322.6 cm, half the radar wavelength) F-region irregularities as well as typical spectral results. Our most important finding is that at least on some occasions there is a quasi-periodic variation in time and space, on scales of approximately 12 minutes and 50 km, of the observed plasma instabilities.

Introduction

The MU (Middle and Upper atmosphere) radar (Fukao et al., 1985a,b) at (34.85° N, 136.10° E) near Kyoto, Japan, can view perpendicular to the geomagnetic field B in the midlatitude F-region, seeing field-aligned irregularities (FAI) from ~ 38° to 43° N. FAI behavior clarifies both large-scale (> 20 km) and small-scale (half the radar wavelength or 322.6 cm) plasma instability processes (Fejer and Kelley, 1980; Kelley and McClure, 1981). We reach three preliminary conclusions: 1) FAI echoes are seen at all ranges (and corresponding monotonically increasing altitudes) observed, but at none preferentially, probably because midlatitude FAIs are not strongly layered in the direction parallel to B (at low latitudes one assumes only weak FAI variation in this direction). 2) A tendency exists for quasi-periodicity in range and/or time of FAI echoes. 3) The Doppler shift is often quite uniform over large regions where echoes are strong. Radial drifts of the order of 100 m/s and spectral widths of 20 to 30 Hz are typical.

The radar looked due north (5° E of magnetic N) at ~ 34° elevation. A 4.8 km or 32 μs 100 kW transmitter pulse at 46.5 MHz was used. The two-way half-power horizontal/vertical beamwidth is 2.3/4.5° (the pencil beam near the zenith distorts at small elevation angles). The east-west resolution is 20 km at 500 km range. The vertical resolution, parallel to B, is set by the FAI aspect sensitivity (Fejer and Kelley, 1980). The locus of perpendicularity with B follows a curved path into the beam near 350 km range (~ 200 km alt) and out again beyond 800 km range (~ 500 km alt). Using other beams containing this locus at smaller ranges, at altitudes from 100 to 140 km, we see E-region FAI correlated in intensity with F-region FAI found simultaneously on more distant magnetic shells. Further discussion of this is beyond our present scope.

At the look angles used, outside the design limits of the distributed transmitter/phased array, two grating lobes look south. Incoherent scatter is well below the cosmic noise and all FAI echoes come from the north beam, so the south beams can be ignored.

Experimental results

Power measurements are shown in Figure 1 in RTI (Range-Time-Intensity) format. Each flux tube is observed at one altitude only, but we see different tubes at a variety of altitudes and thus have indirect evidence regarding FAI distribution along B. To emphasize the perpendicular viewing geometry and the lack of direct altitude profile information, a magnetic shell coordinate, the "apex latitude" of VanZandt et al. (1972), replaces range in our RTI plots. For completeness the annotated latitude tics also approximately mark even 100 km altitude intervals (see caption). The field line Apex radius "A", in geocentric earth radii, corresponds to MacIlwain's parameter L; apex latitude (Alat = $\cos^{-1}(A)^{-1/2}$) is analogous to invariant latitude. Contours of echo power refer to the cosmic noise level, which was nearly constant (it varied <+ 2dB for the antenna position and observing periods used). The lowest contours shown (after integrating 40 to 60 sec) are below this reference.

Figure 1a shows data from 1-2 August 1986. Strong FAI first appeared near 36° N at 2240 hrs JST (Japan Standard Time, 135° E). By 2310 hrs strong echoes had begun at 32° N but had already vanished at 36° N. The leading edge of the echo envelope was relatively straight. The echoes near 32° N lasted for 2 hours. Those at higher latitudes reappeared intermittently. The envelope of the major FAI region is trapezoidal. The trailing edge and several internal features are nearly parallel to the leading edge. The low-latitude edge shows quasi-periodic 12-minute oscillations of >0.4° in apex latitude for fixed contours and > a few dB in intensity at fixed ranges. Other periodicities are visible, e.g., the signal strength oscillates as a function of both range and time just inside the leading edge of the signal.

Figure 1b shows data from 20-21 June 1986. Various echo centers appeared and vanished at

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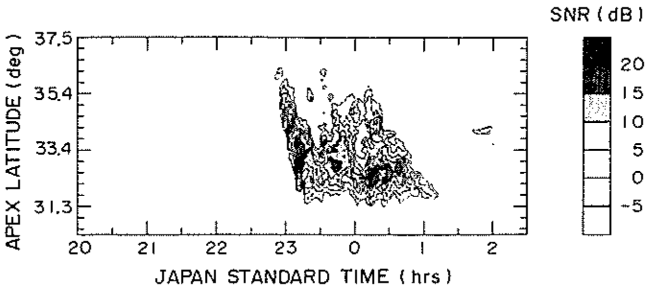

Fig. 1a. Contours of FAI echo signal strength vs. apex latitude and time for 1-2 August 1986. The vertical scale is also nearly linear in the related independent observing parameters, range and altitude. Approximate 100 km altitude intervals are marked by the major (annotated) Alat tics, starting with 200 km altitude at 31.3°. The zero dB reference level is the cosmic noise level before integration.

nearly constant ranges until 02 hrs, when a ridge of strong echoes gradually moved to higher latitudes for about 45 min, then faded into three parallel narrow ridges at ranges evenly spaced and decreasing with time. A tilted ridge at 33.4° and 01 hrs was paralleled by a larger ridge at 34° and 0220 hrs.

