**Atmospheric
Chemistry
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Discussions**

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

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Simulating satellite observations of 100 kHz radio waves

M. Füllekrug et al.

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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 ∼300 km and a power density of ∼22 µW/Hz as observed at ∼660 km height above the ground. The luminosity patches exhibit a southward displacement of ∼450 km with respect to the locations of the LORAN transmitters. The displacement is reduced to ∼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 ∼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 ∼100 km to ∼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 ∼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 ∼50 dB when taking into account a transionospheric attenuation of ∼40 dB.

1   Introduction

Electron beams above thunderclouds are initiated by cosmic ray showers which co-incide 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 ~ 7 MeV and a standard deviation of ~ 6 MeV (Roussel-Durpé 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 asso-ciation 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 pro-cesses 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 exam-ple, 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 ~ 40 dB (Füllekrug et al., 2009). Here we use the LORAN transmissions to simulate the ra-dio 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.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

2 Transionospheric propagation

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

Extra-terrestrial ~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 predicted from modeling the attenuation characteristics of ~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 ~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 ~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 ∼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). Recent modeling showed that the transionospheric attenuation of these radio signals was underestimated by ∼20 dB as inferred from the modeling of novel satellite measurements (Starks et al., 2008).

This contribution aims to clarify the propagation of ∼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 ∼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 ∼0.6144 ms is used to calculate the spectrum of the recorded data with a spectral resolution of ∼1.6276 kHz. The spectrum is smoothed with two neighbouring frequencies such that the final spectral resolution is ∼3.2552 kHz. Subsequently, fourty consecutive spectra are averaged to produce one spectrum each ∼2.048 s. The calculated spectral electric field amplitudes at ∼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 $3°\times3°$ ($\sim334\,km\times334\,km$ at the equator) over 82% of the Earth's surface between ±65 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 $\sim450\,km$ southward displacement with respect to the locations of the LORAN transmitters on the ground.

Eight LORAN transmitters at geographic latitudes $<25°$ 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.

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 $\sim660\,km$ above the ground. The average displacement of the luminosity patch is $\sim450\,km$ southward with respect to the location of the LORAN transmitter (Fig. 2). The luminosity patch has a radius of $\sim300\,km$ 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 $\sim45°$ such that a $1°$ longitude pixel corresponds to $\sim80\,km$. The average electric field intensity of the luminosity patch is $E\approx0.171\,\mu V\,m^{-1}\,Hz^{-1/2}$ such that the total power density P within the luminosity patch is $P=E^2A/Z_0\approx22\,\mu W\,Hz^{-1}$, where $A\approx\pi300^2\,km^2\approx2.83\times10^{11}\,m^2$ is the area covered by the luminosity patch and

$Z_0 = \sqrt{\mu_0/\varepsilon_0} \approx 377\,\Omega$ 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). 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-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, one at low geomagnetic latitudes $L<2.4$ and one at high geomagnetic latitudes $L>2.4$. The discrimination 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 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 residual 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

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

and to keep 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 magnetospheric 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 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 luminosity patch from all transmitters exhibits a maximum of $\sim 0.34\,\mu V\,m^{-1}\,Hz^{-1/2}$ with a ~ 450 km southward displacement and $\sim 0.09\,\mu V\,m^{-1}\,Hz^{-1/2}$ directly above the transmitter location (Fig. 3). The ratio between the observed electric field intensities at maximum and minimum determines an attenuation of ~ 9.2 dB. However, it is not clear whether the minimum electric field intensity is determined by the amplitude resolution of the electric field instrument of $\sim 0.1\,\mu V\,m^{-1}\,Hz^{-1/2}$ (Berthelier et al., 2006), or if the minimum is determined by the natural electromagnetic radio noise environment 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 ~ 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 ∼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 plasmaphere 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 activiy, the differential solar rotation of ∼20–30 days, and the solar cycle of ∼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 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 ~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

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

where the radio wave energy spreads out over spatial distances of ∼1 Mm. The trapping of the radio waves in the magnetospheric duct results in an average southward displacement of ∼450 km with respect to the location of the LORAN transmitter which corresponds to an apparent attenuation of at least ∼10 dB for nadir observations. Taking into account a transionospheric attenuation of ∼40 dB results in a total attenuation of ∼50 dB for nadir observations of 100 kHz radio waves.

