COSPAR-2002 Paper No. D3.4-0028-02

TOWARDS STATISTICAL AND EMPIRICAL MODELS OF THE DISTRIBUTION OF VLF WAVES AT HIGH LATITUDE FROM THE OBSERVATIONS OF THE VIKING SPACECRAFT

F. Darrouzet[1], W. N. Spjeldvik[2], J. F. Lemaire[1], G. Gustafsson[3], C. Hann[1], and C. Dyck[1]

[1]*Belgian Institute for Space Aeronomy, B-1180 Brussels, Belgium*
[2]*Department of Physics, Weber State University, Ogden, Utah 84408-2508, USA*
[3]*Swedish Institute of Space Physics, SE-75121 Uppsala, Sweden*

ABSTRACT

It is of considerable interest to compile a model of the low frequency electromagnetic wave intensity across the polar caps, in and around the auroral zones, as well as at lower latitudes. Waves are playing a dynamic role in the auroral region and can be used to characterize the level of activity in the magnetosphere. At middle latitudes, Very Low Frequency (VLF) and Extremely Low Frequency (ELF) waves are known to scatter trapped energetic electrons, alter their angular and energy distributions, and eventually cause their precipitation into the Earth's atmosphere where it affects the propagation of radio signals. We report here on the development of a data-based model of the electrostatic power spectral density in the VLF band (10-46 kHz) as surveyed onboard the Swedish Viking spacecraft in the high-latitude region in the northern hemisphere. The data have been sorted into bins according to spatial location and wave frequency. A preliminary statistical model is presented showing the mean electric power spectral density versus magnetic local time and versus invariant latitude at fixed height intervals and for fixed frequency bands within the VLF range. The most intense VLF waves are observed at low frequencies (10-19 kHz) and at relatively low altitudes (1500-5500 km). This trend shifts towards higher invariant latitude and higher altitude. The least intense waves are detected between 9 and 15 MLT and for lower invariant latitude. Fitting these statistical averages with simple analytical functions will be a next step in order to produce empirical models.

INTRODUCTION

Studies of plasma waves yield insight into magnetospheric phenomena that are controlled or strongly influenced by wave-particle interactions. It is well known that ELF and VLF waves within the plasmasphere influence the structure of the electron radiation belts (e.g., Lyons and Thorne, 1973) and possibly lower energy protons, and that the resulting mid-latitude energetic electron precipitation strongly influences the lower ionosphere at night and during magnetic storms (e.g., Spjeldvik and Thorne, 1976; Spjeldvik and Lyons, 1980). This is why URSI Commission H (Plasma waves) voted in 1999 a Recommendation to support the modeling effort to survey and map the ELF and VLF wave environment. This Recommendation can be found on the public WEB site of SEVEM (*Survey of ELF and VLF Experiments in the Magnetosphere*: http://www.magnet.oma.be/sevem/index.html) (e.g., Darrouzet et al., 2001). The SEVEM project was created at the Belgian Institute for Space Aeronomy to support and concentrate such an international effort to develop statistical and empirical distributions of ELF & VLF spectra in the magnetosphere. It follows up on pioneering work of NASA teams efforts in the 1960's and 1970's (e.g., Sawyer and Vette, 1976; Vette, 1991) on empirical statistical work on proton and electron distributions in the magnetosphere. The SEVEM project has been placed under the obedience of VERSIM, an IAGA/URSI Joint Working Group on *VLF/ELF Remote Sensing of Ionospheres and Magnetospheres* (http://www.nerc-bas.ac.uk/public/uasd/versim.html).

Several isolated attempts to compile such global world maps of VLF or ELF wave occurrence have been published in the past, but they did not get enough visibility and attention. They would have remained unnoticed without the SEVEM Web site where they are listed. A coordinated effort like that conducted within the SEVEM initiative could bring statistical studies and global mapping of wave phenomena to the space research community's forefront. It should be pointed out that an important contribution has been published along these lines. It is a statistical study of low frequency waves in the equatorial plasmasphere undertaken recently by Andre et al. (2002).

