Radiation belt electron precipitation due to VLF transmitters: Satellite observations

Jean-André Sauvaud, Romain Maggiolo, Christian Jacquey, Michel Parrot, Jean-Jacques Berthelier, R.J. Gamble, Craig.J. Rodger

Radiation belt electron precipitation due to VLF transmitters: Satellite observations

J.-A. Sauvaud,[1] R. Maggiolo,[1] C. Jacquey,[1] M. Parrot,[2] J.-J. Berthelier,[3] R. J. Gamble,[4] and Craig J. Rodger[4]

Received 10 January 2008; revised 3 March 2008; accepted 11 March 2008; published 8 May 2008.

[1] In the Earth's inner magnetosphere, the distribution of energetic electrons is controlled by pitch-angle scattering by waves. A category of Whistler waves originates from powerful ground-based VLF transmitter signals in the frequency range 10–25 kHz. These transmissions are observed in space as waves of very narrow bandwidth. Here we examine the significance of the VLF transmitter NWC on the inner radiation belt using DEMETER satellite global observations at low altitudes. We find that enhancements in the ~100–600 keV drift-loss cone electron fluxes at L values between 1.4 and 1.7 are linked to NWC operation and to ionospheric absorption. Waves and particles interact in the vicinity of the magnetic equatorial plane. Using Demeter passes across the drifting cloud of electrons caused by the transmitter; we find that ~300 times more 200 keV electrons are driven into the drift-loss cone during NWC transmission periods than during non-transmission periods. The correlation between the flux of resonant electrons and the Dst index shows that the electron source intensity is controlled by magnetic storm activity. **Citation:** Sauvaud, J.-A., R. Maggiolo, C. Jacquey, M. Parrot, J.-J. Berthelier, R. J. Gamble, and C. J. Rodger (2008), Radiation belt electron precipitation due to VLF transmitters: Satellite observations, *Geophys. Res. Lett.*, *35*, L09101, doi:10.1029/2008GL033194.

1. Introduction

[2] In the inner radiation belt the distribution function of energetic electrons is controlled by pitch-angle scattering. The most important wave-particle interactions involve Whistler mode waves, including plasmaspheric hiss, lightning generated Whistlers and VLF transmitter signals [*Imhof et al.*, 1986; *Abel and Thorne*, 1998a, 1998b]. A category of Whistler mode indeed originates from powerful ground-based VLF transmitter signals in the frequency range 10–25 kHz [e.g., *Imhof et al.*, 1978, 1981, 1983a, 1983b; *Inan et al.*, 1978, 1984; *Vampola*, 1977; *Vampola and Kuck*, 1978]. Relatively recent theoretical calculations have lead to the rather surprising conclusion that man-made VLF transmissions may dominate losses in the inner radiation belts [*Abel and Thorne*, 1998a]. This finding has sparked considerable interest, suggesting practical human control of the radiation belts [*Inan et al.*, 2003] to protect Earth-orbiting systems from natural and nuclear injections of high energy electrons [*Rodger et al.*, 2006]. The topic is generally known as Radiation Belt Remediation (RBR).

[3] Satellite observations of quasi-trapped ~100 keV electrons in the drift-loss cone have reported "spikes" or enhancements in the flux population associated with the geomagnetic locations of VLF and LF transmitters [see *Datlowe and Imhof*, 1990; *Sauvaud et al.*, 2006; *Datlowe*, 2006, and references therein]. Enhancements of drift-loss cone electron fluxes are expected eastwards of the transmitter location, with cyclotron resonance taking place on field lines near the ground based VLF transmitter. The interacting electrons then drift eastward towards the South Atlantic Anomaly. Transmitters located under a nighttime ionosphere are favored, due to the lower ionospheric absorption of the up-going transmitter waves. It is also the time period where *Parrot et al.* [2007] observe that NWC strongly heats the ionosphere in its corresponding magnetic flux tube.

[4] While strong correlations between drift-loss cone enhancements and transmitter locations have been shown previously, such particle enhancements have yet to be tied directly to transmissions from ground-based VLF transmitters. In addition, the occurrence frequency of drift loss cone enhancements above transmitters has not yet been reported upon. In this paper we combine wave and particle observations from the DEMETER satellite to examine the significance of a ground-based VLF transmitter on the inner radiation belt.

