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The polarization of auroral radio emissions

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Abstract. Ground level observations using two vertical loop antennas oriented at 90° to each other reveal the sense of polarization of several types of auroral radio emissions in the frequency range 30–5000 kHz. Auroral hiss is observed to be right elliptically polarized (RP) with respect to the local magnetic field, consistent with theoretical expectation for the whistler mode and with earlier measurements. Two less well-understood auroral emissions, are found to be left elliptically polarized (LP). This polarization is inconsistent with their generation in the X-mode as suggested by some theories.

Introduction

The auroral ionsphere is an abundant source of radio emissions, some of which are detectable on the ground. At LF/MF/HF, these include auroral hiss at 1 kHz–1 MHz [e.g., *Helliwell*, 1965], MF-burst at ~1.4–4.5 MHz [*Weatherwax et al.*, 1994; *LaBelle et al.*, 1997], and $2f_{ce}$ and $3f_{ce}$ auroral roar at ~ 3 and ~ 4.5 MHz, respectively [*Kellogg and Monson*, 1979; *Weatherwax et al.*, 1993]. The principal generation mechanism for auroral hiss has been described; however, the generation mechanisms of MF-burst and auroral roar remain unknown. These auroral emissions are signatures of important phenomena such as wave/particle interactions and energy exchange processes.

Polarization measurements provide an important clue about the generation mechanism of these auroral radio emissions by placing constraints on the propagation mode in the ionosphere. For example, several researchers have suggested that auroral roar may be generated in the X-mode by the cyclotron maser mechanism operating at F-region altitudes [*Weatherwax et al.*, 1995; *Yoon et al.*, 1996]. This mechanism predicts that auroral roar should be right elliptically polarized. Another possible mechanism of auroral roar involves the conversion of upper hybrid waves to electromagnetic waves [*Gough and Urban*, 1983; *Weatherwax et al.*, 1995]. This mechanism predicts either left-elliptical polarization (LP) or right-elliptical polarization (RP), depending on the mode conversion process. It is therefore possible to eliminate some theories based on the observation of signals propagating in a mode which is forbidden by that mechanism.

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To determine the polarization of various radio emissions crossed loop antennas and associated electronics were installed at Churchill, Manitoba. The first observations with this system are described below.

Instrumentation

For several years auroral radio emissions have been continuously monitored at various northern and southern hemisphere sites using a programmable stepped frequency receiver (PSFR). This receiver is usually programmed to sweep from 30 kHz to 5 MHz every 2 seconds in 10 kHz steps. Data are collected, digitized, and stored by a local computer and sent back to Dartmouth College monthly.

In March 1997, the PSFR at Churchill (58.76°N, 265.92°E, 69.2° invariant latitude) was modified to measure the polarization of received signals. The modified antenna system consists of two vertical 2.5 m^2 loop antennas oriented 90° to each other in an approximately N-S/E-W position. Figure 1 shows a schematic of the two antennas and a simplified block diagram of the system. (In the figure, the two antennas are separated for clarity, but in fact they are physically located on the same vertical mast.) The polarization detector, receiver, and computer are located ~ 100 meters from the antenna to minimize noise pickup.

In the polarization detector, a 90° phase lag is introduced into the signal from the N-S loop. On alternate sweeps this signal is inverted, effectively shifting the phase of the N-S loop signal from −90° to +90° relative to the E-W loop. The input to the receiver is the shifted and switched N-S loop signal summed with the signal from the E-W loop. If the original signals induced in the antenna loops are equal in amplitude but differ in phase by exactly 90°, as would be expected for vertically incident right- or left-circularly polarized waves, the in-

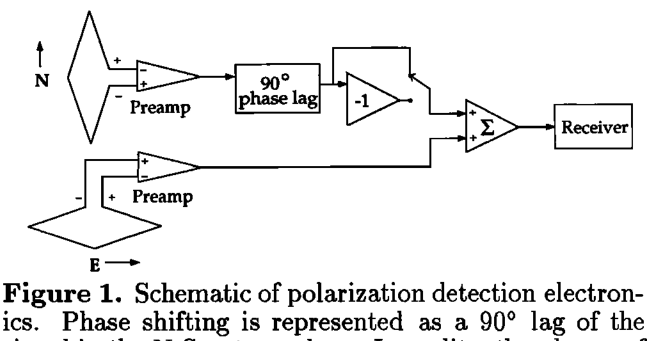

Figure 1. Schematic of polarization detection electronics. Phase shifting is represented as a 90° lag of the signal in the N-S antenna loop. In reality, the phases of both signals are shifted to produce the 90° lag.

