Artificial field-aligned irregularity generation at HAARP and upcoming bistatic coherent imaging campaign

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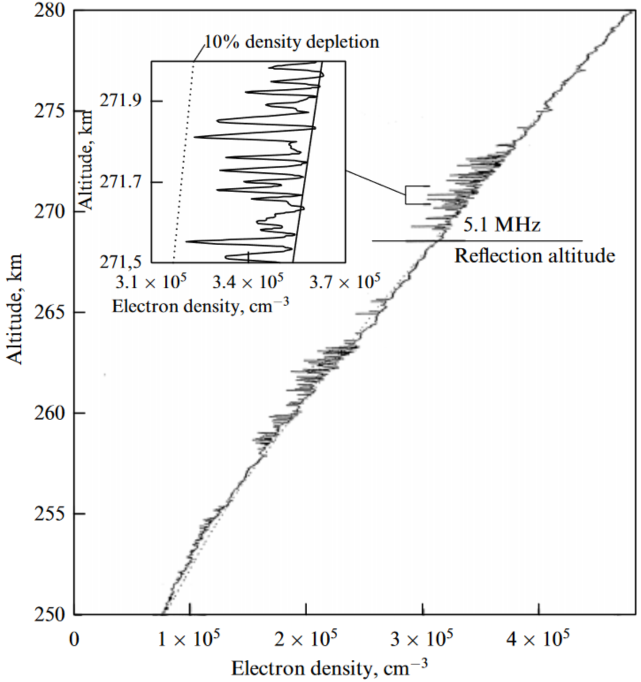
Field-aligned irregularities (FAIs)

Natural and artificial electron density gradient structures in the E- and F-region

- Natural occurrence
  - Caused by plasma instabilities (*Fejer & Kelley 1980*) and associated with electron precipitation (*Kelley+ 1982*)
  - Drift with **E** x **B** velocity in F region, other velocities (e.g. ion-acoustic) in E region
  - Useful HF radar backscatter targets for studying plasma drift and hemispheric convection (*e.g. Chisham+ 2007*)
- Artificial generation
  - Transmitter wave heats the ionosphere when it is in resonance with plasma frequency or upper hybrid frequency (f_{uh})
  - Kelley rocket experiment at Arecibo (1995) provided first in-situ confirmation of artificial FAIs
  - Conventional wisdom: tune heater frequency just below F-region peak plasma frequency (foF2)



(fig. adapted from *Kelley+ 1995, Gurevich+ 2007*)

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Motivation

HAARP transmitter parameters for upcoming imaging campaign

- Want reliable means of generating strong, widespread FAI region using HAARP to provide coherent imaging target.
- If we want to study FAI impacts on HF propagation, we need be able to reliably generate them.
- How can we best use a heating transmitter (like HAARP) to generate F-region FAIs?
- What heater parameters most efficiently generate F-region FAIs over a large geographic region?

→ Parameter variation experiments at HAARP Polar Aeronomy and Radio Science (PARS) summer schools 2023, 2024 and January 2025 campaign

PARS 2023 – beam pattern variation

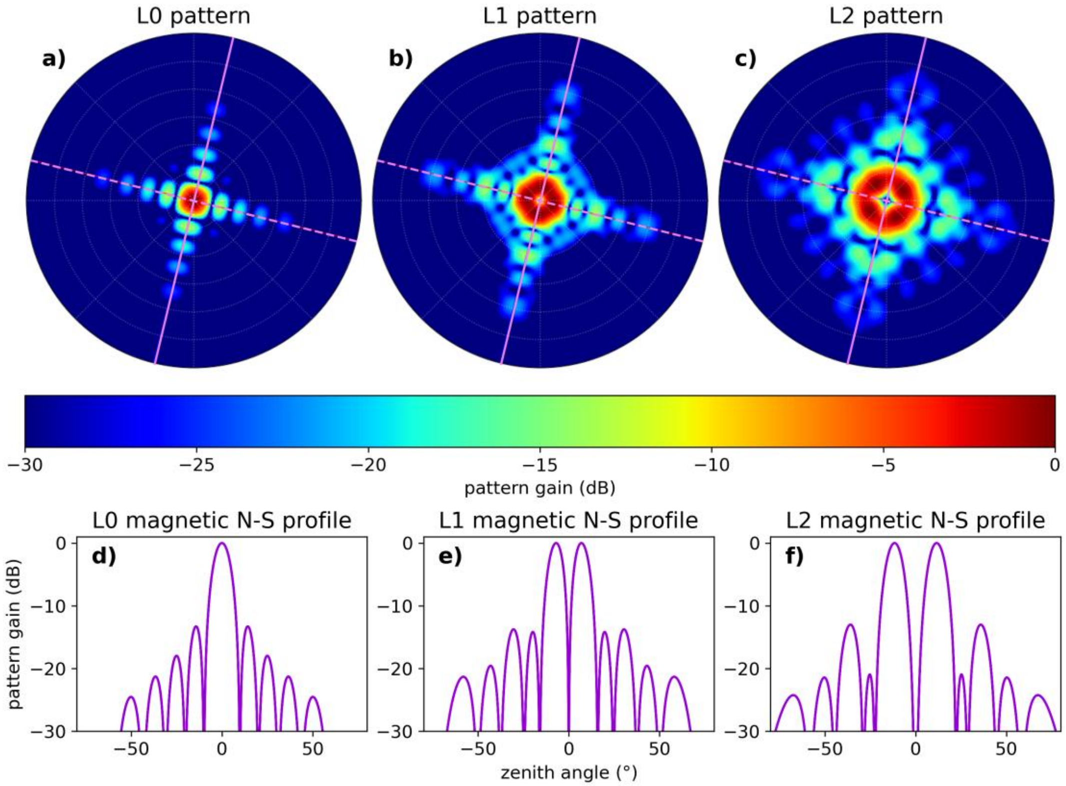
Determine whether broader beam produces strong, widespread FAIs

3 heater beams:

beam	peak power	3dB	1st null
	zenith angle (°)		
L0	0	4.4	9.9
L1	6.9	3.4-11	16
L2	12	7.3-16	22

3 identical* 1-hour experiments

- Heating plan:
  - Alternate 5-minute heater-on and -off times
  - Heat twice each with L0, L1 and L2 beams
- Start times (UTC):
  - Aug 8 22:30; Aug 9 03:00; Aug 13 21:37



PARS 2023 – experiment geometry

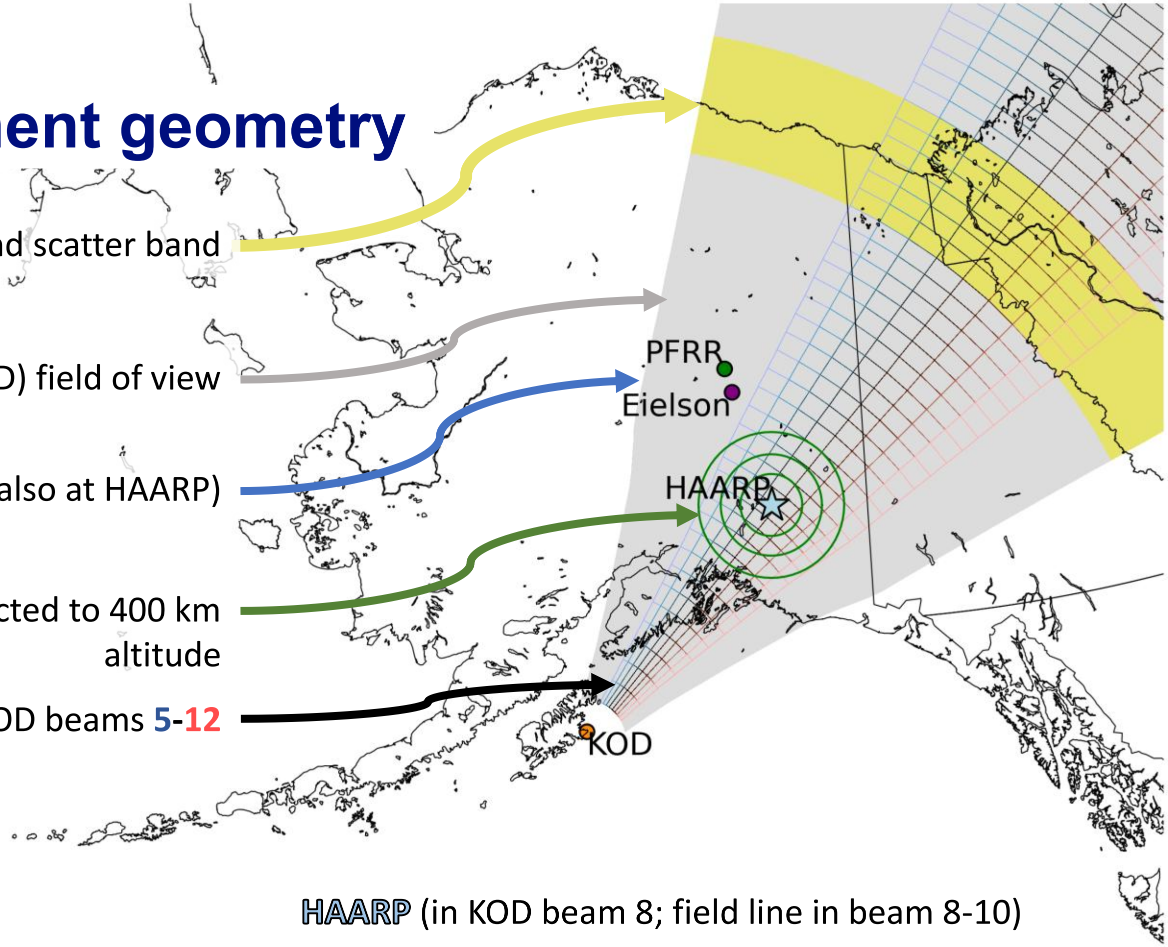
1-hop ground scatter band

Kodiak Island SuperDARN (KOD) field of view

Digisonde stations (also at HAARP)

