Analysis of Solar Magnetoacoustic Waves in Active Regions with High-Energy Solar Flares

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Abstract

Magnetoacoustic waves in solar active regions are shaped by the local magnetic-field topology, and their behavior near polarity inversion lines in δ-type regions remains poorly characterized. In particular, it is unclear how the unique magnetic field structure of the PILs in δ-type regions modify the spatial distribution of oscillation power. To address this question, we analyze SDO/HMI Fe I 6173 A Doppler velocity and magnetic-field observations of NOAA AR11158, AR13663,AR13912, and AR14366. Oscillation power maps are constructed from 8-hourDoppler-velocity intervals shifted by 1 hour and compared with the line of sight(LOS) magnetic field, transverse field, and LOS-field-gradient structure. We find enhanced oscillation power along PILs in two frequency ranges, $0-1$ mHz and$6-11$ mHz. This power enhancement is greatest near regions of highly-inclined(i.e., nearly horizontal) magnetic fields, suggesting 1) correlation between high-field inclinations and high-frequency power enhancement and 2) an acoustic cutoff frequency of ~ 6 mHz, which is the low-end threshold of high-frequency power enhancement. In addition, analysis of high-frequency power enhancement over several days suggests an increase in high-frequency power is correlated with increased magnetic field gradient values in the PIL, suggesting a potential relationship between high-frequency power enhancement and major flaring activity in active regions.

Research Methods

Data Collection and Processing

- HMI line of sight (LOS) velocity and magnetic field data is computed from the photospheric Fe I 6173 Å absorption line.
- Oscillation power from the LOS Doppler shift was calculated by taking the square of the discrete-time Fourier transform.
- LOS magnetic field data was used as is.
- A time cadence of 45 seconds and total sampling time of 8 hours (640 time-steps) was used.
- Each active region is tracked using azimuthal equidistant projection (Postel projection) and then remapped from arcseconds to heliographic degrees.
- All power maps and magnetograms are 30.72 x 30.72 heliographic degrees.
- During data processing, all power maps and magnetograms were zoomed in to highlight the PIL features.

Active Region Analysis

- Studied oscillation power maps from 0–11 mHz in increments of 1 mHz (i.e., 0-1 mHz, 1-2 mHz, et cetera).
- Only active regions possessing delta-type sunspots were studied.
  - Delta type sunspots are characterized as sunspots which specifically possess opposite magnetic field polarities within a singular penumbra.
- Identified the PIL in magnetograms using the magnitude of the 2-dimensional field gradient and compared with each power map to see if power is enhanced along the PIL.
  - Minimum value threshold: all pixels considered to be above a certain gradient magnitude (in units of Gauss per kilometer) were included as a part of the PIL.

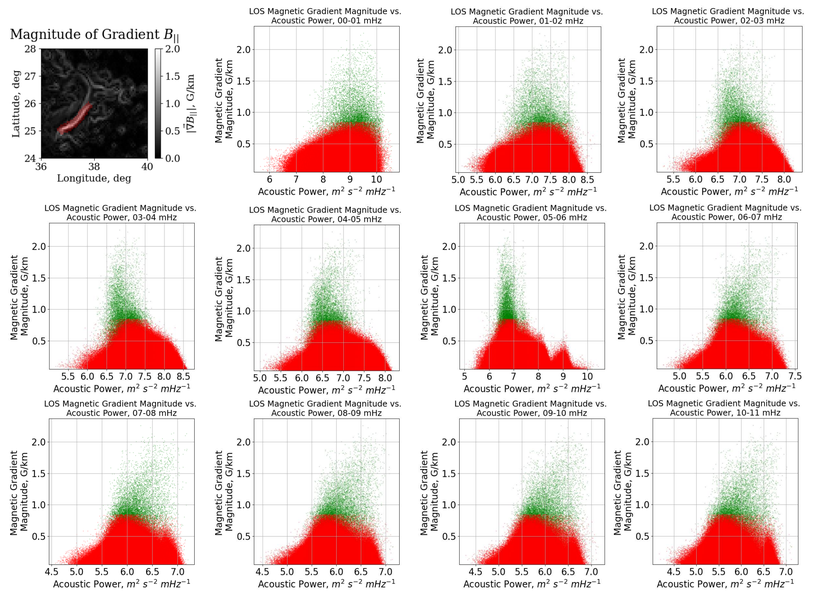

Figure 2: Scatter plots of LOS magnetic field gradient magnitude vs. oscillation power spanning the entire duration of AR13663, for 11 frequency intervals. The data that was measured in the PIL is in green, while the other data is marked red. The 1st image to the top left demonstrates how the PIL was determined: a threshold is set above a certain gradient magnitude (0.85 G/km for AR 13663), and the power enhancement is measured in the region 2 pixels larger than this threshold.

