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Unexpected rapid decrease in phase velocity of submeter Farley-Buneman waves with altitude

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[1] An unexpected and drastic drop in the phase velocity V_{ph} of Farley-Buneman (FB) waves with increasing altitude was observed in the equatorial electrojet over Jicamarca. The effect was detected with the newly employed 430-MHz radar looking vertically. The decrease in V_{ph} was 67 m/s and 36 m/s over 2.4 km for the FB waves moving towards and away from the radar, respectively. By contrast, the 430-MHz data from 20° west displayed little dependence on altitude. Simultaneous observations with a 50-MHz radar at 23° and 51° west also displayed little change of V_{ph} with altitude. We show that electron inelastic cooling which defines gradual transition from super-adiabatic to isothermal processes at 50 MHz (used in majority of observations), becomes unimportant at higher frequencies. The effect is evinced at radar frequencies ≥150 MHz and requires altitude resolution <2 km to be observed. Averaging over >7 km at oblique incidence masks the effect.

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1. Introduction

[2] The daytime electrojet current in the equatorial E region is produced by a vertical polarization electric field that is sufficient to generate two predominant plasma instabilities: large scale gradient-drift as well as both pure and two-step Farley-Buneman (two step FB - as labeled by *St.-Maurice et al.* [2003]). Both processes result in field-aligned irregularities that can be observed with coherent scatter radars when their wavelength is one half of the wavelength of the transmitted radar signal. The fact that gradient-drift instability has a cutoff at smaller wavelengths allows studying the Farley-Buneman (FB) waves undistorted by the gradient-drift processes.

[3] The remarkable property that Farley-Buneman waves travel with a phase speed close to their linear instability threshold has been the reason that both linear and nonlinear approaches of ever-increasing sophistication have been developed to explain this. Nonlinear theories (not discussed in this letter) have been focused on the mechanisms which produce FB waves moving at their linear threshold speed, while linear theories have been aimed at providing more refined expressions for the instability threshold speed as well as understanding the attendant physics. *Farley and Providakes* [1989] were the first who noted that threshold speed of short scale E region irregularities should be evaluated more carefully, based on their observations of high latitude E region irregularities moving with phase speeds clearly faster than the isothermal ion-acoustic speed, and much closer to a speed associated with adiabatic electrons.

[4] Following work of *Farley and Providakes* [1989] there have been two distinct approaches based on non-isothermal electron corrections to tackle this problem. In the series of papers written by Dimant and Sudan, the focus was on an improved kinetic starting point for the instability calculations [*Dimant and Sudan*, 1995, 1997]. The other approach, which is based on Grad's set of fluid equations closed at the heat flow level, self-consistently describes the effects of collisions using Burgers' expressions for collision integrals [*Burgers*, 1969]. This approach has been used in work of *Kissack et al.* [1995, 1997, 2008a, 2008b], *St.-Maurice and Kissack* [2000], and *Kagan and St.-Maurice* [2004].

[5] A significant step forward was made in the paper by *St.-Maurice and Kissack* [2000] that described the physical link between the non-thermal and the isothermal theories. The thermal corrections were presented in such a way that the results of the classical theory could be recovered easily. Despite being limited to zero aspect and flow angles, this approach allowed *St.-Maurice et al.* [2003] to explain, for the first time, the puzzling fact that two-step type-I waves in the lower electrojet moved at speeds up to 50% higher than the isothermal ion acoustic speed. The next step exploring aspect sensitivity [*Kagan and St.-Maurice*, 2004] showed good correspondence to observations [*Kudeki and Farley*, 1989] and good qualitative agreement of observed altitude behavior of Farley-Buneman waves: they are super-adiabatic at lower altitudes and isothermal at high altitudes. The latest development of the theory [*Kissack et al.*, 2008a, 2008b] includes non-zero flow angles (essentially the angle between the E × B direction and the center of the radar beam, important for non-zero zenith angle transmissions) and an arbitrary heat source (with possible applications for high latitudes and heating experiments). The significant step forward by *Kissack et al.* [2008a, 2008b] compared to previous work was presentation of the thermal corrections themselves which now were written to clearly show contributions from each physical process and allow easy comparison with all previous work. Applying this theory to the three-frequency observations of *Balsley and Farley* [1971], *Kagan and Kissack* [2007] showed that frequency dependence predicted by the *Kissack et al.* [2008b] theory matched the data remarkably well. They gave a simplified expression for the phase velocity of Farley-Buneman waves which, along with quick estimates,

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allowed identification of the physical process that dominated behavior of FB waves at a given frequency and altitude.

