

# Calculation of Whistler-Mode Wave Intensity Using Energetic Electron Precipitation

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## Abstract

The energetic electron population measured by multiple low-altitude POES satellites is used to infer whistler-mode wave amplitudes using a physics-based inversion technique. We validate this technique by quantitatively analyzing a conjunction event between the Van Allen Probes and POES, and find that the inferred hiss wave amplitudes from POES electron measurements agree remarkably well with directly measured hiss waves amplitudes. We also use this technique to construct the global distribution of chorus wave intensity with extensive coverage over a broad L-MLT region during the 8-9 October 2012 storm and demonstrate that the inferred chorus wave amplitudes agree well with conjugate measurements of chorus wave amplitudes from the Van Allen Probes. The evolution of the whistler-mode wave intensity inferred from low-altitude electron measurements can provide real-time global estimates of the wave intensity, which cannot be obtained from in-situ wave measurements by equatorial satellites alone, but are crucial in quantifying radiation belt electron dynamics.

## 1. Introduction

Whistler-mode waves including chorus and plasmaspheric hiss have received intense attention recently due to the significant role they play in energetic electron dynamics. Pitch angle scattering of electrons by chorus waves is a dominant cause of electron precipitation into the atmosphere leading to the diffuse and pulsating aurorae [1-4] and chorus waves also provide efficient local acceleration of the relativistic radiation belt electrons through energy diffusion [5-7]. Resonant electron interactions with plasmaspheric hiss play an important role in electron precipitation over a broad range of energies from tens of keV to a few MeV [8]. Particularly, hiss-driven relativistic electron precipitation loss is known to create the slot region between the inner and outer radiation belts [9]. Therefore, it is crucial to understand the global evolution of chorus and hiss wave intensities during various levels of geomagnetic activity. Statistical wave distributions were previously used to evaluate the role of these whistler-mode waves in radiation belt electron dynamics during a geomagnetic storm, since in-situ wave measurements are confined to a limited range in *L*-shell and magnetic local time (MLT). However, whistler-mode wave distributions from statistical results may not accurately represent the specific, instantaneous global wave evolution in any particular individual event.

In the present study, we adopt a physics-based technique to construct the spatiotemporal evolution of whistler-mode wave intensity (chorus and hiss) inferred from in-situ electron measurements by low-altitude POES satellites, using their extensive coverage in *L* and MLT.

## 2. Methodology

To quantify the wave-driven electron precipitation, we use low-altitude electron measurements from multiple POES satellites [10] and wave measurements from the EMFISIS instrument on Van Allen Probes [11]. POES satellites have two particle detectors, which can measure both precipitated and trapped electron fluxes in various energy channels ( $> 30$  keV,  $> 100$  keV, and  $> 300$  keV) [12], and multiple satellites are distributed in a broad MLT range to provide extensive coverage. Quasi-linear diffusion theory [13] and the UCLA Full Diffusion code [1] are used to evaluate the wave-driven electron pitch angle scattering and link the estimated electron pitch angle distribution near the bounce loss cone to the two-directional POES electron measurements. The ratio (*R*) of precipitated and trapped electron fluxes measured by POES, in turn, is used to infer whistler-mode wave amplitudes [14].

