HF signatures of powerful lightning recorded on DEMETER

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Received 15 April 2008; revised 26 September 2008; accepted 1 October 2008; published 29 November 2008.

[1] Emissions in the HF range (1.7 – 3 MHz) are observed at the times of powerful lightning on the low-altitude satellite DEMETER. At ∼700 km, wave activity observed on the *E* field spectrograms recorded on DEMETER during nighttime is mainly dominated by upgoing 0+ whistlers and higher-order dispersed whistlers. Over a period of 30 months, 130 events with HF emissions at frequency ∼2 MHz have been observed at the time of intense 0+ whistlers on VLF spectrograms. A global map of the distribution of events indicates that they do not occur above regions of most thunderstorm activity such as the upper part of South America or the middle of Africa. This lack of occurrence above these two near-equatorial regions is consistent with the high value of the critical frequency of the *F* layer which prevents the transionospheric propagation of the HF component of the lightning pulses up to 700 km. The time, location, intensity, and polarity of the lightning discharges related to a subset of these HF events are determined above the North American region with the National Lightning Detection Network. As most of the events are recorded in Survey Mode when full resolution of the data is not available, the neural network on board DEMETER is used to determine the times of the 0+ whistlers recorded by the satellite with a time accuracy of ∼0.1 s. The impulsive HF events correspond to intense lightning discharges occurring in regions immediately below the satellite. It is assumed that the propagation of these HF pulses up to the altitude of the satellite is favored by local ionospheric heating due to high thunderstorm activities.

Citation: Parrot, M., U. Inan, N. Lehtinen, E. Blanc, and J. L. Pinçon (2008), HF signatures of powerful lightning recorded on DEMETER, *J. Geophys. Res.*, *113*, A11321, doi:10.1029/2008JA013323.

1. Introduction

[2] A large part of the electromagnetic (EM) waves observed by the satellite DEMETER consists of sferics and 0^+ whistlers mainly during nighttime at low latitudes and midlatitudes. Following the classification given by *Smith and Angerami* [1968], 0^+ whistler is a whistler that propagates to the satellites without crossing the magnetic equator. In fact, DEMETER is designed to study ionospheric perturbations in relation with the seismic activity and the man-made activity but its payload which consists of wave and particle analyzers allows other researches. Since the pioneering work of *Storey* [1953] a huge number of papers have been published concerning the generation, the propagation, and the effect of sferics and whistlers in the ionosphere and the magnetosphere but despite a large amount of satellite data, only few observations exist of HF emissions related to lightning. The first observations of effects of lightning were limited to an increase of HF (0.2 – 9 MHz) noise intensities above thunderstorm areas with the satellite RAE-1 at 6000 km altitude [*Herman et al.*, 1973]. The Japanese Ionosphere Sounding Satellite ISS-b on a circular orbit at 1100 km observed typical peaks at 5 and 10 MHz related to lightning discharges when the frequencies were above the critical frequency of the ionosphere [*Kotaki and Katoh*, 1983; *Kotaki*, 1984]. These authors published the first maps of the HF emissions related to the lightning activity for the four seasons as well as noise maps. The experiment Blackbeard on board the satellite Alexis provided the first VHF wave forms of lightning in two frequency bands (28 – 95 MHz, and 100 – 175 MHz). Typical very intense signals formed by two separated pulses of few microseconds were observed. These signals were called Trans Ionospheric Pulse Pairs (TIPPS). TIPPS have been clearly related to lightning activity [*Massey and Holden*, 1995; *Holden et al.*, 1995; *Massey et al.*, 1998]. The satellite FORTE showed that the second pulse is the surface reflected signal and that TIPPS are related with intracloud discharges [*Tierney et al.*, 2001; *Jacobson*, 2003]. The dispersion of the signals was used to retrieve ionospheric parameters [*Roussel-Dupré et al.*, 2001]. At ionospheric altitudes, *Kelley et al.* [1997] reported an HF observation of an EM pulse in connection with a lightning at a frequency below 2 MHz. A first example of the DEMETER HF emissions (∼2 MHz) at the time of intense sferics has been shown by *Parrot et al.* [2008].