HAARP L0, L1, L2 beam main lobes projected to 400 km altitude

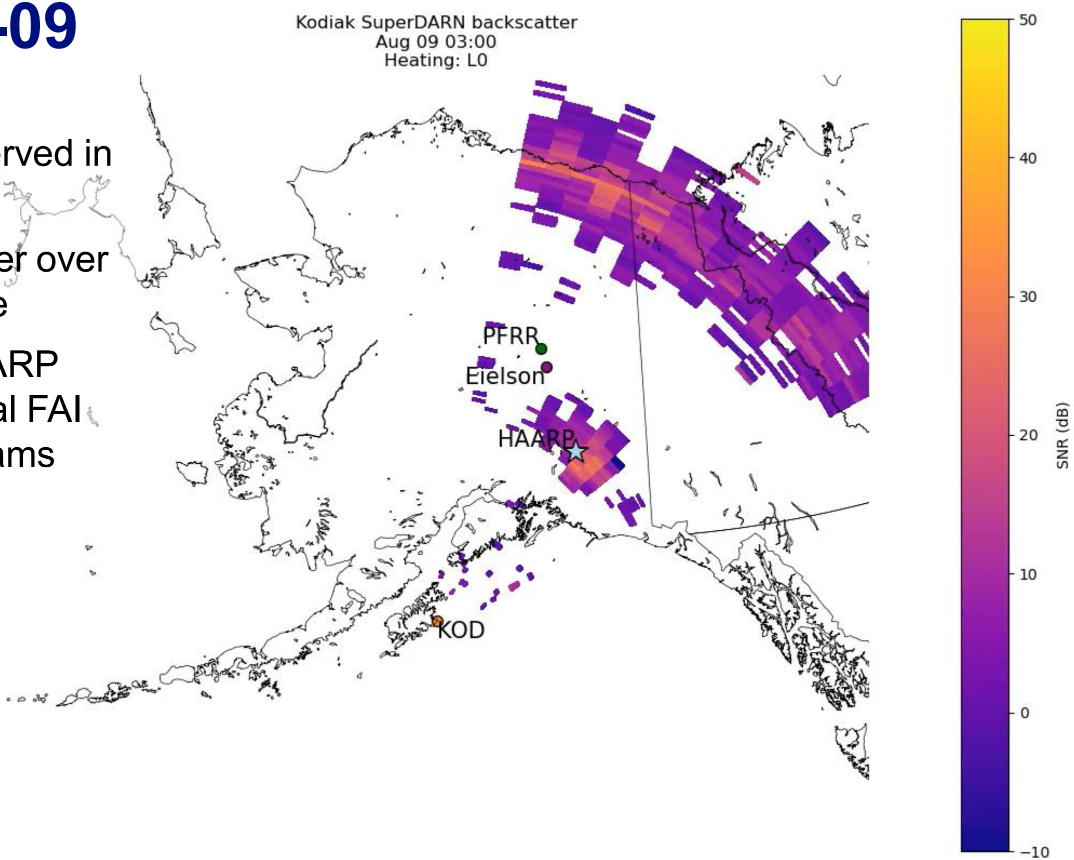
KOD beams 5-12



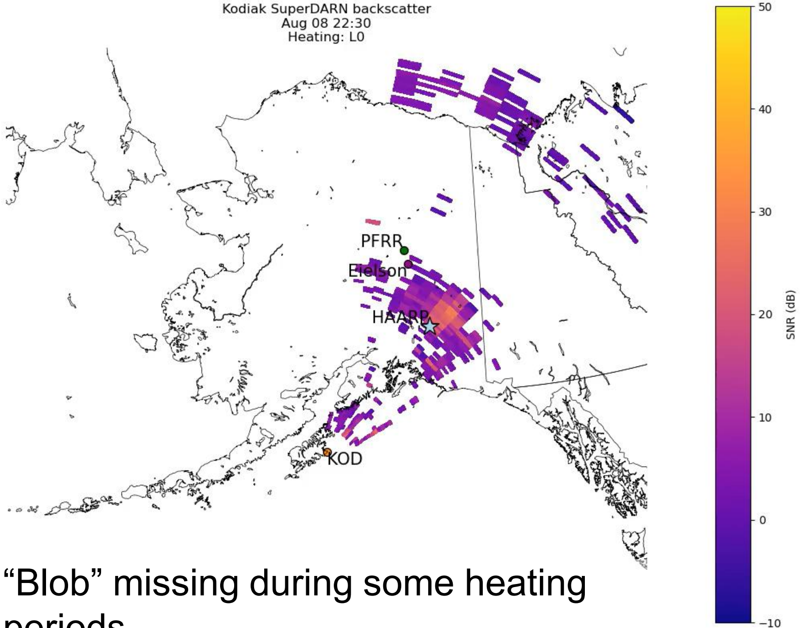
HAARP (in KOD beam 8; field line in beam 8-10)

Kodiak SNR – 2023-08-09

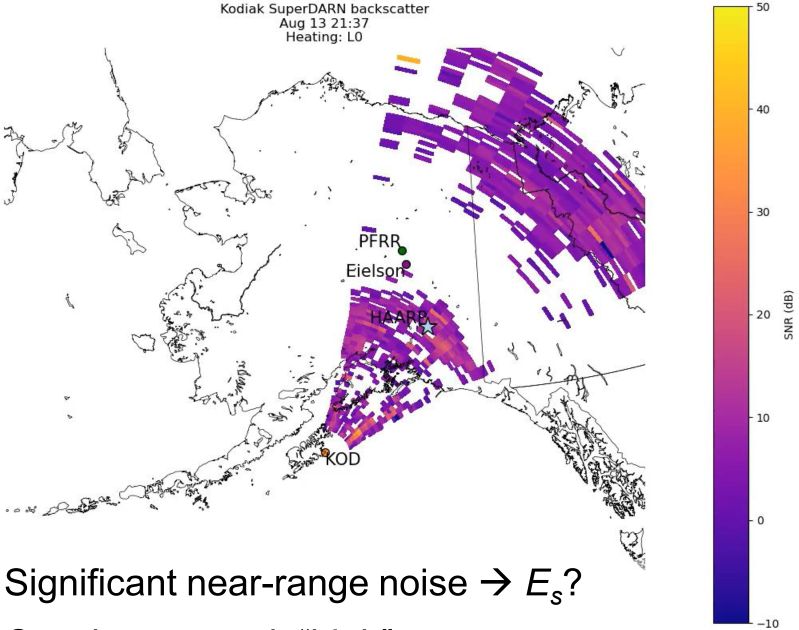
- Clear heating "blob" over HAARP observed in KOD SNR
- L0 and L1 heating produced backscatter over HAARP; L2 returns are shifted in range
- Backscatter in beams farther from HAARP likely located in beam side lobes; actual FAI region probably confined to central beams



