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,USING AN ELECTRON BEAM LAUNCHED ORTHOGONAL TO THE GEOMAGNETIC FIELD AS A LOW FREQUENCY LOOP ANTENNA ABOARD A SPACECRAFT IN LOW EARTH ORBIT,

Thesis

Submitted to

Graduate Engineering and Research
School of Engineering

UNIVERSITY OF DAYTON

In Partial Fulfillment of the Requirements for

The Degree

Master of Science in Electrical Engineering

by

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UNIVERSITY OF DAYTON

Dayton, Ohio

August 1992

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USING AN ELECTRON BEAM LAUNCHED ORTHOGONAL TO THE GEOMAGNETIC FIELD AS A LOW FREQUENCY LOOP ANTENNA ABOARD A SPACECRAFT IN LOW EARTH ORBIT

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ABSTRACT

USING AN ELECTRON BEAM LAUNCHED ORTHOGONAL TO THE GEOMAGNETIC FIELD AS A LOW FREQUENCY LOOP ANTENNA ABOARD A SPACECRAFT IN LOW EARTH ORBIT

Name: Hackett, Ronald D.
University of Dayton, 1992

Advisor: Dr. Gary A. Thiele

In conventional electromagnetic theory, the fields of an antenna are computed from the magnitude and phase of currents flowing in a particular geometry where the geometry is defined by some conducting structure. The only effect of the conducting structure is to define the geometry of the system. In the rarified environment of space, it is possible to form current structures without conducting surfaces. The currents are formed from a flow of charged particles (principally electrons) called beams. The shape of the beams can be controlled by using various combinations of electric and magnetic fields.

This report examines the antenna properties of an electron beam launched orthogonal to the geomagnetic field. The Lorentz force causes such an electron beam to form a loop of current in space that can be used in either a transmit or a receive mode. The differential equations governing the motion of the electrons in the presence of a time varying, propagating electromagnetic field are developed, and the effects of a low density, magnetized plasma environment are considered. This report shows that velocity modulation by the E×B and polarization drift velocities can be used for the receive mode, and density modulation can be used for the transmit mode of a low frequency electron beam loop antenna. This report also examines previous theoretical and experimental work which supports the thesis that an electron beam can function as an antenna, and makes suggestions for the direction of future work in high frequency electron beam antennas.

ACKNOWLEDGMENTS

I would like to express my deep appreciation to all the people who helped complete the work contained in this thesis. The following individuals deserve special recognition for there contributions: Mr. Gywnne Griffiths for calling my attention to this unusual topic, Mr. Tom Sheehan for helping identify NASA missions that experimented with electron beams, Mr. Joseph Wilkson for translations, Captains Mike Johnson and Ed Hume for there help with ionospheric physics, and Mr. Ken Cizadlo for loaning me the computer to write this thesis.

Others deserving of mention are my thesis advisor, Dr. Gary Thiele, for his guidance and help in my admission to the Electrical Engineering Graduate Program and in the preparation of this thesis; my boss, Mr. Allan Haertling, for his tolerance and flexibility; and my wife and children for their support.

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$m = 9.11 \times 10^{-31}$ kilograms	Electron Mass
$e = -1.602 \times 10^{-19}$ Coulombs	Electron Charge
$c = 3 \times 10^{8}$ meters/second	Light Speed
$\epsilon_0 = 8.854 \times 10^{-12}$ farad/meter	Permittivity of Free Space
$\mu_0 = 1.26 \times 10^{-6}$ henry/meter	Permeability of Free Space
1 weber/meter^2 = 1 tesla = 10^{4} Gauss	Magnetic Field Unit Conversions
1 electronvolt (eV) = 1.60×10^{-19} joule = 1.602×10^{-12} erg	Energy Unit Conversions

CHAPTER I

INTRODUCTION

Problems in Space Based Antenna Design

Designing antennas for spacecraft applications is very different from designing antennas for terrestrial purposes. Maxwell's equations still apply, but the medium surrounding the antenna may not be isotropic and free charge may exist. These two assumptions are often used when designing terrestrial antennas. But the greatest challenge to designing spacecraft antennas is not the electrical parameters, it is the mechanical problems that exist in the harsh space environment.

The space environment exposes the antenna to extremes in pressure, radiation, and temperature. Space also exposes the antenna to collisions with small, high velocity particles called micrometeorites. The low pressures of space cause a loss of material through sublimation and out-gassing. While this results in only small losses in most metals, it can radically affect the composition of the dielectrics. The dielectrics are also affected by the large amount of radiation in space, which can chemically alter the composition of the dielectric, changing the properties that prompted the selection of that particular dielectric. Large thermal differentials are also possible in space, where the side of an antenna facing the sun could be hundreds of degrees hotter than the side facing away from the sun. This gives rise to shear stresses inside materials, especially materials that have large thermal expansion coefficients. Significant material loss can also occur because of collisions with micrometeorites. Although microscopic in size, the high velocities give the particles large momentums which can be devastating over time.[1]

Even more challenging are the requirements for launching antennas into space and then deploying them in the space environment. To launch antennas into space, the antennas must fit into small, aerodynamic packages. This is normally accomplished by folding or rolling the antennas to fit under aerodynamic covers. The antenna will be exposed to large accelerations and vibrations and must be sturdy enough to withstand the shock of the launch. The weight of the antenna must be minimized to reduce the forces exerted on the antenna during launch and to maximize the efficiency of the launch vehicle. After the antenna has survived the shock of the launch, it must be expanded, or deployed, from the stowed position to its useful shape.[2]

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[1]A. S. Dunbar, Spacecraft Antennas, Ed. by Karl R. Spangenberg, (New York: McGraw-Hill, 1965), pg 107-111.

[2]Dunbar, pg 117-120.

The deployment phase of the antenna design is critical and has caused several failures in recent years which have severely degraded the capability of the mission they were designed to support. One of the most notable failures occurred when the high gain data link antenna aboard the Galileo space probe, launched from the Space Shuttle in October 1989 to explore the planet Jupiter, failed to deploy. As a result of this failure, the antenna is totally useless, and the amount of data that can be transmitted back to earth will be severely limited.[3] Even the Soviet space program has been plagued with antenna deployment failures. A good example of these mechanical problems occurred in the early 1970's with the 10-meter loop antenna used on the Soviet KRT-10 space telescope. After completing their experiments, the Soviets jettisoned the antenna which subsequently became entangled on the back of the Salyut 6 spacecraft. This required the cosmonauts to make an unscheduled space walk to untangle and jettison the antenna.[4] A more recent example occurred in 1989 when a 20-meter loop antenna failed to deploy on the Intercosmos 24 satellite.[5] Table 1 provides a synopsis of recent antenna failures.

Another problem to be considered is the plasma sheath that surrounds the antenna, particularly in a low earth orbit. The shock wave created by an object moving through a region that is not totally devoid of neutral particles can provide the necessary energy

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[3]Michael Kachmar, "Antenna Glitches Imperil the Goals of Space Program," Microwaves & RF, Nov 1991, Pg 47-8.

[4]Vitaliy Sevastyanov, "Man, Earth, Universe," Television broadcast, Moscow, 16 Jun 1990.

[5]Yaroslav Golovanov, "Just Where Are We Flying To?," Izvestiya, Moscow, Dec 1991.

to ionize the residual neutrals. Because of the additional ionization, a plasma sheath surrounds the antenna and can shield the antenna from the environment outside the plasma sheath. This shielding isolates the antenna from incident electromagnetic fields, and prevents electromagnetic fields generated inside the sheath from escaping. This shielding can result in a complete loss of signals, called a blackout, especially during the re-entry stage of a flight into space.[6]

TABLE 1

MECHANICAL ANTENNA PROBLEMS ABOARD SPACECRAFT

Spacecraft	Agency	Launch Date	Mission	Problem
Galileo	NASA	Oct 89	Exploration (Jupiter)	High-gain antenna did not open completely
Intercosmos 24	Soviet	Sep 89	Ionospheric Research	Low frequency loop antenna did not deploy
Anik E2	Telesat (Canada)	Apr 91	Communications	C-band antenna did not deploy
Gamma Ray Observatory	NASA	Apr 91	Astrophysical Research	High-gain antenna did not deploy
Salyut 6	Soviet	Sep 77	KRT-10 Space Telescope	Loop antenna entangled with spacecraft when jettisoned
Hubble Space Telescope	NASA	Apr 90	Astronomical Research	High-gain antenna did not deploy (ensnared by cable)

[6]Adolph S. Jursa, Handbook of Geophysics and the Space Environment, Air Force Geophysics Laboratory, Hanscom Air Force Base, Mass., 1985, Chapter 7, pg 6-9.

Electron Beam and Plasma Antenna Research

Since the early 1970's, there have been a number of proposals to use either an electron beam or a plasma column as an antenna to overcome the mechanical problems of spacecraft antennas and the shielding caused by the formation of the plasma sheath. Because an electron beam is also a plasma column, both types of research are applicable to this paper. In this section of the paper, some of the previous work in plasma and electron beam antennas and the results will be reviewed.

According to Dwyer et al, the earliest proposal to use atmospheric plasmas as the conducting elements of an antenna came in two separate patents by Vaill and Tidman. Both patents suggested that small amounts of laser energy could be used to direct an electric discharge that would provide the necessary ionization energy thus creating a conducting plasma.[7] Since that time, much theoretical and experimental data that supports the initial claims of Vaill and Tidman has been published. Although the radiation of electromagnetic energy from a plasma column or an electron beam has been demonstrated experimentally, the physical processes responsible for the radiation is still subject to interpretation. Numerous theories have been presented, but a universally accepted formulation has not been developed. Because of the vast amount of research in this and related fields, only the highlights will be covered in this paper. Table 2

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[7]Timothy J. Dwyer, et al, "On the Feasibility of Using an Atmospheric Discharge as an RF antenna," IEEE Transactions on Antennas and Propagation, Vol. AP-32, no. 2, Feb 1984, Pg. 141.

contains a summary of the electron beam experiments conducted in the ionosphere that are discussed in this section.

TABLE 2

ELECTRON BEAM EXPERIMENTS IN THE IONOSPHERE

Experiment	Beam Energy (KeV)	Altitude (Kilometers)	Launch Date	Mission
SEPAC	5.0	240	Nov 83	Study VLF Noise and Spacecraft Charging Effects
PICPAB	7.5	240	Nov 83	Study Ionospheric Effects Induced by Charged Particle Beams
FOCUS	10	250	1987	Study Antenna Properties of Electron Beams and Observation of Electromagnetic Flux Caused by Changes in Tectonic Pressure
CHARGE 2	1-10	160-260	Unknown	Observe Beam Plasma Interactions and Electromagnetic Noise Caused by an Electron Beam Injection
27.010 AE	4	246	Apr 78	Study Plasma Dynamics in the Auroral Ionosphere
ARAKS	Unknown	> 140	1975	Observations of Low Frequency Radio Emissions, Artificial Auroras and Electron Precipitation caused by Electron Beam Injection
GEOS 2	1.2	36,000	1983	Measure Magnetospheric E-field Fluctuations
ECHO I	9.5	270	Aug 1970	Create Artificial Auroras in the Conjugate Hemisphere
APEX	Unknown	4-50	Dec 91	Ionospheric and Magnetospheric Research, Solar Interactions, and Antenna Properties of Electron Beams

Some of the initial work in plasma antennas was done in 1975 by Chandra of the Indian Institute of Technology in New Delhi, and Verma of the Birla Institute of

Technology and Science in Pilani, India. In their work, Chandra and Verma analyzed a cylindrical, semi-conducting plasma excited by a filamentary conductor along the axis of the cylinder. The semi-conducting plasma cylinder is surrounded by a gaseous plasma to simulate the effects of a low earth orbit. In later work they considered using an electric current ring to excite the semi-conducting plasma cylinder. These theoretical works only considered cases were the semi-conducting plasma was infinite in length, which is not practical. They discovered that the plasma antenna would carry a traveling electromagnetic wave, and that the direction of primary radiation was a function of plasma density.[8] [9] [10]

On 9 April 1978, a National Aeronautics and Space Administration (NASA) sounding rocket (27.010 AE) was launched to an altitude of 246 km to explore the physics of the auroral ionosphere. That rocket used an electron beam to probe the ionosphere and a separate subsatellite (called a daughter satellite) to correlate the reaction of the ionosphere to the electron beam. This mother-daughter configuration is depicted in Figure 1. The electron beam was current modulated at 3 kHz and had a beam energy of 4 keV with a maximum current of 80 mA. The received electromagnetic energy at

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[8]J. S. Verma, "Plasma Column as an Antenna System," Proceeding of the Indian National Science Academy, Vol. 48, Sec. A, Sup. 2, 1982, pg 279-282.

[9]Ram Chandra and J. S. Verma, "A Modified Plasma Antenna System," Indian Journal of Radio and Space Physics, Vol. 15, Mar 1976, pg 20-22.

[10]Ram Chandra and J. S. Verma, "Electronically Scannable Narrow-beam Plasma Antenna System Using Semiconducting Plasmas," EI's Electrical and Electronics Annual, 1976, pg 85-88D.

the subsatellite was strongest at 3 kHz which correlated to the current modulation frequency. Holzworth and Koons concluded that the plasma was stable at 3 kHz and that the detected energy at the subsatellite was solely attributed to the energy radiated from the electron beam. There was a short time delay in reception which was attributed to Beam Plasma Discharge (BPD), a phenomenon in which the local, neutral atmosphere is ionized by the electron beam energy.[11]

The CHARGE 2 experiment also used a separate subsatellite and an electron beam to probe the ionosphere. This experiment covered altitudes between 160 and 260 km. An electron beam with energies ranging from 1-10 keV was launched parallel to the geomagnetic field. The beam current was not modulated, consequently there was no frequency correlation of the results. Electromagnetic noise was noted in the VLF spectrum during the electron beam firings. The results were attributed to beam atmosphere interactions. A model was developed which did correlate with the measured data; however, the model is dependent on an assumed cross sectional area of the beam. This uncertainty in the beam cross section is a problem in the analysis and must be determined by statistical methods, such as the Monte Carlo technique.[12]

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[11]R. H. Holzworth and H. C. Koons, "VLF Emissions from a Modulated Electron Beam in the Auroral Ionosphere," Report No. SD-TR-80-77, Air Force Systems Command, Space Division, Los Angeles, 1980.

[12]Torsten Neubert and Peter M. Banks, "Plasma Density Enhancements Created by the Ionization of the Earth's Upper Atmosphere by Artificial Electron Beams," HF Heating Conference, Bergan, Norway, 1990.

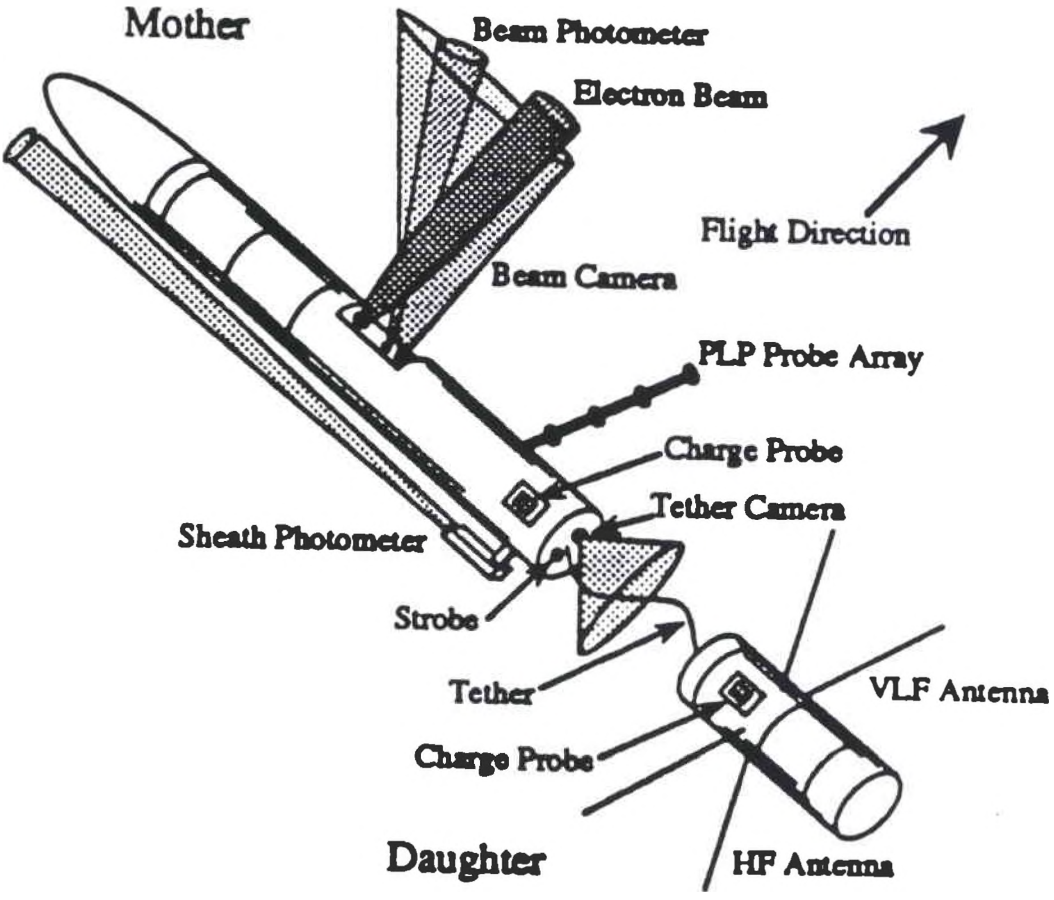

Figure 1: Rocket-borne electron beam experiment using a mother-daughter configuration [Neubert and Banks]

The United States Air Force also investigated modulated electron beams as low frequency antennas. In a 1985 parameter study, a model was developed which assumes an infinite pulse train of electrons which form a helical structure around an ambient geomagnetic field line. The model also assumes that the beam is filamentary (zero diameter) and is not modified by the surrounding plasma. Maxwell's equations are solved using Fourier decomposition in the presence of an anisotropic media. Crude propagation estimates are produced using the results obtained. The report shows that low frequency communications using an electron beam as an antenna is theoretically possible.[13]

NASA has also conducted experiments with electron beams aboard the Space Shuttle. The first of these experiments was proposed by the Japanese, who provided the Space Experiment with Particle Accelerators (SEPAC) package that was lofted to an altitude of 240 km on 28 November 1983 aboard STS-9 as part of the Skylab 1 mission. These experiments were intended to probe plasma effects in the ionosphere, examine spacecraft charging during an electron beam firing, and to measure the VLF electromagnetic noise generated by the electron beam. The experiments did show that a significant amount of VLF noise was generated during the electron beam firings. The electron beam was fired at a number of angles measured relative to the geomagnetic field, but the firings were predominantly parallel to the geomagnetic field. Figure 2 shows a conceptual drawing of the SEPAC experiment. Another related experiment called the Particle Induced by Charged Particle Beams (PICPAB) was also aboard the Skylab 1 mission. PICPAB had a more powerful electron beam than SEPAC, and the beam was current modulated. The configuration of the PICPAB experiment is shown in

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[13]L. E. Johnson, "Experiments in Long-wavelength Communications Using Modulated Electron Beams: A Parameter Study," Pacific-Sierra Research Corp., Rome Air Development Center Report No. RADC-TR-85-133, Los Angeles, August 1990.

Figure 3. As a result of these two experiments, numerous papers have been written on the potential for using electron beams as a space based transmit antenna.[14]

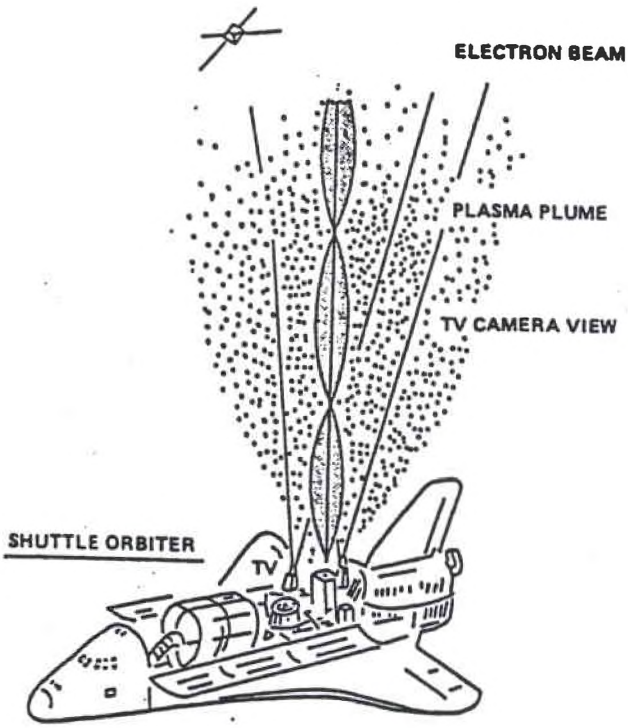

Figure 2: Conceptual Drawing of the SEPAC Experiment [NASA]

[14]T. Obayashi, et al, "Initial Results of SEPAC Scientific Achievement," Earth-oriented Applications of Space Technology, Vol. 5, No. 1, (London: Pergamon Press, 1985), pg 37-45.

