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ELF Remote Sensing of the Lower Ionosphere using Group Velocity of Electromagnetic Radiation from Atmospheric Lightning Discharges

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1. INTRODUCTION

The lowest region of the upper atmosphere plasma environment is the ionospheric D-region, which exists in the altitude range of 65–95 km. D-region electron densities are maximum during the daytime and significantly reduced at night, but the plasma state persists at these altitudes at all hours and dominates the propagation and reflection of electromagnetic waves with frequencies below 100 kHz and the absorption of MF (Medium Frequency: 300 kHz – 3 MHz) and HF (High Frequency: 3 MHz – 30 MHz) waves. The D-region is affected by magnetosphere-ionosphere coupling since energetic electron precipitation from the Earth's radiation belts and solar flare X-ray fluxes increase D-region ionization levels. Therefore monitoring the D-region electron is an important part of space weather monitoring.

Despite its recognized importance, the D-region electron density profile is challenging to diagnose as electron densities are too low for direct sounding and the altitude is too low for spacecraft observations. Rocket measurements provide the only direct observations and it should be noted that global ionospheric models like the International Reference Ionosphere do not provide validated electron density information below 100 km. We present a novel way to perform D-region remote sensing using observations of lightning induced radiation in the ELF (Extremely Low Frequency: 3–300 Hz) band. In contrast to past work using lightning radiation, which relied on amplitude and phase changes over a broad spectrum, we use a single simple parameter of ELF group velocity to obtain the characteristics of the Earth-ionosphere propagation channel. Theoretical analysis and numerical modeling shows that the ELF group velocity can serve as a diagnostic for day-night conditions as well as changes induced by solar flares.

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2. ELF PROPAGATION IN EARTH-IONOSPHERE WAVEGUIDE

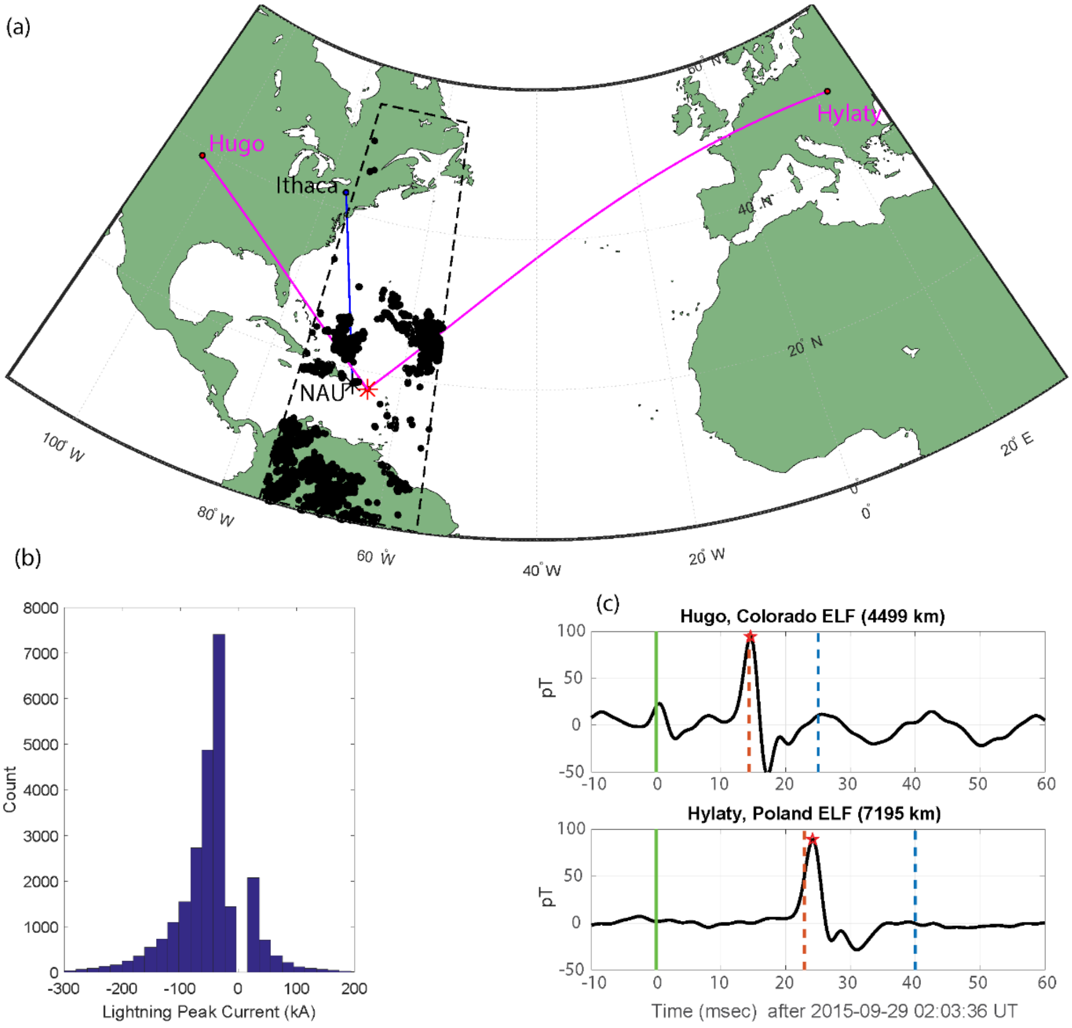
The D-region electron density profile is traditionally modeled using a two-parameter model first introduced in the 1960s. In this model the two key parameters are the reference height *h*' [km] and the steepness parameter β [km^{-1}] as shown below:

$$N(z) = 1.43\times10^{13}\exp\left[(\beta-0.15)z-\beta h'\right] \quad [\mathrm{m}^{-3}]$$

There is a general consensus on the reference height diurnal dependence with $h' < 80$ km during daytime with a minimum at local noon and $h' \geq 80$ km during the nighttime. There is less consensus on the steepness parameter β with daytime ranges of 0.25–0.9 km^{-1} and nighttime ranges 0.25–2.8 km^{-1} reported in the literature. For waves in the Earth-ionosphere waveguide with frequencies below 400 Hz, the group velocity can be significantly less than the speed of light and is affected by the D-region electron density profile. This unique dispersion, which is not present at higher frequencies, is due to the fact that the electric and magnetic fields of the ELF waves do not reach the same maximum altitude. The ionosphere strongly affects the coupling between the fields and the magnetic field can penetrate up to 100 km altitude while the electric field is confined to lower altitudes (Gołkowski *et al.* 2018).

3. ELF OBSERVATIONS AND NUMERICAL MODELING

Observations are made using ELF receivers in Hugo, Colorado, USA and Hylaty, Poland that are part of the World ELF Radiolocation Array (WERA) (Kulak *et al.* 2014). Global lightning



ning occurrence (timing and location) are obtained from the Global Lightning Dataset (GLD360) from Vaisala. The GLD360 network detects only cloud-to-ground (CG) discharges which produce a vertical dipole moment (Said *et al.* 2010). Figure 1 shows an observation scenario from 29 September 2015 where lightning along the North American Atlantic coast is observed with ELF receivers in Colorado and Poland. Only CG lightning discharges with peak currents above 10 kA were used in the analysis since high peak currents of CG return strokes are associated with significant ELF radiation. Panel (b) shows a histogram of the peak current from ~20,000 lightning discharges that were identified by the GLD360 network and also observed in the ELF data. The time domain data in panel (c) of Figure 1 shows the ELF waveforms, the peaks of which are used to obtain group velocity.

For numerical modeling we use the Long Wave Propagation Capability (LWPC) numerical model, which provides a modal solution to wave propagation in the Earth-ionosphere waveguide. Amplitude and phase at each frequency from LWPC is transformed into the time domain using the inverse Fourier transform.

4. RESULTS

Group velocity observations were made on 29 September 2015. Figure 2 shows results of group velocity observed at Hugo, Colorado and Hylaty, Poland from lightning along the North American east coast. The data are shown for the entire day and are averaged from approximately 20,000 lightning discharges occurring within the region of interest. The effect of the day-night transition is clearly seen in the propagation velocity, which increases when the propagation path is on the nightside and decreases for the dayside.

