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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 ∼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 ∼7–9 Mm. The radio waves exhibit an average subionospheric attenuation of ∼5 dB/Mm and it is concluded that the nocturnal transionospheric attenuation of 100 kHz radio waves is ∼35–45 dB. This result enables future space missions to quantify the intensity of lightning discharges associated with transient luminous events and terrestrial γ-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 γ-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 (∼3–30 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 ∼20 kHz needs to be corrected by a factor of ∼20 dB to fit the observations [*Starks et al.*, 2008]. At higher radio frequencies from ∼50 kHz to ∼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 ∼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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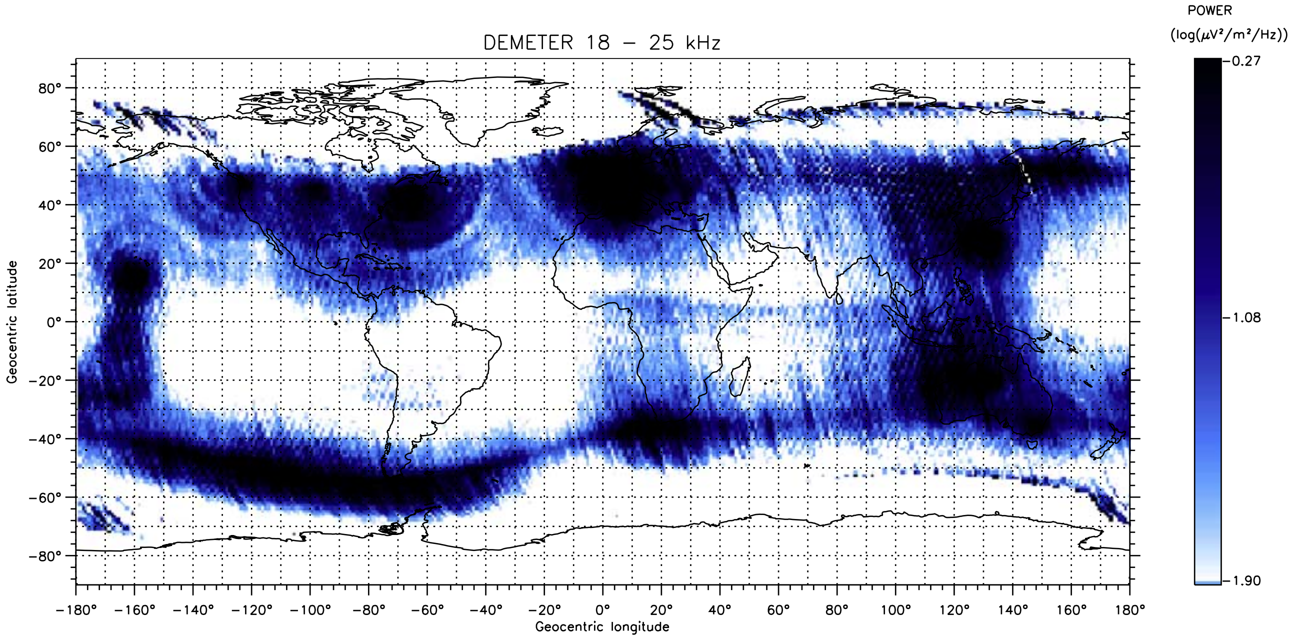

Figure 1. Global observations of 18–25 kHz radio waves emitted by very low frequency transmitters as observed by the DEMETER satellite at ~660 km altitude. The recordings are taken at 22:30 local time and they are averaged from December 2006 to December 2007. The electromagnetic radiation from very low 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 Electrique (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