[6] In the present paper we analyze near simultaneous observations of the equatorial electrojet irregularities at frequencies of 50 and 430 MHz (corresponding to plasma irregularity scales of 3 m and 0.35 m respectively) with the JULIA radar and the newly employed Prototype Advanced Modular Incoherent Scatter Radar (AMISR-P) at the Jicamarca Radio Observatory on 12 March 2005. Both radars transmitted vertically and at both 23° and 51° off zenith to the west with JULIA and 20° off zenith to the west with AMISR-P.

2. Observations and Analysis of Experimental Results

[7] Details on the AMISR-P design and experimental setup as well as the Jicamarca observatory 50-MHz JULIA radar are presented in the paper by *Hysell et al.* [2007]. The AMISR-P design allows essentially simultaneous observations at 20° west and vertically. To compare the results at two frequencies the AMISR-P observations at 430 MHz were interleaved with those of JULIA at 50 MHz at 23° west, 51° west and vertically.

[8] Vertical observations at 430 MHz show an unprecedented drastic drop in the phase velocity V_{ph} of Farley-Buneman (FB) waves with increasing altitude. The decrease in V_{ph} was 67 m/s and 36 m/s over 2.4 km for the FB waves moving towards and away from the radar respectively. By contrast, the 430-MHz data from 20° west displayed little dependence on altitude. Simultaneous observations with the 50-MHz radar at 23° and 51° west also displayed little change of V_{ph} with altitude. In Figure 1 we present the range-velocity-intensity plots (a) and individual normalized spectra (b) for JULIA at 12:37:50 LT and AMISR-P at 12:36:20 LT. Vertical type-1 echoes received by JULIA were dominated by gradient drift processes and since we do not find them a reliable indication of Farley-Buneman waves, we do not discuss them here. As expected, the AMISR-P observations of the Farley-Buneman (FB) waves were not distorted by the gradient-drift processes. Therefore in our analysis below we start with the AMISR-P data.

[9] In Figure 2a we present Doppler velocities observed by AMISR at 12:36:20 LT on 12 March 2005. We mark with stars and solid squares velocities of waves moving towards and away from the radar, respectively. Shaded areas around each data point show the altitude (horizontal scale) and velocity (vertical scale) uncertainty for vertical transmissions (upper panel) and for transmissions at 20° west off zenith (middle panel). The altitude and velocity uncertainties for vertical transmissions were ±0.6 km and ±20 m/s respectively. The phase velocities of waves propagating away and towards the radar were about the same (the two uncertainty intervals overlap). The peaks in the Doppler spectrum were around 460 m/s near 102 km and the peak phase velocity decreased with altitude at a remarkable rate, on average, of 15–28 m/s per km. For oblique transmissions AMISR-P received echoes from a wider altitude range 100–106 km with significantly higher altitude uncertainty of ±3.7–3.9 km averaging signal over more than 7 km. The oblique data displayed little dependence on altitude. Doppler velocities for FB waves moving towards and away from the radar were noticeably different (their uncertainty intervals don't overlap) most probably indicating a strong westward zonal wind.

[10] Without a neutral wind our theory gives the same phase velocity magnitude for FB waves moving away from and towards the radar. Based on experiments by *Kudeki and Farley* [1989], the theory of *Kagan and St.-Maurice* [2004] and the *Kagan and Kissack* [2007] computer simulations of observations in May 1969 [*Balsley and Farley*, 1971] we conclude that the backscatter comes essentially from 0°–0.2° aspect angles. Therefore we calculated phase velocities of FB waves for these two aspect angles, and if our theory is correct then the observed phase velocities in absence of neutral wind should lie in the velocity interval between V_{ph} at 0° and 0.2° aspect angles.

