Interaction of Very Low Frequency (VLF) and Extremely Low Frequency (ELF) Waves in the Ionospheric Plasma and Parametric Antenna Concept

Tony C. Kim
Wright State University

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INTERACTION OF VERY LOW FREQUENCY (VLF) 
AND EXTREMELY LOW FREQUENCY (ELF) WAVES IN 
THE IONOSPHERIC PLASMA AND PARAMETERIC 
ANTENNA CONCEPT 

A Dissertation Submitted in Partial Fulfillment of 
the Doctor of Philosophy Degree 

by 

TONY C. KIM 
B.S., Ohio University 1983 
M.S., Wright State University, 1988 

2017 
Wright State University

Amit Sharma, PhD
Dissertation Co-Director

Doug Petkie, PhD
Dissertation Co-Director

Don Cipollini, PhD
Director, Environment Science PhD Program

Robert E.W. Fyffe, PhD
Vice President of Research and Dean of the Graduate School

Committee on Final Examination

Chris Barton, PhD

Ernie Hauser, PhD

Vladimir Sotnikov, PhD
Abstract

Kim, Tony C. Ph.D., Environmental Science Ph.D. Program, Department of Physics, Wright State University, 2017. Interaction of Very Low Frequency (VLF) and Extremely Low Frequency (ELF) Waves in the Ionospheric Plasma and Parametric Antenna Concept.

This research dramatically increase radiation efficiency of very low frequency (VLF) and extremely low frequency (ELF) antenna in the ionosphere by implementing a concept of a parametric antenna. The research addresses the interaction of the electromagnetic waves in the atmosphere; analyzes the radiation efficiency of different types of RF frequencies (ex: Very low Frequency (VLF) and Extremely Low Frequency (ELF)); and includes different types of antennas, such as dipole and loop antennas, in the ionosphere environment and simulating the differences to verify the parametric antenna concept. This VLF analysis can be performed many ways and this VLF frequency is widely used in space antennas by both military and civilian elements. The VLF waves in the ionosphere are used to create high levels of density irregularities in the radiation belt region and to deflect the energetic electrons and ions from the region to prevent their negative effects on satellite electronics (including the antenna). Therefore, this research addresses the problem of low radiation efficiency of satellite based antenna on conventional loop and dipole antennas used for excitation of electromagnetic VLF/ELF waves in the ionosphere. The research results will be used in the field of ionospheric plasma physics research with applications in satellite space experiments. In particular, the results will be influential in the area of active space experiments for the removal of highly energetic particles in the ionosphere which are harmful to satellite electronics, VLF/ELF communications, and for different commercial applications. This research first looks at a theoretical solution followed by modeling and simulation to prove the parametric antenna concept. Finally, experimentation was performed in the laboratory to validate and verify a theoretical solution and modeling and simulation of parametric antenna.
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<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>$\Omega_i$</td>
<td>Ion-cyclotron frequency</td>
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<tr>
<td>$T_i(e)$</td>
<td>Ion, Electron temperature</td>
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<td>$V(T_i, T_e)$</td>
<td>Thermal ion, electron velocities</td>
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<td>Background density</td>
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<td>$\kappa_N$</td>
<td>Density scale length</td>
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<td>Electron, ion gyroradius</td>
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<tr>
<td>$\nu_{e,n}$</td>
<td>Electron-neutral collision coefficient</td>
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<td>$\omega_{p,i}$</td>
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<td>$B$</td>
<td>Magnetic field</td>
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<tr>
<td>$p_b$</td>
<td>Flute mode</td>
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<tr>
<td>$c$</td>
<td>Speed of light</td>
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<tr>
<td>$CSWAP$</td>
<td>Cost, size, weight, and power</td>
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<td>$E$</td>
<td>Electric field</td>
</tr>
<tr>
<td>$e$</td>
<td>Charge of electron</td>
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<tr>
<td>$s_i$</td>
<td>$i^{th}$ element of signature vector</td>
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<td>$ELF$</td>
<td>Extreme low frequency</td>
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<tr>
<td>$EM$</td>
<td>Electro-magnetic</td>
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<td>$ESF$</td>
<td>Equatorial spread F</td>
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<td>Frequency</td>
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<tr>
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<tr>
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<td>Very low frequency</td>
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<tr>
<td>$Z$</td>
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<td>$\alpha$</td>
<td>Scattered angle</td>
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<tr>
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<td>Plasma beta</td>
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<tr>
<td>$\tau$</td>
<td>Scale time</td>
</tr>
<tr>
<td>$\Theta$</td>
<td>Electric potential</td>
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<tr>
<td>$\delta_n$</td>
<td>Density perturbation</td>
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Chapter 1

Introduction

1.1 Purpose

The purpose of this research is to analyze the radiation efficiency of very low frequency (VLF, 30Hz to 300KHz) and extremely low frequency (ELF, 3Hz to 30Hz) a parametric antenna under ionosphere condition. The research measures the low radiation efficiency of satellite based conventional loop and dipole antennas used for excitation of electromagnetic VLF/ELF waves in the ionosphere. These research results may be used in the field of ionospheric plasma physics research with application to satellite space experiments. In particular, these results may be used in active space experiments for the removal of highly energetic particles in the ionosphere which are harmful to satellite electronics, VLF/ELF communications, and for different commercial applications. Modeling and simulation of existing designs (conventional loop and dipole antennas placed on LEO satellites) revealed radiation efficiencies no greater than 3 percent [4]. This research proposes a new concept, parametric VLF/ULF antenna, for excitation of electromagnetic waves in the ionosphere with radiation efficiency far exceeds existing conventional antenna systems. The proposed approach utilizes two loop antennas transmitting at slightly different frequencies. Each loop antenna excites the predominantly electrostatic part of the VLF wave spectrum in the form of Lower Oblique Resonance (LOR) oscillations. Nonlinear interaction of LOR waves creates a region in the vicinity of loop antennas that acts like a large antenna,
simultaneously re-radiating the VLF and ELF wave energy with order of magnitude greater radiation efficiency [23]. The radiation efficiency (or antenna efficiency) is the ratio of the radiated power to the input power of the antenna: antenna efficiency is a number between 0 and 1. The excitation of electromagnetic waves in magnetized plasma by means of an antenna has potential applications in space experiments.

1.2 Background

The techniques to dramatically increase the antenna radiation efficiency in the fields of military and commercial applications by conducting research is of interest to the communication communities, especially in the Very Low Frequency (VLF) and Extremely Low Frequency (ELF) antennas in the ionosphere environment. Much research has been performed to implement a dipole antenna and loop antenna but lesser research has been on the parametric antenna research [27]. The parametric antenna is two loop antenna in same plane. Using this parametric antenna method solves the problem of low radiation efficiency of satellite based conventional loop and dipole antennas used for excitation of electromagnetic VLF/ELF waves in the ionosphere. This research introduces a new concept; the parametric VLF/ELF antenna for excitation of electromagnetic waves in the ionosphere with radiation efficiency far potentially exceeding the 3% efficiency of existing conventional antenna systems. Currently, only a single loop antenna was used for transmission at one frequency at a time. The proposed approach utilizes two loop antennas transmitting at slightly different frequencies. Furthermore, Modeling and Simulation of existing designs (conventional loop and dipole antennas placed on Low Earth Orbit (LEO) satellites) revealed radiation efficiencies no greater than 3% also [4]. This technique provides VLF and ELF wave energy with order of magnitude greater radiation efficiency to increase the performance of the communication and navigation systems[16] [30]. The radiation of sources immersed in cold magnetized plasma was investigated in the linear case by many authors. With a view of applications for space experiments, a thorough study was conducted by [1]
where the reference to the earlier work can also be found. These authors investigated both the radiation of a current loop and of an electric dipole and computed radiation diagrams for various excitation frequencies involving also the range $\omega_{LH} < \omega < \omega_{ce}$.

1.2.1 Interaction of the EM and Ionosphere/Atmosphere

In order to understand the interaction of the electromagnetic waves in the ionosphere and the atmosphere, one needs to understand the layers of the Earth’s atmosphere that are weakly ionized, and conduct electricity by solar radiation causing a different reaction to the Electromagnetic (EM) shown below in figure 1.1, [17].

![The Layers of the Atmosphere](image)

**Figure 1.1: The layer of the atmosphere [17]**

An important part in an atmospheric environment is formation of electricity in the inner edge of the magnetosphere where the magnetosphere is the region (A magnetosphere is the region of space surrounding an astronomical object in which charged particles are controlled by that object’s magnetic field.) of space surrounding an astronomical object in which charged particles are controlled by that object’s magnetic field, which influences radio
propagation to distant places on the Earth. The free electrons in the magnetosphere allows good propagation of electromagnetic waves in radio communication can be improved by using excitation of the electric currents which provide plenty electricity in the inner edge of magnetosphere, home for aurora, a light display mostly in the night sky of the polar areas, which is caused by excited and light-emitting particles entering the upper atmosphere. It is located approximately in the same region as the top half of the mesosphere and the entire thermosphere in the upper atmosphere from about 40 mi (60 km), continuing upward to the magnetosphere, see figure 1.1. The ionosphere can be further divided into sub-regions according to their free electron density profile that indicates the degree of ionization, and these sub regions are called the D, E, and F Layers and they are shown in Figure 1.2.

Figure 1.2: Ionosphere sub-regions (type of layers)

The D layer is lowest among them.

It absorbs high-frequency radio waves and exists mainly during the day. It weakens gradually then disappears at night, allowing radio waves to reach the
E-layer of the ionosphere, where these waves are reflected back to Earth, then bounce again back into the ionosphere [12].

The E layer (or Kennelly-Heaviside layer) can be found after sunset.

It usually starts to weaken and by night, it also disappears. The E layer absorbs x rays, and it has its peak at about 65 mi (105 km).

The F layer is found above the E layer, above 93 mi (150 km).

It has the highest concentration of charged particles. It has a constant layer where extreme ultra-violet radiation is absorbed. It has two parts: the lower F1 layer and the higher and more electron-dense F2 layer (see figure 1.2).

