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V-shaped VLF streaks recorded on DEMETER above powerful thunderstorms

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[1] We report the observation of unusual V-shaped streaks on VLF spectra observed on the low-altitude satellite DEMETER during its overcrossing of highly active (i.e., high lightning flash rate) thunderstorms. At ∼700 km, wave activity observed on the E-field spectrograms at mid-to-low latitudes during nighttime are mainly dominated by upgoing 0+ whistlers and occasional reflected (from the other hemisphere) whistler components. Over a 3 year period, 87 events with V-shaped streaks associated with intense and numerous 0+ whistlers in VLF range have been observed. Using the National Lightning Detection Network for cases above the North American region indicates that these V-shaped streaks exclusively occur when DEMETER passes above intense isolated thunderstorms, with relatively high (tens per second) lightning flash activity. Using a new model of VLF propagation in the Earth-ionosphere waveguide, and transionospheric leakage to the satellite altitude, it is shown that the funnel-like "V" shape of the streaks is a simple consequence of the mapping to high altitude of frequency-dependent position of mode interference nulls (and crests) within the Earth-ionosphere waveguide.

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1. Introduction

[2] DEMETER is devoted to the study of ionospheric perturbations in relation with the seismic activity and the man-made activity. Its payload consists of wave and particle analyzers. A large part of the electromagnetic (EM) waves observed by DEMETER consists of whistlers mainly during nighttime at low latitudes and midlatitudes [*Parrot et al.*, 2008]. Since the pioneering work of *Storey* [1953] a huge number of papers have been published concerning the generation, the propagation, and the effect of these waves in the ionosphere and the magnetosphere. But the thunderstorm activity is the most important phenomenon in the Earth's atmosphere and much remains to be done to understand all related effects. The purpose of this paper is to present V-shaped emissions recorded by DEMETER in relation with lightning activity. In the past these hyperbolic shapes in the frequency-time spectrogram had been observed solely in the auroral zones by *Smith* [1969], *Mosier and Gurnett* [1969], and *James* [1976]. Studies of Poynting flux indicate that the auroral emissions (also called VLF saucers) are due to whistler mode waves originating below the satellite [*Mosier*, 1971]. More recently, similar events were observed by VIKING [*Lonnqvist et al.*, 1993] and FAST [*Ergun et al.*, 2001, 2003]. FAST observations have shown that energetic electrons (>10 eV) provide the energy source of such VLF saucers. The electron beams are accelerated by a magnetic field-aligned electric field. Although this possibility cannot be ruled out because it is known that lightning discharges induce electron precipitation [*Inan et al.*, 2007], a model to explain such V-shaped emissions is proposed by analogy with the propagation of the emission of a VLF ground-based transmitter in the Earth-ionosphere waveguide.

[3] Section 2 briefly describes the wave experiment which is a part of the scientific payload of DEMETER. Specific V-shaped streak events observed by DEMETER above the United States are shown in section 3. Section 4 is devoted to the model interpretation of the unusual funnel-like V shapes manifested in these events, while conclusions are presented in section 5.

2. DEMETER Wave Experiment

[4] DEMETER is a low-altitude satellite (710 km) launched in June 2004 onto a polar orbit which measures electromagnetic waves all around the Earth except in the auroral zones. The VLF range for the electric field is from DC up to 20 kHz. There are two scientific modes: a survey mode where spectrum of one electric component is onboard computed up to 20 kHz and a burst mode where, in addition to the onboard computed spectrum, waveforms of one electric field component are recorded up to 20 kHz. The burst mode allows performing a spectral analysis with higher time and frequency resolution. Details of the wave experiment can be found in the