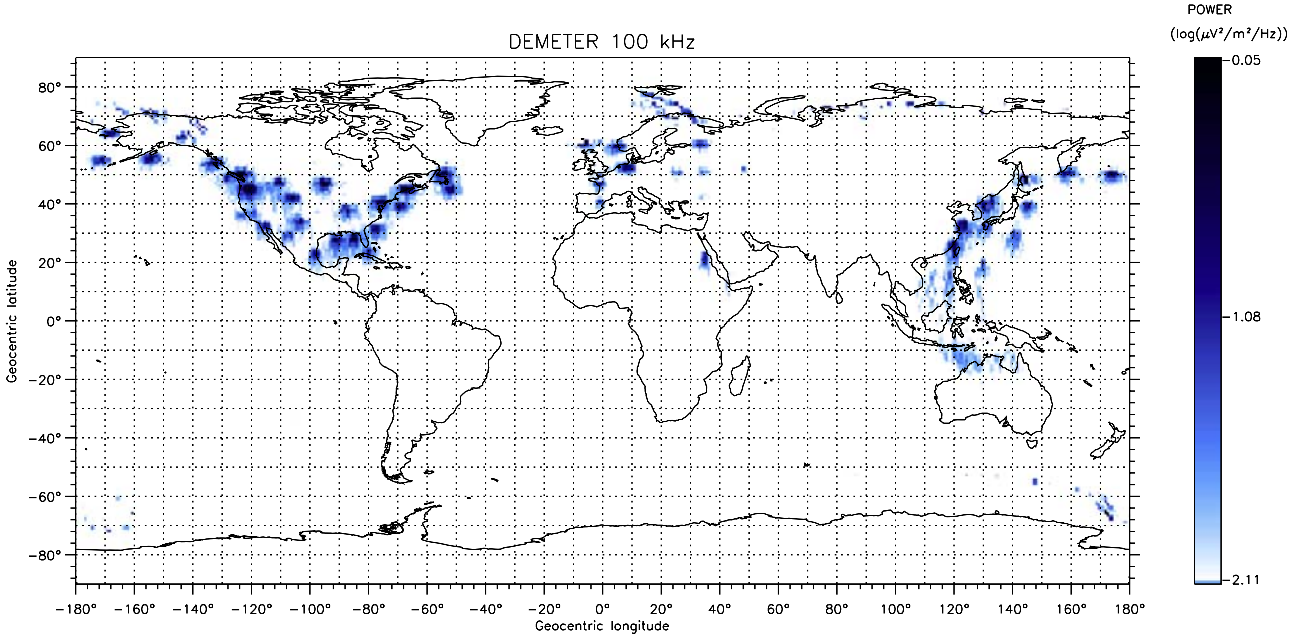

Figure 2. Global observations of 100 kHz radio waves emitted by LORAN transmitters as observed by the DEMETER satellite at ~660 km altitude. The recordings are taken at 22:30 local time and they are averaged from December 2006 to December 2007. The observed electric fields are ~0.1–5 μVm^{-1} Hz$^{-1/2}$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

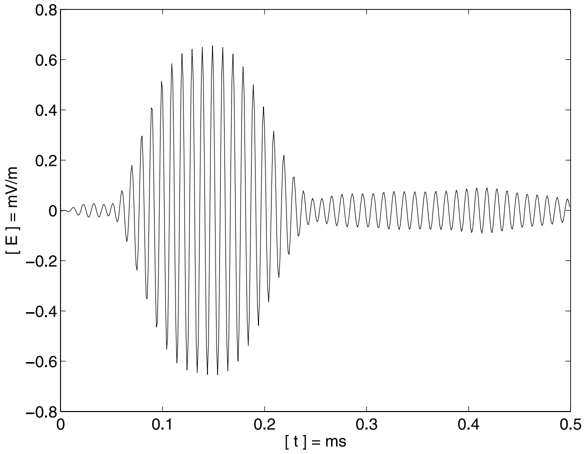

Figure 3. Example of an average LORAN pulse observed at Bath in the UK (51.3°N, 2.3°W) on 22.05.2008 from 03:05–03:20 UT. The pulse is emitted ~7 Mm away from Bath by a LORAN transmitter at Jupiter (JPT) in Florida (27.0°N, 80.1°W).

December 2007 with a spatial resolution of ~1°, i.e., ~120 km at the equator, and covers ±65° invariant latitude, i.e., ~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 ~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 observations at 100 kHz provide comparatively crispy clear images of the transmitters as a result of the stronger subionospheric attenuation at 100 kHz compared to ~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 ~0.1–5 $\mu\mathrm{Vm}^{-1}\ \mathrm{Hz}^{-1/2}$ 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 ~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

