Statistical Analysis of Off-Great Circle Radio Wave Propagation in the Polar Cap

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Summary:

- Off-great circle HF radio propagation occurring in the polar cap is studied with years of data from a polar cap HF radio link between Qaanaaq and Alert.
- Significant off-great circle deflections due to localized density structures such as polar cap patches are found to be very common, especially in the winter and in the morning.
- HF radio signals deflected to off-great circle paths tend to have increased time-of-flights (TOFs), larger Doppler shifts and spreads, and lower signal-to-noise ratios (SNRs).

Background:

- HF radio propagation is an important technology used for long-distance communications and surveillance, especially in locations without alternative infrastructure such as the far north.
- HF radio signals generally travel along great circle paths, but horizontal ionospheric electron density gradients can deflect these signals to off-great circle paths.
- Reception of off-great circle signals can degrade signal quality for communications, and lead to positioning errors for over-the-horizon radar (OTHR).
- Understanding how often signals are deflected and when they are likely to be deflected could help mitigate these effects.

Data:

- Off-great circle propagation was studied using data from an HF radio link, in which signals were sent at multiple frequencies from a transmitter in Qaanaaq to a directional receiver in Alert between June 2012 and August 2016.
- Transmissions were sent between 4 and 30 times per hour at each of the following frequencies: 4.6, 7.0, 8.0, 10.4, 11.1, and 14.4 MHz.
- Signal parameters such as time of flight (TOF), signal-to-noise ratio (SNR), Doppler shift, Doppler spread, and azimuth and elevation angle of arrival were recorded for each received signal.

Results:

- Examination of angle of arrival data (Figure 1) shows frequent, large deflections from the great circle. Deflections often appear as hour long swings about the expected angle of arrival, likely caused by polar cap patches or arcs crossing the propagation path.
- Accompanying Doppler shifts progress from positive to negative with each swing, consistent with patches or arcs approaching, and then receding from the propagation path.

