Ionospheric and Plasmaspheric Science with Low-frequency Interferometers

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Dec. 4, 2015

Introduction

- Interaction between magnetized plasma of Earth's ionosphere and RF waves causes:
  - Refraction
  - Scintillation
  - Faraday rotation
  - Absorption/attenuation

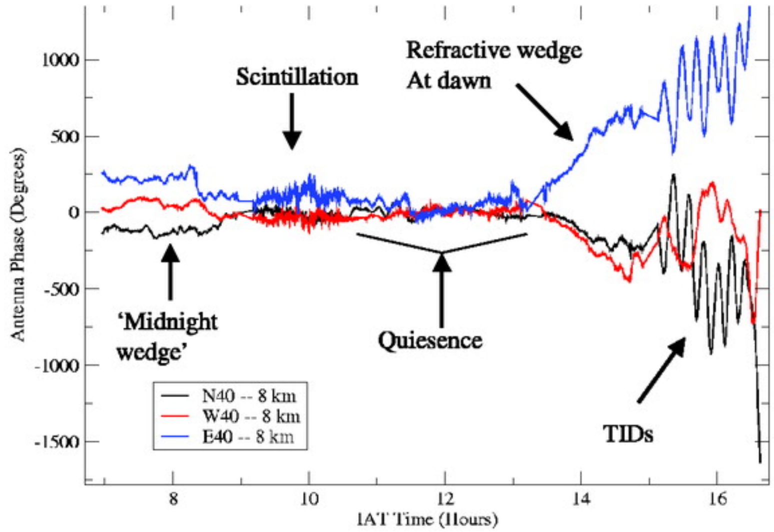
- All of these get stronger/worse at lower frequencies ➔ they are nuisance to HF/VHF systems focused on both basic research (e.g., astrophysics) and applied work (e.g., radars, communications, etc.).

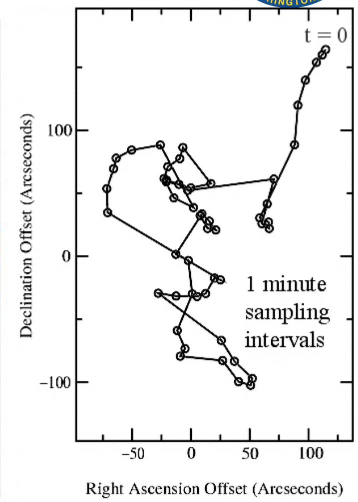
- However, also makes monitoring of HF/VHF propagation a powerful tool for exploring ionospheric dynamics.

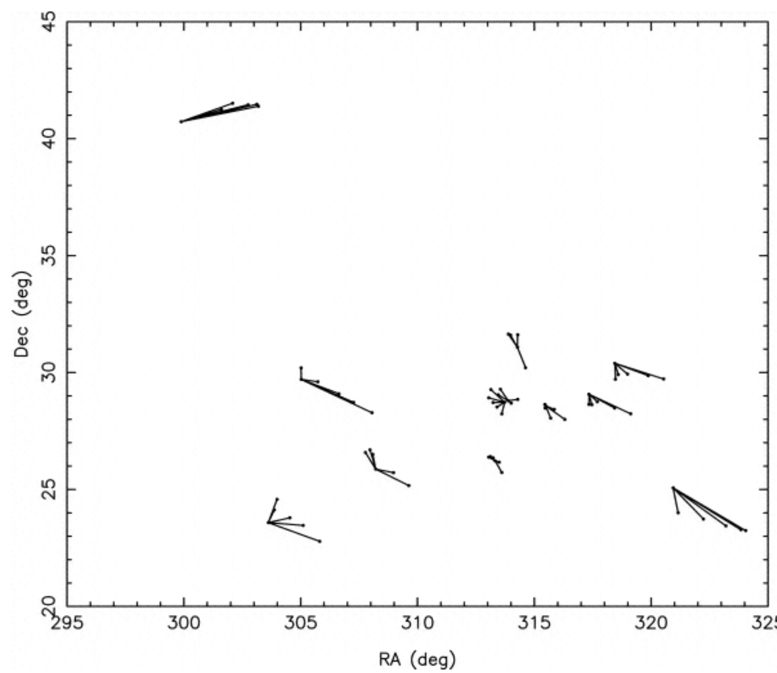
- Instruments and techniques developed for low-frequency radio astronomy have remarkable potential in this regard that has yet to be fully realized.

