

Recent advances in modeling ionospheric stimulated electromagnetic emissions

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Abstract

There has been renewed interest over the past decade in Stimulated Electromagnetic Emissions (SEE) as a powerful diagnostic tool of the modified ionosphere during ground-based ionospheric heating experiments. The more recent observational advances in so-called Narrowband SEE (NSEE) have been accompanied by advances in modeling the plasma parametric processes that generate NSEE. This paper briefly summarizes some of these modeling advances and the applications to ionospheric diagnostics.

1 Introduction

Stimulated Electromagnetic Emissions (SEE) result from re-radiation of electromagnetic (EM) waves from the modified ionospheric plasma during ground-based ionospheric heating experiments that use high power, high frequency (HF) transmitters. These re-radiated (EM) waves are observed by relatively nearby receivers as SEE. Classic SEE consists of spectral lines, existing within the bandwidth of approximately 100 kHz of the transmit (or pump) frequency ω_0 , that result from parametric processes involving mixing of high frequency and low frequency plasma wave modes determined by frequency and wavenumber matching conditions [1]. Significant progress has been made in utilizing SEE as a diagnostic tool [2] since it was first reported in the early 1980s [3].

For the past decade, there has been a concentration on socalled Narrowband SEE (NSEE) that is typically described as SEE within 1 kHz or so of ω_0 . There has been discovery of a plethora of new NSEE lines at the High Frequency Active Auroral Research (HAARP) facility that show significant potential for further diagnostic purposes [4,5]. Key to developing NSEE into a diagnostic is an understanding of the fundamental concepts of the nonlinear plasma wave-wave interactions that produce these new spectral lines. What follows is a very brief description of modeling advances that have been made to interpret the generation and evolution of some of the most prominent (i.e. commonly observed) NSEE spectral lines.

2 Stimulated Brillouin Scatter (SBS)

SBS was the first NSEE spectral line to be observed [6, 7]. Classical SBS results from decay of the transmit EM wave into a backward scattered EM wave and a forward propagating electrostatic ion acoustic wave. The first successful theoretical modeling work was provided by [8] for SBS in a magnetized ionospheric plasma (so-called Magnetized Stimulated Brillouin Scatter MSBS). It is assumed MSBS is generated between the upper hybrid UH and plasma reflection altitudes. Since the first MSBS reports, there have been numerous investigations [e.g. 9,10,11] providing much more detailed characterization. MSBS exhibits two primary spectral lines [7,8]. For the transmit beam at magnetic zenith (MZ), a dominant line is observed shifted below ω_0 by the magnetized ion acoustic (IA) frequency (~10Hz) which is electron temperature (T_e) dependent. Therefore, MSBS may be used as a diagnostic for T_e . This is sometimes called the MSBS IA line. There has been recent work considering important similarities with the Incoherent Scatter Radar (ISR) spectrum which may shed light on further possible MSBS diagnostics [12]. For the transmit beam several degrees off MZ, a dominant line also exists shifted below ω_0 by the oxygen ion gyrofrequency (Ω_{cO} ~50Hz). The low frequency decay mode is an electrostatic ion cyclotron (EIC) wave in this case. This has been referred to as the MSBS EIC line Therefore, MSBS can also be used as a mass spectrometer. An example application is the work of [10] in which metallic ions were measured inside a sporadic E laver from the MSBS EIC line associated with the sodium ions.

Recently, more careful scrutiny of the MSBS IA spectrum has prompted consideration of possibilities of diagnostics for the more strongly nonlinear ionospheric plasma evolution during heating. [13] utilized an EM Particle-IN-Cell (PIC) simulation to investigate observed broadening of the MSBS IA line for increasing pump power. These simulations indicate that such a broadened IA line is indicative of strong IA turbulence and is associated with strong electron heating along the geomagnetic field B_{θ} and also development of cavities in the plasma density in which hot electrons exist. The transfer of energy from the pump wave into electron heating ultimately reduces the MSBS reflectivity within a few seconds after the pump is turned on. Therefore, the MSBS spectrum is also a diagnostic for characterizing ionospheric plasma turbulence associated with pumping. Figure 1 shows results from an EM PIC simulation model near the reflection altitude displaying high pump power broadening of the MSBS IA line and the associated cavity development and elevated electron temperature.

3 Stimulated Ion Bernstein Scatter (SIBS)

SIBS was first reported by [14] and since then, there have been a number of experiments [e.g. 15, 16, 11] that have characterized it in great detail for pumping near the second



Figure 1. MSBS high pump power model near reflection altitude showing: (a) broadened spectral line in HAARP experimental data, (b) PIC simulation broadened spectrum, and (c) associated plasma density cavity with elevated T_e (adapted from [13]).

and third electron gyro-harmonic frequencies ($2\Omega_{ce} \sim 2.8$ MHz, $3\Omega_{ce} \sim 4.2$ MHz). SIBS consists of spectral harmonics spaced by $\Omega_{cO} \sim 50$ Hz, typically below ω_0 . MSBS and SIBS appear to be related since as $\omega_0 \rightarrow n\Omega_{ce}$,

MSBS transitions to SIBS for ω_0 within about 10kHz of $n\Omega_{ce}$ [11] which provides a diagnostic of the proximity of ω_0 to $n\Omega_{ce}$. Recent SIBS modeling [15] has assumed that SIBS is produced at the UH layer from parametric decay of UH or electron Bernstein (EB) waves into downshifted frequency UH/EB waves and a low frequency neutralized ion Bernstein (IB) wave. The original UH/EB wave being produced from conversion of the transmit wave. The SIBS on the ground results from scatter of the downshifted UH/EB wave from ionospheric irregularities. A simplified theory is provided in [15] which, remarkably, describes many of the observed characteristics of SIBS.

