An Automated Frequency Detection Algorithm (AURA) for the Van Allen Probes EMFISIS Waves Instrument

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Abstract

Routine measurements of the electron plasma density, \( n_e \), local to the Van Allen Probes spacecraft enables the contextualization of on board instrument observations. Whether used as a key parameter in wave and/or particle simulations, as a reference to locations inside or outside of the plasmasphere, or as a statistical description of the global plasmaspheric electron density distribution, the determination of \( n_e \) by EMFISIS measurements to an instrumental uncertainty of \( \sim 20\% \) at a cadence of 6 sec greatly aids many studies. We describe here the procedure for extracting electron plasma densities from wave observations of the upper-hybrid resonance band, \( f_{uh} \), in dynamic spectra. AURA, an automated algorithm developed for pipeline data production, is succeeding adequately on a mission coverage to date of 70\% of the orbits. We further discuss its limitations and the error introduced by manual spectral feature interpretation.

1 Introduction

The plasma environment surrounding the earth and within the magnetosphere is host to a “zoo” of plasma waves. Figure 1 illustrates the relative locations of wave phenomena in the equatorial magnetosphere relevant to the Van Allen Probes mission, which is designed to study physical processes responsible for particle acceleration, transport, and loss in the earth’s radiation belts with a pair of lapping satellites (hereafter RBSP-A and RBSP-B) in geostationary transfer orbits (700 km - 5.8 \( R_E \)) at an inclination of \( \sim 10\% \) degrees.

Of the 8 different instruments identically on board each of the spacecraft, the EMFISIS (Electric and Magnetic Field Instrument Suite and Integrated Science) suite captures DC magnetic fields and 3 axes of wave electric and magnetic field measurements from 10 Hz to 12 kHz (Kletzing et al. 2013). The wave electric components are derived from the EFW (Electric Field and Waves) instrument’s electric potential probes and computed in-flight by EMFISIS through the WFR or HFR (Waveform Receiver and High Frequency Receiver respectively) processing units (Wygant et al. 2013).

A proxy for the local electron plasma density is provided by the specialized HFR element that extends the measurement capability of EMFISIS for a single-axis electric field up to 500 kHz. The resultant combined WFR-HFR dynamic spectra (or spectrogram, as shown in Fig. 2) display many wave related phenomena, including the narrowband emission of the upper-hybrid frequency, \( f_{uh} \), in the HFR range. Using the measured electron cyclotron frequency, \( f_{ce} \), from the DC magnetic field, the plasma frequency, \( f_{pe} = 8980\sqrt{n_e} \), can be obtained from the relation

\[
n_e = \frac{(f_{uh}^2 - f_{ce}^2)}{8980^2}
\]

(1)

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where density is in cm$^{-3}$ and frequency is in Hz by correctly identifying $f_{uh}$.

In the next section we describe how the electron density, $n_e$, can be routinely digitized from analog dynamic spectra.
2 Automated Upper-hybrid Resonance Detection Algorithm

The upper-hybrid resonance constitutes a range of frequencies from the lower plasma frequency, $f_{pe}$, to the higher upper-hybrid frequency, $f_{uh}$. This single wave mode propagates perpendicular to the magnetic field and is extraordinary, depending on both the electric and magnetic field strength. Near these resonant frequencies, however, the plasma wave is almost purely electrostatic and involves mainly electron motions. In dynamic spectra (visible in Fig.1), the upper-hybrid resonance is observed as an emission band whose characteristic signatures vary according to the local plasma environment ($n_e$ and $|B|$).

RBSP-A/B orbit near the equatorial plane with a period of about 9 hours. The spacecraft periodically pass inside and through the plasmasphere, a toroidal region of cold ($\leq 1$ eV) and dense ($10^{-3}$ cm$^{-3}$) plasma that is predominantly composed of H$^+$ ions escaping from the ionosphere and electrons whose density decreases exponentially from the earth (Lemaire and Gringauz 1998). Earth’s dipolar magnetic field in the inner magnetosphere serves to trap this plasma in co-rotation with the planet. Geomagnetically active times (parameterized by several indices such as $DST$, $Kp$, and $AE$) indicate enhanced plasma convection across the magnetosphere due to current driven electric fields that can alter energy and density distributions.