Below, Figure 1.3, shows the free electron density profile. The F region is at the highest

![Figure 1.3: Free electron density profile](image)

region in the ionosphere and as such, it experiences the most solar radiation. Typically, the radiation that causes the ionization is between the wavelengths of 100 and 1000 Angstroms. The F layer acts as a "reflector" of signals in the HF portion of the radio spectrum and the density number is the perturbation of density divided by main base density around 20%,
enabling worldwide radio communications. The level of ionization remains much higher. The density of the gases is much lower than other layers, as is much of the ionization that results from ultra-violet light in the middle of the spectrum as well as those portions of the spectrum with very short wavelengths. This is the most important region in the ionosphere for long distance HF radio communications. High Frequency (HF) is used for long distance communication by means of propagation, in which the radio waves are reflected or refracted back to Earth from the ionosphere, allowing communication around the curve of the Earth [26]. The relationship of free electron density and plasma frequency can be represented in (from Wikipedia):

$$\omega_p = \sqrt{\frac{N Z_e^2}{\varepsilon_0 m}}$$

where $N$ = number density of electron, $Z_e^2$ = electric charge, $m$ = effective mass, and $\varepsilon_0$ = permittivity of free space. The above formula is derived under the approximation that the ion mass is infinite due to electrons being so much lighter than ions.

HF (3-30MHz), $w = 10$-100m, shortwave radio.

VLF (3-30 kHz), $w = 10$km-100km, navigation beacons.

ELF (30- 3Hz), $w = 10,000$km-100,000km, underwater communication.

Figure 1.4 shows the wave reflection in different layers as example on F-layer for HF.

1.2.2 Excitation of the wave with different types of antennas

Antennas function by transmitting or receiving electromagnetic (EM) waves. All electromagnetic waves propagate at the same speed in air or in space. This speed is roughly 671 million miles per hour or 1 billion kilometers per hour. This is roughly a million times faster than the speed of sound (which is about 761 miles per hour or 1225 kms per hour at sea level). A radiation pattern defines the variation of the power radiated by an antenna as a
function of the direction away from the antenna. This power variation or efficiency, as a function of the arrival angle, is observed in the antenna's far field.

**Excitation of Dipole Antenna**

In this section, the dipole antenna, with a very thin radius, is considered. In radio and telecommunications, a dipole antenna or doublet is the simplest and most widely used class of antenna. It consists of two identical conductive elements such as metal wires or rods, which are usually bilaterally symmetrical. The dipole antenna is similar to the short dipole except it is not required to be small compared to the wavelength (at which frequency the antenna is operating). For a dipole antenna of length L oriented along the z-axis and centered at z=0, the current flows in the z-direction with amplitude which closely follows the following function [2].

\[
I_z = \left( I_o sin \left( k \left[ \frac{L}{2} - z \right] \right) \right), \quad 0 \leq z \leq \frac{L}{2} \quad (1.2)
\]
\[ I_z = \left( I_0 \sin \left( k \left[ \frac{L}{2} + z \right] \right) \right), \quad \frac{L}{2} \leq z \leq 0 \tag{1.3} \]

Note that this current is also oscillating in time sinusoidally at frequency "f". The current distributions for the quarter-wavelength (left) and full-wavelength (right) dipole antennas are given in figure 1.5. Note that the peak value of the current is not reached along the dipole unless the length (lambda) is greater than half a wavelength. Dipoles are resonant antennas, meaning that the elements serve as resonators, with standing waves of radio current flowing back and forth between their ends. So the length of the dipole elements is determined by the wavelength of the radio waves used. The excitation of this dipole antenna with given current, gives electric type antenna, where electric fields distributed on the surface give resonance cones.

![Dipole antennas](www.antenna-theory.com)

Figure 1.5: Dipole antennas

**Excitation of Loop Antenna**

The small loop antenna is a type of closed loop as shown in figure 1.6. These antennas have low radiation resistance and high reactance, so that their impedance is difficult to match to a transmitter. As a result, these antennas are most often used as receive antennas, where impedance mismatch loss can be tolerated. The radius is "a", and is assumed to be much
smaller than a wavelength, which the loop lies in the X-Y plane ("a" \(<<\) \(\lambda\)).

\[ a \ll \lambda \]

Figure 1.6: Loop antennas

Most of the time, the small loop antenna is also known as a magnetic loop since it behaves electrically as a coil (inductor) with a limited but non-negligible radiation resistance due to its small size compared to one wavelength. It can be analyzed as coupling directly to the magnetic field in the region near the antenna. Since the loop is much smaller than a wavelength, the current at any one moment is nearly constant round the circumference. By symmetry, it can be seen that the voltages induced along the sides of the loop will cancel each other when a signal arrives along the loop axis. The radiation pattern peaks in directions lying in the plane of the loop, because signals received from sources in that plane do not quite cancel due to the phase difference between the arrival of the wave at the near side and far side of the loop. The excitation of this loop antenna with given current gives magnetic type antenna where the magnetic field gives rise to an electric field through Faraday’s law of induction and a electromagnetic wave in the region far from the antenna creates only very low frequency and do not have the resonance cones due to the magnetic field.
Chapter 2

METHODS

The main goal of this research is to carry out particle-in-cell (PIC) simulations using Large Scale Plasma (LSP) code to analyze the concept of two-loop VLF antennas acting as parametric antenna that efficiently radiates in the VLF as well as the ELF portion of the electromagnetic (EM) wave spectrum. This new antenna design can significantly improve radiation efficiencies for antenna embedded in a plasma. The proposed approach utilizes two loop antennas transmitting at slightly different frequencies from the VLF range [9]. The majority (97% percent) of radiated power is antennas power generated by the loop antenna which is going directly into the quasi-electrostatic part of the VLF wave spectrum namely to excite Lower Oblique Resonance (LOR) oscillations. Next, in the vicinity of the antenna system, due to parametric interaction of LOR waves excited, quasi-electrostatic wave energy will be reradiated as the electromagnetic VLF wave energy with order of magnitude greater radiation efficiency in comparison with currently existing conventional antenna systems[14]. It is well known that high energy particles in the radiation belts can damage electronics of commercial satellites. Even with hardening measures, the lifetime and reliability of space systems are often limited by the steady degradation caused by these particles. This can be mitigated by the implementation of technology which reduces the life time of the energetic particles with high power electromagnetic VLF/ELF waves injected into the magnetosphere from LEO/GEO satellites. The main challenge in this approach is, however, to design a viable antenna that efficiently radiates in the electromagnetic (EM) portion of the VLF/ELF
wave spectrum. The analysis of the proposed approach can improve radiation efficiencies and make space based VLF/ELF antennas in the ionosphere/magnetosphere a reality. The proposed approach utilizes two loop antennas transmitting at slightly different frequencies from the VLF range. Parametric interaction of LOR oscillations in the vicinity of the antenna system re-radiates the electromagnetic VLF energy. The goal of the proposed research is to estimate the radiation efficiency of such systems. [10] Parametrically excited electromagnetic VLF/ELF waves are capable of propagating on large distances away from an antenna system. The potential benefits of the proposed antenna system are as follows:

1. Efficient removal of energetic particles from radiation belts and increased lifespans of electronics on commercial and DoD satellites

2. Supports applications of GPS systems

The first antenna generates short scale quasi-electrostatic LOR oscillations in the volume around an antenna with frequency $\omega_1 = (s + \epsilon)\omega_{LH}$ where parameter $s + \epsilon, (\epsilon) << 1$ and $\omega_{LH}$ is the lower hybrid resonance frequency. The second antenna generates short scale quasi-electrostatic LOR oscillations in the volume around an antenna with frequency $\omega_2 = s\omega_{LH}$. Parametric interaction of LOR waves with frequencies $\omega_1$ and $\omega_2$ leads to the generation of electromagnetic VLF whistler waves on combination frequency and ELF waves with the frequency $\Omega_+ = \omega_1 + \omega_2$ and ELF waves with the frequency $\Omega_+ = \omega_1 - \omega_2$.[5]

The preferred configuration of the proposed parametric loop antenna geometry/setup system is presented in figure 2.1.
Figure 2.1: The single loop antenna lies in X-Y plane and the magnetic field B is along Z.

Figure 2.2. shows two concentric loop antennas with radii \( R_1 \) and \( R_2 \) placed on the orbit in the plane perpendicular to the magnetic field of the Earth. Antenna radius of the first loop antenna \( R_1 \) is smaller than the antenna radius of a second loop antenna \( R_2 \) \( (R_1 < R_2) \). Antenna radii are chosen to satisfy the condition \( (R_1)\omega_2 = (R_2)\omega_1 \) where the frequency in the first loop antenna \( \omega_1 \) is slightly larger than the frequency in the second loop antenna \( \omega_2 \) \( (\omega_2 < \omega_1) \). The radii of the first and the second loop antennas should satisfy the relation:

\[
\frac{R_1}{R_2} = \frac{\omega_1}{\omega_2}
\] (2.1)
Figure 2.2: The two loop antenna planes perpendicular to the magnetic field \( B \) of the earth.

In this case, the focal points of both antennas will coincide and will be located at a distance 
\[ H = \left\{ \frac{\omega_0}{\omega_1} R_1 \right\} \] above the common center of an antennas loop planes. This antenna setup allows effective parametric interaction of quasi-electrostatic VLF waves in the near zone of loop antennas.

2.1 Investigation of a parametric antenna radiation pattern

A parametric antenna system consists of two loop antennas. In this section, the focus will be on the numerical simulation effort to be undertaken to understand the linear and non-linear generation of VLF waves in cold, magnetized plasma. Dispersion of VLF waves is given by [11].

\[
\omega^2 = \frac{\omega_{LH}^2}{1 + \frac{\omega_{pe}^2}{k_z c^2}} \left[ 1 + \frac{M k_z^2}{m k^2} \frac{1}{1 + \frac{\omega_{pe}^2}{k_z c^2}} \right]
\]  

(2.2)

where \( \omega_{LH} \) is the lower hybrid frequency, \( \omega_{pe} \) is the electron plasma frequency, \( M \) is the ion mass, \( m \) is the electron mass, and \( c \) is the speed of light. The initial focus will be on the two-dimensional simulation results and this will show the recovery of the theoretical calcu-
lations based on previous research [1] [7] [25]. It can be used for simultaneous parametric excitation of electromagnetic VLF whistler waves and electromagnetic ELF waves. This antenna system should be placed on a satellite and contain an automotive control system which will keep the orientation of two loop antennas planes perpendicular to the magnetic field of the Earth as shown figure 2.3. Potential commercial and DoD applications of this novel antenna design are connected with active VLF/ELF wave-injection in the ionosphere from low Earth orbit satellite systems to provide enhanced precipitation of energetic electrons from the radiation belts [29]. The proposed antenna design allows the creation of controlled injection of VLF/ELF waves with sufficiently large amplitudes to mitigate natural and artificial enhancements of radiation belt fluxes.

Figure 2.3: Loop plane is oriented perpendicular to the Earth’s magnetic field

The orientation of the antenna loop plane, with respect to the Earth’s magnetic field, can
be different, not necessarily perpendicular to the magnetic field of the Earth as shown in figure 2.4 [8].

The proposed parametric antenna system also allows for establishing VLF/ELF communication channels with space based and ground based systems.

