行政院國家科學委員會專題研究計畫　成果報告

子計畫七：利用雷達干涉法對赤道異常區散塊 E 層電子密度不規則體之觀測及研究

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行政院國家科學委員會專題研究計畫成果報告

利用雷達干涉法對赤道異常區散塊 E 層
電子密度不規則體之觀測及研究

Radar interferometry observation and study of sporadic E irregularities in the equatorial anomaly crest zone

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中英文摘要

縱使散塊 E 場列不規則體的背向回波具有很明顯的方向敏感性，但是對主要回波區在地磁東西方向較南北方向為寬的扇形波束而言，如果不規則體以夠大的橫向速度分量在回波區域的東西延伸方向移行，則偏離主軸的橫向漂移速度貢獻到都卜勒速度的分量會因此而增加，波束加寬效應的影響將變大。為檢驗波束加寬效應的影響，利用中壢雷達散塊 E 不規則體回波在地磁東西向的波束寬可達 15°的特性，結合都卜勒速度以及雷達干涉法定位不規則體回波的方位角度、東西向的延伸長度，可以估算不規則體在波束主軸及垂直主軸兩個方向的漂移速度，以及波束加寬所貢獻的頻寬。本報告分析一個回波事件的都卜勒頻譜顯示可能有 20％的觀測頻寬由波束加寬效應的貢獻，因此不規則體在回波區由橫向漂移所產生的頻譜加寬效應可能在窄頻寬的回波頻譜具有不可忽略的影響。

關鍵詞：散塊 E 場列不規則體、方向敏感性、中壢 VHF 雷達、波束加寬效應、都卜勒速度

Abstract

Although the backscatter from field-aligned irregularities associated with sporadic E (Es) layer is extremely aspect-sensitive, the beam broadening effect on Doppler spectral width of the echoes may be significant, provided the extent of the expected echoing region in geomagnetically zonal direction is wide and the velocity component of the cross-radar-beam drift along the major axis of the expected echoing region is large. In order to examine the beam broadening effect on Doppler spectral width, we conducted a radar experiment with interferometry measurement of Es field-aligned irregularities using the Chung-Li VHF radar to determine the true height and the angular position of the field-aligned irregularities in the echoing region. With the knowledge of angular position of the irregularities and the associated Doppler velocity, the along- and cross-radar-beam drift velocities of the irregularities can be estimated. A comparison between observed Doppler spectrum and beam broadening spectrum shows that for the present case more than 20% of the observed Doppler spectral width may be attributed to the beam broadening effect. Therefore, the beam broadening effect caused by the drift of the field-aligned irregularities in the echoing region may play a decisive role in broadening the Doppler spectral width of the Es field-aligned irregularities.

Keywords：sporadic E、field-aligned irregularities 、aspect-sensitive 、beam broadening effect 、Chung-Li VHF radar、Doppler velocity

前言與研究目的

It is generally believed that the spectral width of the radar returns from 3-meter type 2 Es irregularities is strongly related to the growth rate of the irregularities excited through nonlinear cascade process associated with gradient drift instability of primary waves and is not influenced by the beam broadening effect due to highly aspect sensitivity of the backscatter. It is true if the radar beam is pencil-like and the aspect angle of the backscatter from FAI is considerably small. However, it should be noted that the aspect sensitivity effect on the backscatter of FAI is limited only in the geomagnetically meridional direction, not in the geomagnetically zonal direction. This is because in the geomagnetically zonal direction the radar wave vector in the echoing region is always perpendicular to the geomagnetic field line. This feature implies that the configuration of the expected echoing region of FAI will be extremely anisotropic, which is appreciably elongated in the geomagnetically zonal direction and fairly narrow in meridional direction. This article is an attempt to quantitatively investigate the effects of transverse combined with along beam drifts of the FAI in highly anisotropic echoing region on their radar spectral width. Our result shows that the beam broadening effect may play a role in broadening the observed Doppler spectral width, provided the along and transverse beam drift velocities are large.

文獻探討

In fact, with IGRF model, Wang and Chu (2001) shows that the angular coverage of the expected echoing region of the Chung-Li VHF radar in the zonal direction will be as wide as more than 20°, provided the magnetic aspect angle is ±0.25° and the height range of the Es irregularities is 100-120 km. The beam broadening effect induced by the transverse beam drift on the Doppler spectral width of the radar returns from the Es field-aligned irregularities is investigated by Chun and Wang (2003).