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀ | ▶

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀ | ▶

◁ | ▷

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion
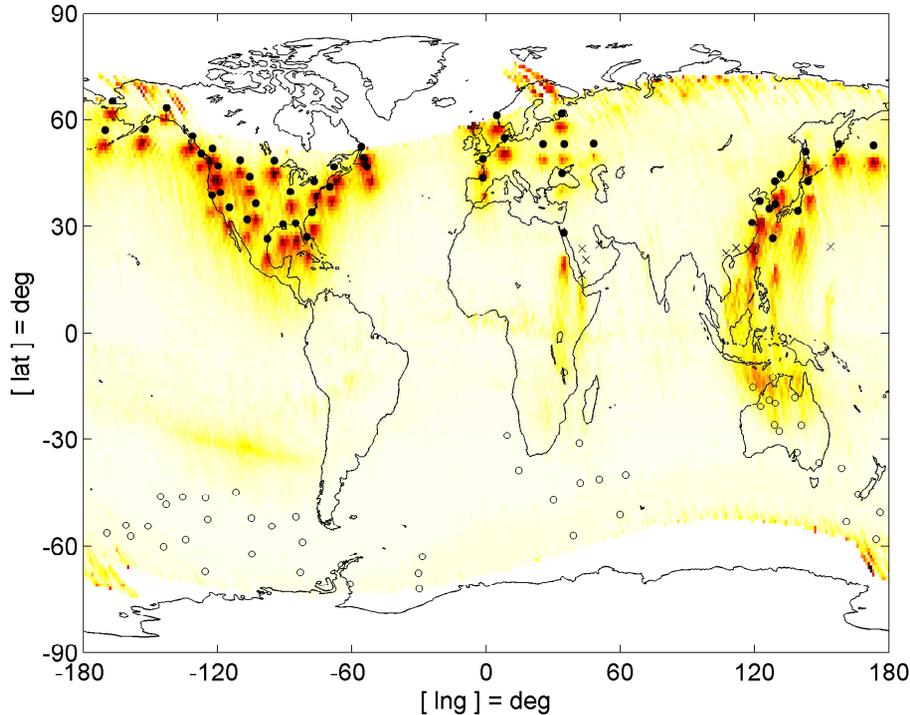
Fig. 1. Fifty Long Range Aid to Navigation (LORAN) transmitters (dots) emit 100 kHz radio waves which illuminate the plasmasphere with luminosity patches (red blobs) as inferred from electric field measurements on board the DEMETER satellite at ~660 km height above the ground. The luminosity patches exhibit a ~450 km southward displacement with respect to the locations of the LORAN transmitters. Eight LORAN transmitters at low latitudes <25° (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.
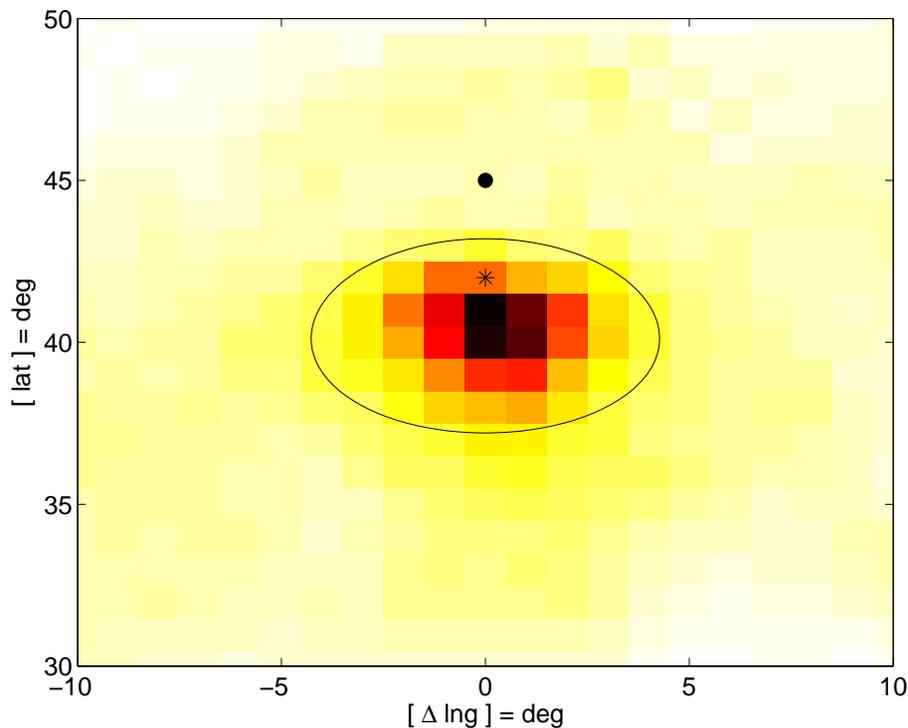
Fig. 2. The average LORAN transmitter (solid dot) illuminates a circular area (red/black blob) of the plasmasphere at ~660 km height. The luminosity patch has a radius of ~300 km (ellipse), a power