It is well known that the high energy particles in the radiation belts can damage the AF space assets. Even with hardening measures, the life span and reliability of space systems are often limited by the steady degradation caused by these particles. This can be mitigated by the implementation of technology which reduces the life span of the energetic
particles with high power electromagnetic VLF/ELF waves injected into the magnetosphere from LEO satellites. The main challenge in this approach is, however, to design viable antenna that efficiently radiates in the electromagnetic (EM) portion of the VLF/ELF wave spectrum [13]. Modeling and simulation of existing designs (conventional loop and dipole antennas) reveal radiation efficiencies no greater than 3 percent [4]. The proposed approach utilizes two loop antennas transmitting at slightly different frequencies from the VLF range. Parametric interaction of LOR oscillations in the vicinity of the antenna system re-radiates the electromagnetic VLF energy with an order of magnitude greater radiation efficiency. Potential commercial and DoD applications of this novel antenna design are connected with active VLF and ELF wave-injection in the ionosphere from low Earth orbit satellite systems to provide enhanced precipitation of energetic electrons from the radiation belts. The proposed antenna design allows creating controlled injection of VLF/ELF waves with sufficiently large amplitudes to mitigate natural and artificial enhancements of radiation belt fluxes.

2.2 Characterization of VLF waves generated by a loop antenna

The excitation of electromagnetic waves in magnetized plasma by means of an antenna is of interest for applications in space experiments. In the present work, first the waves in the whistler frequency range will be investigated, and secondly the particular case of frequencies $\omega$ greater than the lower hybrid resonance $\omega \sim (2/3)\omega_{LH}$, i.e. a geometric mean value of the electron and ion gyrofrequencies in a sufficiently dense plasma with the plasma frequency $\omega_{pe} > \omega_{ce}$ which is the case of the Earth’s ionosphere. The radiation of sources immersed in cold magnetized plasma was investigated in the linear case by many authors. In view of applications for space experiments, a thorough study was conducted by where the reference to the earlier work can also be found [1]. These authors investigated both
the radiation of a current loop and of an electric dipole and computed radiation diagrams for various excitation frequencies, involving also the range $\omega_{LH} < \omega < \omega_{ce}$. Under these conditions, only one mode is excited in a cold plasma and the essential features of the radiation at great distances from the source can be understood from Fig 2.5, where $\kappa_z$, the wave vector component along the magnetic field is plotted schematically against $k_\perp$ the perpendicular component. This is analogous to the wave refractive index surface. In the course of an asymptotic evaluation of the radiation, it can be shown that it goes out in the direction of the normal to the $k_Z(k_\perp)$ curve and decreases with the distance $R$ as $R^{-1}$ everywhere with the exception of the three critical points determining three critical directions: the two inflexion points $d^2k_z/dk_\perp^2$ the field decreases as $R^{-5/6}$ and the point of minimum $dk_z/dk_\perp = 0$ the field decreases as $R^{-1/2}$, which gives the radiation along the external magnetic field. Lower oblique resonance (LOR) waves correspond to the short wavelength inflexion point [4]. It must be said that the inflexion is only obtained with the account of thermal effects and the respective curve is dashed. There is no inflexion in the cold plasma, where the curve approaches an asymptote and the normal to that direction determines the resonance cone. The amplitude here is limited by thermal effects and by the finite loop width. A great deal of the source power is radiated as a quasielectrostatic LOR mode in this direction with $k^2C^2/\omega_{pe}^2 \gg 1$ [6]. A mode with $k^2C^2/\omega_{pe}^2 \sim 1$ propagates along the magnetic field and the real electromagnetic wave, the whistler, with $k^2C^2/\omega_{pe}^2 \ll 1$ is radiated in oblique directions up to an angle - 19.5 degree which is a shadow boundary determined by the long wavelength inflexion point. From this fact it can be concluded that whistlers are radiated comparatively weakly and for their more effective excitation special measures must be taken. For active experiments in the ionosphere, it is important to excite just the non-potential waves which may propagate to large distances from the source. From this point of view, we are interested in the study of the transformation of potential oscillations becomes important, LOR waves with the frequency $\omega_1$ excited by a source, into whistlers and ELF oscillations excited by another high frequency source with the frequency $\omega_2$. 17
Whistlers are excited on combination frequency $\omega_1 + \omega_2$ and ELF waves on combination frequency $\omega_1 - \omega_2$. In this paper, such a mechanism is investigated for an antenna system consisting of a loop antenna exciting high frequency oscillations $\omega_1 \sim (2/3)\omega_{LH}$, and of another loop antenna excited slightly shifted VLF oscillations from the same frequency range. The dipole is placed in the center of the loop and lies in its plane. Such an arrangement may be regarded as a parametric antenna.

2.2.1 VLF wave excitation by a loop antenna

The generation of VLF waves by antennas in plasma is an important topic because of the wide use of antennas in space and laboratory applications, both military and civilian. However, it is well known that the portion of the radiation field that goes directly into the excited electromagnetic spectrum of VLF waves the whistler mode, is small (less than 3 percent) in comparison with the wave energy going into the quasielectrostatic component low oblique resonance (LOR) mode. For this reason, the efficiency of VLF antennas for generation of electromagnetic waves, which can propagate large distance from the source region, is very limited. This work, analyze excitation of waves with frequencies several times above the lower hybrid resonance frequency, but below the electron cyclotron frequency:

$$\omega_{LH} < \omega < \omega_{ce}$$  \hspace{1cm} (2.3)

where $\omega_{LH}$ is given by:

$$\omega^2_{LH} = \frac{\omega_{pe}^2}{1 + \frac{\omega_{pi}^2}{\omega_{ce}^2}}$$  \hspace{1cm} (2.4)

$\omega_{ce}$ is an electron cyclotron frequency, $\omega_{pe}$ and $\omega_{pi}$ are electron and ion plasma frequencies correspondently. Linear excitation of VLF waves by a loop antenna was investigated by many authors [1-3]. Under cold conditions, only one mode is excited in cold plasma and
main features of the radiation far away from the source can be understood from the plot analogous of wave refractive index surface. This plot can be obtained using the expression for the dispersion of VLF waves:

$$\omega^2 = \frac{\omega_{LH}^2}{1 + \frac{\omega_{pe}^2}{k^2 c^2 m_e k^2}}$$  \hspace{1cm} (2.5)

In equation 2.5, $k_z$ is the wave vector component along the magnetic field and $k_\perp$ is perpendicular component. By schematically plotting the wave vector component $k_z$ against $k_\perp$ for a given $\omega$ one can obtain: figure 2.5 [21].

![Wave number surface for a constant $\omega_{LH} < \omega < \omega_{ce}$](image)

Figure 2.5: Wave number surface for a constant $\omega_{LH} < \omega < \omega_{ce}$

A great deal of the source power is radiated as a quasielectrostatic Lower Oblique Resonance (LOR) wave [3] with

$$\frac{\omega_{pe}^2}{k^2 c^2} \gg 1$$  \hspace{1cm} (2.6)

The real electromagnetic mode, the whistler wave, with

$$\frac{\omega_{pe}^2}{k^2 c^2} \ll 1$$  \hspace{1cm} (2.7)

is radiated in oblique directions up to an angle $\sim 19.5^0$, which is the shadow boundary determined by the long wavelength inflexion point and these waves are radiated compara-
tively weakly. For many ionospheres applications, it is important to increase the level of the radiated power which is going into the electromagnetic part of the excited wave spectrum whistler waves.

Below is analysis in 2D showing the efficiency of excitation of VLF waves by a single loop antenna operating at a frequency which excites waves with frequencies above the Lower Hybrid frequency. Also will carry out 2D PIC simulation of VLF wave excitation using the implicit code LSP.

2.2.2 Description of numerical methods

A well-developed particle-in-cell plasma simulation tool was used to study the generation of electromagnetic and quasi-electrostatic electric and magnetic fields due to a loop and dipole antenna. The computer code called Large Scale Plasma [LSP] provides a variety of boundary conditions (periodic, outlet, PML, conducting and others) and also utilizes both explicit and implicit algorithms for evolving the particles in time and solving for the self-consistent fields [3]. Since the evolution of the plasma and fields occurs on time scales much greater than the so-called CFL condition and also on spatial scales much larger than the electron Deybe length, Advantage has been taken of the implicit algorithms by using spatial scales much larger than the Debye length and time steps several times that of the CFL-constrained time step. In two dimensions (2D) and three dimensions (3D), the evolution of the quasi-electrostatic Whistler wave (also called the Lower Oblique Resonance mode) will be studied through the use of a ring antenna placed in the center of the simulation domain. In 2D, the simulation domain is established in the x-z plane. To ensure that correct resolving of the physics and to also prepare for the 3D simulations which are computationally expensive, simulations were performed with the following cell sizes: \( \Delta x = \Delta z = 50 \text{ cm}, 100 \text{ cm}, 200 \text{ cm} \) and \( 400 \text{ cm} \). Also utilized was an explicit field solver with \( dt = 0.9 \times dt_c \), and implicit field solver with \( dt = 2 \times dt_c, 3 \times dt_c \) and \( 5 \times dt_c \), where \( dt_c \) is the
CFL = (dt_c) constrained time step. Excellent agreement exists between dx = dz = 50 cm, 100 cm, and 200 cm. Noticeable differences are seen with dx = dz = 400 cm. Furthermore, good agreement exists between \( dt = 0.9 \times dt_c \), \( 2 \times dt_c \), and \( 3 \times dt_c \). For all results presented in this report, outlet and conducting boundary conditions were utilized. Both particles are free to level the simulation domain. However, because plasma is cold and there is little numerical heating, no plasma leaves the simulation domain. Therefore, no plasma particles need to be re-introduced at the boundary.

