

# Simulating satellite observations of 100 kHz radio waves from relativistic electron beams above thunderclouds

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**Abstract.** Relativistic electron beams above thunderclouds emit 100 kHz radio waves which illuminate the Earth's atmosphere and near-Earth space. This contribution aims to clarify the physical processes which are relevant for the spatial spreading of the radio wave energy below and above the ionosphere and thereby enables simulating satellite observations of 100 kHz radio waves from relativistic electron beams above thunderclouds. The simulation uses the DEMETER satellite which observes 100 kHz radio waves from fifty terrestrial Long Range Aid to Navigation (LORAN) transmitters. Their mean luminosity patch in the plasmasphere is a circular area with a radius of  $\sim 300$  km and a power density of  $\sim 22 \mu\text{W}/\text{Hz}$  as observed at  $\sim 660$  km height above the ground. The luminosity patches exhibit a southward displacement of  $\sim 450$  km with respect to the locations of the LORAN transmitters. The displacement is reduced to  $\sim 150$  km when an upward propagation of the radio waves along the geomagnetic field line is assumed. This residual displacement indicates that the radio waves undergo  $\sim 150$  km sub-ionospheric propagation prior to entering a magnetospheric duct and escaping into near-Earth space. The residual displacement at low ( $L < 2.14$ ) and high ( $L > 2.14$ ) geomagnetic latitudes ranges from  $\sim 100$  km to  $\sim 200$  km which suggests that the smaller inclination of the geomagnetic field lines at low latitudes helps to trap the radio waves and to keep them in the magnetospheric duct. Diffuse luminosity areas are observed northward of the magnetic conjugate locations of LORAN transmitters at extremely low geomagnetic latitudes ( $L < 1.36$ ) in Southeast Asia. This result suggests that the propagation along the geomagnetic field lines results in a spatial spreading of the radio wave energy over distances of  $\sim 1$  Mm. The summative assessment of the electric field intensities measured in space show that nadir observations of terrestrial 100 kHz radio waves, e.g., from relativistic electron beams above thunderclouds, are attenuated by at least  $\sim 50$  dB when taking into account a transionospheric attenuation of  $\sim 40$  dB.

## 1 Introduction

Electron beams above thunderclouds are initiated by cosmic ray showers which coincide with intense lightning discharges (Füllekrug et al., 2010; Roussel-Dupré and Gurevich, 1996). The primary cosmic ray proton penetrates the Earth's atmosphere with an energy of  $\sim 10^{16}$  eV (Gurevich and Zybin, 2005) and strips off electrons from the air molecules. The resulting energetic electrons are accelerated by the electric fields following an intense lightning discharge and develop into a quickly growing non-linear electron avalanche process (Gurevich et al., 2004, 2003, 2002). The primary electrons can reach relativistic energies with a mean of  $\sim 7$  MeV and a standard deviation of  $\sim 6$  MeV (Roussel-Dupré et al., 2008) prior to escaping into near-Earth space (Inan, 2005; Lehtinen et al., 2000, 1996). It is indeed possible to observe terrestrial relativistic electrons in space with particle detectors on satellites (Carlson et al., 2009; Dwyer et al., 2008; Feldman et al., 1996, 1995; Burke et al., 1992), but the direct association with individual intense lightning discharges remains to be made.

Another possibility to detect electron beams above thunderclouds is to observe their broadband electromagnetic radiation (Füllekrug et al., 2010), but the physical processes which are relevant for the spatial spreading of radio wave energy from the middle atmosphere into near-Earth space are not very well understood. For example, it was only recently reported that terrestrial 100 kHz radio waves can actually be observed in space by the DEMETER satellite with a signal attenuation of  $\sim 40$  dB (Füllekrug et al., 2009). Here we use the LORAN transmissions to simulate the radio waves emitted from relativistic electron beams above thunderclouds to gain an improved understanding of the physical processes below and above the ionosphere which are relevant for radio observations of relativistic electron beams on board of satellites.

## 2 Transionospheric propagation

Electromagnetic radiation from lightning discharges can penetrate the ionosphere at least up to  $\sim 200$  km height and it exhibits occasionally whistler-type dispersion characteristics with a maximum nose frequency of  $\sim 100$  kHz (Kelley et al., 1997, 1990).

Extra-terrestrial  $\sim 100$  kHz radio waves of magnetospheric origin have been reported to penetrate into the Earth's atmosphere in the auroral regions (Benson et al., 1988). Subsequent model calculations suggested a spatial spreading of the radio wave energy over several thousand kilometers in latitude (Horne, 1995).

The electromagnetic radiation emitted from 85–128 kHz transmitters at low geomagnetic latitudes ( $L \approx 1.54$ ) in Japan was observed at magnetic conjugate locations in Australia with a weak dependence on geomagnetic activity (Nishino et al., 1989). Subsequent modeling of the measurements tentatively suggested a southward sub-ionospheric propagation of the radio waves prior to entering a magnetospheric duct, a propagation along the geomagnetic field line to the magnetic conjugate location, and a final southward sub-ionospheric propagation to the receiver. This scenario was pre-

dicted from modeling the attenuation characteristics of  $\sim 100$  kHz radio waves. The analysis also predicted that the smallest attenuation is expected for wave normal angles parallel to the magnetic field line (Tanaka et al., 1989). On the other hand, the modeling of 5 kHz radio waves suggests that the radio waves are more easily trapped from the side, i.e., with wave normal angles perpendicular to the magnetic field lines (Strangeways and Rycroft, 1980).