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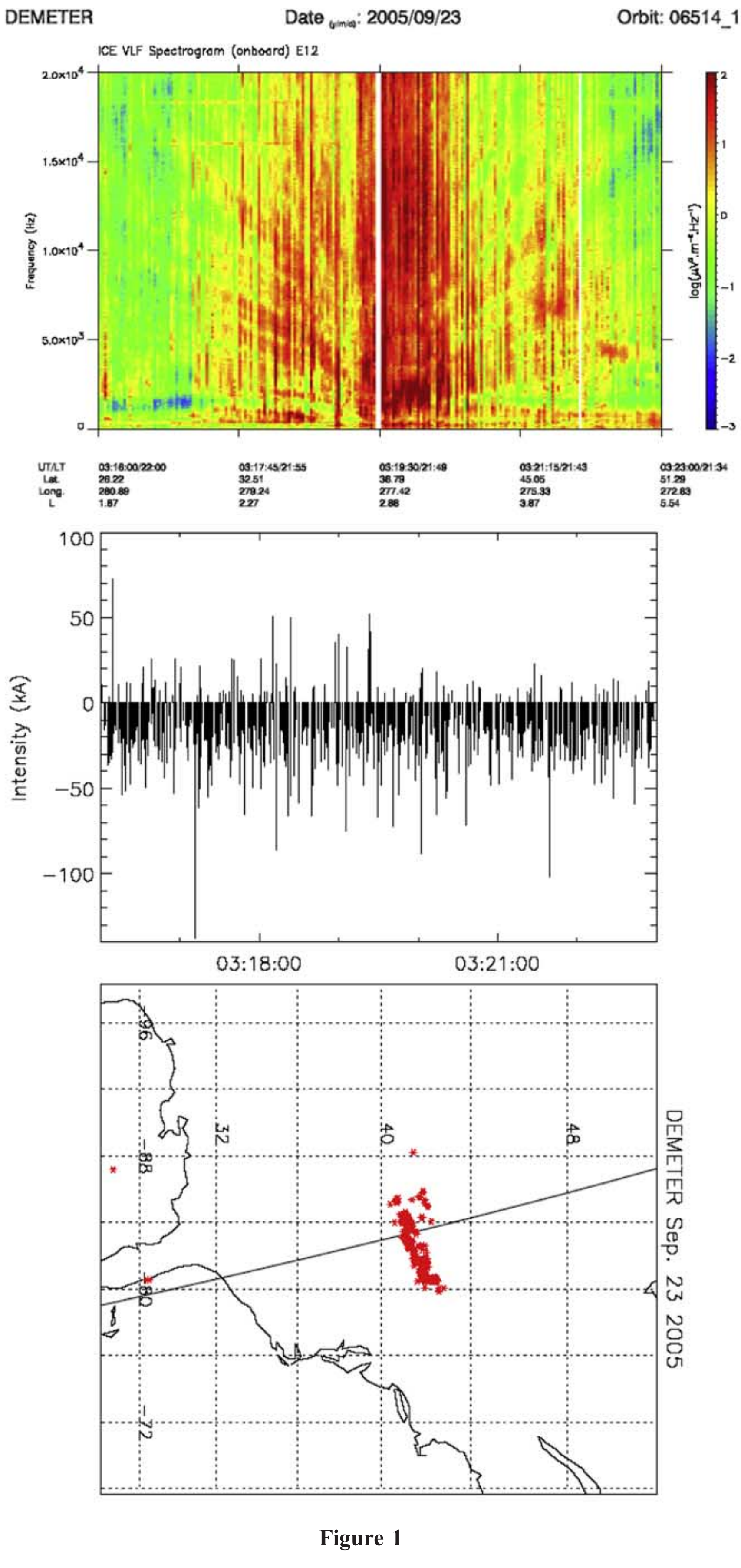
DEMETER
Date (y/m/d): 2005/09/23
Orbit: 06514_1
ICE VLF Spectrogram (onboard) E12
Frequency (Hz)
2.0×10^4
1.5×10^4
1.0×10^4
5.0×10^3
0
log(µV².m⁻².Hz⁻¹)
UT/LT 03:16:00/22:00 03:17:45/21:55 03:19:30/21:49 03:21:15/21:43 03:23:00/21:34
Lat. 26.22 32.51 38.79 45.05 51.29
Long. 280.89 279.24 277.42 275.33 272.83
L 1.87 2.27 2.88 3.87 5.54
Intensity (kA)
100
50
0
−50
−100
03:18:00
03:21:00
DEMETER Sep. 23 2005
32
40
48
-96
-88
-80
-72

Figure 1

works by *Parrot et al.* [2006] and *Berthelier et al.* [2006].

