Radio Waves in the Ionosphere: Propagation, Generation, and Detection

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ABSTRACT

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We discuss various topics concerning the propagation, generation, and detection of high-frequency (HF) radio waves in the Earth's ionosphere. With regards to propagation, we derive a full wave Hamiltonian and a polarization evolution equation for electromagnetic waves in a cold, stratified magnetoplasma. With regards to generation, we will be concerned with three experiments conducted at the ionosphere- radio wave interaction research facilities at Sura, Russia and Tromsø, Norway. These facilities operate high power HF transmitters that can inject large amplitude electromagnetic waves into the ionosphere and excite numerous nonlinear processes. In an experiment conducted at the Sura facility, we were able to measure the full state of polarization of stimulated electromagnetic emissions for the first time. It is expected that by using the technique developed in this experiment it will be possible to study nonlinear polarization effects on powerful HF pump waves in magnetoplasmas in the future. In another experiment conducted at the Sura facility, the pump frequency was swept automatically allowing rapid, high-resolution measurements of SEE dependence on pump frequency with minimal variations in ionospheric conditions. At the Tromsø facility we discovered by chance a highly variable, pump induced, HF emission that most probably emanated from pump excited sporadic E. Regarding detection, we have proposed a set of Stokes parameters generalized to three dimension space; and we have used these parameters in an invention to detect the incoming direction of electromagnetic waves of multiple frequencies from a single point measurement.

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Alla memoria del mio amato padre, “Nanni” Carozzi
. . . och till Mamma

The following dissertation concerning the Trinity, as the reader ought to be informed, has been written in order to guard against the sophistries of those who disdain to begin with faith, and are deceived by a crude and perverse love of reason.

St. Augustine of Hippo,
On the Trinity

This thesis is based on the following papers, which will be referred to in the text with a capital "P" and a Roman numeral:

P-I **Parameters characterizing electromagnetic wave polarization**
T. D. Carozzi, R. Karlsson, and J. Bergman
Phys. Rev. E **61**, 2 (2000).

P-II **Full Polarimetry Measurements of SEE. First Results**
T. D. Carozzi, B. Thidé, T. B. Leyser, G. Komrakov, V. Frolov, S. Grach and E. Sergeev
Submitted to Journal of Geophysical Research, April 2000.

P-III **High resolution measurements of SEE dependence on pump frequencies close to the fourth electron cyclotron harmonic**
T. D. Carozzi, B. Thidé, T. B. Leyser, M. Holz, G. Komrakov, V. Frolov, S. Grach and E. Sergeev
Submitted to Journal of Geophysical Research, (2000).

P-IV **Observations of nonstationary radio emission induced by a powerful high-frequency radio wave incident on sporadic** *E*
T. D. Carozzi, T. B. Leyser, J-O. Hall, and M. T. Rietveld
Submitted to Geophysical Research Letters, (2000).

P-V **Hamiltonian formulation of radio wave propagation in a cold, stratified magnetoplasma**
T. D. Carozzi
IRF Scientific Report 268, (2000).

P-VI **Evolution equations for radio wave polarization in a cold, stratified magnetoplasma**
T. D. Carozzi
IRF Scientific Report 271, (2000).

P-VII **Method and system for obtaining direction of an electromagnetic wave**
J. Bergman, T. Carozzi, and R. Karlsson
Swedish Patent Publication No. 512 219 (2000), (International Patent Publication WO 99/66341).

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CHAPTER 1

INTRODUCTION – *How a few waves sparked a technological tsunami*

It has been said of our time that it is the age of information and global communication. If this is so, it all started in St. John's, Canada a cold and snowy December day in 1901, just less than 100 years ago . . .

> "Shortly before midday I placed the single earphone to my ear and started listening. The receiver on the table before me was very crude – a few coils and condensers and a coherer – no valves, no amplifiers, not even a crystal. But I was at last on the point of putting the correctness of all my beliefs to test. The answer came at 12:30 when I heard, faintly but distinctly, pip-pip-pip. I handed the phone to Kemp: "Can you hear anything?" I asked. "Yes," he said. "The letter S." He could hear it. I knew then that all my anticipations had been justified. The electric waves sent out into space from Poldhu had traversed the Atlantic – the distance, enormous as it seemed then, of 1,700 miles – unimpeded by the curvature of the earth. The result meant much more to me than the mere successful realization of an experiment. As Sir Oliver Lodge has stated, it was an epoch in history. I now felt for the first time absolutely certain that the day would come when mankind would be able to send messages without wires not only across the Atlantic but between the farthermost ends of the earth."