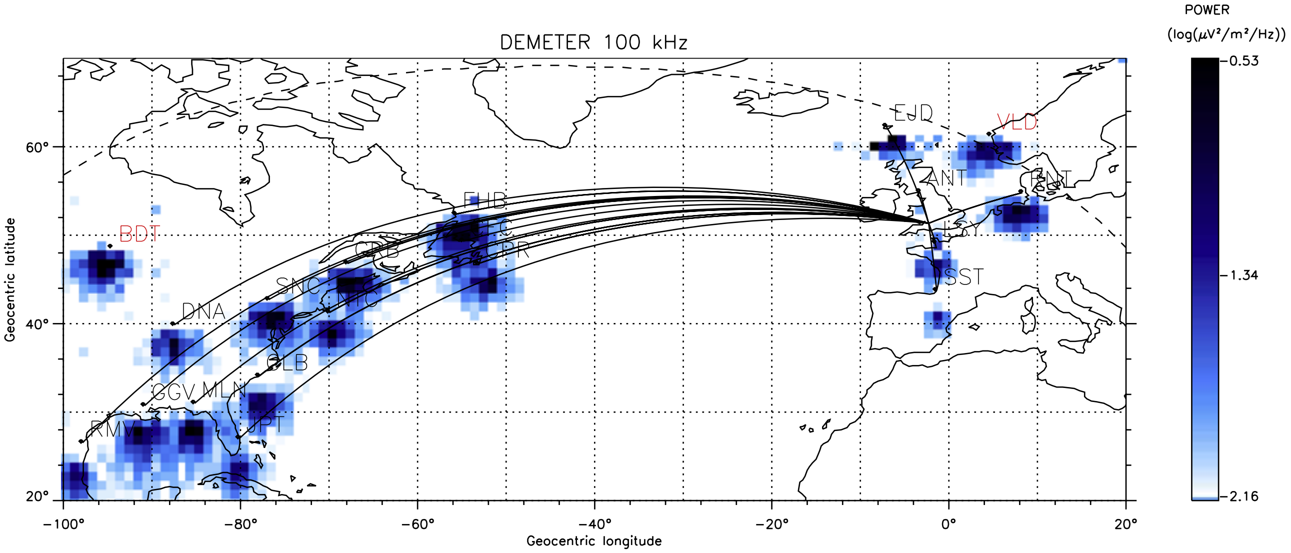

Figure 4. Seventeen LORAN transmitters in the northern hemisphere (solid dots) are recorded at Bath in the UK (51.3°N, 2.3°W) on 22.05.2008 from 03:05–03:20 UT. The transmitted radio waves travel along different great circle paths to the receiver (solid lines). The location of the terminator defines 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).

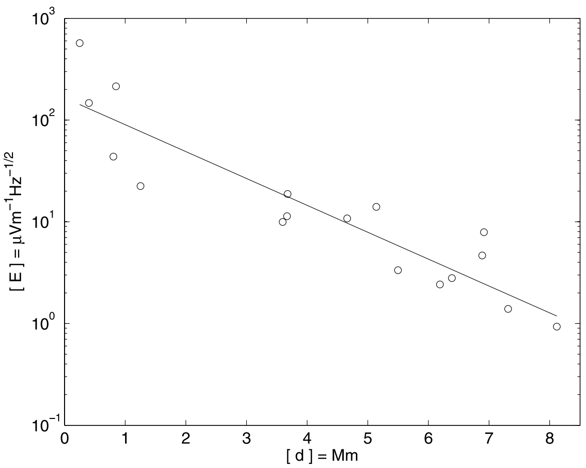

Figure 5. The observed electric field strengths of the LORAN pulses decrease with increasing distance from the transmitter (open circles). The electric field decrease spans ~2 decades (~40 dB) for distances up to ~8 Mm (solid line) which corresponds to a nocturnal attenuation of ~5 dB/Mm for 100 kHz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

amplitudes decrease exponentially with distance and they have fallen off by ~2 orders of magnitude (~40 dB) at a distance of ~8 Mm. This decrease of the field strength corresponds to an attenuation of ~5 dB/Mm. A more precise log-linear fit to the observations results in an attenuation of ~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 ~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 ~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 ~660 km above the transmitter and at a distance of ~7–9 Mm away from the transmitter. This attenuation may exhibit a temporal and spatial variability determined by the ionosphere which remains to be determined. 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 γ-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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References

Benson, R., M. Desch, R. Hunsucker, and G. Romick (1988), Ground-level detection of low- and medium-frequency auroral radio, *J. Geophys. Res.*, *93*, 277–283.

Berthelier, J., et al. (2006), ICE, the electric field experiment on DEMETER, *Planet. Space Sci.*, *54*, 456–471.

Blanc, E., F. Lefeuvre, R. Roussel-Dupre, and J. Sauvaud (2007), TARANIS: A microsatellite project dedicated to the study of impulsive transfers of energy between the earth atmosphere, the ionosphere, and the magnetosphere, *Adv. Space Res.*, *40*, 1268–1275.

Boeck, W., O. Vaughan, R. Blakeslee, B. Vonnegut, M. Brook, and J. McKune (1995), Observations of lightning in the stratosphere, *J. Geophys. Res.*, *100*, 1465–1475.