Plasma waves are prominently observed at high latitudes, in the auroral zone and in the geomagnetic cusp region, especially at low altitudes. In an effort to begin a systematic study of the high latitude region, we report here results from a statistical study of VLF wave power spectral densities observed in the northern hemisphere by the wave experiment V4H (Bahnsen et al., 1988) on the Swedish VIKING spacecraft from March to December 1986. The experiment measured two components of the electric field using two 80 m dipole antennae located perpendicular to the spin axis of the spacecraft. We have used only one component because the other one was very often corrupted or noisy. The signal has been Fourier-analyzed onboard Viking by a Stepped Frequency Analyzer, with, in standard operation, a time resolution of 2.4 sec and a frequency resolution of 1 kHz. These electric field power spectral densities were downloaded from a French data center, the CDPP (*Centre de Données de la Physique des Plasmas*: http://cdpp.cesr.fr/), (Darrouzet and Lemaire, 2002). We describe below the statistical rate of occurrence of 10-46 kHz VLF power spectral densities for geomagnetic invariant latitudes in the range 50-90 degrees, for magnetic local times (MLT) ranging from 0 to 24 hours, and for geographic altitudes ranging from 1500 to 13500 km.

STATISTICAL RESULTS

Invariant latitude dependence

It is reasonably expected that wave activity should exhibit significant variations with spatial location. Figure 1 depicts the statistical results for the period March-December 1986 as overall VLF power spectral densities at 10-46 kHz and MLT=00-24 hr, i.e., no resolution in magnetic local time. The four panels show the electric field power spectral densities in invariant latitude bins: 50-60, 60-70, 70-80 and 80-90 deg. Each panel plots curves for the four altitude bins we have used: 3000, 6000, 9000 and 12000 km, each with height range ±1500 km.