[11] In Figure 2a the theoretically predicted V_{ph} for vertical (upper panel) and oblique transmissions (middle panel) are plotted as solid black lines for a 0° aspect angle and as dashed black lines for 0.2° aspect angle. The computation codes are based on the *Kagan and St.-Maurice* [2004] theory for vertical transmissions (0° flow angle) and on the *Kissack et al.* [2008b] theory for oblique transmissions at 20°-west flow angle. The procedure uses ionospheric parameters from the MSIS and the geomagnetic field from the IGRF models for the time and location of the experiment. These are used to calculate electron and ion collisional frequencies (using formulary from *Schunk and Nagy* [2000]) and gyro frequencies. Based on the results of *Kagan and Kissack* [2007] in our calculations we used the corrected rate of inelastic cooling $\delta_e = 0.007$ instead of 0.003 used in estimates before, and the rate of temperature dependence on neutral frequency $g = [\frac{T_{e0}}{\nu_e}\frac{\partial \nu_e}{\partial T_e}]_{T_{e0}} = \frac{5}{6}$ as in our previous work.

[12] There are two comments in order on the *Kagan and St.-Maurice* [2004] and *Kissack et al.* [2008a, 2008b] theories of Farley-Buneman waves at marginal stability. The first is about correctness of using fluid equations for describing submeter irregularities. In order to show that our fluid model is not running into the problem we estimate the altitude limitation of FB wavelength imposed by the fluid theory (Landau damping on ions in particular). For ionosphere parameters over Jicamarca on 12 March 2005 this fluid limitation scale is 0.09 m near 100 km, 0.19 m near 104 km, 0.29 m near 106 km and 0.43 m near 108 km. Since in observations of interest 0.35-m backscatter came from 100–106 km altitudes (Figure 2a) the fluid approach is valid and application of our fluid model to 430-MHz observations is justified.

[13] The second comment relates to the fact that for altitudes of 100–110 km a much simplified expression for a marginal phase velocity given by *Kagan and Kissack* [2007] describes FB waves quite well. The uncertainty is less than 3% which is definitely much less than observational uncertainty. In running both full and simplified codes we found that below about 100 and above about 110 km there are cases (depending on time and location) in which the uncertainty may reach up to 10%. Despite the fact that all plots in this paper were produced by running our full code, we have found by running our full and simplified codes that formula (1) by *Kagan and Kissack* [2007] is very handy for the purpose of quick estimates giving adequate V_{ph} of FB waves near 100–110 km.

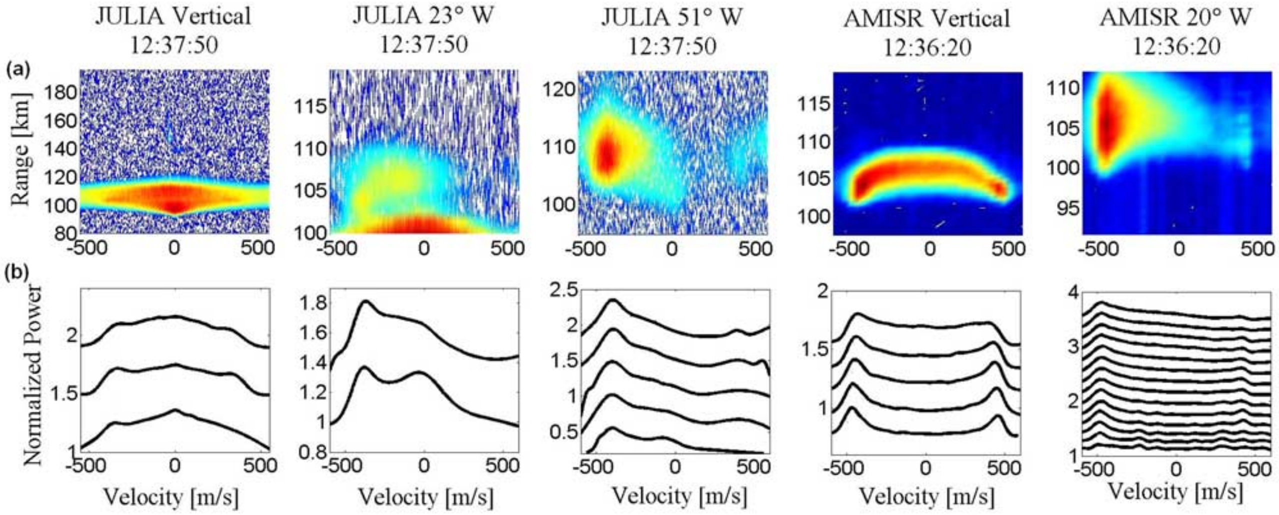


Figure 1. (a) Range-velocity-intensity plots and (b) individual normalized spectra for JULIA and AMISR-P.

