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## Transionospheric attenuation of 100 kHz radio waves inferred from satellite and ground based observations

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[1] Around fifty LORAN (LONG RANGE Navigation) transmitters in the northern hemisphere currently launch continuously pulsed 100 kHz radio waves into the Earth's atmosphere for marine navigation. It is discovered that the 100 kHz radio waves from the LORAN transmissions can be detected by the DEMETER satellite at an altitude of  $\sim 660$  km above the transmitters. These novel electric field measurements in space enable the determination of the nocturnal transionospheric attenuation by comparison with ground based electric field measurements. The electric field measurements on the satellite indicate that the nocturnal transionospheric attenuation of 100 kHz radio waves from LORAN transmissions is equivalent to a nocturnal subionospheric attenuation of the 100 kHz radio waves at a distance of  $\sim 7\text{--}9$  Mm. The radio waves exhibit an average subionospheric attenuation of  $\sim 5$  dB/Mm and it is concluded that the nocturnal transionospheric attenuation of 100 kHz radio waves is  $\sim 35\text{--}45$  dB. This result enables future space missions to quantify the intensity of lightning discharges associated with transient luminous events and terrestrial  $\gamma$ -ray flashes. **Citation:** Fullekrug, M., M. Parrot, M. Ash, I. Astin, P. Williams, and R. Talhi (2009), Transionospheric attenuation of 100 kHz radio waves inferred from satellite and ground based observations, *Geophys. Res. Lett.*, 36, L06104, doi:10.1029/2008GL036988.

### 1. Introduction

[2] The recent discovery of terrestrial  $\gamma$ -ray flashes [Inan, 2005; Smith *et al.*, 2005; Dwyer *et al.*, 2003; Fishman *et al.*, 1994], sprites [Neubert, 2003; Lyons, 1996; Sentman *et al.*, 1995; Boeck *et al.*, 1995; Franz *et al.*, 1990], and blue jets [Krehbiel *et al.*, 2008; Su *et al.*, 2003; Pasko *et al.*, 2002] has led to the preparation of three dedicated space missions including the TARANIS satellite [Blanc *et al.*, 2007]. One module of the TARANIS payload aims at recording the low frequency electromagnetic radiation from lightning discharges and subsequent transient phenomena. For the interpretation of the measurements, it is important to determine if the electromagnetic radiation can be observed on the satellite and a quantitative value for the transionospheric attenuation is required to infer the intensity of the radiating source. For example, very low frequency ( $\sim 3\text{--}30$  kHz)

transmitters and lightning discharges launch electromagnetic waves into space where the waves interact with the ionospheric and magnetospheric plasma [e.g., Clilverd *et al.*, 2008; Platino *et al.*, 2006, and references therein]. As a result, the space based observation of electromagnetic radiation from very low frequency transmitters exhibits a complex spatial pattern including electromagnetic radiation reflected from the geomagnetically conjugate hemisphere (Figure 1). It was only recently discovered that the transionospheric attenuation at frequencies around  $\sim 20$  kHz needs to be corrected by a factor of  $\sim 20$  dB to fit the observations [Starks *et al.*, 2008]. At higher radio frequencies from  $\sim 50$  kHz to  $\sim 300$  kHz the knowledge on the transionospheric propagation of radio waves is even more scarce. Some experimental and theoretical evidence for transionospheric wave propagation below and near the ionospheric plasma frequency has been reported [e.g., Parrot *et al.*, 2008; Rothkaehl and Parrot, 2005; Wang *et al.*, 2005; Kelley *et al.*, 1997; Horne, 1995; Tanaka *et al.*, 1989; Benson *et al.*, 1988, and references therein] but no quantitative information on the transionospheric attenuation has emerged so far. Part of the reason is that the location and the electromagnetic field strength of the causative source of the observed radio waves is generally not known. One possibility to improve this situation is to use well defined transmitters and to discriminate the satellite based observations of radio waves against ground based observations for which the subionospheric wave propagation constant is very well known [Tomko and Hepner, 2001; Chapman *et al.*, 1966]. This contribution describes the first step into this direction: The nocturnal transionospheric attenuation of 100 kHz radio waves from LORAN transmissions is determined by combining novel electric field measurements on board the DEMETER satellite with electric field measurements on the ground.