Kodiak SNR – 2023-08-08, 08-13

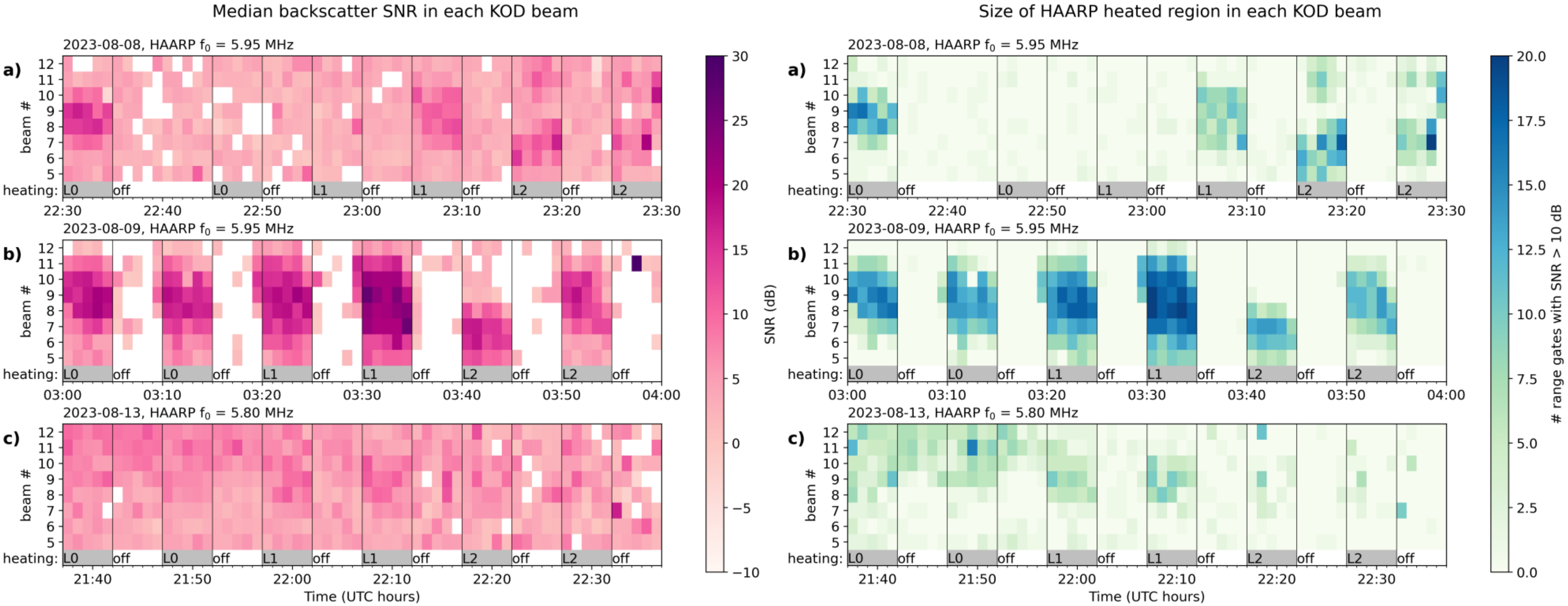


- “Blob” missing during some heating periods



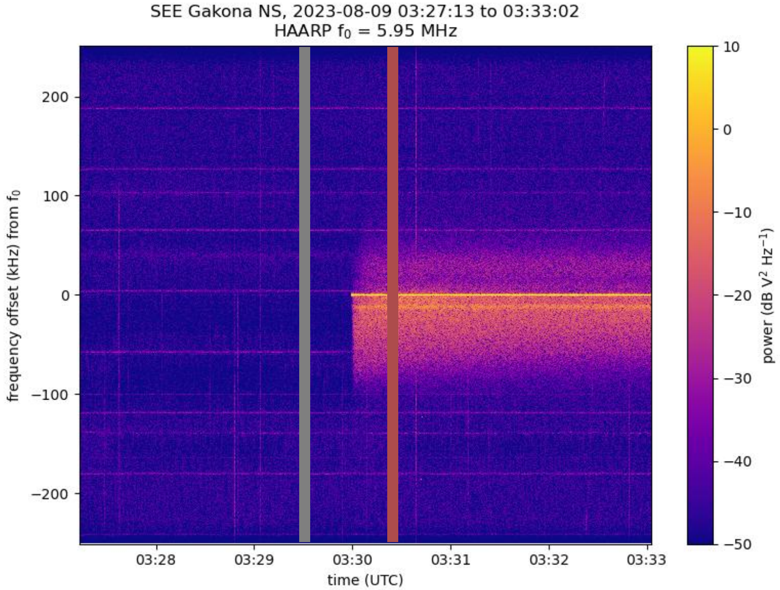
- Significant near-range noise → E_s?
- Consistent, weak “blob” appearance

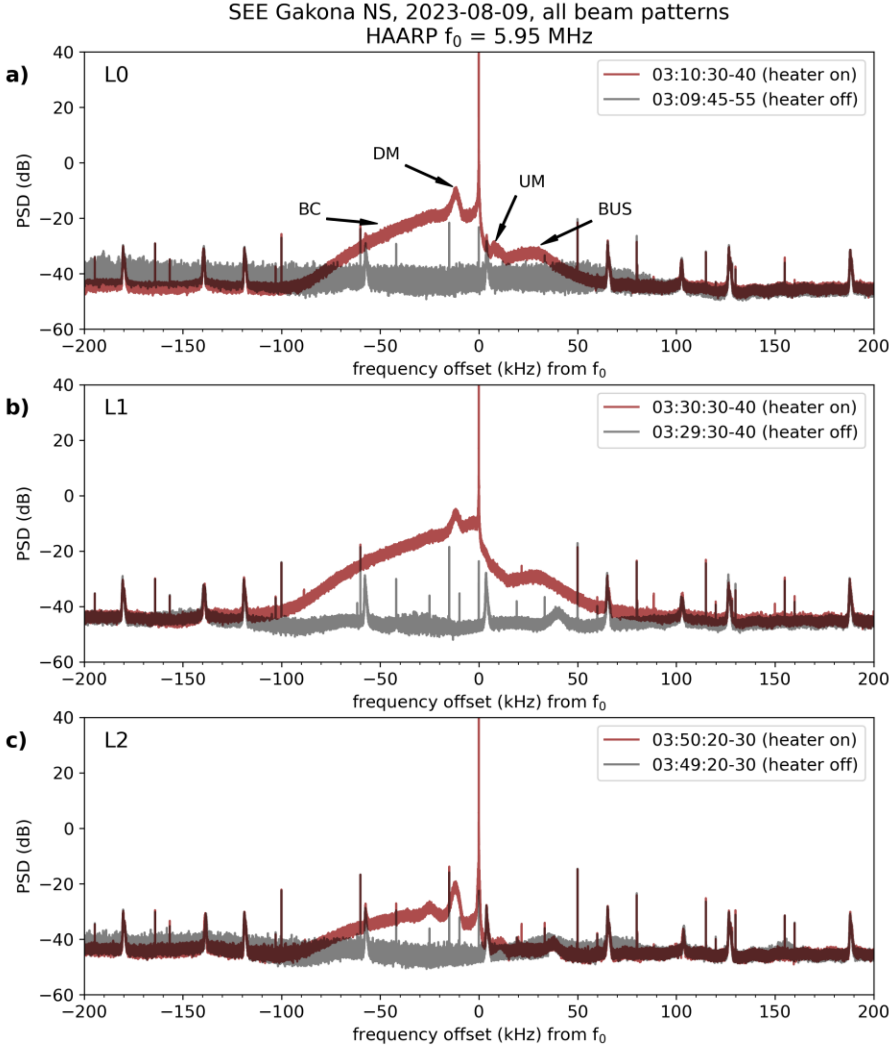
Kodiak SNR statistics in high-res range gates 20-60



Stimulated electromagnetic emissions (SEE)

SEE measurements during the August 9 experiment show strongest upper-hybrid spectral features during L1 heating.

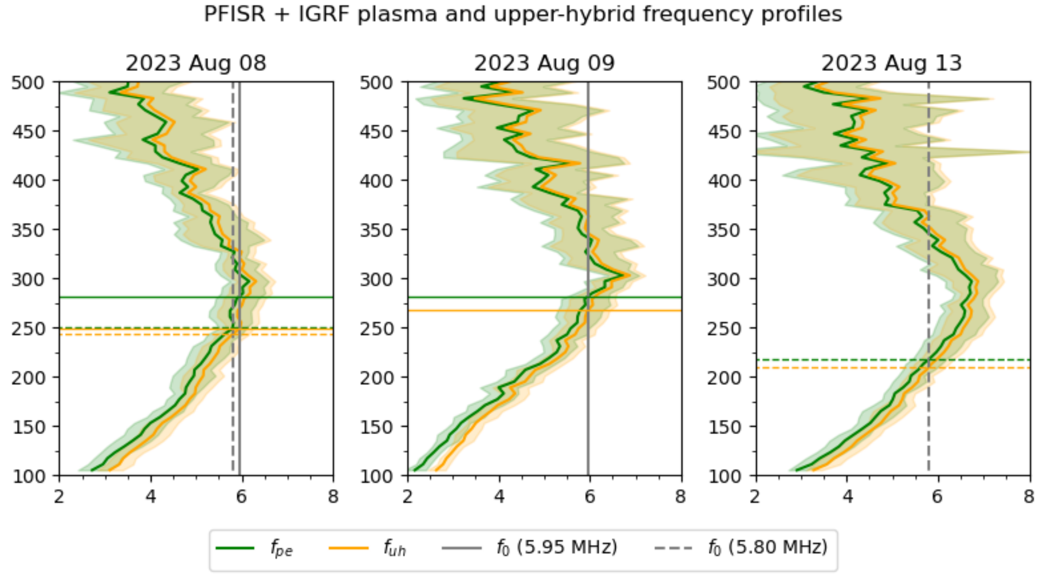




*What was the foF2?