### 2.3 VLF antenna immersed in a cold-magnetized plasma

A snapshot of \( |E| \) at \( t = 5661 \text{ ns} \) of a loop antenna immersed in a cold, magnetized plasma in the X-Z plane is shown in Figure 2.6. The antenna is driven at frequency \( \omega_A = 1.31X \times 10^6 \text{ rad/s} \) which has a period of 4796 ns. Therefore, the time shown in Figure 2.7 occurs just after one antenna period. The temperature of the plasma is 0 eV, which allows for comparison with theory [24] [15]. Finite temperature (a few eV) simulations will be presented below. The plasma conditions are initialized to represent ionospheric conditions. Therefore, density is initialized to \( 10^5 \text{ cm}^{-3} \) and the background magnetic field is 0.3 Gauss, which lies in the Z-direction. The antenna is orientated in such a way that the normal to the plane of the antenna is in the Z-direction. The antenna is simulated by driving a sinusoidally varying current into the X-Z plane in the region \( 5 \text{ m} < x < 5.5 \text{ m} \) and out of the plane in the region \(-5.5 \text{ m} < x < -5 \text{ m} \). Therefore, the antenna radius is 5 m, with a thickness of 0.5 m. The spatial grid is discretized on a grid that sets \( \Delta x = \Delta z = 2m \), and the simulation is established in the X-Z plane that extends from \(-Lx < x < Lx \), \(-Lz < z < Lz \), where \( Lx = 840 \text{ m} \) and \( Lz = 750 \text{ m} \). Therefore, the number of cells in the x- and z-direction is \( nx = 840 \) and \( nz = 750 \). Twenty macro-particles per cell were used. The ion species is \( H^+ \), with realistic \( H^+ \) to electron mass ratio. Only a subset of the simulation
domain is shown in Figure 2.6 in order to highlight the essential physics. Figure 2.6 shows
the same data as Figure 2.7, but magnified to compare with theoretical results [15]. The
resonance cone angle, $\Theta_c$, is calculated from Fisher and Gould 1971.

\[ \sin^2(\varTheta_c) = \frac{\omega_A^2(\omega_{pe}^2 + \omega_A^2 + \omega_{ce}^2)}{2 \omega_{pe} \omega_{ce}} \]  \hspace{1cm} (2.8)

Above is equation 2.8 where $\omega_A$ is the antenna frequency, $\omega_{pe}$ is the electron plasma
frequency, and $\omega_{ce}$ is the electron cyclotron frequency. According to this equation (2.8), $\Theta_c$
is 0.2615 radians. Calculating $\Theta_c$ from Figure 2.7, $\Theta_c$ is found to be 0.2768 radians, which
shows reasonable agreement between theory and simulation (less than 10 percent different).
Also shown in Figure 2.7 are the cones D1 and D2, which correspond to the same curves
in Figure 2.8 [6]. For a easy comparison Figure 2.9 shows theoretically that two different resonance cones appear, D1 and D2. On the X-axis, the two cones converge at the antenna radius (5m) [denoted a in (Karpman, 1986)]. On the Z-axis, the two different D1 curves cross at $\frac{\Upsilon}{\Omega}$, where $\Upsilon$ is defined (Karpman, 1986). For the simulation parameters relevant to Figure 2.8, $\frac{\Upsilon}{\Omega}$ to be $\sim$ 18 m. The two curves cross at Z-axis $\sim$ 25 m, which is close to the theoretical value.

In order to further compare linear theory from Fiala, Kruchina and Sotnikov, 1987 and Sotnikov, et al. (1993) with the simulation, the Fourier transform of $|E_x|$ from the simulation is overlaid with the theoretical dispersion curves Figure 2.9. Good agreement is found between the full dispersion curve and the simulation result.

The black curve is the full dispersion given by:
\[ \omega^2 = \frac{\omega_{LH}^2}{1 + \frac{\omega_{pe}^2}{k^2 c^2}} 1 + \frac{m_i}{m_e} \frac{k_i^2}{k^2} \frac{1}{1 + \frac{\omega_{pe}^2}{k^2 c^2}} \]  \hspace{1cm} (2.9) \\

Equation 2.9 where \( \omega_{LH} \) is the lower hybrid frequency, \( \omega_{pe} \) is the electron plasma frequency, \( M \) is the ion mass, \( m \) is the electron mass, and \( c \) is the speed of light. The red curve in Figure 2.9 is the electrostatic approximation to the dispersion curve given by:

\[ \omega = \Omega_{pe} \left| \frac{k^2}{c^2} \right| \]  \hspace{1cm} (2.10) \\

and the blue curve is the EM approximation to the dispersion curve given by:

\[ \omega = \Omega_{pe} \left| \frac{k^2}{c^2} \frac{k^2 c^2}{\omega_{pe}^2} \right| \]  \hspace{1cm} (2.11) \\

and the black curve is the full theoretical dispersion curve. All colors indicate amplitude. Where \( \Omega_{ce} \) is the electron cyclotron frequency. The shadow boundary is the point of inflection of the Electromagnetic (EM) dispersion curve, which occurs at \( \kappa_\perp \approx 0.5 \omega_{pe}/c \), and indicates the transition from the EM dominated portion of the dispersion curve to the
Figure 2.9: The color plot shows the log of $-\text{ExKparp-kpert}$.
Electrostatic (ES) dominated portion of the dispersion curve. The highest amplitude fields (and therefore the most power) occur in the ES portion of the wave electric field.

Electrostatic (ES) is defined as properties of stationary or slow moving electric chargers and Electromagnetic (EM) is defined as a radiation energy that is propagated through free space or through a material medium in the form of electromagnetic waves, such as radio waves, visible light, and gamma rays. The term also refers to the emission and transmission of such radiant energy. The amount of power in the EM and ES portions of the electric field can be quantified by performing a k-space filter on the fields. First Fourier transform the electric field and perform a k-space filter such that the field corresponding to wave numbers above some threshold (which is determined by the Shadow boundary) belong to the ES portion of the field. The field corresponding to wave numbers below this same threshold belongs to the EM portion of the field.

Once the filter is applied, the inverse Fourier transform is performed, which yields the Electrostatic (ES) and Electromagnetic (EM) contributions to the total field. The result of
this calculation is shown in Figure 2.10 and Figure 2.11. Clearly, the amplitudes are larger in the ES portion of the E-field than the EM portion, as expected.
Chapter 3

LARGE SCALE PLASMA (LSP)

3.1 What is Large Scale Plasma (LSP)?

LSP is a 3-D electromagnetic particle-in-cell (PIC) code designed for large scale plasma simulations in either cartesian, cylindrical, or spherical coordinate systems. LSP can also be used in 1-D and 2-D geometries. The code is designed to perform on parallel as well as serial platforms. LSP is written in C using an object-oriented style. Thus, there are classes for Grid, Cell, Field, and Particle objects, consisting of data structures and member functions which operate on the data. There are two electromagnetic field algorithms available in the LSP code: a standard explicit and an implicit algorithm \cite{3}. An iterative electrostatic algorithm is also available for situations in which fields are slowly varying. Algorithms are implemented for field emission, transmission line modes, external circuits, dielectrics, dispersive magnetic materials, secondary electron generation in materials, multiple scattering and energy loss, surface heating and energy deposition, desorption of neutrals from surfaces, ionization of neutrals, and interparticle collisions. The design allows new physics models to be added in a systematic manner. Some of the example plots are in figure 3.1 \cite{3}.
LSP algorithm includes:

1. Two electromagnetic field algorithms available: a standard (explicit) Yee leapfrog algorithm, and an implicit algorithm. The implicit algorithm is particularly useful in relaxing the courant limit on the time step.

2. An iterative electrostatic algorithm is also available for situations in which fields are slowly varying.

3. A first-order wave-absorbing boundary condition.


5. A cloud-in-cell (CIC) particle description which significantly reduces the noise level of the simulation.
6. A direct implicit particle/field push used in either the PIC or CIC models.

7. Algorithms are implemented for field emission, auxiliary circuit models, dielectrics, dispersive magnetic materials (RF absorption), secondary electron generation in materials, multiple scattering and energy loss, surface heating and energy deposition, desorption of neutrals from surfaces, ionization of neutrals, and interparticle collisions. A hybrid fluid model has been implemented to work in concert with the collision algorithms.

8. The plasma environment and the antenna components of the single loop 2D and 3D antenna.

9. A parametric antenna, composed of a single loop antenna and a dipole antenna, is believed to be capable of overcoming the limitations imposed by plasma on more conventional RF sources regarding output power of EM waves.

10. The radiated power of both parametric antenna components separately, and then combined, to gain an understanding of the rate of power conversion to whistler waves.

11. EM wave using a loop antenna without plasma.

12. External magnetic field.

13. Perfectly matched layer boundary condition.

### 3.2 Input variables

The input file is divided up into a number of sections dealing with various aspects of simulation design. Each section consists of a section header, contained in square brackets,
followed by the input parameters belonging to that section. Table 3.1 shows the input parameters and description of the each parameters [3].
<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Title</td>
<td>Simulation title which, when specified, overrides the default code-generated title.</td>
</tr>
<tr>
<td>Control</td>
<td>Time step, time limit, algorithmic and diagnostic parameters.</td>
</tr>
<tr>
<td>Grid</td>
<td>Defines overall simulation grid coordinates and spacing.</td>
</tr>
<tr>
<td>Regions</td>
<td>Specifies zones into which the simulation space is broken up.</td>
</tr>
<tr>
<td>Objects</td>
<td>Geometrically shaped objects which describe the simulation structure.</td>
</tr>
<tr>
<td>Boundaries</td>
<td>Boundary conditions on the simulation other than conducting boundaries, which are specified in the [Objects] section.</td>
</tr>
<tr>
<td>Potentials</td>
<td>Iteration parameters and boundary values for the electrostatic field solver.</td>
</tr>
<tr>
<td>Materials</td>
<td>Allows for user-specified materials beyond those which are available internally.</td>
</tr>
<tr>
<td>Circuit Models</td>
<td>Circuit models used as adjuncts to the simulation grid.</td>
</tr>
<tr>
<td>Volume Models</td>
<td>Grid-conformal rectangular regions of dielectrics, magnetic materials current drive, etc.</td>
</tr>
<tr>
<td>Liner Models</td>
<td>Parameters for a simple imploding liner.</td>
</tr>
<tr>
<td>Sub grid Models</td>
<td>Specifies parameters for the 5 so-called sub grid models, such as a smooth slope.</td>
</tr>
<tr>
<td>Substrate Models</td>
<td>Neutral ion source model for a metallic plate embedded in a ceramic material.</td>
</tr>
<tr>
<td>External Fields</td>
<td>Specifies externally applied electric and/or magnetic field.</td>
</tr>
<tr>
<td>Particle Species</td>
<td>Specifies parameters such as charge, mass, etc. for each particle species present.</td>
</tr>
<tr>
<td>Particle Creation</td>
<td>Particle generation models: injection, emission, etc.</td>
</tr>
<tr>
<td>Particle Collapse</td>
<td>Control parameters for reduction of particle number by coalescence of macroparticles.</td>
</tr>
<tr>
<td>Particle Migration</td>
<td>Control parameters for electrons between kinetic and fluid states.</td>
</tr>
<tr>
<td>Particle Extraction</td>
<td>Used to generate data files of particles crossing specified planes.</td>
</tr>
<tr>
<td>Particle Interaction</td>
<td>Controls interactions between particle species for ionization and scattering models.</td>
</tr>
<tr>
<td>Particle Diagnostics</td>
<td>Used to generate data files containing particle diagnostic measurements as functions of some specified variable.</td>
</tr>
<tr>
<td>Particle Targets</td>
<td>Used to generate 2-D diagnostic maps of cumulative fluency energy and divergence of particles passing through target planes.</td>
</tr>
<tr>
<td>Functions</td>
<td>Specifies tabulated or analytic functions to be used during the simulation</td>
</tr>
</tbody>
</table>

Table 3.1: Table of Input Variables for LSP Simulation Runs
3.3 Description of the input files for LSP Model

Diagram shows the input deck flow of the LSP program (the Table 3.2) which shows the order of the input deck that is normally used in setting up a run. Figure 3.2 shows the pictorial order of the input decks.