density of ~22 µW/Hz, and it exhibits a southward displacement of ~450 km with respect to the location of the LORAN transmitter. The apparent location of the LORAN transmitter at ~660 km height is located ~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 ~150 km suggests that the radio waves undergo sub-ionospheric propagation prior to entering a magnetospheric duct and escaping into near-Earth space.
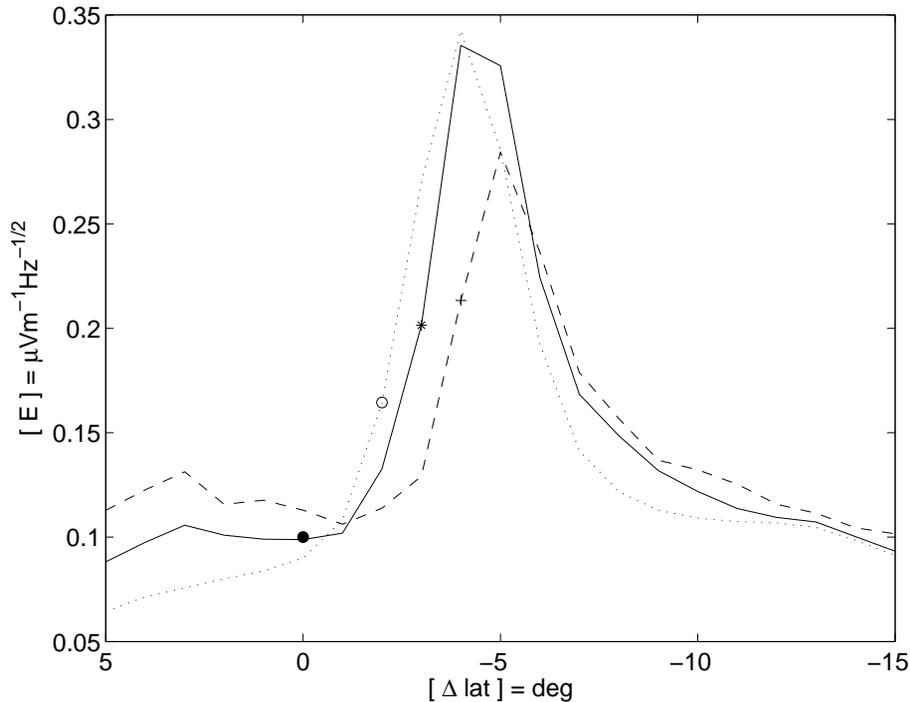
Fig. 3. The latitude scans through the mean luminosity patches from all LORAN transmitters (solid line), transmitters at low (*L*<2.4) geomagnetic latitudes (dashed line), and at high (*L*>2.4) geomagnetic latitudes (dotted line) are referenced to the mean transmitter location (dot). The apparent transmitter locations at ∼660 km height are located southward when an upward propagation of the radio waves along the geomagnetic field lines is assumed. The remaining residual displacement ranges from ∼100 km for low latitude transmitters (plus), ∼150 km for all transmitters (star), to ∼200 km for high latitude transmitters (circle). 