- Gakona and PFRR ionosondes were down or intermittent
- Eielson ionosonde and PFISR were used to obtain foF2
- IGRF added to compute f_{uh} profiles
- **Strongest SuperDARN returns** and **SEE spectral features** appear to have been generated when the **heater frequency** was **at or just above the ionosonde-estimated foF2**

→ Need to better understand FAI dependence on f_0 / foF2



Experiment time (UTC)	Estimated foF2 (MHz) - ionosonde	Estimated foF2 (MHz) - PFISR	Heater frequency (MHz)
Aug 8, 22:30-23:30	5.50-5.75	5.8-6.6	5.95
Aug 9, 03:00-04:00	5.75-5.90	6.1-6.5	5.95
Aug 13, 21:37-22:37	6.10-6.20	6.5-7.5	5.80

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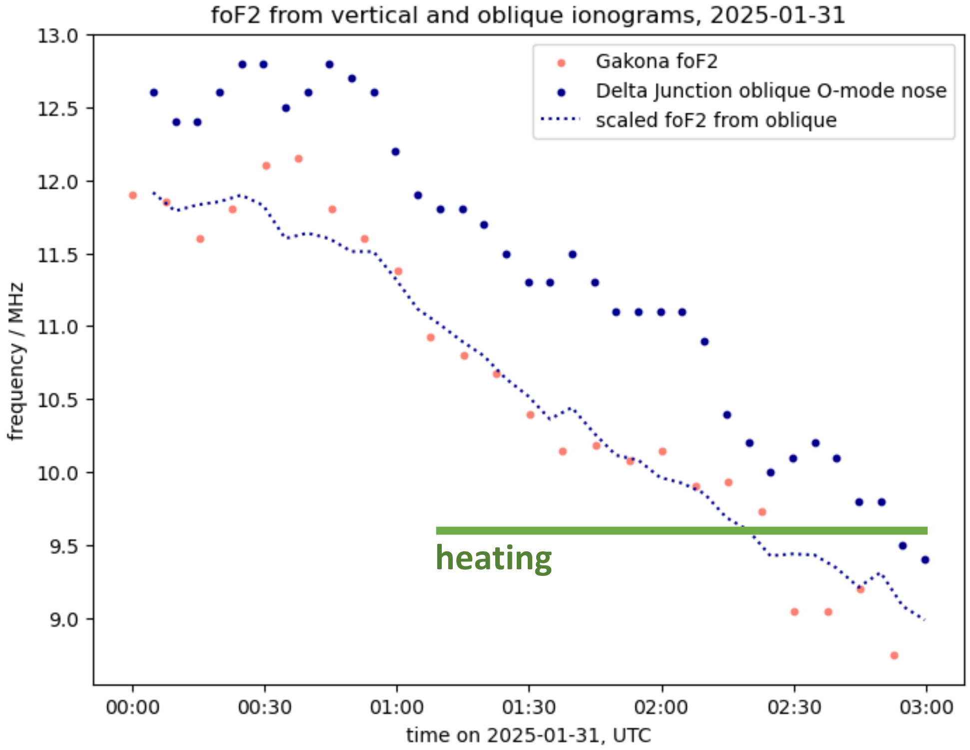
January 2025 – foF2 variation

Determine ideal heater frequency relative to foF2 for FAI generation

- Tried sweeping heater frequency around foF2 at PARS 2024 → foF2 in forbidden transmission band, unable to heat near it
- January 2025: heat at F-region sunset, let foF2 descend through constant heater frequency
- Three experiment times (UTC): Jan 30 01:00-02:30, 03:30-04:30; Jan 31 01:10-02:30
- Heating plan: determine foF2 from Gakona Digisonde and oblique ionogram, heat 100-500 kHz below and wait for foF2 to descend



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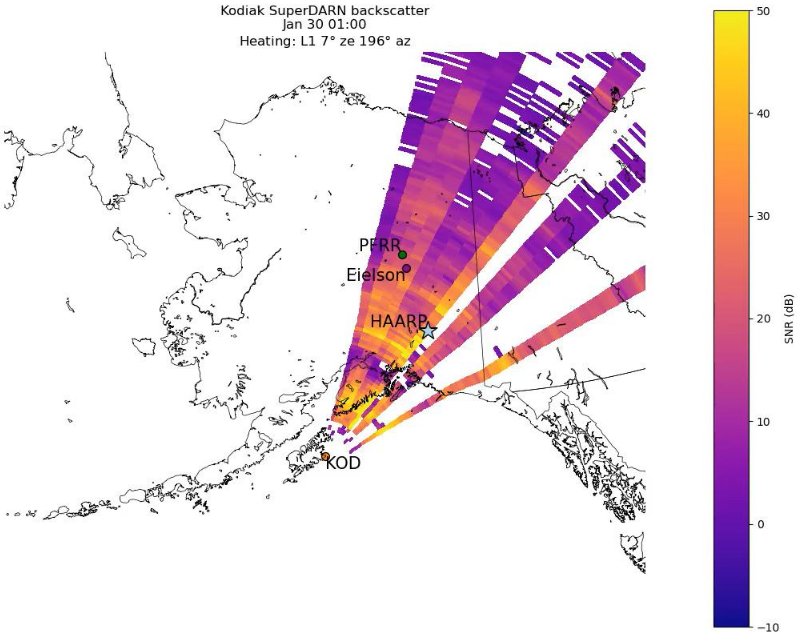
2025-01-30: SuperDARN returns



01:00-02:30 UTC

- SuperDARN beams have different SNR:
  1. Returns in some beams are missing intermittently
  2. Other beams with returns occasionally show significantly different overall SNR compared to adjacent beams (e.g. compare beams 7 and 8 at 01:00).

  Interference from nearby transmitter caused SuperDARN beam dropouts.

- SNR range features:
  1. Near-range high-SNR returns are present for most of this time period
  2. Multiple ground scatter bands evident

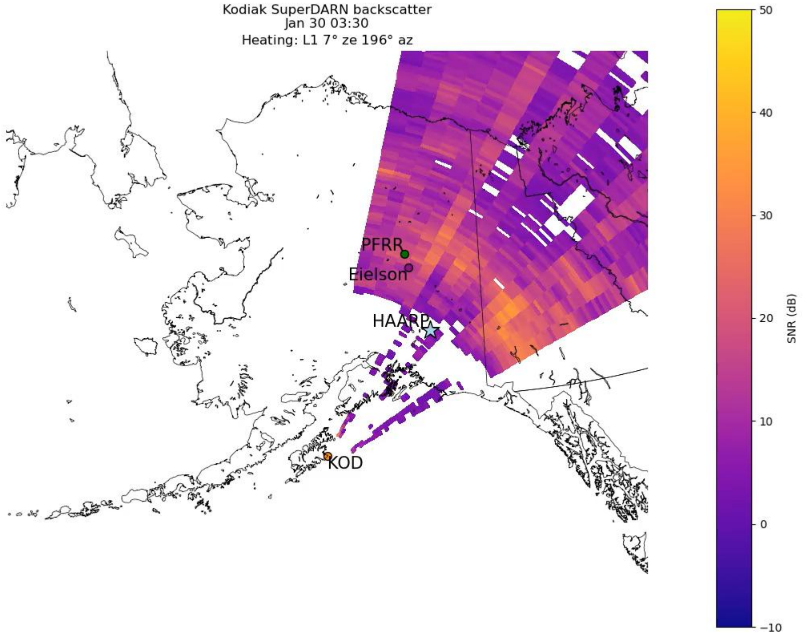
  Most likely blanketing sporadic-E during experiment time.