Terrestrial electromagnetic radiation from  $\sim 0.1$ –9 MHz television and radio transmitters seems to result in a rather diffuse luminosity above Europe and Asia as inferred from measurements on board the CORONAS-1 and AUREOL-3 satellites, but no similar radio wave energy was observed over North America (Rothkaehl and Parrot, 2005). Modeling of the transionospheric propagation of  $\sim 55$  MHz radio waves from terrestrial radio transmitters suggested that ionospheric perturbations can lead to a complex pattern of radio wave amplitudes, wave propagation time delays, doppler frequency shifts, and direction of arrival distortions (Wang et al., 2005).

The electromagnetic radiation emitted by terrestrial  $\sim 16$ –25 kHz transmitters propagates easily through the ionosphere and subsequently penetrates near-Earth space, where the degree of ducting along the geomagnetic field line depends on geomagnetic latitude (Clilverd et al., 2008). Detailed modeling showed that the transionospheric attenuation of these radio signals was underestimated by  $\sim 20$  dB as inferred from novel satellite measurements (Starks et al., 2008). It was only recently discovered that lightning discharges which produce transient airglows above thunderclouds, denoted sprites, causes proton and  $0^+$  whistlers in space as observed by the DEMETER satellite (Lefeuvre et al., 2009). This novel observation leads to the question how the radio waves of relativistic electron beams above thunderclouds would be affected during their transionospheric propagation.

This contribution aims to clarify the propagation of  $\sim 100$  kHz radio waves from the middle atmosphere into near-Earth space and their ducting along the geomagnetic field line to quantify their total signal attenuation. This simulation helps to plan observations of radio waves from relativistic electron beams above thunderclouds by the forthcoming French microsatellite TARANIS of the “Centre National d’Études Spatiales” which is dedicated to the study of impulsive energy transfers between the Earth’s atmosphere, the ionosphere and the magnetosphere (Lefeuvre et al., 2008; Blanc et al., 2007).

### 3 Plasmaspheric luminosity patches

The DEMETER spacecraft orbits around the Earth at an altitude of  $\sim 660$  km above the ground in a sun synchronous orbit at 22:30 and 10:30 LT. The “Instrument Champ Électrique” (ICE) on board the DEMETER satellite measures the electric field in space with spherical electric field sensors and an integrated data processing unit to record the energy of radio waves in the survey mode (Berthelier et al., 2006).

Each data segment is recorded for a time interval of 0.6144 ms length while the consecutive time

interval of  $\sim 0.6144$  ms is used to calculate the spectrum of the recorded data with a spectral resolution of  $\sim 1.6276$  kHz. The spectrum is smoothed with two neighbouring frequencies such that the final spectral resolution is  $\sim 3.2552$  kHz. Subsequently, forty consecutive spectra are averaged to produce one spectrum each  $\sim 2.048$  s. The calculated spectral electric field amplitudes at  $\sim 100$  kHz are averaged from December 2006 to December 2007 and over a latitude dependent area to reduce the variability of the originally recorded data. The resulting electric field intensity is mapped with spatial resolution of  $3^\circ \times 3^\circ$  ( $\sim 334$  km  $\times$  334 km at the equator) over 82% of the Earth's surface between  $\pm 65^\circ$  invariant latitude.

The measurements show 50 plasmaspheric luminosity patches in the Northern Hemisphere (Fig. 1). The luminosity patches are attributed to the pulsed 100 kHz radio waves from the Long Range Aid to Navigation (LORAN) transmitters which are used for marine navigation (United States Coast Guard, 1994). The luminosity patches exhibit a  $\sim 450$  km southward displacement with respect to the locations of the LORAN transmitters on the ground.

Eight LORAN transmitters at geographic latitudes  $< 25^\circ$  do not show a clear correspondence to any luminosity patches, either because the LORAN transmitter was not in use during the observation period, and/or the luminosity patches at low latitudes are more diffuse, i.e., spread over a large spatial area, as a result of the wave propagation regime at low geomagnetic latitudes.