[3] The purpose of this paper is to study the HF emissions recorded by DEMETER in relation with lightning activity in

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0148-0227/08/2008JA013323

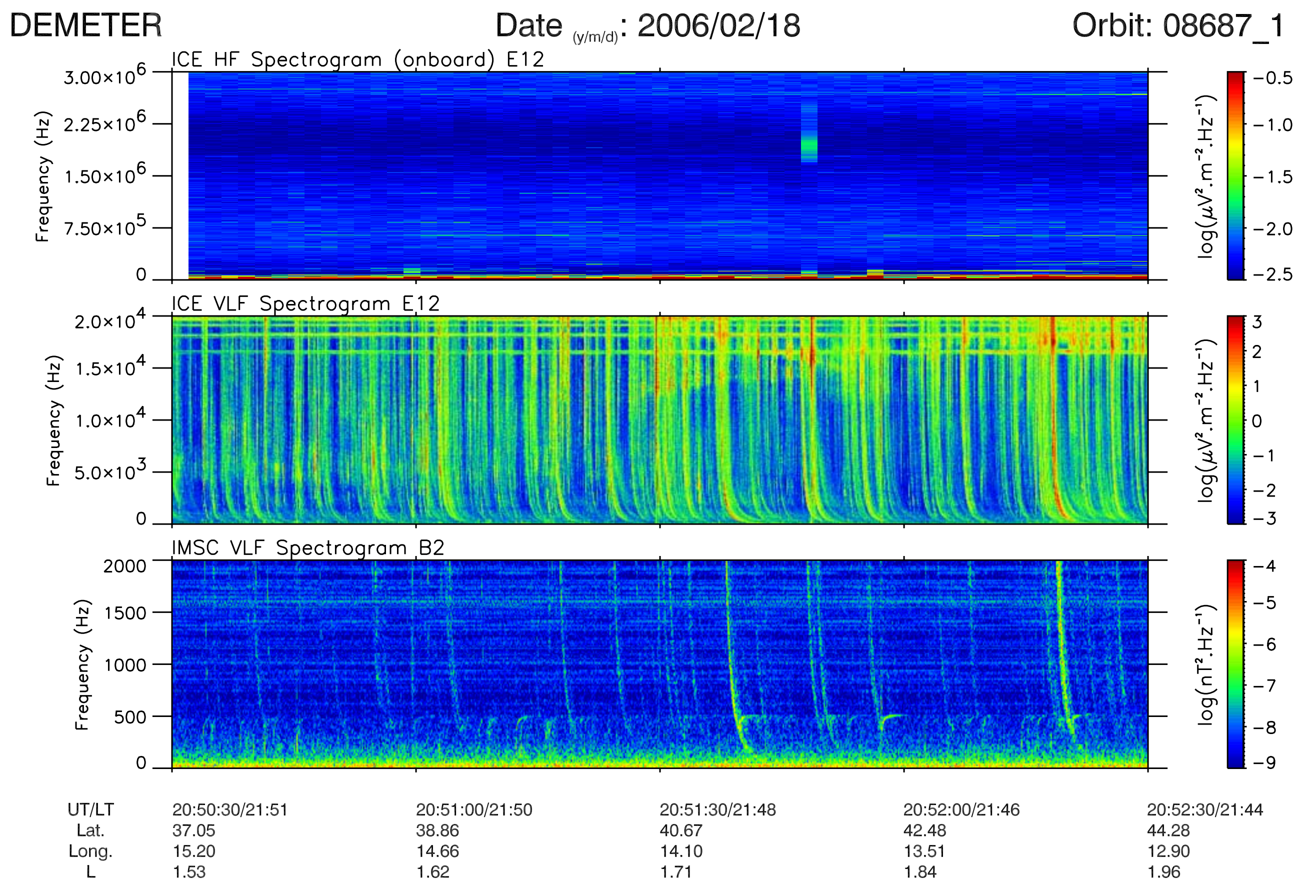

Figure 1. Spectrograms recorded by DEMETER on 18 February 2006 during two minutes. It concerns (top) electric component in the HF range up to 3 MHz, (middle) the same component in the VLF range up to 20 kHz, and (bottom) a magnetic component up to 1.5 kHz. A pulse with maximum amplitude of 7 μV/m is observed in the top spectrogram at 1.95 MHz. The parameters below the spectrograms indicate universal time (UT), local time (LT), geographic latitude and longitude, and the McIlwain parameter L. The electric component E12 is perpendicular to the orbital plane of the satellite, whereas the direction of the magnetic component B2 makes an angle of 45° with the Earth's magnetic field. The VLF spectrograms are dominated by 0+ (very few dispersion) and one-hop (larger dispersion) whistlers. Proton whistlers can be also seen in the bottom spectrogram around 500 Hz.

order to determine their characteristics, their occurrences, and their relations with the intensity of the parent lightning. Section 2 briefly describes the wave experiment which is a part of the scientific payload of DEMETER. Specific HF events observed by DEMETER are shown and their occurrences are discussed in section 3. Section 4 is devoted to the characteristics of the lightning which are related to these HF events. Some 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 continuously measures electromagnetic waves