Synthesis Imaging Interferometers

- Low-frequency capabilities of RF interferometers designed for synthesis imaging severely affected by dynamic ionosphere (e.g., VLA, GMRT, LOFAR, MWA).
- Gradients in total electron content (TEC) translate to phase gradients within the array; to first order, causes source position shifts; under active conditions, source blurred beyond recognition.
- Was major limiting factor to angular resolution and field of view for low-frequency arrays until new calibration techniques (e.g., self-cal., field-based cal., etc.) were developed and implemented.



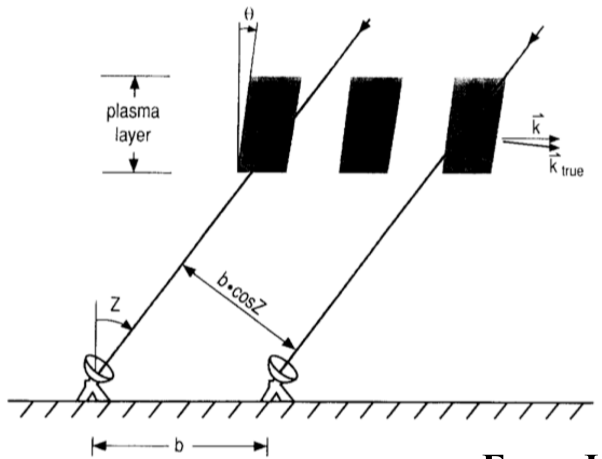


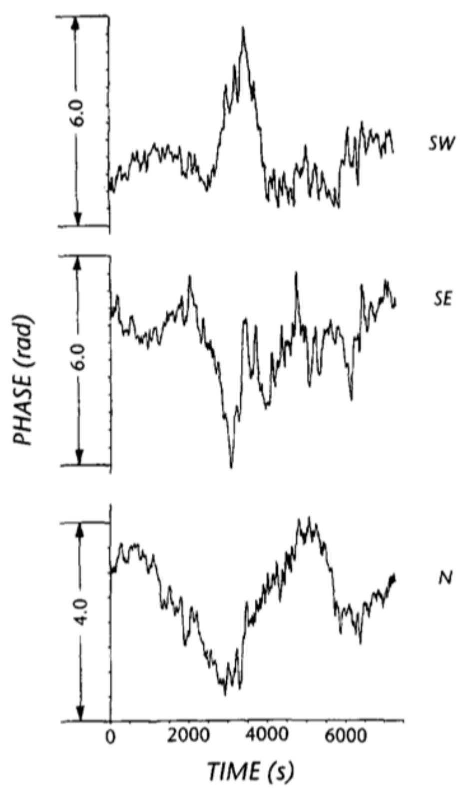


From Kassim et al. (2007). ***Above*****: The effect of ionospheric fluctuations on a single strong source.** ***Left*****: The impact of differential refraction over relatively large FoV.**

Turning Trash into Treasure

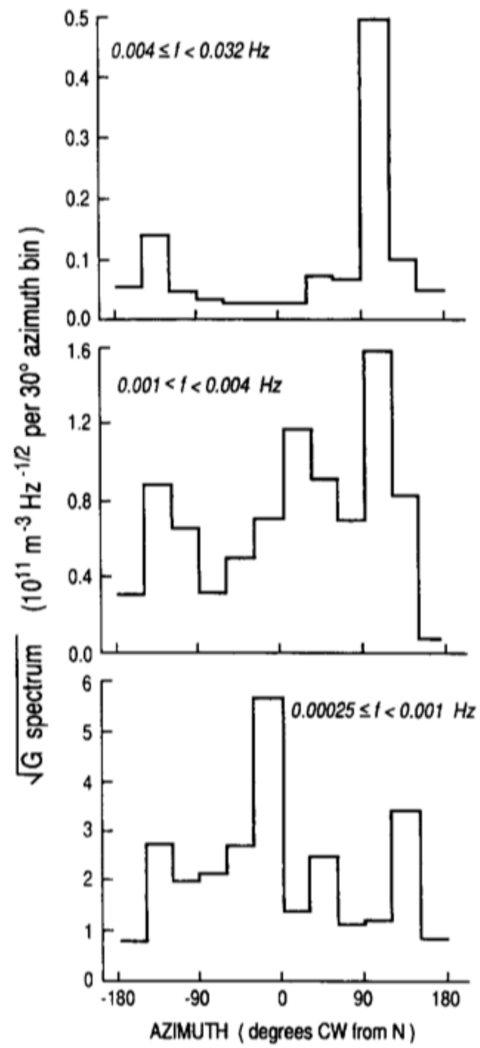
- The advent of self-calibration opened the skies to high angular resolution imaging below 500 MHz. But, early on, potential for ionospheric calibration data for science was recognized.
- Pioneering work by Jacobson and Erickson in late ‘80s/early ‘90s demonstrated sensitivity and utility of VLA P-band (330 MHz) system for ionospheric work.