#### 110 4 Southward displacement in Northern Hemisphere

The geographic coordinates of the fifty LORAN transmitters are used as reference points to superimpose the observed electric field intensities and to study in more detail the average displacement of the luminosity patches at satellite heights of  $\sim 660$  km above the ground. The average displacement of the luminosity patch is  $\sim 450$  km southward with respect to the location of the LORAN transmitter (Fig. 2). The luminosity patch has a radius of  $\sim 300$  km which appears as an ellipse in Fig. 2 because the longitudes are not great circles on the spherical Earth. The average latitude of the LORAN transmitters is  $\sim 45^\circ$  such that a  $1^\circ$  longitude pixel corresponds to  $\sim 80$  km. The average electric field intensity of the luminosity patch is  $E \approx 0.171 \mu\text{V m}^{-1} \text{ Hz}^{-1/2}$  such that the total power density  $P$  within the luminosity patch is  $P = E^2 A / Z_0 \approx 22 \mu\text{W Hz}^{-1}$ , where  $A \approx \pi 300^2 \text{ km}^2 \approx 2.83 \times 10^{11} \text{ m}^2$  is the area covered by the luminosity patch and  $Z_0 = \sqrt{\mu_0 / \epsilon_0} \approx 377 \Omega$  is the free space wave impedance.

The southward displacement strongly suggests that the radio waves propagate upward along the geomagnetic field line into near-Earth space. Tracing the geomagnetic field line from the LORAN transmitters up to the DEMETER orbital height at  $\sim 660$  km results in a mean apparent southward displacement of the LORAN transmitter of  $\sim 300$  km (Fig. 2) when the Space Physics Data Facility (SPDF) Modelweb (Gustafsson et al., 1992; Tsyganenko et al., 1987) of the National Aeronautics and Space Administration (NASA) is used ([http://omniweb.gsfc.nasa.gov/vitmo/cgm\\_vitmo.html](http://omniweb.gsfc.nasa.gov/vitmo/cgm_vitmo.html)). The residual southward displacement of  $\sim 150$  km can not be explained with a propagation of the

radio waves along the geomagnetic field line. It rather indicates, that the radio waves undergo a sub-  
ionospheric propagation of  $\sim 150$  km prior to entering a magnetospheric duct and escaping into near-  
130 Earth space. This picture implicitly includes the statement that the inclination of the geomagnetic  
field line plays an important role in the trapping of the radio waves.

It is therefore expected that the radio waves from different geomagnetic latitudes will propagate  
for varying distances within the Earth-ionosphere cavity before leaving it and escaping into near-  
Earth space. This hypothesis can be tested by discriminating the LORAN transmitters in two groups,  
135 one at low geomagnetic latitudes  $L < 2.4$  and one at high geomagnetic latitudes  $L > 2.4$ . The discrim-  
ination value of  $L = 2.4$  is chosen here to split the LORAN transmitters in two equal groups with  
25 transmitters. The southward displacement is best studied with a latitude scan across the maximum  
of the luminosity patch because the latitudes are great circles on the Earth and the radio waves do not  
exhibit any longitudinal displacement. The residual southward displacement is indeed dependent on  
140 the geomagnetic latitudes of the transmitters. The luminosity patch from LORAN transmitters at  
low geomagnetic latitudes ( $L < 2.4$ ) exhibits a residual southward displacement of  $\sim 100$  km and the  
luminosity patch from LORAN transmitters at high geomagnetic latitudes ( $L > 2.4$ ) exhibits a resid-  
ual southward displacement of  $\sim 200$  km (Fig. 3). This result strongly suggests that the smaller  
inclination of the geomagnetic field lines at low latitudes helps to trap the radio waves and to keep  
145 them in the magnetospheric duct. Alternatively, the higher inclination of the geomagnetic field lines  
at high latitudes may inhibit the trapping of the radio waves and help to keep them out of the mag-  
netospheric duct. In any case, the experimental results indicate that 100 kHz radio waves penetrate  
magnetospheric ducts more easily from the side, i.e., with wave normal angles perpendicular to the  
magnetic field lines. This sideways coupling of electromagnetic energy into a magnetospheric duct  
150 was predicted by use of model calculations for 5 kHz radio waves (Strangeways and Rycroft, 1980),  
but it was never confirmed by radio wave experiments.

The latitude scan through the mean luminosity patch allows to quantify the apparent attenuation  
of 100 kHz radio waves for nadir observations as planned with the TARANIS satellite. The mean lu-  
minosity patch from all transmitters exhibits a maximum of  $\sim 0.34 \mu\text{V m}^{-1} \text{ Hz}^{-1/2}$  with a  $\sim 450$  km  
155 southward displacement and  $\sim 0.09 \mu\text{V m}^{-1} \text{ Hz}^{-1/2}$  directly above the transmitter location (Fig. 3).  
The ratio between the observed electric field intensities at maximum and minimum determines an  
attenuation of  $\sim 9.2$  dB. However, it is not clear whether the minimum electric field intensity is deter-  
mined by the amplitude resolution of the electric field instrument of  $\sim 0.1 \mu\text{V m}^{-1} \text{ Hz}^{-1/2}$  (Berthe-  
lier et al., 2006), or if the minimum is determined by the natural electromagnetic radio noise envi-  
160 ronment in space. As a result, the real attenuation of the radio waves resulting from the southward  
displacement may be larger such that the determined attenuation of  $\sim 10$  dB can only be considered  
to be a lower bound for the signal attenuation.