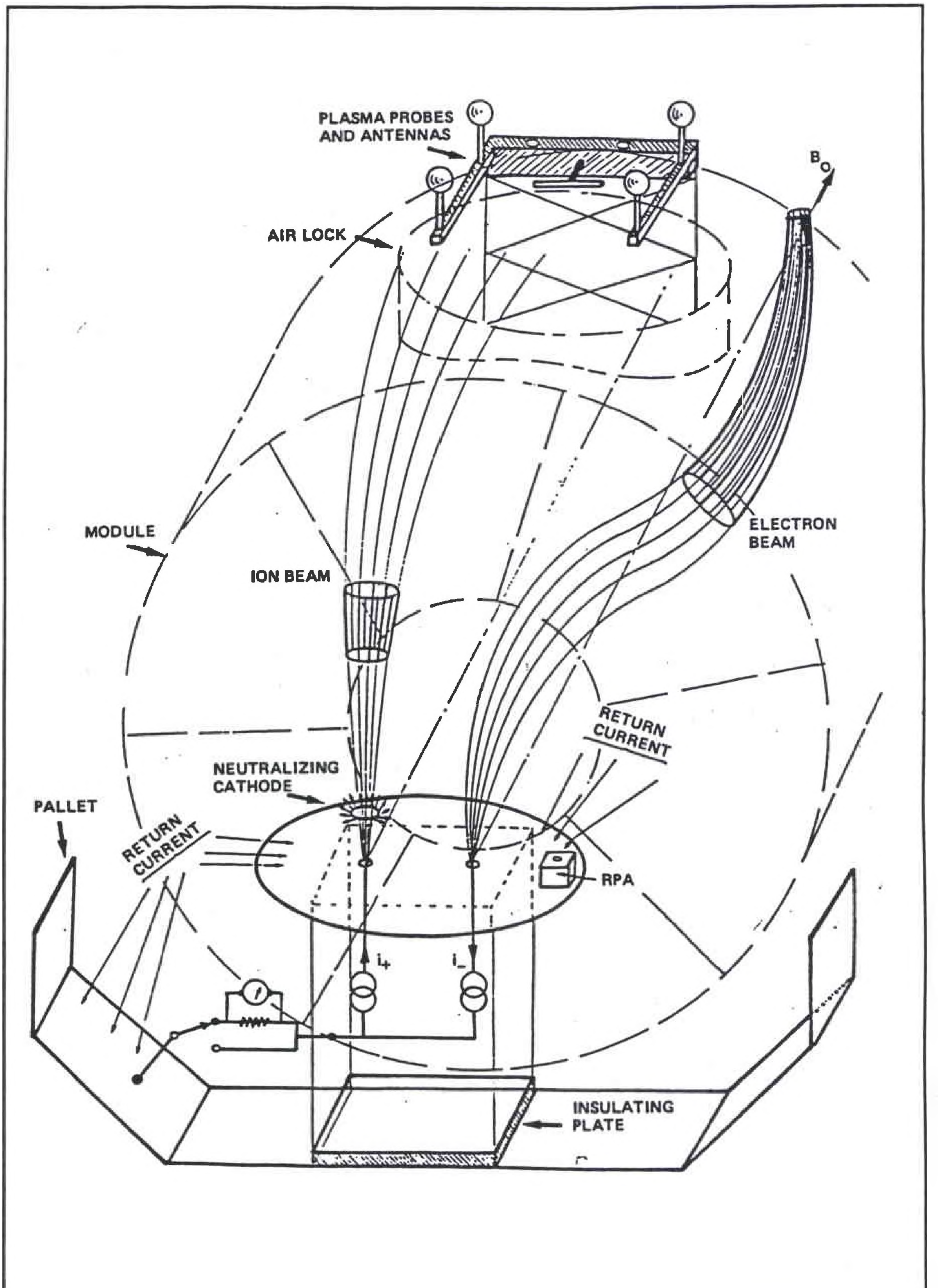

Figure 3: Configuration of the PICPAB Experiment [NASA]

In 1987 Professors Snedkov and Snedkov investigated the radiative properties of electron beams fired parallel to the geomagnetic field. This investigation assumed a current based on the flow of electrons in the beam and substituted that current into the standard radiation integrals for a linear element antenna. The efficiency of this electron beam antenna was computed using the definition of the Pederson conductivity, which deals with the conductivity of a magnetized plasma in the direction parallel to the magnetizing field. In this article, Snedkov and Snedkov dismiss using electron beams with other orientations to the magnetic field because of low efficiency.[15] However, by 1988 Snedkov and Trubitsyn published an article about an electron beam antenna in which the beam was launched orthogonal to the geomagnetic field.[16] In fact, Snedkov and Trubitsyn announced an operational test of their electron beam antenna aboard the Soviet space station MIR in a 1990 television broadcast.[17] A news release in Pravda also announced the successful operational testing of an electron beam antenna called project FOKUS.[18] Figure 4 shows a photograph of the Soviet device published in a Soviet trade journal.

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[15] B. A. Snedkov and A. B. Snedkov, "The Radiative Properties of Injected Electron Beams," radiotekhnika, No. 6, (Moscow: Scripta Technica, 1987), pg 60-2.

[16] B. A. Snedkov, et al, "Electron Gun for Active Experiments," Instruments and Experimental Techniques, Vol. 13, No. 2, Part 2, Mar-Apr 1988, (New York: Consultants Bureau, 1988).

[17] Sevastyanov.

[18] "Comments of MIR Electron Beam Antenna Studies," Pravda, Feb 19, 1989, Moscow.

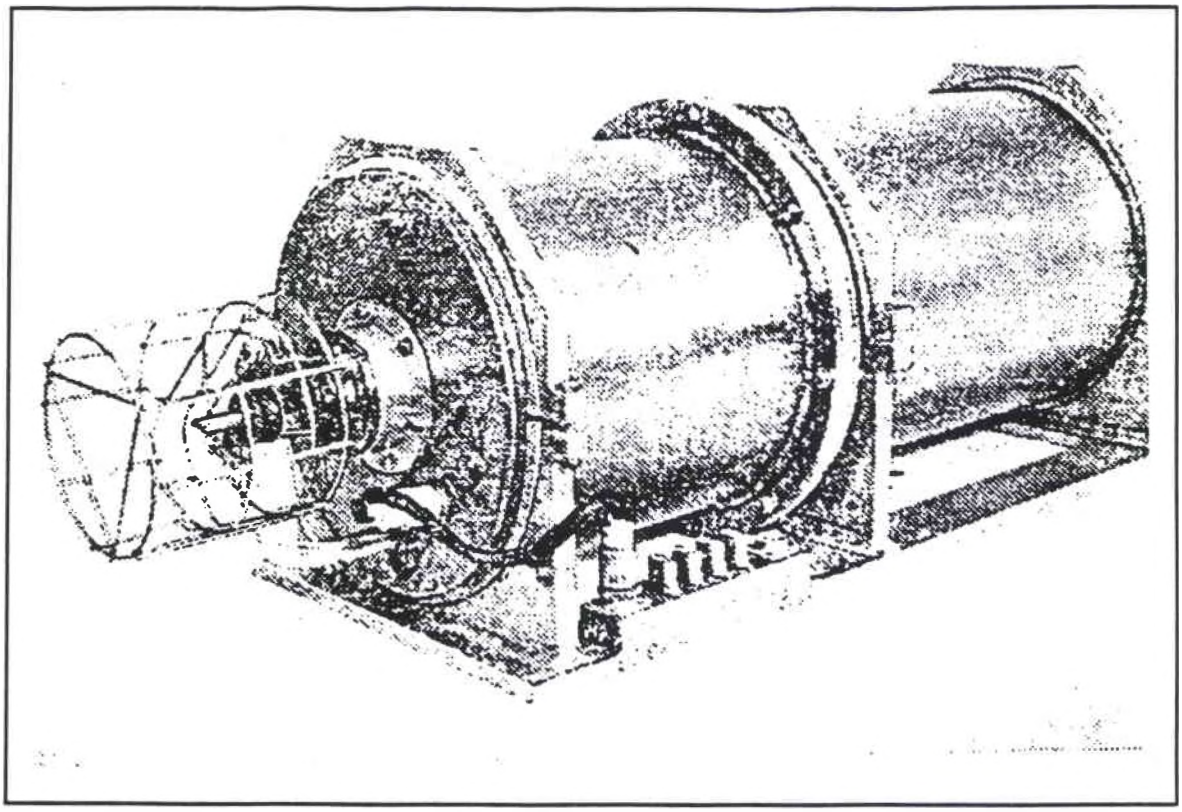

Figure 4: Photograph of the Soviet Electron Beam Antenna Device [Snedkov and Trubitsyn]

The European Space Agency (ESA) used an electron beam loop on the GEOS 2 geostationary satellite to measure magnetospheric electric field fluctuations. Launched in 1983, the GEOS 2 satellite measures the time required for a 1.2 KeV electron beam launched orthogonal to the geomagnetic field to return to the satellite. The transit time is then used to determine the magnitude of the electric field. A magnetometer senses the geomagnetic field and provides attitude control data to the spacecraft. E×B drift velocities are assumed to dominate, and drift velocities of 1-50 kilometers per second can be detected. This makes the sensitivity of the measurement system approximately 0.1

millivolt per meter at 100 nanoteslas.[19] This satellite is particularly important to this thesis because of the similarity between the electron beam probe and the proposed electron beam antenna.

The Echo 1 experiment used a 9.5 KeV electron beam launched parallel to the geomagnetic field to create artificial auroras in the conjugate hemisphere. Echo 1 was lofted in 1970 to an altitude of 270 km aboard a sounding rocket. Geomagnetic field lines reach a maximum separation near the equator and converge in the polar regions. The points in the northern and southern hemispheres that share common magnetic flux lines are called conjugate points. The electrons launched from Echo 1 would travel parallel to the geomagnetic field lines. When the flux lines converge beyond a certain point, the electrons cannot pass between the field lines and they will reflect back toward to opposing conjugate point. An artificial aurora is created at the reflection point, and Echo 1 measured the magnitude of the return current caused be the reflection.[20]

In 1975, the French and the Soviets performed a series of joint rocket borne experiments that used an electron beam to probe the ionosphere. These experiments were given the project name ARAKS. Measurements for the ARAKS experiments

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[19]H. Junginger, et al, "A Statistical Study of Dayside Magnetospheric Electric Fluctuations with Periods Between 150 and 600 s," Journal of Geophysical Research, vol. 89, no. A7, pg 5495, Jul 1984.

[20]D. G. Cartwright and P. J. Kellogg, "Observations of Radiation from an Electron Beam Artificially Injected into the Ionosphere," Journal of Geophysical Research, vol. 79, no. A10, pg 1439, (1974).

showed that the backscattered electrons from the electron beam in the vicinity of the rocket were 1 to 2 orders of magnitude higher than predictions based on collisional theory. The magnitude of backscattered electrons above 140 km remain relatively constant. Artificial auroras and electron precipitation caused by multiple reflections between conjugate points similar to the Echo 1 experiments were observed, and low frequency electromagnetic emissions were detected.[21]

The Soviet APEX (APEhKS), also called Intercosmos 25, is satellite borne experiment similar to the ARAKS experiments. Apex was launched in December 1991 and was the first satellite to be launched into a highly elliptical orbit. This makes APEX the first experiment to use an electron beam probe at altitudes above 300 km. APEX uses a separate subsatellite, called Magion, to measure the response from both electron beam and plasma injections into the ionosphere.[22] Data from the APEX experiment is still being assimilated, so very little reporting is available. The stated purpose of the APEX experiment are:[23]

1. Initiation and observation of auroras and radio emissions in the auroral region.

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[21]V. N. Oraevskij, E. V. Mishin, and Yu. Ya. Ruzhin, "Artificial Injection of Charged Particles in Near-Earth Space," Electromagnetic and Plasma Processes from the Sun to the Earth's Core, (Moscow: Nauka Press, 1989).

[22]newspaper release

[23]Oraevskij, Mishin, and Ruzhin.

2. Study the dynamics of electron and plasma bunches in the near earth ionospheric plasma.

3. Study the electrodynamic coupling of electromagnetic waves in the magnetosphere and ionosphere.

4. Study non-linear wave structures in the disturbed ionosphere.

5. Study the radio emission characteristics of modulated plasma columns and electron beams.

Figure 5 shows a schematic diagram of the APEX experiment presented at the Committee on Space Research (COSPAR) conference, 1990 in Bergen, Norway.

Experiments with electron beams and plasma antennas have also been conducted in terrestrial laboratories, usually in a plasma chamber. These chambers allow scientists to duplicate small scale space plasmas in evacuated chambers. While the low density space environment can be duplicated in these laboratories, the microgravity conditions cannot. For small particles like electrons, the increase in gravity still has a negligible effect, but larger particles like ions may encounter field distortions which will not be encountered in the space environment. Three such terrestrial experiments are discussed in this thesis.

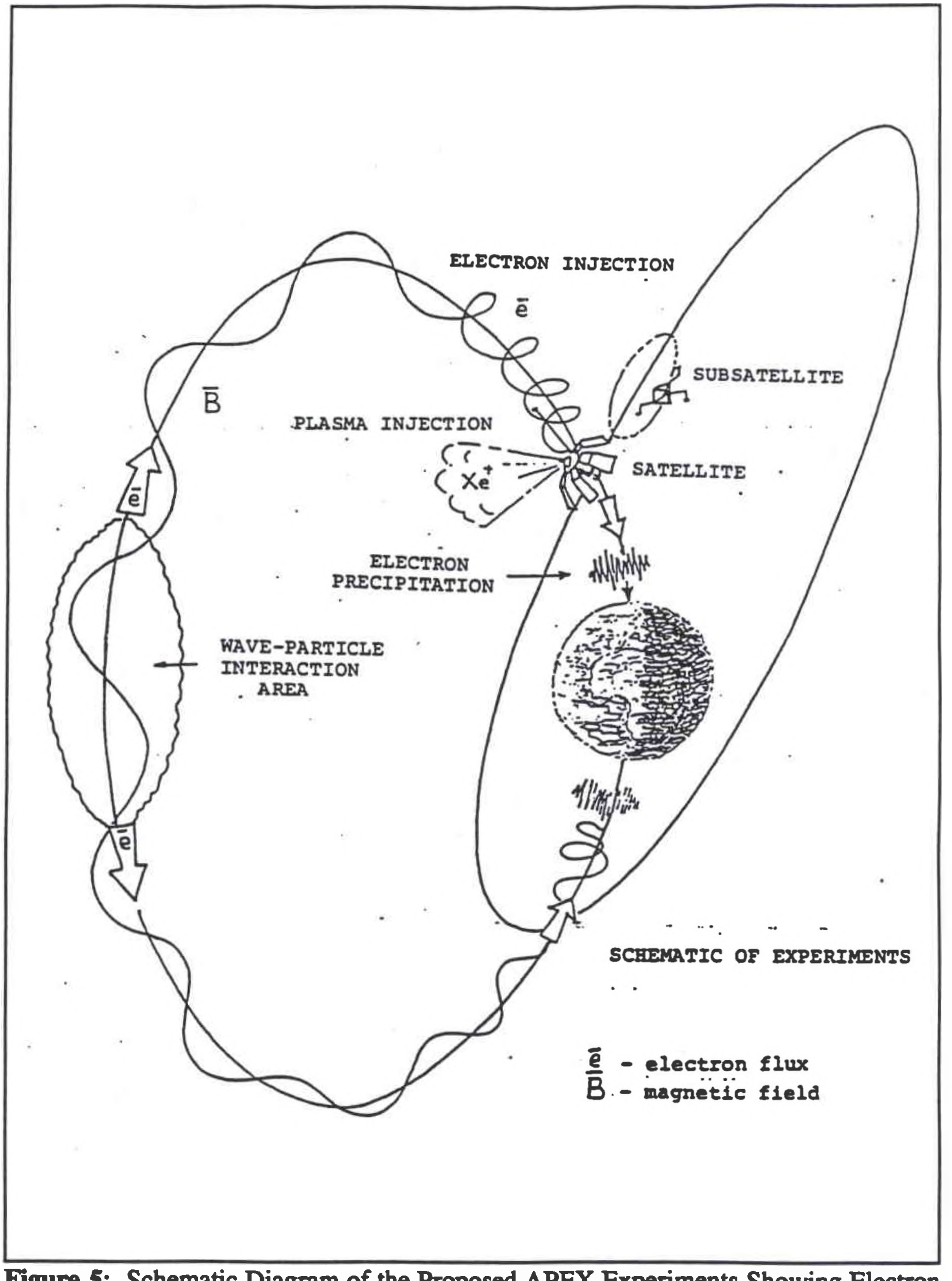

Figure 5: Schematic Diagram of the Proposed APEX Experiments Showing Electron Precipitation Caused by Multiple Reflections Between Conjugate Points in the Magnetosphere [COSPAR]

In a proof of concept experiment, Dwyer et al used a plasma column generated in the normal atmosphere using laser beams as an antenna. The experimental

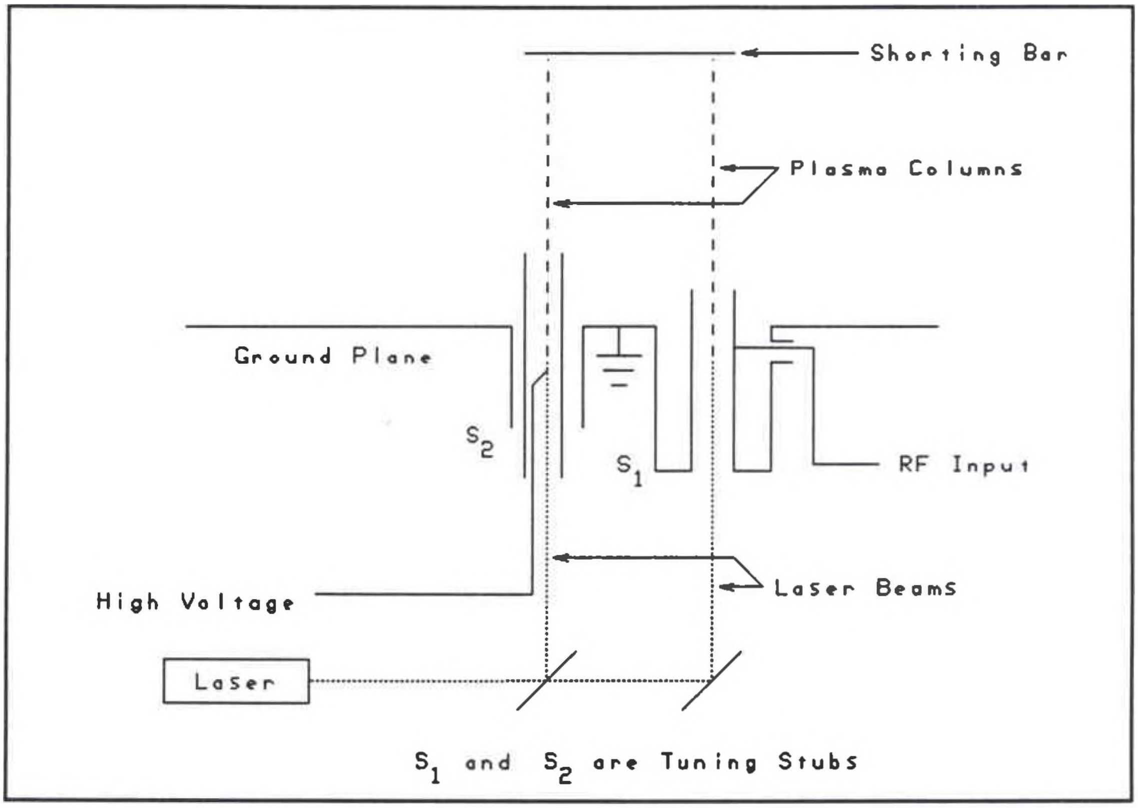

Figure 6: Proof of Concept Experimental Arrangement (Dwyer, et al)

arrangement is shown in Figure 6. A folded monopole geometry was used to make both ends of the beam accessible for the experiment. A high voltage source provided the ionizing energy, and a 112 MHz RF field was coupled to the other end of the plasma antenna. The reference antenna was another folded monopole antenna constructed of copper. The plasma antenna was used both as a transmitting and a receiving antenna and was found to operate almost as well as the reference antenna (0 to -2 dB relative to the reference antenna). Problems in sustaining the plasma limited the experimental durations to approximately 2 milliseconds.[24] While this antenna is not practical, it does demonstrate the capability of a plasma column to operate as an RF antenna.