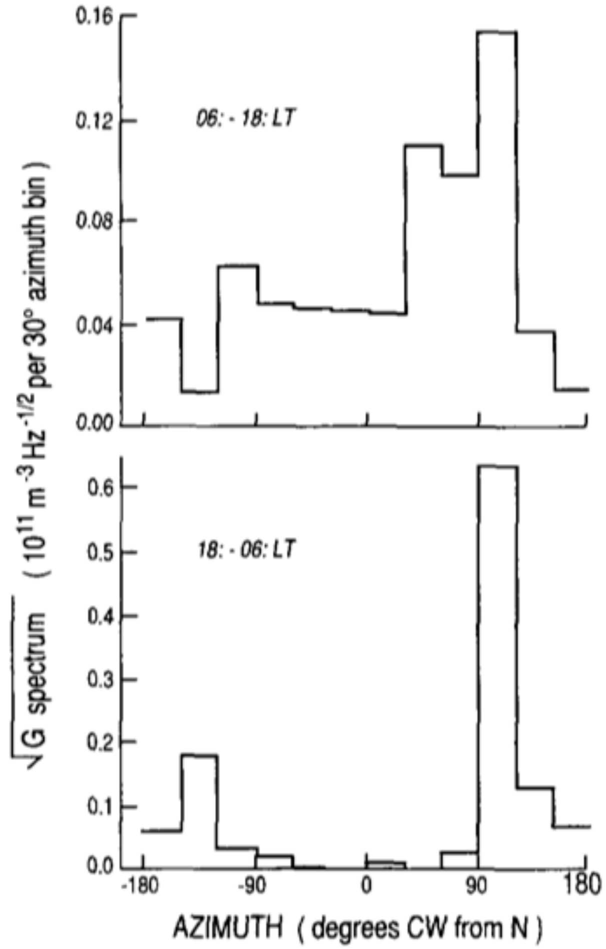
From Jacobson & Erickson (1992), schematic and P-band phase time series showing impact of plasma wave on VLA data; plane wave model fit over the array per oscillation frequency to extract wavenumber vector.

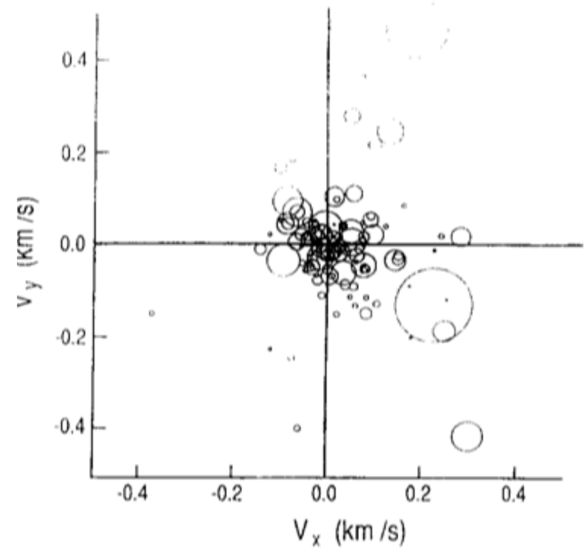
Mar.-Sep. 1990; 47 P-band sessions; mostly A-config.; below shows azimuth distributions for detected waves.



Turning Trash into Treasure (cont.)