2. Instrumentation

[5] DEMETER is the first of the Myriade series of microsatellites developed by the French National Center for Space Studies (CNES). This low-cost science missions was placed in a circular Sun-synchronous polar orbit at an altitude of 710 km at the end of June 2004 [*Parrot*, 2006]. Data are available at magnetic latitudes <65°, providing observations around two local times (~10:30 LT and 22:30 LT). The IDP particle instrument carried onboard DEMETER is unusual in that it has a very high energy resolution and a high geometric factor. In normal "survey" mode the instrument measures electron fluxes in the drift loss cone (or just outside) with energies from 70 keV to 2.34 MeV using 128 energy channels every 4 seconds [*Sauvaud et al.*, 2006]. Resolution depends on the operational mode of the satellite, being either 17.8 keV in "survey" mode or 8.9 keV in "burst" mode. The payload is also made of several plasma and wave instruments including the ICE instrument, which provides continuous measurements of the power spectrum of one electric field component in the VLF band [*Berthelier et al.*, 2006].

[1]CESR/University of Toulouse-CNRS, Toulouse, France.
[2]LPCE CNRS, Orléans, France.
[3]CETP CNRS, Saint Maur, France.
[4]Department of Physics, University of Otago, Dunedin, New Zealand.

0094-8276/08/2008GL033194

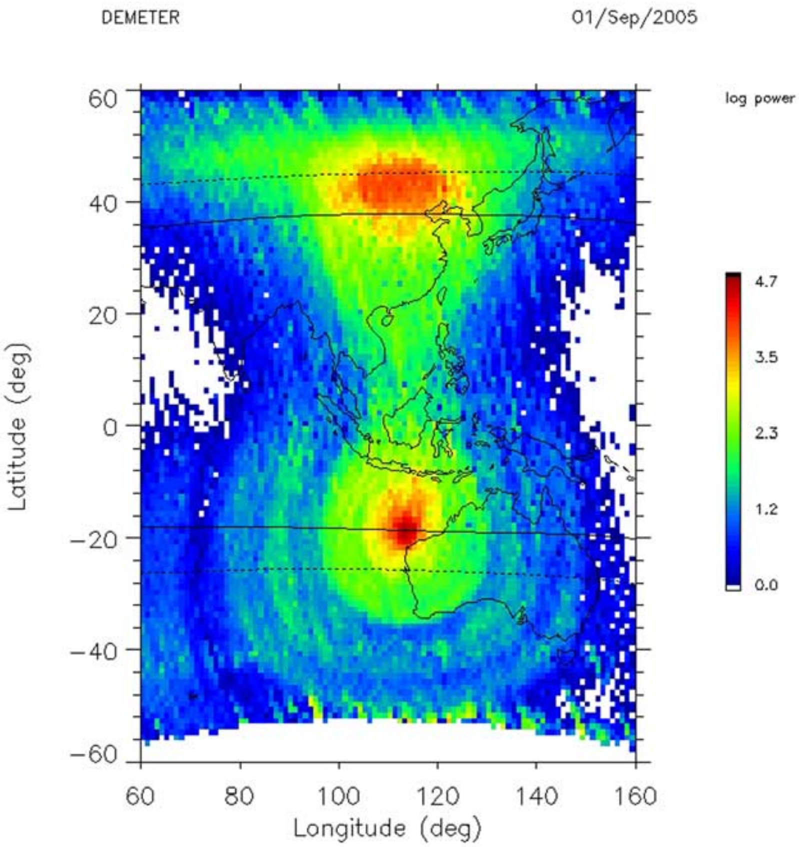

Figure 1. Geographic display of the average power received by the ICE instrument on DEMETER from the NWC transmitter at 19.8 kHz. L-shell contours computed at the satellite altitude (700 km) are also shown (L = 1.4 and L = 1.7). In a large region around the transmitter, there are interferences of the VLF modes. The wave power is given in $\mu V^2/(m^2.Hz)$.