These are the words of Guglielmo Marconi (1874–1937) the first man to communicate wirelessly over the Atlantic. *Radio*, the term we now use for this phenomena, was coined just following year in 1903. The technological impact of this invention are still with us today and can only increase in the future. Somewhat incredibly, physists are still today at work trying to understand various aspects of radio. And to the human mind this marvelous invention, in which voices from the other side of the Earth resound inside a box, will always be a form of scientific magic.[1]

Not only is radio the starting point of the modern communications society, it is also the central theme of my thesis. This doctoral dissertation in space

[1] It seems even Albert Einstein was of this opinion when he said "*One ought to be ashamed to make use of the wonders of science embodied in a radio set, the while appreciating them as little as a cow appreciates the botanical marvels in the plants she munches.*"

Figure 1.1: Guiliemo Marconi in 1901 during his classic experiment with transatlantic radio. Note the radio equipment on the table and the empty food tins in the cupboard. Alas, little has changed in experimental radio research.

physics, which will be summarized in the pages to follow, deals with various topics related to radio waves in the ionosphere. In particular, it deals with some extensions of radio wave *propagation* theory, some experimental findings on the *generation* of secondary radio waves induced by large amplitude radio waves in the ionosphere, and some work on the *detection*, identification, and characterization of radio waves in terms of generalized polarization concepts. In writing this summary, I have used the metaphor of a theater play: the ionosphere is the stage, the radio waves are the actors, wave polarization is the masks or costumes of actors, and the intrigue is the research on the induced radio waves from the ionosphere known as *stimulated electromagnetic emissions* or SEE. An attempt at presenting and explaining the popular science background on each of these concepts will be made. Where it is appropriate, the contributions of the papers which constitute this thesis, will be presented. And along the way, we will be guided by the spirit of Marconi. This summary closes by discussing some views on the future or continuations of the work found in the thesis. Finally, a concise summary over each of the thesis papers is given.

CHAPTER 2

EARTH'S IONOSPHERE – *The Stage*

1 Discovery of an "Electrically Conducting Region" Around the Earth

Marconi's classic experiment across the Atlantic was *not* the first time wireless transmission had been demonstrated. There were successful attempts at radio communication by Marconi himself before 1901, and there are even claims that the Russian Popov developed the radio before Marconi. So why then was this achievement so important that it overshadowed previously successful attempts and what was the motivation to award him with a Nobel prize in 1909? Simply because virtually *no one* believed radio signals could be transmitted that far. It was a common understanding that Hertzian waves, as radio waves were called at the time after their discoverer H. Hertz, could only travel in straight lines or line-of-sight paths. Due to the curvature of the Earth, it was therefore only possible to transmit a distance of no more than 100 km. Many of the great minds of the day deemed Marconi's vision of global communication as ludicrous; and in anyway, what would it be good for? In his final years, when Marconi received in Australia a radio signal which had traveled half way across the Earth from England, he had at last fulfilled his dream, and in the process brought the world closer together.

At the same moment Marconi's trans-atlantic experiment had proven successful, a new field of science was born. Clearly it was necessary to explain how a radio wave could get from Poldhu, Cornwall to St. Johns, Newfoundland. Most the great physicists of the time simply suggested that a special type of electromagnetic wave was involved that followed the curvature of Earth. The boldest proposition to solve this problem came in 1902 from American engineer A. Kennelly and British physicist O. Heaviside. They suggested that an electrically conducting region in the atmosphere could explain Marconi's results. This came at a time when the region above the atmosphere was assumed to be a perfect vacuum, namely outer space, long before rockets could detect *in situ* what was out there. It was not until 1925, through the work of E. V. Appleton, M. A. F. Barnett, G. Breit, and M. A. Tuve using radio techniques and theory, that the region now known as the *ionosphere* was proven unambiguously.

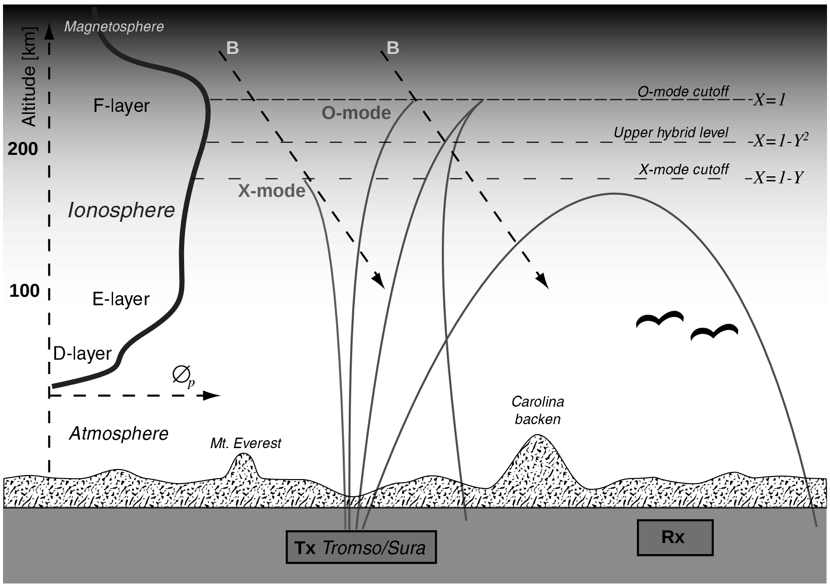

Figure 2.1: The Earth's radio ionosphere.