- Early VLA work by Jacobson & Erickson led to discovery, initially called magnetic eastward directed (MED) waves.
- Later figured out that these were field-aligned irregularities (FAIs) within the lower plasmasphere.
- To the VLA observing cosmic source, these appear as fast-moving plane waves moving roughly toward magnetic east due to (nearly) co-rotating nature of plasmasphere.

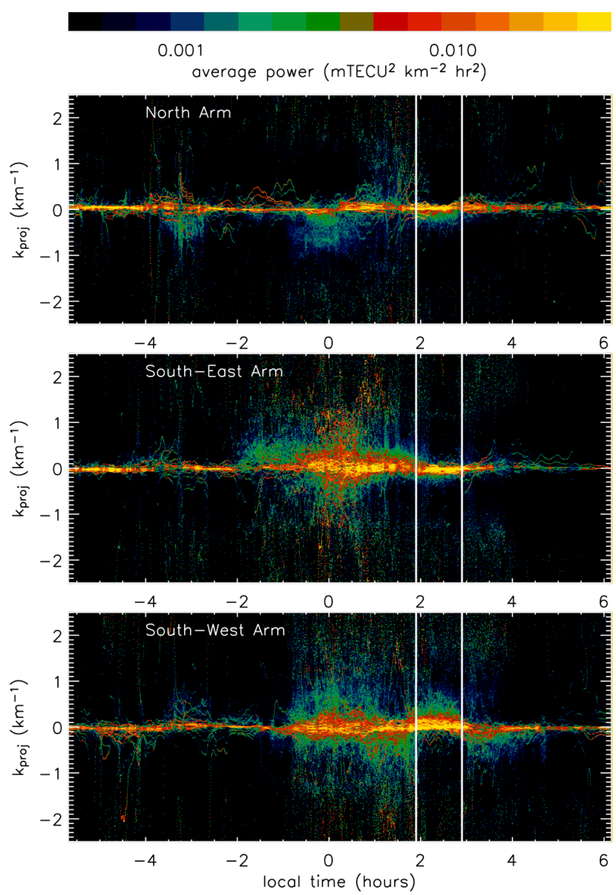




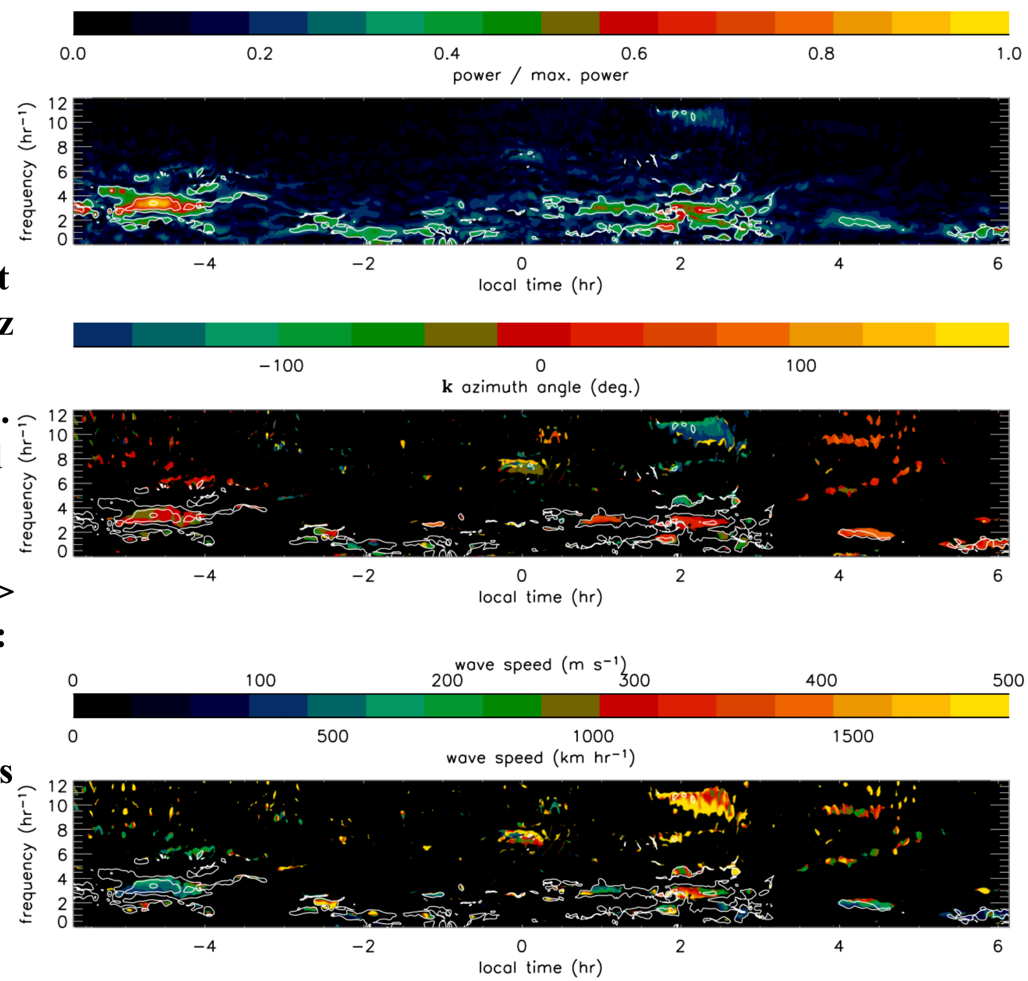
MED waves were prominent during Mar.-Sep. 1990 campaign; appear to move faster than other waves and more prominent at night.