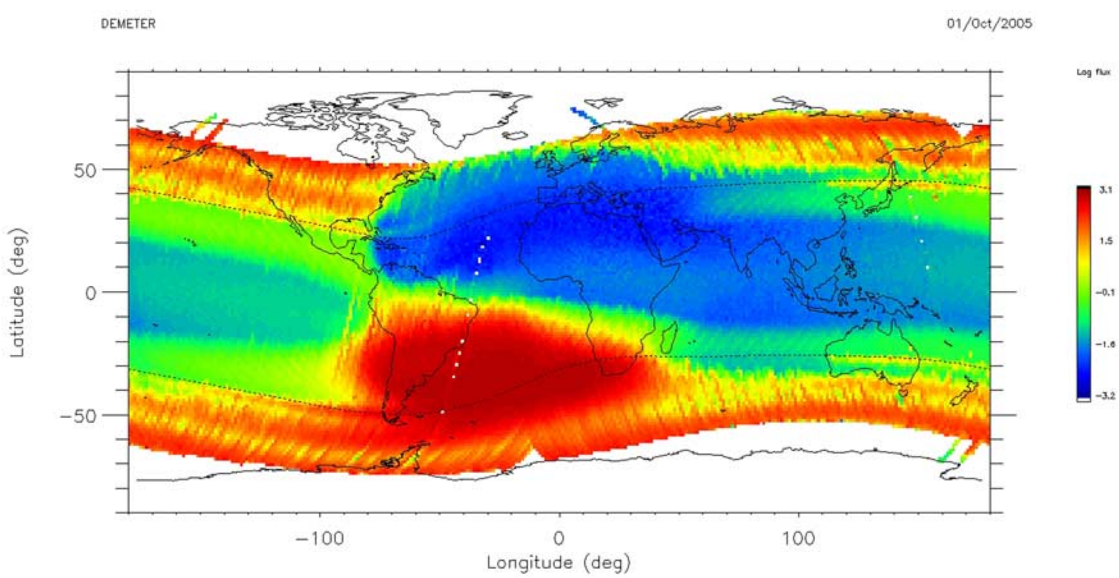

Figure 2. Geographical distribution of quasi trapped electron fluxes at an energy of 200 keV. The L = 1.7 contours, computed at 700 km altitude, are also shown. Note the large flux enhancement inside the South Atlantic Anomaly and its counterpart with weak fluxes in the Northern Hemisphere. At the highest magnetic latitude (~±65°), the satellite encounters the auroral zones. The outer radiation belt is detected at all longitudes, at latitudes ranging from −45° (−180° longitude) to −60° (−90° longitude). On the contrary, the electron structure associated with NWC is only detected from the west coast of Australia eastwards and follows the L (= 1.7) contours as expected from the electron drift motion. Fluxes are given in $e^-/(cm^2.ster.keV)$.

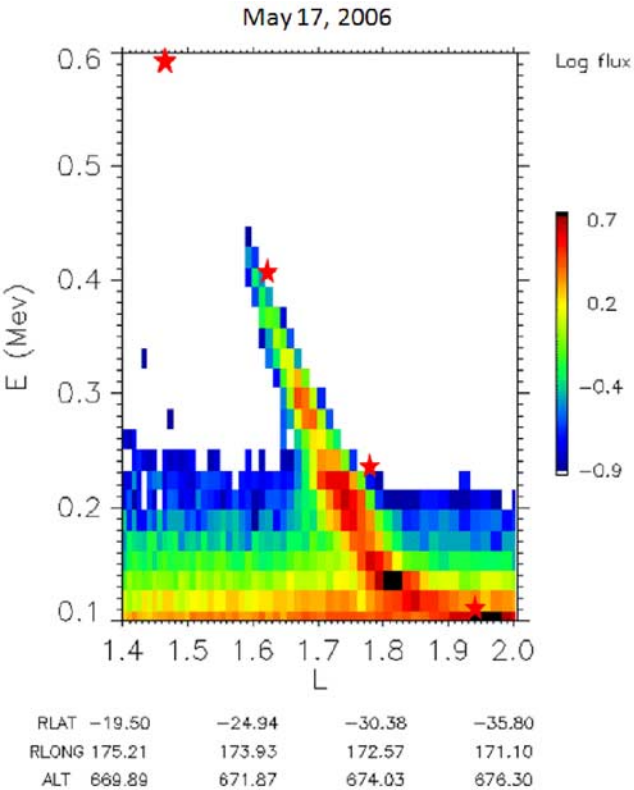

Figure 3. Energy-L spectrogram showing a dispersed electron structure corresponding to the "NWC dispersion trace" displayed in Figure 2 for 200 keV. The data were obtained on May 17, 2006 around 22:30 UT, during a quiet magnetic period. The satellite is flying over the Southern Hemisphere at L values between 1.4 and 2.0. The stars represent the results of the computation of the resonant energy according to a simple equatorial magnetic field model and to the ISO-IRI model of the equatorial thermal plasma density (see text).

