Chorus Wave Observations from Van Allen Probes: Quantifying the Impact of the Sheath Corrected Electric Field

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Abstract

A technique has recently been established to quantify the variable coupling impedance between the electric field spherical double probes sensors on the Van Allen Probes and the magnetospheric plasma. A sheath impedance model has been developed to describe how this instrument-plasma coupling affects the amplitude and phase of electric field wave measurements. A full sheath-corrected EMFISIS dataset has been produced. Here, we quantify how measured chorus wave properties, including electric field wave power and the Poynting vector, are impacted by the sheath correction. This is achieved by performing a direct comparison between the uncorrected and sheath-corrected datasets. It is found that the sheath-corrected electric field chorus wave power is typically 2-9 times larger than the uncorrected measurement, depending on wave frequency. The sheath correction typically increases the Poynting flux by a factor of ~2, and causes the polar angle of the Poynting vector, $\theta_p$, to switch hemisphere from parallel to anti-parallel propagation in ~2% of cases. The uncorrected data exhibit significant deviations from the theoretically predicted relationship between the wave vector and the Poynting vector, whereas this relationship is well-reproduced with the sheath-corrected data.

1 Introduction

The Van Allen Probes measured the wave electric field using spherical double probe sensors mounted on long centrifugally deployed wire booms in the spin-plane, with shorter rigid booms along the spin-axis. Intervals of favorable wave, magnetic field, and antenna geometry have been used to calculate each component of the whistler-mode wave electric field from magnetic field observations and cold plasma theory. A direct comparison between these theoretically predicted values, and those measured by the spacecraft, allowed for the variable coupling impedance between the instrument and the plasma to be quantified and modeled [1]. This model has been applied to the entire Van Allen Probes EMFISIS dataset in order to mitigate the impact of these effects on both the amplitude and phase of the measured electric field. A full sheath-corrected EMFISIS L4 dataset has recently been made available to the community.

The dynamics of Earth's outer electron radiation belt is, in part, driven by interactions with whistler-mode chorus waves. Chorus can cause rapid acceleration of electrons up to relativistic energies, as well as drive precipitation of particles into the atmosphere during microbursts and diffuse auroral precipitation. Chorus is typically observed between 0.05 and 0.90 $f_{ce}$, where $f_{ce}$ is the equatorial electron cyclotron frequency. Prior to the development of the sheath corrected dataset, numerous studies directly investigated the electric field chorus wave power [2, 3], in part, because of how the high-amplitude parallel electric field component associated with oblique chorus [4] can drive nonlinear electron acceleration through Landau resonance [5]. The Poynting vector, which is determined from both magnetic and electric field observations, has also been investigated with results used to determine the chorus source region location, size, and dynamics [6, 7, 8]. Here, we perform direct comparisons between the uncorrected observations and the sheath-corrected chorus wave data, quantifying the impact of the sheath correction on the electric field wave power, as well as the Poynting vector magnitude and direction.

2 Chorus Identification

The first step in identifying chorus waves is to limit observations to time periods when the Van Allen Probes spacecraft are located outside of the plasmasphere. We further limit data based on wave measurements, isolating intervals with, i) waves above the instrument background levels observed between 0.05 and 0.90 $f_{ce}$, ii) ellipticity [9] and 2D degree of coherence in the polarization plane [10] greater than 0.5, and iv) planarity [11] greater than 0.6. These criteria ensure right-hand circularly polarized plane waves, as is expected for whistler-mode chorus.

The selection criteria for isolating chorus signals are based solely on magnetic field observations which are unaffected by sheath effects, meaning the same criteria are applicable to both the uncorrected and sheath-corrected data. Having
extracted chorus waves from the extensive Van Allen Probes dataset, we statistically investigate wave characteristics, and perform a direct comparison between the uncorrected and sheath-corrected data.

