Changes in Polarization State of Transionospheric Radio Waves Driven by Difference in O- and X-mode Power

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ABSTRACT

The Radio Receiver Instrument (RRI) of the Swarm-E/e-POP satellite can determine the polarization state of transionospheric radio waves. Coordinated experiments between ground transmitters and RRI show that the radio wave ellipticity oscillates from linear to circular when observed poleward of the transmitters. The RRI observations showed circularly polarized waves farther away from transverse propagation alignment. For radio waves with similar power in the O- and X-modes, the magnetoionic theory shows that the radio waves are circularly polarized for transverse propagation only (aspect angle ~90°). However, the X-mode power was found to dominate over the O-mode at low elevations to the north of transmitter. The radio wave polarization states are modeled after accounting for difference in power between the O- and X-modes. The results show that the dominance of X-mode at select elevation angles resulted in significant change in the radio wave ellipticity.

1. INTRODUCTION

Transionospheric radio wave propagation occurs when a radio wave travels from the Earth into space through the ionosphere or vice versa. The polarization state of radio waves depends on the direction of propagation with respect to the local geomagnetic field and background electron density in the ionosphere (Budden, 1961; Davies, 1990). Faraday rotation of radio waves are extensively studied and well understood (Gillies et al., 2012; Danskin et al., 2018). However, works on radio wave ellipticity are limited (Danskin et al., 2018; Pandey et al., 2022).

Pandey et al. (2022) investigated the ellipticity angle variations of radio waves for a special case when only O-mode propagated through the ionosphere. Danskin et al. (2018) observed that radio wave ellipticity angles were unusually large poleward of a HF transmitter at Ottawa, Canada. The radio wave polarization state varied from linear to circular, although the wave propagation was not transverse to the local geomagnetic field. The magnetoionic theory with equal power in O- and X-modes suggests that the radio waves can be circularly polarized only within a few degrees of transverse propagation alignment. Therefore, observed variations in radio wave ellipticity demand a detailed investigation to understand the transionospheric radio wave polarization state. The present work provides a possible scenario for the generation of circularly polarized radio waves even when the wave propagation is farther away from the transverse alignment.

2. **OBSERVATIONS**

The Enhanced Polar Outflow Probe (e-POP) payload on the CASSIOPE/Swarm-E satellite has eight scientific instruments (Yau & James, 2015). The Radio Receiver Instrument (RRI) of e-POP consists of two 6-m orthogonal dipoles (James et al., 2015). The RRI measurements were used to compute the polarization state of radio waves transmitted from HF transmitter at Ottawa, Canada. For details of polarization state calculations see Danskin et al. (2018).

Figure 1 contains the ellipticity angles of radio waves observed by RRI during slew to transmitter passes of the e-POP satellite. In Figure 1a, the range of ellipticity angles decreased with increasing aspect angle (i.e., larger deviations from the transverse propagation alignment). For aspect angles up to 120°, the radio waves had all possible polarization states from linear to circular. At aspect angles above 120°, the radio wave polarization states remained within linear and elliptical. Figure 1b revels that the circularly polarized radio waves were observed at low elevations when the satellite was northward of the transmitter.