<table>
<thead>
<tr>
<th>Input</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>Region.</td>
</tr>
<tr>
<td>ii</td>
<td>Grid.</td>
</tr>
<tr>
<td>iii</td>
<td>Objects.</td>
</tr>
<tr>
<td>iv</td>
<td>Volume Model.</td>
</tr>
<tr>
<td>v</td>
<td>Boundaries.</td>
</tr>
<tr>
<td>vi</td>
<td>External fields.</td>
</tr>
<tr>
<td>vii</td>
<td>Particle species.</td>
</tr>
<tr>
<td>viii</td>
<td>Particle creation.</td>
</tr>
<tr>
<td>ix</td>
<td>Function.</td>
</tr>
</tbody>
</table>

Table 3.2: Order of Input Variables for LSP simulation run

Figure 3.2: Layout of order of input deck for LSP
3.4 Setting 2D & 3D input deck for proof of concept

Figure 3.3 illustrates the single loop antenna. The following description is actual input parameters for the single loop antenna that will be used in the simulations. It has parameters for the radii, current, and frequency of the antenna.

1. Plasma Density:
2. Simulation Domain Size:
3. Grid Size (dx):
4. Time Step (dt):
5. Number of particle in a cell:
6. Loop antenna radius:
7. Loop antenna current:
8. Loop antenna frequency:
9. Electron temperature:

Figure 3.3: Single loop antenna
Figure 3.4 shows the two loop antenna each with inner and outer loop antennas. The inner antenna corresponding to the other inner antenna as the outer antenna corresponds to the outer antenna. The actual double loop antenna input deck was used for the simulation. Now two input parameters exist for the 1st antenna and 2nd antenna radius, current, and frequency.

1. Plasma Density:
2. Simulation Domain Size:
3. Grid Size (dx):
4. Time Step (dt):
5. Number of particles in a cell:
6. Loop antenna-1 radius:
7. Loop antenna-2 radius:
8. Loop antenna-1 current:
9. Loop antenna-2 current:
10. Loop antenna-1 frequency:
11. Loop antenna-2 frequency:
12. Electron temperature:

Figure 3.4: Double loop antenna corresponding to the other double loop antenna
Chapter 4

Modeling and Simulation Results

4.1 Single loop Antenna: 2D PIC simulation of VLF wave generation

The modeling and simulation of the LSP was ran by using the setup of a 2D-simulation of single loop antenna with input parameters defined in the previous chapter 3. Figure 4.1 shows a diagram of the single loop antenna with magnitude(E) pointing at the Z-axis [18].

Table. 4.1 shows actual 2D input values used for "Single Loop Antenna Simulation". From the input parameter, four cases were ran by varying the input parameters so one can see the best optimal results. This is the case of loop antenna frequency (Lower Hybrid frequency or VLF frequency) at $2.5\omega_{LH}$. The VLF frequency was fixed at $2.5\omega_{LH}$ for other variables except for the Result 4 case and the investigated 3 type of VLF frequencies. Results for the four runs example are shown in Table 4.2 [19].
<table>
<thead>
<tr>
<th>Input</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma density</td>
<td>$1 \times 10^{14}/m^3$</td>
</tr>
<tr>
<td>Simulation domain size</td>
<td>$2\lambda_{pe} \approx 200m$</td>
</tr>
<tr>
<td>Grid size (dx)</td>
<td>2 m</td>
</tr>
<tr>
<td>Time step (dt)</td>
<td>50 ns</td>
</tr>
<tr>
<td>Number of particles in a cell</td>
<td>1</td>
</tr>
<tr>
<td>Loop antenna radius</td>
<td>10 m</td>
</tr>
<tr>
<td>Loop antenna current</td>
<td>8 A</td>
</tr>
<tr>
<td>Loop antenna frequency</td>
<td>$2.5\omega_{LH}$</td>
</tr>
<tr>
<td>Electron temperature</td>
<td>0.98eV</td>
</tr>
<tr>
<td>Ion temperature</td>
<td>0.345eV</td>
</tr>
</tbody>
</table>

Table 4.1: Table of input values representing region of the simulation case

<table>
<thead>
<tr>
<th>Results</th>
<th>Type of results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Result 1:</td>
<td>Variation with Simulation Time.</td>
</tr>
<tr>
<td></td>
<td>fixed dt=50ns.</td>
</tr>
<tr>
<td></td>
<td>4/5 cycle, 1 cycle, and 2 cycle.</td>
</tr>
<tr>
<td>Result 2:</td>
<td>Variation with Time Step.</td>
</tr>
<tr>
<td></td>
<td>Time Step at 4/5 cycle.</td>
</tr>
<tr>
<td></td>
<td>$0.25\omega_{pe}, 0.5\omega_{pe}, 1.0\omega_{pe}$.</td>
</tr>
<tr>
<td>Result 3:</td>
<td>Variation with Number of Particles in a Cell.</td>
</tr>
<tr>
<td></td>
<td>Number of particle 1, 3, and 6.</td>
</tr>
<tr>
<td></td>
<td>fixed dt = 50ns.</td>
</tr>
<tr>
<td>Result 4:</td>
<td>Loop antenna frequency at 1 particle.</td>
</tr>
<tr>
<td></td>
<td>$\omega = 2.5\omega_{LH}$ , $\omega = 5.0\omega_{LH}$ , and $\omega = 10.0\omega_{LH}$</td>
</tr>
<tr>
<td></td>
<td>fixed with 1 particle.</td>
</tr>
</tbody>
</table>

Table 4.2: Four results by varying the different parameters
Figure 4.1: The single loop antenna
4.1.1 Result 1: Variation with simulation time

Result 1: Simulation Time at dt=50ns: 4/5 cycle (Figure 4.2), 1 cycle (Figure 4.3), 2 cycle (Figure 4.4). The simulation time variation is necessary to determine the minimum time needed to properly obtain the expected resonance cone.

Figure 4.2: Result single loop 1-1: 1.85e4 ns (4/5 cycle)

Figure 4.3: Result single loop 1-2: 7.75e4 ns (1 cycle)
As one can see in Figures 4.2, 4.3, and 4.4 resonance cone expands and echo (light green around the center) fills all the areas as the cycle increases. Furthermore, when the cycle further increases, the concentration of the echo clearly stays in the center of the images.

### 4.1.2 Result 2: Variation with time step

Result 2: Time Step at 4/5 cycle: $0.25/\omega_{pe}$ (Figure 4.5), $0.5/\omega_{pe}$ (Figure 4.6), $1.0/\omega_{pe}$ (Figure 4.7). The time step was varied in the simulation to determine the reasonable value that yields the expected resonance cone in a reasonable computational time. As one can see in the Figures 4.5, 4.6, and 4.7, the resonance cone did not change much from $0.25/\omega_{pe}$ to $0.5/\omega_{pe}$. The resonance cone coverage changed when the $\omega_{pe}$ increased to 1.0, which covers wider area but is weaker in magnitude (E).
Figure 4.5: Result single loop 2-1: $0.25/\omega_{pe}$

Figure 4.6: Result single loop 2-2: $0.5/\omega_{pe}$
4.1.3 Result 3: Variation with number of particles in a cell

Result 3: Number of Particles at dt = 50ns and 4/5 cycle:

Particle=1 (Figure 4.8), Particle=3 (Figure 4.9), Particle=6 (Figure 4.10).

This step was necessary to determine the effect of the number of particles per cell used and their effect on the expected resonance cone. No noticeable difference was observed in 2D. Varying the number particles from particle 1 to 6 did not change the result because the number of particles is still very small number.
Figure 4.8: Result single loop 3-1: 1 particle

Figure 4.9: Result single loop 3-2: 3 particles
4.1.4 Result 4: Loop antenna frequency at 1 particle

Results 4: $\omega = 2.5\omega_{LH}$ (Figure 4.11), $\omega = 5.0\omega_{LH}$ (Figure 4.12), and $\omega = 10.0\omega_{LH}$ (Figure 4.13). This step was necessary to determine loop antenna frequency and its effect on the expected resonance cone.

Figure 4.10: Result single loop 3-3:6 particles

Figure 4.11: Result single loop 4-1: $\omega = 2.5\omega_{LH}$
Figure 4.12: Result single loop 4-2: $\omega = 5\omega_{LH}$

Figure 4.13: Result single loop 4-3: $\omega = 10.0\omega_{LH}$

Varying the $\omega = 2.5\omega_{LH}$ up to $\omega = 10.0\omega_{LH}$ did change the resonance cone in both the X-axis and Z-axis direction. Figures 4.12 and 4.13 are different only in scale time.
In summary, running the single loop antenna in 2D did not provide much increase in the magnitude (E) whether the input parameter was number cycle, variation of time step, number of particles, and/or antenna frequency.

4.2 Single Loop Antenna: 3D PIC simulation of VLF wave generation

This 3D run is the result of the single loop antenna that was ran with the following parameters. Table 4.3 shows the 3D Setup Parameters for Single Loop Antenna and Figure 4.14 and Figure 4.15 show the 3D output plots.

<table>
<thead>
<tr>
<th>Input</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Time</td>
<td>$\frac{4}{5}\omega_{loop}$</td>
</tr>
<tr>
<td>Time step (dt)</td>
<td>50 ns</td>
</tr>
<tr>
<td>Grid size (dx)</td>
<td>2 m</td>
</tr>
<tr>
<td>Number of particles in a cell</td>
<td>1</td>
</tr>
<tr>
<td>Boundary Condition</td>
<td>Free Space</td>
</tr>
<tr>
<td>Loop antenna frequency</td>
<td>$2.5\omega_{LH}$</td>
</tr>
</tbody>
</table>

Table 4.3: Input Variables for 3D single loop VLF antenna

Figure 4.14: Single loop 3D plot with option for input
Figure 4.14 shows the user option to change the parameters to look at the specific items for the plot within the grid size. Figure 4.15 shows very specific parameters without other plots to investigate the isosurface and resolution within the X-Y-Z coordinates. It is showing the magnitude (E) on the Z-axis.
4.3 Parametric Antenna: 2D simulation of VLF wave generation

This section investigates the parametric antenna in a 2D simulation. The diagram of the two loop antenna is plotted in the figure 4.16, which shows the antenna (two loop antenna) is in the XY - plane at Z=0. The following assumptions were used: 1. Simulation time step was possible at the inverse plasma frequency ($1/\omega_{pe}$) at the plasma density $n = 1 \times 10^{11} m^{-3}$, 2. Noisy electric field was shown around $z = 0$ area in 3D simulation, 3. Plasma density affected lower hybrid resonance frequency, 4. When the resonance frequency $\omega$ was in the range of $2 \sim 3\omega_{LH}$, lower hybrid resonance frequency, the resonance cone was clearly shown [20].