Large-scale and small-scale electric fields dictate the morphological evolution of the plasmasphere as well as its spatial extent to a boundary known as the plasmapause. Though variously defined with respect to global activity and instantaneous response, the plasmapause is typically treated as a factor of 5 decrease in electron number density within a dimension of $\Delta L \leq 0.5$, where $L$ is the Mc-Ilwain L-parameter (Carpenter and Anderson 1992). Thus, the detection of the upper-hybrid frequency, $f_{uh}$, for purposes of identifying the local plasma electron density is challenged by the presence of other peak emissions for observations taken outside the plasmasphere where low densities and highly variable conditions dominate (see labeled plasmapause crossing in Fig. 1).

For the Van Allen Probes mission, the spacecraft undergo plasmapause crossings mainly during geomagnetically active times when the plasmasphere is constrained to lower L shells. The EMFISIS combined WFR-HFR elements can capture frequencies from 10 Hz - 500 kHz, but identification of $f_{uh}$ below the range of the HFR under 10 kHz is severely limited by a loss of signal power when compared to the background in spectral data (note behavior below $f_{ce}$ in Fig. 1). Due to instrumental response (see Kletzing et al. 2013), the effective upper frequency (maximum density) capable of being measured by the HFR is 400 kHz (2000 cm$^{-3}$).

With one spectrum produced every 6 s at a frequency resolution of 5%, any density measurements extracted from HFR spectral data will correspondingly be binned at 10% increments. Assuming that the upper-hybrid frequency is a continuous function of time, $f_{uh}(t)$ (i.e. for every local condition), the method for obtaining plasma density measurements must be able to connect together the discrete nature of spectral data (in frequency and time) and also work within time periods where observations of $f_{uh}$ are possible. We have therefore devised an Automated Upper-hybrid Resonance Detection Algorithm (AURA) to search for $f_{uh}$ spanning both halves of an RBSP orbit from perigee to apogee since the frequency is well observed in the plasmasphere.

2.1 Rule of Hysteresis

AURA employs a restricted searching approach to detect a relative peak frequency signal embedded in an individual spectrum. Optimized parameters and a bootstrapping method (see §2.2) ensure with some uncertainty that the recorded values indeed correspond to the upper-hybrid frequency, $f_{uh}$. Although, visual inspection and manual correction is applied for complete processing in most cases. This semi-automated technique depends on the observation that $f_{uh}$ is usually the most distinct narrowband feature in a spectrogram, except for measurements taken outside of the plasmapause where significant interpretation is necessary.
In the ideal scenario, AURA proceeds via a rule of hysteresis (RoH) that assumes each successive spectrum contains a peak frequency associated with $f_{uh}$ near the previously identified spectral record (i.e. there is not a significant change in frequency of the binned signal within a 6 sec sampling cadence). The routine operates in a two-dimensional array of equidistant binned frequency rows by sequential spectral columns, essentially treating a spectrogram as an image with logarithmic power values (magnitudes) at each coordinate position. AURA’s behavior then most nearly matches the prominence of visually apparent emission in the traditional manner of considering the dynamic spectra of the EMFISIS waves instrument.

Automation works in concert with the RoH only when AURA can be successfully initiated on the upper-hybrid emission band. Such a starting condition takes advantage of the limitation that EMFISIS cannot measure densities greater than 2000 cm$^{-3}$, for which $f_{uh}$ would exceed 400 kHz. Thus, for each orbital pass of both RBSP-A/B spacecraft through the plasmasphere there is an hour gap near perigee where no signal is observed at the highest frequencies of the HFR. This observation motivates the application of AURA on an orbit-by-orbit basis where $f_{uh}$ is expected to generally decrease from higher frequencies perigee to apogee.