Chapman, F., D. Jones, J. Todd, and R. Challinor (1966), Observations on the propagation constant of the Earth-ionosphere waveguide in the frequency band 8 c/s to 16 kc/s, *Radio Sci.*, *1*, 1273–1282.

Clilverd, M. A., C. J. Rodger, R. Gamble, N. P. Meredith, M. Parrot, J.-J. Berthelier, and N. R. Thomson (2008), Ground-based transmitter signals observed from space: Ducted or nonducted?, *J. Geophys. Res.*, *113*, A04211, doi:10.1029/2007JA012602.

Dwyer, J., et al. (2003), Energetic radiation produced during rocket-triggered lightning, *Science*, *299*, 694–697.

Fishman, G., et al. (1994), Discovery of intense gamma-ray flashes of atmospheric origin, *Science*, *264*, 1313–1316.

Franz, R., R. Nemzek, and J. Winckler (1990), Television image of a large upward electrical discharge above a thunderstorm system, *Science*, *249*, 48–51.

Horne, R. (1995), Propagation to the ground at high latitudes of auroral radio noise below the electron gyrofrequency, *J. Geophys. Res.*, *100*, 14,637–14,645.

Inan, U. (2005), Gamma rays made on earth, *Science*, *307*, 1054–1055.

Kelley, M., S. Baker, R. Holzworth, P. Argo, and S. Cummer (1997), LF and MF observations of the lightning electromagnetic pulse at ionospheric altitudes, *Geophys. Res. Lett.*, *24*, 1111–1114.

Krehbiel, P., J. Riousset, V. Pasko, R. Thomas, W. Rison, M. Stanley, and H. Edens (2008), Upward electrical discharges from thunderstorms, *Nat. Geosci.*, *1*, 233–237.

Lyons, W. (1996), Sprite observations above the U.S. high plains in relation to their parent thunderstorm systems, *J. Geophys. Res.*, *101*, 29,641–29,652.

Neubert, T. (2003), Sprites and their exotic kin, *Science*, *300*, 747–749.

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

Pasko, V., M. Stanley, J. Mathews, U. Inan, and T. Wood (2002), Electrical discharge from a thundercloud top to the lower ionosphere, *Nature*, *416*, 152–154.

Platino, M., U. Inan, T. Bell, M. Parrot, and E. Kennedy (2006), DEMETER observations of ELF waves injected with the HAARP HF transmitter, *Geophys. Res. Lett.*, *33*, L16101, doi:10.1029/2006GL026462.

Rothkaehl, H., and M. Parrot (2005), Electromagnetic emissions detected in the topside ionosphere related to human activity, *J. Atmos. Sol. Terr. Phys.*, *67*, 821–828.

Sentman, D., E. Wescott, D. Osborne, D. Hampton, and M. Heavner (1995), Preliminary results from the Sprites94 aircraft campaign: 1. Red sprites, *Geophys. Res. Lett.*, *22*, 1205–1208.

Smith, D., L. Lopez, R. Lin, and C. Barrington-Leigh (2005), Terrestrial gamma-ray flashes observed up to 20 MeV, *Science*, *307*, 1085–1088.

Starks, M., R. Quinn, G. Ginet, J. Albert, G. Sales, B. Reinisch, and P. Song (2008), Illumination of the plasmasphere by terrestrial very low frequency transmitters: Model validation, *J. Geophys. Res.*, *113*, A09320, doi:10.1029/2008JA013112.

Su, H., R. Su, A. Chen, Y. Wang, W. Hsiao, W. Lai, L. Lee, M. Sato, and H. Fukunishi (2003), Gigantic jets between a thundercloud and the ionosphere, *Nature*, *423*, 974–976.

Tanaka, Y., M. Nishino, and K. Lynn (1989), On the propagation of LF whistler-mode waves deduced from conjugate measurements at low latitudes, *Planet. Space Sci.*, *37*, 1215–1226.

Tomko, A., and T. Hepner (2001), Worldwide monitoring of VLF-LF propagation and atmospheric noise, *Radio Sci.*, *36*, 363–369.

United States Coast Guard (1994), COMDTINST M16562.4A: Specification of the transmitted LORAN-C signal, U.S. Coast Guard, Washington, D. C.

Wang, L., J. MacDougall, and H. James (2005), Ionospheric structure effects on HF radio wave propagation for the Enhanced Polar Outflow Probe (e-POP) satellite mission, *Radio Sci.*, *39*, RS2019, doi:10.1029/2003RS002975.

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