Figure 1c shows RTI data from 3-4 August 1986. The contours slope upward in Alat (upward and outward in distance along the beam) with time, first in the large strong patch centered at 2330 hrs and later in the parallel patches at 2350 hrs. Two weaker patches at higher latitudes at 00 hrs have the opposite slope.

Sample Doppler data from this night at 2332 hrs in Figure 1c are shown in Figure 2a. Positive velocities imply northward/upward radial drifts. Many spectra are observed to be steeper on one side than on the other. The half-power spectral widths are 20-30 Hz; aliasing limits are ± 200 m/s or ± 62 Hz. It appears these spectra are not aliased. The strongest signals yield a "ghost" spectral maximum at the negative of the velocity of the true spectral maximum. The ghost is an artifact of the imperfect detectors. It is, in fact, a friendly ghost, helping us see which are the strongest peaks (they are compressed by the log scale). Multiple spectral maxima occur at the nearest and farthest ranges shown, where signals are weaker, as well as at two central ranges, where the ghosts appear.

Figure 2b shows the northward drift vs. apex latitude and time for the same night, found by fitting a Gaussian to spectral data including that of Figure 2a. The statistical errors are small, only a few m/s. Fitting the observations to a Gaussian model is adequate for present purposes, although for detailed study of multiple or asymmetric spectra better schemes might be found. Note that the major regions of strong signal in Figure 1c correspond to the regions of large uniform northward drift centered near 2330 and 2350 hrs in Figure 2b, with the drift near zero between these patches.

The spectral and drift data of Figure 2 are typical examples. Wider and narrower spectra and larger drifts are sometimes seen. Aliasing occasionally occurs. Preliminary analysis indicates the spectra do not tend to widen as echo strength increases, as they do (except for bottomside altitudes) near the equator (McClure and Woodman, 1972; Woodman and LaHoz, 1976). Also, these midlatitude drifts (e.g., Figure 2b and other similar examples) appear to be more

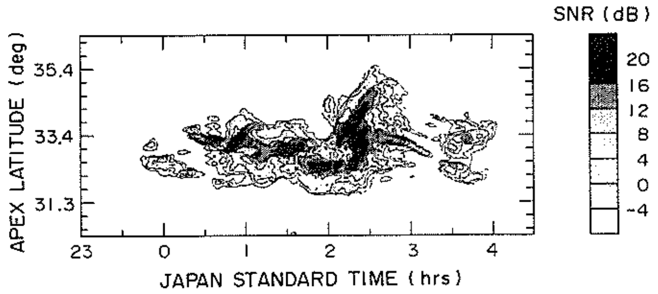

Fig. 1b. Data from 20-21 June 1986. See caption of Figure 1a for details.

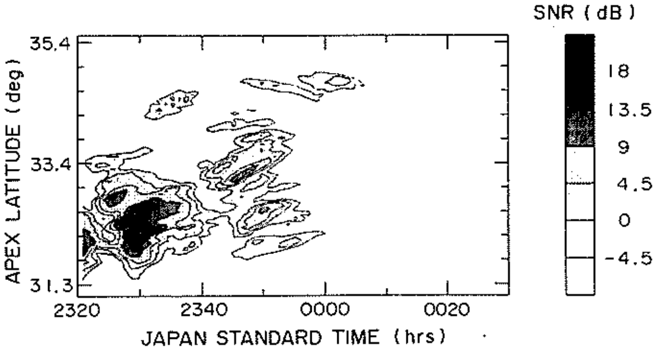

Fig. 1c. Data from 3-4 August 1986. See caption of Figure 1a for details.

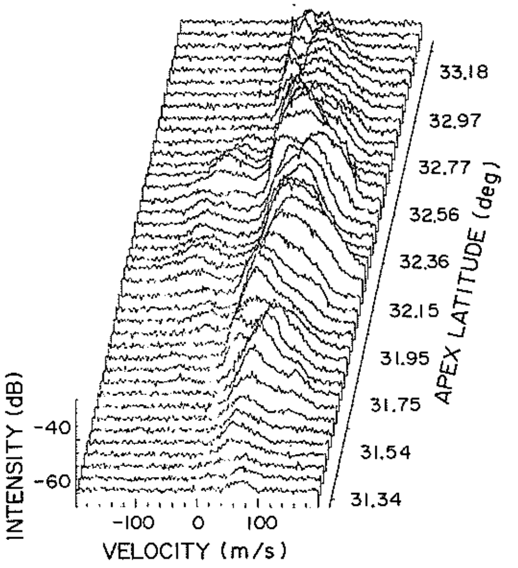

Fig. 2a. Frequency spectra vs. range for 66 sec centered on 2332 hrs on 3 August 1986 (cf. Fig 1c). A 32 µs (4.8 km) transmitter pulse was used for all observations. A Gaussian was fit in the least-square sense to these and similar spectra, and the resulting Doppler velocities are shown in Fig. 2b.