The Japanese used a plasma chamber for some of the preliminary work leading to the SEPAC experiments aboard Spacelab 1. These experiments were conducted in the National Space Development Agency (NASDA) Space Chamber located at Tsukuba, Japan. In these experiments, the Japanese measured the effects of electromagnetic interference (EMI) of an electron beam firing in a simulated space environment. The electron beam was fired for a period of one second with the EMI measurements being take for a 0.8 second interval beginning 0.15 second after the electron beam firing was initiated. Significant broadband noise was observed during the electron beam firings.[25] The electron beam was not modulated, so there is no frequency correlation in the observed

Figure 7: Photograph of an Electron Beam Test in the NASDA Space Chamber [NASA]

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[24]T. Dwyer, et al, "Characteristics of an Atmospheric Discharge Plasma as an RF Antenna," Naval Research Laboratory, Report No. 4815, May 1982.

[25]Tatsuzo Obayashi, et al, "SEPAC System Test in NASDA Space Chamber," Institute of Space and Astronautical Science, Report No. 599, Tokyo, Japan, Jun 1982.

results, and the broadband noise is primarily attributed to beam-plasma interactions. Figure 7 shows a photograph of the NASDA electron beam experiment showing the characteristic curvature of the electron beam cause by the geomagnetic field.

Purpose of This Study

This study will examine the effects of a time varying electromagnetic wave on an electron beam launched orthogonal to the Earth's geomagnetic field. The primary focus of the paper will be on the capability for such an electron beam to function as either a transmitting or a receiving antenna. This report will not consider the coupling of an electromagnetic wave to the surface of the electron beam, as suggested by some previous works, because of the difficulty in defining the surface of the electron beam, and because the electron beam is free to move in three dimensions depending on the forces applied to the antenna. Interactions between the electron beam and the ambient plasma, including plasma instabilities caused by the injection of an electron beam into a tenuous plasma, are beyond the scope of the report and are not considered.

CHAPTER II

ELECTRON BEAMS IN SPACE

Single Electrons in Static Electric and Magnetic Fields

The movement of an electron in the presence of a strong magnetic field is given by the Lorentz force law. In this section, only static fields are considered because this condition closely approximates the intended case of an electron beam traveling under the influence of the Earth's geomagnetic field. The Lorentz force law is given as:

$$\bar{F}_M = q\bar{v} \times \bar{B} = q|\bar{v}||\bar{B}| \sin\theta \ \hat{n} \tag{1}$$

where $\bar{F}_M$ is the force (in Newtons) exerted on the electron by the magnetic field, q is the charge of the electron in coulombs, $\bar{v}$ is the velocity vector of the electron in meters/second, $\bar{B}$ is the magnetic field vector in webers/meter, θ is the angle between $\bar{v}$ and $\bar{B}$, and $\hat{n}$ is the unit vector perpendicular to $\bar{v}$ and $\bar{B}$ with a direction defined by the right-hand rule. If the electron's path (velocity vector) is perpendicular to the magnetic field, then the acceleration vector ($\bar{a}$) will be orthogonal to the velocity vector, and the electron's trajectory will be a circle in the plane perpendicular to the magnetic field as shown in Figure 8. The circle with a centered dot indicates that the B-field vector points out of the plane of the paper. Because of the dependence on electron velocity, the magnetic field will have no effect on an electron at rest.

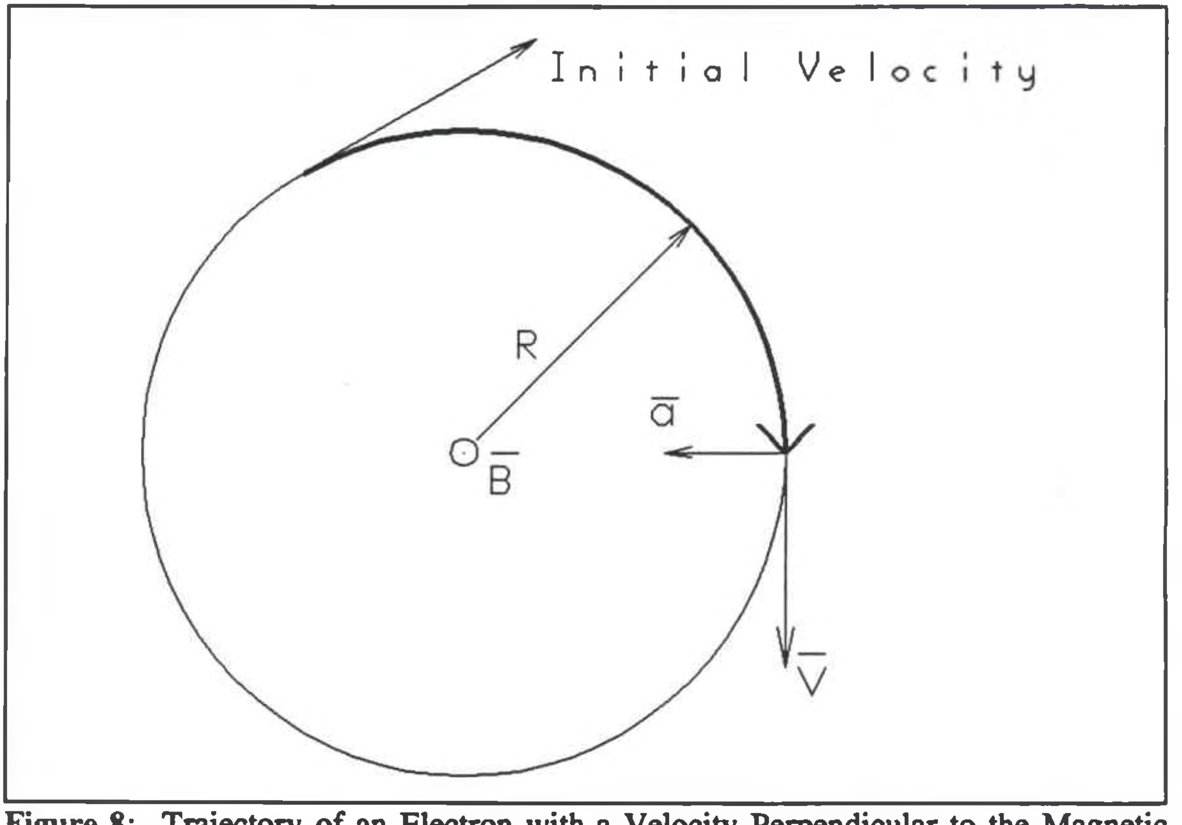

Figure 8: Trajectory of an Electron with a Velocity Perpendicular to the Magnetic Field

If the electron's velocity vector is parallel to the magnetic field, then the electron's path or trajectory will not be altered by the presence of the magnetic field. This implies that electron beams launched parallel to the geomagnetic field will follow a roughly linear path, which has been the assumption of most previous work. Since the geomagnetic field lines are actually curved, a linear electron beam will develop a perpendicular velocity component, but because of the large scale of the geomagnetic field curvature relative to the short assumed length of the linear electron beam, the perpendicular velocity component is negligible. An electron beam launched at any angle between the two cases cited will contain elements of both a circular and a linear trajectory, thus forming a helical trajectory.

The radius (R) of the electron's trajectory when launched perpendicular to a magnetic field is found by setting the magnetic force equal to the centrifical force and solving for the radius:

$$R = \frac{m|\bar{v}|}{q|\bar{B}|} \tag{2}$$

where m is the mass of the electron. The electron moves along this circular path with an angular velocity called the cyclotron or gyro frequency, which is given by:

$$\omega_c = \frac{|\bar{v}|}{R} = \frac{q}{m}|\bar{B}| \tag{3}$$

In order for equations 2 and 3 to be valid, the velocity of the electron ($\bar{v}$) is assumed to be constant in the region of interest. If the velocity changes are small relative to the initial velocity, then the velocity may be considered constant. Furthermore, this velocity must also be small relative to the speed of light; otherwise, the electron mass will not be a constant because of relativistic effects. An electron velocity one order of magnitude or more smaller than the speed of light ($0.1c$) is sufficient to meet nonrelativistic conditions.

In the presence of an electrostatic field, the electron will be accelerated in a direction parallel to the electric field. This acceleration does not require some initial velocity as in the case for the magnetostatic field. The force on the electron is given by:

$$\bar{F}_E = q\bar{E} \tag{4}$$

If the electron has no initial velocity, the final velocity and the energy of the electron can be determined by knowing the value of the electric field used to accelerate the electron. This formula is useful for determining the velocity of the electron beam at the point where it will be inserted into the geomagnetic field. Figure 9 shows the movement of an electron in an electrostatic field.

$$E = \frac{1}{2}m\,|\bar{v}|^2 = eV_a \tag{5}$$

V_a is the potential between the cathode producing the electrons and the anode used to accelerate the electrons. This potential difference in turn determines the size of the circular path when the electron is launched perpendicular to the magnetostatic field.

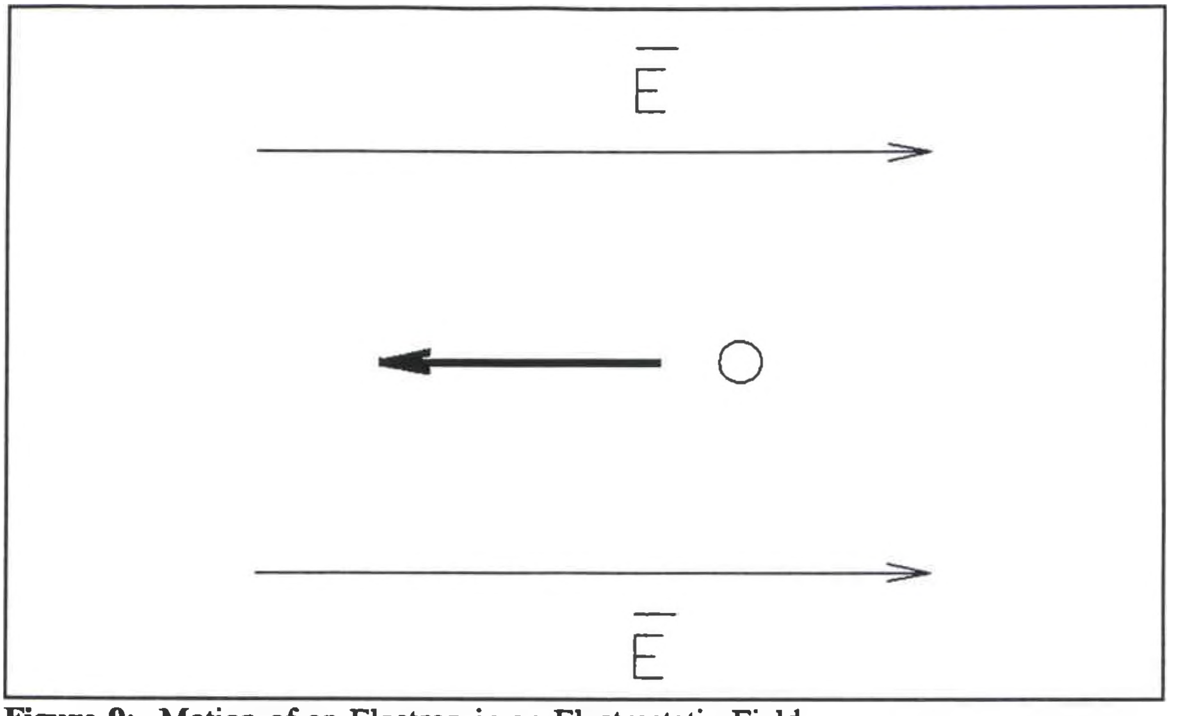

Figure 9: Motion of an Electron in an Electrostatic Field

Next, consider an electron moving in a combined electromagnetic field. For a complete treatment of electrons in a combined electric and magnetic field, see Bakisk[26] or Artsimovich and Lukyanov.[27] The force on the electron can be found by adding equations (1) and (4). Since only non-relativistic velocities will be considered, the acceleration is found by dividing the force by the mass of the electron giving:

$$\frac{d\bar{v}}{dt} = \frac{e}{m}(\bar{E} + \bar{v}\times\bar{B}) \tag{6}$$

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[26]Robert Bakish, Ed., Introduction to Electron Beam Technology, Wiley & Sons, New York, 1962, Pg 37-43.

[27]Artsimovich and Lukyanov, pg 105-121.

where e is the charge (q) of an electron. Because the electric field will accelerate an electron at rest, the initial velocity can be zero. There are two cases to be considered: one with the electric field parallel to the magnetic field and one with the electric field perpendicular to the magnetic field.

Considering first the case of parallel static fields, the scalar accelerations may are written from equation (6) as:

$$v_x' = \frac{e}{m} v_y B_z \tag{7}$$

$$v_y' = -\frac{e}{m} v_x B_z \tag{8}$$

$$v_z' = \frac{e}{m} E_z \tag{9}$$

The prime notation indicates differentiation with respect to time. Equation (7) and (8) are coupled and represent the affects of only the static magnetic field. Equation (9) is completely independent of the velocities in (7) and (8) and represents only the contribution from the static electric field. Both fields are completely decoupled in these equations and may be considered separately. The superposition of the two independent motions creates the helical trajectory shown in Figure 10.

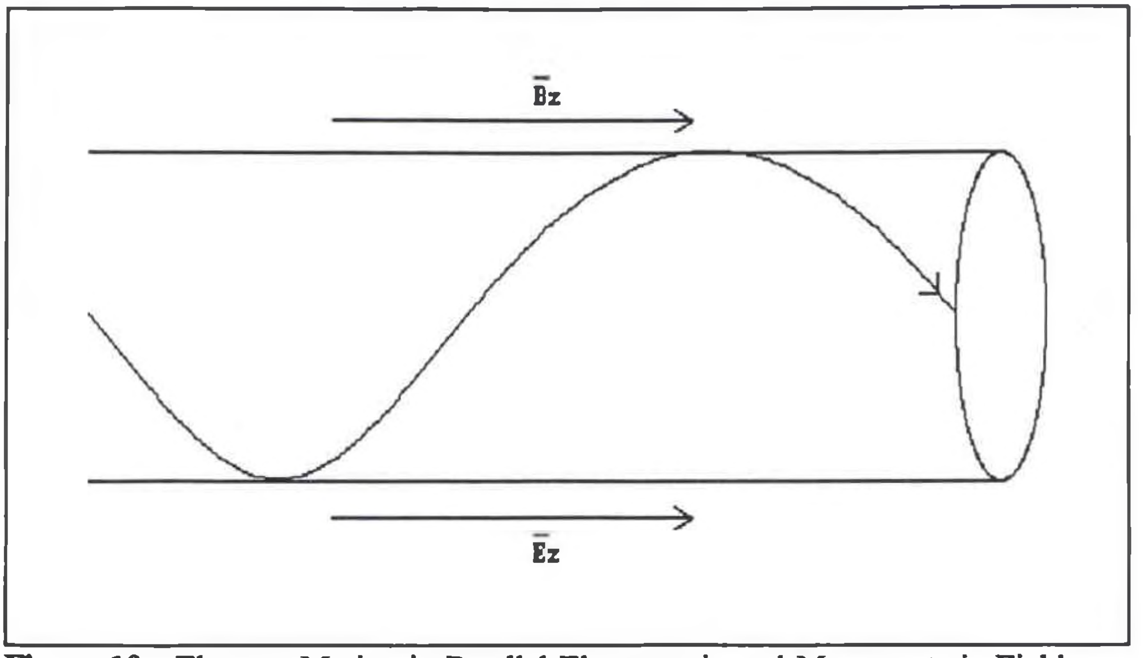

Figure 10: Electron Motion in Parallel Electrostatic and Magnetostatic Fields

In the case of perpendicular static fields, the coupling between the three scalar acceleration equations is evident.

$$v_x' = \frac{e}{m} v_y B_z \tag{10}$$

$$v_y' = \frac{e}{m}(E_y - v_x B_z) \tag{11}$$

$$v_z' = 0 \tag{12}$$

The solution to this system of differential equations is easily obtained:

$$v_y = C_1\cos(\omega_c t) + C_2\sin(\omega_c t) \tag{13}$$

$$v_x = \frac{E_y}{B_z} + C_1\sin(\omega_c t) - C_2\cos(\omega_c t) \tag{14}$$

$$v_z = C_3 \tag{15}$$

The constants in these equations are obtained from the initial velocities in the three principle directions. These equations show that the only velocities induced by the two perpendicular fields are the circular motion in the x-y plane caused by the magnetic field, and a linear velocity in the x-direction. Because this linear velocity is perpendicular to both the electric and magnetic fields, it is usually called the E×B drift. The trajectory for the case of an electron's motion in perpendicular static fields is given in Figure 11.

Electrons in Time Varying Electromagnetic Fields

Referring to Figure 12, assume that there is a static magnetic field that corresponds to the geomagnetic field oriented in the z-direction. There is also an incident electromagnetic field which can be described as:

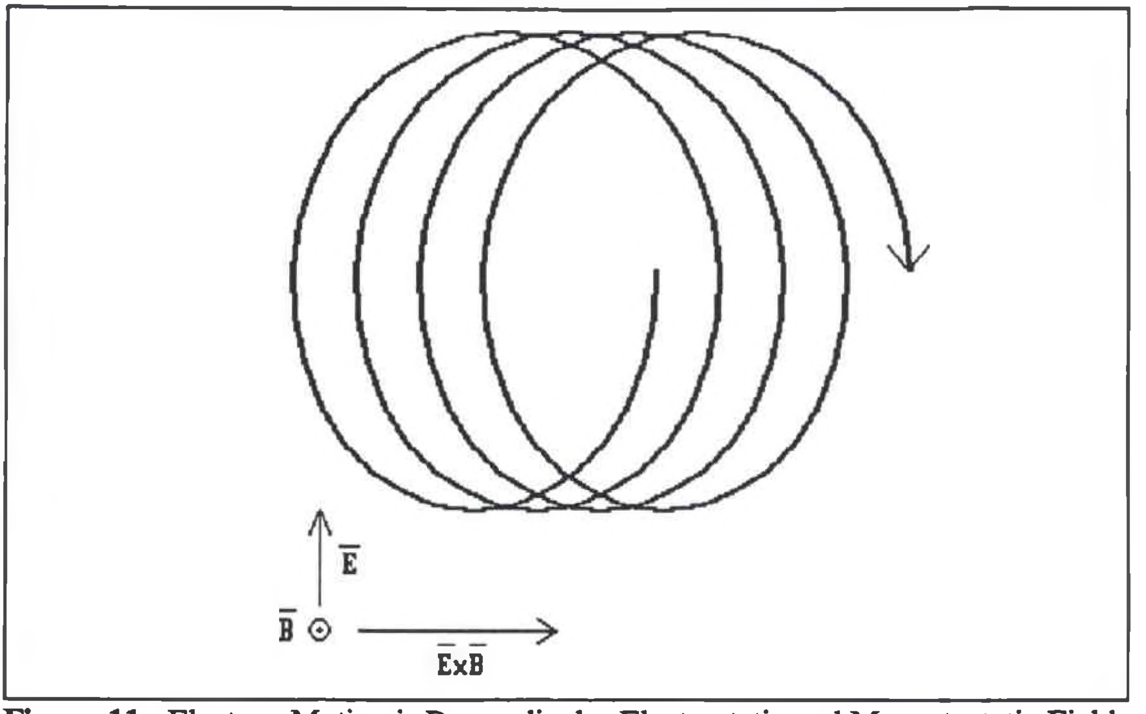

Figure 11: Electron Motion is Perpendicular Electrostatic and Magnetostatic Fields

$$\bar{E}_i = -E_i\, e^{j(\omega t - \beta y)}\, \hat{x} = -E_x \hat{x} \tag{16}$$

$$\bar{B}_i = \frac{E_i}{\eta} \mu_0 e^{j(\omega t - \beta y)}\, \hat{z} \tag{17}$$

where η is the impedance of free space (approximately 377 ohms) and μ_0 is the permeability of the medium. The total B-field is given by the summation of the static and incident fields and is given by:

$$\bar{B} = \bar{B}_g + \bar{B}_i = B_z \hat{z} \tag{18}$$

Separating the velocity into components and taking the cross product with the B-field gives:

$$\bar{v} \times \bar{B} = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ v_x & v_y & v_z \\ 0 & 0 & B_z \end{vmatrix} = v_y B_z \hat{x} - v_x B_z \hat{y} \tag{19}$$