Cycling through half-orbits, AURA begins at perigee and terminates at apogee (forwards or backwards in time for outbound/inbound passes respectively) when processing a spectrogram array. At the highest frequency bin of the HFR, the routine pinpoints the first record whose value is 1 greater (logarithmically) than the minimum magnitude in that bin. This ad hoc threshold is sufficient to locate $f_{uh}$ and apply the RoH, but false positives require that most traces of $f_{uh}$ through an orbit be trimmed manually near perigee. To track $f_{uh}$ as the RBSP-A/B spacecraft pass through different local plasma surroundings, RoH is further technically specified to single out the most probable and most prominent semi-continuous signal characteristic of $f_{uh}$.

Once a starting coordinate (frequency bin, spectral time) is determined, AURA proceeds with each successive spectra to search for a peak magnitude in a limited range of bins centered around the seed frequency. The values in this range are reduced by the minimum magnitude and weighted by an optimized central gaussian profile to correlate the product with a distribution of probability (whose parameters are detailed in Fig. 4). Since the upper-hybrid resonance appears as a narrowband emission in HFR spectrograms extending from the lower $f_{pe}$ to the higher $f_{uh}$ (see Eqn. 1), this simple RoH assumption can result in significant toggling over several frequency bins ($\sim 3$) for a cumulative uncertainty of about 20% depending on the observed narrowing of the resonant emission.
Figure 3: Shown in black is an example digitized trace of \(f_{uh}\) as processed by AURA without any manual intervention. At low geomagnetic activity (Kp < 2) the Van Allen Probes spacecraft are retained in the plasmasphere. Note that the approach to perigee is characterized by excessive toggling in the trace as the \(f_{uh}\) signal broadens. Inset detail provides context for the peak searching technique applied at the white bar in the next figure.

\[
g(x) = a \exp \left( \frac{(x - b)^2}{2c^2} \right) + d
\]

- parameters –

\[
\alpha = \frac{1}{N V 2^\delta} \quad \delta = \text{seed frequency bin number}
\]

\[
\epsilon = 3 \quad d = 0
\]

Figure 4: Spectral power in green around the seed frequency of the previous record is reduced logarithmically by the minimum value in a \(+/−10\) range of frequency bins for the spectra considered. The set of new magnitude values (log10) corresponding to these bins are then each weighted in blue by a multiplicative factor shown in red. In this normalization, observed spectral features are diminished on a probabilistic scale (gaussian profile) away from the seed frequency for the assumed continuous signal. Identifying peak magnitude thus results in a frequency bin containing the greatest power nearest the previous record. Discontinuous changes in \(f_{uh}\) outside of the nominal weighting range challenge accurate detection by AURA.

### 2.2 Bootstrapping Method

Exceptions to the RoH warrant the use of a method to detect failure as the seeding of spurious frequencies and to restart AURA robustly on \(f_{uh}\). A measure of the routine’s “fidelity” is indexed by a running displacement from seed value in frequency bins for the previous 1 min spectral interval such that an overall positive change of 8 bins indicates that recorded values are deviating from the expected perigee to apogee decreasing trend of \(f_{uh}\). This ad hoc measure serves as a check to initiating a bootstrapping method that predicts the target \(f_{uh}\) from potential measurements taken concurrently by the EFW instrument.

Using an equilibrium condition for currents flowing into and out of the RBSP-A/B spacecraft, a numerical relation between the spacecraft’s potential measured along a pair of EFW spherical sensors and the local electron plasma density can be expressed as

\[
n_e = N_0 \exp(V_{sc}/v_0) + N_1 \exp(V_{sc}/v_1)
\]

(2)
where \( n_e \) is in \( \text{cm}^{-3} \) and \( V_{sc} \) in volts is the average potential across an axis of two probes in the spin-plane \((V_1 + V_2)/2\) (see Wygant et al. 2013, Escoubet et al. 1997). The unknown constants in this relation are determined for month-long calibration intervals by non-linearly fitting against manually extracted densities from a series of EMFISIS observations of \( f_{uh} \) and processed EFW potential measurements. For each interval, 10 - 20 orbits covering the time span and a range of density values are chosen explicitly for this purpose.