put signal to the receiver alternates between zero and twice the induced signal strength. On the other hand, a linearly polarized signal induces in-phase signals in the antenna loops which result in a constant input signal to the receiver, there being no difference between shifting the N-S signal forward or backward in phase in this case. To assist in data analysis, a marker is recorded during part of the noninverted sweep to allow sweep identification, and a calibration signal that simulates a received right-cirularly polarized signal is periodically inserted into the antennas. In order to determine polarization using this technique, the measured signals must be relatively constant in amplitude and polarization during two consecutive meaurements ($\sim$ 2 s); signals whose amplitude varies faster than that may register a false or indeterminant polarization. The sense of polarization (right or left) is determined by noting the relative signal strengths of the two sweeps and comparing that to the marker.

The interpretation above assumes that the electronics are perfect. It is difficult to shift a single signal by 90° over a wide bandwidth, but it is easy to shift both the N-S and E-W loop signals such that the phase of the N-S loop signal lags the E-W loop signal by $\sim$ 90° over a range of approximately two decades. The error in phase shift over the 0.05–5.0 MHz frequency range is less than ten degrees, implying that the maximum amplitude difference between consecutive sweeps for either right- or left-circularly polarized vertically incident signals is about 20 dB which is less than the observed differences of the real signals described below.

In this paper all wave polarizations are measured with respect to the local magnetic field. The electric field vector of a right-handed circularly polarized (RCP) wave rotates clockwise in time as viewed in the direction of the magnetic field. In this case, for a receiver in the Northern Hemisphere the electric field vector rotates clockwise as seen by an observer looking down on the antennas. This definition is standard in plasma physics [e.g., *Chen*, 1984] and is used in previous auoral radio emission polarization studies [*Tanaka et al.*, 1976].

Observations

Figure 2 shows an auroral hiss event recorded starting at 0548 UT on March 16, 1997, lasting approximately 3 minutes, and extending from the lower bound of the instrument (30 kHz) into the AM-broadcast band above 500 kHz. Dark horizontal lines on this spectrogram represent fixed-frequency man-made transmissions. In contrast to the fixed-frequency signals, the auroral hiss is clearly elliptically polarized because alternate receiver sweeps differ in amplitude. Careful inspection reveals that the observed dark-light pattern corresponds to RP. This result is consistent with previous auroral hiss polarization measurements using several techniques [*Tanaka et al.*, 1976]. Also, auroral hiss is believed to propagate in the whistler mode in the ionosphere, which implies RP, consistent with the observation. This observation of auroral hiss provides a natural calibration of the polarization detector.

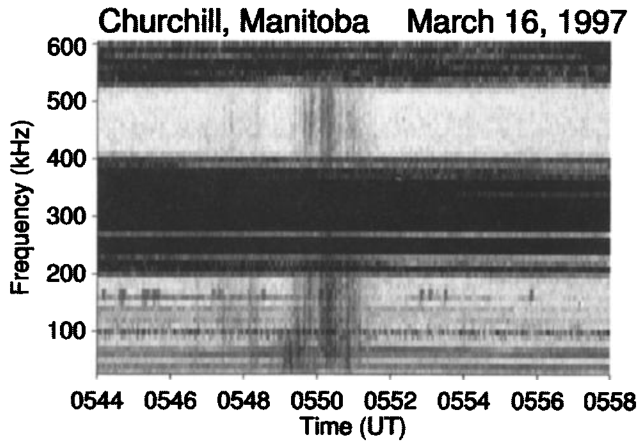

Figure 2. A raw spectrogram recorded by the swept frequency receiver during a time when auroral hiss occurs at frequencies from 30 kHz to above 500 kHz. Alternate sweeps are dark or light, showing that the waves are elliptically polarized. Careful inspection reveals that they are right-hand polarized, as expected on theoretical grounds and on the basis of previous measurements.

Figure 3*a* (top panel) is a spectrogram showing three types of auroral radio emissions recorded 0445–0459 UT on April 4, 1997. Auroral hiss occurs below $\sim$ 500 kHz beginning near 0452 UT lasting for $\sim$ 5 minutes and again during the last $\sim$ 30 seconds of the record. MF-burst is the broadband ($\sim$2 MHz) emission above $\sim$1.5 MHz and correlated with the auroral hiss. Auroral roar is the relatively narrowband ($\delta f \sim$ 200 kHz) emission at $\sim$3 MHz beginning near 0448 UT and ending near 0453 UT. Horizontal dark bands are fixed-frequency transmissions; the band from 550–1600 kHz is the AM broadcast band. The sweep identification marker is at 1–1.25 MHz. Clearly, alternate sweeps are light or dark, implying that they are elliptically polarized. Careful inspection shows that the MF-burst and auroral roar are LP and auroral hiss is RP.