2025-01-30: SuperDARN returns

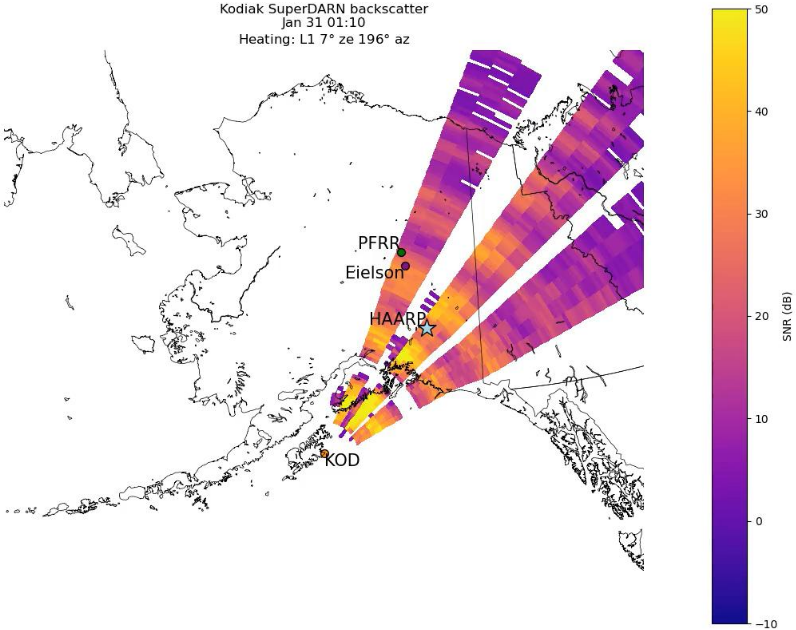
03:30-04:30 UTC

- SNR is generally more consistent across beams, but some issues remain
- SNR range features:
  1. Near-range high-SNR scatter is no longer present
  2. Heated “blob” over HAARP appears at 03:34 when heater frequency is lowered from 7.3 MHz to 5.95 MHz
  3. Multiple ground scatter bands still present, motion is not strictly along SuperDARN beam direction

  Blanketing sporadic-E



2025-01-31: SuperDARN returns



01:10-02:30 UTC

- SuperDARN beams have different SNR:
  1. Returns in some beams are missing intermittently
  2. Other beams with returns occasionally show significantly different overall SNR compared to adjacent beams (e.g. compare beams 7 and 8 at 01:23).

  Interference from nearby transmitter caused SuperDARN beam dropouts.

- SNR range features:
  1. Near-range high-SNR returns are present for most of this time period
  2. Quasi-periodic high-SNR bands; move throughout experiment period

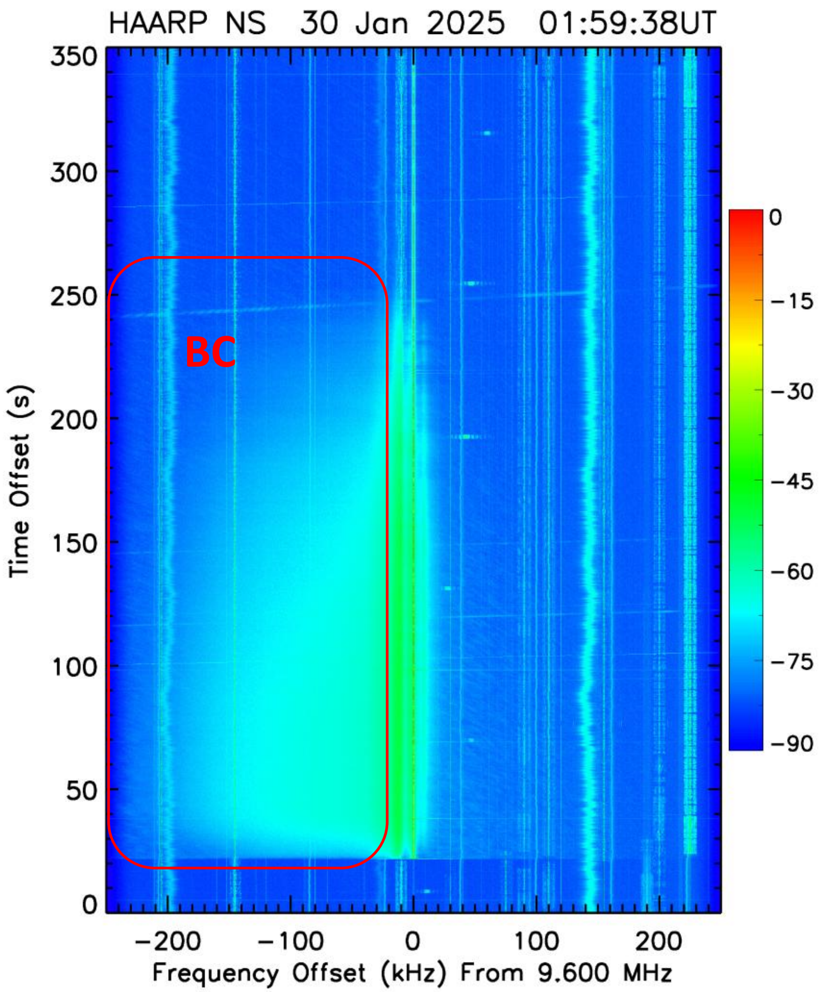
  Blanketing sporadic-E.

Transient SEE features

Ex: BC development and fadeout (1/30)

- Heating at 9.6 MHz, foF2 descending from about 9.3 MHz to about 8.9 MHz in spectrogram period
- “Broad continuum” (BC) develops along with “downshifted maximum” (DM) and “upshifted maximum” (UM) at turnon
- Spectral features do not return until heater frequency is adjusted at 02:16:00 UTC

→ Transient SEE features may be associated with foF2 descending from above to below heater frequency, but foF2 is not known to sufficient precision yet.



Summary of results

- The HAARP L1 beam (moderate width) most effectively generated strong FAIs over a large region. L0 beam (narrow) was also effective over a smaller region. L2 beam (widest) produced inconsistent return SNR.

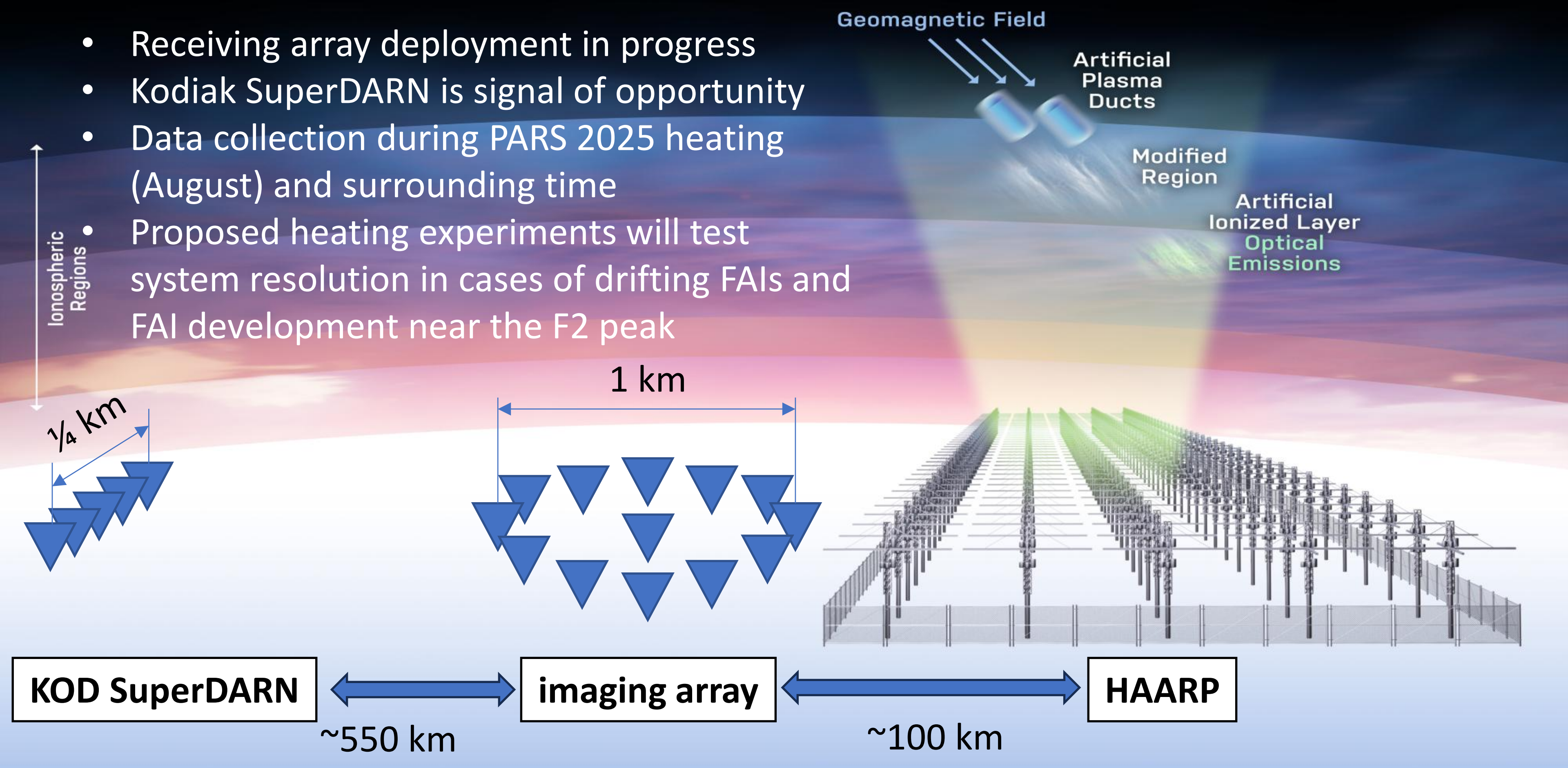
- The three August 2023 experiments likely spanned different heating regimes relative to the foF2 and f_{uh}.