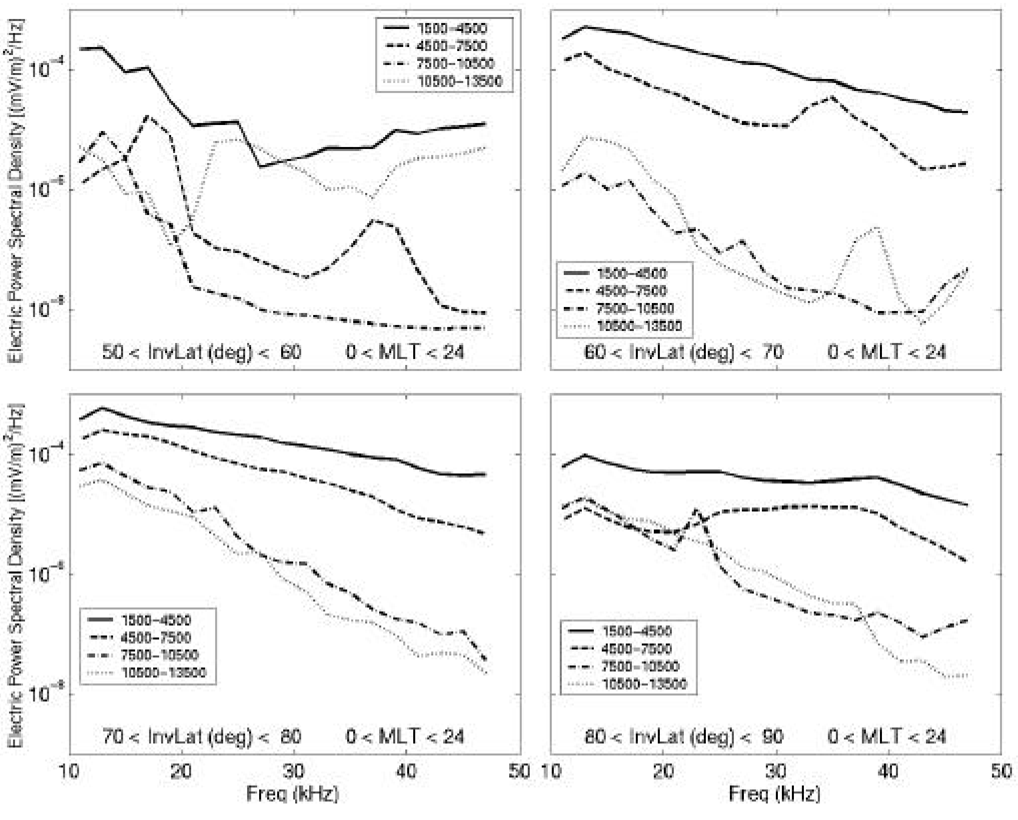

Fig. 1. VLF electric field power spectral densities versus frequency averaged over all magnetic local times are shown for different ranges of invariant latitudes in the Northern Hemisphere. The data are collected over the period March-December, 1986 by the V4H experiment onboard the Swedish Viking spacecraft.

The wave data at low invariant latitudes (50-60 deg) and middle altitude (4500-10500 km) indicate lower wave intensity above 20-25 kHz. The rather irregular spectra indicate either that there are peaks in the spectra or that the sample is not homogeneous. Additional data are needed to check these hypotheses. This situation is changed at 60-70 deg invariant latitude where the low altitude data exhibit a near power-law distribution in the whole range of VLF frequencies. This power-law spectrum is observed up to 80 deg invariant latitude. In contrast, at very high invariant latitudes the spectra flatten out at 15-35 kHz and suggest significant wave intensity with power spectral plateau-to-peak at 30-35 kHz. In a more detailed study, we will also examine the dependence of these average spectra on the level of geomagnetic activity and magnetic local time.

Magnetic local time dependence

It is reasonable to expect magnetic local time variations of the VLF wave intensity (from magnetospheric emissions), and also some wave energy contributions from man-made sources (VLF transmitters that have geographic longitude and latitude distributions). Nevertheless, much of the naturally occurring wave energy is expected to stem from magnetospheric sources, such as auroral wave-particle interactions, polar cusp region (quasi-standing?) waves, the magnetopause current layer, wave-particle interaction induced wave growth, and other phenomena. The four panels in Figure 2 illustrate the magnetic local time variations of the VLF electric field waves as seen in the night sector (MLT=21-03 hr), the dawn sector (MLT=03-09 hr), the noon sector (MLT=09-15 hr), and the dusk sector (MLT=15-21 hr). In each panel we have plotted the electric field intensities at altitudes: 3000, 6000, 9000 and 12000 km (each with height range ±1500 km). This figure averages over all invariant latitudes (50-90 deg) in this study, and as latitudinal averages we notice that the VLF waves are most intense in the night sector (MLT=21-03 hr) and at the lower altitudes, below 7500 km. The dawn sector data illustrate wave intensities that are somewhat more evenly distributed over altitudes, and roughly following power laws over the 10-40 kHz frequency interval. The front side of the magnetosphere at MLT=09-15 hr shows lesser intense VLF waves, particularly at the higher frequencies. There is a remarkably large qualitative difference between the night side (first panel) and the dusk side (last panel), so that in the dusk sector our statistically averaged data demonstrate little altitude dependence of the wave intensities. Indeed, the intensities at the different altitudes are largely overlapping. Except in the day side, it seems that the wave intensity decreases with altitude.