all around the Earth except in the auroral zones when the invariant latitude is larger than 65°. Concerning the electric field, the high-frequency (HF) range is from DC up to 3.33 MHz whereas the very low frequency (VLF) range is from 0 to 20 kHz. There are two scientific modes: a survey mode and a burst mode when the satellite is above active seismic regions. During the mission burst modes have been also set over different regions for specific purposes. Spectrum of one electric component is onboard computed in the HF and VLF ranges during the survey mode. During the burst mode waveforms of the same electric field component are recorded up to 20 kHz in addition to the spectrum. The burst mode allows the performance of a spectral analysis with higher time and frequency resolution. In HF, the signals are sampled at 6.66 MHz and digitized with 8 bits. The HF data acquisition is performed on 40 data snapshots each 0.6144 ms long and evenly spaced in the 2.048 s elementary interval of the VLF channel acquisition. Individual power spectra are calculated for each snapshot with a frequency resolution of 3.25 kHz and averaged to provide a power spectrum every 2.048 s. In burst modes, the averaged power spectrum and waveform data for a single 0.6144 ms interval are available. Through a telecommand order, the selected waveform interval can be either the first of the 40 intervals or the one with the maximum total power over the entire HF bandwidth. In survey modes, the power spectra are the only information available. Whatever the mode, a neural network gives the times of the 0+ whistlers and one-hop whistlers recorded on