- Interpretation of SuperDARN data from January 2025 experiments is complicated by blanketing sporadic-E; please help!

Bistatic imaging campaign geometry

(fig. adapted from *Cummings+ 2024*)

- Receiving array deployment in progress
- Kodiak SuperDARN is signal of opportunity
- Data collection during PARS 2025 heating (August) and surrounding time
- Proposed heating experiments will test system resolution in cases of drifting FAIs and FAI development near the F2 peak



Questions

- How can we better understand what was happening in the ionosphere during previous experiments?

- How can we better use SuperDARN as a diagnostic tool (and bistatic radar transmitter?) in an upcoming imaging campaign?

Thanks!

LANL: Erin Lay
Chris Jeffery
Ian Cummings

UAF: Paul Bernhardt
Mike McCarrick
Chynna Spitler
Evans Callis
Jessica Matthews

Penn State: Bill Bristow

NRL: Stan Briczinski

AFRL: Ken Obenberger

Birmingham: David Themens

PARS 2024 speakers and participants

References

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Further reading – SEE, artificial duct experiments:

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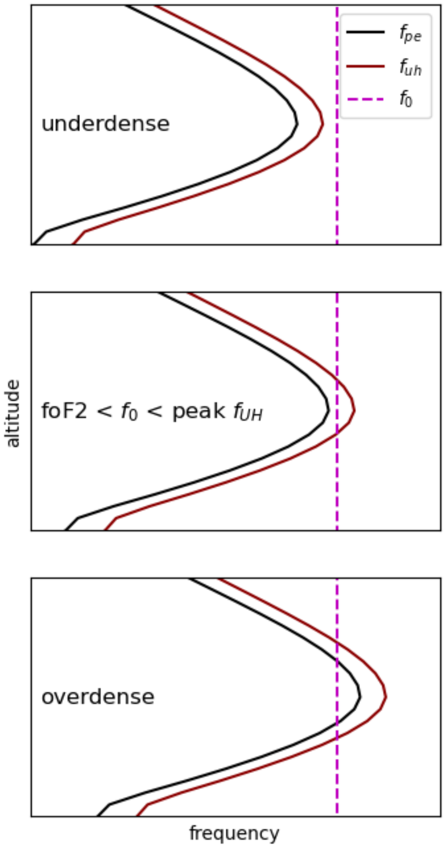
Extra slides

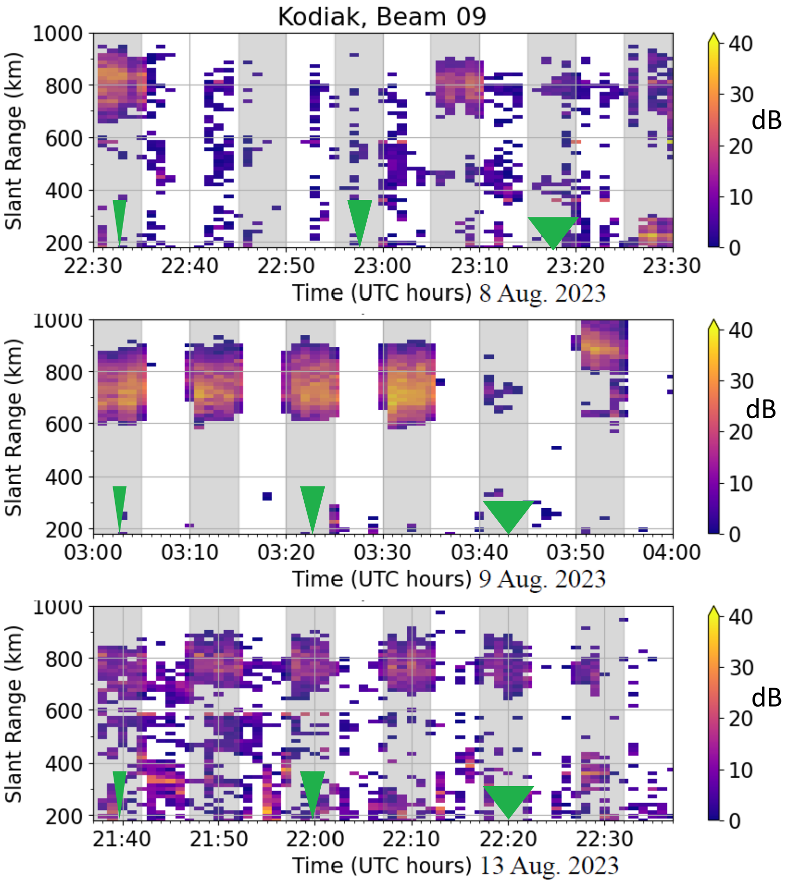
Heating scenarios

- foF2 < peak f_{UH} < f_0 (*underdense*): no resonance with heater wave except with intermittent ionosphere density variation

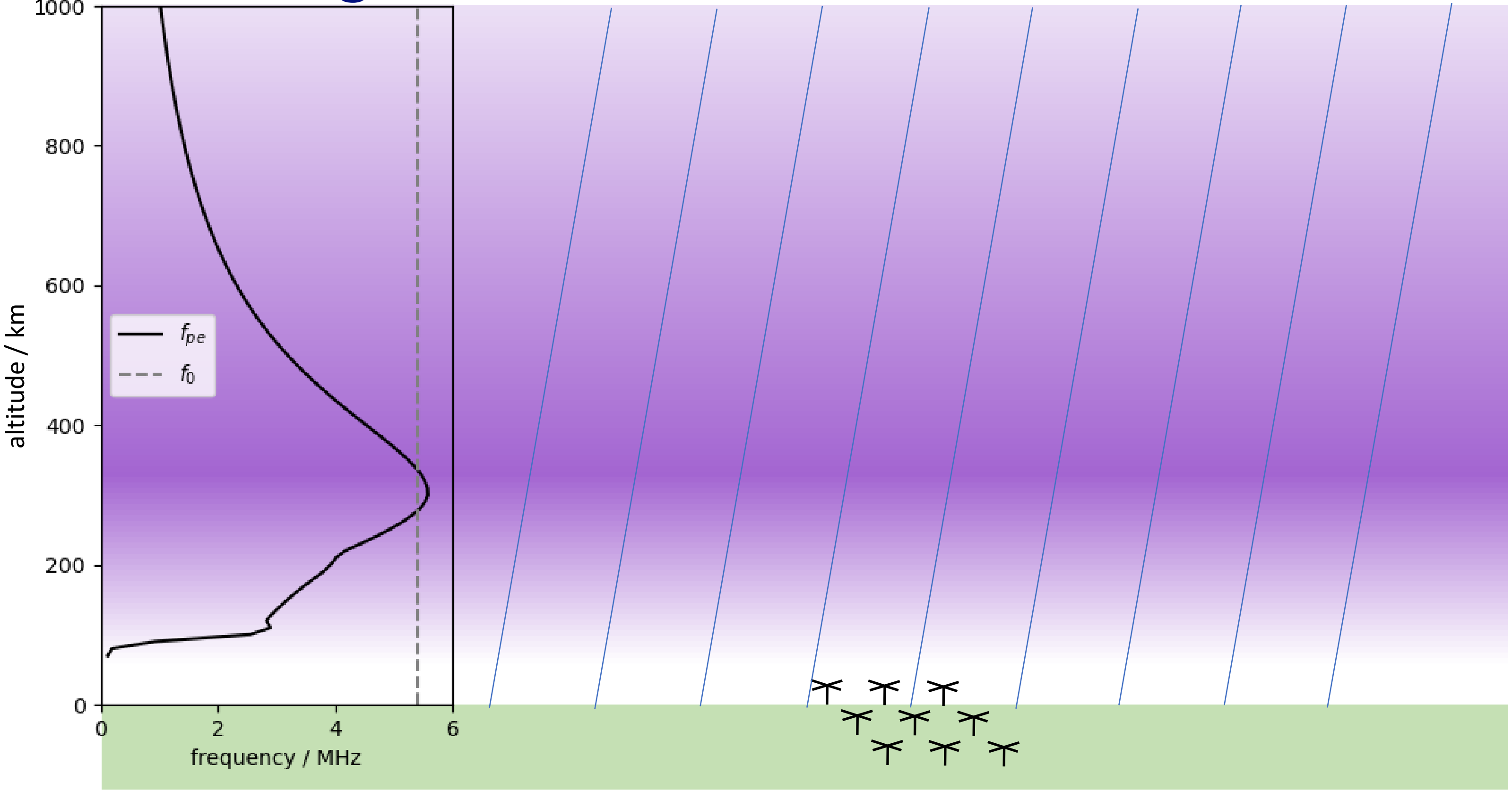
- foF2 < f_0 < peak f_{UH} : upper hybrid resonance near ionosphere peak