They showed that the Doppler spectral width of the Es field-aligned irregularities is not only the function of the transverse beam drift velocity, but also related to the zonal extent of the plasma structure.

研究方法

The data employed in this research were taken on August 18, 1997, from 20:13:47LT to 20:45:01LT by the Chung-Li VHF radar. Fig.1 presents the range-time-intensity (RTI) distribution of the radar returns. As indicated, the echoes occur in the range extent from about 126 km to 138 km in a form of irregular structure. At a first glance, the echoes appeared quasi-periodically in a form of clump structure with range extents of about 7-15 km and periods of about 2-4 minutes. Fig.2 presents selected range variation of the normalized Doppler spectra for the period 20:19:02 – 20:24:07 LT. As indicated, with the increase of the range, the mean Doppler velocity increases smoothly from about -44 m/s to -52 m/s. In addition, the Doppler spectral width changes slightly with the increase of the range. Fig.3 shows the projections of the echo patterns for the data presented in Fig.2 on three mutually orthogonal planes, that is, vertical plane (top panel) formed by the vertical axis and horizontal axis in the geomagnetically meridional direction, azimuth plane (middle panel) formed by the vertical axis and horizontal axis in the geomagnetically zonal direction, and horizontal plane (bottom panel) with abscissa in the geomagnetically zonal direction and ordinate in the geomagnetically meridional direction. Interferometry analysis shows that the plasma structures of the field-aligned irregularities responsible for the quasi-periodic echo patterns in RTI plot consist of two kinds of the structures, one is categorized into a thin layer located at heights around 101 and 105 km with vertical thickness of about 1-2 km and horizontal extents of about 20-25 km and the other one is categorized into a patch-like structure located at height around 101 km with thickness of about 2-3 km and horizontal extent of about 5-8 km. Therefore, it is irrelevant to infer the plasma structure of the field-aligned irregularities from the information provided by the echo patterns presented in the RTI plot.

結果與討論

Fig.4 is a schematic chart showing the relation between the radial velocity at point P in the expected echoing region (shaded region) and the drift velocity components $V_{\|}$ and $V_{\perp}$ on the cross section of an oblique radar beam steered perpendicular to the magnetic field line, where θ is the cone angle of point P with respect to antenna beam axis (i.e., line AO), ϕ is the clock (or azimuth) angle of point P measured with respect to the major axis (i.e., line bO) of the expected echoing region, β is the angle subtended at point a in the plane comprising beam axis AO and line Aa, and α is the angle measured in the plane comprising beam axis AO and the major axis of the expected echoing region, $V_\perp$ and $V_{||}$ are, respectively, the drift velocity components along and transverse radar beam axes, and ϕ_0 is the azimuth angle of $V_{||}$ relative to the major axis of the expected echoing region. Therefore, the radial velocity at a point on the cross section of the antenna beam can be formulated in terms of $V_{||}$ and $V_\perp$ below

$$V_r = V_\perp \cos\theta + V_{||} \cos(\phi - \phi_0) \sin\theta \quad (1)$$

In order to facilitate mathematical manipulation, $V_{||}$ and $V_\perp$ are assumed to be constant in the resolution volume. It is not difficult from Fig.4 to show that the relations $\cos\phi \sin\theta \cong \sin\alpha$ and $\sin\phi \sin\theta \cong \sin\beta$ are valid, provided θ, α, and β are so small that the approximations $\tan\alpha \cong \sin\alpha$ and $\tan\theta \cong \sin\theta$ are valid. As a result, (1) reduces to

$$V_r \cong V_\perp \cos\theta + V_{||} \cos\phi_0 \sin\alpha + V_{||} \sin\varphi_0 \sin\beta \quad (2)$$