### 2. Satellite Based LORAN Detection

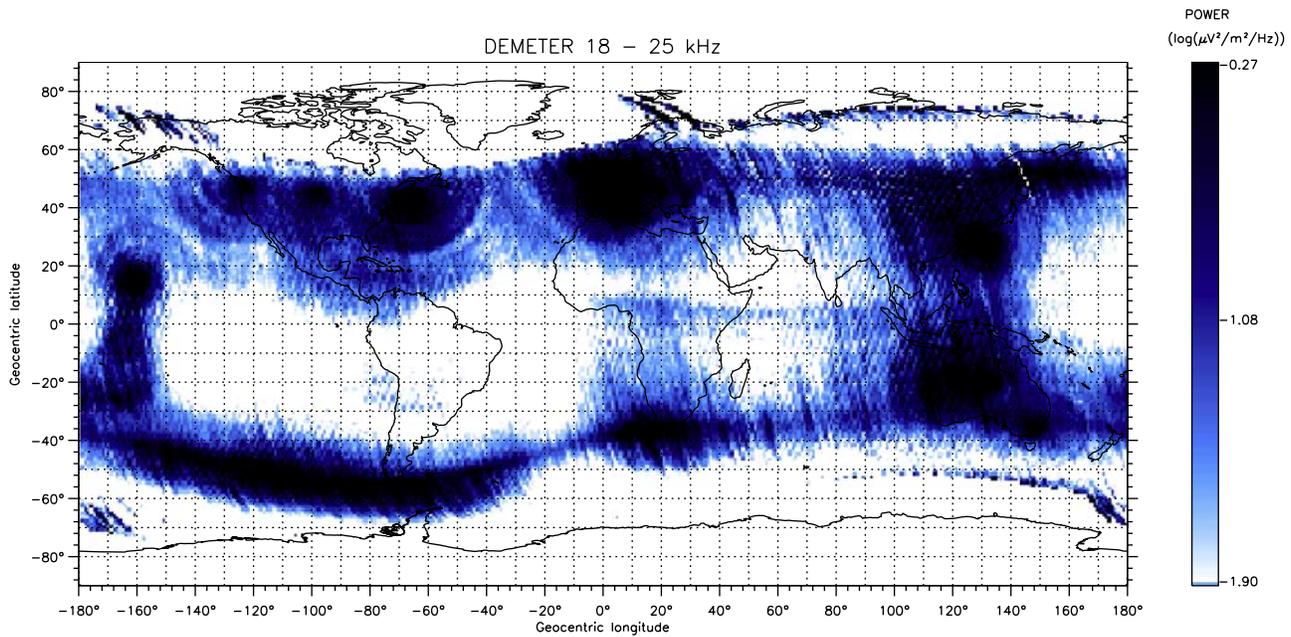
[3] The planned experiment requires a well specified source of radio waves as well as satellite and ground based observations of these radio waves. In this study, we chose to use 100 kHz radio waves emitted by LORAN transmitters [United States Coast Guard, 1994]. Around fifty LORAN transmitters in the northern hemisphere currently launch continuously pulsed 100 kHz radio waves into the Earth's atmosphere for marine navigation. The repetition pattern (phase coding) of these pulses uniquely identifies the emitting LORAN transmitter.

[4] The satellite based electric field measurements are conducted on board the DEMETER spacecraft at an orbital altitude of  $\sim 660$  km. The DEMETER satellite is in a sun synchronous orbit at 22:30 and 10:30 local time. This study