3. V-shaped Events Received Onboard the Satellite

[5] Figure 1 (top) shows a VLF spectrogram of the electric field recorded on 23 September 2005 between 0316:00 and 0323:00 UT. Many 0+ whistlers occur during these 7 min. Around 0320:00 UT their number (i.e., rate of occurrence) and their intensity reach a maximum. This event has been selected above the United States because there exists a very efficient National Lightning Detection Network (NLDN) recording the time, location, intensity and polarity of cloud-to-ground lightning discharges. The occurrence of these lightning discharges as function of the time is given in Figure 1 (middle) together with their intensities. Their geographical positions are shown in Figure 1 (bottom). Only lightning discharges occurring between 0316:00 and 0323:00 UT and in the map of Figure 1 (bottom) are taken into account. It can be seen that the thunderstorm is very well confined. The maximum intensity of the whistlers in the spectrum at 0320:00 UT occurs when the satellite is just above the thunderstorm region. In addition to the whistlers many V-shaped emissions centered on this location can be observed in Figure 1 (top). On each side of this region many arms with different slopes are seen. Figure 2 shows another example of such V-shaped emissions. The presentation is the same as in Figure 1, but it can be checked in Figure 2 (bottom) that the orbit track of DEMETER is a little bit away from the thunderstorm regions. This leads to a slightly different pattern in the spectrogram of Figure 2 (top) where the bottom of the V is round rather than sharp. Other examples of such emissions were registered by DEMETER during nighttime when thunderstorm activity is particularly intense. During 3 years, 87 events with V-shaped emissions have been observed.

4. Model Interpretation of the V-shaped Streaks

[6] The V-shaped streaks observed at DEMETER altitude are reminiscent (at least in shape) of the so-called VLF saucers, that have been previously observed on low-altitude satellites [*Smith*, 1969; *James*, 1976], which have been interpreted to be a manifestation of the upward propagation of whistler mode waves from a point source below the satellite altitude. The V or “saucer-like” shape in those emissions are manifested by the frequency dependence of the whistler mode refractive index surface, which produce group velocity vectors (i.e., raypath directions) that are further away from the vertical for higher-frequency wave energy. However, the VLF saucer phenomena are observed only in the auroral and subauroral regions, and the source of radiation is believed to be Cerenkov radiation produced by precipitating energetic electrons [*Ergun et al.*, 2003].

[7] The clear association of the V-shaped streaks reported herein with active thunderstorms may at first thought be suggestive of a mechanism similar to that for VLF saucers, possibly involving enhanced electron precipitation produced by the high rate of lightning activity in the associated thunderstorms. In this connection, regions of enhanced precipitation have been recently observed on DEMETER in association with active thunderstorms [*Inan et al.*, 2007]. However, while the VLF saucer signature usually consists of only one V feature, the V-shaped streaks here generally consist of a multiple V features, which would then imply the possibility of many source regions possibly distributed in altitude. In addition, the intensity of electron precipitation produced/maintained by lightning is generally much smaller than that which occurs in the auroral/subauroral regions, so that any resultant Cerenkov radiation would also be much smaller. It must be also reported that no particle precipitation has been observed at the time of these events. Another important difference is the time duration of the V-shaped emissions related to thunderstorm activity which is much more important than for the VLF saucers observed in the auroral zones.