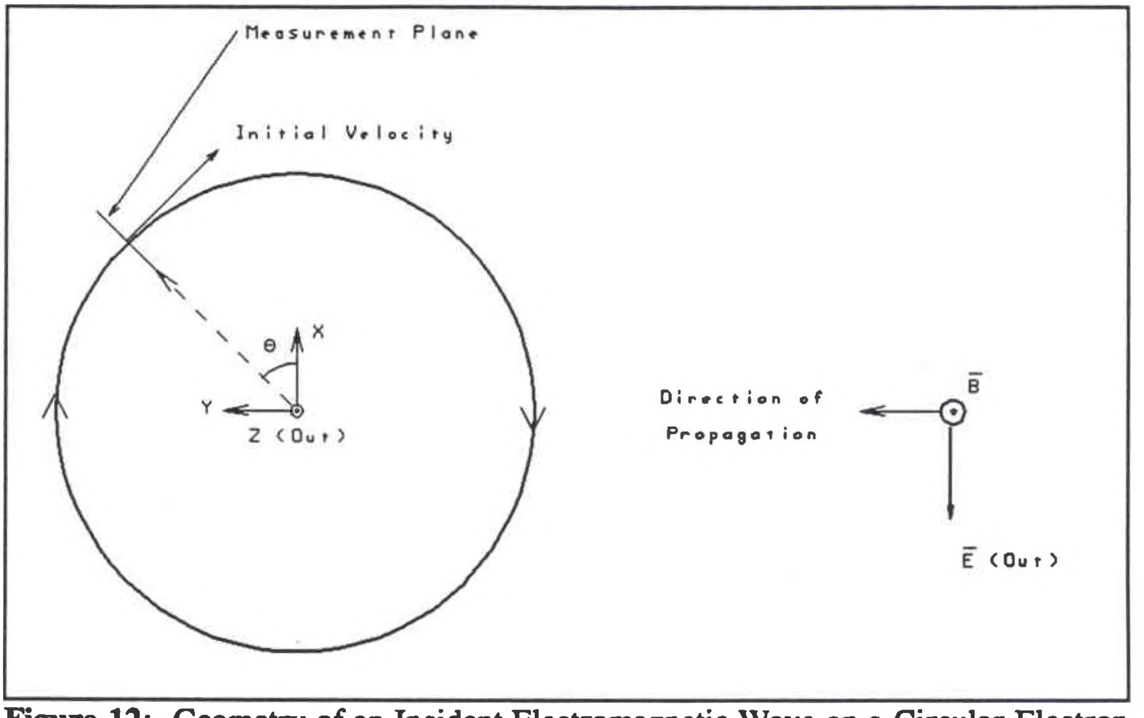

Figure 12: Geometry of an Incident Electromagnetic Wave on a Circular Electron Beam with the Incident Magnetic Field Parallel to the Geomagnetic Field

Substituting (19) into the Lorentz equation and separating the result into scalar equations gives:

$$v_x' = \frac{e}{m}(-E_x + v_y B_z) \tag{20}$$

$$v_y' = \frac{e}{m}(-v_x B_z) \tag{21}$$

$$v_z' = 0 \tag{22}$$

where *e* and *m* are the charge and mass of the electron respectively, and the prime notation indicates differentiation with respect to time. Equation (22) shows there is no velocity in the z-direction if there is no initial velocity in that direction. Since time harmonic fields are being assumed, all high order derivatives will exist and will be continuous. Solving equation (21) for v_x, differentiating, and setting it equal to equation (20) yields the following differential equation:

$$v_y'' - \frac{B_z'}{B_z}v_y' + \left(\frac{e}{m}B_z\right)^2 v_y - \left(\frac{e}{m}\right)^2 B_z E_x = 0 \tag{23}$$

Equation (23) is a second order, non-homogeneous, non-linear differential equation with variable coefficients which is a formidable problem to solve. The equation is non-linear because the incident fields are dependent on the position of the electron which is the integral of the velocity. If the diameter of the loop is constrained to be small relative to a wavelength in free space, then the change in the field as a function of position is small and can be ignored. The following constraint is sufficient to linearize equation (23):

$$d \le \frac{\lambda}{10\pi} \tag{24}$$

where λ is the wavelength of the incident field. Equation (23) can be further simplified when the relative magnitude of the static, geomagnetic field is compared to the incident magnetic field. Assuming an incident electric field of 100 microvolts per meter, the incident magnetic field will be:

$$B_i = \frac{E_i}{\eta}\mu_0 = \frac{100}{377}(4\pi\times10^{-7}) = 3.33\times10^{-7}\frac{\mu A}{m^2} = 3.33\times10^{-9}\,Gauss \tag{25}$$

where μ_0 is the permeability of free space, and η is the impedance of free space. The static geomagnetic field is given by:

$$B_g \approx 0.31\left(\frac{R_e}{r}\right)^3 Gauss \tag{26}$$

where R_e is the average radius of the earth (6370 km) and r is the altitude in kilometers.[28] At an altitude of 300 km, the geomagnetic field is approximately 0.27 Gauss, which is 8 orders of magnitude greater than the incident magnetic field given in equation (25). The incident magnetic field is also 9 orders of magnitude smaller than the

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[28]R. W. Shunk, "The Terrestrial Ionosphere," Solar-Terrestrial Physics, Ed. by R. L. Carovillano and J. M. Forbes, 1987, pg 609-676.

incident electric field. Using this information to evaluate the coefficients in equation (23) gives:

$$\frac{B_z'}{B_z} = \frac{j\omega B_i e^{j\omega t}}{B_g + B_i e^{j\omega t}} \approx 0 \tag{27}$$

$$B_z^2 = B_g^2 + B_g B_i e^{j\omega t} + B_i^2 e^{2j\omega t} \approx B_g^2 \tag{28}$$

$$B_z E_x = B_g E_i e^{j\omega t} + B_i E_i e^{2j\omega t} \approx B_g E_i e^{j\omega t} \tag{29}$$

Using the definition of the electron gyro frequency in (3), which is the frequency at which electrons will circulate around the geomagnetic field:

$$\omega_c = \frac{e}{m} B_g \tag{30}$$

and combining this information with equations (24) and (27) through (29) into equation (23) yields an ordinary, linear, non-homogeneous differential equation that can be evaluated easily.

$$v_y'' + \omega_c^2 v_y - \frac{e}{m}\omega_c E_i e^{j\omega t} = 0 \tag{31}$$

The homogeneous solution to (31) is well known, and is given by:

$$v_y = C_1 \cos(\omega_c t) + C_2 \sin(\omega_c t) \tag{32}$$

where the constants C_1 and C_2 are determined from the initial velocity of the electron. This part of the solution gives the characteristic curvature to the electron's trajectory and accounts for the circular loop of the beam. The non-homogeneous part of the solution is found by assuming a solution in the form of a constant multiplied by the time exponential, substituting into (31) and solving for the constant. The total solution for (31) is given by:

$$v_y = C_1 \sin(\omega_c t) + C_2 \cos(\omega_c t) + \frac{eE_i}{m}\left(\frac{\omega_c}{\omega_c^2 - \omega^2}\right)e^{j\omega t} \tag{33}$$

The result in (33) is not surprising. It can be shown that for non-relativistic velocities, the electric field effects on an electron's trajectory dominates over the magnetic field affects.[29] This implies that the incident electric fields will have a much more pronounced effect on the electron trajectory than the incident magnetic field. The sensitivity of the electron beam loop to the electric field comes from the electron's freedom to move in three dimensions. The standard loop antenna with the constraint given in (24) is sensitive to the magnetic field, not the electric field because the electrons

[29]Peter T. Kirstien, Gordon S. Kino, and William E. Waters, Space-Charge Flow, McGraw-Hill: New York, 1967, pg 6-7.

in the metallic loop are prevented from moving in directions perpendicular to the filamentary conductor. The particular solution in (33) corresponds to the E×B drift of the static field case given in (14).

Differentiating (33), substituting into (21) and solving for the velocity in the x-direction gives:

$$v_x = j\omega \frac{eE_i}{mB_z} e^{j\omega t} \left(\frac{\omega_c}{\omega_c^2 - \omega^2} \right) - C_1 \cos(\omega_c t) + C_2 \sin(\omega_c t) \tag{34}$$

Equation (34) also shows a time dependence coupled to the incident electric field, and a constant circular trajectory caused by the large, static geomagnetic field. The particular solution in (34) corresponds to a drift caused by the time varying fields called the polarization drift.[30]

The velocity in the z-direction is found by integrating (22):

$$v_z = C_3 \tag{35}$$

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[30]Francis F. Chen, Introduction to Plasma Physics and Controlled Fusion, Volume 1: Plasma Physics, 2nd ed., Plenum Press, New York, 1984, pg 39-40.

Equation (35) shows that the electromagnetic fields cause no electron motion in the z-direction; therefore, the only motion in the z-direction is caused by the initial velocity in the z-direction which corresponds to the constant C_3.

Both equations (33) and (34) have the following restriction for the incident electric field frequency (ω) to prevent the velocities from becoming infinite:

$$\left(\frac{\omega_c}{\omega_c^2 - \omega^2}\right) < \infty \quad \therefore \quad \omega_c < \omega \tag{36}$$

This restriction comes from the assumption made in (24) and can be derived by setting the diameter in (24) equal to twice the gyroradius (2):

$$d = \frac{v}{2\omega_c} \leq \frac{\lambda}{10\pi} \tag{37}$$

Since the velocity must be non-relativistic for this development to hold, the maximum velocity may be taken to be $0.1c$, where c is the velocity of light in the medium. Using (37) to solve for the maximum frequency gives:

$$\omega \leq \frac{2\pi c}{\lambda} = \frac{2\pi c}{\frac{20\pi}{\omega_c}(0.1c)} = \omega_c \tag{38}$$

Next, consider an incident electromagnetic field as shown in Figure 13 with the fields given by:

$$\bar{E}_i = E_i e^{j(\omega t + \beta y)}\hat{z} = E_z\hat{z} \tag{39}$$

$$\bar{B}_i = \frac{E_i}{\eta}\mu_0 e^{j(\omega t + \beta y)}\hat{x} = B_x\hat{x} \tag{40}$$

Therefore, the total B-field is given by:

$$\bar{B} = B_x\hat{x} + B_z\hat{z} \tag{41}$$

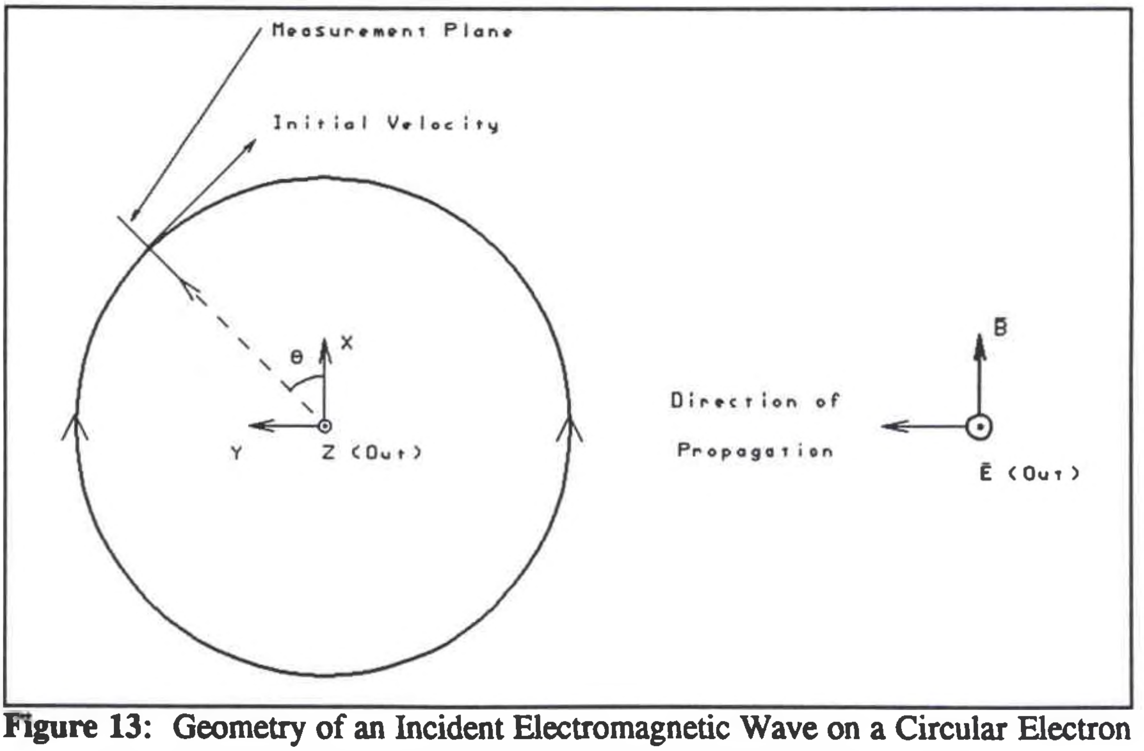

Figure 13: Geometry of an Incident Electromagnetic Wave on a Circular Electron Beam with the Incident Electric Field Parallel to the Geomagnetic Field

where B_z is the static, geomagnetic field. Following the same development as before, the three scalar equations for acceleration are:

$$v_x' = \frac{e}{m}(v_y B_z) \tag{42}$$

$$v_y' = \frac{e}{m}(v_z B_x - v_x B_z) \tag{43}$$

$$v_z' = \frac{e}{m}(E_z - v_y B_x) \tag{44}$$

Using these equations to derive the differential equation in terms of v_x yields:

$$v_x''' + \left(\frac{B_x'}{B_x}\right)v_x'' + (\omega_{cz}^2 - \omega_{cx}^2)v_x' + \omega_{cz}^2\left(\frac{B_x'}{B_x}\right)v_x - \left(\frac{e}{m}\right)^2 B_x B_z E_z = 0 \tag{45}$$

where the x and z subscripts appended to the gyrofrequency indicates the B-field causing that gyrofrequency. Again, the small loop assumption is needed to linearize (45). Noting that the term:

$$\frac{B_x'}{B_x} = j\omega \tag{46}$$

and taking advantage of orthogonality allows (45) to be separated into two equations which are in quadrature (90 degrees time phase) with respect to each other. Because of the difference in magnitudes between the incident and geomagnetic fields, the following substitution is possible:

$$\omega_{cz} >> \omega_{cx} \quad \therefore \quad \omega_{cz}^2 - \omega_{cx}^2 \approx \omega_{cz}^2 \equiv \omega_c^2 \tag{47}$$

The resulting accelerations are:

$$v_x''' + \omega_c^2 v_x' - \left(\frac{e}{m}\right)^2 B_x B_z E_z = 0 \tag{48}$$

$$j\omega v_x'' + j\omega\, \omega_c^2 v_x = 0 \tag{49}$$

The homogeneous solutions for both differential equations is similar to (32). Because (49) has no relationship to the incident fields, it is of little value in this analysis. The particular solution for (48) can be found by assuming a solution in the form of a constant multiplied by the time exponential squared. However, noting the small magnitudes of the incident fields, the non-homogeneous term in (49) is approximately zero which means the incident fields have a small and negligible affect on the velocity in the x-direction. Therefore, the particular solutions for v_x and v_y are zero. Substituting this information into (44) and integrating gives the particular solution for v_z:

$$v_z = -j\frac{e}{m\omega}E_i e^{j\omega t} \tag{50}$$

The result agrees with the static field case where the electric field is parallel to the magnetic field. The velocity induced by the electric field is completely decoupled from the velocity induced by the magnetic field.

In the final case, an electromagnetic wave is assumed to be propagating along the geomagnetic field. This case is shown in Figure 14 with the incident fields given by:

$$\bar{E}_i = E_i e^{j(\omega t + \beta z)}\hat{x} = E_x\hat{x} \tag{51}$$

$$\bar{B}_i = \frac{E_i}{\eta}\mu_0 e^{j(\omega t + \beta z)}\hat{y} = B_y\hat{y} \tag{52}$$

Combining (51) and (52) with the static magnetic field and solving for the accelerations yields:

$$v_x' = \frac{e}{m}(E_x + v_y B_z - v_z B_y) \tag{53}$$

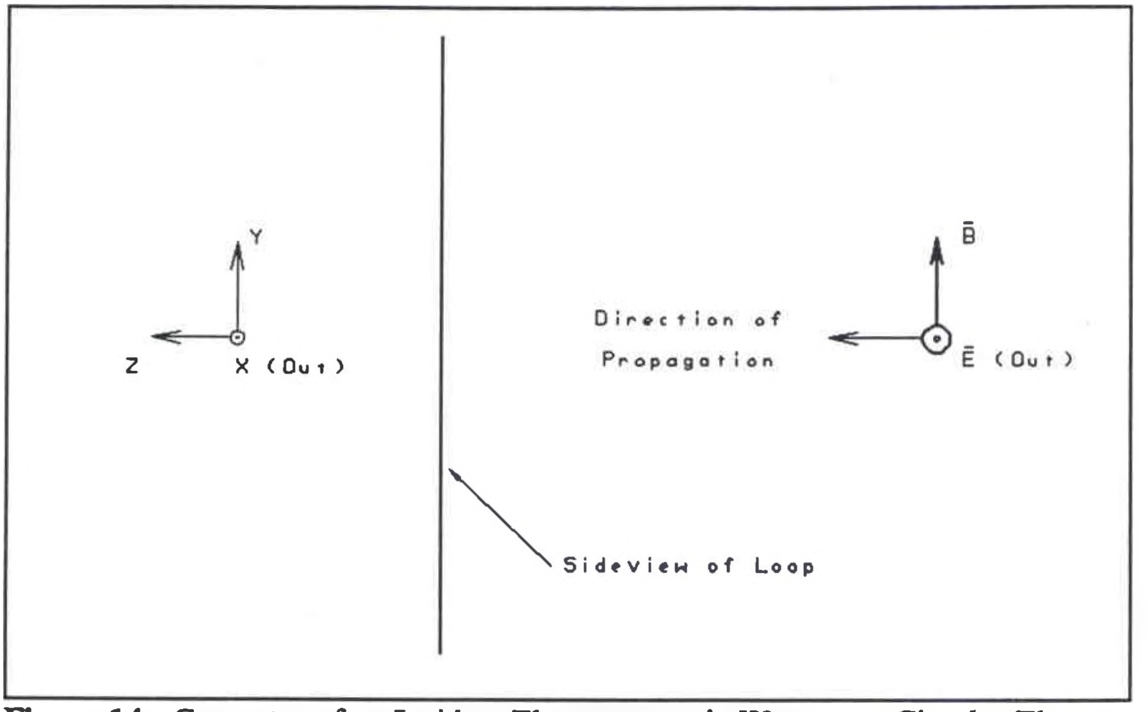

Figure 14: Geometry of an Incident Electromagnetic Wave on a Circular Electron Beam with the Incident Electric and Magnetic Fields Parallel to the Geomagnetic Field

$$v_y' = \frac{e}{m}(-v_x B_z) \tag{54}$$

$$v_z' = \frac{e}{m}(v_x B_y) \tag{55}$$

The resulting differential equation in terms of v_y is:

$$v_y''' + \left(\omega_c^2 + \frac{e}{m}B_y\right)v_y' + \frac{e}{m}\omega_c E_x' = 0 \tag{56}$$

Again applying the small loop assumption, using the difference in magnitude between the incident and static magnetic fields, and integrating, equation (56) can be simplified to:

$$v_y'' + \omega_c^2 v_y + \frac{e}{m}\omega_c E_x = 0 \tag{57}$$

The solution of this differential equation is similar to the previous solutions. The resulting particular solutions are:

$$v_y = -\frac{e}{m}E_i\left(\frac{\omega_c}{\omega_c^2 - \omega^2}\right)e^{j\omega t} \tag{58}$$

$$v_x = -j\omega\frac{e}{m}\frac{E_i}{B_z}\left(\frac{\omega_c}{\omega_c^2 - \omega^2}\right)e^{j\omega t} \tag{59}$$

$$v_z = C_3 \tag{60}$$

This solution is identical to the solutions obtained in equations (33) through (35) except for the sign. The difference in sign is caused by the electromagnetic fields direction of incidence and is of no consequence. This solution is reasonable because the electric field is perpendicular to the geomagnetic field, as in the first case, and the incident magnetic fields are negligible.