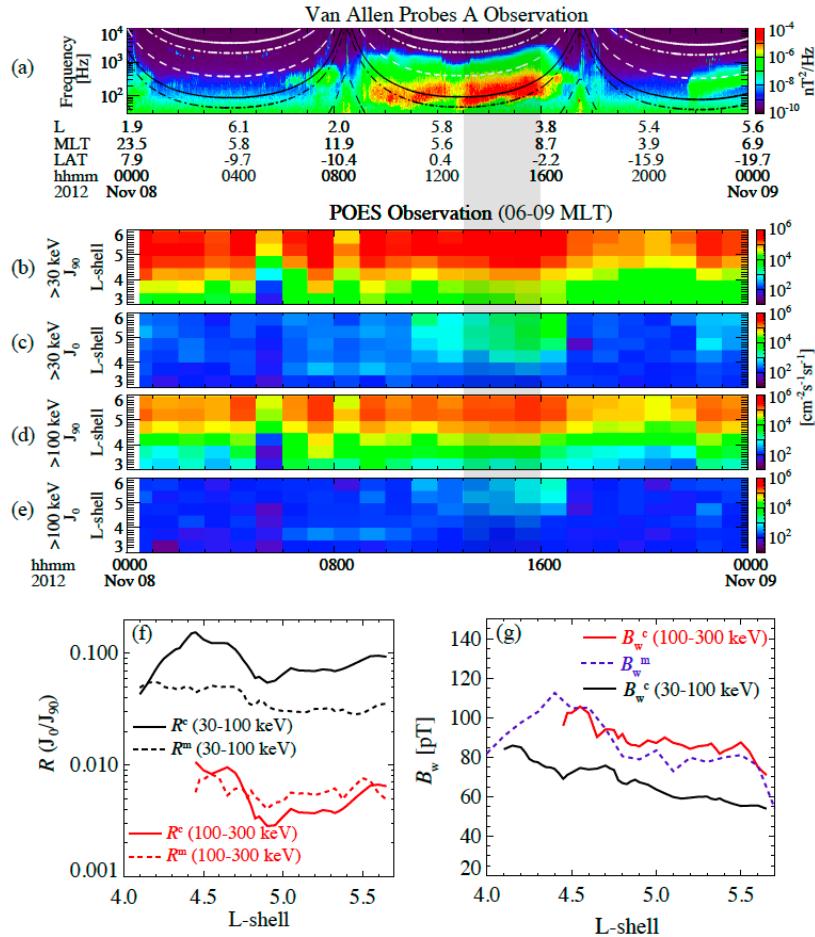
### 3. Results

We apply this technique to both hiss and chorus waves to infer their wave amplitudes and compare them with directly measured waves amplitudes, as shown in Sections 3.1 and 3.2. This technique is also used to construct the spatiotemporal evolution of chorus wave intensity on a global scale using electron observations from multiple POES satellites.

#### 3.1 Hiss waves

We conduct a quantitative analysis for a hiss-driven electron precipitation event, which occurred over 13-16 UT on 8 November 2012, when Van Allen Probe A observed strong plasmaspheric hiss over  $3.8\text{-}5.8 R_E$  near the dawn sector (Figure 1a). During the same period, electron fluxes measured by the POES satellites near the dawn sector exhibit pronounced electron precipitation in the energy channel of  $> 30 \text{ keV}$  (Figure 1c) and  $> 100 \text{ keV}$  (Figure 1e), showing remarkable correlation with the enhanced hiss wave intensity.

Based on the hiss wave spectrum, electron energy spectrum, and plasma density measured by the Van Allen Probes, we calculate bounce-averaged electron pitch angle diffusion coefficients near the bounce loss cone to estimate the ratio of precipitated and trapped electron fluxes at  $30\text{-}100 \text{ keV}$  ( $R^c$  ( $30\text{-}100 \text{ keV}$ )) and  $100\text{-}300 \text{ keV}$  ( $R^c$  ( $100\text{-}300 \text{ keV}$ )) using the physics-based technique described above. Comparison of the calculated and directly measured  $R$  from