[14] Note, that in case off-vertical transmissions (a non-zero flow angle) the Dimant-Sudan thermal instability [*Dimant and Sudan*, 1997] contributes to the threshold phase velocity of FB waves introducing asymmetry for east and west transmissions at low frequencies. This instability occurs for negative flow angles corresponding to the radar looking east for a daytime equatorial electrojet. For positive flow angles (west transmissions) the *Dimant-Sudan* thermal instability might still be induced but requires significantly higher threshold velocities than the ion-acoustic speed [*Dimant and Sudan*, 1997]. This theory predicts that radar observations of the phase velocity of type-1 irregularities west off zenith would be higher than for the east and vertical (if the last are not smeared by gradient-drift processes) transmissions. The Dimant-Sudan instability has a cutoff at shorter wavelengths, so one would expect the 0.35-m FB waves to be unaffected by the Dimant-Sudan thermal processes. This is to a smaller degree valid for 1-m waves. For 50-MHz transmissions this east-west asymmetry would be noticeable.

[15] From upper panel in Figure 2a one can easily see that theoretical predictions for vertical observations at 430 MHz match the data very well. The *Kagan and St.-Maurice* [2004] theory explains the decrease in V_{ph} with altitude by decreasing effect of thermal corrections. Near about 110 km the effect becomes negligible and V_{ph} is essentially an isothermal ion acoustic speed (shown in solid gray line) as predicted by classical theory [*Farley*, 1963; *Buneman*, 1963]. The dashed gray line denotes the speed associated with adiabatic electrons. The rate of the change in a phase velocity largely depends on the wavelength and altitude of backscatter echoes (more details in Discussion).

[16] Assuming that the difference between away and towards traveling FB waves in oblique AMISR-P transmissions are due to a neutral wind (since at such high frequency the FB waves are unaffected by gradient-drift processes) we find the velocity of the FB wave shown by hollow triangles in the lower panel of Figure 2a. Note that the theoretically expected phase velocity at a 0° aspect angle lies inside the shaded area of observed V_{ph}, neutral drag subtracted. The neutral wind is westward with velocities changing from 86 m/s near 100 km to 111 m/s near 106 km (with the same uncertainty of 20 m/s).