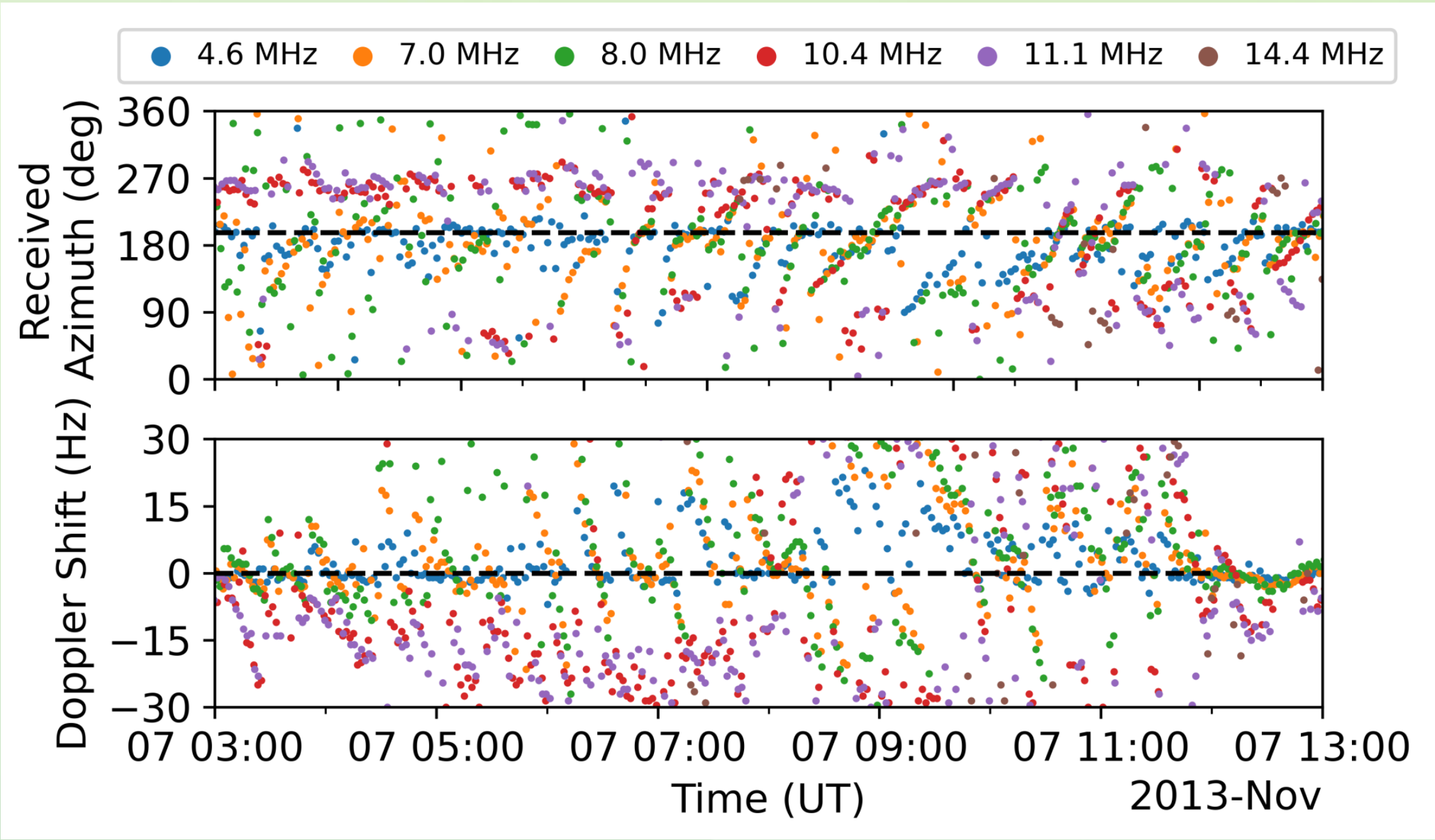

Figure 1: Azimuthal angle of arrival (top), and Doppler shift (bottom) from 3:00 to 13:00 UT on 07 Nov 2013. Frequency of signals is indicated by colour.

- A single year of uninterrupted transmissions (April 2013 - 2014) was used to study the prevalence and size of azimuthal deflections.
- Figure 2 shows the normalized distribution of deflections for each frequency, and Table 1 shows the % of signals that were received with > 30° deflections from the great circle heading.
- Note that > 70% of received 11.1 MHz signals experienced deflections > 30°!