Building on the Past

- Methods pioneered by Jacobson & Erickson have been expanded upon, replacing plane-wave fits with full 3-D (2 spatial, one temporal) spectral analysis.
- Can probe and characterize medium to fine scale structure.

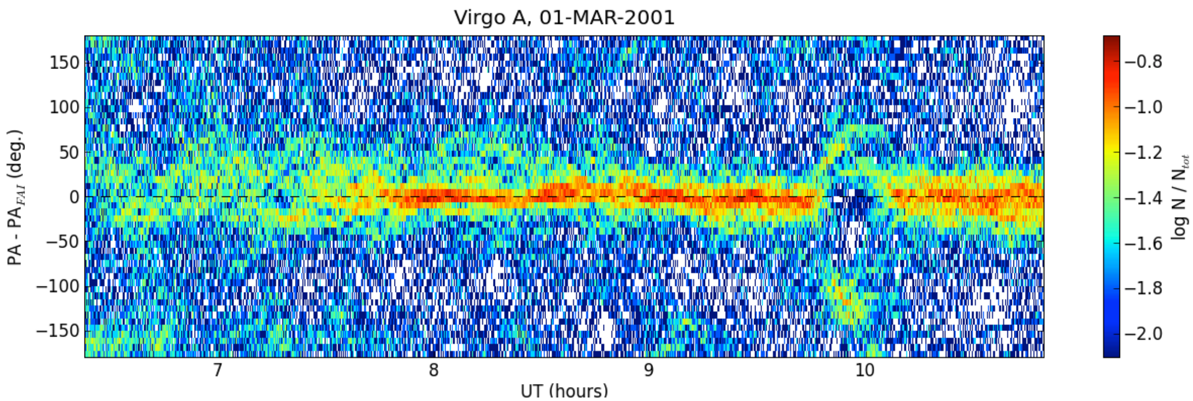


Spectral analysis from ~12 hour VLA run on Cyg A at 74 and 330 MHz ("4P mode") from Aug. 2003. *Right*: Spectral properties of fluctuations comparable or > the array. *Left*: Spectral properties on fine scales scales along VLA arms.