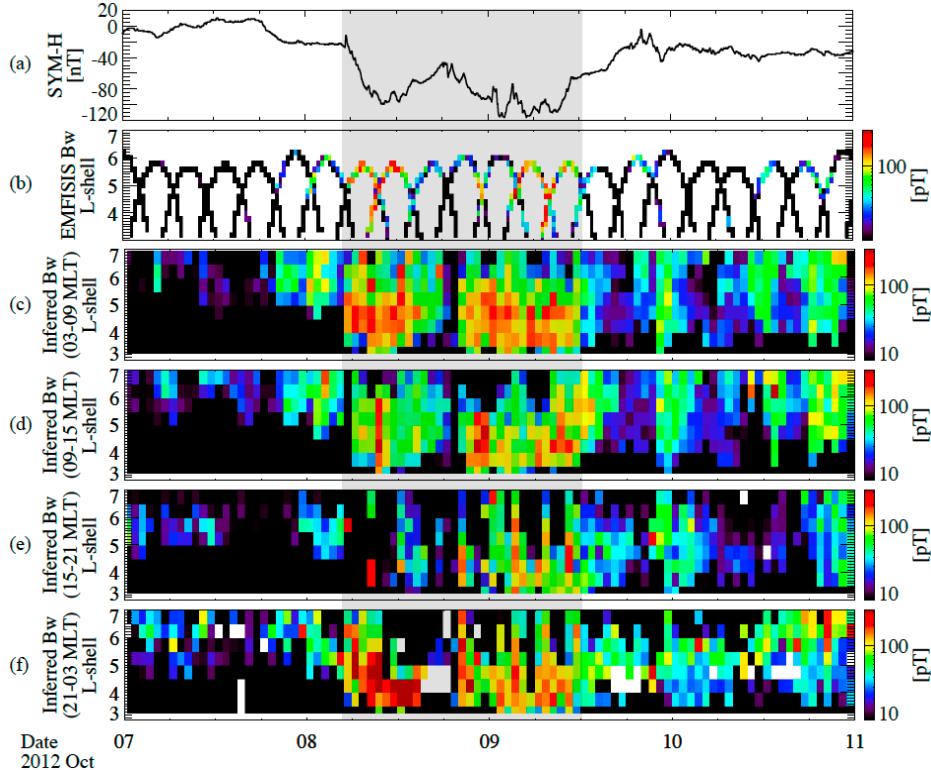


**Figure 1. Comparison of the measured and calculated  $R$  and hiss wave amplitude ( $B_w$ ).** (a) Frequency-time spectrogram of the magnetic field spectral density measured by the EMFISIS instrument on Van Allen Probe A, where the white lines indicate  $f_{ce}$  (solid),  $0.5 f_{ce}$  (dot-dashed), and  $0.1 f_{ce}$  (dashed) and the black lines indicate  $f_{LHR}$  (solid) and  $0.5 f_{LHR}$  (dot-dashed), where  $f_{ce}$  and  $f_{LHR}$  are the equatorial electron cyclotron frequency and lower hybrid resonance frequency, respectively. (b) and (c) Trapped ( $J_{90}$ ) and precipitated ( $J_0$ ) electron fluxes observed by the POES satellites over 6-9 MLT for  $> 30 \text{ keV}$ . (d) and (e) are the same as (b) and (c) but for electron energy of  $> 100 \text{ keV}$ . (f)  $R$  ( $J_0/J_{90}$ ) calculated using measured wave spectral intensity and plasma parameters ( $R^c$ : solid black line) and directly measured from two-directional POES measurements ( $R^m$ : dashed black line) for  $30\text{-}100 \text{ keV}$  electrons. Red lines represent similar quantities to black lines but for electron energies of  $100\text{-}300 \text{ keV}$ . (g) Directly measured hiss wave amplitudes on EMFISIS integrated over 40-4000 Hz ( $B_w^m$ : blue dashed line) and calculated hiss wave amplitudes using  $R^m$  of  $30\text{-}100 \text{ keV}$  ( $B_w^c$ : black line) and  $100\text{-}300 \text{ keV}$  ( $B_w^c$ : red line).

POES (Figure 1f) exhibits fairly good agreement particularly for the energy channel of 100-300 keV. We also calculate hiss wave amplitudes ( $B_w^c$  in solid red line) using the measured  $R^m$  from the 100-300 keV channel, which show remarkable agreement with the directly measured hiss wave amplitudes ( $B_w^m$  in dashed blue line) by EMFISIS (Figure 1g). This agreement suggests that this technique, based on quasi-linear diffusion theory, can be used to estimate hiss wave amplitudes from the ratio of precipitated and trapped electron fluxes.

### 3.2 Chorus Waves

We apply the same technique to chorus waves and construct their global distribution as a function of  $L$ -shell in various MLT ranges during a double dip storm, which occurred during 07-10 October in 2012 (Figure 2). The chorus wave amplitudes inferred from  $R$  (30-100 keV) over 03-09 MLT (Figure 2c) agree well with the conjugate measurements of chorus wave amplitudes by the EMFISIS instrument on the Van Allen Probes (Figure 2b) in the similar MLT sector. Both inferred and directly measured chorus wave amplitudes intensify during the two dips measured by the SYM-H index (gray region), and the chorus wave intensity is much weaker during other periods. These strong chorus waves led to very efficient local acceleration of seed electrons to multi MeV energies within  $\sim$ 12 hours, consistent with relativistic electron measurements by Van Allen Probes [7]. Furthermore, the chorus wave intensities in the night (21-03 MLT) and dawn (03-09 MLT) sectors are larger than that in the day (09-15 MLT) and dusk (15-21 MLT) sectors, consistent with previous statistical results [15]. The evolution of the chorus wave intensity inferred from low-altitude electron measurements can provide real-time global estimates of the wave intensity over a broad L-MLT region (Figure 2c-2f), which cannot be obtained from in-situ wave measurements by equatorial satellites alone, but are crucial in quantifying radiation belt electron dynamics.



**Figure 2. Evolution of whistler-mode chorus wave intensity measured by Van Allen Probes and inferred from low-altitude electron measurements (30-100 keV) by multiple POES satellites during 07-10 October 2012. (a) Sym-H index, (b) lower-band chorus wave amplitudes integrated over  $0.1 - 0.5 f_{ce}$  measured by the EMFISIS instruments on both Van Allen Probes A and B. (c)-(f) Inferred chorus wave intensity from the ratio of precipitated and trapped electron fluxes in various MLT ranges.**

### 4. Summary

Using a physics-based technique, we calculate whistler-mode hiss and chorus wave intensities from the ratio of precipitated and trapped electron fluxes measured by multiple low-altitude POES satellites. The correlation between the measured hiss wave amplitudes by the Van Allen Probes and inferred wave amplitudes from POES electron measurements is remarkable during the analyzed conjunction event, indicating that this technique is capable of estimating actual wave intensity with fairly good accuracy. We also apply this technique to chorus waves and construct a global

distribution of chorus wave intensities over the extensive range during the 9 October 2012 storm, which cannot be obtained from the equatorial satellites alone. Such a data-driven dynamic whistler-mode wave distribution could be critically important for the evaluation of radiation belt electron dynamics during various geomagnetic activities.

## 5. Acknowledgments

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