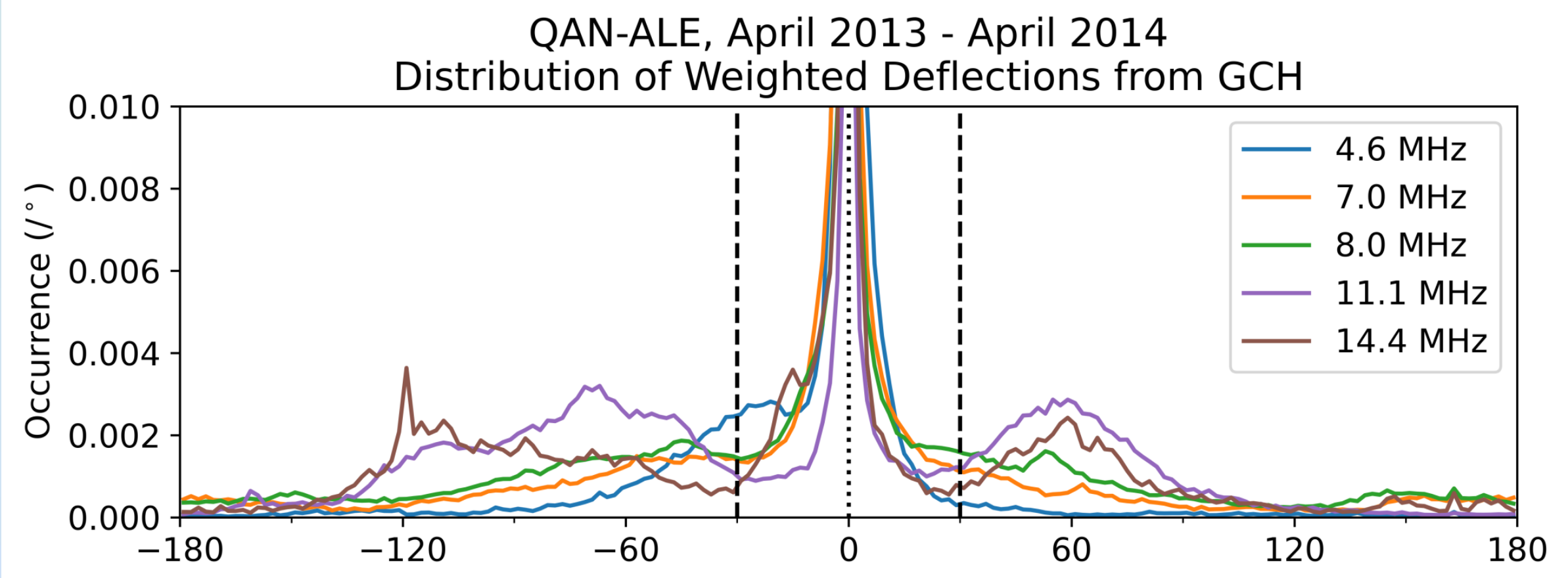

Figure 2: Normalized distributions of deflection from the great circle heading from 01 April 2013 to 2014. Vertical dashed lines indicate +/- 30°, and the vertical dotted line indicates 0°. Deflections were weighted by the inverse of transmission rate to ensure all parts of the year were represented equally.

Frequency (MHz)	4.6	7.0	8.0	11.1	14.4
Received > 30° (%)	16.0	33.7	46.8	70.7	54.0
Transmitted > 30° (%)	11.9	31.2	46.3	53.9	60.7

Table 1: Percentage of transmitted and received signals with azimuthal deflections > 30° from 01 April 2013 to 2014.

Results (cont.):

- Median magnitude of deflection vs MLT and week of the year were evaluated to determine when deflections were most likely to occur (Figure 3).
- Deflections were most common in the morning sector and in the winter. The high prevalence of deflections in winter matches known polar cap patch occurrence trends.