![Figure 4.16: The two loop antenna.](image)
4.3.1 Case 1: 2D parametric antenna with antenna frequency at $2.5\omega_{LH}$

Table 4.4 shows the antenna parameters that were used to generate the plots. Three results were plotted by varying 3 cycle times, 4 time steps, and 3 number of particles.

<table>
<thead>
<tr>
<th>Input</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Density</td>
<td>$1 \times 10^1/m^3$</td>
</tr>
<tr>
<td>Lower Hybrid Frequency</td>
<td>$1.18 \times 10^6 rad/s$</td>
</tr>
<tr>
<td>F-Layer</td>
<td>500km</td>
</tr>
<tr>
<td>Time step (dt)</td>
<td>50ns</td>
</tr>
<tr>
<td>Grid size (dx)</td>
<td>2 m</td>
</tr>
<tr>
<td>H atom</td>
<td>$1E5/cm^3$</td>
</tr>
<tr>
<td>Electron Temp $T_e$</td>
<td>9.8eV</td>
</tr>
<tr>
<td>Ion Temp $T_i$</td>
<td>0.345eV</td>
</tr>
<tr>
<td>dx</td>
<td>200cm</td>
</tr>
<tr>
<td>Antenna frequency $\omega_1$</td>
<td>$2.5\omega_{LH}$</td>
</tr>
<tr>
<td>Antenna frequency $\omega_2$</td>
<td>$2.4\omega_{LH}$</td>
</tr>
<tr>
<td>Loop Antenna Current</td>
<td>8A</td>
</tr>
<tr>
<td>Particle in cell</td>
<td>1</td>
</tr>
<tr>
<td>Loop antenna Radius (R1)</td>
<td>9.6m</td>
</tr>
<tr>
<td>Loop antenna Radius (R2)</td>
<td>10m</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>$3 \times 10^{-6}T$</td>
</tr>
</tbody>
</table>

Table 4.4: 2D Parametric Antenna with $\omega = 2.5\omega_{LH}, 2.4\omega_{LH}$
Result 1: Simulation time at dt = 50ns: 4/5 cycle, 1 cycle, 2 cycles

Figure 4.17: Result two loop at 4/5 cycle with $\omega = 2.5\omega_{LH}, 2.4\omega_{LH}$

Figure 4.18: Result two at 1 cycle with $\omega = 2.5\omega_{LH}, 2.4\omega_{LH}$
In the parameric antenna, varying the cycle definitely shows the changes in the resonance cone. Increase in the cycle gives higher definition and some side lobe effects. As the cycle increases resonance expands wider in x-axis.
Result 2: Time step at 4/5 cycle: 0.25/\omega_{pe}, 0.5/\omega_{pe}, 1/\omega_{pe}, 1.5/\omega_{pe}

Figure 4.20: Result two loop at 0.25/\omega_{pe} at plasma density n = 1 \times 10^{11} m^{-3}

Figure 4.21: Result two loop at 0.5/\omega_{pe} at plasma density n = 1 \times 10^{11} m^{-3}
Figure 4.22: Result two loop at $1/\omega_{pe}$ at plasma density $n = 1 \times 10^{11} m^{-3}$

Figure 4.23: Result two loop at $1.5/\omega_{pe}$ at plasma density $n = 1 \times 10^{11} m^{-3}$

Varying the value of inverse plasma frequency from $0.25/\omega_{pe}$ to $1.0/\omega_{pe}$ did not change any resonance cone expansion but at the $1.5/\omega_{pe}$ changes in the resonance cone were definitely present. It increased both power and width of the resonance cone.
Result 3: Number of particles at dt=50ns and 4/5 cycle: 1, 3, 6

Figure 4.24: Result two loop at 1 particle

Figure 4.25: Result two loop at 3 particle
Increase in the number of particles did not change the magnitude power nor the shape of the resonance cone.
4.3.2 Case 2: 2D parametric antenna with antenna frequency at $10.0 \omega_{LH}$

Table 4.5 shows the antenna parameters that were used to generate the plots. Three results were plotted by varying 3 cycle times, 4 time steps, and 3 number of particles. This is at antenna frequency at $10.0 \omega_{LH}$.

<table>
<thead>
<tr>
<th>Input</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Density</td>
<td>$1 \times 10^{11}/m^3$</td>
</tr>
<tr>
<td>Lower Hybrid Frequency</td>
<td>$1.18 \times 10^5 rad/s$</td>
</tr>
<tr>
<td>F-Layer</td>
<td>500km</td>
</tr>
<tr>
<td>Time step (dt)</td>
<td>50ns</td>
</tr>
<tr>
<td>Grid size (dx)</td>
<td>2 m</td>
</tr>
<tr>
<td>H atom</td>
<td>$1E5/cm^3$</td>
</tr>
<tr>
<td>Electron Temp $T_e$</td>
<td>9.8eV</td>
</tr>
<tr>
<td>Ion Temp $T_i$</td>
<td>0.345eV</td>
</tr>
<tr>
<td>dx</td>
<td>200cm</td>
</tr>
<tr>
<td>Antenna frequency (ω1)</td>
<td>$10 \omega_{LH}$</td>
</tr>
<tr>
<td>Antenna frequency (ω2)</td>
<td>$9.9 \omega_{LH}$</td>
</tr>
<tr>
<td>Loop Antenna Current</td>
<td>8A</td>
</tr>
<tr>
<td>Particles in cell</td>
<td>1</td>
</tr>
<tr>
<td>Loop antenna Radii (R1)</td>
<td>9.9m</td>
</tr>
<tr>
<td>Loop antenna Radii (R2)</td>
<td>10m</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>$3 \times 10^{-8} T$</td>
</tr>
</tbody>
</table>

Table 4.5: 2D Parametric Antenna with $\omega = 10\omega_{LH}, 9.9\omega_{LH}$
Result 1: Simulation time at $dt = 50$ns: 4/5 cycle, 1 cycle, 2 cycles

Figure 4.27: Result two loop at 4/5 cycle with $\omega = 10\omega_{LH}, 9.9\omega_{LH}$

Figure 4.28: Result two loop at 1 cycle with $\omega = 10\omega_{LH}, 9.9\omega_{LH}$
Figure 4.29: Result two loop at 3 cycle with $\omega = 10\omega_{LH}, 9.9\omega_{LH}$

Changing the cycle time minimally changed the magnitude power and resonance cone but at the higher cycle time created expansion of resonance cone higher and wider in X and Z axies due to field propagation in time. The overall shape change from the previous figures is due to the frequency with $\omega = 10\omega_{LH}, 9.9\omega_{LH}$, which it was not true in lower frequency from the previous section at frequency with $\omega = 2.5\omega_{LH}, 2.4\omega_{LH}$.
Result 2: Time step at 4/5 cycle: $0.25/\omega_{pe}$, $0.5/\omega_{pe}$, $1/\omega_{pe}$, $1.5/\omega_{pe}$

Figure 4.30: Result two loop at $0.25/\omega_{pe}$

Figure 4.31: Result two loop at $0.5/\omega_{pe}$
Did not see any changes in the magnitude ($E$) and resonance cone due to the variation of inverse plasma frequency from the $0.25/\omega_{pe}$ to $1.5/\omega_{pe}$. 

Figure 4.32: Result two loop at $1/\omega_{pe}$

Figure 4.33: Result two loop at $1.5/\omega_{pe}$
Result 3: Number of particles at $dt=50$ns and $4/5$ cycle: 1, 3, 6

Figure 4.34: Result two loop with 1 particle

Figure 4.35: Result two loop with 3 particles
Figure 4.36: Result two loop with 6 particles

No changes in the resonance cone due to the change in the number of particles.
4.4 Parametric Antenna: 3D simulation of VLF wave generation

4.4.1 Case 1: 3D Double Loop Antenna with $\omega_1 = 2.5\omega_{LH}$ & $\omega_2 = 2.4\omega_{LH}$ and $R_1 = 10\text{m}$ & $R_2 = 9.6\text{m}$

Table 4.6 shows the parameters that was used to plot the 3D parametric antenna with $\omega_1 = 2.5\omega_{LH}$ and $\omega_2 = 2.4\omega_{LH}$. In this section, all the results are plotted in both electric field and magnetic field in both linear scale and log scale.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-Layer</td>
<td>500km.</td>
</tr>
<tr>
<td>H atom</td>
<td>$1E5/cm^2$</td>
</tr>
<tr>
<td>Boundary condition</td>
<td>Free space</td>
</tr>
<tr>
<td>Plasma Density</td>
<td>$1X 10^{11}/m^3$</td>
</tr>
<tr>
<td>Lower-hybrid frequency</td>
<td>$1.18X 10^5 \text{rad/s}$</td>
</tr>
<tr>
<td>Simulation domain size</td>
<td>$2\lambda_{pe} \approx 200\text{m}$</td>
</tr>
<tr>
<td>Grid size (dx)</td>
<td>2 m</td>
</tr>
<tr>
<td>Time step (dt)</td>
<td>50 ns</td>
</tr>
<tr>
<td>Number of particle in a cell</td>
<td>1</td>
</tr>
<tr>
<td>Loop antenna radius (R1)</td>
<td>10 m</td>
</tr>
<tr>
<td>Loop antenna radius (R2)</td>
<td>9.6 m</td>
</tr>
<tr>
<td>Loop antenna current</td>
<td>8 A</td>
</tr>
<tr>
<td>Loop antenna frequency ($\omega_1$)</td>
<td>$2.5\omega_{LH}$</td>
</tr>
<tr>
<td>Loop antenna frequency ($\omega_2$)</td>
<td>$2.4\omega_{LH}$</td>
</tr>
<tr>
<td>Electron temperature (Te)</td>
<td>9.8eV</td>
</tr>
<tr>
<td>Ion temperature (Ti)</td>
<td>0.345eV</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>$3X10^{-5}T$</td>
</tr>
</tbody>
</table>

Table 4.6: 3D Parametric Antenna $\omega = 2.5\omega_{LH}, 2.4\omega_{LH}$
Result 1-1: Electric Fields (linear scale)

Figure 4.37: Linear of XZ plane at Y=0, 3D parametric electric field

Figure 4.38: Linear of YZ plane at X=0, 3D parametric electric field
Figure 4.39: Linear of XY plane at Z=0, 3D parametric electric field

Figure 4.40: Linear of XY plane at Z=40000, 3D parametric electric field
Figures 4.37 to Figure 4.40 shows 3D parametric electric field in linear scale with different angle view of the cross section of the resonance cone such as x=0, y=0, and z=0. Due to the singularity appears only for quasi-electrostatic waves, resonance wave appears in electric field only. The magnetic field plot do not have resonance cone due to Whistler having magnetic field (EM waves). This are true for rest of the plots in both electric field and magnetic field for next section.