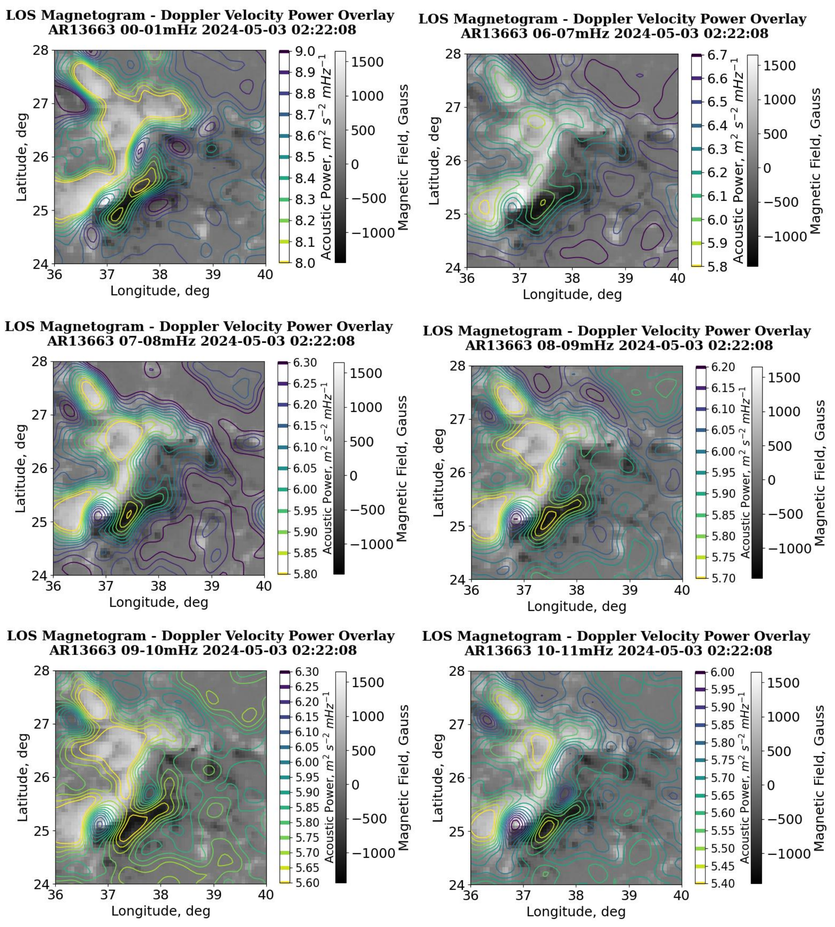

Figure 3: Contour maps of oscillation power from 0–1, 6–7, 7–8, 8–9, 9–10, and 10–11 mHz frequency ranges of AR13663 on 2024-05-03. All contour maps are overlaid on the LOS magnetogram at the time of maximum soft X-ray emission during the 2024-05-03 X1.6 flare. As supported by Figure 2, there is a noticeable enhancement of oscillations at the PIL for the selected frequency ranges

Results

Active Region Observations

- The PILs have the greatest magnetic field gradient magnitude in the entire active region.
- Oscillation power is amplified in and around the PILs in the 0-1 and 6-11 mHz frequency ranges; however, finding enhanced oscillation power in an active region does not necessarily mean it is part of a PIL.

Solar Flare Observations

- The oscillation power is enhanced during solar flare activity in the 0–1 and 6–11 mHz frequency ranges.
- The enhanced oscillation power during the solar flare is a much more accurate measurement than the well-known sudden increase in magnetic field.
  - This is because sudden changes in magnetic field result in measurement artifacts from HMI; measuring oscillation power avoids this issue as the data is averaged out over an eight-hour period.
- More research must be conducted to pinpoint how this enhanced power affects the physics of the flare.

Conclusions

- Oscillation power is clearly enhanced within and slightly outside the PIL.
- There is clearly a general positive correlation between the increase in the magnetic field gradient magnitude and high-frequency oscillation power during high energy flare onset. Thus, analyzing power enhancement at high frequencies could emerge as an alternative method for detecting flares.
- The next step in my research plan is to see *why* power is enhanced along the PIL and what causes only certain frequency ranges to be enhanced.
- I also plan to analyze oscillations detected at chromospheric and coronal absorption lines.