3 Electric Field Wave Power

Figure 1 shows the median electric field power spectral density of chorus waves as a function of normalized wave frequency, \( f/f_{ce} \), with the uncorrected data, \( E_{w}^{uncor} \), and the sheath-corrected data, \( E_{w}^{cor} \), shown in blue and red, respectively. It is evident that \( E_{w}^{cor} \) is significantly larger than \( E_{w}^{uncor} \) over the entire chorus wave frequency band. For lower frequencies, \( E_{w}^{cor} \) is a factor of \( \sim 2 \) larger than \( E_{w}^{uncor} \). This factor increases with increasing wave frequency up to a local maximum of \( \sim 6 \) near 0.40 \( f_{ce} \), decreases down to \( \sim 4 \) near 0.60 \( f_{ce} \), before increasing again to a factor of \( \sim 9 \) by 0.90 \( f_{ce} \). We do note that there are occurrences where these factors can substantially deviate from these median values, and whilst they may serve as a guide as to the impact of the sheath correction, the relative orientation between the spin-axis of the spacecraft and the background magnetic field has a strong impact on these quantities, since the sheath correction is applied in the instrument coordinate system.

![Figure 1. Median uncorrected, \( E_{w}^{uncor} \) (blue), and sheath-corrected, \( E_{w}^{cor} \) (red), electric field power spectra for chorus as a function of normalized wave frequency, \( f/f_{ce} \).](image1)

Understanding how the sheath correction can impact the electric field chorus wave power is crucial given that the electric field can accelerate electrons through Landau and cyclotron resonances [12, 13, 14].

4 Poynting Vector

Since electric field observations are required to determine the Poynting vector, it too is impacted by the sheath correction. In a similar manner to the electric field analysis, the median spectrum of Poynting flux is determined using the uncorrected, \( S_{w}^{uncor} \), and sheath-corrected, \( S_{w}^{cor} \), data products. Figure 2 (top) shows \( S_{w}^{uncor} \) (blue) and \( S_{w}^{cor} \) (red) as a function of \( f/f_{ce} \). It is evident that \( S_{w}^{cor} \) is larger than \( S_{w}^{uncor} \) for all frequencies. In comparison to the electric field observations where the factor between the uncorrected and sheath-corrected values showed a strong dependence on wave frequency, the factor between \( S_{w}^{uncor} \) and \( S_{w}^{cor} \) is relatively constant for all frequencies, with \( S_{w}^{cor} \) being a factor of \( \sim 2 \) greater than \( S_{w}^{uncor} \) over the entire chorus wave frequency band. Actual values vary between 1.30 and 2.55, depending on wave frequency.

The sheath correction not only affects the magnitude of the Poynting vector, but also its direction. The polar angle of the Poynting vector, \( \theta_{S} \), is defined as the angle between the Poynting vector and the background magnetic field. Numerous previous studies have used \( \theta_{S} \) to determine the chorus source region location, size, and dynamics by investigating the position where \( \theta_{S} \) transitions from propagation with a component parallel to the background magnetic field (\( \theta_{S} < 90^\circ \)), to propagation with a component anti-parallel to the background magnetic field (\( \theta_{S} > 90^\circ \)). Here, we quantify how the sheath correction may impact such studies by determining the percentage of observations where the sheath correction causes \( \theta_{S} \) to flip hemispheres, from parallel to anti-parallel. The results of this analysis are presented in Figure 2 (bottom) as a function of \( f/f_{ce} \).

![Figure 2. (top) Median Poynting flux spectra, \( S_{w}^{uncor} \) (blue), and \( S_{w}^{cor} \) (red), determined from the uncorrected and sheath-corrected electric field, respectively. (bottom) Percentage of observations where the sheath correction causes \( \theta_{S} \) to flip hemisphere from \( \theta_{S} < 90^\circ \) to \( \theta_{S} > 90^\circ \), or vice-versa.](image2)