## 5 Northward displacement in Southern Hemisphere

The ducting of 100 kHz radio waves along the geomagnetic field lines suggests that the radio waves could be observed in the magnetically conjugate hemisphere (Tanaka et al., 1989) and that the radio wave energy is spread over many thousand kilometers (Horne, 1995). A close inspection of the 100 kHz radio wave energy observed on DEMETER at the geomagnetic conjugate locations of the LORAN transmitters reveals that some transmitters in East Asia exhibit indeed a diffuse luminosity northward of their conjugate locations in Australia and Southeast Asia (Fig. 4). All these transmitters are located at extremely low geomagnetic latitudes ( $L < 1.36$ ) with comparatively short geomagnetic field lines. The diffuse character of the luminosity strongly indicates that the energy of the radio waves is indeed spread over  $\sim 1$  Mm when propagating along the geomagnetic fields lines. This spreading of the radio wave energy seems to be proportional to the length of the geomagnetic field line, as no diffuse luminosity is observed at the conjugate locations of the LORAN transmitters at high geomagnetic latitudes ( $L > 1.36$ ) in North America and Europe (Fig. 1). The observational limit is given here by the amplitude resolution of the radio wave experiment on board the DEMETER satellite and/or the natural electromagnetic noise environment in space. Future satellite missions with a lower instrumental noise floor may therefore be able to detect the faint diffuse luminosity signals of 100 kHz radio waves at the conjugate locations of high geomagnetic latitude ( $L > 1.36$ ) transmitters.

## 6 Variability of 100 kHz radio wave intensities

The 100 kHz radio waves launched into near-Earth space by the LORAN transmitters undergo sub-ionospheric propagation prior to magnetospheric ducting along the geomagnetic field lines. It is therefore expected that the naturally varying state of the ionosphere and the plasmasphere affect the observed radio wave intensities. For example, solar short wave radiation affects the electron density of the ionosphere and hence the sub-ionospheric and transionospheric propagation. Particles from the solar wind are trapped along the geomagnetic field lines and they affect the electron density in the plasmasphere and hence the ducting along the geomagnetic field lines. Both effects are more generally related to solar variability associated with transient bursts of solar activity, the differential solar rotation of  $\sim 20$ – $30$  days, and the solar cycle of  $\sim 10$ – $12$  years. The revolution of the Earth around the Sun introduces a characteristic latitude dependent seasonal variability of the ionosphere which affects the ionospheric plasma frequency and hence the sub-ionospheric and transionospheric propagation. It is therefore interesting to ask the question how well the electric field intensities observed on the DEMETER satellite are related to the actual power of the LORAN transmitters. The subsequent analysis is limited to LORAN transmitter powers  $< 1000$  kW listed by the International LORAN Association because larger transmitter powers at low geomagnetic latitudes in East Asia are only known with little confidence from private sector sources.

The 100 kHz radio wave intensities observed on the DEMETER satellite show that more powerful LORAN transmitters generally produce larger electric field intensities, but the electric field intensities exhibit a large variability (Fig. 5). This variability is related to the sub-ionospheric propagation of the radio waves, the transionospheric attenuation, and the ducting along the geomagnetic field lines in the plasmasphere. The discrimination between LORAN transmitters at high ( $L > 2.14$ ) and low ( $L < 2.14$ ) geomagnetic latitudes seems to indicate that the observed electric field intensities at low latitudes may be less variable. The smaller variability at low latitudes may result from the shorter radio wave propagation distance along the geomagnetic field lines and/or the more efficient trapping of the radio waves by the ducts forming along geomagnetic field lines which have a smaller inclination at low latitudes as compared to high latitudes. The smaller variability at low latitudes may therefore support the prediction that the radio waves are more efficiently trapped from the side of the duct (Strangeways and Rycroft, 1980). However, a detailed analysis of the seasonal variation of electric field intensities observed by the DEMETER satellite may help to quantify the annual modulation of the transionospheric attenuation of 100 kHz radio waves in future studies.

## 7 Summary

The electric field intensities of 100 kHz radio waves emitted by LORAN transmitters on the ground are observed by the DEMETER satellite at an orbital altitude of  $\sim 660$  km height above the ground. The observations show that the radio waves undergo sub-ionospheric propagation prior to entering a magnetospheric duct sideways and propagating subsequently along the geomagnetic field line to the conjugate hemisphere where the radio wave energy spreads out over spatial distances of  $\sim 1$  Mm. The trapping of the radio waves in the magnetospheric duct results in an average southward displacement of  $\sim 450$  km with respect to the location of the LORAN transmitter which corresponds to an apparent attenuation of at least  $\sim 10$  dB for nadir observations. Taking into account a transionospheric attenuation of  $\sim 40$  dB results in a total attenuation of  $\sim 50$  dB for nadir observations of 100 kHz radio waves. Recent ground based observations of relativistic electron beams shortly following sprite discharges (Füllekrug et al., 2010) indicate that the electron beams at mid-latitudes exhibit radio wave intensities  $\sim 130 \mu\text{V m}^{-1} \text{ Hz}^{-1/2}$  which reduce to  $\sim 0.4 \mu\text{V m}^{-1} \text{ Hz}^{-1/2}$  after a transionospheric attenuation of  $\sim 50$  dB at nadir. This estimate is considered to be only a first order approximation because it does not yet take into account the relativistic forward beaming of the electromagnetic radiation, the fact that lightning discharges at equatorial latitudes are more powerful than at mid-latitudes and the estimate neglects the ionospheric variability from monthly to decadal time scales which are the subject of future studies.