- f_0 < foF2 < peak f_{UH} (*overdense*): upper hybrid resonance at lower altitude

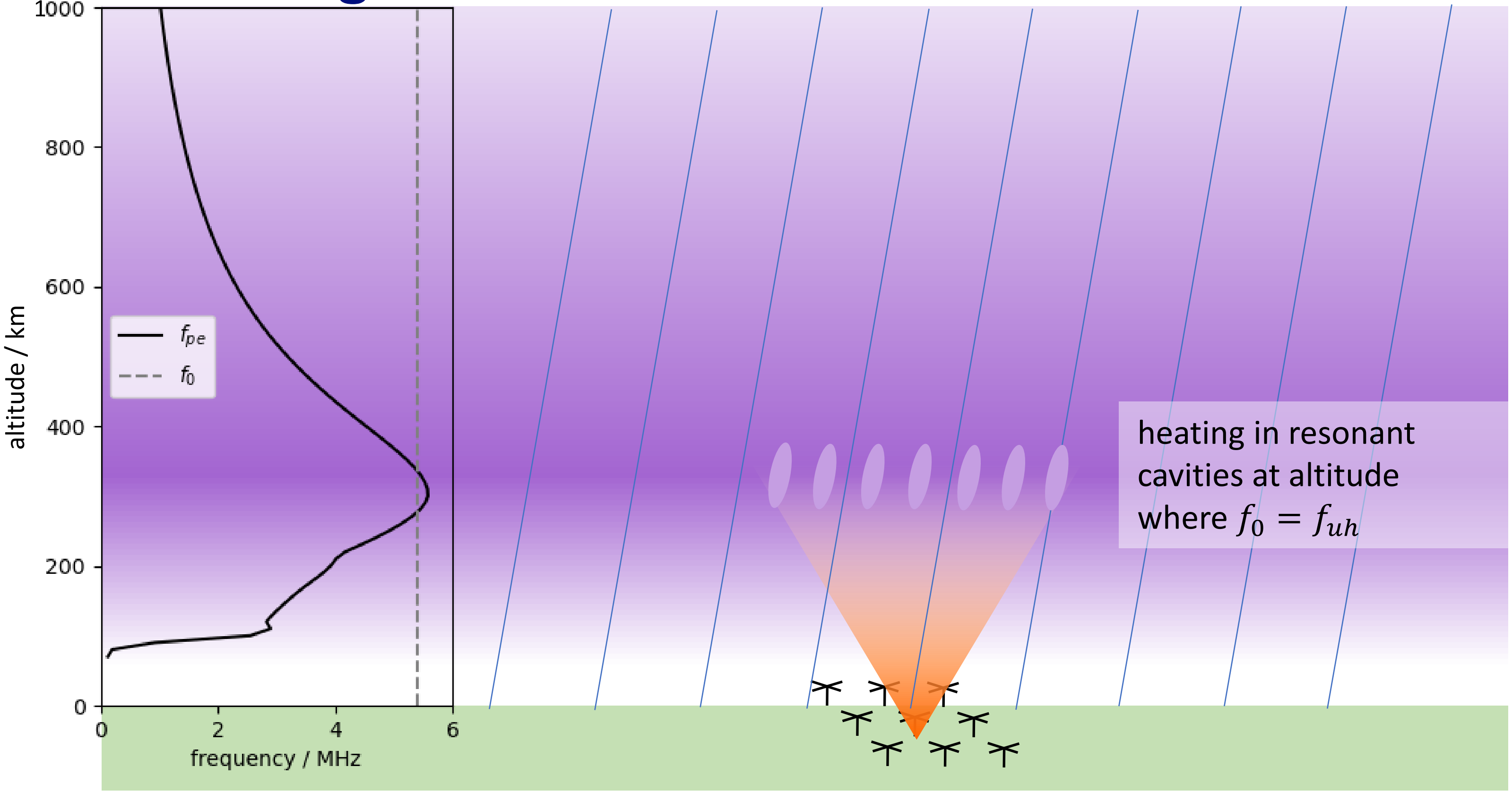




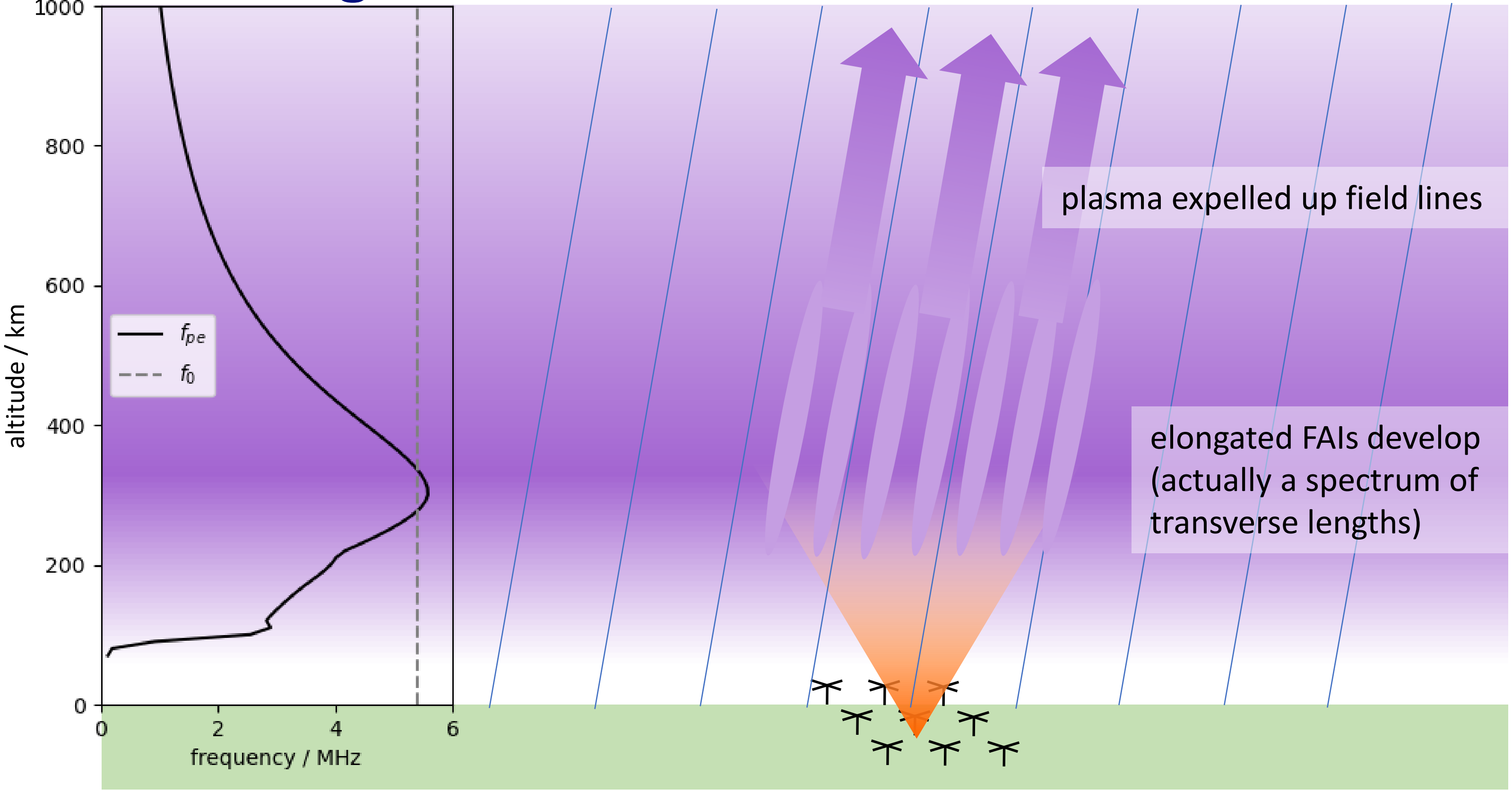
Artificial FAI generation



Artificial FAI generation



Artificial FAI generation

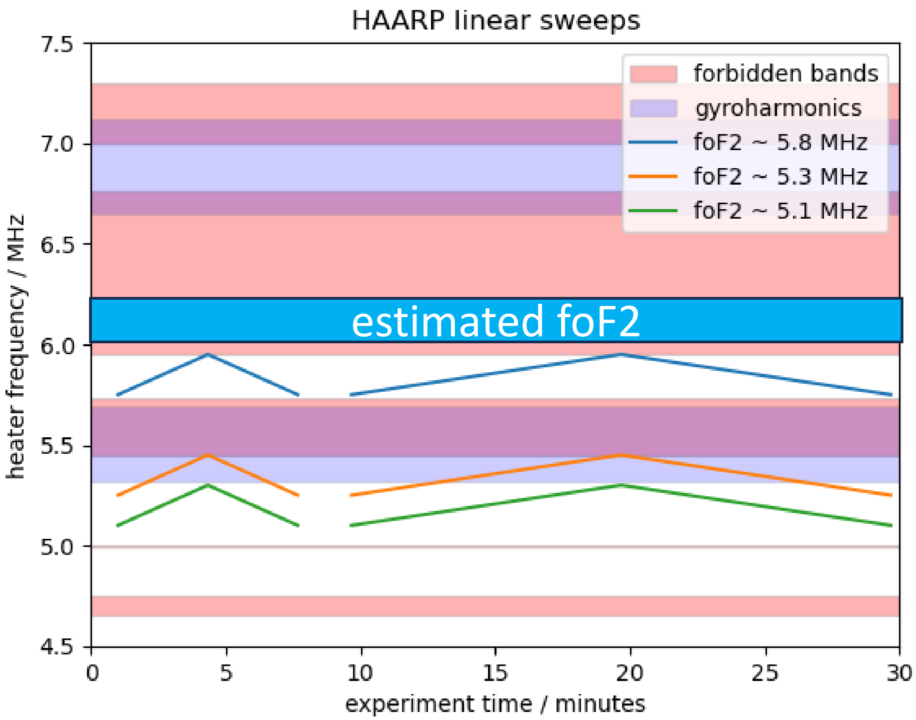


FAI generation at HAARP – 2024 PARS experiments

Experiment design

- Vary heater frequency relative to foF2
- Experiment plan
  - Sweep f_0 from below foF2 to above, and back down
  - Two different sweep rates:
    - Fast (60 kHz/min) in case of volatile ionosphere conditions
    - Slow (20 kHz/min) to maximize frequency resolution with SuperDARN measurement cadence (1 minute)
  - Adjust center frequency just before experiment depending on foF2 estimate
- Two experiment periods:

	foF2 estimate
Aug 14 21:30-22:00 UTC	**6.0-6.1 MHz**
Aug 15 02:30-03:00 UTC	**6.2-6.3 MHz**