Acknowledgements

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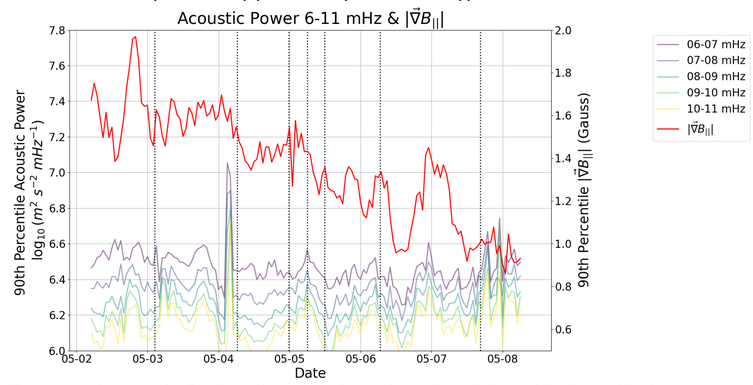

Figure 4: 2d magnetic field gradient magnitude data plotted alongside the oscillation power spectra from 6-11 mHz that is present in the PIL of AR 13663. There is a clear correlation between the increasing magnetic field and enhanced oscillation power during the temporal evolution of AR 13663.

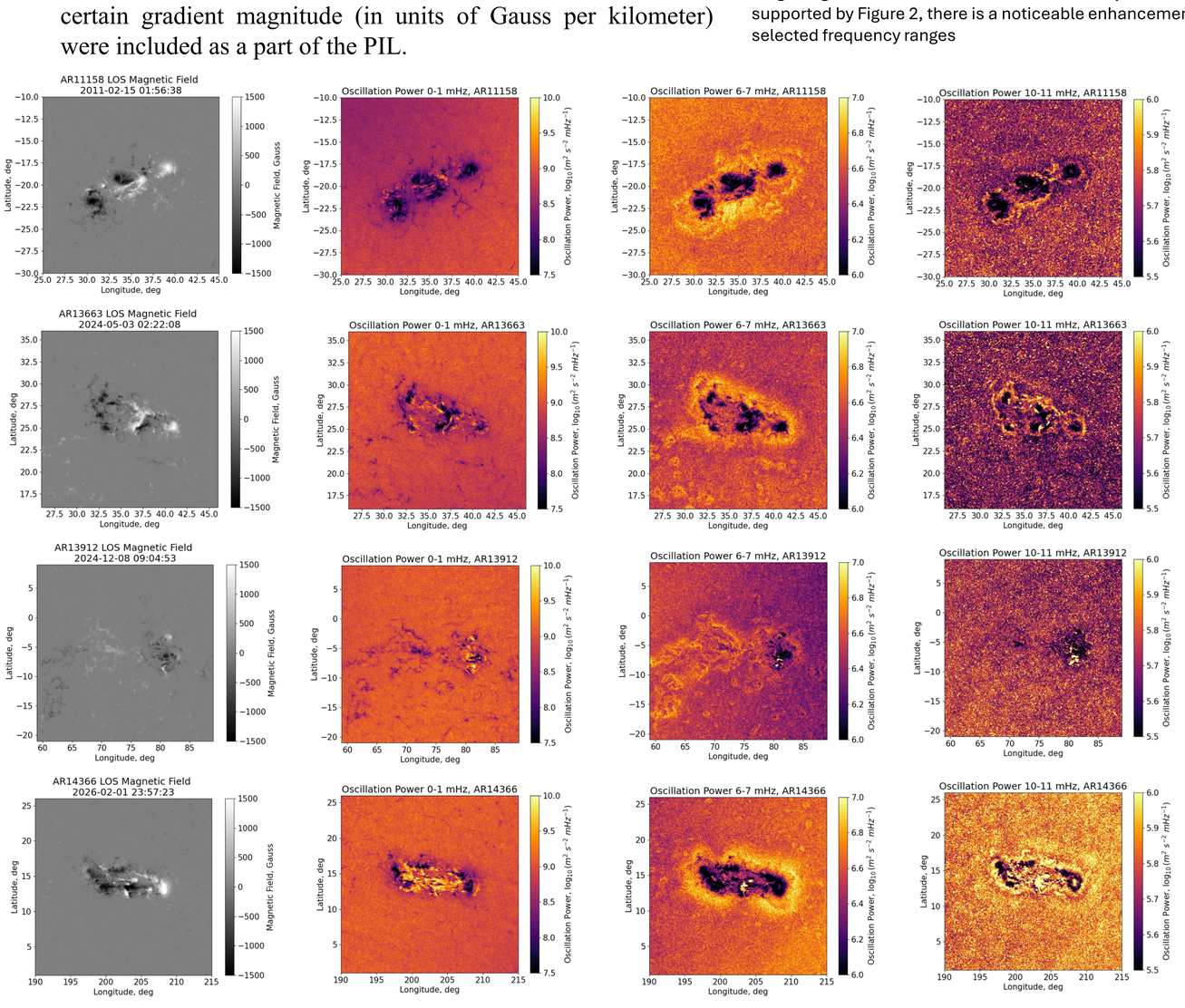

Figure 1: Oscillation power maps for NOAA AR11158, AR13663, AR13912, and AR14366 in the 0-1 mHz, 6-7 mHz, and 10-11 mHz frequency bands alongside the LOS magnetogram for each region (far left). There is apparent power enhancement in all four regions in the form of 1) acoustic halos, outside each active region and 2) small bursts in enhanced power within each active region, specifically in the polarity inversion line (PIL).