[8] We herein put forth a much simpler but nevertheless interesting explanation for the observed V-shaped streaks, in terms of mapping to high altitude of frequency-dependent position of mode interference nulls (and crests) within the Earth-ionosphere waveguide. The key to this explanation is to note that the rate of 0+ whistler occurrence intensifies as the spacecraft approaches the center of the V shape, which coincides with the crossing of the geocentric footprint of the active thunderstorm. In this context, the high lightning rate in these thunderstorms essentially acts as a nearly continuous broadband transmitter, with the spatial nulls/crests thus being continuously visible as the spacecraft approaches the center of the storm.

[9] To test the validity of this concept, we use a new full wave model of VLF propagation within, the Earth-ionosphere waveguide as well as in the overlying stratified ionosphere [*Lehtinen and Inan*, 2008]. Figure 3 shows calculated VLF intensity of the whistler mode wave intensity at 120 km altitude as a function of horizontal distance x from a ground-based point vertical dipole source radiating equal power at all frequencies. The calculations were performed using the new full wave model of *Lehtinen and Inan* [2008], for an axisymmetric horizontally stratified ionosphere with a vertical geomagnetic field. For slightly tilted geomagnetic field, the results are expected to be qualitatively similar to those presented here. The “streaks” of maximum intensities in this plot are due to interference of

Figure 1. (top) Spectrogram of an electric component in the VLF range up to 20 kHz on 23 September 2005 between 0316:00 and 0323:00 UT. The two vertical white lines delimit the occurrence of a burst mode. The parameters below the spectrograms indicate universal time (UT), local time (LT), geographic latitude and longitude, and the McIlwain parameter L. (middle) Intensities in kA and occurrences of the lightning discharges for the same time interval as in Figure 1 (top). (bottom) Red stars indicate the geographical positions of the lightning discharges shown in Figure 1 (middle). The black line is the ground track of the DEMETER orbit. Its time interval corresponds to the time interval of Figure 1 (top); that is, the map has the same limits in geographical latitude as the spectrogram of Figure 1 (top).