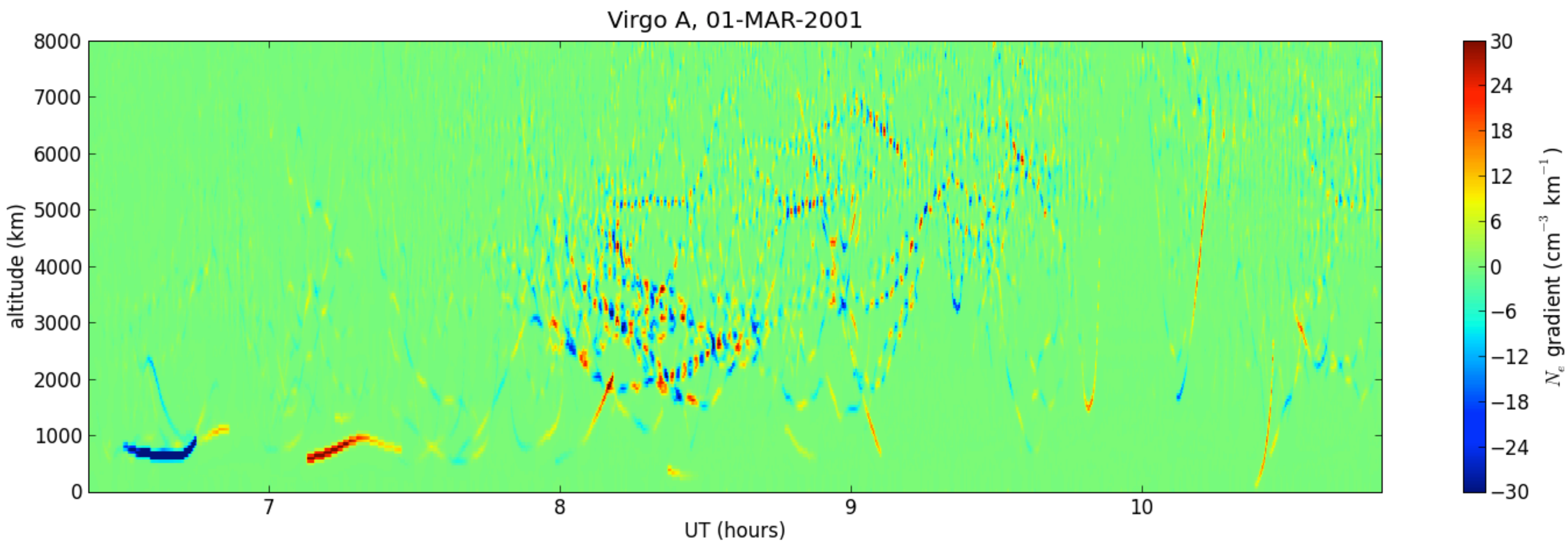


Building on the Past (cont.)

- Spectral analysis can separate out/identify plasmaspheric FAIs and reconstruct radial structure (similar to tomography).



From ~6 hour VLA 74 MHz run on Virgo A on 01 March 2001. *Left*: Distribution of difference in measured disturbance azimuth and predictions for plasmaspheric FAIs. *Below*: Radial mapping of fluctuations consistent with plasmaspheric FAIs.