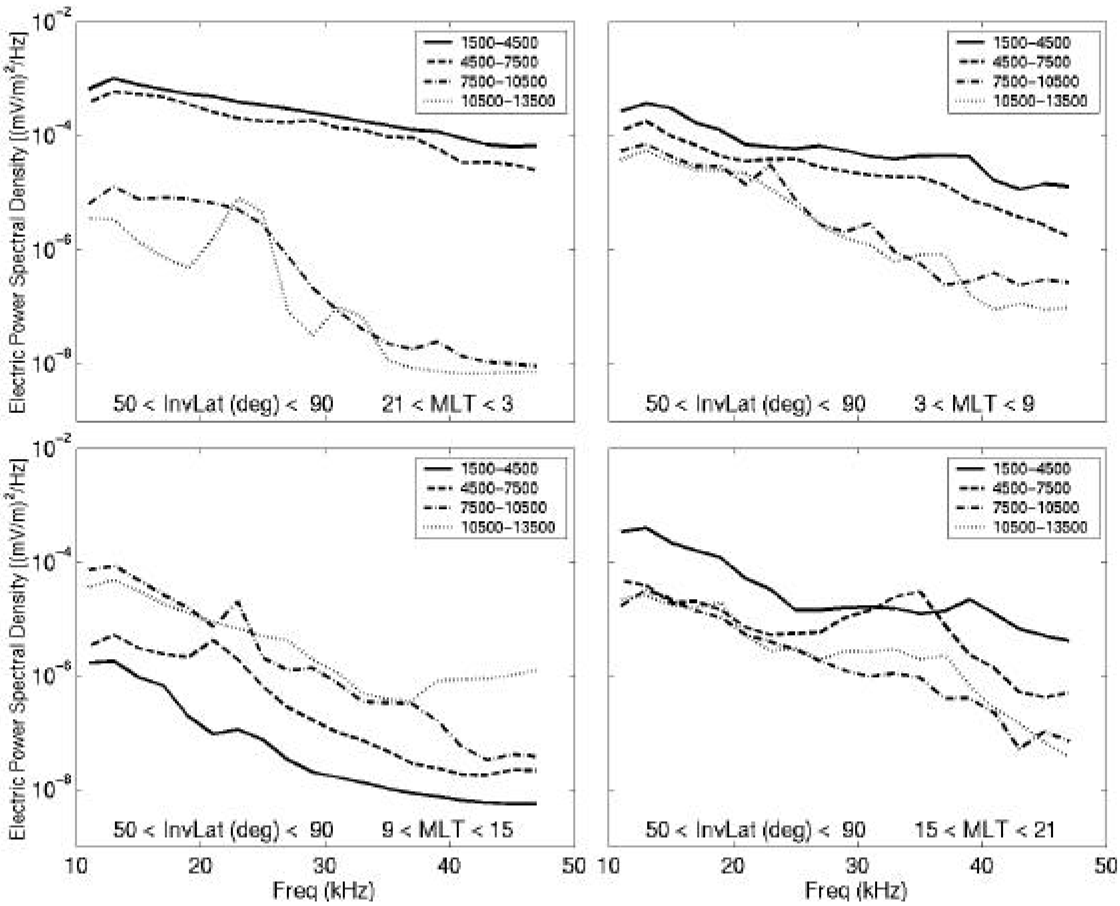

Fig. 2. VLF electric field power spectral densities versus frequency averaged over all invariant latitudes are shown for different ranges of magnetic local times in the Northern Hemisphere, for the same time period as Figure 1.

Frequency dependence

We have detected a significant variation of the VLF electric field intensity with altitude, magnetic local time, and invariant latitude. The altitude dependence is also strongly frequency dependent. At 10-19 kHz, the more intense waves are found at the lower altitudes (1500-2500 km) and at the lower invariant latitudes (54-60 deg). The trend shifts towards higher altitudes (2500-5500 km) with higher invariant latitudes (66-80 deg). This trend appears much weaker, and the wave intensities are lower, when higher VLF wave frequencies are considered. For example, at 19-28 kHz and at higher frequencies the waves are primarily present at 70-80 deg invariant latitude and at 2500-4000 km. These results are exhibited in Figure 3 which is a gray scale binned distribution with the four panels containing the selected VLF frequency bins (10-19, 19-28, 28-37, 37-46 kHz), and each panel having a 24-bin height resolution between 1500 and 13500 km versus a 20-bin invariant latitude resolution from 50 to 90 deg.