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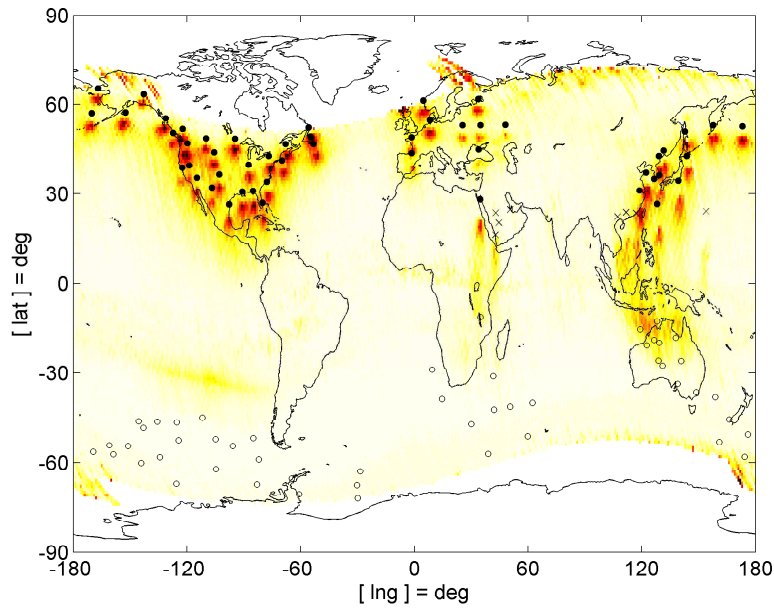
235 nates of the magnetic field lines are calculated with the Space Physics Data Facility (SPDF) Modelweb of the National Aeronautics and Space Administration (NASA). The work was supported by the Centre National de la Recherche Scientifique (CNRS) through the E-CANES Research Group (GDRE). The International Space Science Institute (ISSI) kindly supported and hosted the Coupling of Atmospheric Regions with Near-Earth Space (CARNES) team meetings which stimulated this work.