Points are excluded from the fitting procedure if they occur during conditions that obscure EFW readings such as changes to probe bias, in photoelectron emission, or the presence of instrumental interference. Thus, if a failure check is not passed and the presently searched spectra occurs during an event where Eqn. 2 does not explicitly apply (e.g. spacecraft charging, eclipse, and maneuver events) then AURA will “forecast” ahead to the next nominal spectral time past a buffer window to where Eqn. 2 is again applicable. This trigger allows the routine to track \( f_{uh} \) to a high degree of success by resetting AURA for a 1 minute interval during which the EFW predicted frequencies calculated from Eqn. 1 & 2 are seeded for the search instead.

Figure 5: AURA’s trace of \( f_{uh} \) in the EMFISIS HFR spectrogram is shown as the black line, whereas the white line corresponds to the frequencies predicted by the EFW instrument’s density-potential correlation determined by Eqn. 2. The necessary coefficients for the prediction are presented in the following figure. Inset detail displays rapid changes in the frequency signal not captured by the routine and rerouted around by the bootstrapping method for overall greater success. Even at low geomagnetic activity (Kp < 2) the plasmasphere exhibits much structure from the inferred relation between \( f_{uh} \) and \( n_e \) (Eqn. 1).
$n_s = N_0 \exp(V_{sc}/v_0) + N_1 \exp(V_{sc}/v_1)$

- parameters -

$N_0 = 7583 \quad N_1 = 94.6 \quad v_0 = .382 \quad v_1 = 2.341$

Figure 6: A comparison between the EMFISIS extracted $f_{uh}$ and the EFW prediction for this particular interval demonstrates less than a 10% difference between the two techniques, further motivating their applicability when conditions allow unimpaired observations. Only two instances in which a separation of greater than 40% (roughly 4 frequency bins) occurs after which AURA is quickly reset by the bootstrapping method.

3 Processed Data Survey

 failure $< \frac{1}{4}$ and visually apparent signal

$\frac{1}{4} <$ failure $< \frac{1}{2}$ and some interpretation necessary

$\frac{1}{2} <$ failure and concealed signal
Figure 7: Categorizing orbits processed by AURA in terms of degree of nominal (∼ 10%) $f_{uh}$ extraction yields 3 partitions of data, labeled A, B, and C in the figure where the magenta line indicates a time range where failure occurs. Type A refers to 70% of the HFR orbit spectrograms from mission start (September 2012) to full MLT coverage (July 2014) successfully digitized into density records with less than 1/4 visually determined as needing correction (a single orbit at 6 sec cadence may contain as many as 4000 points). Type B constitutes 20% of the data set that is contaminated by 1/4 to 1/2 misidentified records, but nevertheless is quickly remedied by manual inspection. The final category, Type C, coincides with high geomagnetic activity where severe convection erodes the plasmasphere to low L shells and is observed as strong emission after a plasmapause crossing. Around 10% of these cases present considerable difficulty in identifying routinely or visually any $f_{uh}$ signal. This digitizing effort is further complicated by spacecraft charging, which renders the EFW potential readings as an ineffective guide during the event interval. RBSP-B orbits differ in degree of completion by 5–10% for each category due to instrumental differences that alter the nominal behavior of AURA. There are roughly 3700 orbits covering all MLT sectors routinely processed in this manner by AURA for both spacecraft combined to date.

REFERENCES


C.P. Escoubet et al., Density in the magnetosphere inferred from ISEE 1 spacecraft potential. J. of Geophys. Res. 102, A8 (1997)