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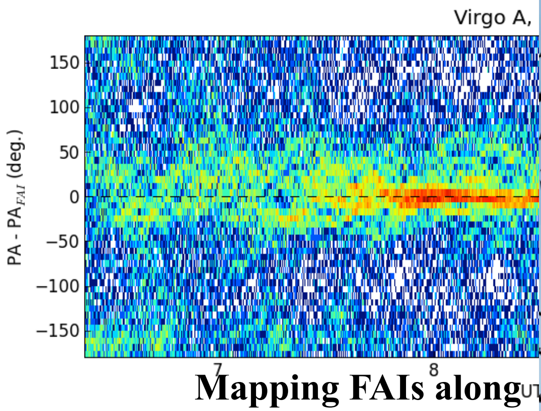
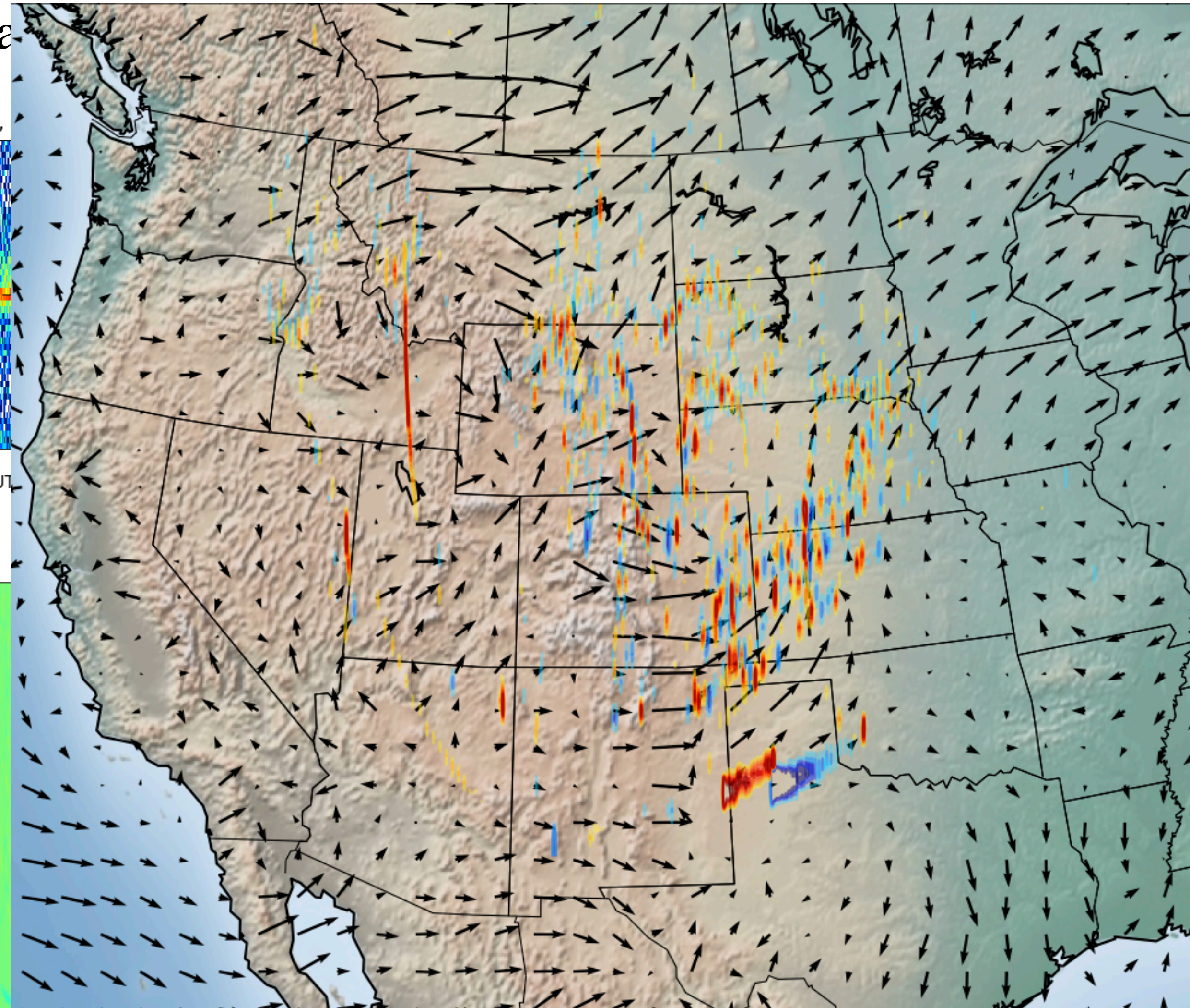


Mapping FAIs along field lines to ionosphere hints at fluctuations in ion pressure due to standing mountain waves; computations with SAMI2 model imply this is plausible.