[6] We focus upon the powerful US Navy transmitter with call sign "NWC" (19.8 kHz, 1 MW radiated power, North West Cape, Australia, L = 1.45). NWC is extremely well positioned to have a potential influence upon >100 keV electrons in the inner radiation belt; most other powerful VLF transmitters are located at much higher L-shells, leading to resonances with <10 keV electrons. Figure 1 shows the average spectral power received by DEMETER's ICE instrument in a ~195 Hz band centered on 19.8 kHz, for nighttime orbits occurring from September 2005 to December 2006. The location of NWC corresponds to the maximum signal in the Southern Hemisphere. However, in the DEMETER data, NWC produces high power levels in both the source and conjugate hemispheres, although the conjugate location is shifted polewards, in agreement with the ray tracing calculations of unducted VLF waves launched from the Earth by *Abel and Thorne* [1998a, 1998b] and as discussed by *Clilverd et al.* [2008]. Figure 1 provides a nice example of diffraction pattern for VLF waves crossing the ionosphere. According to the propagation of waves in anisotropic plasma, it is not surprising that the diffraction pattern is not visible in the conjugate hemisphere.

[7] DEMETER also observes NWC transmissions during the day in the same time period, but at power levels which are typically ~1200 times lower (i.e. ~31 dB) due to increased ionospheric absorption. This is reasonably consistent with the ~28 dB estimated daytime ionospheric absorption for a 20 kHz signal [*Helliwell*, 1965, Figure 3–3]. As the pitch-angle scattering efficiency is proportional to Whistler mode wave field strength rather than power [e.g., *Chang and Inan*, 1983], this suggests that the transmissions from NWC should be ~35 times more effective during local nighttime.

3. Drift-Loss Cone Observations

[8] The geographical distribution of the quasi trapped electron fluxes for an energy of 200 keV, as deduced from measurements by the IDP instrument is given in Figure 2. The selected DEMETER orbits in the time period October 2005–October 2006 have been used. Note the large flux enhancement inside the South Atlantic Anomaly (SAA) and its counterpart with weak fluxes in the Northern Hemisphere. At the highest latitudes, the satellite approaches the auroral zones. The outer radiation belt is detected at all longitudes, at geographic latitudes ranging from ~ −50° to −60° at a longitude of 180°. At the same longitude, 200 keV electrons are also measured in the slot region at latitudes ranging from ~ −40° to −50°. On the other hand, the electron structure associated with NWC is only detected eastward of the west coast of Australia, as expected from the electron drift motion. Fluxes inside this drift path are enhanced as the satellite is flying over regions with lower magnetic field close to the Earth, reaching a maximum west of the South Atlantic Anomaly. The trace disappeared east of the anomaly, in accordance with model computations showing that the quasi-trapped 'NWC electrons' (measured to have a pitch-angle close to 90° by the IDP spectrometer) are precipitating in the atmosphere of the SAA. Note that the electron structure is displaced poleward of the transmitter. This is expected as the Whistler waves reach higher L-shells at the equator that that of the transmitter and as the wave-particle interaction takes place close to the magnetic equator [e.g., *Abel and Thorne*, 1998a].

[9] Along a single satellite orbit, the electron structure, related to the NWC transmitter, shows a clear latitudinal dispersion as exemplified in Figure 3. This figure shows the differential electron fluxes measured above the Southern Hemisphere by the IDP instrument on May 17, 2006, at longitudes from 171° to 175°, as a function of the McIlwain L parameter. The corresponding pass lasts less than 10 minutes. We use the term "wisp " to describe the feature measured between $L \approx 1.8$ and 1.4 which shows a decrease in energy with increasing L, as expected from cyclotron resonance [e.g., *Koons et al.*, 1981; *Chang and Inan*, 1983]. In Figure 3, the red stars give the results of computations of the resonant energy from first order equatorial cyclotron resonance with waves at 19800 Hz from NWC. For the computations we use a simple equatorial magnetic field model and the plasmaspheric density deduced from the ISO_IRI IZMIRAN code. The IZMIRAN plasmasphere model [*Chasovitin et al.*, 1998; *Gulyaeva et al.*, 2002] is an empirical model based on Whistler and satellite observations. It presents global vertical analytical profiles of electron density smoothly fitted to IRI electron density profile at