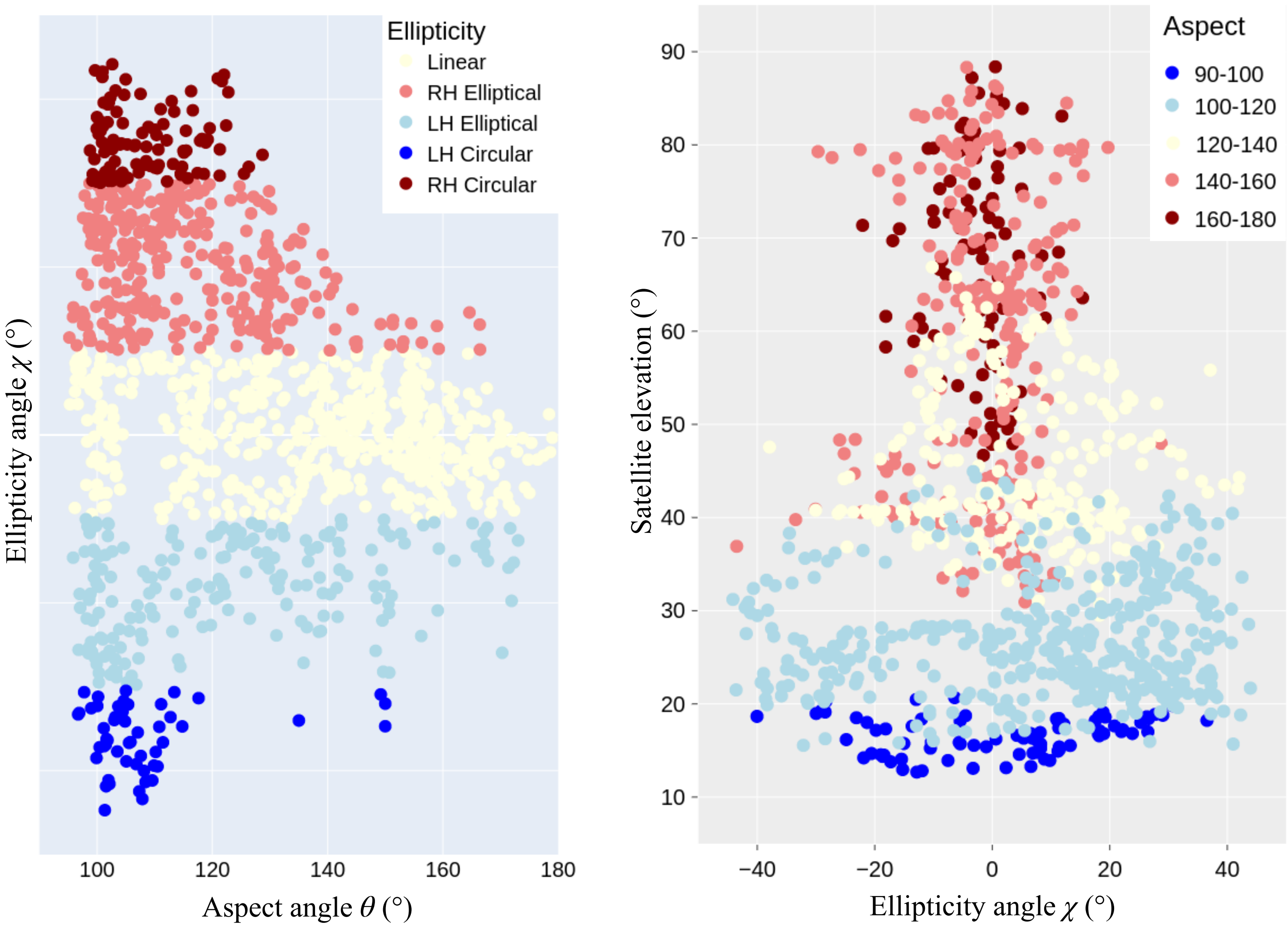

Figure 1. Observations of radio wave ellipticity angles w.r.t. (a) aspect angle, and (b) satellite elevations. The colored scale in right panel corresponds to different set of aspect angles.

3. **MODELING**

In absence of collisions, the wave-polarization ratio (ρ) is given by the equation 1.

$$\rho = i\frac{{Y_T}^2}{2Y_L(1-X)} \pm i\sqrt{\frac{{Y_T}^4}{4{Y_L}^2(1-X)^2}+1} \tag{1}$$

where $X = (\omega_p/\omega)^2$, $Y = \omega_c/\omega$, $Y_T = \sin(\theta)$, and $Y_T = \cos(\theta)$. X represents the ratio of ω_P^2 to ω^2. Aspect angle θ is the angle between radio wave propagation direction and local geomagnetic field. Terms ω, ω_c and ω_p correspond to the radio wave frequency, gyro-frequency, and plasma frequency, respectively. For more details see Budden (1961) and Gillies et al. (2010).