The preceding analysis provides solutions to the differential equations arising from an incident electromagnetic wave in each of the three principle planes. The trajectory of an electron in the presence of the geomagnetic field and an incident electromagnetic field may be modeled as a static magnetic field with a time varying electric field because of the large static field and the non-relativistic velocities. Since any incident electromagnetic wave can be decomposed into these three principle orientations, the total solution can be found by finding solutions in the three principle planes and combining the solutions through the principle of superposition.

Dynamic Effects

Because the electron beam loop will be moving through the ionosphere with the spacecraft, the dynamic effects caused by orbital motion must be considered. In the case were the coordinate system is fixed to the electron beam loop, the change in beam velocity as a function of time is the total derivative. When the reference frame is fixed to a point in space and the electron beam loop is allowed to move with respect to that reference frame, then the total derivative must account for spatial as well as temporal changes. The general equation accounting for the movement of the electron beam loop with respect to a fixed coordinate system is called the magnetohydrodynamic continuity equation, which is given by:

$$\frac{\partial\bar{v}}{\partial t} + \frac{\partial\bar{v}}{\partial x}\frac{dx}{dt} + \frac{\partial\bar{v}}{\partial y}\frac{dy}{dt} + \frac{\partial\bar{v}}{\partial z}\frac{dz}{dt} = \frac{e}{m}(\bar{E} + \bar{v}\times\bar{B}) \tag{61}$$

To simplify this equation, a new operator is defined:

$$(\bar{v}\cdot\nabla)\bar{v} = \frac{\partial\bar{v}}{\partial x}\frac{dx}{dt} + \frac{\partial\bar{v}}{\partial y}\frac{dy}{dt} + \frac{\partial\bar{v}}{\partial z}\frac{dz}{dt} \tag{62}$$

This new operator is called the convective derivative of the system which gives the rate of change as a function of position in space. The derivative with respect to time is called the local derivative, and the local and convective derivatives together form the total derivative of the system. The standard form of the magnetohydrodynamic equation is:

$$\frac{\partial\bar{v}}{\partial t} + (\bar{v}\cdot\nabla)\bar{v} = \frac{e}{m}(\bar{E} + \bar{v}\times\bar{B}) \tag{63}$$

For the magnetohydrodynamic equation to be valid, the velocity of the particles at a point (x,y,z) must be the same. Under this condition, the flow is said to be laminar.

Both the orbital motion of the spacecraft and the trajectory of the electron beam loop are representative of uniform circular motion. The acceleration for uniform circular motion is directed toward the center of curvature and is parallel to the radius. This acceleration (called centripetal acceleration) is given by:

$$a = \frac{v_t^2}{r} \tag{64}$$

where v_t is the tangential velocity and r is the radius of curvature. The velocity in (63) can be separated into two tangential components: one tangential to the orbit of the spacecraft and one tangential to the electron trajectory. The tangential velocity of an orbiting spacecraft at an altitude of 300 km is approximately 7000 meters per second. The tangential velocity of the electron beam trajectory is found by multiplying the circumference of the loop by the gyrofrequency. At 300 km, the gyrofrequency is approximately 750 kHz, and the circumference of a 10 keV electron beam is 78.5 meters, making the tangential velocity approximately 5.9×10^7 meters per second. The radius of curvature for the spacecraft orbit is equal to the radius of the Earth added to the altitude of the spacecraft, or 6670 km, which is very large relative to the 12.5 meter radius of the electron trajectory. Using equation (64) shows that the acceleration caused by the orbiting spacecraft is very small relative to the acceleration of the particles in the electron beam. Since the orbital acceleration corresponds to the convective derivative, the following approximation can be made:

$$\frac{\partial \bar{v}}{\partial x} \approx \frac{\partial \bar{v}}{\partial y} \approx \frac{\partial \bar{v}}{\partial z} \approx 0 \qquad (65)$$

From (65), the contribution of the convective derivative cause by the movement of the electron beam loop can be neglected.

The next stage in the analysis process is to expand the theory of single particle trajectories in an electromagnetic field to include multiple particles. When considering a multiple particle beam, the coulomb interaction between the particles must be considered. Since each particle has charge, each particle will exert a force on all neighboring charges. Because of symmetry, the total electric field of an infinite column of charged particles will be radial to the axis of symmetry. Because the electrons are negatively charged, the radial E-field will point inward as shown in Figure 15. The self electric field of the column will tend to cause the electrons in the column to move away from the axis of symmetry in a direction perpendicular to that axis.

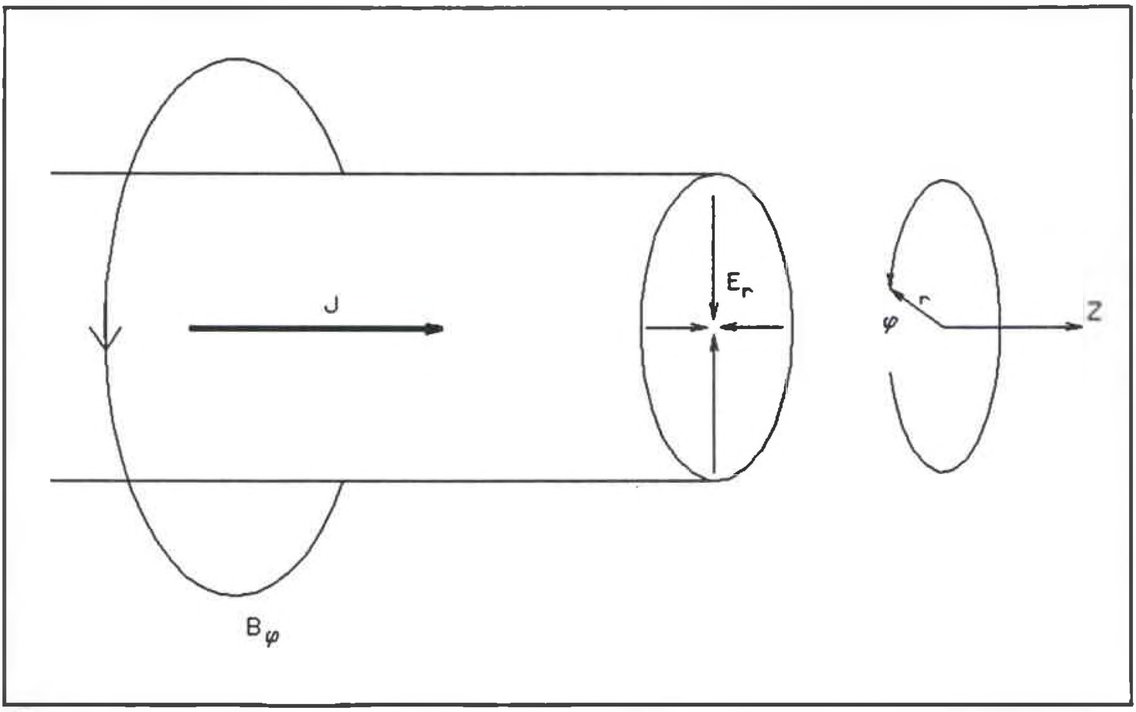

Figure 15: Self Electric and Magnetic Fields of a Cylindrical Electron Beam

Modeling the electron beam as an infinite column of electrons flowing with a velocity parallel to the axis of symmetry, it is evident that an electron beam constitutes a flow of electric current. By the Biot-Savart law a flow of electric current will be surrounded by a magnetic field. The velocity of the electrons in the presence of the self magnetic field will tend to cause the beam to converge toward the axis of symmetry. It can be shown that for non-relativistic velocities, the self electric field of an infinite column of electrons is much greater than the self magnetic field,[31] hence the cross sectional area of an electron beam will tend to increase (or diverge) as the beam propagates through space.

The divergence of an electron beam as it propagates is an undesirable quality, and numerous focusing techniques have been devised to control the divergence. In this context, focusing refers to controlling the divergence of the electron beam as it propagates through space. Auxiliary electric and magnetic fields are generally used to control divergence. Snedkov and Snedkov have proposed the long range focusing of an electron beam using high frequency gradient fields[32] or quadrupolar radio frequency

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[31]Kirstein, et al, pg 6-7.

[32]B. A. Snedkov and A. B. Snedkov, "Motion of Electron Beam in a High-Frequency Gradient Field," Soviet Journal of Communications Technology and Electronics, Vol 32, No. 12, Scripta Technica, Moscow, Dec 1987, Pg 72-76.

fields.[33] Both techniques work well for linear electron beams, but neither conforms easily to the problem of a circular electron beam.

The natural curvature of magnetic fields would make a magnetic focusing technique a better choice for focusing a circular electron beam. One of the best known, and one of the most useful magnetic focusing technique is called Brillouin focusing. Figure 16 shows a three dimensional sketch of the Brillouin focusing technique, and Figure 17 shows an end view depicting the Larmor circulation and the E×B drift. An axial magnetic field is applied to the beam which works in conjunction with the divergence caused by the self electric field of the beam. The velocity imparted to the electrons in the beam by the self electric field is perpendicular to the axial magnetic field. The Lorentz force caused by this velocity and the auxiliary magnetic field changes the radial velocity into a curved trajectory. The radius of the circulation is half the radius of the electron beam, and the frequency of circulation, called the Larmor frequency, is half of the gyrofrequency. This circulation of the electrons prevents the divergence of the electron beam. Because the static fields are orthogonal, there will be an E×B drift. The cross product of E_r and B_z will be in the ϕ-direction which indicates that the Larmor circulation will also circulate around the axis of symmetry.

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[33]B. A. Snedkov and A. B. Snedkov, "Long-range Focusing of Electron Beams by Quadrupole RF Fields," Soviet Physics: Technical Physics, Vol. 55, No. 9, American Institute of Physics, Sep 1985, pg 1089-91.

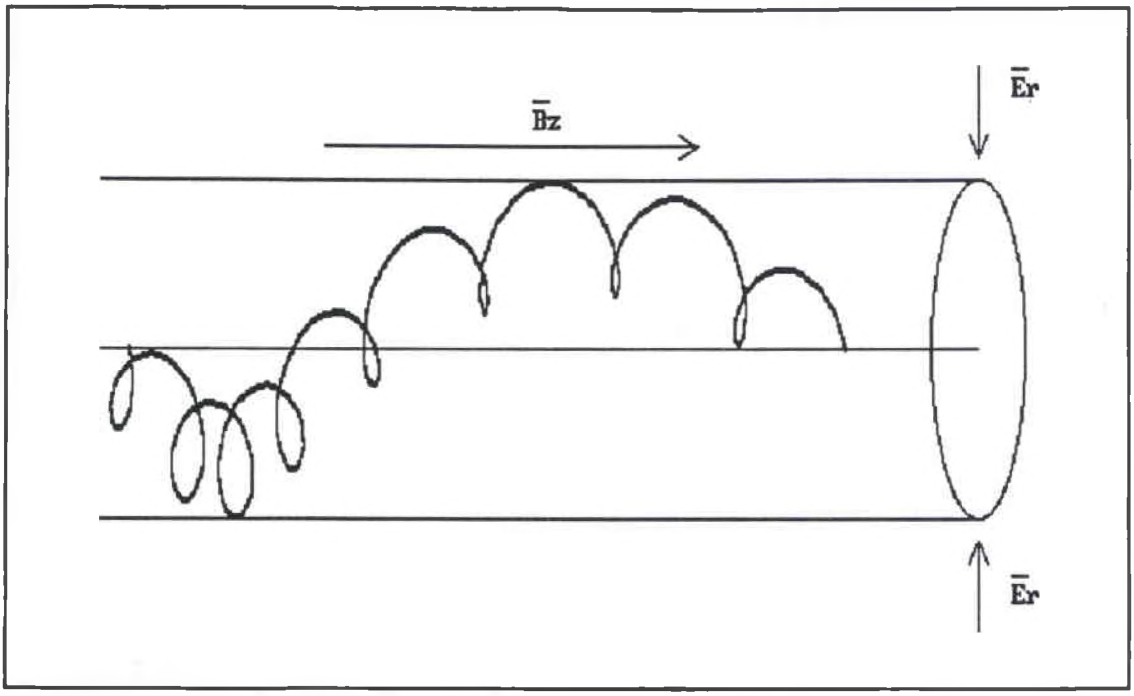

Figure 16: Brillouin Focusing of a Cylindrical Electron Beam

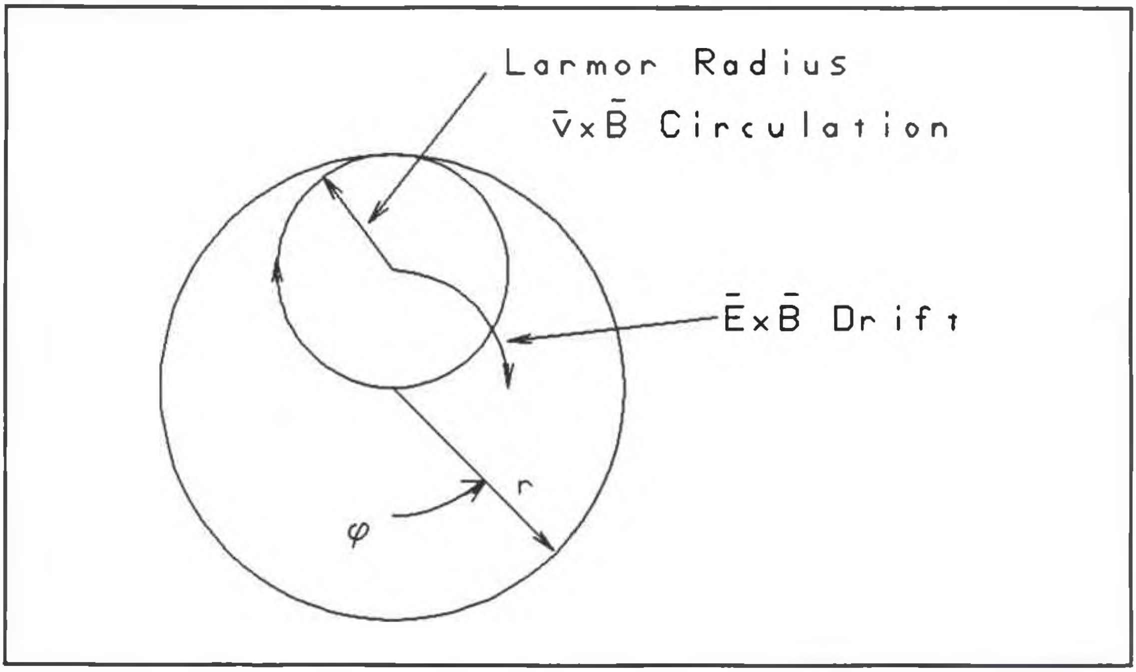

Figure 17: Brillouin Focusing of a Cylindrical Electron Beam, End View

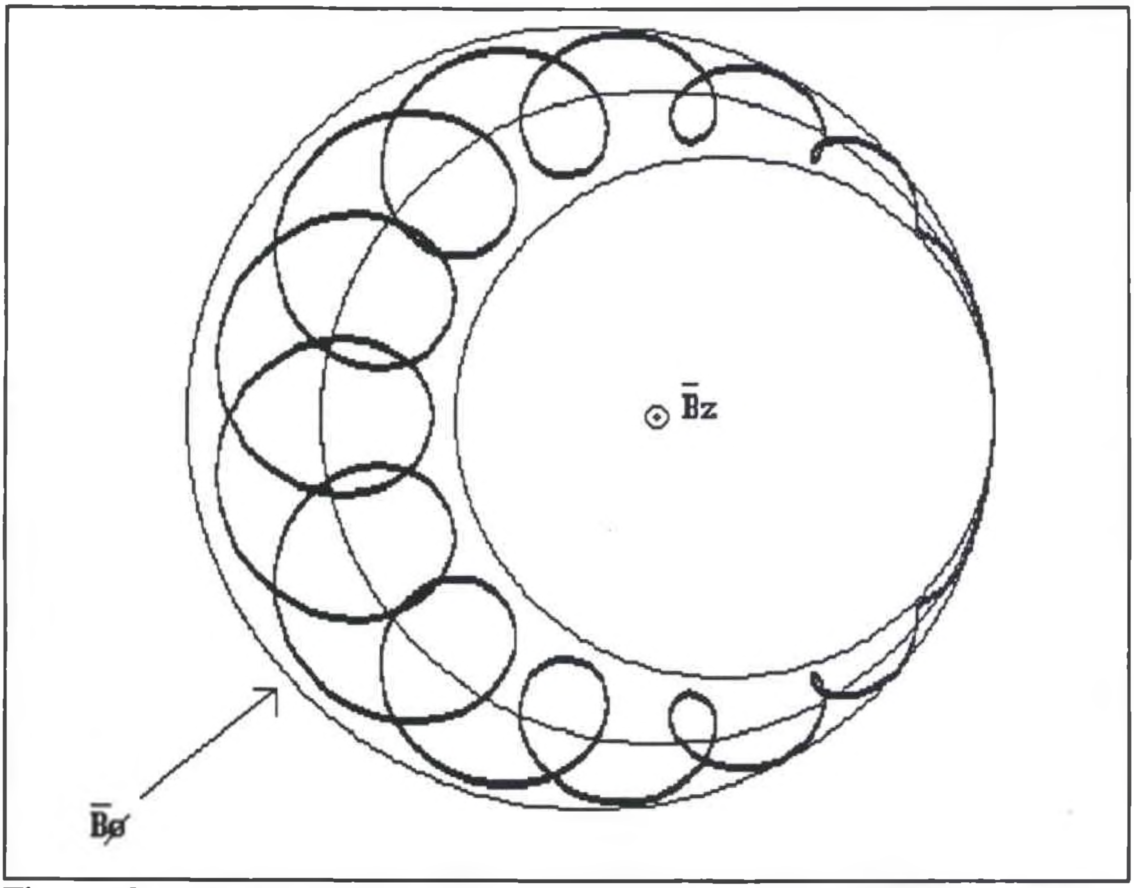

Figure 18: Brillouin Focusing of an Electron Beam Loop

Brillouin focusing will work with the electron beam loop that has been proposed, but the diameter of the plasma column is still not constant. As shown in Figure 18, as the beam moves around the magnetic loop, the distance from the magnetic source increases for half of the cycle and decreases for half of the cycle. Because the magnitude is inversely proportional to the square of the distance, the beam will be more tightly focused near the magnetic source. Ideally, the beam would have the same diameter after completing the loop, but because of collisions with other particles in the path, principally other electrons in the beam, the ending cross section may be larger than the initial cross section.

As a consequence of the changing cross section, the density of the beam will change as a function of space. It is assumed in this report that the density at a point in space is constant; consequently, the changes in density at the measurement plane can be ignored. Brilliouin focusing and the changing cross section of the beam will induce radial and tangential velocities on the electrons. These velocities will be perpendicular to the axis of the beam and parallel to the measurement plane. (See Figure 19). Since the only velocities of interest in determining the current are perpendicular to the measurement plane, the parallel velocities can be ignored.

The Plasma Environment

Now that the trajectory of an electron beam in empty space has been determined, the effect of the real space environment may be considered. For this paper, a target altitude of 300 km has been selected. At this altitude, the environment will consist of free electrons, positively charged ions and neutral molecules. Because of stratification in the upper atmosphere, the primary species for the ions will be atomic oxygen, and

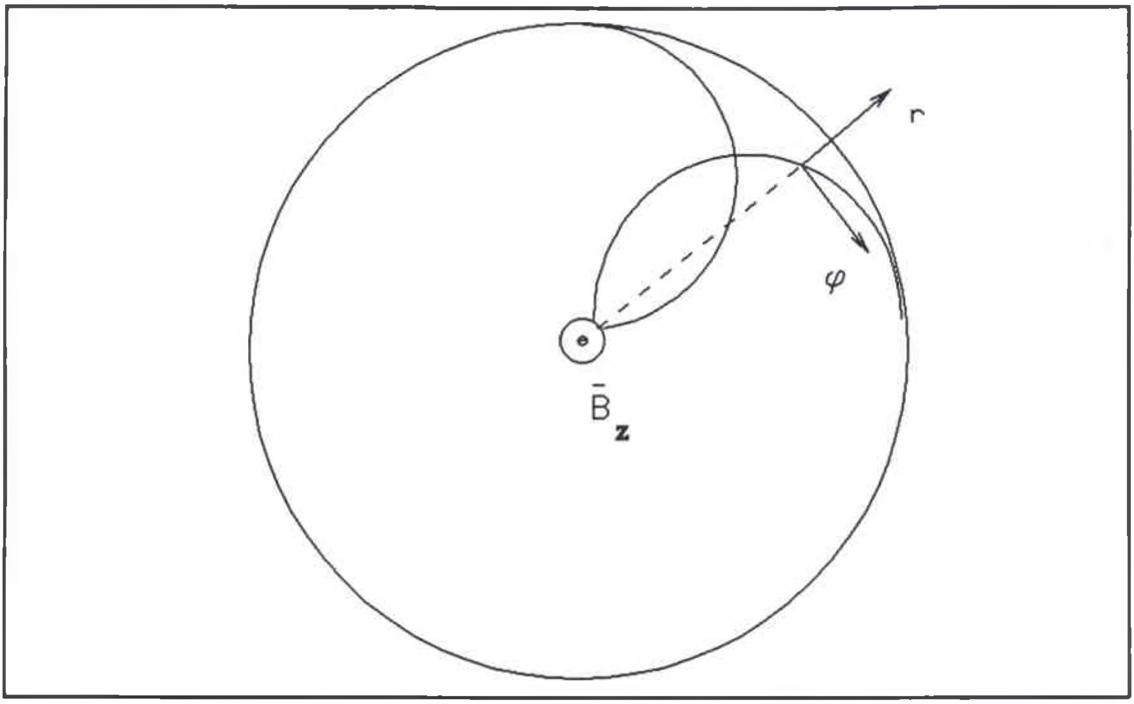

Figure 19: Velocities Induced in an Electron Beam by Brillouin Focusing

neutrals will be atomic oxygen and nitrogen. The plasma environment causes three effects which must be considered in the electron beam antenna design.