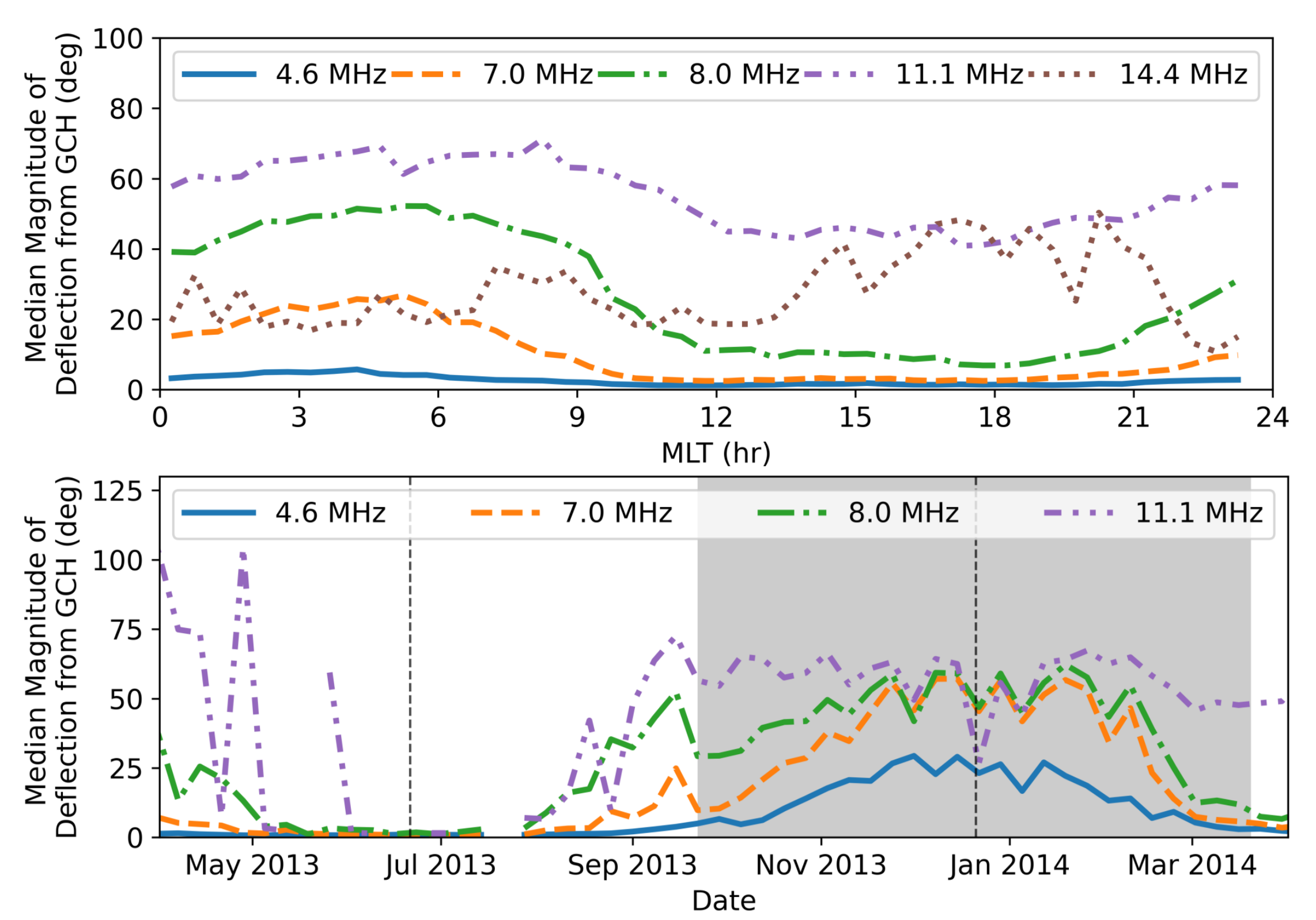

Figure 3: Median magnitude of deflection versus MLT (top), and week of year (bottom). Frequency is indicated by colour and line style. The shaded period in the bottom panel indicates winter (Sept 22 – Mar 20).

- Figure 4 shows normalized 2D histograms of deflections and relevant signal parameters, showing how these parameters are affected by off-great circle propagation.
- Larger deflections are associated with increased TOFs, lower SNRs, a larger range of possible Doppler shifts, and larger Doppler spreads.