The positive and negative signs in equation (1) correspond to the Ordinary (O) and Extraordinary (X) modes of radio waves. The value of ellipticity angle χ is calculated using $\tan^{-1}(\rho)$. Note that the O- and X-modes have equal amplitude of ellipticity angles but opposite signs or rotational sense.

Ellipticity angles of O- and X-modes were calculated corresponding to different combinations of the radio wave and plasma frequency. Figures 2a and 2b display the amplitude of ellipticity angles of individual wave modes. The ellipticity of wave modes primarily depends on the aspect angle. Individual O- and X-modes are circular for radio wave prorogation away from transverse alignment, and linear when wave propagation is within a few degrees of transverse alignment.

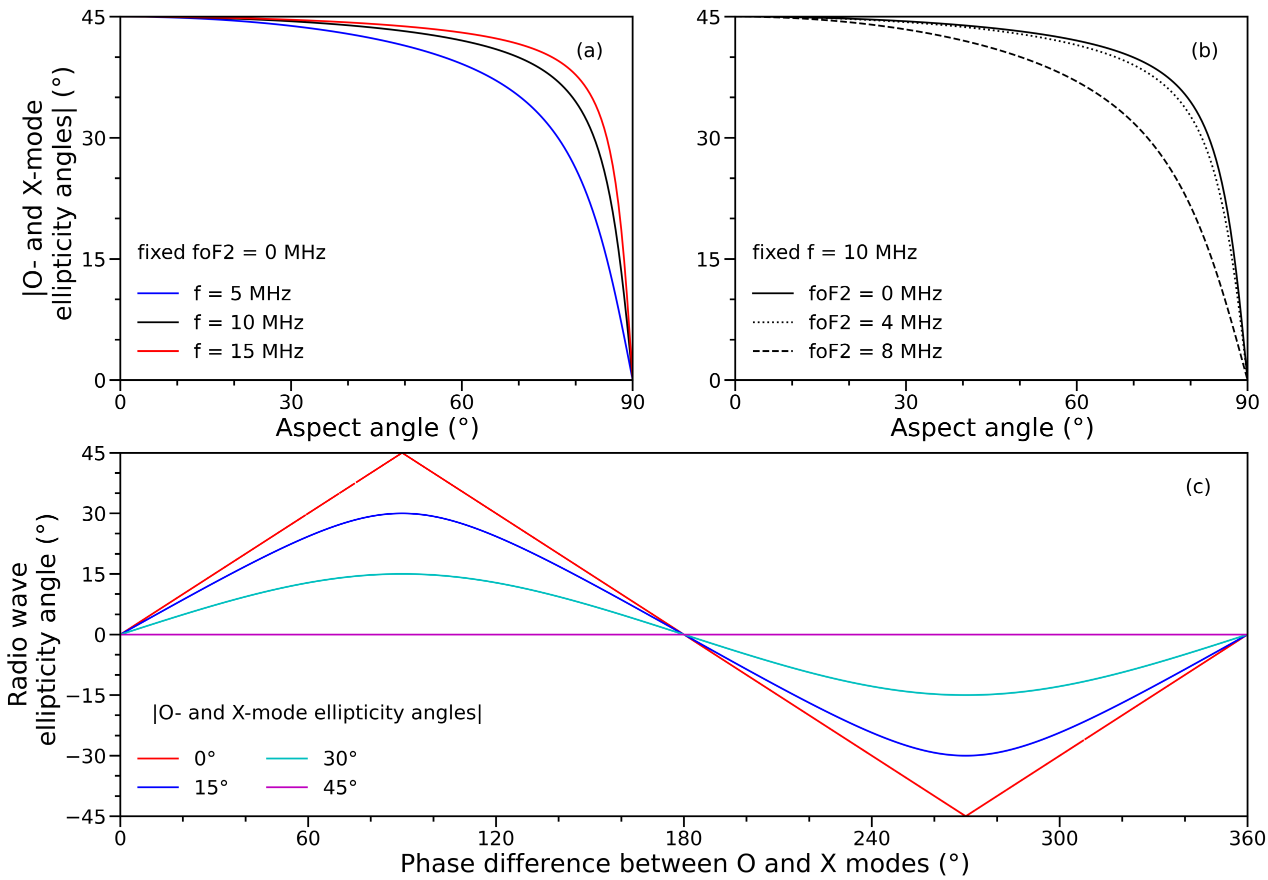

Figure 2. (a)-(b) Absolute values of the O- and X-mode ellipticity angles calculated at different aspect angles, (c) modeled ellipticity angles of radio waves generated by combining the O- and X-modes of different polarization states.