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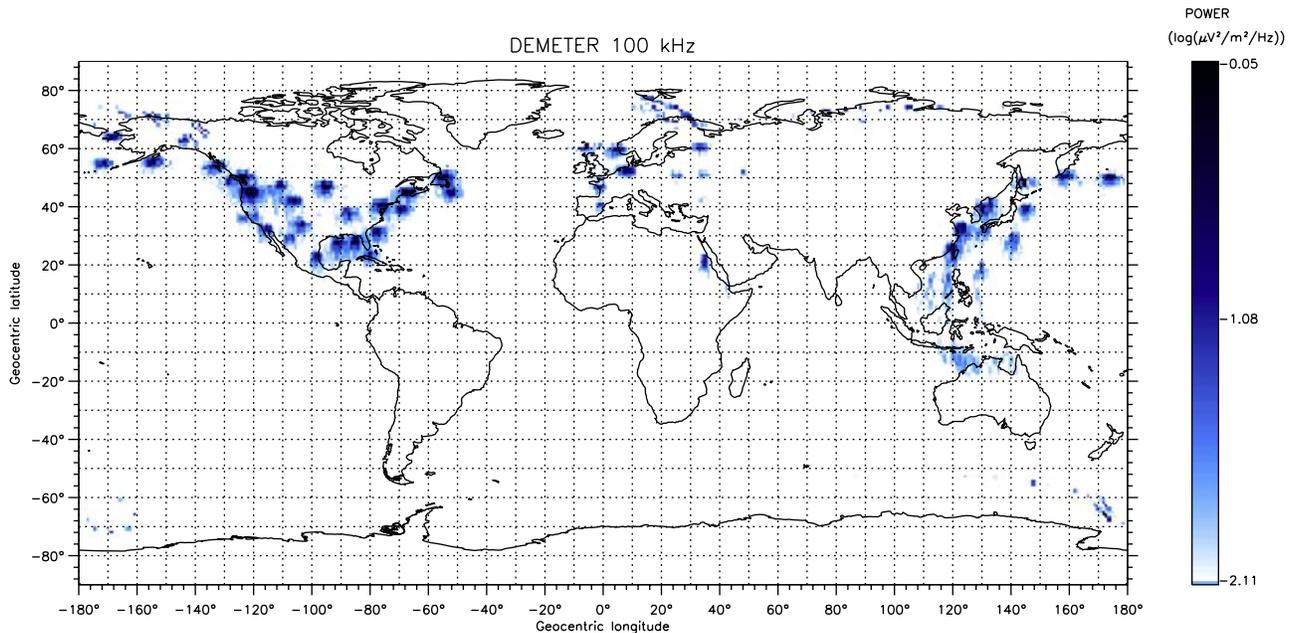
<sup>3</sup>General Lighthouse Authorities, Trinity House, London, UK.



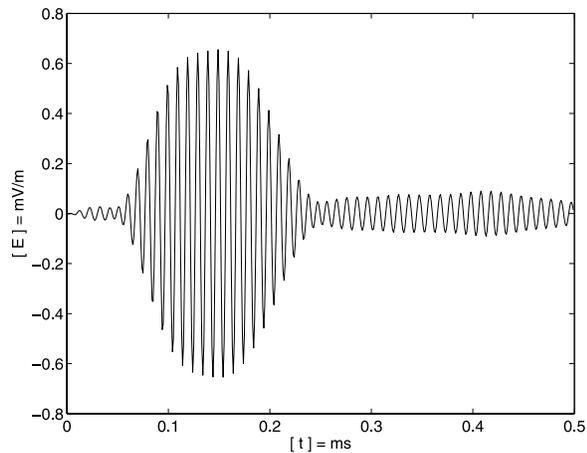
**Figure 1.** Global observations of 18–25 kHz radio waves emitted by very low frequency transmitters as observed by the DEMETER satellite at ~660 km altitude. The recordings are taken at 22:30 local time and they are averaged from December 2006 to December 2007. The electromagnetic radiation from very low frequency transmitters exhibits a complex spatial pattern including electromagnetic radiation reflected from the geomagnetically conjugate hemisphere (compare to Figure 2).

focuses on nocturnal wave propagation conditions since the sunlit solar panel produces electromagnetic interference which substantially degrades the quality of the 100 kHz recordings during day time. The Instrument Champ

Electric (ICE) experiment uses spherical electric field sensors and an integrated data processing unit to calculate average electric field spectra in the survey mode [Berthelier *et al.*, 2006]. This data is averaged from December 2006 to



**Figure 2.** Global observations of 100 kHz radio waves emitted by LORAN transmitters as observed by the DEMETER satellite at ~660 km altitude. The recordings are taken at 22:30 local time and they are averaged from December 2006 to December 2007. The observed electric fields are  $\sim 0.1\text{--}5 \mu\text{Vm}^{-1} \text{Hz}^{-1/2}$  which is similar to ground based electric field measurements  $\sim 7\text{--}9$  Mm away from a LORAN transmitter (compare to Figure 5). The equivalent transionospheric attenuation is then  $\sim 35\text{--}45$  dB for 100 kHz radio waves.