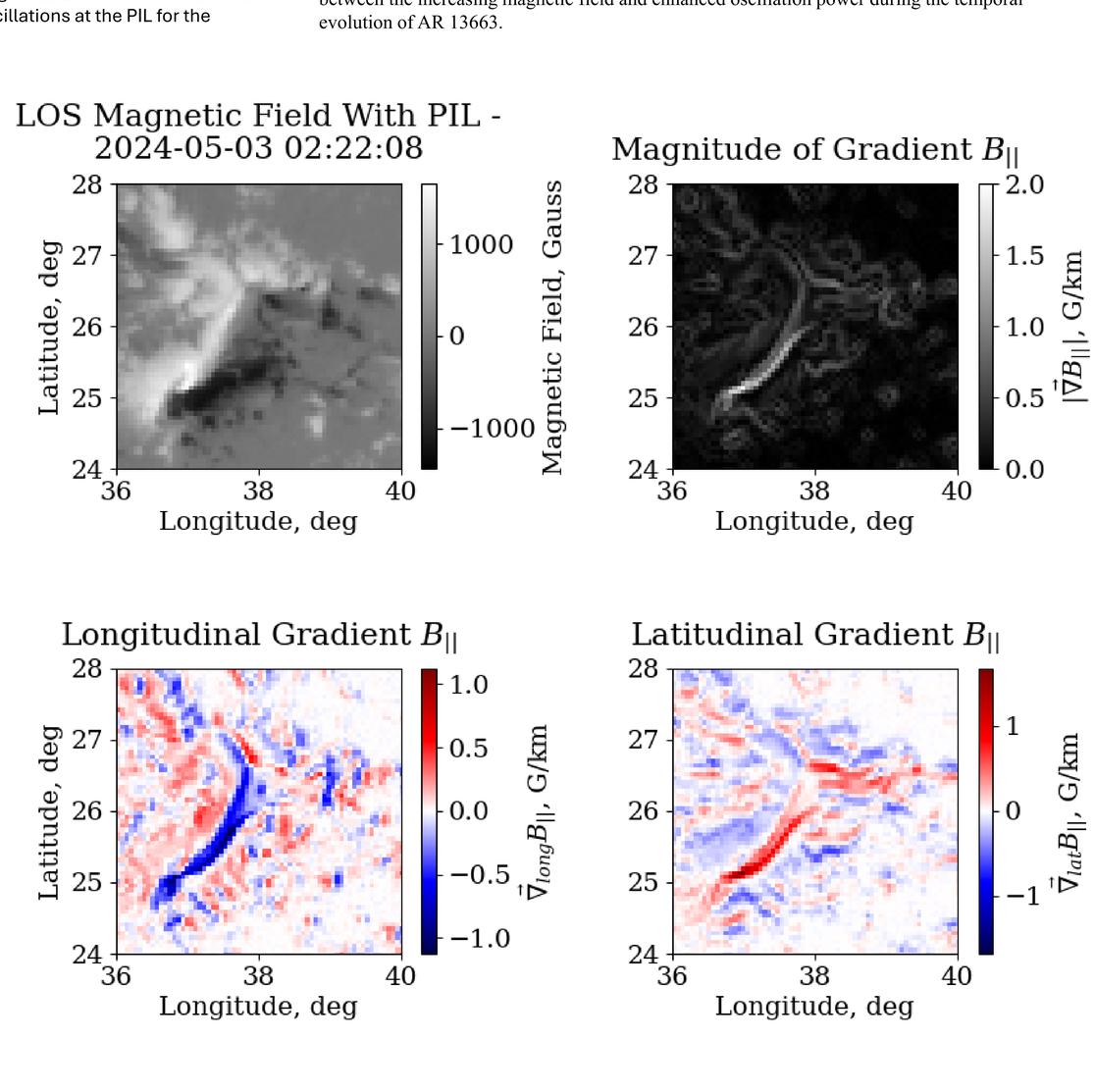

Figure 5: LOS magnetogram compared to gradient magnitude, longitudinal gradient, and latitudinal gradient, as shown on the top right, bottom left, and bottom right, respectively. Calculating the magnitude of the gradient gives the most reliable indication of where the PIL is located.