2 A Modern View

An illustration of the Earth's radio ionosphere, as it is known today, is shown in Figure 2.1. The most important and defining feature of the ionosphere is the presence of ionized gas. In the ionosphere, the amount of ionized gas compared to neutral gas becomes sufficiently large to radically change the properties of the whole mixture, to the point that it no longer behaves as a pure gas. It is reasonable to consider such a condition as the fourth state of matter; and this state was given the name *plasma* by Langmuir during the 1920s. Since the ionosphere can be seen as an enormous naturally occurring plasma volume, ionospheric research and plasma physics are naturally closely intertwined.

The ionosphere maybe the closest naturally occurring example of a plasma, but as plasma, it is not unique. In fact, the major part of the *visible* matter in the universe is in a plasma state. The study of our ionosphere has therefore enormous value in our understanding of the rest of plasma universe.

The plasma roof of the Earth, or ionosphere, is not simply idly floating above our heads: it needs to be constantly replenished. The Earth is continuously bombarded from outer space by various types of radiation. Some of the radiation has such high energy that it may strike out electrons orbiting gas atoms in the atmosphere and thereby creating ions and free electrons in the process. The number of free electrons per unit volume is known as the *plasma density*. Roughly put, the fundamental differences in the various kinds of such *ionizing radiation* results in a layering of the ionosphere in altitude. On average, the plasma density as a function of altitude becomes significant somewhere below 90 km and the region up to this height is called the *D* region.

Above the *D* region, between 90 to 130 km, we reach the *E* region, where there is a peak in plasma density. Just above this, the plasma density falls slightly, only to reach a global maximum in plasma density somewhere in the altitude range of 130–1000 km, which is known as the *F* region. After the *F* region, the plasma density drops as one approaches the outer regions the Earth's plasma environment known as the *magnetosphere*.

CHAPTER 3

HIGH FREQUENCY RADIO WAVES – *The Actors*

Today, a hundred years after man made radio waves were first evidently passed through a plasma, we have a good understanding of how radio waves propagate. We are now aware of the different modes of propagation, where the wave reflect, how their amplitude swells as they reflect and many other things. In fact, ionospheric radio on the whole is straight forward engineering nowadays. This does not mean, however, that few questions remain on radio ionosphere. And neither does it mean that new theoretical understandings of radio wave propagation are not called for.

1 Theoretical Research

Traditionally, the theory of radio wave propagation in stratified, magnetized plasmas is discussed in terms of a linear fourth order ordinary differential equation, which are derived from Maxwell's equations together with an appropriate permittivity tensor. In P-V, I show how it is possible to construct a Hamilton formalism which reproduces the fundamental differential equations. This Hamiltonian formalism is not to be confused with the Hamiltonian formulation used ray tracing or geometrical optics. In ray tracing one obtains a set of canonical equations for the path of the ray and its refractive index vector. The Hamiltonian in this case is a suitable dispersion relation. The Hamiltonian introduced in P-V is not a dispersion relation and furthermore it generates the *full wave* equations in contrast to the approximate eikonal equations.

Another very different approach to radio wave propagation theory is to study the evolution of bilinear forms of the electric and magnetic field components. These bilinear forms are in part related to electromagnetic energy and electromagnetic energy flux, but also to electromagnetic wave polarization. The formulation used in P-VI is to derive a system of equations which govern the evolution of the polarization into a magnetoplasma gradient.

The formalisms of radio wave propagation summarized here were developed in the interest of providing a starting point for the study of nonlinear polarization effects of large amplitude radio waves in a magnetoplasma. The field of nonlinear interaction between radio wave and plasmas is a very active field in radio/plasma research. We will have more to say on one aspect of this research later, but before we do this, we have more to say on the radio waves themselves, namely how they are to be characterized.

CHAPTER 4

POLARIZATION – *The Masks of the Actors*

Long before Hertz discovered the radio wave, scientists were doing research on electromagnetic wave propagation under the more familiar name of optics. It soon became apparent that light, unlike sound waves or water, could not be characterized fully only by its amplitude or intensity. Certain characteristics of light invisible to the human eye must exist in order to explain experimental results. The most famous characterization of light was due to Stokes. He introduced four real quantities I,U,V,Q and described how these could be determined using a few optical filters and a series of intensity measurements. After Maxwell introduced the concept of electromagnetic fields and the equations that describe them it was seen that the Stokes parameters could be expressed as bilinear forms of these fields

$$\begin{aligned} I &= |E_x|^2 + |E_y|^2 && (0.1)\\ Q &= |E_x|^2 - |E_y|^2 && (0.2)\\ U &= 2\Re\,(E_x E_y^*) && (0.3)\\ V &= 2\Im\,(E_x E_y^*) && (0.4) \end{aligned}$$

where x and y are directions orthogonal to the light beam.