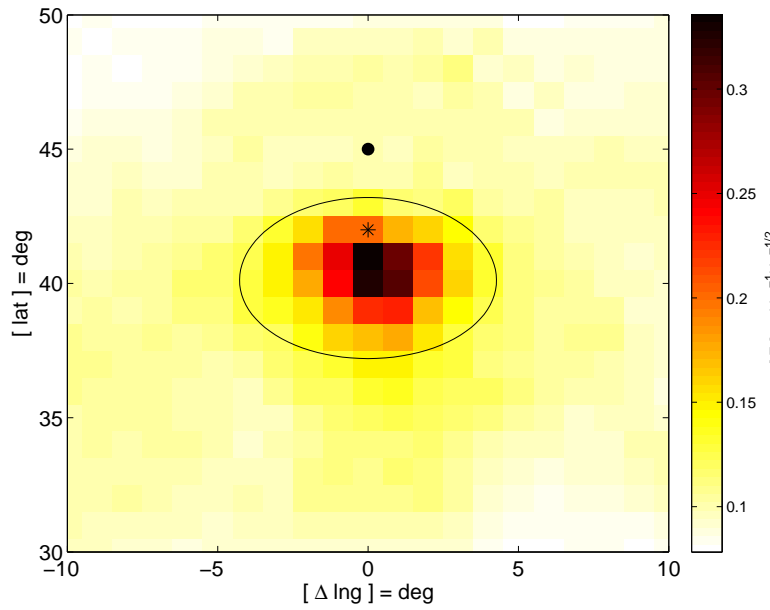
## References

- Benson, R., Desch, M., Hunsucker, R., and Romick, G.: Ground-level detection of low- and medium-frequency auroral radio, *J. Geophys. Res.*, 93, 277–283, 1988.
- Berthelier, J., Godefroy, M., Leblanc, F., Malingre, M., Menvielle, M., Lagoutte, D., Brochot, J., Colin, F., Elie, F., Legendre, C., Zamora, P., Benoist, D., Chapuis, Y., Artru, J., and Pfaff, R.: ICE, the electric field experiment on DEMETER, *Planet. Space Sci.*, 54, 456–471, 2006.
- Blanc, E., Lefeuvre, F., Roussel-Dupré, R., and Sauvaud, J.: 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, 2007.
- Burke, W., Aggson, T., Maynard, N., Hoegy, W., Hoffman, R., Candy, R., Liebrecht, C., and Rodgers, E.: Effects of a lightning discharge detected by the DE 2 satellite over hurricane Debbie, *J. Geophys. Res.*, 97, 6359–6367, 1992.
- Carlson, B., Lehtinen, N., and Inan, U.: Observations of terrestrial gamma-ray flash electrons, in: *Coupling of Thunderstorms and Lightning Discharges to Near-Earth Space*, edited by: Crosby, N., Huang, T., and Rycroft, M., American Institute of Physics, Melville, 84–91, 2009.
- Clilverd, M., Rodger, C., Gamble, R., Meredith, N., Parrot, M., Berthelier, J., and Thomson, N.: Ground-based transmitter signals observed from space: ducted or nonducted?, *J. Geophys. Res.*, 113, 1–12, 2008.
- Dwyer, J., Grefenstette, B., and Smith, D.: High-energy electron beams launched into space by thunderstorms, *Geophys. Res. Lett.*, 35, 1–5, 2008.
- Feldman, W., Symbalisty, E., and Roussel-Dupré, R.: Association of discrete hard X ray enhancements with eruption of Mount Pinatubo, *J. Geophys. Res.*, 100, 23829–23834, 1995.
- Feldman, W., Symbalisty, E., and Roussel-Dupré, R.: Hard X ray survey of energetic electrons from low-Earth orbit, *J. Geophys. Res.*, 101, 5195–5209, 1996.
- Füllekrug, M., Parrot, M., Ash, M., Astin, I., Williams, P., and Talhi, R.: Transionospheric attenuation of 100 kHz radio waves inferred from satellite and ground based observations, *Geophys. Res. Lett.*, 36, 1–4, 2009.
- Füllekrug, M., Roussel-Dupré, R., Symbalisty, E. M. D., Chanrion, O., Odzimek, A., van der Velde, O., and Neubert, T.: Relativistic runaway breakdown in low frequency radio, *J. Geophys. Res.*, 115, 1–10, 2010.
- Gurevich, A. and Zybin, K.: Runaway breakdown and the mysteries of lightning, *Phys. Today*, 58, 37–43, 2005.
- Gurevich, A., Duncan, L., Medvedev, Y., and Zybin, K.: Radio emission due to simultaneous effect of runaway breakdown and extensive atmospheric showers, *Phys. Lett. A*, 301, 320–326, 2002.
- Gurevich, A., Duncan, L., Karashtin, A., and Zybin, K.: Radio emission of lightning initiation, *Phys. Lett. A*, 312, 228–237, 2003.
- Gurevich, A., Medvedev, Y., and Zybin, K.: Thermal electrons and electric current generated by runaway breakdown effect, *Phys. Lett. A*, 321, 179–184, 2004.
- Gustafsson, G., Papitashvili, N., and Papitashvili, V.: A revised corrected geomagnetic coordinate system for epochs 1985 and 1990, *J. Atmos. Terr. Phys.*, 54, 1609–1631, 1992.
- Horne, R.: Propagation to the ground at high latitudes of auroral radio noise below the electron gyrofrequency, *J. Geophys. Res.*, 100, 14637–14645, 1995.
- Inan, U.: Gamma rays made on Earth, *Science*, 307, 1054–1055, 2005.