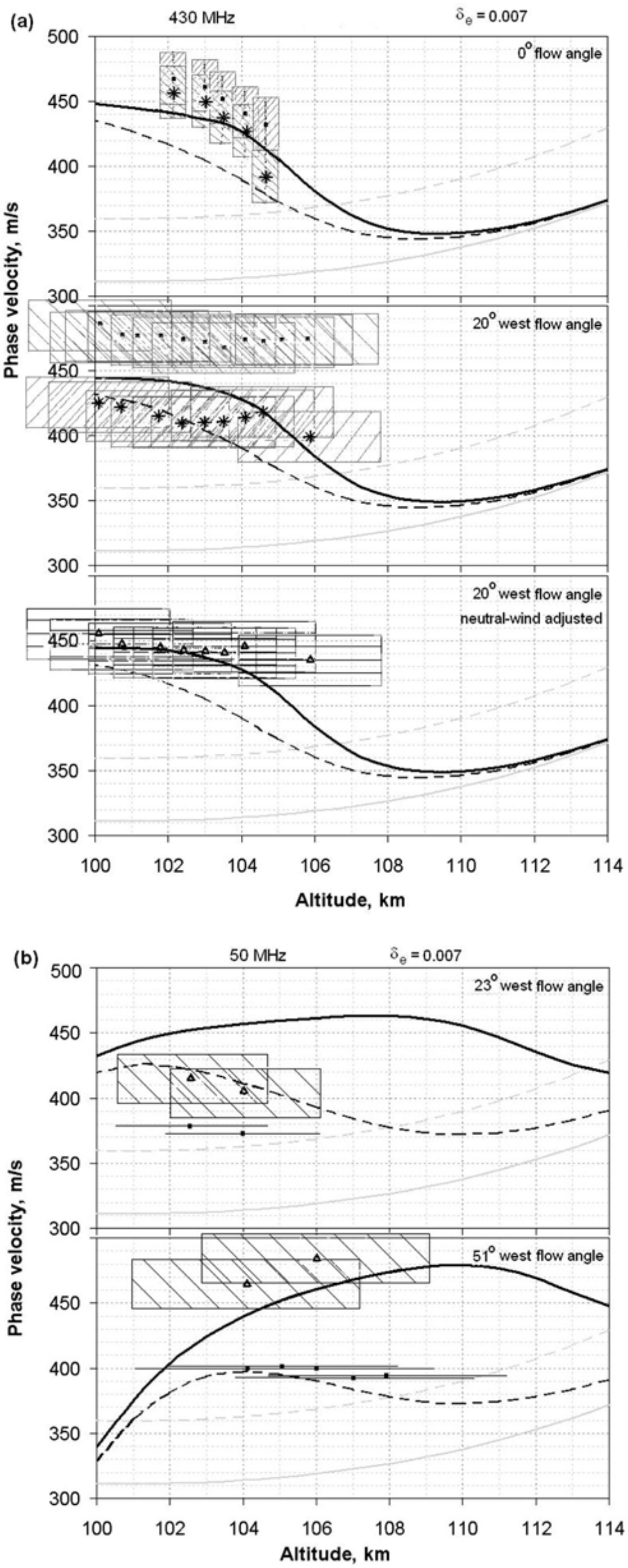
[17] Since JULIA radar echoes at 23°-west came from 3-m irregularities only about 5 km apart from the 0.35-m waves sampled by AMISR observing at 20°-west, we assume that winds were about the same. This brings us to Figure 2b in which we plot with the same designations as in Figure 2a observed and theoretically predicted phase velocities for 50-MHz echoes at 23°- and 51°-west flow angles. Note that JULIA observed only waves moving away from the radar (solid black squares). Again the shaded areas of neutral wind-corrected phase velocities lie inside the theoretically predicted V_{ph} between 0.2° and 0° aspect angles.

[18] Irregularities highlighted by the JULIA radar at 51°-west are about 45 km from the ionospheric volume observed by AMISR-P at 20°-west, so it is not that certain whether the neutral wind is of the same strength. We plot observed and theoretically predicted phase velocities of FB waves at a 51°-west flow angle in the lower panel of Figure 2b. Solid and gray lines show isothermal ion acoustic and adiabatic velocities, solid black squares are for observed Doppler velocities of FB waves moving away from the JULIA radar and hollow triangles correspond to V_{ph} corrected accordingly to the neutral winds found from the oblique AMISR-P observations. Here a velocity observational uncertainty was only about 0.6 m/s, the observational altitude uncertainty shown with horizontal black lines was ±2.1 and ±3.2 km for 23°-west and 51°-west transmissions respectively. Since we derived a neutral wind velocity from AMISR-P data that have ±20 m/s uncertainty, we applied the same uncertainty for the neutral wind-corrected phase velocities of 3-m FB waves. We conclude that both the observed Doppler shift and the neutral wind-corrected phase velocities of F-B waves are in a good correspondence with the theoretical predictions.

3. Discussions and Conclusions

[19] We have analyzed the results of experimental studies of Farley-Buneman waves over Jicamarca by probing the

equatorial electrojet at Bragg's scales 3 and 0.35 m. We have shown that the advanced linear theory [*Kagan and St.-Maurice*, 2004; *Kissack et al.*, 2008a, 2008b] explains well the altitude dependence of V_{ph} for JULIA vertical, 23- and 51-degree west transmissions, and observations of AMISR-P at 0 and 20 degrees west. The remarkable match of the linear theory predictions to observations seems to further confirm the long suspected fact that whatever the nonlinear process generating FB waves is, it produces waves moving at their linear threshold speed.