Unfortunately there is a major limitation in the Stokes parameter since they can only be used in cases when the direction of propagation of the wave is known and well defined, such as for a light beam or plane wave. If we remove the assumption of a unique, or *a priori* known, direction of propagation, we are forced to consider also the z component of the electric field. This third component is not present in the original definition of Stokes parameters and it is not immediately apparent how this should be extended. In P-I, a generalization of the Stokes parameters is presented. This generalization is based on the fact that if we expand the coherency matrix of the electric field defined as

$$\mathbf{J} = \begin{pmatrix} |E_x|^2 & E_x E_y^* \\ E_x E_y^* & |E_x|^2 \end{pmatrix} \quad (0.5)$$

in terms of the Pauli spin matrices we observe that

$$\mathbf{J} = I\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + Q\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + U\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} + V\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad (0.6)$$

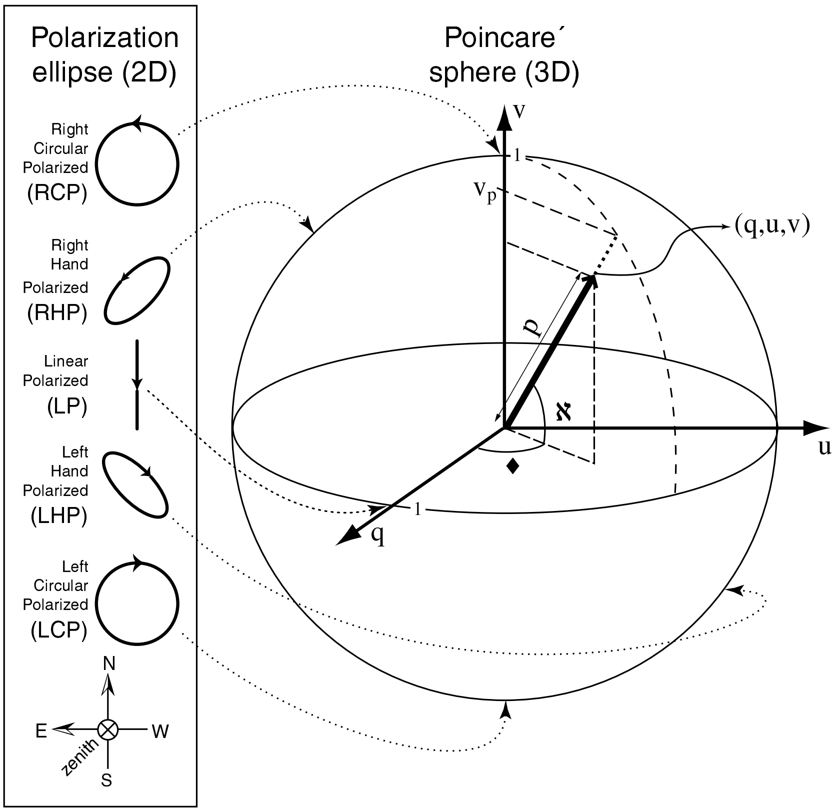

Figure 4.1: The Poincaré sphere is a construction to visualize the polarization of light. It can thought of as the phase space of quasi-monochromatic waves. The poles of the sphere, represent circularly polarized waves, while the equator represents linearly polarized waves. The meridians represent different tilt angles of the polarization ellipse. Finally, the radial dimension represents the degree of polarized or coherency of the wave: the surface of the sphere represents states of pure waves while the origin represents the completely random or *unpolarized* state. This particular Poincaré sphere has been drawn to represent radio waves measured on the ground and therefore the handedness is with respect to nadir and the tilt angle is with respect to the North-South magnetic meridian.

In other words, the Stokes parameters are the Pauli spin matrix components of the coherency matrix of the transverse electric field. Furthermore, it is well known that the Pauli spin matrices are a representation of the generators of the SU(2) group. A natural extension of the Stokes parameters in this context is to consider the outer product of the *entire* electric field and its conjugate, and to expand this outer product using the generators of the SU(3) group. This is precisely what was carried out in paper P-I.

CHAPTER 5

SEE – *The Intrigue*

1 Short history of HF ionospheric modification experiments

One of the most incredible aspects of Marconi's 1901 experiments was that they were performed without the aid of amplification! Soon vacuum tubes appeared and the output power of radio transmitters could be increased to improve reception quality. The increase in transmitter power grew to the point where in 1930 the so called Luxemburg effect was observed; a phenomena which is most readily explained in terms of nonlinearity. A Dutch scientist was listening to the signal from a transmitter located in Beromünster but was surprised to hear at the same time a different radio station located in Luxemburg. Compared to our everyday experience of sound this is a truly surprising effect: imagine listening to a note on a violin which suddenly is shifted in tone as a powerful cello note is played. Phenomena such as these are in principle always possible to achieve if one of the waves involved, called the *pump*, is powerful enough to heat or significantly stress the medium it passes through. When the other wave, called the *probe*, passes through the region stressed by the pump, the probe will pickup the modulation of the pump. In this way, information has passed from the pump to the probe through the changes induced in medium by the pump.

The effects of powerful radio waves on the ionosphere was eventually studied more systematically during the 1970s when dedicated radio facilities were constructed. These facilities were originally called *heaters* since they were built with the anticipation that they would increase the electron temperatures in the ionosphere above them. Basically a heater is not very much more than a commercial radio transmitter in the high frequency (HF) range. Their antennas, however, typically transmit *vertical* beams incident on the ionosphere. One can typically modulate the beam, choose it's polarity and sometimes frequency and other parameters of scientific interest.