Note that the angular extent of the expected echoing region along geomagnetic field line direction (i.e., in β direction) for the Es field-aligned irregularities is tremendously narrow, generally smaller than 1°, leading to the magnitude of the term $V_{||}\sin\phi_0\sin\alpha$ in (2) is very small due to $\sin\beta \sim 0$. Note also that from Fig.4 the relation $\tan^2\theta = \tan^2\alpha + \tan^2\beta$ is held and the approximation $\theta \sim \alpha + \beta$ is therefore valid for the enormously small value of β. Because of this, (2) reduces to

$$V_r \cong V_\perp \cos\alpha + V_{||} \cos\phi_0 \sin\alpha \quad (3)$$

The beam broadening effect on the Doppler spectrum of the echoes from Es field-aligned irregularities has been investigated by Chu and Wang (2003). They found that the beam broadening spectrum of the Es field-aligned irregularities is not only a function not only of transverse and along the radar beam axis, but also governed by the position and horizontal extent of the plasma structure in the echoing region. By assuming that the antenna beam pattern and the distribution of the reflectivity of the irregularities are both Gaussian and the drift velocity of the irregularities is constant, Chu and Wang (2003) derived the beam broadening spectral width σ_B (defined as the second moment of beam broadening spectrum) as follow

$$\sigma_B = \frac{V_{||} \cos\phi_0}{\sqrt{2}\sqrt{1/\sigma_{ia}^2 + 1/\sigma_{ba}^2}} \quad (4)$$

where $\sigma_{ia}^2 = \sigma_{ix}^2 / R^2$, $\sigma_{ba}^2 = \sigma_{bx}^2 / R^2$, R is the range, and σ_{ix} and σ_{bx} represent the extents of the backscatter of the field-aligned irregularities and the antenna beam width in x (i.e., along the major axis of the expected echoing region) direction, respectively. Note that in deriving (4) the contour of the radial velocity in the echoing region is treated as the straight line to simplify the mathematical manipulation. The straight line approximation of the contour is valid for the conditions that the ratio of the drift velocity component along the radar beam axis to that transverse the radar beam is small (less than 0.3) and/or the echoing region is enormously narrow in the direction perpendicular to the drift direction of the transverse beam axis (Chu,2002; Chu and Wang, 2003). From (4), it is clearly shows that, except for the transverse beam drift velocity $V_{||}\cos\phi_0$, the angular extent σ_{ia} of the plasma structure in the echoing region and the antenna beam width in the geomagnetically zonal direction are also crucial factors affecting the magnitude of σ_B. Therefore, once the angular coverage and the drift velocity components of the irregularities along and transverse radar beam in the echoing region are obtained from interferometry measurement, the corresponding beam broadening spectral width can be estimated in accordance with (4). Fig.6 compares the observed Doppler spectral width of the Es field-aligned irregularities with the corresponding beam broadening spectral width for the data the same as used in Fig.5, in which only the Doppler spectra of the thin layer located at around 105 km as presented in Fig.3 are employed for the spectral width analysis. It is clearly from Fig.6 that the contribution of the beam broadening spectral width to the observed Doppler spectral width may be as large as more than 20%, providing a concrete evidence that the beam broadening effect on observed Doppler spectral width of the Es field-aligned irregularities is significant and cannot be ignored.

Once the characteristics of the plasma irregularities are obtained in terms of the interferometry measurement, the mean Doppler velocity V_r and the spectral width σ_B of the beam broadening spectrum can be calculated in accordance with the relation

$$S(f) = C\exp\left[-\left(V_r + V_D\right)^2 / 2\sigma_B^2\right] \qquad (5)$$

,where C is a constant as a complication function of radar parameter, target reflectivity, drift velocity, wavelength and range. Figure 7 shows examples of comparing observed self-normalized Doppler spectra (solid curve) with the normalized beam broadening spectra (dotted curve), where each of the observed spectra is the 49 s averages for the radar returns from the irregularities occurred in the respective range bin during the period 20:19-20:24 LT and the corresponding beam broadening spectrum is calculated in accordance with (5) for the radar return data. As indicated, irrespective of the broad and narrow radar spectra in the ranges 126.6 - 129 km, the main bodies of the spectra were dominated by the respective beam broadening spectra, strongly suggesting the extraordinarily weak turbulent activities of the corresponding plasma irregularities.

If we remove the beam broadening spectral width σ_B from the observed Doppler spectral width σ_o in accordance with the following expression (Hocking , 1985)

$$\sigma_p^2 = \sigma_o^2 - \sigma_B^2 \qquad (6)$$

where σ_P can be considered as the contribution of the fluctuations of the plasma turbulences to the observed Doppler spectral width. Fig.8 presents the variation of σ_P with the mean angular position of the irregularities in the echoing region. As indicated, no systematic variation of σ_P with the mean angular position of the irregularities is seen in the echoing region within 5° from the radar beam axis. However, for the region greater than 5° the magnitude of σ_P remarkably increases with the increase of the zonal distance of the irregularities from the beam axis. Presumably, one plausible cause that can account for this phenomenon is the inhomogeneous distribution of the fluctuation strengths of the irregularities in the echoing region, namely, the plasma turbulences are more active in the region away from the boresight direction than that close to the beam axis. More observational evidences are needed to support this speculation.