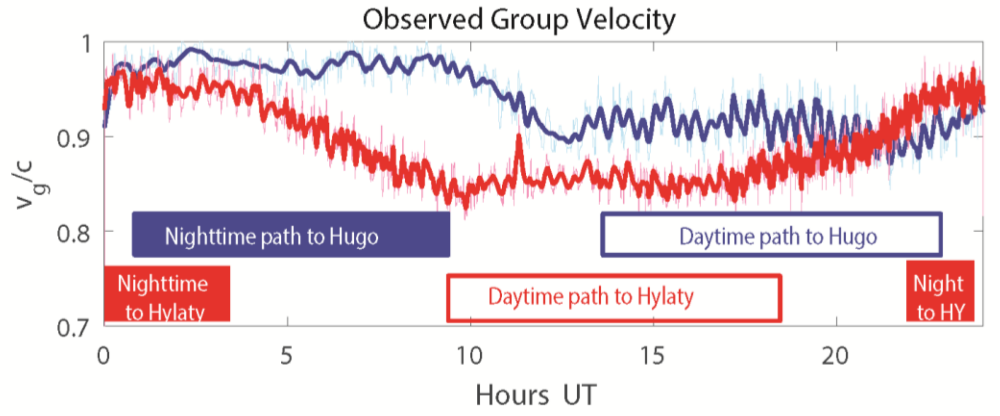


Fig. 2. Group velocity, v_g, as a fraction of the speed of light, c, from observations at Hugo, Colorado and Hylaty, Poland from North American lightning shown in Figure 1. The light traces are 20-point median filtered raw data, and dark traces are additional smoothed using a 100-point moving average. The group velocity increases for nighttime conditions and decreases for daytime conditions.

Figure 3 shows the ELF wave group velocity predicted by the LWPC simulation for different values of h' and β parameters along the path from the Caribbean (near Puerto Rico) to Hugo, Colorado and Hylaty, Poland. The velocity values fall in the range of $0.85c – 0.95c$,

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Fig. 1. (a) Map showing receiver locations in Hugo, Colorado and Hylaty, Poland and CG lightning event locations observed on 29 September 2015 (black dots), and propagation paths are used in numerical modeling (pink). (b) Histogram of lightning peak current from GLD360 network. (c) Example of ELF waveforms from a single lightning discharge from which group velocity is extracted. Figure adapted from Gołkowski *et al.* (2018).

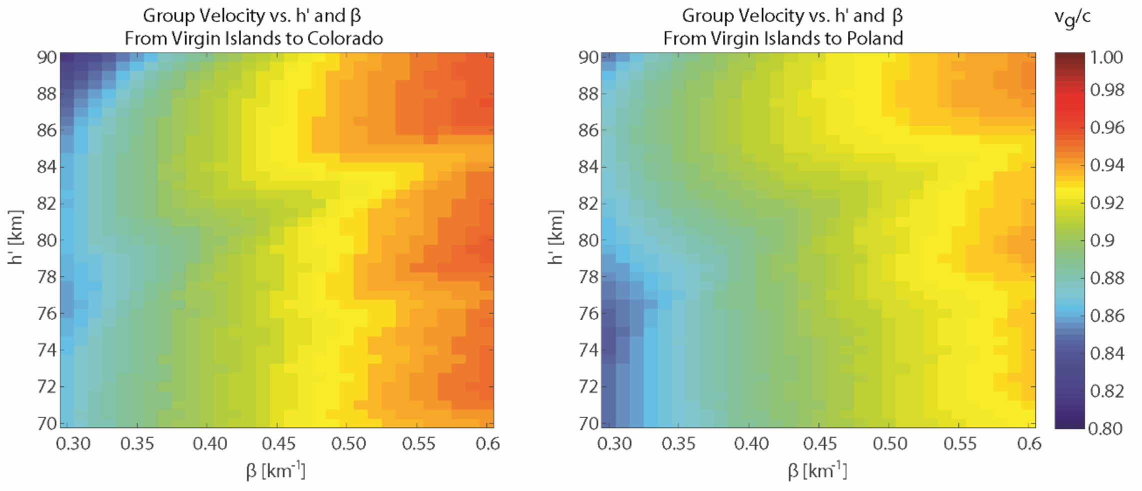

Fig. 3. ELF wave group velocity predicted from LWPC simulation for propagation paths to Hugo (left) and to Hylaty (right) illustrated in Fig. 1 for different combinations of h' and β.

where c is the speed of light in agreement with observations in Figure 2. The values for the Hugo path are at times slightly higher than for the Hylaty path. In both cases the group velocity shows a strong β dependence and much weaker dependence on h' suggesting that ELF group velocity observations can be an effective way to diagnose the steepness of the D-region ionospheric profile.