**Result 1-2: Electric Fields (log scale)**

![Log of XZ plane at Y=0, 3D parametric electric field](image)

Figure 4.41: Log of XZ plane at Y=0, 3D parametric electric field

Figures 4.41 to Figure 4.44 shows 3D parametric electric field in log scale with different angle view of the cross section of the resonance cone such as x=0, y=0, and z=0. Trend
Figure 4.42: Log of YZ plane at X=0, 3D parametric electric field

Figure 4.43: Log of XY plane at Z=0, 3D parametric electric field

did not change but the power doubled (see the scale changes).
Figure 4.44: Log of XY plane at $Z=40000$, 3D parametric electric field
Result 2-1: Magnetic Fields (linear scale)

Figure 4.45: Linear of XZ plane at Y=0, 3D parametric magnetic field

Figure 4.46: Linear of YZ plane at X=0, 3D parametric magnetic field

Figures from 4.45 to figure 4.48 are plot of the magnetic field in linear scale. The power
is concentrated in the center and has weak power everywhere else. When $z=40000$, nothing can be seen due to scale limits.
Result 2-2: Magnetic Fields (log scale)

Figure 4.49: Log of XZ plane at Y=0, 3D parametric magnetic field

Figure 4.50: Log of YZ plane at X=0, 3D parametric magnetic field

Figure 4.49 to Figure 4.52 are the same as the above plots but now in the magnetic field
Figure 4.51: Log of XY plane at Z=0, 3D parametric magnetic field

Figure 4.52: Log of XY plane at Z=40000, 3D parametric magnetic field

plot in log scale. The results are almost the same as linear scale. The power is concentrated in the center with weaker power everywhere else. When looking at the Z=40000, one does not see any power, due to all the power being outside of the scale.
Result 3: Iso-surface at $5.3 \times 10^{-6} kV/cm$

Figure 4.53: Iso-surface at $5.3 \times 10^{-6} kV/cm$

Figure 4.53 shows that the 3D Double Loop Antenna with $\omega_1 = 2.5\omega_{LH}$ & $\omega_2 = 2.4\omega_{LH}$ and $R_1=10m$ & $R_2=9.6$ at iso-surface $5.3 \times 10^{-6} kV/cm$. 
4.4.2 Case 2: 3D Double Loop Antenna with $\omega_1 = 10.0\omega_{LH}$ & $\omega_2 = 9.9\omega_{LH}$ & $R_1 = 10\text{m}$ & $R_2 = 9.6\text{m}$

Table 4.7: shows the input parameters that were used to plot the 3D parametric antenna with frequency ($\omega = 10\omega_{LH}$&$9.9\omega_{LH}$). In this section, all the results are plotted in both electric field in linear and log scale and magnetic field in linear and log scale.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-Layer</td>
<td>500km.</td>
</tr>
<tr>
<td>H atom</td>
<td>$1E5/cm^3$</td>
</tr>
<tr>
<td>Boundary condition</td>
<td>Free space</td>
</tr>
<tr>
<td>Plasma Density</td>
<td>$1X\times10^{11}/m^3$</td>
</tr>
<tr>
<td>Lower-hybrid frequency</td>
<td>$1.18X\times10^5rad/s.$</td>
</tr>
<tr>
<td>Simulation domain size</td>
<td>$2\lambda_{pe}\approx200m$</td>
</tr>
<tr>
<td>Grid size (dx)</td>
<td>2 m</td>
</tr>
<tr>
<td>Time step (dt)</td>
<td>50 ns</td>
</tr>
<tr>
<td>Number of particle in a cell</td>
<td>1</td>
</tr>
<tr>
<td>Loop antenna radius (R1)</td>
<td>10 m</td>
</tr>
<tr>
<td>Loop antenna radius (R2)</td>
<td>9.6 m</td>
</tr>
<tr>
<td>Loop antenna current</td>
<td>8 A</td>
</tr>
<tr>
<td>Loop antenna frequency ($\omega_1$)</td>
<td>$10.0\omega_{LH}$</td>
</tr>
<tr>
<td>Loop antenna frequency ($\omega_2$)</td>
<td>$9.9\omega_{LH}$</td>
</tr>
<tr>
<td>Electron temperature (Te)</td>
<td>9.8eV</td>
</tr>
<tr>
<td>Ion temperature (Ti)</td>
<td>0.345eV</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>$3X10^{-5}T$</td>
</tr>
</tbody>
</table>

Table 4.7: 3D Parametric Antenna $\omega = 10\omega_{LH}, 9.9\omega_{LH}$
Result 1-1: Electric Fields (linear scale)

Figure 4.54: Linear of XZ plane at Y=0, 3D parametric electric field

Figure 4.55: Linear of YZ plane at X=0, 3D parametric electric field
Figure 4.56: Linear of XY plane at Z=0, 3D parametric electric field

Figure 4.57: Linear of XY plane at Z=40000, 3D parametric electric field
Result 1-2: Electric Fields (log scale)

Figure 4.58: Log of XZ plane at Y=0, 3D parametric electric field

Figure 4.59: Log of YZ plane at X=0, 3D parametric electric field
Figure 4.60: Log of XY plane at Z=0, 3D parametric electric field

Figure 4.61: Log of XY plane at Z=40000, 3D parametric electric field
Result 2-1: Magnetic Fields (linear scale)

Figure 4.62: Linear of XZ plane at Y=0, 3D parametric magnetic field

Figure 4.63: Linear of YZ plane at X=0, 3D parametric magnetic field
Figure 4.64: Linear of XY plane at Z=0, 3D parametric magnetic field

Figure 4.65: Linear of XY plane at Z=4000, 3D parametric magnetic field
Result 2-2: Magnetic Fields (log scale)

Figure 4.66: Log of XZ plane at Y=0, 3D parametric magnetic field

Figure 4.67: Log of YZ plane at X=0, 3D parametric magnetic field
Figure 4.68: Log of XY plane at Z=0, 3D parametric magnetic field

Figure 4.69: Log of XY plane at Z=40000, 3D parametric magnetic field
Result 3: Iso-surface at $9.5 \times 10^{-6} \text{kV/cm}$

Figure 4.70: Iso-surface at $9.5 \times 10^{-6} \text{kV/cm}$

Figure 4.70 shows the 3D Double Loop Antenna with $\omega_1 = 10.0\omega_{LH}$ & $\omega_2 = 9.9\omega_{LH}$ and $R_1=10\text{m}$ & $R_2=9.6\text{m}$ at iso-surface at $9.5 \times 10^{-6} \text{kV/cm}$. The diameter of the inner loop antenna and outer loop antenna are larger due to the higher $\omega$ value. The center of the X-Y-Z coordinate system has some side lobe effects.
Chapter 5

VLF Antenna Results

5.1 Comparison of single loop vs two loop antennas

In this chapter, results from the modeling & simulation of the single loop antenna and double loop antenna in both 2D & 3D are shown. Figure 5.1 shows a diagram of the single loop antenna and Figure 5.2 show the diagram of the two loop antenna at Z=0 orientation and figure 5.3 show the single loop antenna at X=0 orientation.

Figure 5.1: The single loop antenna
Figure 5.2: The two loop antenna at Z=0

Figure 5.3: The single loop antenna at X=0
5.1.1 3D Input parameters for single & parametric antenna:

Table 5.1 shows the 3D Setup Parameters for Single Loop Antenna with $2.5\omega_{LH}$

<table>
<thead>
<tr>
<th>Input</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Time</td>
<td>$4/5\omega_{loop}$</td>
</tr>
<tr>
<td>Time step (dt)</td>
<td>50 ns</td>
</tr>
<tr>
<td>Grid size (dx)</td>
<td>2 m</td>
</tr>
<tr>
<td>Number of particle in a cell</td>
<td>1</td>
</tr>
<tr>
<td>Boundary Condition</td>
<td>Free Space</td>
</tr>
<tr>
<td>Loop antenna frequency</td>
<td>$2.5\omega_{LH}$</td>
</tr>
</tbody>
</table>

Table 5.1: Input Variables for 3D single loop

Table 5.2 shows the 3D Setup Parameters for Two loop Antenna

<table>
<thead>
<tr>
<th>F-Layer</th>
<th>500km</th>
</tr>
</thead>
<tbody>
<tr>
<td>H atom</td>
<td>$1E5/cm^3$</td>
</tr>
<tr>
<td>Boundary condition</td>
<td>Free space</td>
</tr>
<tr>
<td>Plasma Density</td>
<td>$1X10^{11}/m^3$</td>
</tr>
<tr>
<td>Lower-hybrid frequency</td>
<td>$1.18X10^5 rad/s$</td>
</tr>
<tr>
<td>Simulation domain size</td>
<td>$2\lambda_{pe} \approx 200m$</td>
</tr>
<tr>
<td>Grid size (dx)</td>
<td>2 m</td>
</tr>
<tr>
<td>Time step (dt)</td>
<td>50 ns</td>
</tr>
<tr>
<td>Number of particle in a cell</td>
<td>1</td>
</tr>
<tr>
<td>Loop antenna radius (R1)</td>
<td>10 m</td>
</tr>
<tr>
<td>Loop antenna radius (R2)</td>
<td>9.6 m</td>
</tr>
<tr>
<td>Loop antenna current</td>
<td>8 A</td>
</tr>
<tr>
<td>Loop antenna frequency ($\omega_1$)</td>
<td>$2.5\omega_{LH}&amp;10.0\omega_{LH}$</td>
</tr>
<tr>
<td>Loop antenna frequency ($\omega_2$)</td>
<td>$2.4\omega_{LH}&amp;9.9\omega_{LH}$</td>
</tr>
<tr>
<td>Electron temperature (Te)</td>
<td>9.8eV</td>
</tr>
<tr>
<td>Ion temperature (Ti)</td>
<td>0.345eV</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>$3X10^{-8} T$</td>
</tr>
</tbody>
</table>

Table 5.2: Input Values for 3D Parametric Antenna
5.1.2 3D Output for single & parametric antenna:

Figure 5.4. shows the 3D output plot for single loop with $\omega = 2.5\omega_{LH}$. Figure 5.5. shows the 3D output plot parametric antenna with $\omega_1 = 2.5\omega_{LH}$ & $\omega_2 = 2.4\omega_{LH}$.