The nonlinear evolution of SIBS has also been modeled with more sophisticated electrostatic Particle-in-Cell (PIC) plasma models [17]. The results agree with the experimental observations quite well and also indicate electron heating across B_{θ} as $\omega_0 \rightarrow n\Omega_{ce}$. As the pump power is increased, more harmonics in SIBS are generated and this is accompanied with more electron heating. Therefore, observation of SIBS may be associated with the degree of heating of the plasma electrons [16]. Since the spectral lines are space approximately by Ω_{cO} , SIBS may also be used to detect various ion species as well. For example, [18, 19] has observed SIBS harmonics at the proton gyro-frequency (Ω_{cH}) that were proposed to result from proton precipitation associated with geomagnetically disturbed conditions. Figure 2 shows an electrostatic PIC simulation of SIBS generation at the UH layer and the associated electron heating across B_{θ} .

4 Ion Acoustic Parametric Decay (IAPD)

The so-call IAPD instability produces a relatively broad emission line (100s of Hz) that occurs a few 100 Hz below ω_0 for pumping near $2\Omega_{ce}$ [15]. It has been shown that IAPD is related to SIBS (and thus proposed to be produced at the UH layer), and it is often observed with absorption lines spaced by Ω_{cO} [15]. [16] proposed that for pumping near $3\Omega_{ce}$, the same parametric process that produces the IAPD also produces the so-called Downshifted Peak (DP) in the classic wideband SEE spectrum. The IAPD is produced by decay of UH/EB waves into lower frequency UH/EB waves and oblique ion acoustic waves that propagate nearly perpendicular to B_{θ} . The simplified theory of [15] describes the behavior of the IAPD remarkably well. The shift of the IAPD line below ω_0 is therefore dependent on the ion acoustic frequency and it can also be used for a T_e diagnostic. The theory implies a distinction between SIBS and IAPD is the direction of the pump electric field E_{θ} relative to B_{θ} at the interaction altitude, with SIBS dominating when E_{θ} becomes very close to perpendicular to B_{θ} .

Nonlinear evolution of the IAPD has been investigated in [17]. Associated with the IAPD, is strong electron velocity distribution tail heating along B_{θ} . There is strong Langmuir-like turbulence in which cavities develop in the electron density and associated collapse of these cavities accelerate the electrons. Therefore, presence of this NSEE

spectral line provides information on the state of the plasma turbulence and nonlinear evolution. It is also interesting to note that the IAPD spectral line has been associated with the creation of artificial ionization layers and may provide insight into the initiation process [17]. Figure 3 shows results of an electrostatic PIC simulation showing the electron heating along B_{θ} .



Figure 2. SIBS model near the UH layer showing: (a) HAARP experimental data, (b) PIC simulation of associated perpendicular electron heating for $\omega_0 \rightarrow n\Omega_{ce}$, (c) associated simulation spectrum (adapted from [17]).

5 Conclusions and Future Directions

There has been substantive progress over the past decade in developing NSEE into a diagnostic of the modified ionosphere and modeling has been a critical component of this progress. The models have primarily been used to interpret the fundamental wave-wave interaction processes and their nonlinear evolution. However, there are still unresolved frontiers involving important further development and application of the models. Most experiments use pumping near $n\Omega_{ce}$ to investigate unique and important gyro-harmonic behavior. This requires much more complex EM magnetized kinetic plasma models to investigate these phenomena. Significant progress has been

made with SIBS and the IAPD using electrostatic magnetized kinetic plasma model approximations [17]. However, at this time, fully EM magnetized kinetic models (analytical or plasma simulations) necessary for MSBS have not been developed and applied to the observations. Utilization of such models would surely aid further development of diagnostic capability. The complex gyroharmonic impact on MSBS is still not well understood. This would appear to be important for diagnostic capabilities involving multi-ion component ionospheric plasmas since the strength of the MBS EIC lines appear to vary with the proximity of ω_0 to $n\Omega_{ce}$ [10]. Ongoing development of suitable magnetized PIC simulation models such as [13] will clearly be critical in making further progress. Finally, during recent experiments, there have been observations of NSEE spectral lines, described here, associated with Second Harmonic Generation (SHG) near $2\omega_0$ [20]. There are currently no quantitative models for this SHG NSEE. It is clear such models would greatly contribute to further developing SHG into an important diagnostic for the modified ionosphere.



Figure 3. IAPD model near the UH layer showing: (a) HAARP experimental data, (b) PIC simulation spectrum, and (c) associated parallel electron velocity distribution tail heating (adapted from [17]).

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