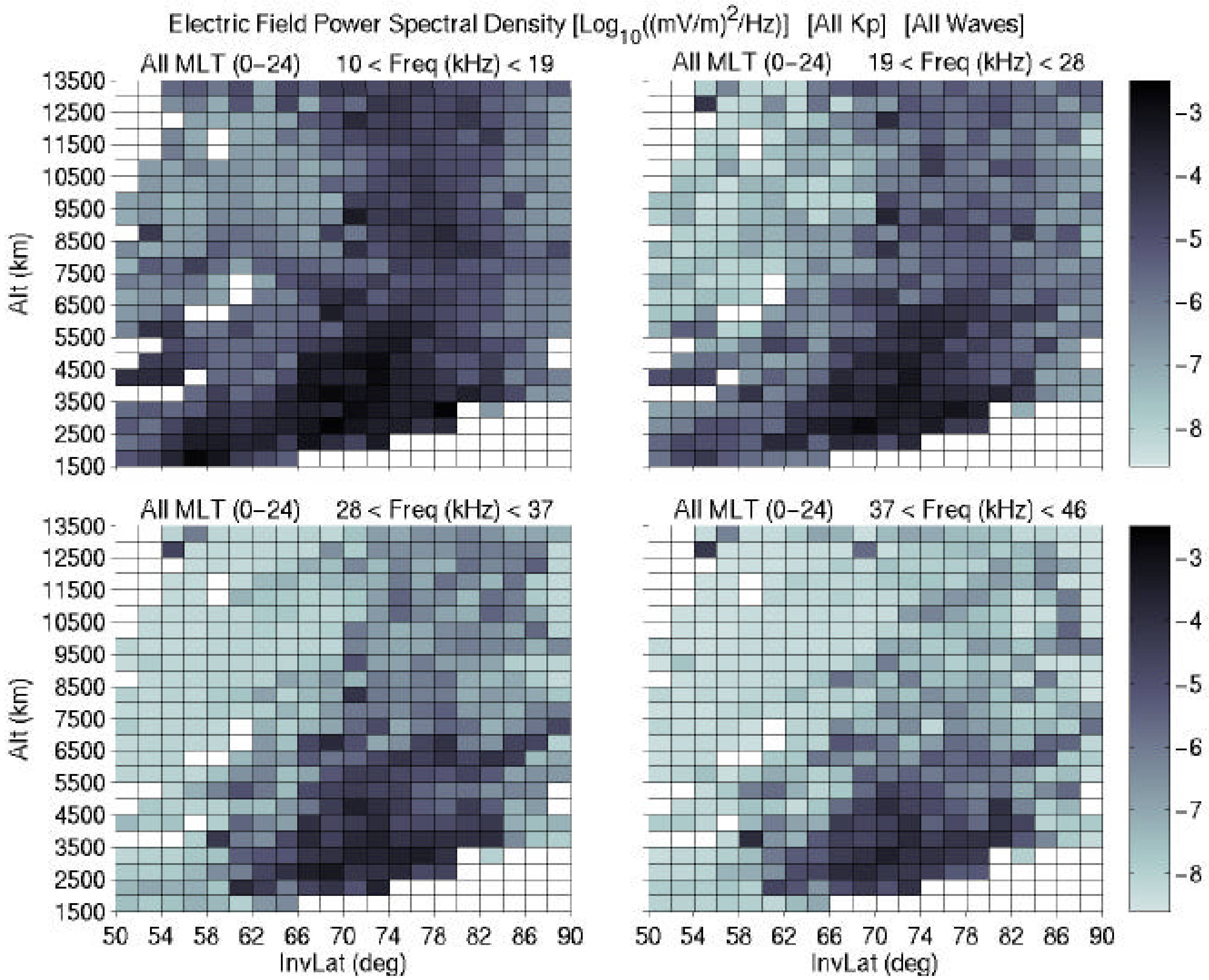

Fig. 3. Gray scale rendering of the logarithm of the VLF electric field wave intensity in four frequency bins averaged over all magnetic local time sectors in the Northern Hemisphere, for the same time period as Figure 1.

SUMMARY AND CONCLUSIONS

We have conducted a statistical study of the VLF electric field power spectral densities in the Earth's magnetosphere using data from the V4H experiment onboard the Swedish Viking spacecraft. Over the time period March-December 1986, we have detected systematic spatial variations of the VLF wave energy. We find the highest wave energy preferentially at low frequencies (10-19 kHz) and at relatively low altitudes (1500-5500 km). There appears to be much less VLF wave activity above 6000 km. The least intense VLF waves are observed between 9 and 15 MLT. Average spectra, standard deviation from this average, and third order moment of the statistical distribution have also been calculated for each bin, but this will be discussed in a future more comprehensive paper.