Figure 2c displays the ellipticity angles of radio waves generated by combining O- and X-modes. Individual modes were constrained to follow the magnetoionic theory of radio wave propagation: the semi-major axis of the two modes were orthogonal to each other, and both modes had the same ellipticity magnitude but opposite rotation sense (positive values for O-mode and negative values for X-mode). The two modes were combined at different phase differences to model all possible polarization states of radio waves. Note that the two modes were assumed to have equal power. Results show that the radio wave ellipticity is distinctly different from the individual wave modes. Linear O- and X-modes resulted in radio waves with all possible polarizations states from linear to circular, whereas the circular O- and X-modes resulted in only linearly polarized radio waves.

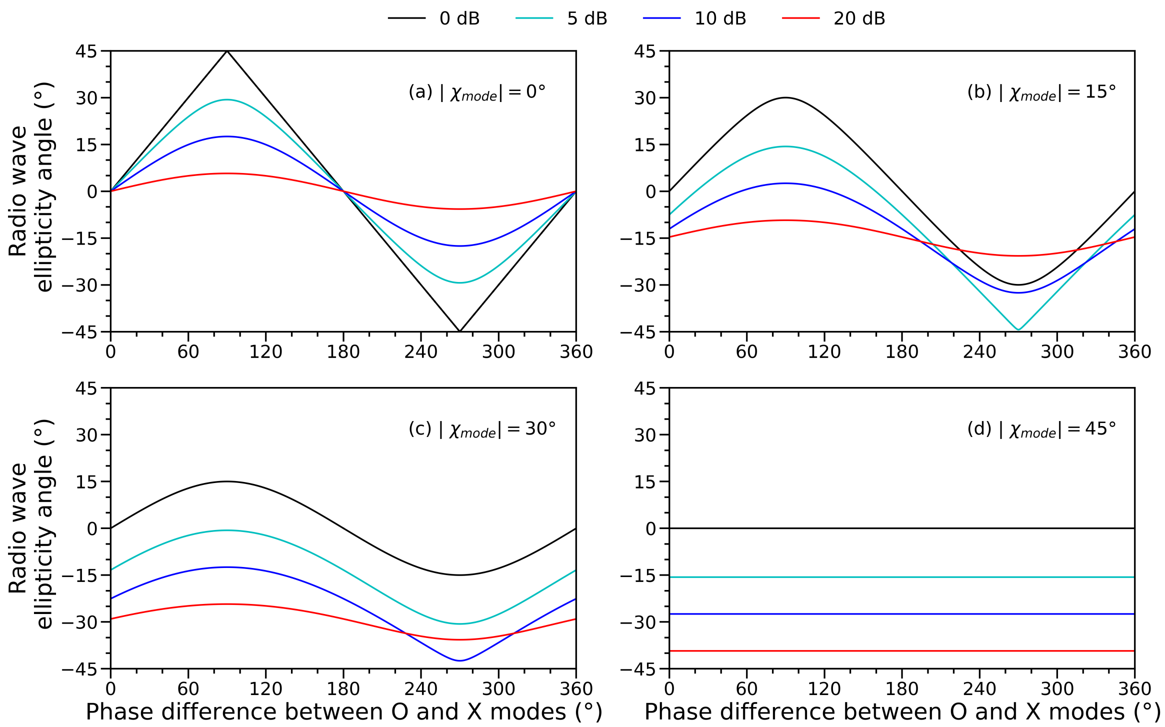

Figure 3. Modeled changes in polarization states of radio waves corresponding to different levels of the X-mode power w.r.t. the O-mode. Panels (a)-(d) display changes in final radio waves that are generated from O- and X-modes with ellipticity angles 0°, 15°, 30° and 45° respectively.