In the terrestrial environment, and electron beam will travel only a short distance before being scattered by collisions with the dense neutral molecules in the lower atmosphere. It is therefore necessary to determine if the atmosphere is sufficiently rarified at 300 km to allow an electron beam to propagate over a distance longer than the circumference of the electron beam loop. The mean free path in meters of a particle traveling in a region of larger particles is given by:[34]

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[34]Paul A. Tipler, Modern Physics, (New York: Worth, 1978), pg 76.

$$l \approx \frac{1}{n\pi(r_1 + r_2)^2} \tag{66}$$

where r_1 is the radius of the larger particle in meters, n is the number density of that particle per cubic meter in the region of interest, and r_2 is the radius of the smaller particle in meters. The radius of a nitrogen molecule is used because it is larger than the radius of atomic oxygen. Since a nitrogen molecule is so much larger than an electron, r_2 is essentially zero. Using the radius of the nitrogen molecule[35] and the neutral density from the mean reference atmosphere,[36] the mean free path at 300 km is:

$$\frac{1}{8.456\times10^{14}\pi(1.8\times10^{-10})^2} = 1.162\times10^4 \; meters \tag{67}$$

An electron beam loop with a 10 KeV energy will produce a loop with a circumference of 78.5 meters at 300 kilometers. This large value for the mean free path relative to the circumference of an electron beam loop indicates that collisions with neutral molecules can be neglected.

In a region containing charged particles, the electrical interactions between charged particles must be considered, especially if physical collisions with neutral

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[35] Tipler, pg 79.

[36] Adolph S. Jursa, Handbook of Geophysics and the Space Environment, Air Force Geophysics Laboratory, Hanscom Air Force Base, Mass., 1985, chapter 14, pg 30.

molecules can be neglected as previously demonstrated. These electrical "collisions" are referred to as coulomb collisions. Since the electric fields of charged particles extend theoretically to infinity, the effect of coulomb collisions is continuous, resulting in a continuous deformation of the particle trajectory. Two kinds of coulomb collisions must be considered: electron-electron and electron-ion collisions. Because the ions are much more massive than electrons, it is possible to consider ions to form a fixed background through which the electrons travel. Electron-ion collisions are much more significant the electron-electron collisions, so only the former needs to be considered. The mean free path of an electron travelling in a region of fixed ions is given by:[37]

$$\lambda_{ei} \approx \frac{4.5}{15}\times 10^{5}\frac{T_e^2}{n} \qquad (68)$$

where T_e is the kinetic electron temperature and n is the number density. In this equation, n is generic because the number if electrons is assumed to equal the number of ions to preserve charge balance in the region. Using the International Reference Ionosphere (IRI) model[38] to determine the seasonal variations of the kinetic electron temperature (Figure 20) and density (Figure 21), the mean free path is determined as a function of longitude for a single orbit of a spacecraft over the equator at 300 km

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[37]L. A. Artsimovich and S. Yu. Lukyanov, Motion of Charged Particles in Electric and Magnetic Fields, Mir, Moscow, 1980, pg 198.

[38]D. Bilitza, "International Reference Ionosphere 1990," NSSDC/WDC-A-R&S 90-22, Goddard Space Flight Center, Greenbelt, MD, 1990a.

altitude. (See Figure 22). This shows that the minimum free path is still sufficient to permit an electron beam to complete a single loop.

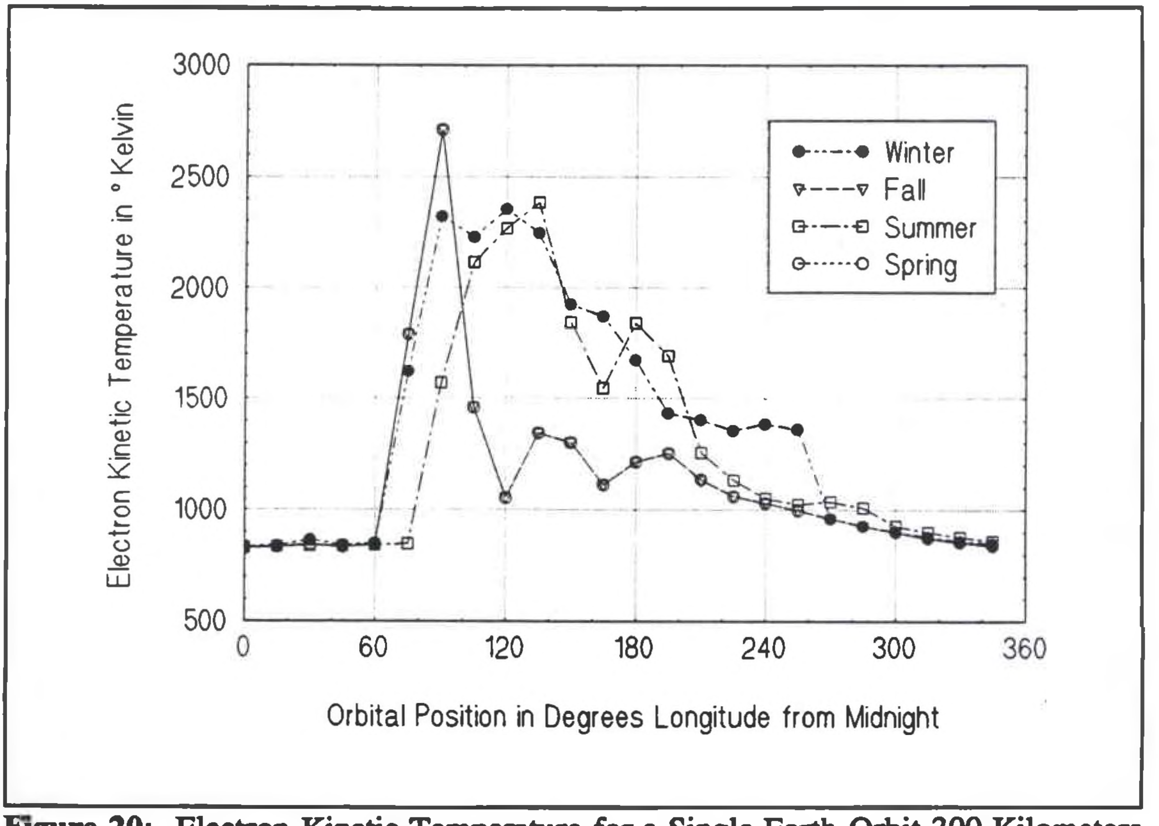

Figure 20: Electron Kinetic Temperature for a Single Earth Orbit 300 Kilometers over the Equator

The effects of a plasma on the propagating electromagnetic wave must also be included in the analysis. A plasma in the presence of a static magnetic field (as is the case of the geomagnetic field) is anisotropic which means that the permittivity is a function of the direction of propagation. There are three cases to be considered. In the first case, the direction of propagation is perpendicular to the static magnetic field, and

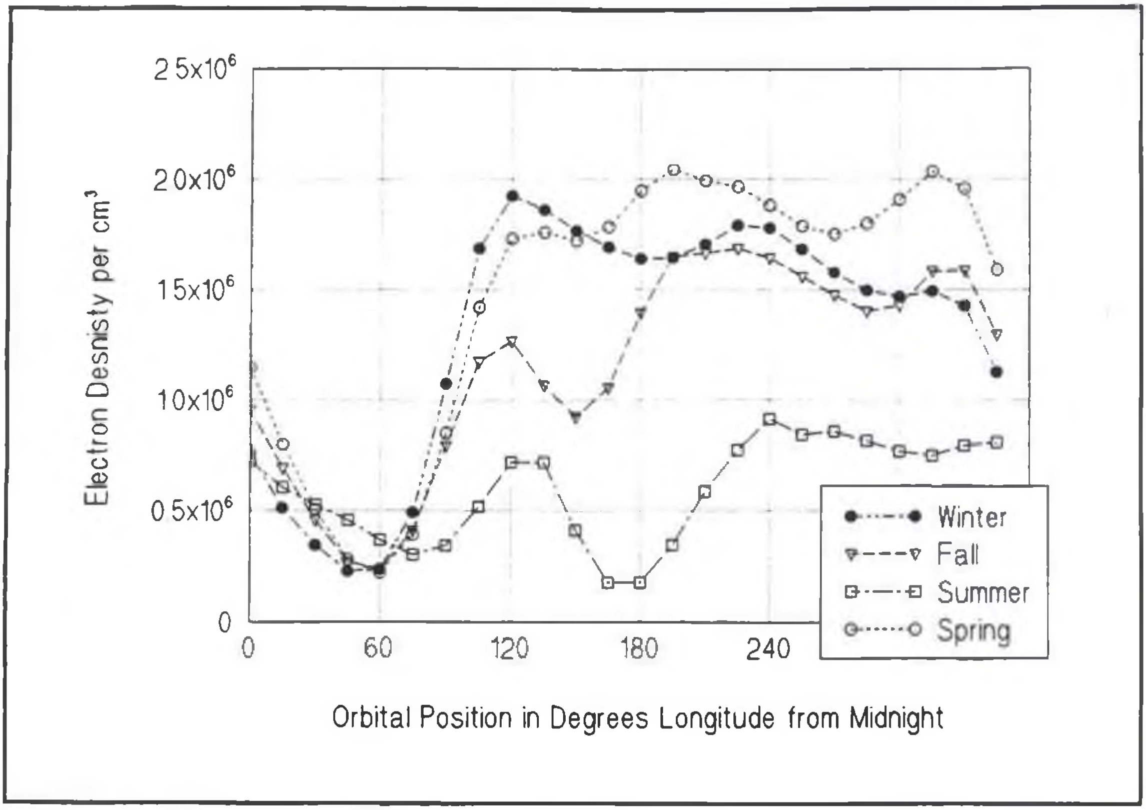

Figure 21: Electron Number Density for a Single Earth Orbit 300 Kilometers over the Equator

the electric field is parallel to the magnetic field. This particular orientation is referred to as the ordinary wave and propagates as if the static magnetic field were not present. If the propagating field is rotated ninety degrees about the direction of propagation such that the electric field is perpendicular to the static magnetic field, then a small longitudinal component of the electric field parallel to the direction of propagation will develop. This is referred to as the extraordinary wave. In the final case, the direction of propagation is parallel to the geomagnetic field. In this situation, an elliptically polarized wave develops. This causes the phenomenon called Faraday rotation.

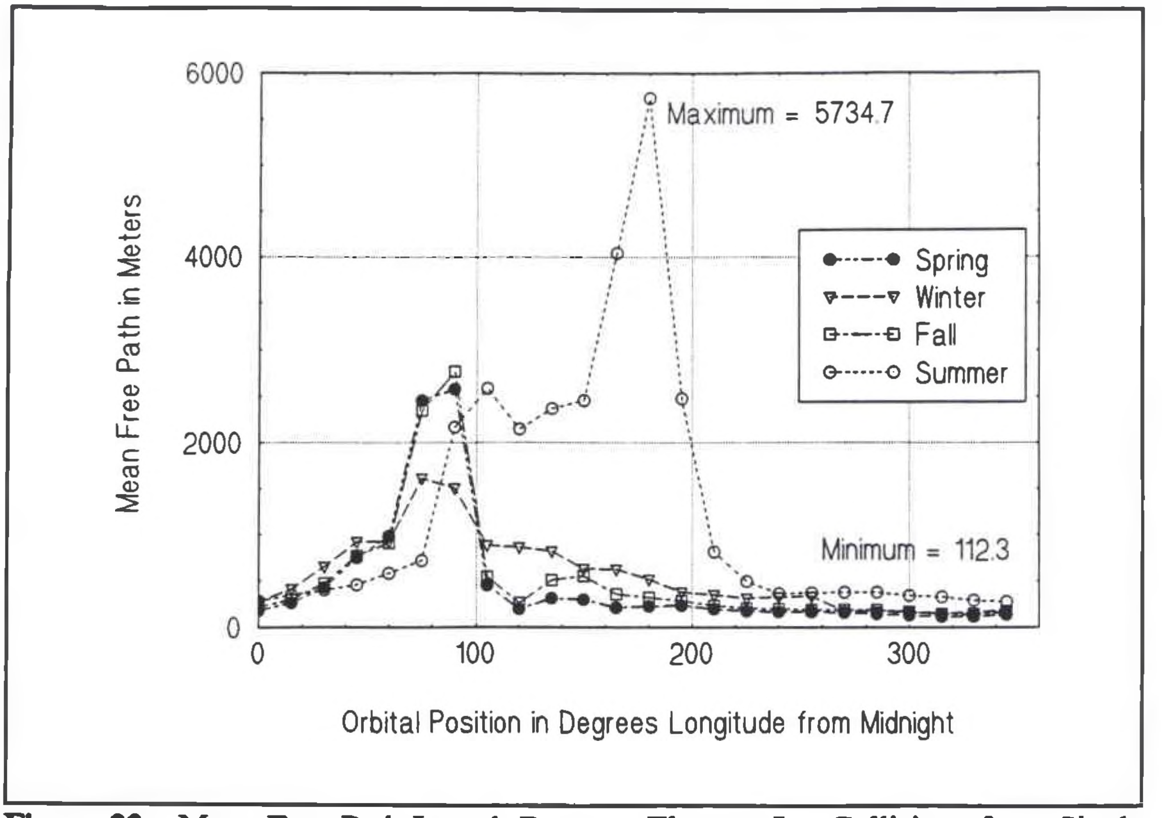

Figure 22: Mean Free Path Length Between Electron-Ion Collisions for a Single Earth Orbit 300 Kilometers over the Equator

Mathematically, the effect of a non-isotropic medium is computed using a tensor to represent the permittivity of the medium. This tensor is of rank two, or a dyadic. For the ionosphere, the tensor permittivity is given by:

$$\overline{\overline{\epsilon}} = \begin{bmatrix} \epsilon_{11} & -j\epsilon_{12} & 0 \\ j\epsilon_{21} & \epsilon_{22} & 0 \\ 0 & 0 & \epsilon_{33} \end{bmatrix} \tag{69}$$

where the epsilons are constants related to the gyrofrequency, the critical or plasma frequency, and the incident field frequency.[39] In the frequency domain, the electric flux density ($\bar{D}$) is given by:

$$\bar{D} = \bar{\bar{\epsilon}} \cdot \bar{E} \tag{70}$$

Since the electric flux density is independent of the medium, and assuming an incident plane wave, the same flux density that existed outside the ionospheric plasma must exist inside the plasma. In an isotropic media, the flux density is:

$$\bar{D} = \begin{bmatrix} D_x \\ D_y \\ D_z \end{bmatrix} \tag{71}$$

While the component terms in (71) may be complex, there are no cross coupled terms. Using linear algebra techniques to solve (69) for the electric field and (70) for the inverse (or conjugate) tensor gives:

$$\bar{E} = \left(\bar{\bar{\epsilon}}\right) \cdot \bar{D} \tag{72}$$

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[39]John D. Kraus, and Keith R. Carver, Electromagnetics, 2nd Ed., (New York: McGraw-Hill, 1973), pg. 729-34.

where,

$$\left(\overline{\overline{\epsilon}}\right)^{-1} = \begin{bmatrix} \epsilon_{22}\epsilon_{33} & -j\epsilon_{21}\epsilon_{33} & 0 \\ j\epsilon_{12}\epsilon_{33} & \epsilon_{11}\epsilon_{33} & 0 \\ 0 & 0 & \epsilon_{11}\epsilon_{33}-\epsilon_{21}\epsilon_{12} \end{bmatrix} \frac{1}{\epsilon_{11}\epsilon_{22}\epsilon_{33}+\epsilon_{12}\epsilon_{21}\epsilon_{33}} \tag{73}$$

Equations (72) and (73) show a cross coupling between the x and y components of the electric fields caused by the anisotropic medium. These cross coupled terms are in phase quadrature making the electric field in the medium complex. This complex electric field can still be resolved into three principal coordinates, so the complex electric field will still fit the model developed in the preceding sections. Furthermore, since the complex electric fields do not add any spatial dependence to the field, the small loop assumption remains valid in the vicinity of the electron beam loop.

Spacecraft Charging

A spacecraft moving in a region of charged particles, such as the ionospheric plasma of a low earth orbit, will absorb charges from the region until the spacecraft reaches a potential that causes the current flowing between the region and the spacecraft to become zero. If this potential becomes excessive, then electromagnetic interference and even arcing can severely degrade or damage spacecraft components. For this reason, charging effects must be considered in designing any equipment that will be used aboard a spacecraft. This is particularly true of a charged particle beam, such as an electron beam, which can increase spacecraft charging.

The primary mechanism of spacecraft charging are the ambient, free electrons in the ionospheric plasma. As the spacecraft moves through the plasma, it absorbs electrons into exposed conducting surfaces. As the negative charges build up, some of the electrons on the conducting surfaces will be released back into the plasma. These electrons are referred to as secondary or backscattered electrons. Ions will also contact the conducting surfaces of the spacecraft where they will exchange charge with the surface. Photoionization caused by solar heating of the exposed spacecraft surfaces will cause the sunlit side of the spacecraft to attain more positive potentials than the dark side of the spacecraft. As a result, significant potentials between different parts of a spacecraft may exist.[40]

Charged particle beams can exacerbate the spacecraft charging problems if not properly designed. One of the missions of the SEPAC experiment was to observe spacecraft charging during an electron beam firing. The electron source for SEPAC was pulsed to kept the charging intervals low, and the return current from the plasma to the spacecraft was also monitored to prevent excessive charging. SEPAC results showed that spacecraft charging was significant, and the spacecraft charging from the electron beam firing was equal to the energy of the electron beam. Spacecraft charging also limited the

[40]Jursa, chapter 7.

maximum current that could be obtained from the electron beam to about 100 milliamps. This limitation was attributed to the large positive potential of the spacecraft which attracted the electrons in the beam, preventing them from departing the spacecraft.[41]

Because spacecraft potentials are predominantly negative, electron beams have been proposed as a means of controlling spacecraft potentials. The flux of ambient electrons into the spacecraft generally exceeds the electron flux out of the spacecraft caused by photoionization and backscatter. This excess negative charge could be collected and then ejected from the spacecraft using an electron beam or other electron emitting devices.[42]

Spacecraft charging considerations are inherent to the electron beam loop antenna. Ideally the same number of electrons departing from the electron source will return to the spacecraft after completing one trip around the loop. This neglects the small number of electrons lost because of collisions with neutrals and the coulomb effects of ions. The return current could by used to balance spacecraft charging by channeling the returning electrons back to the source through the system power supply.

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[41]Chin S. Lin and James Koga, "Spacecraft Charging Potential During Electron-Beam Injections Into Space Plasmas," IEEE Transactions on Plasma Science, vol. 17, no. 2, Apr 1989, pg 205-209.

[42]R. Grard, et al, "Spacecraft Potential Control with Electron Emitters," Spacecraft Charging by Magnetospheric Plasmas, Ed. by Alan Rosen, American Institute of Aeronautics and Astronautics, 1975.