In this study, we display power spectral densities rather than wave amplitudes as in the work of Andre et al. (2002), in order to be consistent with most earlier statistical studies (e.g., Green and Boardsen, 1999; Parrot, 1990). In fact, power spectral densities measured at the geostationary altitude were the basis for computations of magnetic radial diffusion coefficients in the Earth's radiation belts (e.g., Arthur et al., 1978; Lanzerotti et al., 1978).

During the time span considered in our study there were naturally several magnetic storms and substorms. The data have been collected over a wide range of geomagnetic conditions as reflected in the histogram of the Kp-index, AE-index and other measurements of the level of geomagnetic activity. Figure 4 illustrates the histogram of Kp-index values during the period over which the data have been collected. The Kp distribution shows that values of 1 to 3 (low activity) are most prevalent, but there are few data sets with Kp>5.

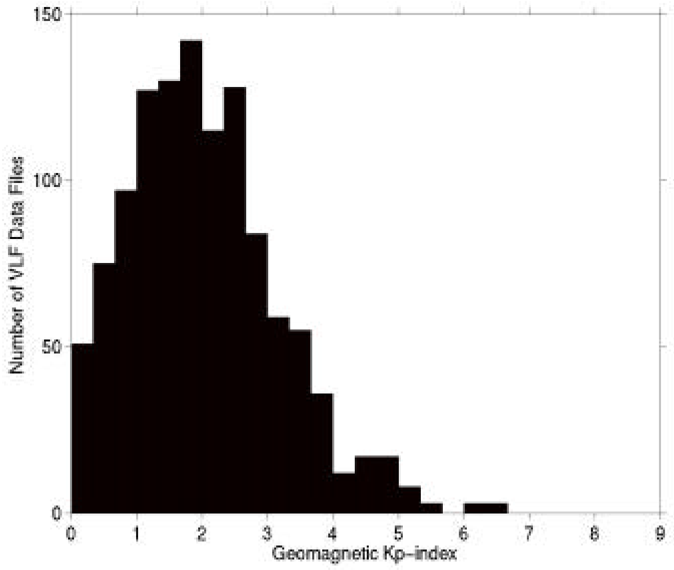

Fig. 4. Distribution of geomagnetic Kp-index values of the time intervals during which the 1162 V4H data files used in this study have been collected between March and December 1986.

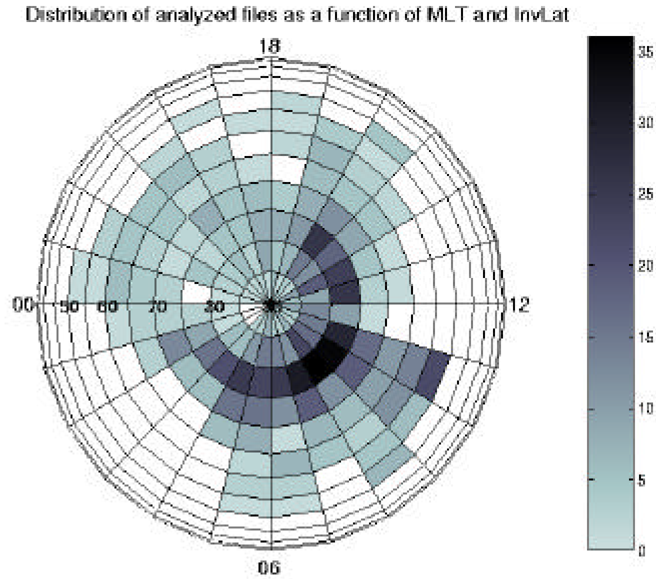

Fig. 5. Distribution as a function of magnetic local time and invariant latitude of the 1162 V4H data files used in this study collected between March and December 1986.

Future research will be directed towards delineating the VLF wave emissions during different geophysical conditions, and will include data from the ELF frequency range as well, which are available from the V4L experiment of Viking. Due to the limited coverage of the database, it is not yet appropriate to attempt to fit the average with analytical and parametrical functions in order to build an empirical model.