Figure 3*b* (bottom panel) shows the polarization of the signals as a grayscale. In this display, white and black pixels correspond to LCP and RCP waves respectively. Elliptically polarized waves are represented as gray pixels between the two extremes, with linear polarization being at the middle of the gray band (half way between white and black). As expected, the auroral hiss shows up as dark pixels implying right-hand polarization. In contrast, both MF-burst and auroral roar are left-hand polarized. There are two sweeps at the onset of an auroral substorm near 0453 UT during which the polarization measurement momentarily implies that the auroral roar is RP, but at this time the auroral roar amplitude is probably highly time variable, as is known from fine structure measurements [e.g., *LaBelle et al.*, 1997; *Shepherd et al.*, 1996], and under such conditions the polarization measurement cannot be trusted.

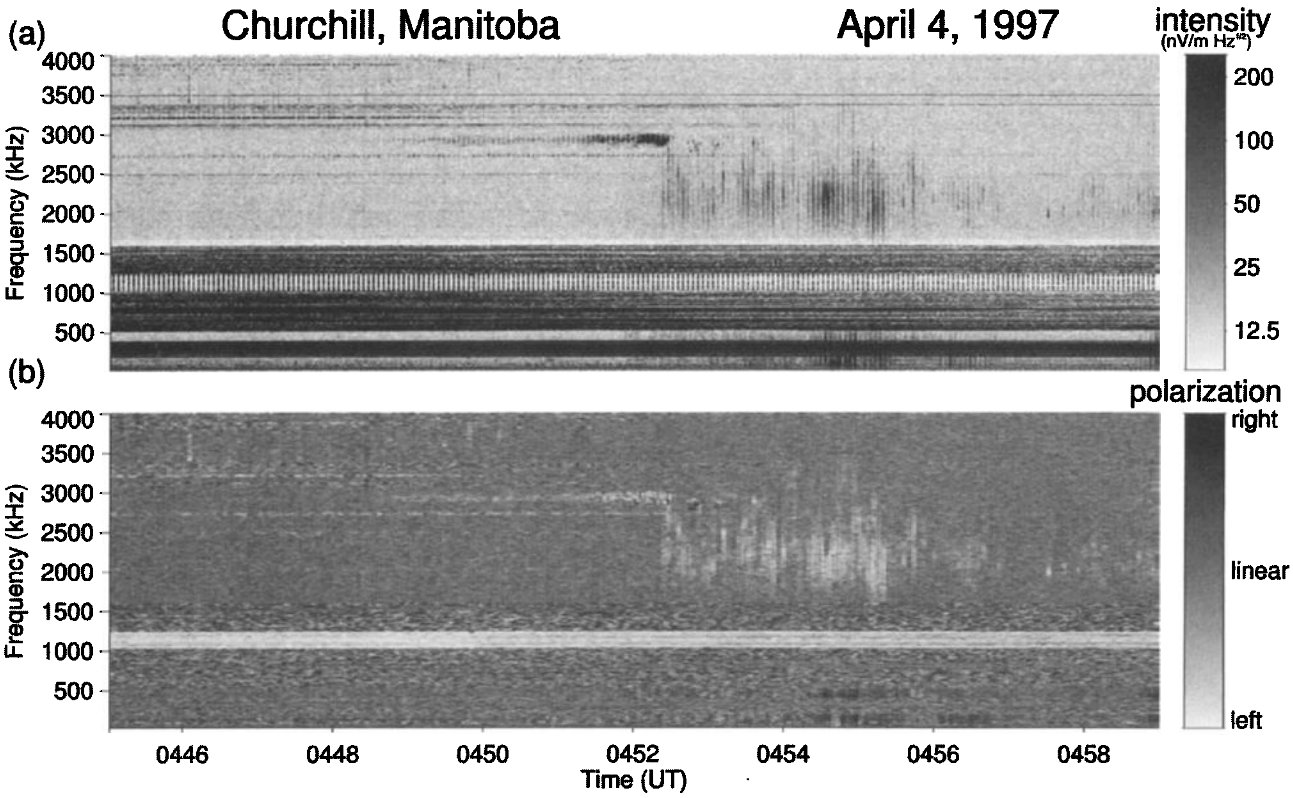

Figure 3. (a) Raw reciever output showing the three distinct types of emissions: auroral hiss, auroral roar, and MF-burst. The banded appearance of all three implies that they are elliptically polarized. (b) Polarization of emissions showing that auroral hiss is right-hand polarized, while MF-burst, auroral roar, and the calibration signal at 1.0–1.25 MHz are left-hand polarized.