Figure 5.4: 3D Single Loop $\omega_1 = 2.5\omega_{LH}$

Figure 5.5: 3D Two Loop $(\omega_1) = 2.5\omega_{LH}$ & $(\omega_2) = 2.4\omega_{LH}$
5.1.3 3D Output for parametric antenna:

Figure 5.6 shows the 3D output plot for $(\omega_1) = 2.5\omega_{LH}$ and $(\omega_2) = 2.4\omega_{LH}$. Figure 5.7 shows the 3D output plot $(\omega_1) = 10.0\omega_{LH}$, $(\omega_2) = 9.9\omega_{LH}$.

Figure 5.6: 3D Two Loop $(\omega_1) = 2.5\omega_{LH}$ & $(\omega_2) = 2.4\omega_{LH}$

Figure 5.7: 3D Two Loop $(\omega_1) = 10.0\omega_{LH}$ & $(\omega_2) = 9.9\omega_{LH}$
5.2 2D Parametric antenna plots

Three simulations were performed. The first simulation with an loop antenna frequency at the $2.5 \omega_{ LH }$ which is shown in Figure 5.8. The second simulation with an loop antenna frequency at the $2.8 \omega_{ LH }$ which is shown in Figure 5.9. The third simulation with both loop (parametric) antennas is shown in the Figure 5.10. The simulation plotting both antennas was conducted by subtracting the resulting fields from the separate runs from the run that had both antennas. After taking Fourier Transforms in time at a specific spatial location in the simulation domain. Performed FFT at Y-axis parameter ”Ex” and Plotted Ex(omega, x0, z0), where x0 = 20 m and z0 = 200 m with respect to the antenna location [22].

![Figure 5.8: 2D Two Loop ($\omega_1$) = 2.5$\omega_{ LH }$](image)
Figure 5.9: 2D Two Loop \( (\omega_2) = 2.8\omega_{LH} \)

Figure 5.10: Both Antenna \( (\omega_1) = 2.5\omega_{LH} \) and \( (\omega_1) = 2.8\omega_{LH} \)
Figure 5.11 is a plot that combines each figures from the previous plot with resonance cone plots side by side for comparison. The simulations showing real-space plots on the right is the formation of the VLF resonance cones. It is in frequency space and it is plotted \( \text{Mag}(E) \) vs \( \omega \), which shows the increase in wave power at \( 0.3 \omega_{LH} \), which is the difference in frequency between the two other VLF antenna. Also showing in the plot is an increase in wave power at the expected frequency as this research predicted from the beginning.

![Figure 5.11: Image of the mag (E) versus \( \omega \)](image)

### 5.3 3D Parametric antenna plots

This section is the result of 3D simulation of the parametric antenna. All the simulations performed show the research hypothesis that the parametric antenna concept creates ELF and VLF signal at \( w_4 = w_1 - w_2 \) and \( w_3 = w_1 + w_2 \) frequency and at the same time the magnitude at both VLF and ELF increases almost one order of magnitude. This convincing
evidence shown that an array of two VLF antennas driven at two close frequencies, leads to an ELF mode. The plot in figure 5.12 shows the magnitude of $E$ as a function of frequency normalized to the lower hybrid frequency. Figure 5.13 shows a close up of the figure 5.12 in a red circle showing two colored curves corresponding to a simulation with only $\omega_1 = 2.5\omega_{LH}$ and $\omega_2 = 2.8\omega_{LH}$. The black curve is from a simulation with both antennas. This parametric antenna concept was just awarded a patent with U.S. Patent number 9,527,608.

Figure 5.12: Plot of the Mag($E$) with $\omega_{LH}$ for all antennas

Figure 5.14 extracts only the parametric antenna plots from the 5.13 to show the presence of a mode at $0.3\omega_{LH}$. The presence of the ELF frequency is clear at lower frequency due to parametric antenna. The parametric antenna created higher VLF magnitude in both main & sidelobe and also created high ELF in the lower frequency as shown (Peak Magnetic Field ($E$)).
Figure 5.13: Plot of the Mag($E$) with frequency zoom in circle areas

Figure 5.14: Plot of the Mag($E$) with only parametric antenna
Figure 5.15 is showing a wave power spectrum diagram from the VLF wave on actual flight test conducted in "CHARGE-2B" flight test [16]. For this flight test, the electron beam modulation frequency was around 17.95kHz, as seen by the peak in magnetic field near 18kHz. At about 2kHz with respect to the 18kHz looking at the main sidelobe, notice that there is also an extreme low frequency (ELF) emission. It shows a VLF creating the higher ELF magnitude at lower frequency. This confirms the concept of the parametric antenna by both M&S and experimentation. Figure 5.16 is showing the flight profile of the actual flight test of the "CHARGER 2B". Experimentation to observed the values of the angles of propagation with respect to the earth magnetic field, which shown as VLF at 78 degree and ELF at 84 degree. The trajectory altitude was 266 km.

![Wave Power Spectrum Diagram](image)

Figure 5.15: Actual Flight Test dat of "CHARGE-2B"
Experimentally observed values of the angles of propagation with respect to the Earth magnetic field are:

\[ VLF: \ \theta_1 \sim 78^0 \quad HLF: \ \theta_2 \sim 84^0 \]

Figure 5.16: Flight profile of "CHARGE-2B"
Chapter 6

Experimentation Results

As described and shown in the previous chapter about the theoretical for the parametric antenna interaction between electrostatic lower oblique resonance (LOR) and electromagnetic lower oblique resonance which can produce electromagnetic whistler waves in a cold magnetized plasma\[28\]. It was also demonstrated theoretically that this interaction can more efficiently generate electromagnetic whistler waves than by direct excitation of a conventional loop antenna. It is also shown in the previous modeling & simulation chapter results of the modeling & simulation of the VLF and interaction of the two VLF (parametric antenna) and plotted 2D and 3D of the different parameters. This experimentation shows the set up of the parametric antenna validating the both theoretical and M&S result by using a scaled experiment in a plasma chamber that was designed and built utilizing a high density, uniform plasma source. Figure 6.1 shows the large plasma chamber and figure 6.2 show the close up look at the Quad Helicon source to the large plasma chamber. Figure 6.3 shows the two type of the loop antenna (parametric antenna) with spacing of 85 micron-meter and figure 6.4 show the parametric antenna with 26 micron-meter spacing, both were tested in the large plasma chamber. All the experimentation was set up and experimentation was conducted in the laboratory by a researcher in the Plasma Physics Sensors Laboratory (PPSL) lab at the Air force Research Laboratory (AFRL) showing the results that validate the theory and modeling and simulation.
Figure 6.1: Large Plasma Chamber

Figure 6.2: Quad Helicon Source producing an Argon plasma
This experimentation validates the initial parametric antenna concept that creates the ELF and VLF at different frequencies due to the interaction of the two loop antennas. The experiment data was presented at the APS conference by Mr. Nate Zechar and Dr. Vladimir Sotnikov [31].

1. Verify capability to produce whistler waves figure 6.5

2. Verify capability to produce VLF figure 6.6
In summary, the experimentation of the parametric antenna concept was demonstrated in the plasma laboratory by investigating the excitation of sideband emissions due to interaction of the VLF signal from a loop antenna \((f = 60\ MHz, I = 0.4\ A)\) with ion acoustic waves excited by a low frequency source \((f = 100\ KHz, I = 0.07\ A)\). Parametrically excited sideband emission at \(f = 60.1\ MHz\) has almost twice the magnetic field amplitude in comparison with a single loop emission at \(f = 60\ MHz\).
Chapter 7

Summary

An important part of atmospheric electricity, which forms the inner edge of the magnetosphere, influences radio propagation to distant places on the Earth. The free electrons allow good propagation of electromagnetic waves in radio communication but can be much improved by using excitation of the electric currents. The purpose of the proposed research was to analyze the radiation efficiency of very low frequency (VLF) and extremely low frequency (ELF) antennas in the ionosphere by implementing a concept of a parametric antenna which excite the electromagenetic currents. This dissertation addressed the concern of the low radiation efficiency of satellites based on conventional loop and dipole antennas.

Research was conducted to dramatically increase radiation efficiency of very low frequency (VLF) and extremely low frequency (ELF) antennas in the ionosphere by implementing a concept of a parametric antenna. Each loop antenna excites predominantly the electrostatic part of the VLF wave spectrum in the form of Lower Oblique Resonance (LOR) oscillations. Nonlinear interaction of LOR wave creates a region in the vicinity of loop antennas that acts like a much larger antenna, simultaneously re-radiating the VLF and ELF wave energy with an order of magnitude greater radiation efficiency. Also shown by the modeling and simulation using the parametric antenna increase in the radiation efficency on both VLF and creating the ELF. The results of the single loop antenna and double (parametric) loop antenna by running a variety of parameters such as varying the time step, loop antenna radii, antenna frequencies, and number of particle in cells were investigated and shown.
Furthermore, in the "VLF Results" chapter 5, it showed the plot of 2D and 3D runs both magnitude versus low hybrid frequency and image of resonance cone that change with parametric antenna. The results definitely show the increase of the power due to the two VLF antenna and generating the ELF power. This report solved the concerns of low radiation efficiency of satellite based conventional loop and dipole antennas used for excitation of electromagnetic VLF/ELF waves in the ionosphere. Completed characterization of VLF waves generated by loop antenna, ran the 2D PIC simulation of VLF wave excitation by a loop antenna, analysis the data, and worked with post processing to visualize obtained simulation results, including radiated patterns and resonance cones. I ran a 2D simulation of VLF/ELF wave generation by two loop antennas due to parametric coupling and ran a 3D simulation of VLF wave generation by a single loop antenna using a parallelization technique on HPC post processor data analysis. All of the LSP 2D runs were performed by both desktop computer and HPC computer. Selected LSP 3D was performed only in the HPC due to run time. Limited parameters were varied to investigate the frequency, simulation time, time step, and number of particles. Showed the theoretical, modeling simulation, and observed limited test experimentation from the PPSL laboratory by experimentalist to validate/verify prove of the concept. All the test experimentation data was generated from LSP simulation and is shown in Chapter 4 & 5 as Modeling and Simulation and VLF Results. This technique provided VLF and ELF wave energy with an order of magnitude greater radiation efficiency to increase the performance of the communication and navigation systems.
Bibliography