計畫成果自評

The beam broadening effect may be crucial and should be taken into account in explaining the characteristics of the Doppler spectral width of the Es irregularities if the zonal coverage of the expected echoing region (or effective antenna beam patter) is large enough and the along- and cross-radar-beam drift velocities are intense. Therefore, the contribution of the beam broadening spectral width should be removed from the observed Doppler spectral width before it is employed for further applications. The full paper of this report will be submitted to ***Ann. Geophys.***

參考文獻

Chu, Y.H., Beam broadening effect on oblique MST radar Doppler spectrum, ***J. Atmos. Oceanic Techno.***; **19**, 1,955-1,967, 2002

Chu Y. H., and C. Y. Wang, Radial velocity and doppler spectral width of echoes from field-aligned irregularities localized in the sporadic E region, J. Geophys. Res., 108(A7), 1282, dio: 10. 1029/2002JA009661, 2003.

Hocking, W.K., Measurement of turbulent energy dissipation rates in the middle atmosphere by radar techniques: A review, ***Radio Sci.***, **6**, 1403-1422, 1985

Wang C. Y., and Chu Y. H., Interferometry investigations of blob-like sporadic E plasma irregularity using the Chung-Li VHF radar, J. Atmos. Solar-Terr. Phys., 123-133, 2001.

圖表

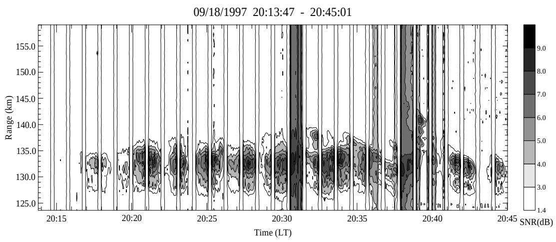

Fig. 1：Range-time-intensity contour plot for Es field-aligned irregularities observed by the Chung-Li VHF radar.

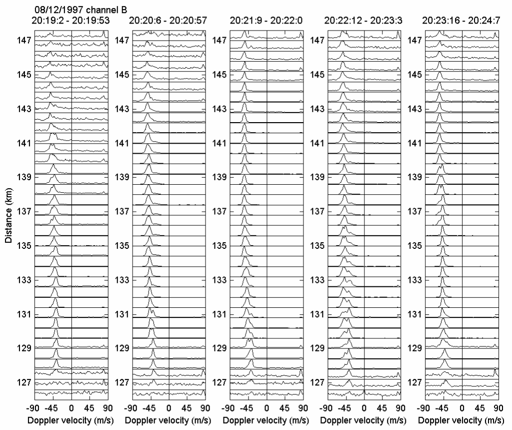

Fig.2: Range variation of self-normalized Doppler spectra.

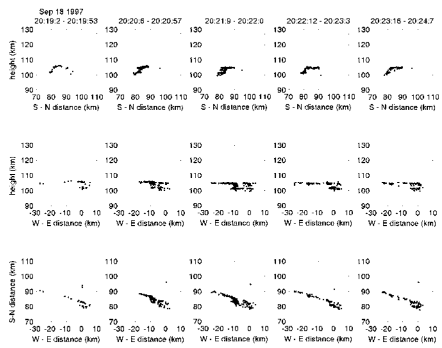

Fig. 3 ： Spatial structure of the corresponding echo patterns projected on mutually orthogonal planes, that is, vertical plane (top panel), azimuth plane (middle panel), and horizontal plane (bottom panel).