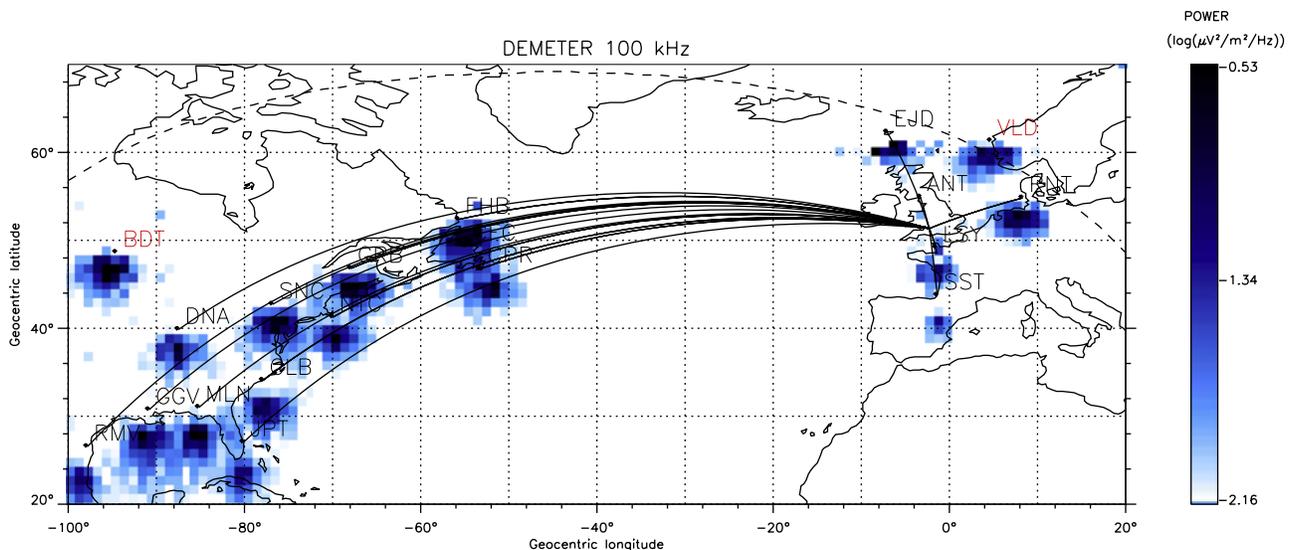
**Figure 3.** Example of an average LORAN pulse observed at Bath in the UK (51.3°N, 2.3°W) on 22.05.2008 from 03:05–03:20 UT. The pulse is emitted  $\sim 7$  Mm away from Bath by a LORAN transmitter at Jupiter (JPT) in Florida (27.0°N, 80.1°W).

December 2007 with a spatial resolution of  $\sim 1^\circ$ , i.e.,  $\sim 120$  km at the equator, and covers  $\pm 65^\circ$  invariant latitude, i.e.,  $\sim 82\%$  of the entire Earth's surface. The localized enhancement of the spectral amplitudes of the 100 kHz radio waves from the LORAN transmissions can clearly be distinguished (Figure 2). These novel satellite observations push forward the boundary of the knowledge base on transionospheric radio wave propagation from  $\sim 20$  kHz to 100 kHz, i.e., by almost one order of magnitude. Quite naturally, the observations represent new physics as it can be ascertained from the comparison of the two global radio maps displayed in Figures 1 and 2: The satellite observa-

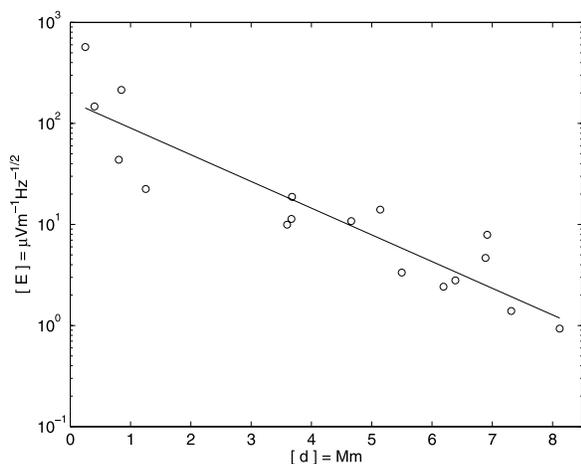
tions at 100 kHz provide comparatively crispy clear images of the transmitters as a result of the stronger subionospheric attenuation at 100 kHz compared to  $\sim 20$  kHz radio waves. In addition, the locations of the LORAN transmitters are slightly shifted southward, possibly as a result of the radio wave propagation through the ionosphere and/or ducting along the geomagnetic field line. The spectral amplitudes of the LORAN transmissions observed on the DEMETER satellite range from  $\sim 0.1$ – $5 \mu\text{V m}^{-1} \text{ Hz}^{-1/2}$  and they enable a quantitative comparison with ground based observations.