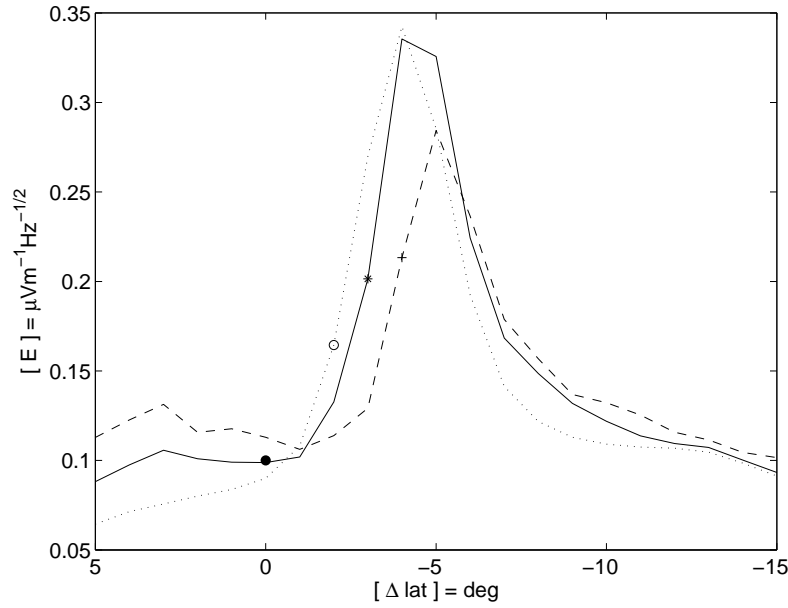
- Kelley, M., Ding, J., and Holzworth, R.: Intense ionospheric electric and magnetic field pulses generated by lightning, *Geophys. Res. Lett.*, 17, 2221–2224, 1990.
- 280 Kelley, M., Baker, S., Holzworth, R., Argo, P., and Cummer, S.: LF and MF observations of the lightning electromagnetic pulse at ionospheric altitudes, *Geophys. Res. Lett.*, 24, 1111–1114, 1997.
- Lefevre, F., Marshall, R., Pinçon, J., Inan, U., Lagoutte, D., Parrot, M., and Berthelier, J.: On remote sensing of transient luminous events' parent lightning discharges by ELF/VLF wave measurements on board a satellite, *Journal of Geophysical Research*, 114, 2009.
- 285 Lefevre, F., Blanc, E., Pinçon, J., Roussel-Dupré, R., Lawrence, D., Sauvaud, J., Rauch, J., Feraudy, H., and Lagoutte, D.: TARANIS – a satellite project dedicated to the physics of TLEs and TGFs, *Space Sci. Rev.*, 137, 301–315, 2008.
- Lehtinen, N., Walt, M., Inan, U., Bell, T., and Pasko, V.:  $\gamma$ -ray emission produced by a relativistic beam of runaway electrons accelerated by quasi-electrostatic thundercloud fields, *Geophys. Res. Lett.*, 23, 2645–  
290 2648, 1996.
- Lehtinen, N., Inan, U., and Bell, T.: Trapped energetic electron curtains produced by thunderstorm driven relativistic runaway electrons, *Geophys. Res. Lett.*, 27, 1095–1098, 2000.
- Nishino, M., Tanaka, Y., and Lynn, K.: Doppler shifts of LF whistler-mode signal observed at a low-latitude ( $L=1.54$ ), *Planet. Space Sci.*, 37, 825–836, 1989.
- 295 Rothkaehl, H. and Parrot, M.: Electromagnetic emissions detected in the topside ionosphere related to human activity, *J. Atmos. Sol.-Terr. Phys.*, 67, 821–828, 2005.
- Roussel-Dupré, R. and Gurevich, A.: On runaway breakdown and upward propagating discharges, *J. Geophys. Res.*, 101, 2297–2311, 1996.
- Roussel-Dupré, R., Colman, J., Symbalisty, E., Pasko, V., and Sentman, D.: Physical processes related to  
300 discharges in planetary atmospheres, *Space Sci. Rev.*, 137, 51–82, 2008.
- Starks, M., Quinn, R., Ginet, G., Albert, J., Sales, G., Reinisch, B., and Song, P.: Illumination of the plasmasphere by terrestrial very low frequency transmitters: model validation, *J. Geophys. Res.*, 113, 1–16, 2008.
- Strangeways, H. and Rycroft, M.: Trapping of whistler-waves through the side of ducts, *J. Atmos. Sol.-Terr. Phys.*, 42, 983–994, 1980.
- 305 Tanaka, Y., Nishino, M., and Lynn, K.: On the propagation of LF whistler-mode waves deduced from conjugate measurements at low latitudes, *Planet. Space Sci.*, 37, 1215–1226, 1989.
- Tsyganenko, N., Usmanov, A., Papitashvili, V., Papitashvili, N., and Popov, V.: Software for computations of the geomagnetic field and related coordinate systems, Soviet Geophysical Committee, Special Report, 1–58, 1987.
- 310 United States Coast Guard: Specification of the transmitted LORAN-C signal, COMDTINST M16562.4A, Washington DC, USA, 1994.
- Wang, L., MacDougall, J., and James, H.: Ionospheric structure effects on HF radio wave propagation for the Enhanced Polar Outflow Probe (e-POP) satellite mission, *Radio Sci.*, 39, 1–10, 2005.



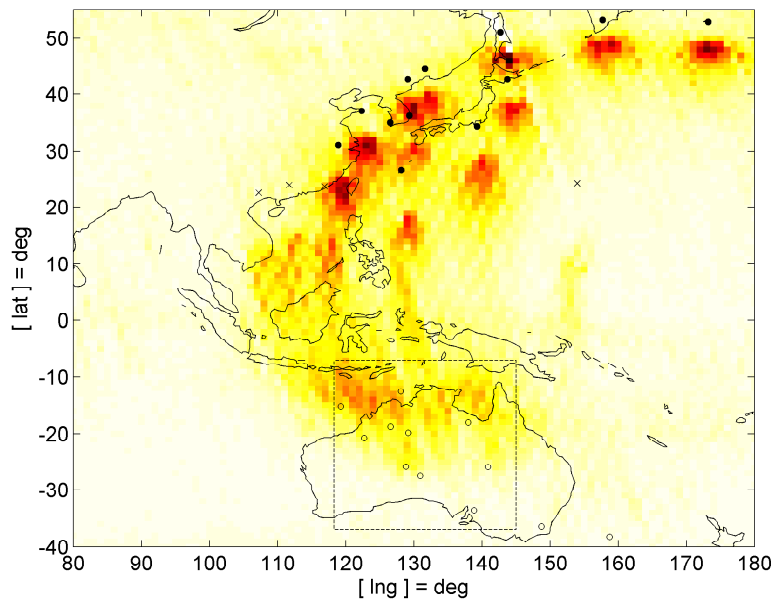
**Fig. 1.** Fifty Long Range Aid to Navigation (LORAN) transmitters (dots) emit 100 kHz radio waves which illuminate the plasmasphere with luminosity patches (red blobs) as inferred from electric field measurements on board the DEMETER satellite at  $\sim 660$  km height above the ground. The luminosity patches exhibit a  $\sim 450$  km southward displacement with respect to the locations of the LORAN transmitters. Eight LORAN transmitters at low latitudes  $< 25^\circ$  (crosses) do not show a clear correspondence to any luminosity patch. The geomagnetic conjugate locations of the LORAN transmitters (circles) show that some transmitters in East Asia exhibit a diffuse luminosity northward of their conjugate location in Australia and Southeast Asia.