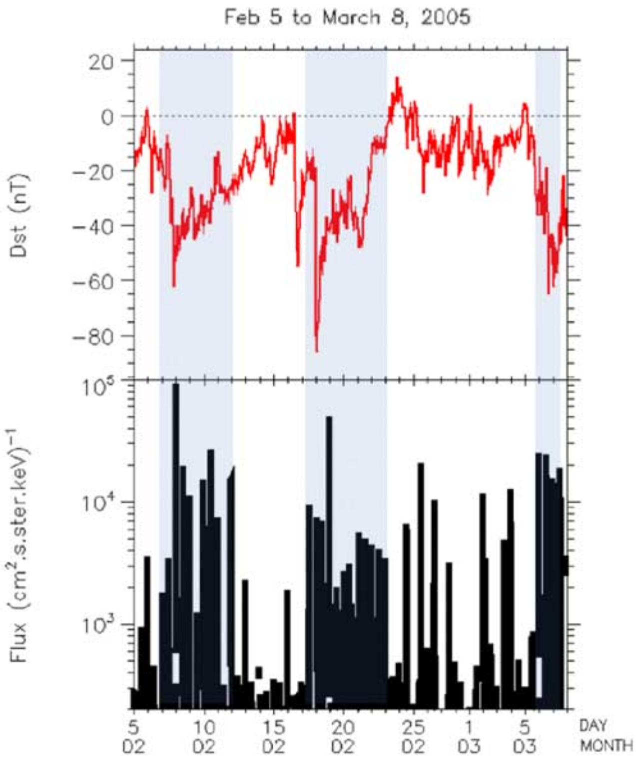

Figure 4. (top) Dst index from February 05, 2005 to March 08, 2005. (bottom) Variation, during the same time period, of the flux electrons at 250 keV taken in the longitude sector 105°–180° and in the latitude band from 38° to 48° which includes the drifting electron cloud shown in Figure 2.

1000 km altitude and extended towards the plasmapause (up to 36,000 km). For the smooth fitting of the two models, the shape of the IRI topside electron density profile is improved using ISIS 1, ISIS 2, and IK19 satellite inputs [*Gulyaeva et al.*, 2002]. The model density profile depends on the geomagnetic activity (Kp) and on the solar flux (sunspot number). The agreement between measured and computed resonant energy is satisfactory. Note however that the density model which depends on a number of parameters is not intended to give absolute values for the case presented in Figure 3.

[10] As shown in Figure 2, the wisps are observed east of NWC. Wisps are observed only for nighttime half-orbits, almost certainly due to the much lower ionospheric absorption of NWC transmissions through the nighttime ionosphere. NWC was not transmitting from the beginning of the DEMETER lifetime, in June 2004 to mid October 2004. Over this time period, none of the satellite orbits showed wisps in the drift-loss cone fluxes. The wisps reappeared immediately after this time period, when NWC was transmitting again. This provides conclusive evidence of the linkage between wisps and transmissions from NWC.

[11] In order to examine the magnitude of wisp events they are compared to the background electron fluxes when NWC was not transmitting. Wisp fluxes at 200 keV show a (geometric) mean enhancement factor of ~300.

[12] Variations in the wisp fluxes are apparent in the DEMETER electron data. Because the resonant wave intensity is constant, the flux changes of resonant electrons should be controlled by variations in the source intensity. In order to examine the correlation between geomagnetic activity and flux changes of the dispersed electron structure, Figure 4 displays the Dst variation during a 33-day period and the associated variation of the electron flux at 250 keV, as measured in the longitude sector 105 to 180°, at the latitudes of the electron drifting structure shown in Figure 2. As expected [e.g., *Rodger et al.*, 2007], the flux is increased during active magnetic periods resulting from a succession of moderate storms. Note that the electron fluxes follow the Dst variations quite well, indicating a short electron life time.