### 3. Ground Based LORAN Detection

[5] The LORAN transmissions are recorded on the ground with a sensitive capacitive electric field probe near Bath in the UK (51.3°N, 2.3°W), on 22.05.2008. During the night, the 100 kHz radio waves from the LORAN transmissions propagate over thousands of kilometers. For example, the LORAN transmitter at Jupiter in Florida (27.0°N, 80.1°W) is  $\sim 7$  Mm away from Bath and can clearly be distinguished in the ground based recordings (Figure 3). The recordings have been averaged over a time interval of 15 minutes from 03:05–03:20 UT to remove the incoherent interference from lightning discharges and nearby LORAN transmissions. During this time interval, a total of 25 LORAN transmitters was observed. A subset of those 17 LORAN transmitters with the largest signal to noise ratio are used for the subsequent quantitative analysis (Figure 4). All these LORAN transmitters are located within an area of nocturnal wave propagation conditions defined by the location of the terminator, i.e., the day-night boundary. The spectral amplitudes of the 100 kHz radio waves are calculated from the pulses of all 17 LORAN transmitters and they are ordered with respect to their distance to the receiver near Bath (Figure 5). The observed spectral



**Figure 4.** Seventeen LORAN transmitters in the northern hemisphere (solid dots) are recorded at Bath in the UK (51.3°N, 2.3°W) on 22.05.2008 from 03:05–03:20 UT. The transmitted radio waves travel along different great circle paths to the receiver (solid lines). The location of the terminator defines an area of nocturnal wave propagation for use in this study (dashed line). The LORAN transmitters BDT and VLD are not used for the analysis. The transionospheric propagation of the radio waves results in an apparent southward displacement of the LORAN transmitters as observed by the DEMETER satellite (patches).



**Figure 5.** The observed electric field strengths of the LORAN pulses decrease with increasing distance from the transmitter (open circles). The electric field decrease spans  $\sim 2$  decades ( $\sim 40$  dB) for distances up to  $\sim 8$  Mm (solid line) which corresponds to a nocturnal attenuation of  $\sim 5$  dB/Mm for 100 kHz radio waves.

amplitudes decrease exponentially with distance and they have fallen off by  $\sim 2$  orders of magnitude ( $\sim 40$  dB) at a distance of  $\sim 8$  Mm. This decrease of the field strength corresponds to an attenuation of  $\sim 5$  dB/Mm. A more precise log-linear fit to the observations results in an attenuation of  $\sim 5.3$  dB/Mm, in excellent agreement with the subionospheric radio wave propagation constant [Chapman *et al.*, 1966]. This agreement demonstrates that the ground based observations are representative for nocturnal radio wave propagation conditions. The spectral amplitudes observed on the ground at distances  $\sim 7$ – $9$  Mm from the LORAN transmitter are equivalent to the spectral amplitudes observed on the DEMETER satellite (compare to Figure 2). It is concluded that the 100 kHz radio waves from LORAN transmissions exhibit a nocturnal transionospheric attenuation of  $\sim 35$ – $45$  dB.

[6] It is interesting to note that the observed electric field strengths exhibit a considerable variability which may result from the varying effectivity with which the power of the transmitter is converted to electromagnetic radiation. The observed variability may also result from the different ground/ionospheric conductivities along the different propagation paths. The disentanglement of these additional secondary factors is not straightforward. For example, the normalisation of the observed electric field strengths with the listed power of the transmitters effectively decreases the quality of the fit rather than increasing it. This surprising result clearly indicates that the secondary additional factors require more detailed separate studies.

#### 4. Summary

[7] LORAN transmitters emit 100 kHz radio waves which are detected in space and at large distances on the ground. The nocturnal attenuation of the radio waves is 35–45 dB at an altitude of  $\sim 660$  km above the transmitter and at a distance of  $\sim 7$ – $9$  Mm away from the transmitter. This attenuation may exhibit a temporal and spatial variability determined by the ionosphere which remains to be deter-

mined. The dense network of LORAN transmitters enables an imaging and prediction of the lower ionosphere in the northern hemisphere which may be attempted in future studies. The observed transionospheric attenuation helps to estimate the magnitude of the radio waves emitted by lightning discharges associated with sprites and terrestrial  $\gamma$ -ray flashes which are planned to be observed on board the TARANIS satellite. For this application, it is desirable to determine the frequency dependence of the transionospheric radio wave propagation constant in the years to come.

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