[20] Theory [*Kagan and Kissack*, 2007; *Kissack et al.*, 2008b] predicts that for meter and submeter FB waves thermal diffusion and thermal conduction processes completely dominate inelastic electron cooling [see *Kagan and Kissack*, 2007, Figure 4]. As a result within a narrow altitude range of 2–2.5 km, the FB wave behavior at 150 MHz and at 430 MHz should change from super-adiabatic at lower altitudes directly to isothermal at high altitudes, resulting in the drastic drop in V_{ph}. In order to observe such a rapid change of V_{ph} the altitude resolution should be less than the altitude range over which this change happens, as it was the case for AMISR-P observations at vertical incidence. The short altitude coverage makes it difficult to detect the rapid change in V_{ph} at oblique incidence, because of a much higher altitude uncertainty than in vertical transmissions. The altitudes of the narrow transition region for a given time and location depend on a radar frequency.

[21] In Figure 3 we give another example of high frequency observations of FB waves in the daytime electrojet from a 2-frequency (50 and 150 MHz) experiment [*Balsley and Farley*, 1971]. The radar was operated sequentially at frequencies of 49.92 and 146.25 MHz at 45° off zenith to the west. The fact that two sequential spectra at the same frequency were almost identical, allowed Balsley and Farley to conclude that the ionospheric conditions were about the same. Note, that here the radar backscattered signal was averaged over the entire electrojet. We ran the same routine as above to calculate phase velocities of Farley-Buneman waves at 12:36 LT on 10 March 1970 to compare them with those observed by *Balsley and Farley* [1971] at 50 and 146 MHz, which were 392 and 430 m/s respectively. Note that according to our theoretical predictions, $V_{ph}^{146} > V_{ph}^{50}$ could be satisfied only at altitudes lower than 101.4 km. Note also that we do not know the true altitude of backscatter. In this narrow altitude range 100–101.4 km where $V_{ph}^{146} > V_{ph}^{50}$ the theoretically predicted phase velocities between 100.5 and 101 km give V_{ph}^{146} = 430 m/s and V_{ph}^{50} = 392 m/s, in remarkably good agreement with observations.

[22] Finally we note that from a theoretical point of view [see *Kissack et al.*, 2008b, Figure 6] the phase velocity of Farley-Buneman waves does not increase with an increasing radar frequency at all altitudes. This dependence takes place largely due to the electron inelastic energy exchange when the latter dominates thermal conduction/thermal diffusion

Figure 2. Phase velocities (a) at 430 MHz and (b) at 50 MHz on 12 March 2005. Stars and solid squares show data for FB waves moving towards and away from the radar, respectively. Open triangles show a V_{ph} magnitude that would be observed in absence of a zonal neutral wind. Shaded areas around each data point show the altitude (horizontal scale) and velocity (vertical scale) uncertainty. Solid and dashed black lines are theoretically predicted V_{ph} for a 0° and 0.2° aspect angle, respectively. An isothermal ion acoustic speed is shown in solid gray line. The dashed gray line denotes the adiabatic process.

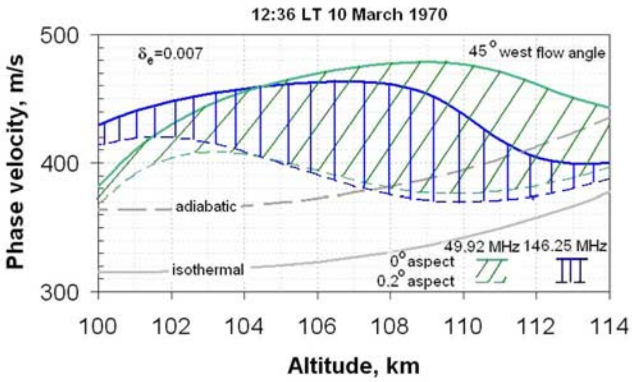


Figure 3. Theoretical predictions for the phase velocity of Farley-Buneman waves for 45°-west (+45° flow angle) transmissions at 146.25 MHz (blue) and 49.92 MHz (green) for δ_e = 0.007 around 12:36 LT on 10 March 1970. Solid and dashed lines correspond to 0° and 0.2° aspect angles, respectively. Shaded areas between solid and dashed lines of the same color denote the predicted magnitudes of phase velocity at a given frequency as function of altitude.

and transport processes. This, in turn, is defined by ionosphere parameters which are different at the same altitude for different time and location.

[23] When inelastic electron cooling is not important, the FB phase velocity becomes independent of wavenumber (and radar frequency). This happens, when transport processes take over at lower altitudes (the same is true for higher wavenumbers; super-adiabatic behavior) or when thermal conduction dominates at higher altitudes (isothermal behavior).

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