4. Summary and Conclusions

[13] Previous studies have reported the existence of enhancements in drift-loss cone electron fluxes in the inner radiation belt, and have associated them with the operation of a powerful VLF transmitter. Theoretical calculations have also indicated that such transmitters may play a dominant role in inner radiation belt electron lifetimes, and thus that man-made transmitters may allow practical control of electron fluxes in the inner belt. In this paper we have combined wave and particle observations from the DEMETER satellite to examine the significance of the ground-based VLF transmitter NWC on the inner radiation belt. This transmitter is extremely well positioned to have a potential influence upon inner radiation belt >100 keV electrons.

[14] We have found that enhancements in the ~100–600 keV drift-loss cone electron fluxes are directly linked to NWC operation and ionospheric absorption. Daytime ionospheric absorption levels mean that pitch-angle scattering efficiency due to NWC will be ~35 times lower than nighttime, and due to this, no drift-loss cone electron flux enhancements were observed above the daytime ionosphere. In contrast, nighttime measurements made eastward of the operational transmitter contained enhancements. No enhancements were observed during periods when NWC was not transmitting. This provides conclusive evidence of the linkage between drift-loss cone electron flux enhancements and transmissions from NWC. Typically, there are ~300 times more 200 keV electrons present in the drift-loss cone due to NWC transmissions when contrasted with periods when NWC is non-operational. The variation of the energy of enhanced electron fluxes with L is consistent with first-order cyclotron resonance between inner belt electrons and 19.8 kHz waves from NWC, with the interaction taking place at or near the geomagnetic equator. Finally, the source of the variations of the flux content of the energy dispersed structure has been shown to be linked to magnetic storms and related injections.

[15] **Acknowledgments.** The authors wish to thank the International Space Science Institute (ISSI) for supporting the WFM (ISSI#89) team meetings. This work was supported by the French national center for space research (CNES). We are grateful to Emmanuel Penou, who developed the software for data display.

References

Abel, B., and R. M. Thorne (1998a), Electron scattering loss in Earth's inner magnetosphere-1: Dominant physical processes, *J. Geophys. Res.*, *103*, 2385–2396.

Abel, B., and R. M. Thorne (1998b), Electron scattering and loss in Earth's inner magnetosphere: 2. Sensitivity to model parameters, *J. Geophys. Res.*, *103*, 2397–2407.

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

Chang, H. C., and U. S. Inan (1983), Quasi-relativistic electron precipitation due to interactions with coherent VLF waves in the magnetosphere, *J. Geophys. Res.*, *88*, 318–328.

Chasovitin, Y. K., T. L. Gulyaeva, M. G. Deminov, and S. E. Ivanova (1998), Russian Standard Model of Ionosphere (SMI), in *COST251TD* (98)*005*, edited by A. Vernon, pp. 161–172, Rutherford Appleton Lab., Didcot, U. K.

Clilverd, M. A., C. J. Rodger, R. J. 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.

Datlowe, D. (2006), Differences between transmitter precipitation peaks and storm injection peaks in low-altitude energetic electron spectra, *J. Geophys. Res.*, *111*, A12202, doi:10.1029/2006JA011957.

Datlowe, D. W., and W. L. Imhof (1990), Cyclotron resonance precipitation of energetic electrons from the inner magnetosphere, *J. Geophys. Res.*, *95*, 6477–6491.

Gulyaeva, T. L., H. Xueqin, B. W. Reinisch, and W. Bodo (2002), Plasmaspheric extension of topside electron density profiles, *Adv. Space Res.*, *29*, 825–831.

Helliwell, R. A. (1965), *Whistlers and Related Ionospheric Phenomena*, Stanford Univ. Press, Stanford, Calif.

Imhof, W. L., J. B. Reagan, and E. A. Gaines (1978), The energy selective precipitation of inner zone electrons, *J. Geophys. Res.*, *83*, 4245–4254.

Imhof, W. L., J. B. Reagan, E. E. Gaines, and R. R. Anderson (1981), The significance of VLF transmitters in the precipitation of inner belt electrons, *J. Geophys. Res.*, *86*, 11,225–11,234.

Imhof, W. L., J. B. Reagan, H. D. Voss, E. E. Gaines, D. W. Datlowe, J. Mobilia, R. A. Helliwell, U. S. Inan, J. Katsufrakis, and R. G. Joiner (1983a), The modulated precipitation of radiation belt electrons by controlled signals from VLF transmitters, *Geophys. Res. Lett.*, *10*, 615–618.