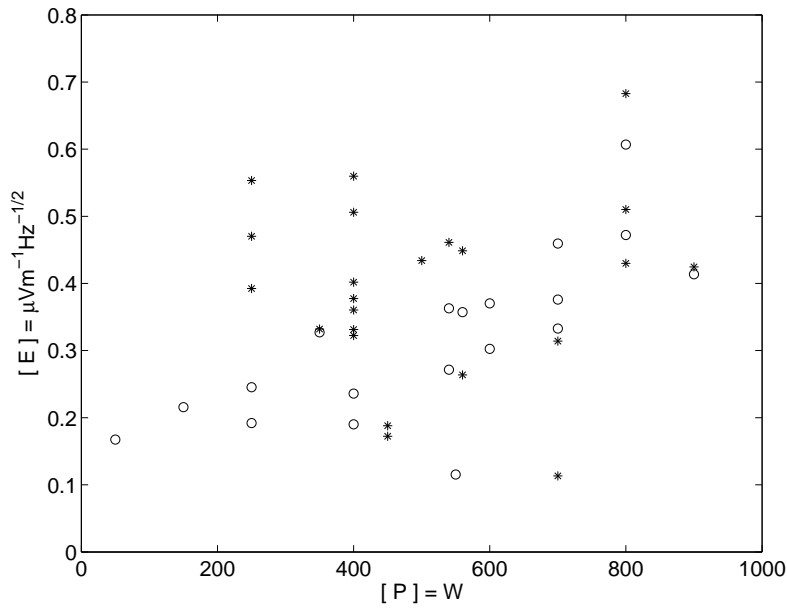
**Fig. 2.** The average LORAN transmitter (solid dot) illuminates a circular area (red/black blob) of the plasmasphere at  $\sim 660$  km height. The luminosity patch has a radius of  $\sim 300$  km (ellipse), a power density of  $\sim 22 \mu\text{W}/\text{Hz}$ , and it exhibits a southward displacement of  $\sim 450$  km with respect to the location of the LORAN transmitter. The apparent location of the LORAN transmitter at  $\sim 660$  km height is located  $\sim 300$  km southward (star) when an upward propagation of the radio waves along the geomagnetic field line is assumed. The remaining residual southward displacement of  $\sim 150$  km suggests that the radio waves undergo sub-ionospheric propagation prior to entering a magnetospheric duct and escaping into near-Earth space.



**Fig. 3.** The latitude scans through the mean luminosity patches from all LORAN transmitters (solid line), transmitters at low ( $L < 2.4$ ) geomagnetic latitudes (dashed line), and at high ( $L > 2.4$ ) geomagnetic latitudes (dotted line) are referenced to the mean transmitter location (dot). The apparent transmitter locations at  $\sim 660$  km height are located southward when an upward propagation of the radio waves along the geomagnetic field lines is assumed for low latitude transmitters (plus), for all transmitters (star) and for high latitude transmitters (circle). The remaining residual displacement between the apparent transmitter locations and the maximum intensities of the corresponding luminosity patches range from  $\sim 100$  km for low latitude transmitters,  $\sim 150$  km for all transmitters and up to  $\sim 200$  km for high latitude transmitters. The varying residual displacement suggests that the smaller inclination of the geomagnetic field lines at low latitudes helps to trap the radio waves and to keep them in the magnetospheric duct.



**Fig. 4.** Some LORAN transmitters in East Asia (dots) emit radio waves which are observed as a diffuse illumination of the plasmasphere northward of their corresponding geomagnetic conjugate locations in Australia and Southeast Asia (circles in dashed box). These conjugate locations correspond to LORAN transmitters at extremely low geomagnetic latitudes ( $L < 1.36$ ). The observed diffuse luminosity suggests that the propagation along the geomagnetic field lines spreads the radio wave energy over large spatial distances of  $\sim 1$  Mm.



**Fig. 5.** The electric field intensities measured by the DEMETER satellite at  $\sim 660$  km height are related to the power of the LORAN transmitters at high ( $L > 2.14$ ) geomagnetic latitudes (stars) and at low ( $L < 2.14$ ) geomagnetic latitudes (circles), but they exhibit a large variability as a result of the sub-ionospheric propagation and ducting along the geomagnetic field lines. The electric field intensities at low latitudes appear to be less variable as a result of the shorter radio wave propagation distance along the geomagnetic field lines. The smaller variability may also be related to the more efficient sideways trapping of radio waves by the ducts forming along geomagnetic field lines which have a smaller inclination at low latitudes as compared to high latitudes.