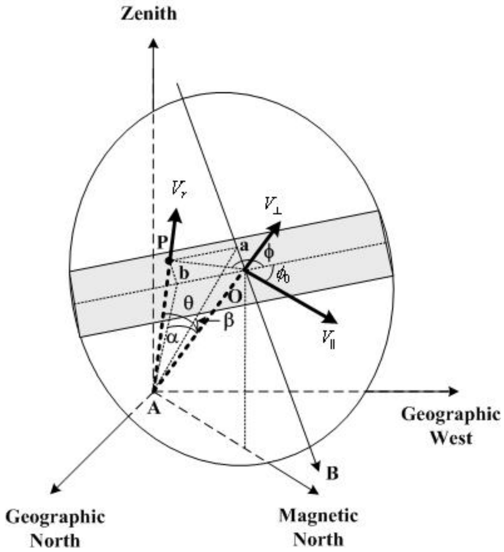

Fig. 4：Schematic diagram showing the geometry relation of the point P in expected echoing region (shaded area) of the field-aligned irregularities, in which the azimuth angle ϕ and ϕ_0 are defined to be positive (negative) if it is measured counter-clockwise (clockwise) with respect to the main axis of the expected echoing region.

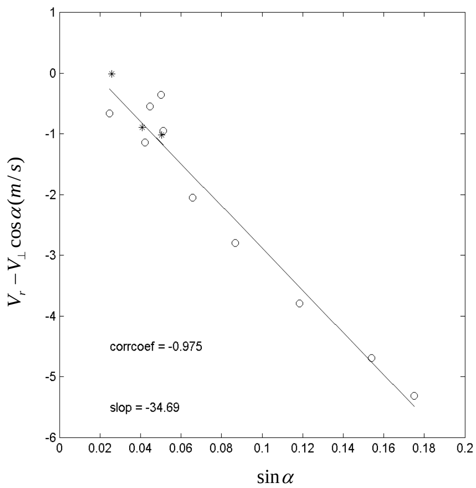

Fig. 5：Scatter diagram of the observed values $V_r - V_\perp \cos\alpha$ versus $\sin\alpha$, in which each point represents the data at different range bins. The points marked with circle and asterisk are, respectively, the echoes of the thin layer located at about 105 km and those of the patch-like structure centered at height about 101 km, as shown in Fig.3.

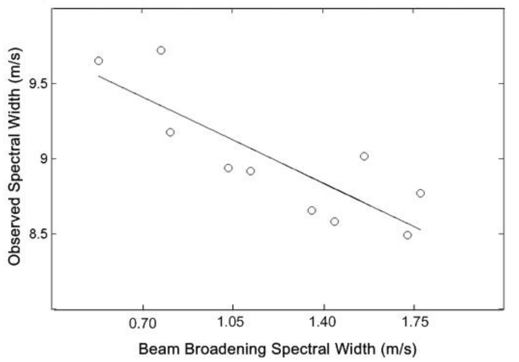

Fig. 6：Scatter diagram of observed Doppler spectral width of the Es field-aligned irregularities versus beam broadening spectral width for the data same as in Fig.5.

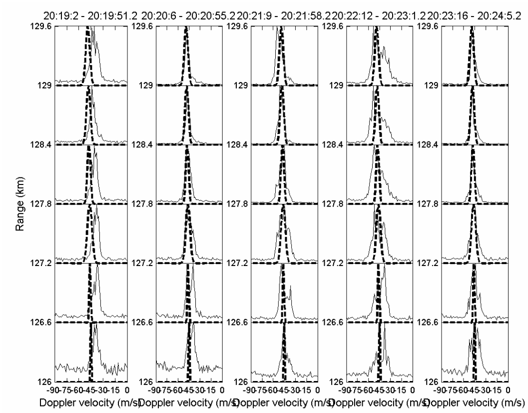

Fig. 7: Examples of comparing observed self-normalized Doppler spectra (solid curve) with the normalized beam broadening spectra (dotted curve),

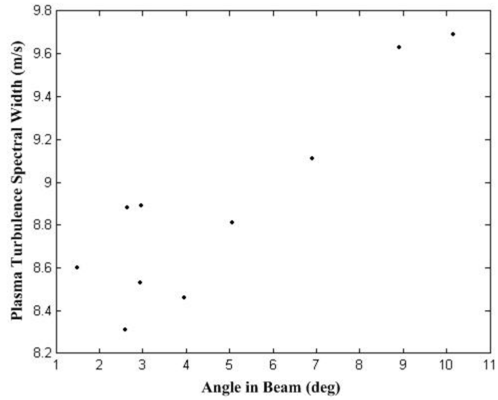

Fig.8：Variation of the component of Doppler spectral width caused by the fluctuations of the plasma turbulences with the mean angular position of the plasma irregularities in the echoing region.