CHAPTER III

ELECTRON BEAM ANTENNA HYPOTHESIS

Receiving Antenna Theory

Conventional wire antenna theory uses a filamentary current to compute the electromagnetic fields associated with an antenna. This filamentary current is typically constrained to flow in a single direction controlled by the shape of a conductor with a cross-section that is small relative to a wavelength. Since the electron beam is in essence a filamentary flow of current, it would seem that the electron beam could simply replace the filamentary current used in conventional antenna theory as proposed by Snedkov.[43] This analysis assumes that the electron beam is constrained to follow the same path as the electrons in the conductor, which is in general not true. Electrons in free space are free to drift depending on the forces applied to them whereas the electrons flowing in the conductor are prevented from drifting in directions perpendicular to the conductors surface. Therefore, the actual electron trajectory must be computed based on the applied forces as a part of analyzing an electron beam antenna.

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[43]B. A. Snedkov, "Radiative Properties ...," pg 60-2.

If the time varying current is known, then the incident fields can be determined. The current in beam of electrons is based on the charge density (ρ) and the velocity ($\bar{v}$) of the electrons. If both the charge density and the velocity vary as a function of time, then the current density ($\bar{J}$) in space will be given by:

$$\bar{J}(t) = \rho(t)\ \bar{v}(t) \tag{74}$$

The amount of current (I) passing through an arbitrary surface (s) is given by:

$$I(t) = \int \bar{J}(t) \cdot d\bar{s} \tag{75}$$

where $d\bar{s}$ is the unit vector normal to the surface. If the charge density and velocity are constant at the point where the electrons are injected into the environment, then any changes in the charge density and velocity will be caused by the environment and can be detected at the receiving plane by measuring the current.

The time variations imposed on the velocity have already been examined in the previous chapter. The density variations must also be examined before proceeding. Consider an electron beam formed by a long column of electrons flowing parallel to the axis. Assume that all accelerations are parallel to the flow of electrons. If all the electrons in that beam are subjected to identical accelerations, then the density of the beam at any point in the beam will remain constant. However, if different parts of the beam are subjected to different accelerations, then the velocities of different groups of electrons will vary. Faster electrons will overtake slower electrons increasing the density in that region and decreasing the density in the region formerly occupied by the faster electrons. This density modulation principal is used to advantage in such devices as the traveling wave tube.[44]

To keep the density modulation to a minimum in the electron beam loop antenna, the difference in acceleration must be minimized. Since the electric field changes as the electrons traverse the loop, the electrons entering the loop will be subjected to different accelerations than the electrons leaving the loop at the distant end. If the frequency of the electric field variations is constrained to be small relative to the time required for an electron to traverse the loop, then it is reasonable to assume the density of the electron beam is constant. Since the time required to traverse the loop is the inverse of the gyrofrequency (assuming the magnetic field is constant), the necessary frequency constraint is:

$$\omega \ll \omega_c \tag{76}$$

[44]Joseph E. Rowe, Nonlinear Electron-wave Interaction Phenomena, Academic Press, New York, 1965.

Assuming a factor of one third is sufficient to make (76) true, then the operating frequencies will be less than about 250 kHz. This is consistent the Soviet antenna research which operated at frequencies below 125 kHz.[45]

Because the density remains constant, the velocity variations provide the only variations to the current. Since the measurement plane, defined by the normal vector $d\vec{s}$, is always parallel to the z-axis, the velocity variations along the z-axis will have no effect on the current. Comparing this with the results of Chapter 2 shows that the electron beam loop antenna in the receive mode will be sensitive to incident electric fields that are perpendicular to the geomagnetic field. Electric fields parallel to the geomagnetic field will have no effect on the measured electron beam current. Because of the small loop assumption, the fields are constant everywhere on the loop regardless of where the source is located. Therefore, the direction of the incident electric field is not important. This leads to two different antenna patterns depending on the polarization.

Referring to Figure 23, consider a halfwave dipole transmit antenna oriented parallel to the geomagnetic field with the feedpoint in the plane of the loop. As the dipole is moved around the loop in the plane of the loop, the polarization of the dipole remains constant relative to the geometric field. Since the dipole and its electric field are parallel to the geomagnetic field, the received signal strength is zero and the

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[45]B. A. Snedkov, D. N. Ovodova, and A. V. Tukmanov, "A Transmitting Device with an Accelerating Electron Beam in an Experiment with Active Plasma," Pribory I Tekhnika Eksperimenta, No. 1, pg 225-6, (Moscow, 1986).

measurement antenna is in the null of the antenna pattern. Looking in any orthogonal plane, the dipole begins parallel to the geomagnetic field, but changes orientation as the dipole moves around the loop in the orthogonal plane. At ninety degrees, the dipole and its electric field are perpendicular to the geomagnetic field which produces a pattern maximum. The resulting antenna pattern is dependent on sin(ϕ) where gamma is the angle between the incident electric field and the geomagnetic field caused by the direction of incidence. This pattern is similar to the antenna pattern of a large loop antenna.

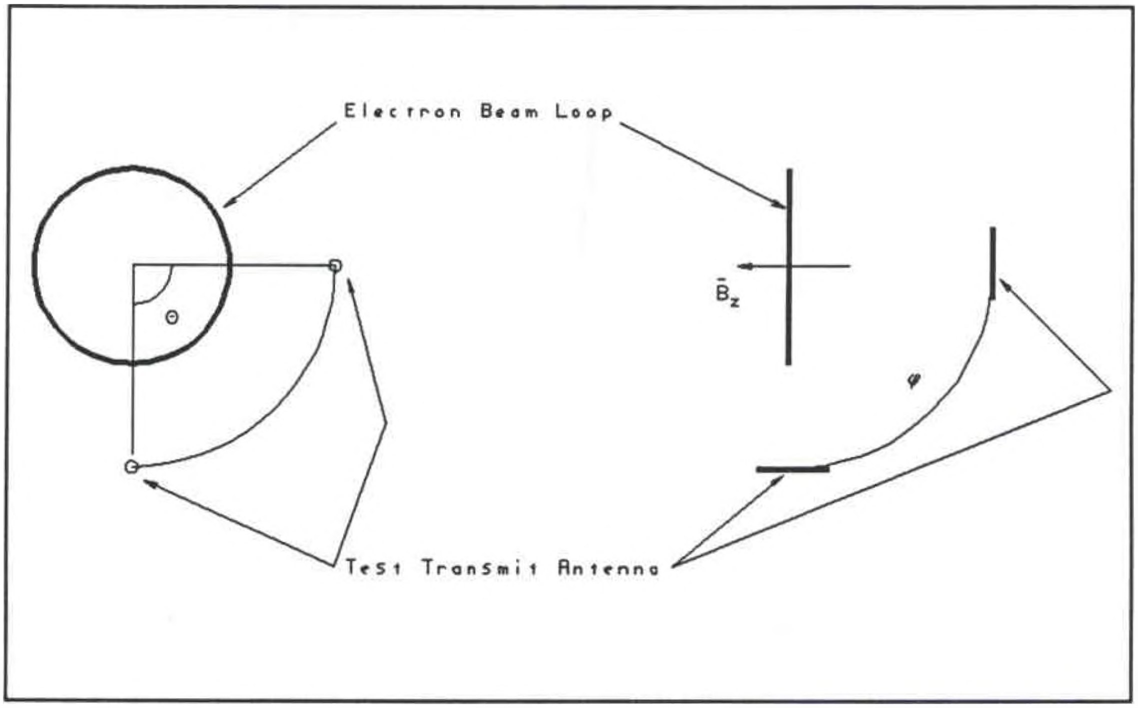

Figure 23: Measuring the Antenna Pattern of the Electron Beam Loop Antenna, Parallel Polarization

Next consider a halfwave dipole transmit antenna oriented perpendicular to the geomagnetic field with the feedpoint in the plane of the loop. (See Figure 24). As the dipole moves around the loop, the dipole and its electric field are always perpendicular to the geomagnetic field. The same is also true in any plane orthogonal to the plane of the loop. Hence this polarization is always perpendicular to the geomagnetic field regardless of the direction of incidence making the loop isotropic for this polarization.

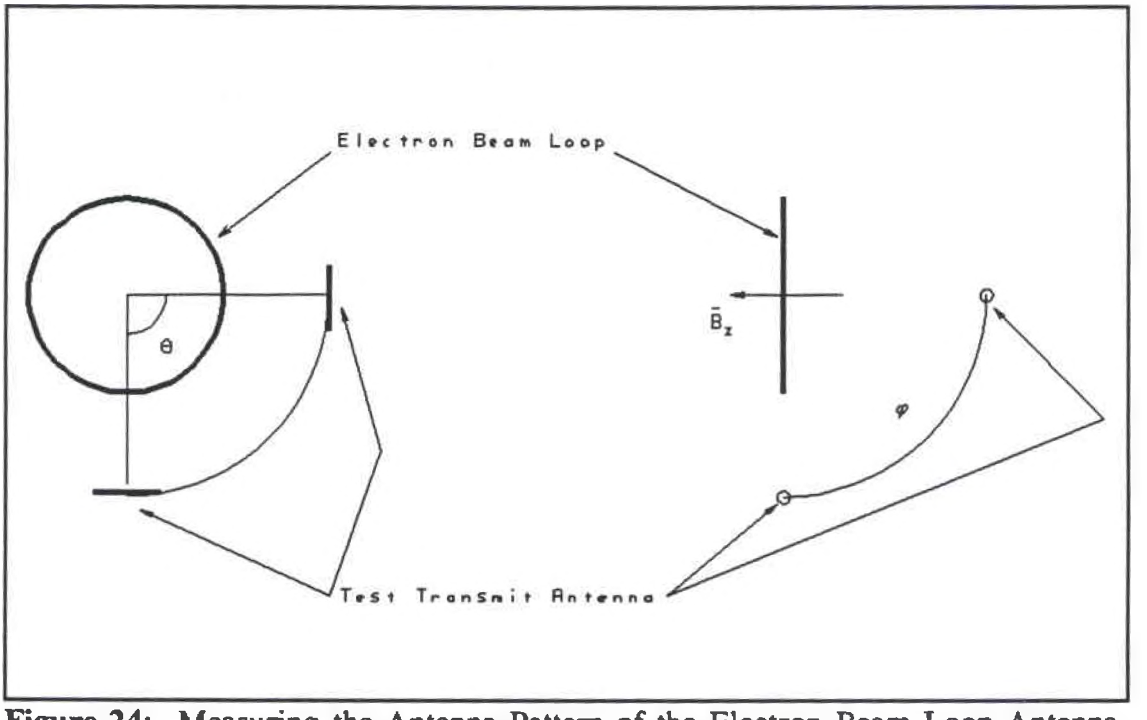

Figure 24: Measuring the Antenna Pattern of the Electron Beam Loop Antenna, Perpendicular Polarization

This result is reasonable because electromagnetic waves in free space are transverse (TEM) to the direction of propagation. Even in a magnetized plasma, electromagnetic waves are predominantly TEM. This means that any wave propagating parallel to the geomagnetic field will always have its electric field vector perpendicular to the geomagnetic field. The electric field vectors of a wave traveling perpendicular to the geomagnetic field can be divided into two cases: one with the electric field component parallel to the geomagnetic field, and one with the electric field component perpendicular to the geomagnetic field. The first case gives the sin(ϕ) antenna pattern, and the second case gives the isotropic antenna pattern.

The incident direction of the propagating electromagnetic field will also affect the antenna pattern because the E×B drift and the polarization drift are not equal. Using θ as defined in Figures 11-13, the unnormalized antenna pattern factor caused by the direction of the incident wave relative to the unit normal vector of the measurement plane is found by taking the magnitude of the sum of the E×B drift and the polarization drift. The unnormalized antenna pattern for plane waves with the E-field vector perpendicular to the geomagnetic field is:

$$F(\theta) = \frac{e}{m} E_i \left(\frac{\omega_c}{\omega_c^2 - \omega^2} \right) \sqrt{\cos^2\theta - \frac{\omega}{B_z} \sin^2\theta} \tag{77}$$

This factor is combined with the polarization factor (1 or sin(ϕ)) to give the correct unnormalized antenna pattern for the electron beam loop antenna in the receive mode.

Note that the velocity in (74) is the sum of the initial velocity and the drift velocities caused by the E×B drift and the polarization drift. Since the initial velocity and density for the proposed receive antenna are constant, variations in the current will only be caused by the drift velocities. In that respect, the current in (75) can be considered to be the sum of a constant, or direct current caused by the initial velocity and a time varying, or alternating current caused by the drift velocities. The drift velocities are actually caused by a distortion of the electron trajectory from a perfect circle, but because the incident fields are assumed to be small, the distortion is negligible.

Furthermore, it is reasonable to assume that a receiver system could be devised that would take advantage of density modulation. Such an antenna would probably have a very narrow bandwidth because the length of the electron path as a function of frequency would be critical. The velocity based receive system developed in the preceding paragraphs is not dependent on the path length as long as the path length does not exceed the specified values. This makes the bandwidth of the velocity based receive system greater than a system based on density modulation. From (77), the gain of the velocity based receive system increases exponentially with frequency, especially when the antenna is oriented such that the polarization drift is dominant.

Transmitting Antenna Theory

Because the geometry of the electron beam antenna is not fixed, reciprocity may not apply. The transmit properties of the electron beam antenna could be substantially different than the properties of the velocity based receive antenna. Those receive properties, developed in the previous section, are based on velocity changes caused by small distortions in the circular trajectory, and no mechanism has been proposed to cause those distortions in the transmit antenna. Furthermore, transmit antennas generally require high power to provide reasonable signal levels at the receiver. High power requires large current variations in the transmit antenna, which in turn requires large variations in the electron density, the electron velocity, or both. The geometry of the electron beam antenna is dependent of the initial and drift velocities of the electrons, so significant variations in these velocities would cause significant changes in the electron beam geometry. The distortions which were assumed to be negligible in the receive mode of a velocity based receive system may not be negligible in a velocity based transmit antenna. It is therefore desirable to consider a transmit system based on density modulation.

If the velocity variations caused by an incident electric field is assumed to be small compared to the magnitude of the current variations in the transmit antenna, then the velocity of the electrons in the beam can be considered constant. With the velocity held constant, the current flowing through the beam will be a function of the electron density and the cross sectional area at each point along the beam. Although the density changes as it moves around the loop, the cross sectional area changes inversely to the density, so the number of electrons crossing any cross sectional plane and hence the current will be approximately the same as the initial conditions. This assumes that density modulation by any incident field is negligible, which is reasonable considering the magnitude of incident fields and the small loop constraint. Since the current at any point in the beam is the same as the current at the source, the current in the beam can be modulated by modulating the electron density at the source. Since the velocity of the electrons in the beam is constant, the diameter of the electron beam loop will be constant. If the maximum cross section of the beam is small relative to a wavelength, then it is acceptable to consider the beam to be a filamentary current concentrated at the axis of the electron beam. Since the diameter of the beam cross section must be smaller than the diameter of the loop, and the loop is already constrained by the small loop assumption, then the filamentary assumption is valid.

Once the filamentary current assumption has been made, the problem is identical to the problem of radiation from a small metallic loop antenna. Since the electron-beam antenna acts like a loop antenna, the size of the loop in wavelengths (n) must be determined. This is accomplished by dividing the physical size of the loop (l) by the wavelength (λ) as shown in equation (78). The overall size of the loop is the circumference of a circle with R being equal to the gyro radius.

$$n = \frac{l}{\lambda} \tag{78}$$

$$l = 2\pi R \tag{79}$$

Assuming the electron beam is launched perpendicular to the geomagnetic fields and substituting in the relationship between wavelength and frequency gives:

$$n = \frac{2\pi m f |\bar{v}|}{q |\bar{B}| c} \quad (80)$$

where: $\bar{v}$ = velocity of the electrons in the beam.

f = modulation carrier frequency

$m = 9.11 \times 10^{-31}$ Kg (electron mass)

$q = -1.602 \times 10^{-19}$ coulombs (electron charge)

$c = 3 \times 10^{8}$ meters/second (speed of light)

$\bar{B} = 0.27 \times 10^{-4}$ webers/meter (geomagnetic field)

To meet the small loop requirements, the wavelength ratio (n) must be smaller than a tenth ($n < 0.1$). A small loop antenna has a pattern maximum in the plane of the loop, which would make the antenna useful for transmitting signals to the Earth. A large loop antenna has a pattern maximum along the line perpendicular to the plane of the antenna, which would point the pattern maximums into space where they are not useful. Computing values for n at various frequencies and electron energies shows that the beam diameter is consistent with the small loop assumption and the frequency and velocity constraints required in this analysis.

Table 3 lists the loop diameter, velocity, and maximum frequency for an electron beam loop with various energies. These computations show the electron-beam antenna is a usable antenna for terrestrial communications that range from very low frequencies to about 1 MHz. The shaded areas in the table indicate electron velocities which may be considered nonrelativistic. These calculations do not account for the presence of the spacecraft. This frequency is higher than for the receive mode because of the constraints required to prevent density modulation caused by the time varying incident fields. The same modulation exists in the transmit mode, but the density modulation from the initial conditions is larger than the modulation from the incident fields, so the incident field modulations can be ignored.

TABLE 3

ELECTRON BEAM LOOP TRANSMIT PARAMETERS

Beam Energy (eV)	Velocity Relative to Light	Loop Diameter (meters)	Maximum Frequency
100	0.002	2.5	3.82 MHz
500	0.044	5.6	1.71 MHz
1000	0.063	7.9	1.21 MHz
5000	0.140	17.7	540 kHz
10,000	0.198	25.0	380 kHz

The maximum charge density and hence the maximum current that can be obtained by the electron beam is limited by the charged particles in the beam. This effect is called the space-charge limitation and is given by:

$$J = \frac{4}{9}\epsilon_0\sqrt{2\frac{e}{m}}\frac{V_a^{\frac{3}{2}}}{d^2} \qquad (81)$$

where d is the distance between the cathode and the accelerating anode, V_a is the potential difference between the cathode and the accelerating anode, and ϵ_0 is the permittivity of the medium between the cathode and accelerating anode (assumed to be the same as the permittivity of free space). The space-charge effect is caused by the repulsion of new electrons entering the system at the cathode by the electrons already in the system. A convenient measure of the space-charge limitation of an electron beam is the ratio of the current to the three-halves power of the voltage. This ratio, called the perveance of the electron beam, has no physical meaning, but is roughly analogous to conductance.[46] In a conventional antenna, the maximum current is limited to the maximum heat that can be dissipated by the antenna elements. In the electron beam antenna, the maximum current is limited by the perveance of the system.

Electron Beam Antenna Configuration

In this section, a proposed design for the electron beam loop antenna will be presented. Elements of both the transmit and receive systems will be included. The proposed design is a top level design only and does not include specifics on the design of each component.

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[46]Robert Bakish, Ed., Introduction to Electron Beam Technology, Wiley & Sons, New York, 1962.

There are many possible designs for the cathode source of the electrons, but only two have been used in space. The standard cathode is a directly heated, thermionic emitter constructed of tantalum or tungsten. The electric current passing through the element provides the necessary energy to liberate electrons by heating the element. This type of cathode is easy and inexpensive to construct, making it an ideal choice for throw-away applications like sounding rockets. The disadvantage of a directly heated element is the amount of power required to operate it. A better design for long duration space missions is an indirectly heated cathode. An indirectly heated cathode is still a thermionic design (uses heat to liberate the electrons), but the amount of energy required to liberate electrons (the work function) is significantly less than the metallic elements used in directly heated cathodes. Indirectly heated cathodes use materials that are coated or impregnated with materials that increase the availability of free electrons. These cathodes are heated by a separate heater wire that is usually located inside the cathode. Because the oxides used in these cathodes degrade when exposed to normal atmospheric pressure and density, the cathode must be kept in an evacuated container until the device reaches the intended altitude.[47]

Figure 25 shows the schematic diagram of the proposed design of the electron beam antenna, and Figure 26 shows the functional block diagram of the system. This design uses an indirectly heated cathode source to reduce power requirements. Focusing

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[47]Ilan A. Blech, "Properties of Materials," Electronic Engineers Handbook, 2nd ed., Donald G. Fink and Donald Christiansen, Eds., (New York: McGraw-Hill, 1982), Chap. 6, Pg. 97-105.

magnets will be required in the drift tube portion of the electron gun to compensate for the geomagnetic fields. Without the magnets, the electrons would follow a curved trajectory reducing the efficiency of the gun. The magnets keep the electron beam flowing in a straight line past the accelerating anodes. The field between the cathode source and the accelerating anodes give the electrons in the beam the velocity as shown in equation (5).

A grid is imposed between the cathode source and the accelerating anodes to control the number of electrons that are allowed to pass through the gun. This permits the current density modulation proposed in the previous section. The modulation grid is connected to the modulator and is only used in the transmit mode. An electromagnet located between the electron gun and the receiver plate is used as the Brillouin focusing magnet that controls the beam divergence after the beam leaves the gun.