Imhof, W. L., J. B. Reagan, E. E. Gaines, and R. R. Anderson (1983b), Narrow spectral peaks in electrons precipitating from the slot region, *J. Geophys. Res.*, *88*, 8103–8110.

Imhof, W. L., H. D. Voss, M. Walt, E. E. Gaines, J. Mobilia, D. W. Datlowe, and J. B. Reagan (1986), Slot region electron precipitation by lightning, VLF chorus, and plasmaspheric hiss, *J. Geophys. Res.*, *91*, 8883–8894.

Inan, U. S., T. F. Bell, and R. A. Helliwell (1978), Nonlinear pitch angle scattering of energetic electrons by coherent VLF waves in the magnetosphere, *J. Geophys. Res.*, *83*, 3235–3253.

Inan, U. S., H. C. Chang, and R. A. Helliwell (1984), Electron precipitation zones around major ground-based VLF signal sources, *J. Geophys. Res.*, *89*, 2891–2906.

Inan, U. S., T. F. Bell, J. Bortnik, and J. M. Albert (2003), Controlled precipitation of radiation belt electrons, *J. Geophys. Res.*, *108*(A5), 1186, doi:10.1029/2002JA009580.

Koons, H. C., B. C. Edgar, and A. L. Vampola (1981), Precipitation of inner zone electrons by Whistler-mode waves from the VLF transmitters UMS and NWC, *J. Geophys. Res.*, *86*, 640–648.

Parrot, M. (2006), Preface: Special issue of *Planetary and Space Science* 'DEMETER', *Planet. Space Sci.*, *54*(5), 411–412, doi:10.1016.j.pss.2005.10.012.

Parrot, M., J. A. Sauvaud, J. J. Berthelier, and J. P. Lebreton (2007), First in-situ observations of strong ionospheric perturbations generated by a powerful VLF ground-based transmitter, *Geophys. Res. Lett.*, *34*, L11111, doi:10.1029/2007GL029368.

Rodger, C. J., M. A. Clilverd, T. Ulich, P. T. Verronen, E. Turunen, and N. R. Thomson (2006), The atmospheric implications of radiation belt remediation, *Ann. Geophys.*, *24*, 2025–2041.

Rodger, C. J., M. A. Clilverd, N. R. Thomson, R. J. Gamble, A. Seppälä, E. Turunen, N. P. Meredith, M. Parrot, J. A. Sauvaud, and J.-J. Berthelier (2007), Radiation belt electron precipitation into the atmosphere: Recovery from a geomagnetic storm, *J. Geophys. Res.*, *112*, A11307, doi:10.1029/2007JA012383.

Sauvaud, J. A., T. Moreau, R. Maggiolo, J.-P. Treilhou, C. Jacquey, A. Cros, J. Coutelier, J. Rouzaud, E. Penou, and M. Gangloff (2006), High-energy electron detection onboard DEMETER: The IDP spectrometer, description and first results on the inner belt, *Planet. Space. Sci.*, *54*, 502–511.

Vampola, A. L. (1977), VLF transmission-induced slot electron precipitation, *Geophys. Res. Lett.*, *4*, 569–572.

Vampola, A. L., and G. A. Kuck (1978), Induced precipitation of inner zone electrons: 1. Observations, *J. Geophys. Res.*, *83*, 2543–2551.

J.-J. Berthelier, Centre d'Etudes des Environnements Terrestre et Planétaires, 4 avenue de Neptune, F-94107 Saint Maur des Fosses, France. (jean-jacques.berthelier@cetp.ipsl.fr)

R. J. Gamble and C. J. Rodger, Department of Physics, University of Otago, P.O. Box 56, Dunedin, New Zealand. (rgamble@physics.otago.ac.nz; crodger@physics.otago.ac.nz)

C. Jacquey, R. Maggiolo, and J. A. Sauvaud, Centre d'Etude Spatiale des Rayonnements, a Avenue du Colonel Roche, F-31028 Toulouse Cedex 4, France. (jacquey@cesr.fr; maggiolo@cesr.fr; sauvaud@cesr.fr)

M. Parrot, Laboratoire de Physique et Chimie de l'Environnement, 3A avenue de la Recherche Scientifique, F-45071 Orleans Cedex 2, France. (mparrot@cnrs-orleans.fr)