5. SUMMARY

We have shown that the group velocity of lightning radiation in the ELF band can be used as a diagnostic of the D-region ionosphere. This new technique provides unique access to the β value (steepness) of the two parameter D-region ionospheric model. The β parameter has been difficult to quantify using other techniques. The group velocity technique can also be used to diagnose the D-region during solar flares. Using this technique a small number of ELF receivers and lightning detection data can provide a global D-region diagnostic.

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TELEDETEKCJA NAJNIŻSZEJ WARSTWY JONOSFERY PRZY POMOCY PRĘDKOŚCI GRUPOWEJ PROMIENIOWANIA ELEKTROMAGNETYCZNEGO ELF OD WYŁADOWAŃ ATMOSFERYCZNYCH

Streszczenie

Najniżej położona warstwa jonosfery to warstwa D na wysokości 65–95 km. Koncentracja elektronów osiąga maksimum w ciągu dnia i znacznie spada w nocy, ale materia w stanie plazmy utrzymuje się na tych wysokościach całą dobę. Plazma w tej warstwie ma dominujący wpływ na propagację i odbijanie się fal radiowych z częstotliwościami poniżej 100 kHz i absorbcje fal w pasmach MF (Medium Frequency – częstotliwości średnie) i HF (High Frequency – wysokie częstotliwości). Warstwa D wyraźnie odczuwa efekty sprzężenia jonosfera–magnetosfera, skoro wysyp energetycznych elektronów z pasm radiacyjnych i rozbłyski słoneczne znacznie zmieniają koncentracje elektronów w tej warstwie. Dlatego monitorowanie stanu warstwy D jest ważnym elementem monitorowania pogody kosmicznej.

Mimo kluczowej roli warstwy D w różnych zjawiskach, bezpośredni pomiar koncentracji plazmy w tej warstwie jest możliwy jedynie w trakcie drogich eksperymentów rakietowych, gdyż jej wysokość jest zbyt niska, by posłużyć się pomiarami satelitarnymi, a koncentracja elektronów jest za mała na pomiar jonosondami. Teledetekcja z falami w pasmie ELF (Extremely Low Frequency – krańcowo niskie częstotliwości) i VLF (Very Low Frequency – bardzo niskie częstotliwości) pozostaje, jako jedyna metoda pozwalająca na monitorowanie warstwy D długotrwale na szerokim obszarze.

Prezentujemy tu nowy sposób teledetekcji przy pomocy prędkości grupowej fal elektromagnetycznych pochodzących z wyładowań atmosferycznych doziemnych w pasmie ELF. W odróżnieniu od poprzednich prac o podobnym charakterze, gdzie monitorowanie amplitudy i fazy na szerokim pasmie było konieczne, obecne podejście bazuje na pojedynczym parametrze, który jest stosunkowo łatwo dostępny.

Propagacja fal w falowodzie ziemia–jonosfera w częstotliwościach poniżej 400 Hz zachodzi w warunkach mocnej dyspersji, która nie istnieje podczas propagacji przy wyższych częstotliwościach. Owa dyspersja powoduje, że prędkość grupowa odzwierciedla profil koncentracji elektronowej warstwy D, szczególnie tzw. „stromość” profilu która wyraża się parametrem β w klasycznym dwuparametrowym modelu tej warstwy. Informacja o występowaniu i lokalizacji wyładowań atmosferycznych pochodzi z sieci GLD360, a fale ELF są obserwowane za przy pomocy stacji odbiorczych sieci WERA w Kolorado USA i w Polsce. Opisane tu obserwacje i symulacje z użyciem programu LWPC dowodzą, że metoda ta nadaje się do określenia zmian warstwy D w warunkach dzień–noc oraz w czasie perturbacji w wyniku rozbłysku słonecznego. Metoda pozwala na globalne monitorowanie warstwy D używając wyłącznie sieci WERA i GLD360.