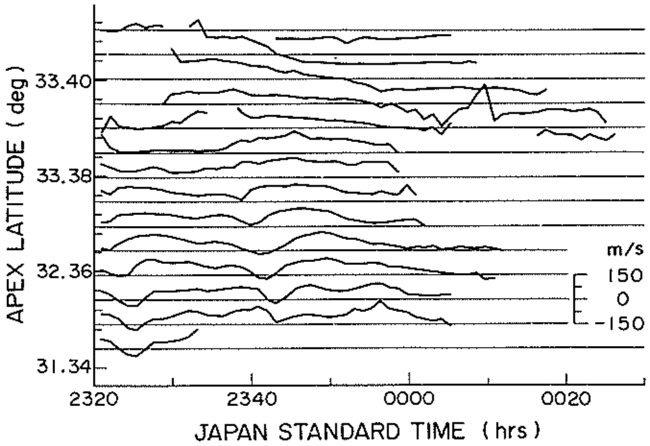

Fig. 2b. See caption for Figure 2a.

uniform in time and space than are typical low latitude drifts (McClure and Woodman, 1972; Woodman and LaHoz, 1976). "Beam broadening" (Hocking, 1985) sometimes geometrically widens narrow spectra, e.g. for some middle atmosphere data from the MU and other radars. We think this has not occurred here, at least for the data of Figure 2, though it might happen for some kinds of FAI spectra and viewing geometries.

Discussion

Having two or more slightly different scattering centers inside the finite resolution cell could cause the multi-peaked spectra observed; this is believed to be the case even using the world's largest similar system at Jicamarca, Peru (Woodman and LaHoz, 1976). There, even with twice our range resolution and 3.3 times better E-W resolution (resulting from a 10 times larger antenna), "composite" multi-peaked spectra were common (Woodman and LaHoz, 1976). Also, the spectral widths and spectral asymmetries we observe are common in equatorial F-region FAI data, and may have similar explanations.

The observed drifts are scattering-center phase velocities. They may be the same as or differ from the bulk plasma drift (Farley et. al., 1970; Fejer and Kelley, 1980). Our typical values are near 100 m/s, but sometimes 200 or (aliased) 300 m/s are observed, comparable to equatorial values for both irregularity bulk (McClure et al., 1977) and FAI drifts (Woodman and LaHoz, 1976). Our radial drifts are usually but not always approximately equal to the slope of a corresponding structure in the RTI maps. Near 2230 hrs this slope in Fig. 1c is 0.4°/10 min or ~ 74 m/s, in agreement with values of Figure 2b. See also a similar result in Figure 7 of Woodman and LaHoz (1976).

We find no tendency for the RTI maps (e.g., Figure 1 and similar plots) to show echoes preferentially from either bottomside or topside altitudes (the smaller or larger of the ranges displayed). Instead, the FAI patches are seen to start, endure, move to and/or end at any latitude (F-region height) between the highest and lowest covered. Sometimes they fill all these latitudes. This indirect evidence suggests that the 322.6 cm FAI are probably not strongly layered in the direction parallel to B. Near the dip equator, where the magnetic geometry is rotated by ~ 60°, bottomside FAI is the most continuous, first to appear and last to vanish (Woodman and LaHoz, 1976). It is believed related to a km-scale bottomside plasma instability category (Valladares et al., 1983; Cragin et al., 1985); an independent larger-scale bottom-to-topside "plasma-bubble-related" category (Fejer and Kelley, 1980; Kelley and McClure, 1981) also exists at the equator. Briefly, since equatorial and midlatitude boundary conditions as well as FAI morphology differ, we think one or more new categories are needed to explain our results. Near the equator usually only the gradients perpendicular to B are considered. At midlatitudes, strong gradients of total plasma number density and other parameters sometimes exist in this direction (Behnke, 1979), but gradients parallel to B always exist and may also be important in FAI generation.

Periodicities are seen at various scales in midlatitude FAI: we show 12 min quasi-periodic behavior (Figure 1a) and elongated parallel echo centers spaced 0.5° apart (Figure 1b). Other diagnostic techniques have shown that traveling ionospheric disturbances (TIDs) and other kinds of waves are ubiquitous in the atmosphere. Recently a relation between TIDs and both nighttime and daytime (sic) ionogram spread F was established at midlatitudes (Bowman et al., 1987). The larger-scale periodicities we see in patches of small-scale FAI may suggest another link between atmospheric waves and F-region plasma instabilities. An HF Doppler system (Tsutsui et al., 1984) located in Kyoto detected 12-min oscillations but no TIDs in the F region at the same time as and only a few hundred km southeast from those of Figure 1a (Minoru Tsutsui, private communication). No one-to-one correlation could be established between these oscillations and those of Figure 1a. The Brunt-Vaisala period at night can be near 12 min, which could explain the period seen in both data sets. The oscillatory FAI of Figure 1a are unique: further analysis and new observations are being conducted.

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