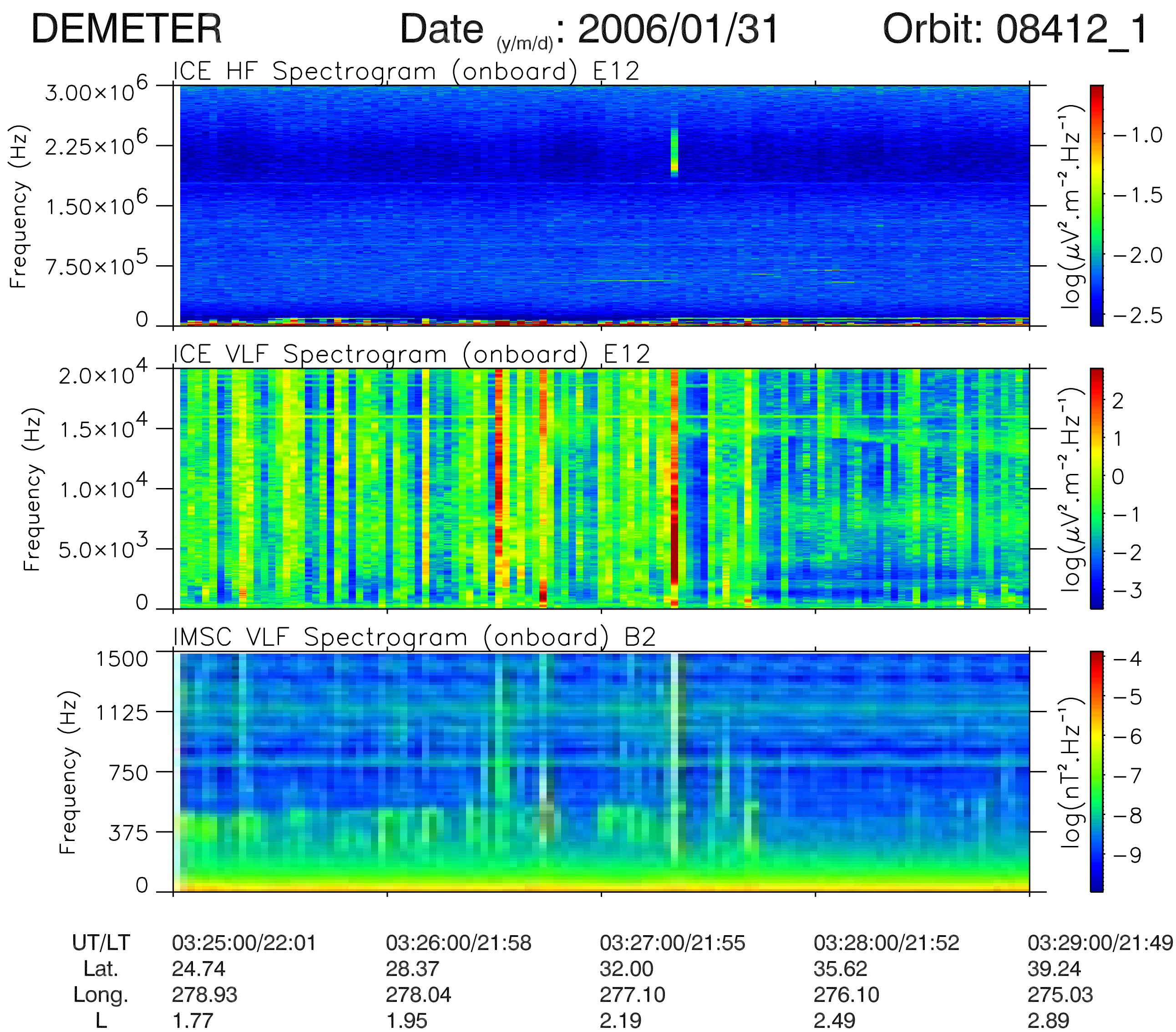

Figure 2. Same presentation as in Figure 1, but the data are now recorded on 31 January 2006, when the satellite is in survey mode above the United States. Four minutes of data are displayed. The lightning associated with the HF pulse has a current intensity of +55.2 kA. A pulse with maximum amplitude of 14 μV/m is observed in the top image at 1.95 MHz.

the satellite with their associated dispersion, with a temporal accuracy of the order of 0.1 s [*Elie et al.*, 1999]. This neural network uses as input the individual VLF spectra of the selected electric component which are onboard computed and then averaged to produce the final spectrum sent in the telemetry. Details of the wave experiment are given by *Parrot et al.* [2006] and *Berthelier et al.* [2006].

3. HF Events Received on Board the Satellite

[5] Figure 1 shows an event recorded on 18 February 2006 during two minutes when the acquisition system was in burst mode. The top image shows the onboard computed HF spectrogram of an electric component between 0 and 3 MHz. The middle image represents the VLF spectrogram of the same component between 0 and 20 kHz, and the bottom image displays the VLF spectrogram of a magnetic component between 0 and 1.5 kHz. These two latter spectrograms are computed from the full resolution data of the experiment. An increase in the HF spectrogram around 2 MHz at ~2021:50 UT is evident. This increase corresponds to the time of an intense 0+ whistler in the middle and bottom images (note that the apparent time broadening of the HF emission is due to the low resolution time (2 s) of the spectrogram in the HF range). Over a period of 2 years, 130 similar events were observed at nighttime (2230 LT which is the local time of the DEMETER measurements) examining ~10000 spectrograms (each of them corresponds to one half-orbit, i.e., 35 min of data). In the spectrogram displays the HF enhancements always correspond to intense 0+ whistlers, but only few of the intense 0+ whistlers produce such HF emissions. Most of the 130 events are recorded when the satellite is in survey mode when the time resolution of the onboard computed