One of the first modern heaters was built in Platteville in the United States, 1970. Soon it was found that heaters could do more than just heat the ionospheric plasma. It was observed that they could induce a number surprising effects such as the parametric decay instability and the oscillating two stream instability. Very soon after Platteville, heaters were built around the world at such diverse locations as Arecibo, Puerto Rico; Nizhny Novgorod, Russia (for-

Figure 5.1: The Sura heating facility near Vasil'Sursk, Russia.

merly Gorky, Sovjet); and Tromsø, Norway. Although these facilities are now highly venerable, they are still in active use today and continue to generate new discoveries and scientific output.

Two of the papers included in this thesis are based on observations made in 1998 at the Sura facility near the small village of Vasil'Sursk, 100 km east of Nizhny Novgorod, Russia. A photograph of part of the antenna is shown in Figure 5.1. Another paper was made in 1999 at the Ramfjordsmoen facility locate. It is shown in Figure 5.2.

2 Stimulated Electromagnetic Emissions (SEE)

Almost 20 years ago, it was discovered that not only can a powerful radio wave excite plasma waves and processes in the ionosphere, the HF perturbed plasma could *reradiate* electromagnetic waves detectable on the ground. These induced secondary radio waves, discovered by B. Thidé, were later given the name *stimulated electromagnetic emissions* or *SEE*. In Figure 5.3, one can see one of the very first SEE spectra. The picture is of the display of a Hewlett-Packard spectrum analyzer which, at the time of the photograph, was positioned in a valley adjacent to the valley where the Tromsø transmitter is located. The Tromsø transmitter, being essentially monochromatic, appears on the spectrum analyzer display as a line spectrum. As one can see for oneself, not only is the transmitter signal visible in the middle of the display, but considerable energy exists in the sidebands, especially the lower sideband.

Theoretically, the problem of how plasma can, under certain conditions, radiate electromagnetic waves is of fundamental importance, involving such phenomena as solar bursts, auroral kilometric radiation, Jovian emissions and SEE.

Figure 5.2: The EISCAT heating facility near Tromsø, Norway.

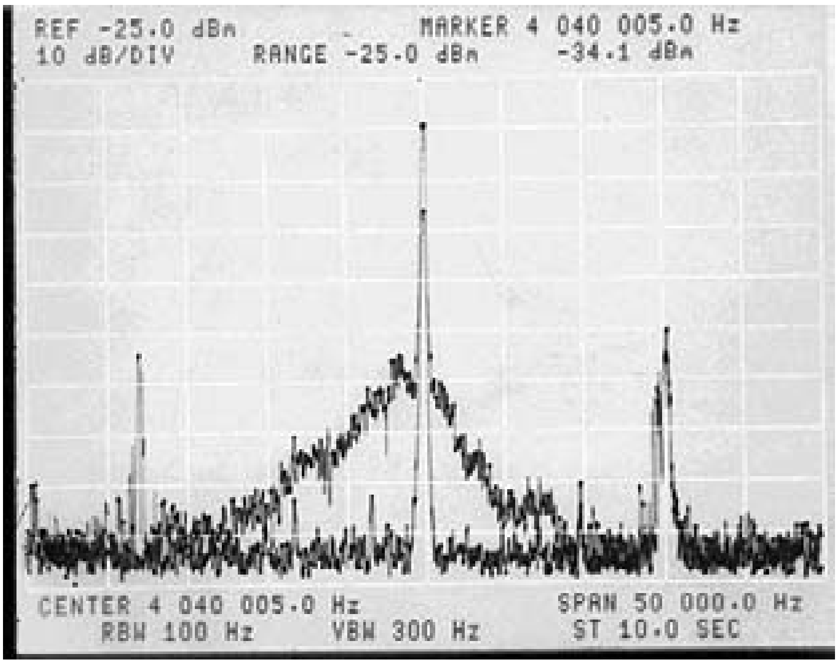

Figure 5.3: Photography of the display of a spectrum-analyzer showing one of the very first measurements of SEE.