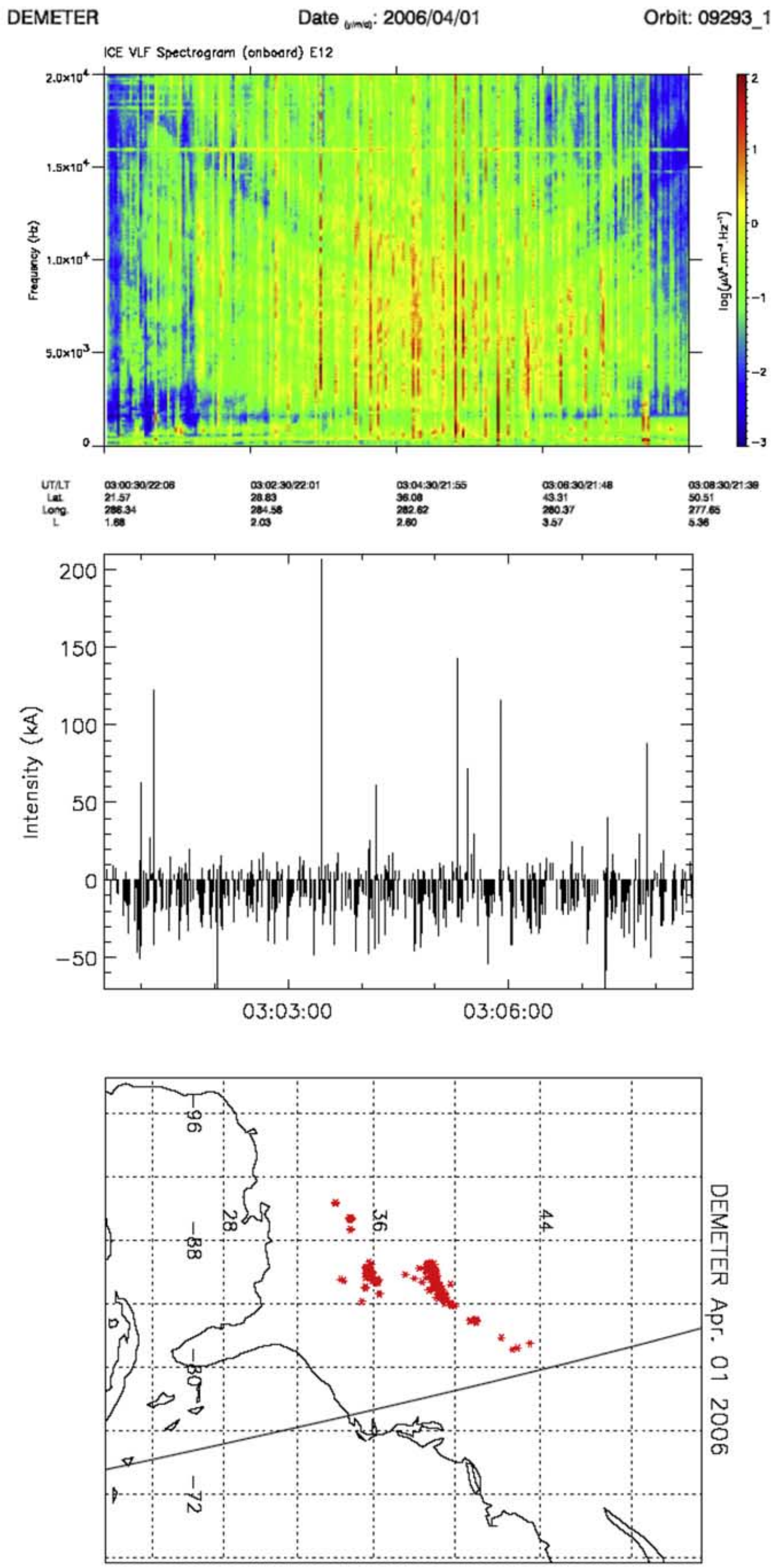

Figure 2. Same as in Figure 1 for data recorded on 1 April 2006 between 0300:30 and 0308:30 UT.

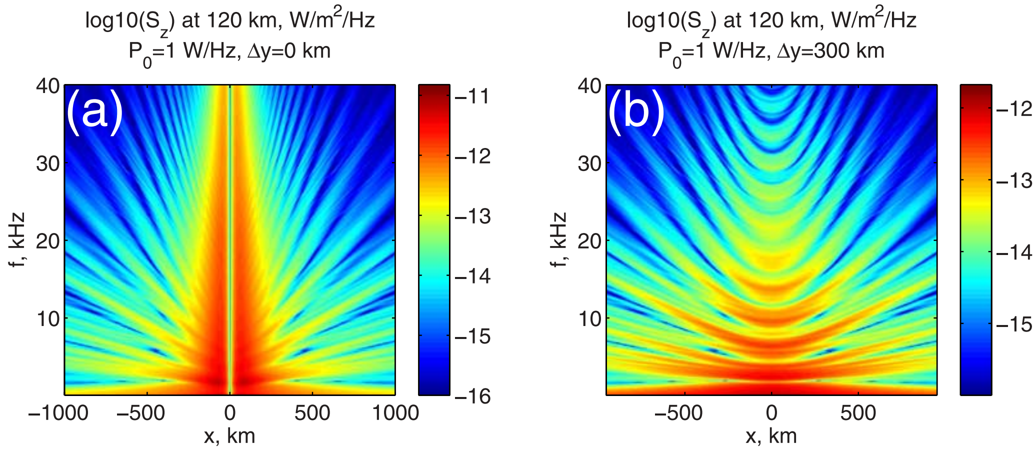

Figure 3. Modeling of the phenomena observed in Figures 2 and 3 (top). Whistler mode wave intensity at 120 km altitude as a function of horizontal distance x from a ground-based point vertical dipole source. Calculation is done when the source is (a) right below the satellite or (b) at a lateral distance $y = 300$ km.