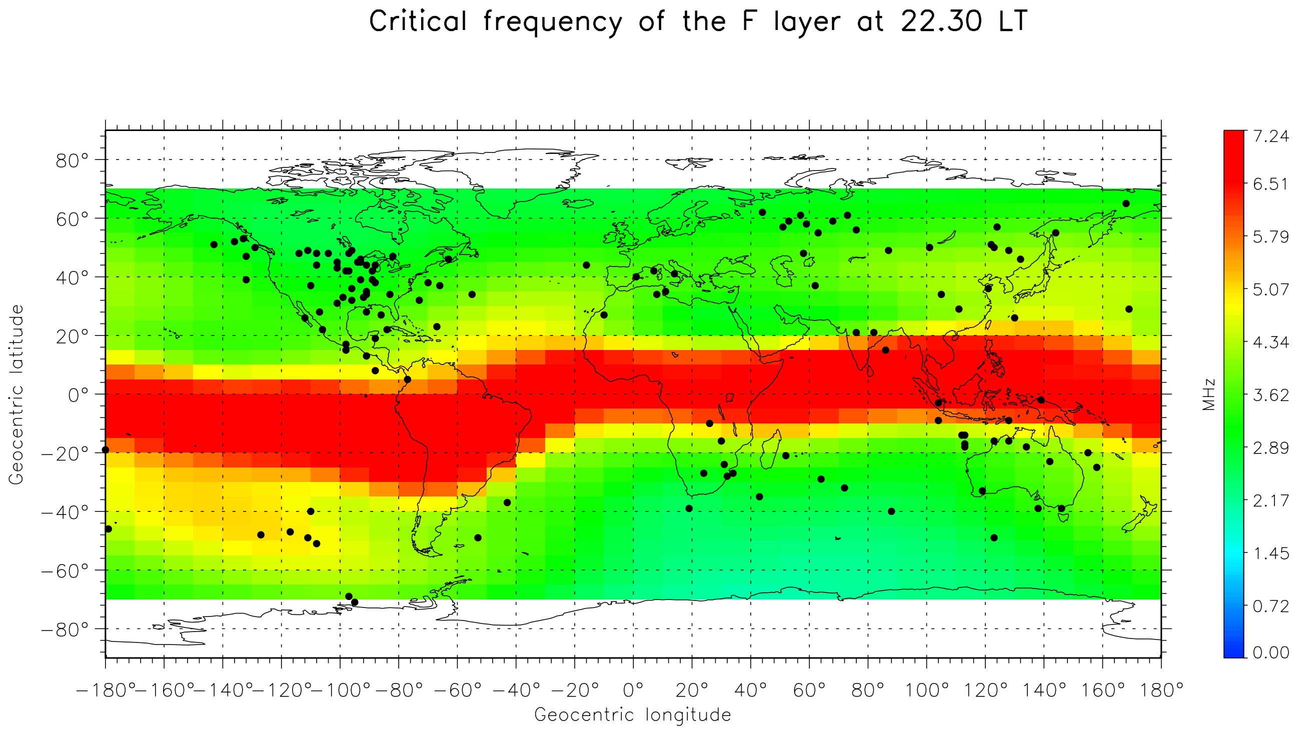

Figure 3. Location of DEMETER subsatellite points at the time of the 130 HF events (black dots) and map showing the values of the critical frequency of the ionospheric *F* layer at 2230 LT in MHz according to the color scale on the right.

spectrogram is 2 s. An example of a survey mode spectrogram is given in Figure 2 displaying an event which is similar to the one shown with high resolution in Figure 1. Four minutes of data are represented and the event can be seen at 0327:19 UT. It is evident from the middle image that HF emission corresponds to an intense 0+ whistler within 2 s, while two other intense 0+ seen around 0326:40 UT are not accompanied with an HF pulse.