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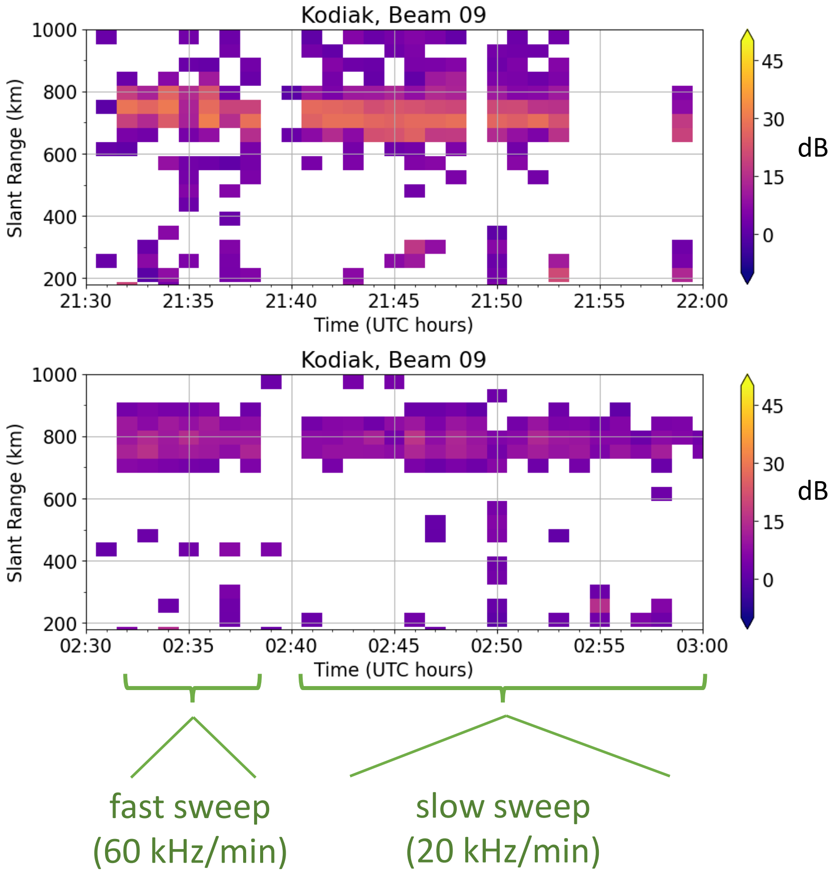
FAI generation at HAARP – 2024 PARS experiments

First results

- SuperDARN
  - Timing of backscatter aligns with experiment plan
  - Backscatter returns are brighter during Aug 14 experiment
  - Aug 14 experiment missing returns in part of downward sweep

→Heating closer to foF2 on Aug 14

→Lower-altitude heating on Aug 15

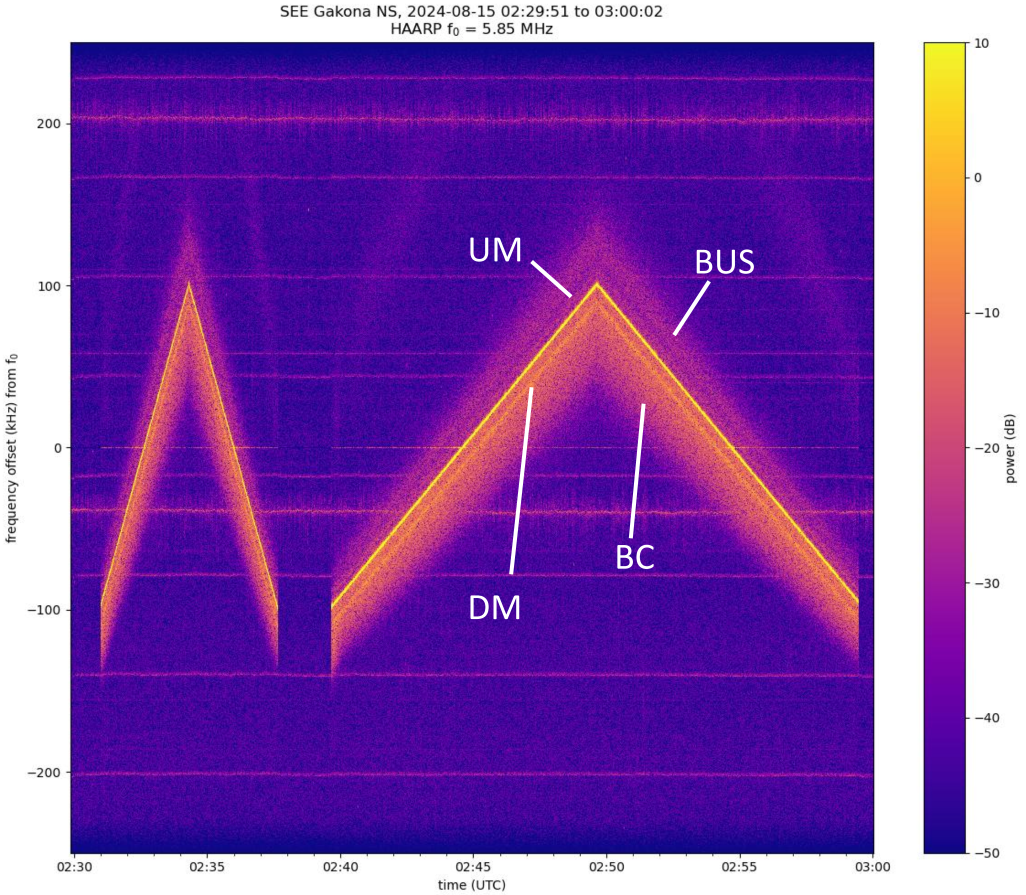


FAI generation at HAARP – 2024 PARS experiments

First results

- SEE measurements
  - DM, UM, BC, BUS again observed
  - Broad structures (BC & BUS) brighten and broaden with increasing heater frequency
  - Upshifted structures much stronger in Aug 15 experiment

→ Stronger reflected/stimulated signal during low-altitude heating



BC: broad continuum
BUS: broad upshifted structure
DM: downshifted maximum
UM: upshifted maximum

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