Auroral emissions were seen on 38 of the 78 days of observation between March 15 and June 1, 1997. For purposes of accumulating statistics, an event is defined as an auroral emission that is detected for longer than 30 seconds and is separated by at least 10 minutes from other events. Table 1 shows the sense of polarization of all events which occurred during the observation period, as determined from spectrograms similar to those shown in Figure 3*b*. Table 1 shows that auroral hiss is right elliptically polarized and MF-bursts and $2f_{ce}$ auroral roar are both left elliptically polarized. While the statistics establish that these emissions are almost entirely left-hand polarized, more statistics are needed to exclude the possibility that a few percent of these emissions are right-hand or linearly polarized. The few events in the unknown column of the table are due to interference from strong atmospherics. An atmospheric produces an output to the receiver which resembles a broadband signal that is strongly polarized in either direction, depending on the sign of the induced phase shift during the event. The impulsive nature of these signals obscure the polarization of coincident waves and illustrate the effect of a signal which varies in amplitude faster than the sweep period of the receiver.

Table 1. Polarization of auroral hiss, auroral roar, and MF-burst events from Churchill, Manitoba, between March 15 and June 1, 1997.

Type of Event	Right	Left	Unknown
Hiss	17	0	4
MF-Burst	0	23	4
Roar	0	46	3

Interpretation

The experiment described above establishes that the MF-burst and $2f_{ce}$ auroral roar emissions are left-hand polarized, in contrast to auroral hiss which is right-hand polarized. For all three emissions, the mean power difference between alternate sweeps, during which the signals constructively and destructively sum, averages -10 dB. The instrumental error in this measurement due to phase inaccuracies in the polarization detection electronics is the order of -20 dB. The departure from circular polarization inferred from our measurements can in principle be interpreted either in terms of finite ellipticity of the polarization or in terms of off-zenith incidence of a perfectly circularly polarized wave. In practice, other factors limit the observed degree of polarization so that it is not possible to quantitatively infer more from the data than the sense of polarization. Foremost among these factors is the variability of the signals. High time resolution measurements show that both MF-burst [*LaBelle et al.*, 1997] and auroral roar [*LaBelle et al.*, 1995; *Shepherd et al.*, 1996] amplitudes vary on time scales far shorter than the 2 s time scale needed to make a polarization measurement. The fast time-scale variations effectively impart noise into the system which biases the result away from perfect circularity. Another possible factor is the effect of the component of the wave reflected from the conductive ground underlying the antenna.

As mentioned in the introduction, in the case of auroral roar the polarization measurement has significant implications for theories. Several authors have calculated that for realistic loss-cone distribution functions the X-mode cyclotron maser instability operating at F-region altitudes can have a growth rate exceeding electron-neutral collision frequencies [*Weatherwax et al.*, 1995; *Yoon et al.*, 1996]. However, *Yoon et al.* [1996] point out that only the X-mode will reach the ground from this mechanism, because the O-mode remains trapped in the ionosphere. Hence this mechanism predicts that the waves should be right-hand elliptically polarized. The measurement of LP for auroral roar emissions excludes this mechanism. The cyclotron instability also excites trapped Z-mode waves with high growth rates at locations where the upper hybrid frequency matches the cyclotron harmonics [e.g., *Kaufmann*, 1980; *Yoon et al.*, 1997], and it has been suggested that these waves may convert by a variety of mechanisms to either L-O mode or R-X mode electromagnetic waves [*Gough and Urban*, 1983; *Weatherwax et al.*, 1995]. This mechanism therefore predicts either LP or RP radiation depending on the conversion mechansism and hence is not excluded by the polarization measurements presented above. Another suggested mechanism involves the interaction of upper hybrid waves near harmonics of the gyrofrequency [*Willes and Bale*, 1997; *Winglee and Dulk*, 1986] However, the polarization measurements place a constraint on the conversion mechanisms which may be considered in these theories.

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