Figure 3 illustrates the effect of difference in O- and X-mode powers on the radio wave polarization states. The results obtained show that the radio wave ellipticity changes significantly when the X-mode power is higher than the O-mode. With increasing power in the X-mode, the linear O- and X-modes no longer produce the circularly polarized radio waves (Figure 3a). In fact, the linear O- and X-modes resulted in linearly polarized radio waves when X-mode dominated the O-mode. A shift in radio wave ellipticity angle is noted for the waves that are generated from the circular O- and X-modes (Figure 3d). Figures 3a and 3d suggest that the radio wave ellipticity approaches towards the X-mode ellipticity as the X-mode power increases.

The condition for generation of circularly polarized radio waves changed significantly with the increase in power of one mode (here, X-mode). With relatively stronger X-mode power, circularly polarized radio waves are generated from the elliptical O- and X-modes (Figures 3c-d). However, these circularly polarized radio waves do not display all rotation sense (sign of ellipticity angle) like those degenerated from linear O- and X-modes with equal power (black line in Figure 3a). Rotation sense of these circularly polarized radio waves is governed by the dominant mode (here, X-mode).

4. **DISCUSSION**

Swarm-E RRI observations showed that the radio waves were circularly polarized over a wide range of aspect angle farther away from transverse propagation alignment (Figure 1). However, the magnetionic theory suggests that only linear wave modes can result in circularly polarized radio waves when O- and X-wave modes have equal power (Figure 2c). The individual wave modes are linear when the wave propagation is within a few degrees of transverse alignment. Therefore, the observations of circularly polarized radio waves farther away from transverse propagation alignment could not be explained with the assumption of equal powers in O- and X-modes, that is commonly used.

Gillies et al. (2010) modeled the relative power of X-mode with respect to the O-mode for radio waves transmitted from SuperDARN radars in Canada. The authors showed that the two wave modes have a significant difference in O- and X-mode powers at low elevations to the north of the transmitter. The modeling results shown in Figure 3 revealed that the condition for generation of circularly polarized radio waves changes when one wave mode is stronger that the other. Under significantly large power in one mode, the circularly polarized radio waves were generated from the superposition of elliptical O- and X-modes. Note that the O- and X-modes are elliptical farther away from the transverse propagation alignment as shown in Figures 2a and 2b. Therefore, it is possible that the circularly polarized radio waves were observed in RRI experiments due to higher power in the X-mode than the O-mode.

Modeling results (Figure 3) showed that the dominant wave mode governs the rotation sense (sign of ellipticity angle) of circularly polarized radio waves that appear farther away from the transverse propagation alignment. The RRI observations showed that the rotation sense of radio waves changed when e-POP satellite was eastward or westward of the ground transmitter at Ottawa (Danskin et al., 2018). Recently, Pandey et al. (2022) showed that the rotational sense of radio waves would appear opposite when RRI points towards and away from the ground transmitter. Additionally, Eyiguler et al. (2022) showed that the rotation sense of radio waves were opposite in the South and North of the transmitter even a slew-to-transmitter pass. Therefore, a detailed investigation is needed to identify the rotation sense of individual wave modes and radio waves simultaneously and confirm whether the X-mode and radio waves have the same rotation sense.

5. **SUMMARY**

The RRI observations consistently show that the transionospheric radio polarization oscillates from linear to circular poleward of the radar at low elevations. The circularly polarized radio waves were observed over a wide range of aspect angles (~96-120°) farther away from the transverse propagation. However, from magnetoionic theory with equal powers in the individual O- and X-modes the circularly polarized waves were expected just a few degrees around the transverse propagation. The present investigation resolved this problem using a theoretical model that calculates the radio wave polarization after accounting for possible changes in the X-mode power relative to the O-mode.

The modeling results showed that the elliptically polarized O- and X-modes under the condition of relatively stronger X-mode resulted radio waves with polarization states oscillating between linear and circular. Modeled values showed that for such a condition the sense of rotation of radio waves must be same as the dominant mode (here, X-mode). A detailed investigation is planned to confirm whether the X-mode and radio waves have the same rotation sense.

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