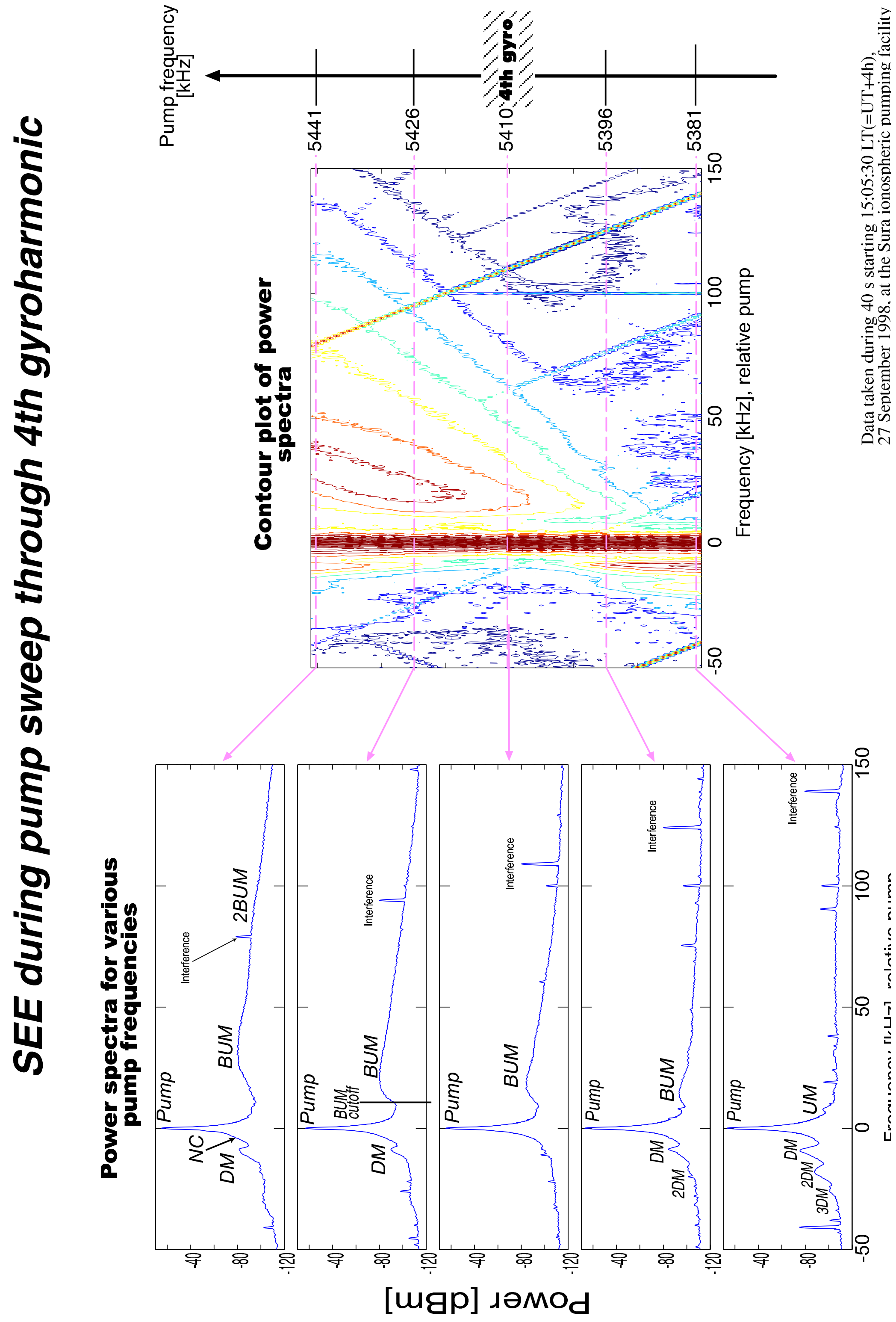

Figure 5.4: The many faces of SEE. Spectra of SEE have a very sensitive dependence on the proximity to a gyroharmonic. This illustration shows the different SEE features and their relation to pump frequency relative to the fourth gyroharmonic. These spectra are actual measurements and not a sketch or cartoon.

Despite their importance, these processes are still poorly understood. What makes SEE so interesting is that it is possible to study such phenomena under controlled and repeatable conditions.

During the final afternoon of an experimental campaign in 1998 at the Sura, HF pump facility in Vasil'Sursk, I was given the opportunity to perform two experiments related to SEE. The first was a very simple experiment: the pump was swept over a frequency range centered on a gyroharmonic. In the second experiment, the complete state of polarization of steady state SEE was measured.

The most important parameter determining the SEE features is the proximity of the pump frequency to an electron cyclotron harmonic. The number of different spectral signatures of SEE is most bewildering until the spectra are organized according to pump frequency and an order is perceived. The sweep experiment discussed in P-III clearly shows how SEE spectra vary with pump frequency in the particularly interesting frequency interval which includes the fourth gyroharmonic. It was anticipated that the pump sweep experiment would not give any information that was not already known. However, it eventually became clear that the greatly improved frequency resolution and the ability to reduce the detrimental effects of ionospheric variability made it possible to make new discoveries. For instance, comparison of the DM resonance with the 2DM resonance curve and also the 3DM resonance curve provide evidence for the cascade model for DM generation. Also, it was discovered that there are weak BUM emissions below the BUM cutoff, a region where current BUM generation models predict that there should not be any emissions. Judging by the results of the pump sweep experiment, it could be very useful to repeat the technique.