different propagation modes which are excited in the Earth-ionosphere waveguide and can be observed by a satellite passing over, e.g., a thunderstorm region, since the intensity pattern at 120 km approximately maps to satellite altitudes due to mostly collinear propagation of the whistler waves, along nearly radial raypaths in these regions. Figure 3a is related to observation shown in Figure 1 when the satellite goes exactly over the thunderstorm whereas Figure 3b is related to observation shown in Figure 2 when the satellite goes next to the thunderstorm.

[10] The fact that in Figure 3a the "streaks" approximately follow the lines x/f = const can be understood in the following manner. The maxima in intensity occur at a fixed phase difference $\Delta\varphi$ between strongest waveguide modes. The horizontal wave number for the nth mode is $k_x = (k_0^2 - k_n^2)^{1/2}$, where $k_0 = \omega/c = 2\pi/\lambda$ is the vacuum wave number, and k_n is an approximately frequency-independent vertical wave number. Assume that the ionosphere is reflecting the VLF waves at height h. Then the vertical wave numbers can be calculated to be $k_n = n(2\pi/h)$. In the following, we use approximation $k_n \ll k_0$; that is, $n(2\pi/h) \ll 2\pi/\lambda$. The strongest modes have low values of n, so this approximation is equivalent to $h \gg \lambda$ (where λ is the wavelength in vacuum), which holds for frequencies above around 5 kHz, since the reflection height is around 70 km.

[11] The phase of the wave in nth mode at distance is $\varphi = k_{xn}x - \omega t + \varphi_{0n}$. For the two strongest modes with vertical wave numbers k_1 and k_2 we calculate the phase difference between them:

$$
\begin{aligned}
\Delta\varphi &= k_{x1}x - k_{x2}x + \Delta\varphi_0 \\
&= \left[\left(k_0^2 - k_1^2\right)^{1/2} - \left(k_0^2 - k_2^2\right)^{1/2}\right]x \\
&\approx (1/2)\left(k_2^2 - k_1^2\right)\left(k_0^2 - k_1^2\right)^{-1/2}x + \Delta\varphi_0 \\
&= (1/2)\left(k_2^2 - k_1^2\right)(x/k_{x1}) + \Delta\varphi_0
\end{aligned}
$$

where $\Delta\varphi_0 = \varphi_{01} - \varphi_{02}$ and we used the fact that $(k_2^2 - k_1^2) \ll (k_0^2 - k_1^2)$. The difference of the initial phases $\Delta\varphi_0$ can in principle depend on the frequency ω. However, a source in the form of a delta function (such as a lightning) produces waves at different frequencies which all have the same phase at the location of the source. So we neglect this dependence and assume that $\Delta\varphi_0$ = const. Thus, the condition of $\Delta\varphi$ = const translates into x/k_x = const, which is the same as x/f = const for $k_0 \gg k_{1,2}$. The purpose of this derivation is to understand the pattern provided by the full wave calculations presented in Figure 3a and is not completely rigorous because of a number of approximations. The experimental data should be compared against the more accurate results of the full wave calculations.

5. Conclusions

[12] This paper shows the characteristics of V-shaped streaks observed on the DEMETER satellite during nighttime periods when a high rate of 0+ whistler activity is observed in association with lightning discharges. Ground-based NLDN data are used to show that these V-shaped streaks are observed above highly active and isolated thunderstorm regions. The properties of the observed V-shaped streaks appear to be consistently explained using a new model of VLF propagation in the Earth-ionosphere waveguide, and transionospheric leakage to the satellite altitude. It is shown that the funnel-like V shape of the streaks is a simple consequence of the mapping to high altitude of frequency-dependent position of mode interference nulls (and crests) within the Earth-ionosphere waveguide.

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