A flat conducting plate oriented perpendicular to the electron beam could be used to capture the returning electrons. In the transmit mode, the current from the plate would be channeled back to the power supply to balance the circuit and reduce spacecraft charging. In the receive mode, the return current would have to be separated into direct and alternating components. The direct component would be returned to the power supply to reduce spacecraft charging while the alternating current would be amplified and detected.

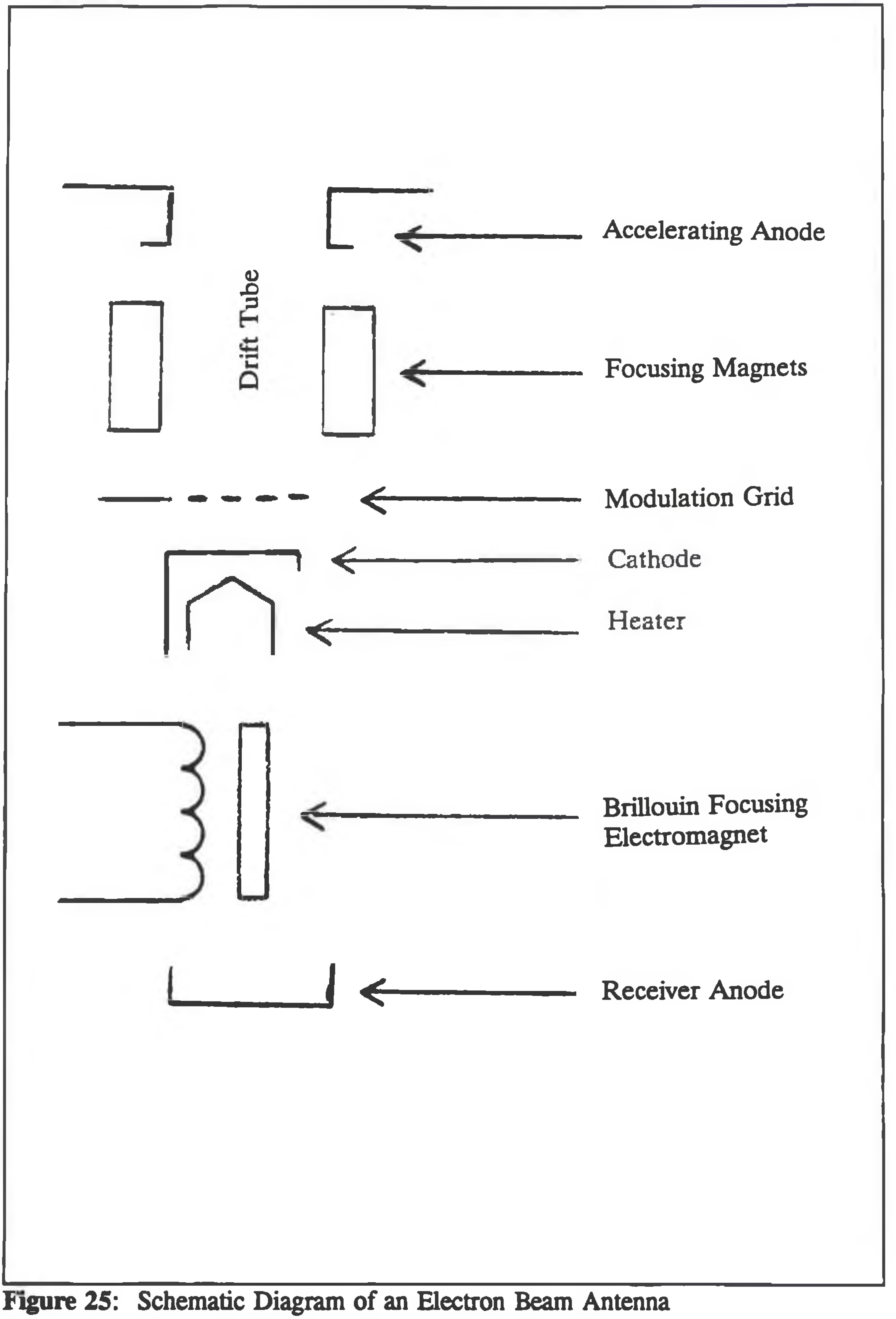

Figure 25: Schematic Diagram of an Electron Beam Antenna

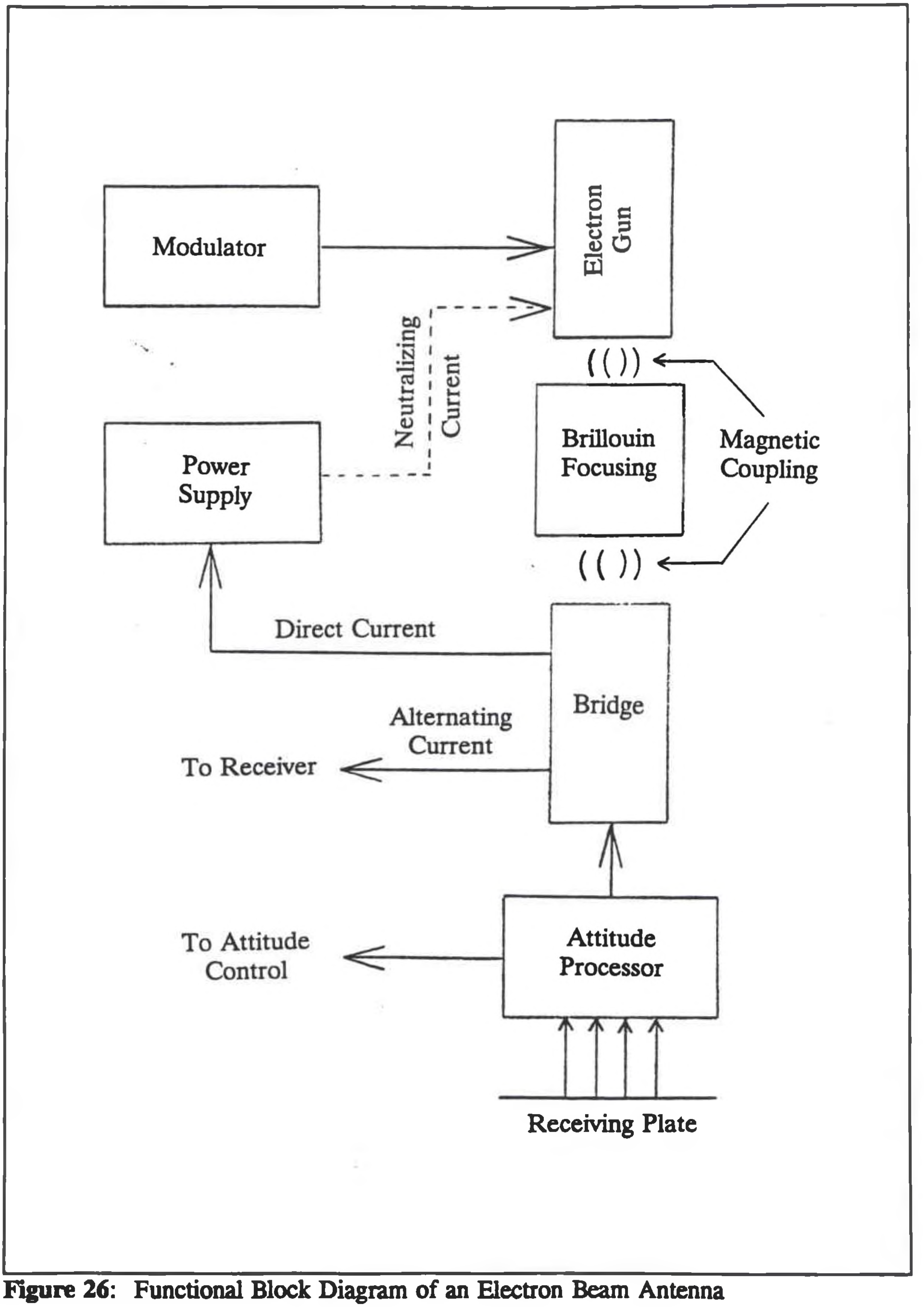

Figure 26: Functional Block Diagram of an Electron Beam Antenna

Some system is required to keep the electron beam antenna oriented orthogonal to the geomagnetic field. This system would have to monitor the geomagnetic field, compute the attitude requirements and provide that information to the attitude control system of the antenna or spacecraft. A separate magnetometer could be used as in the GEOS 2 design; however, there is another possibility that uses the electron beam itself to monitor the geomagnetic field.

The electron beam will only return to the center of the conducting plate if the beam is exactly perpendicular to the geomagnetic field. Any other orientation will cause the beam to move away from the center of the plate because the beam will have an initial velocity component parallel to the geomagnetic field. This shift away from the plate center can be used to sense the orientation of the geomagnetic field.

Figure 27 shows a conducting plate that has been divided into electrically isolated sections. As the beam shifts away from the center of this plate, the amount of current flowing into different sections of the plate will change. By comparing the currents between diametrically opposed sections, the direction and magnitude of the beam shift can be measured. This data would then be provided to the attitude control system to return the system to the proper orientation relative to the geomagnetic field. The receiving plate could be easily constructed as a multilayer, etched printed circuit board. A solid layer behind the receiving plate would shield the system equipment from electron incident on the areas between conducting surfaces. Small holes could be etched in the solid layer to permit access to the receiving plate assembly.

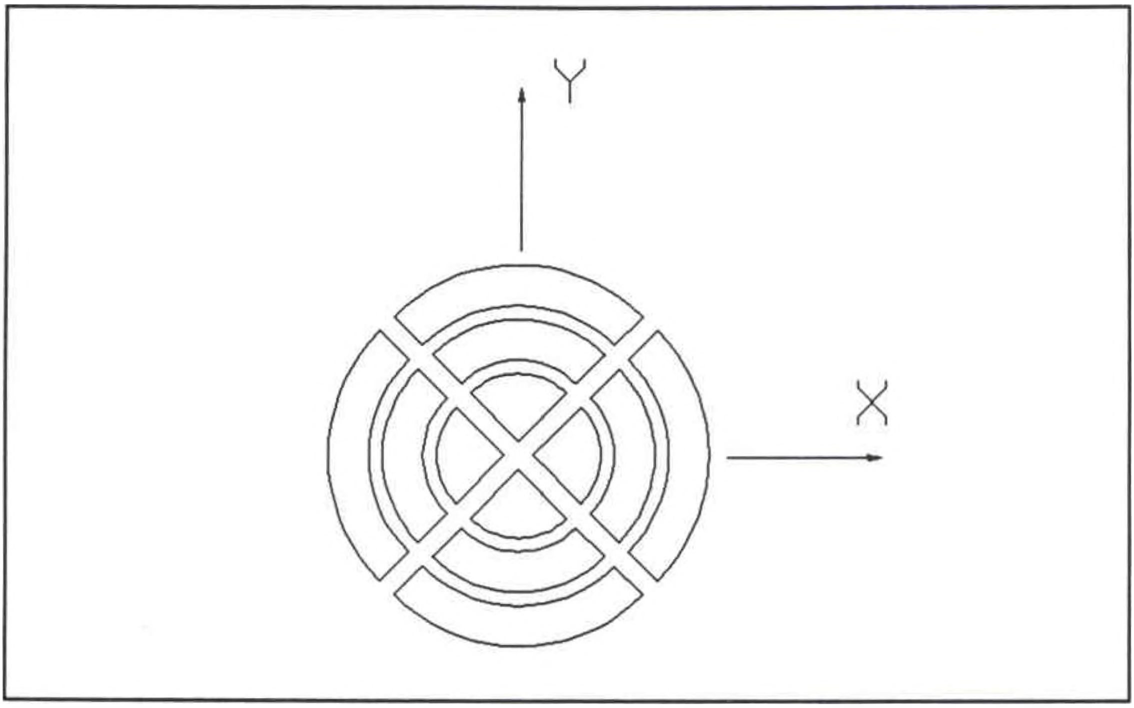

Figure 27: Receiving Plate Design to Sense the Geomagnetic Field Orientation

Efficiency, Power Requirements and Limitations

The efficiency of antennas is computed by comparing the useful power radiated by the antenna with the amount of power input to the antenna. The radiated power can be related to the power dissipated in a fictitious resistance, called the radiation resistance, by a current equal to the input current of the antenna. The difference between the radiated power and the input power is the amount of power dissipated as heat by the ohmic resistance of the antenna. The efficiency of the antenna can then be represented as a ratio of the radiation and ohmic resistances of the antenna as follows:

$$e = \frac{R_R}{R_R + R_O} \tag{82}$$

where R_R is the radiation resistance, and R_O is the ohmic resistance.

The efficiency for the conventional small loop antenna is low because the ohmic resistance is close to the value of the radiation resistance. For the conventional small loop antenna is approximated by:[48]

$$R_R = 20\pi^2\left(\frac{C}{\lambda}\right)^4 \tag{83}$$

where C is the circumference of the loop. From the small loop assumption ($C < \lambda/10$), the radiation resistance is less than five ohms. The ohmic resistance for the conventional small loop antenna is typically a few tenths of an ohm, which results in a relatively low efficiency.

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[48]Constantine A. Balanis, Antenna Theory: Analysis and Design, (New York: Wiley & Sons, 1982), pg. 170.

The electron beam loop antenna is probably more efficient than the conventional small loop antenna because the electron beam approximates a perfect conductor. The ohmic resistance of the conventional small loop antenna is caused by electron collisions with the molecules in the lattice of the metal conductor. In this case, the free path length of the electron is much smaller than the circumference of the metallic loop. As previously shown, the free path length between electron-neutrals and electron-ion collisions for the electron beam antenna are much larger than the circumference of the loop, making the probability of such collisions and the corresponding resistance small. Assuming the radiation resistance of the electron beam loop antenna to be approximately the same as the radiation resistance of the conventional small loop antenna, then the efficiency of the electron beam antenna must be higher than the efficiency of the conventional small loop antenna.

Although the efficiency of the electron beam antenna is higher than for the conventional loop antenna, the power requirements will likely be higher. This is particularly true in the case of receive mode antennas because the conventional small loop is passive, requiring no power while the electron beam antenna requires a continuous supply of power to maintain the beam. A conventional antenna would require amplifiers and an detector which could make the power requirements for the two antennas comparable, but those calculations are beyond the scope of this report. While the power requirements of a conventional antenna would be comparable to the power in the electron beam itself, additional power is required to heat the cathode which could make the power requirements for the electron beam antenna higher than for the conventional antenna.

The bandwidth of the electron beam antenna may be higher than the bandwidth of a conventional loop antenna because of impedance matching. In conventional antennas, the antenna impedance must closely match the impedance of the transmission line so that most of the electrical energy in the transmission line is transferred to the antenna. Differences in the impedances will result in some of the electrical energy being reflected back into the transmission line. If the impedance mismatch is large, most of the energy will be reflected and very little will reach the antenna. In the case of the small loop antenna, the antenna impedance changes rapidly with frequency[49] while the impedance of the transmission line is constant, making the instantaneous bandwidth of the antenna small. In the case of the electron beam antenna, the electrical energy in the system is converted to mechanical energy (launching a charged particle) which could be a stable process independent of frequency if the electron gun is properly designed. This invariance with frequency could give the electron beam antenna a broad instantaneous bandwidth.

There are two limitations for the electron beam antenna which do not apply to conventional antennas. First, the electron beam antenna must be used in an environment where the free path length of the electrons is much larger than the circumference of the

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[49]Balanis, pg. 184-6.

electron beam loop. Because of this limitation, the electron beam loop antenna can only be used aboard spacecraft and high altitude rockets. This restriction does not affect the communication link, only the location of the electron beam antenna. The electron beam antenna could be used for communications with Earthbound stations as well as other spacecraft. The second limitation comes for the dependence on the geomagnetic field. This antenna could not be used on deep space missions where interplanetary magnetic fields are insignificant. The dependence on the geomagnetic field could also restrict the useful domain of the antenna to equatorial regions as assumed in this report. In the polar regions, the geomagnetic field changes rapidly as the position of the spacecraft changes. It may not be possible to maintain the proper orthogonal orientation of the antenna in the polar regions.

CHAPTER IV

SUMMARY AND CONCLUSIONS

An electron-beam antenna uses a flow of charged particles to perform the functions of typical transmit or receive elements. Electromagnetic theory states that the radiation from an antenna is caused by the electric currents flowing on the conducting surface. The antenna structure not only contains the currents, but the size and shape determines the current distribution. If it were possible to direct the currents without conducting surfaces, then the physical structure could be eliminated. This is the theoretical basis behind the electron-beam antenna.

An electron-beam antenna could provide effective communications between spacecraft and Earth stations, much like a conventional loop antenna. The charged particle beam of these "massless" antennas is generated by an electron gun and received with a collector/detector anode. While the antenna can communicate with either terrestrial or space-based antennas, the electron beam antenna itself must be located in space.

An electron-beam antenna offers certain advantages over conventional antennas in space-based applications. First of all, the apparatus for operating the electron beam is very lightweight. The electron gun used in the Soviet experiments (to emit the charged particles) is of fairly simple construction and could fit in a person's hand according to Snedkov. This small size allows for considerable weight saving on a spacecraft. Although saving weight is an important consideration, the elimination of an actual antenna structure also offers many space-saving advantages. An electron-beam antenna does not interfere with other structures, such as solar cells, which are external to the spacecraft. Also, an electron-beam antenna avoids the problem of mechanical deployment. According to Professor B. A. Snedkov, the antenna is deployed as simply as "turning on a switch."[50] While Professor Snedkov's remark is an oversimplification, an electron beam antenna would be much easier to deploy than a large loop antenna.

One major limitation of an electron-beam antenna is that the charged particle beam can only be used in a very low density atmosphere. In a dense atmosphere, such as the atmosphere near the Earth's surface, collisions with neutral molecules cause a beam of electrons to scatter, disintegrate, and rapidly decay. The currents can not be controlled in order to simulate a conventional antenna. Even at the high altitudes used by reconnaissance aircraft, the atmosphere is probably too dense to operate an electron-beam antenna. Therefore, the electron-beam antenna is probably limited to space-based applications only.

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[50]Sevastyanov.

Another limitation comes from the electron-beam antenna's dependence on the Earth's magnetic field. Since orthogonality must be maintained to keep the beam focused on the receiving element, the electron-beam antenna is probably limited to use in the equatorial regions. The geomagnetic field orientation changes rapidly with position in the polar regions which would make it difficult to maintain orthogonality. The antenna would probably be most useful on spacecraft in equatorial orbits like the MIR space station of the Space Shuttle.

The power requirements for a system using an electron beam antenna are probably higher than the power requirements for a system using a conventional loop antenna. An electron beam antenna would need power to heat the cathode and the accelerator anode which gives the electron beam its velocity. A conventional loop antenna requires no power once it has been deployed. Power requirements are a critical consideration on a spacecraft which will have limited amount of power available.

CHAPTER V

DIRECTIONS FOR FUTURE WORK

The antenna system developed and presented in this paper operates at frequencies below 200 kHz in the receive mode, and up to 1 MHz in the transmit mode. These frequencies are useful for research and communications with submarines, but low frequencies severely limit the data rates. Low frequencies are also subjected to high attenuation when propagating through the ionosphere, particularly on the dayside of the Earth where the D layer is well established. It is therefore desirable to continue this research into higher frequencies where the equations of motion become non-linear.

A high frequency electron beam antennas has already been demonstrated by Dwyer, et al. In their experiment, they proved a plasma column configured as a halfwave, folded monopole operated nearly as well as a reference monopole at 112 MHz.[51]

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[51]T. Dwyer, D. P. Murphy, and J. M. Perin, "Characteristics of an Atmospheric Discharge Plasma as an RF Antenna," Naval Research Laboratory, Report No. 4815, May 1982.

The non-linearity of the electron beam antenna at higher frequency also offers some intriguing possibilities in high gain antenna design. Rowe discusses an electron beam flowing through a plasma column which is moving in the opposite direction. As a special case, the outer plasma column can be considered stationary which would be a reasonable approximation of an electron beam propagating through the ionosphere. Rowe shows that the non-linear nature of the dispersion equation could give rise to signal gains similar to those observed in traveling wave tubes which have similar dispersion equations.[52]

The development of a high gain, electron beam antenna would be of significant importance to space research. As discussed in Chapter 1, several research missions have been severely restricted because of antenna deployment failures. By eliminating the mechanical structure that caused the failure, the number of future failures could be greatly reduced.

[52]Joseph E. Rowe, Nonlinear Electron-wave Interaction Phenomena, Academic Press, New York, 1965.

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