The importance of wave modality for SEE generation has been known ever since their discovery. It is observed that only O-mode transmission induce SEE and that the SEE themselves were mainly O-mode. Of course the modality is just one aspect of the more general concept, state of polarization (SOP). In the last experiment conducted during 1998 SEE campaign, I attempted to measure the full SOP of steady state SEE. The technique employed was to simultaneously measure both the North–South and the East–West aligned segments of the Sura facilities receiving antenna using two synchronized, digital, HF sampling units. After the actual experiment, the digital data needed to be processed to derive a spectrum for four quantities which characterize the SOP and are related to the four Stokes parameters. The results were conveniently visualized using a specially designed graphical aid based on the Poincaré sphere. It was found that the SEE did not have a trivial SOP, i.e. they were not simply left-hand circularly polarized. In fact the ellipticity of the BUM tended from LHP to linearity for lower and lower frequency values within the BUM. This may either be an indication of X-mode contribution or of an increase in the obliqueness of the incoming emissions perhaps orthogonal to the local magnetic field. It was also found that there were noticeable differences in the SOP depending on whether the pump was slightly above or below the gyroharmonic. Finally, it was interesting to find that the received pump wave, which upon transmission had been almost pure LCP or O-mode, was found to be RHP during steady state conditions.

After continuous wave (CW) transmission of an HF pump on the order of a minute, the spectrum of the SEE will attain so called steady state. This means that the SEE spectrum changes only gradually on a time scale of minutes corresponding to natural variations in the ionosphere. It was therefore very surprising to observe, during an experimental campaign at Tromsø heating facility, pump induced emissions which did not exhibit steady state. They were only clearly recognized as a systematic effect when the received HF signals were shown in terms of spectrograms. By contrast, when the received HF signals were viewed in terms of instantaneous spectra they were at first incorrectly interpreted as interference. The emissions, which we called *high frequency, induced, dynamic emissions* (HIDE), appeared on the spectrogram as multiple streaks which at times moved together, ascending or descending in frequency. An individual streak could come into existence within a fraction of a second, could last several seconds and then vanish in less than a second. The emissions were clearly induced by the heater as was evidenced by their almost immediate appearance and disappearance as the pump turned on and off respectively. The ocean was mainly O-mode polarized and induced during O-mode pumping just like SEE but they were also observed during X-mode transmission unlike SEE. A convincing explanation for the ocean has yet to be suggested.

3 Environmental aspects

Clearly, radio has had a enormously beneficial effect on our society and the future of wireless communication and other application is to say the least enormous. But as with all technological advances, there may be side effects. It is obvious that much has changed in the 100 years since the simple radio experiment of Marconi. From the ground we have TV, radio, mobile telephones, weather radars, navigational radars; and from space we have telemetry systems, satellite TV, radio, microwave remote sensing and so on. These radio based systems are expanding rapidly in both number and radiated power and very soon we will see ambitious space based projects such as global wireless internet and personal visual-audio telephony.

Now most people are familiar with the ozone layer and its role as protective blanket, shielding delicate ecosystems from dangerous ultraviolet radiation from the sun. Regrettably, fewer people are familiar with the ionosphere and its analogous role in protecting Earth from dangerous forms of radiation. In fact, the ionosphere is the direct result of *ionizing radiation* impacting on our neutral atmosphere.

As the radio stress on the Earth's ionosphere increases and society's dependence on radio based systems grows, a better scientific understanding of the effects of high power radio waves on the ionosphere would be highly useful. And even though some have been critical of the environmental impact of ionospheric modification facilities in the past, these facilities are after all the best controlled source for studying the environmental aspects of radio. Clearly it is wiser to know in advance what one can regret in the future.

CHAPTER 6

CONCLUSION AND OUTLOOK – *How they all lived happily ever after…*

Much on the work in this thesis has more the nature of starting points rather than closing point for research. Several techniques have been developed here, such the HF polarimetry technique, the direction finding technique, and the pump sweep technique, which will hopefully prove fruitful in future experiments in radio wave–ionospheric interaction experiments. As far as future experiments are concerned, there are too many for one lifetime to suffice, therefore it may be wise to mention a few here.

Concerning the pump sweep, it would ultimately be very interesting to sweep the pump through the entire ionosphere, as this would give a catalogue of all the pump frequency dependent HF emissions in the ionosphere. It would be interesting to further explore the emence possibilities of nonmonochromatic pump waves of which the pump sweep is an example. For instance, at the Tromsø facility, we recently attempted an psuedo-incoherent pump wave experiment in which the coherency of the transmitted signal could be varied parametrically. This could be used to explore the dependence of nonlinear plasma processes on the coherency of the pump.

The HF polarimetry technique was intended to be used to measure nonlinear polarization effects on large amplitude waves in plasmas. In future it would be very interesting to try to observe the radio–plasma analogues of the Kerr effect or the inverse Faraday effect in ionospheric pump experiments and a host of other self-action or pump-probe interaction polarization effects. Furthremore a simple search for induced X-mode emissions is duely called for. Finally an extension of the single point HF polarimetry to include the full advantages interferometry could have enormous potential.

It would also be valuble to continue work on nonlinear polarization effects in radio wave–plasma interactions, which to my mind is well developed in optics but not as well know in nonlinear plasma study. In this direction, generalizations of the polarization concept to higher orders of correlation should be investigated, such as $\langle E_1 E_2 E_3 \rangle$ which can directly give signatures of three-way interactions. Some work is already underway such as a covariant formulation of the concept of polarization. Explicit characterisation of all well-known plasma waves in terms of these generalized polarization parameters should be carried out in the future.