[6] The local characteristic frequencies electron gyrofrequency, plasma frequency, and upper hybrid frequency are 0.92 (1.01), 1.1 (0.9), and 1.43 (1.35) MHz respectively for event in Figure 1 (Figure 2). They do not correspond to the HF frequency band of the events seen in the top images of Figures 1 and 2. The source of this emission must therefore lie below the satellite, as it is not a local phenomenon occurring at the altitude of the satellite. The geographic distribution of occurrence of events is shown in Figure 3 with the locations of DEMETER corresponding to the ground geocentric radial footprint of the satellite. Event occurrence appears to be equally distributed over regions of intense thunderstorm activity except over two main zones: the upper part of the South America and Central Africa. Insight into the reason why such HF pulses starting at ~2 MHz are only observed above particular regions can be gained from a global map of the critical frequency of the *F* layer which is overplotted in Figure 3. These critical frequencies were obtained from the IRI2001 model [*Bilitza*, 2001]. This model was used at the local nighttime of the measurement by the satellite (2230 LT) and, for a given geographical position, the maximum frequency was selected regardless of the altitude of the *F* layer h_mF. Under these conditions, h_mF varies between 300 and 360 km depending on the location. Looking to Figure 3, it is clearly seen that there exists a large region around the magnetic equator where the values of the critical frequency are very high (5 – 7 MHz), thus preventing the penetration of the lightning HF pulses up to the altitude of the satellite for our frequency range of observation. On the contrary at midlatitudes, for example, above the United States, the critical frequency can be as low as 2 MHz, and the upper frequency part of the HF pulses can thus be observed at DEMETER altitude. This correspondence indicates that the lower frequency of the HF events observed by DEMETER matches the value of the critical frequency of the *F* layer below the satellite. However, it can be seen that very few events are present in Indonesia close to the magnetic equator. This may be due to the fact that we compare with a model of the critical frequency of the *F* layer and sometimes this frequency could be lower at specific times or the penetration of the HF pulses could be due to local ionospheric irregularities.

4. Characteristics of the Lightning Discharges Related to the HF Events

[7] In order to determine the characteristics of the lightning discharges related to the HF events, the North American region is selected because many HF events occur there and there exists a very efficient National Lightning Detection Network (NLDN), recording the time, location, intensity and polarity of cloud-to-ground lightning discharges. The time of the lightning-generated 0+ whistlers recorded by DEMETER in association with an HF pulse event is determined in order to find to which lightning observed by NLDN it corresponds. One difficulty is the fact that the HF

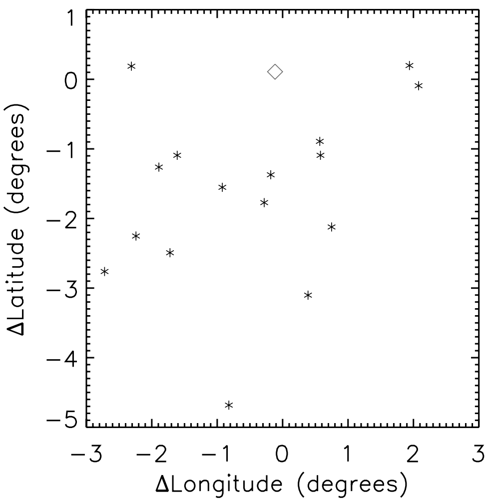

Figure 4. Relative positions of DEMETER (stars) in geographic latitude and longitude when an HF pulse event is observed (diamond).

events over the United States are recorded when the satellite is in survey mode with the time resolution of the spectrograms being only 2 s. The NLDN data show that in 2 s many lightning discharges can occur in close vicinity. To remove any time ambiguities that might occur, data from the neural network on board DEMETER are used. The characteristics of 16 lightning discharges associated with HF emissions were determined (the event shown in Figure 2 is included). The HF events are seen to correspond to relatively high values of peak current. This current is regularly distributed between −30.5 kA and −113.2 kA (average value is −62.8 ± 27.6 kA). Among the sixteen events, twelve are related to a negative CG discharge. A comparison between the location of the lightning and the location of DEMETER at the time of the HF pulse observation (Figure 4) indicates that the causative lightning discharges which produce the HF pulses occur within 400 km from the geocentric radial footprint of the satellite but with a slight equatorward displacement.