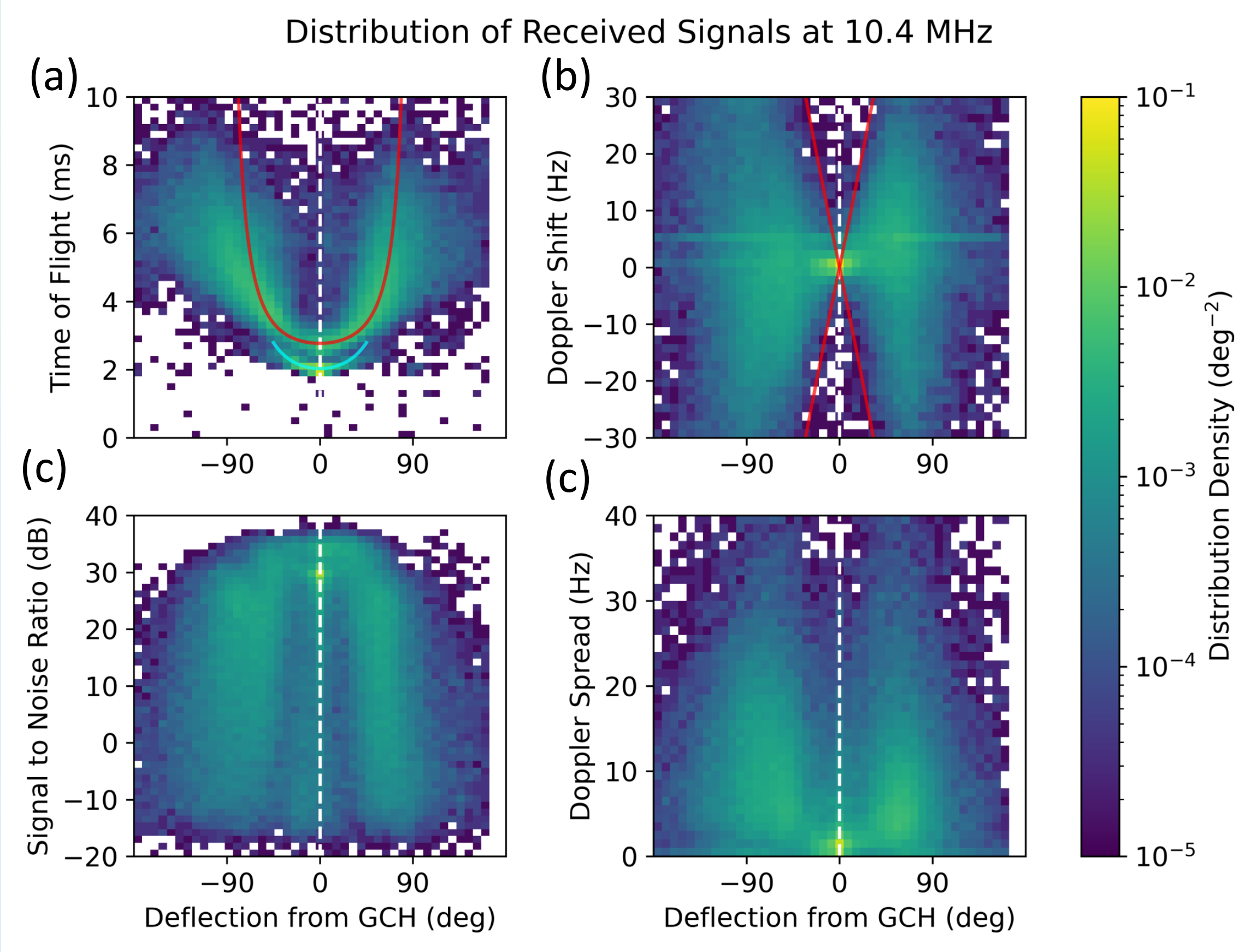

Figure 4: Discrete distribution density of received 10.4 MHz signals versus deflection from the great circle heading and (a) TOF, (b) Doppler shift, (c) SNR, (d) Doppler spread. Only radio signals received during local winter (between fall and spring equinoxes) were considered. Zero deflection is indicated by a vertical white dashed line. Overlaid curves in (a) and (b) show the expected time of flight and Doppler shift according to a simple model of ionospheric disturbances crossing halfway between Qaanaaq and Alert at (red) 300 and (blue) 100 km altitude respectively.

Discussion:

- These results have shown that large azimuthal deflections are very common for HF radio propagation in the polar cap, especially in the morning and in the winter.
- Deflections appear as swings about the expected angle of arrival, consistent with deflection off localized ionospheric density structures crossing the propagation path, and occur most often in winter, consistent with known patch occurrence trends.
- Responses of TOF and Doppler shift can be explained with a simple model of reflection off localized ionospheric disturbances crossing halfway between Qaanaaq and Alert at F region altitudes. Figure 5 shows the relevant geometry.