Finally, the accidental “discovery” of emissions induced in sporadic E of a nonstationary nature should also be followed up. Combined experiments with incoherent and coherent radars would be of great value in this exploration.

Alas, only time can tell which of these topics will see the light of day...

CHAPTER 7

Paper Summaries

P-I. *Parameters characterizing electromagnetic wave polarization*

The Stokes parameters characterize the properties of quasi-monochromatic, electromagnetic plane waves. In P-I a generalization of the Stokes parameters is presented which includes all three components of the electric or magnetic field and in addition allows for wide-band waves. The generalization is based on the decomposition of the full three-dimensional spectral correlation matrix in terms of base matrices representing generators of the SU(3) group.

P-II. *Full Polarimetry Measurements of SEE. First Results*

Nonlinear effects in ionospheric plasma caused by high power radio waves has been known since the 1930s. By controlled experiments it has been realized that large amplitude radio waves can excite secondary electromagnetic waves at frequencies different from that of the mother wave. One class of such induced secondary emissions, in the high-frequency regime, are the stimulated electromagnetic emissions (SEE). In the study of their properties, the focus in the past has been to analyze the time development of the power of SEE spectra under various conditions. In this paper, we develop a theory and a technique to detect the full state-of-polarization (SOP) of SEE, of the power is but one out of a total of four parameters. The technique was used in an experiment conducted at the Sura HF wave-ionosphere interaction facility. The results show that the SEE could have distinguishing SOP properties. In the future, other experiments could employ this technique to study nonlinear *polarization* effects in large amplitude electromagnetic wave in a magnetoplasma as a complement to the traditional spectral analysis.

P-III. *High resolution measurements of SEE dependence on pump frequencies close to the fourth electron cyclotron harmonic*

It is well established that spectra of stimulated electromagnetic emissions are extremely sensitive to the pump frequencies proximity to electron gyroharmonics. Unfortunately, the detailed study of this dependence has been limited to manually tuning and retuning the pump, which can take minutes and is only feasible to perform for a maximum of a few tens of frequency increments. This paper deals with an experiment in which we utilized an automated pump frequency stepping procedure which resulted in data of such high resolution and minimal ionospheric variation that new discoveries on the generation of SEE were made. For instance, we found evidence for a cascade model to explain the generation of the downshifted maximum (DM) feature of the SEE. We also observed emissions associated with the broad upshifted maximum (BUM) but were below the supposed cut-off frequency for the BUM. This technique could be used at high gyroharmonics to resolve the DM intensity minimum to determine if it actually consists of *two* minima as predicted by some theories.

P-IV. *Observations of nonstationary radio emission induced by a powerful high-frequency radio wave incident on sporadic E*

By accident, during a campaign focusing on the measurement of SEE at the Tromsø heating facility in November 1999, we observed very unusual pump induced HF emission. The intermittent, highly variable nature of this emission is very unlike traditional SEE, which are typically highly stable and eventually exhibit a steady state. The emission bears a striking resemblance to naturally occurring auroral roar emission and also to zebra-pattern fine structure of solar bursts. Analysis of the elapsed time between ground wave reception and sky wave reception revealed that the emissions were probably emanating from excited sporadic E. This would then be the first direct observation of HF emission generated in sporadic E.

P-V. *Hamiltonian formulation of radio wave propagation in a cold, stratified magnetoplasma*

The theory of low power radio waves in the ionosphere can be roughly broken into two categories: ray tracing, in which one derives wave propagation by minimizing the phase length of the wave path or full wave solutions, in which the Maxwells equations are solved directly assuming wave propagation in a plane stratified cold magnetoplasma. The full wave theory in this case consists of a fourth order ordinary differential equation in the vertical dimension variable. As it turns out, it is possible to derive a Hamiltonian function, terms of the horizontal electric and magnetic field components and their adjoints and the height variable. P-V introduces this Hamiltonian.

P-VI. *Evolution equations for radio wave polarization in a cold, stratified magnetoplasma*

In this paper, we develop a theory for the evolution of parameters related to the polarization of electromagnetic wave in a cold, stratified magnetoplasma. It is demonstrated that if the proper representation is used, some of the parameters will be conserved under the propagation of the radio wave. This formalism is though to be a starting point for the development of a theory for nonlinear *polarization* effects in large amplitude radio waves in the ionosphere.

P-VII. *Method and system for obtaining direction of an electromagnetic wave*

This paper is a patent describing an apparatus which determines the incidence direction of an impinging electromagnetic wave. This is done using some basic properties of electromagnetic radiation. The described system is comparable to other direction finding techniques such as interferometry or the use of high gain antennas. The advantage of our technique is that it requires only a single point measurement, in contrast to interferometry, and it avoids the complexities involved in using high gain antennas (which requires either a mechanical angular sweep or a complex multiple antenna arrangement).

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