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.
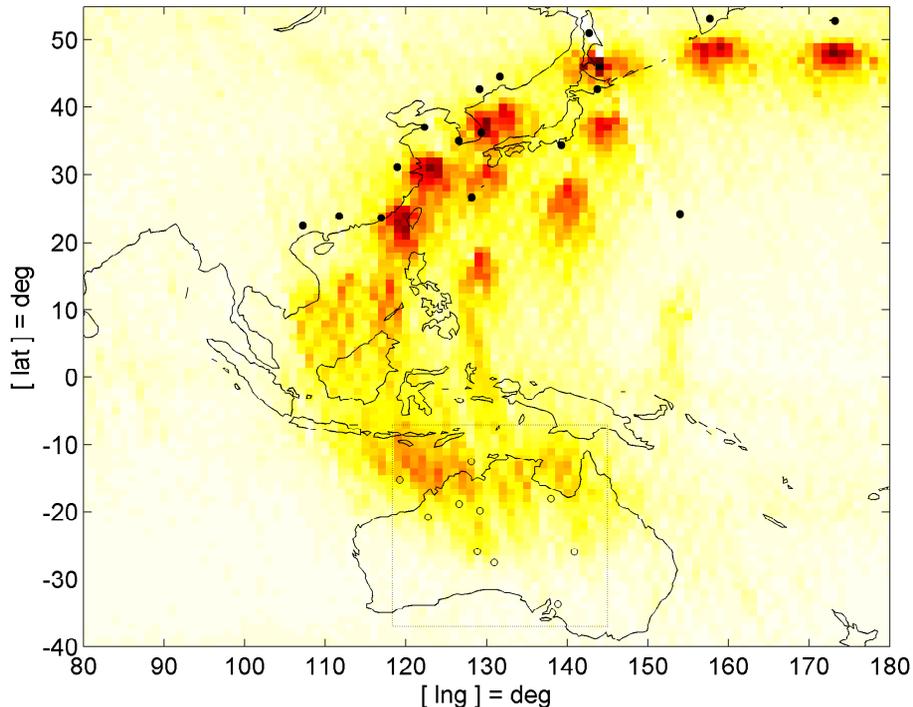
Fig. 4. Some LORAN transmitters in East Asia (dots) emit radio waves which are observed as a diffuse illumination of the plasmasphere northward of their corresponding geomagnetic conjugate locations in Australia and Southeast Asia (circles). The conjugate locations inside the dotted box correspond to 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 ~1 Mm.
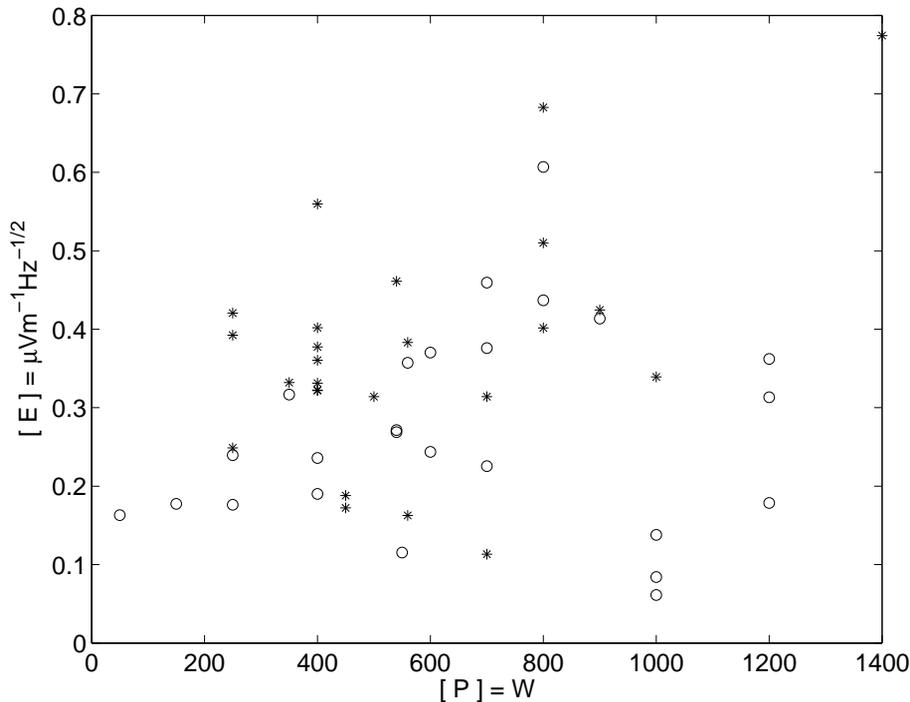
Fig. 5. The electric field intensities measured by the DEMETER satellite at ~660 km height are related to the power of the LORAN transmitters at high ($L > 2.14$) geomagnetic latitudes (stars) and at low ($L < 2.14$) geomagnetic latitudes (circles), but they exhibit a large variability as a result of 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.