[8] The fact that the causative lightning flashes that produce the HF events which reach to satellite altitude occur in close proximity of the satellite footprint can be understood with the use of HF ray tracing to determine refraction of rays in a typically horizontally stratified ionosphere. In a stratified ionosphere, the escape of HF radiation with $f > f_H$ (the electron gyrofrequency) is only possible when $f > f_{Fmax}$ (the critical frequency of the *F* layer), i.e., $X_{max} < 1$, where $X = f_p^2/f^2$ (f_p is the plasma frequency). In this case, the escaping mode is the ordinary mode. For the extraordinary mode, the condition is stricter, $X_{max} < 1 - Y$, where $Y = f_H/f < 1$. Figure 5 shows a ray tracing simulation of the ordinary mode, in the plane of the geomagnetic field at the angle $\theta_B = 45°$ with the vertical, with $f_H = 1.6$ MHz, $f = 2$ MHz and $f_{Fmax} = 1.99$ MHz. In such a case, when f is only slightly above f_{Fmax}, the escaping rays in the plane of B_0 have the zenith angle in the range $|\theta| < \sim\theta_S$, where θ_S is the so-called Spitze angle given by $\sin(\theta_S) = \{Y/(Y+1)\}^{1/2} \sin(\theta_B)$. In the plane perpendicular to B_0, the zenith angles are $|\theta| < \sim\arcsin(\{1 - X_{max}\}^{1/2})$. The calculations were performed for electron density shown in Figure 6, which is a nighttime ionosphere profile, produced by IRI model [*Bilitza*, 2001]. Figure 5 suggests that the escaping HF radiation is shifted horizontally in the direction opposite to that of the geomagnetic field line (northward in the northern hemisphere). However, the presented observations show that the escaping HF radiation is detected at the position shifted horizontally in the direction of the geomagnetic field line (southward for the northern hemisphere). This discrepancy might be due to formation of density depletion ducts along the geomagnetic field, which would favor the escape of HF radiation along the geomagnetic field lines. Other HF pulses have been also observed above a powerful VLF transmitter named NWC by *Parrot et al.* [2007]. They showed that, in the magnetic flux tube with a footprint at NWC, there are large density perturbations which create a waveguide where HF and VLF components of the lightning spectrum are not attenuated (except that there is a HF cutoff due to the *F* layer as it is here). Such ionospheric heating by thunderstorm activities have been already reported by *Inan et al.* [1993]. *Liao et al.*

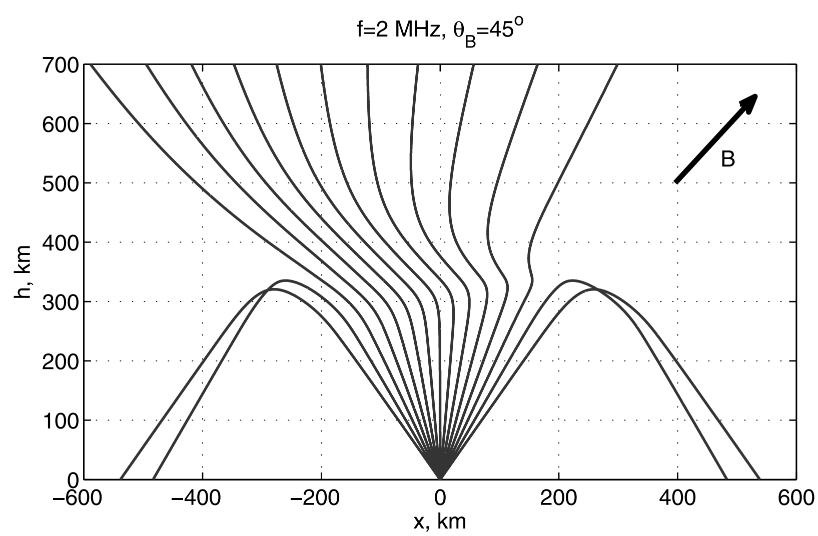

Figure 5. HF ray tracing of the ordinary mode as a function of the altitude.