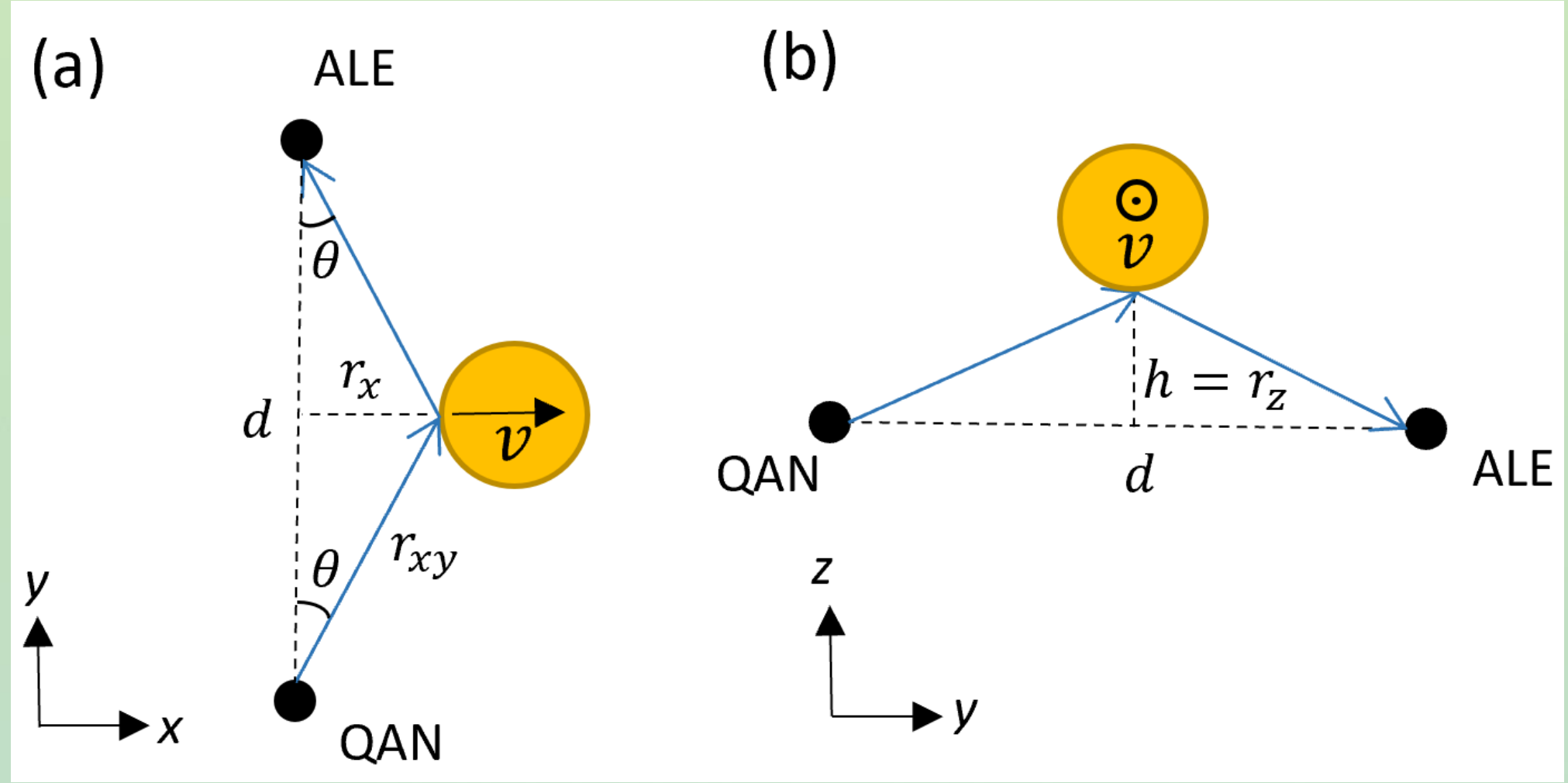

Figure 5: Diagram showing an idealized 1-hop vertical reflection with lateral deflection off of an electron density enhancement. The left side (a) shows a top down view, while the right side (b) shows a vertical view.

- From this model, expected TOF and Doppler shift can be computed as
  - $\mathrm{TOF} = \frac{2}{c}\sqrt{h^2 + \left(\frac{d/2}{\cos\theta}\right)^2}$
  - $\Delta f = \frac{vf}{c}\frac{d\tan\theta}{\sqrt{h^2 + \frac{d^2}{4\cos^2\theta}}}$
- Red curves overlaid on Figure 4 (a and b) where h=300 km show this model is consistent with observations.
- These results represent a significant source of error for the operation of OTHR in polar regions.
- OTHR uses TOF and Doppler shift information to determine the location and speed of targets. Therefore, commonplace azimuthal deflections in the polar cap could lead to errors in positioning and speed estimates.
- Results shown here could inform future research focused on mitigating the effects of off-great circle propagation on OTHR.

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