This study has been based on electric field data from one spacecraft, which recorded measurements during 10 months but only in the northern hemisphere. This is why the distribution of the data as a function of magnetic local time and invariant latitude shown on Figure 5 is not equally distributed in space. Most of the data used in this work are at MLT between 3 to 15 hr, and at invariant latitude above 60 deg. This indicates the necessity to continue similar statistical studies with other suitable well instrumented spacecraft with durable data collection. Multi-spacecraft missions, like Cluster, are of course ideal in order to have statistical models of low frequency waves in other parts of magnetosphere. In a next step it would be valuable to extend our modeling effort by using the WHISPER and STAFF wave experiments. Furthermore, with these modern wave data, other Stokes parameters of the VLF waves could be determined in addition to the power spectral densities. Therefore more comprehensive statistical and empirical models could be developed in the future with the Cluster wave observations.

ACKNOWLEDGMENTS

This study has been conducted at the Belgian Institute of Space Aeronomy in Brussels in the framework of the PRODEX CLUSTER and SEVEM projects supported by the OSTC (Belgian Federal Office for Scientific, Technical and Cultural Affairs). This support is acknowledged by the authors. We are also very grateful to Dr. A. Bahnsen, principal investigator of the V4H experiment for giving us permission to use these data which are archived at the CDPP in Toulouse. We gratefully acknowledge the support and excellent cooperation of Chris Harvey and his team at the CDPP.

REFERENCES

Andre, R, F. Lefeuvre, F. Simonet, et al., A First Approach to Model the Low-Frequency Wave Activity in the Plasmasphere, *Ann. Geophysicae*, **20**, 981-996, 2002.

Arthur, C. W, R. L. McPherron, and L. J. Lanzerotti, Geomagnetic Field Fluctuations at Synchronous Orbit, 1. Power Spectra, *J. Geophys. Res.*, **83**, 3859-3865, 1978.

Bahnsen, A., M. Jespersen, E. Ungstrup, et al., First Viking Results: High Frequency Waves, *Phys. Scripta*, **37**, 469-474, 1988.

Darrouzet, F., J. F. Lemaire, and A. Orr, The SEVEM Project: Statistical ELF and VLF Environment Models, *Space Science Research in Belgium, 1994-2000*, 103-107, 2001.

Darrouzet, F., and J. F. Lemaire, The SEVEM project: Statistical ELF and VLF Environment Models, *Le Bulletin du Centre de Données de la Physique des Plasma*, **N5**, Janvier 2002.

Green, J. L., and S. A. Boardsen, Confinement of nonthermal continuum radiation to low latitudes, *J. Geophys. Res.*, **104**, 10307-10316, 1999.

Lanzerotti, L. J., D. C. Webb, and C. W. Arthur, Geomagnetic Field Fluctuations at Synchronous Orbit, 2. Radial Diffusion, *J. Geophys. Res.*, **83**, 3866-3870, 1978.

Lyons, L. R., and R. M. Thorne, Equilibrium Structure of Radiation Belt Electrons, *J. Geophys. Res.*, **78**, 2142-2149, 1973.

Parrot, M., World map of ELF/VLF emissions as observed by a low-orbiting satellite, *Ann. Geophysicae*, **8**, 135-146, 1990.

Sawyer, D. M., and J. I. Vette, AP-8 Trapped Proton Environment for Solar Maximum and Solar Minimum, *NASA/GSFC, NSSDC/WDC-R&S* Rep. 76-06, Dec. 1976.

Spjeldvik, W. N., and R. M. Thorne, Maintenance of the Middle Latitude Nocturnal D-Layer by Energetic Electron Precipitation, *Journal of Pure and Applied Geophysics*, **114**, 497-508, 1976.

Spjeldvik, W. N., and L. R. Lyons, On the Predictability of Radiation Belt Electron Precipitation into the Earth's Atmosphere Following Magnetic Storms, *Solar-Terrestrial Predictions Proceedings*, (editor: R. F. Donnelly), IV, B59, 1980.

Vette, J. I., The AE-8 Trapped Electron Model Environment, *NASA/GSFC, NSSDC/WDC-A-R&S* Rep. 91-24, Maryland, 1991.

E-mail address of F. Darrouzet: Fabien.Darrouzet@oma.be
Manuscript received ; revised ; accepted