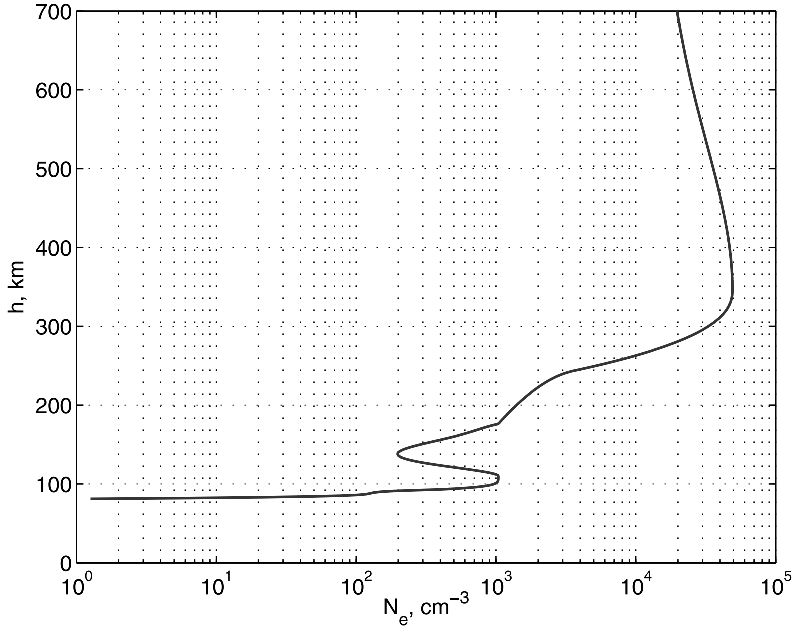

Figure 6. Nighttime ionospheric electron density profile used to obtain Figure 5.

[1989] have also shown that the lightning-produced VLF waves can cause important modifications in the ionospheric plasma (explosive spread *F*) by a parametric instability. Investigating the effect of the VLF transmitter NAU on the ionosphere, *Labno et al.* [2007] found that these powerful VLF waves can propagate along waveguides formed by spread *F* density perturbations and excite lower hybrid waves which accelerate electrons. It is therefore assumed that the propagation of the HF pulses observed by DEMETER at the times of lightning is due to ionospheric heating by thunderstorm activities below the satellite. Regarding the low number of these HF events, one can say that this mechanism is not so efficient as man-made waves.

5. Conclusions

[9] Unusually intense HF emissions are observed on the satellite DEMETER during nighttime and above active thunderstorm regions. HF pulses are not observed above a broad region around the magnetic equator because the high value of the critical frequency of the *F* ionospheric layer in this region stops the propagation of the lightning pulses. By comparison with ground-based NLDN data for DEMETER passes over the United States, it is shown that the HF emissions correspond to relatively intense lightning discharges with mainly negative CG current. It also appears that these HF emissions are observed by the satellite only when the corresponding intense lightning discharges occur immediately below the satellite within a few hundred kilometers of its geocentric footprint.

[10] **Acknowledgments.** This work is based on observations with the electric field experiment ICE embarked on DEMETER, which is operated by the Centre National d'Etudes Spatiales (CNES). The authors thank J. J. Berthelier, the PI of ICE, for the use of the data. S. Berthelin from the DEMETER Mission Center in Orléans is deeply acknowledged for help in data handling. The authors wish to thank the International Space Science Institute (ISSI) for supporting the WFM (ISSI 89) team meetings which stimulated this work. The NLDN data were provided courtesy of Vaisala, Inc., under a Research Collaboration Agreement with Stanford University. The Stanford work was supported by the Office of Naval Research under MURI grant N000140710789 with subcontract Z822802-A to Stanford University.

[11] Amitava Bhattacharjee thanks Anatoly V. Streltsov and another reviewer for their assistance in evaluating this paper.

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