It is found that for low frequencies, up to 5.4% of observations flip hemisphere after the sheath correction has been applied. However, for \( f/f_{ce} \) values above 0.125 this percentage drops below 1%, and is typically only a few
tenths of a percent. Considering all frequencies, we find that the Poynting vector determined from sheath-corrected observations is in the same hemisphere as the uncorrected value (parallel or anti-parallel to the background magnetic field) in ~98% of cases. As such, the sheath correction causes the Poynting vector to flip hemispheres in only ~2% of cases, with these primarily at low frequencies. We therefore conclude that previous studies which used Van Allen Probes observations of $\theta_g$ to determine the location, scale size, and dynamics of the chorus source region are likely to achieve the same result if repeated using the sheath-corrected data. Due to the different instrumentation and spacecraft orientation used during other missions, the impact of sheath effects may be different. As such, these results are only valid for the Van Allen Probes, with investigation of other missions (e.g., MMS) ongoing.

5 Comparison between $k$ and $S$

For whistler-mode waves in a cold plasma, a theoretical relationship [15] exists between the wave vector, $k$, and the Poynting vector, $S$. Figure 3 shows the refractive index surface, $n$, in a cold plasma in the field-aligned coordinate system for a wave frequency of 1.5 kHz, an electron cyclotron frequency of 10 kHz, and a plasma frequency of 20 kHz. The Gendrinn angle, $\theta_G$, and the resonance cone, $\theta_R$, are shown by dotted and dashed lines, respectively. For each wave vector, $k$, the Poynting vector, $S$, is normal to the refractive index surface. Let us consider two wave vectors defined by $k_1$ (red) and $k_2$ (blue). For $k_1$, the polar wave vector angle, $\theta_{k_1}$, is less than $\theta_G$, meaning that both $k_1$ and $S_1$ are oriented in the positive $n_\perp$ direction. For $k_2$, the polar wave vector angle, $\theta_{k_2}$, is greater than $\theta_G$, which results in $k_2$ being oriented in the positive $n_\perp$ direction, but $S_2$ being oriented in the negative $n_\perp$ direction.

![Figure 3. The theoretical relationship between the $k$ and $S$ for whistler-mode waves in a cold plasma.](image)

As such, the absolute value of azimuthal angle of the wave vector subtracted from the azimuthal angle of the Poynting vector, $|\phi_S - \phi_k|$ is equal to 0° in the case of $k_1$ and $S_1$ but equal to 180° in the case of $k_2$ and $S_2$. This relation is true for all wave vector directions, meaning $|\phi_S - \phi_k| = 0°$ for $\theta_k < \theta_G$, and conversely $|\phi_S - \phi_k| = 180°$ for $\theta_k > \theta_G$. The validity of this relationship is explored using both the uncorrected and sheath-corrected data.

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However, comparison between the uncorrected and sheath-corrected data presented in Figure 4 demonstrates that the expected relationship between $k$ and $S$, as shown in Figure 3, is generally well reproduced by the sheath-corrected data, whereas significant deviations from the expected relationship exist in the uncorrected observations.

6 Conclusions

In this study, a direct statistical comparison of chorus wave properties derived from the uncorrected and sheath-corrected Van Allen Probes EMFISIS data has been performed. It is found that the sheath-corrected electric field chorus wave power is typically a factor between 2 and 9 times larger than the uncorrected observations, depending on wave frequency. The Poynting flux derived from the sheath-corrected data is typically a factor of ~2 larger than that obtained using the uncorrected observations. The sheath correction causes the polar angle of the Poynting vector, $\theta_S$, to flip hemisphere in only ~2% of chorus wave observations. The uncorrected and sheath-corrected datasets are tested against the theoretical relationship between $k$ and $S$ for whistler-mode waves in a cold plasma. This relationship is well-reproduced by the sheath-corrected data, whereas the uncorrected observations show significant deviations from these expected values.

Overall, this study provides the first direct comparison between the sheath-corrected electric field observations and the uncorrected data product, quantifying the impact that the sheath correction has on chorus wave observations. These results help frame the context of previous studies based on uncorrected electric field wave observations by providing statistically averaged values describing the impact of the sheath correction on chorus wave properties.

Acknowledgements

NASA Grant 80NSSC21K0519, EU's Horizon 2020 grant agreement No. 870452. MSMT grant L1USA23152.

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