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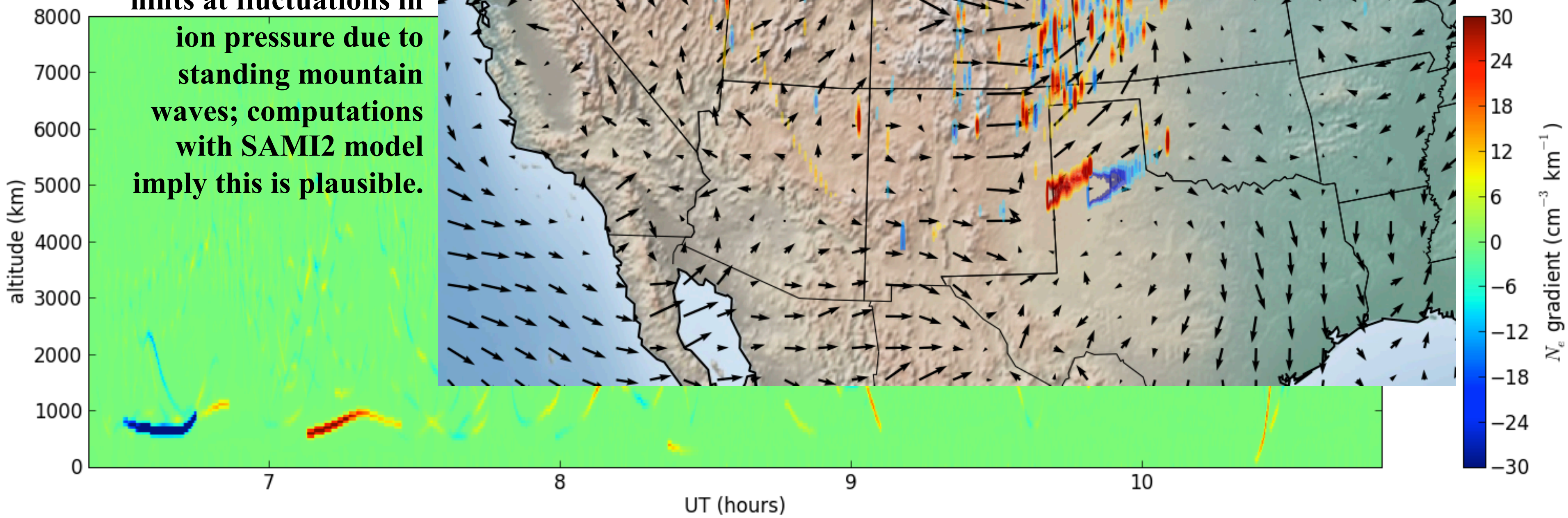
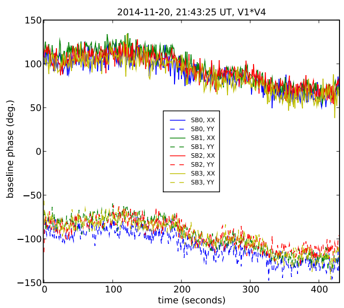


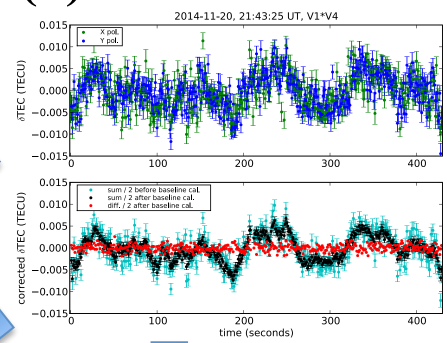
Moving Forward with VLITE

❖ VLITE running ionospheric spectral analysis automatically (in near real time) on roughly 14 hours of P-bad data per day; about 10% of that reaches ΔTEC precision <0.001 TECU ➔ no longer relegated to handful of low frequency campaigns.

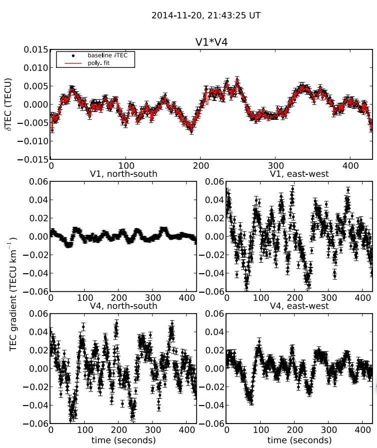
(a) **Raw phases; 4 sub-bands , 2 polarizations**



(b) **De-trend, convert to δTEC, and combine**

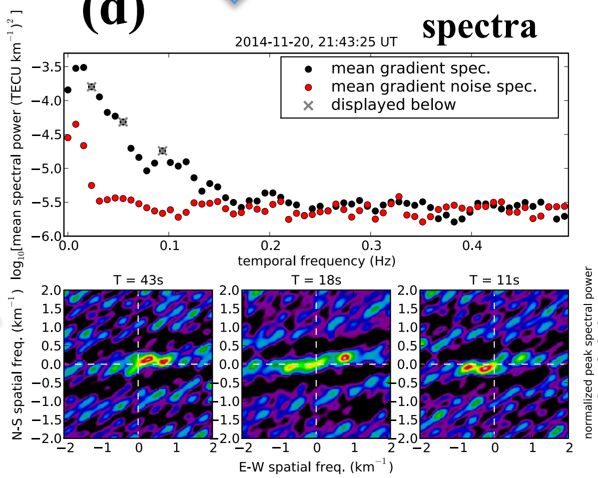


(c)

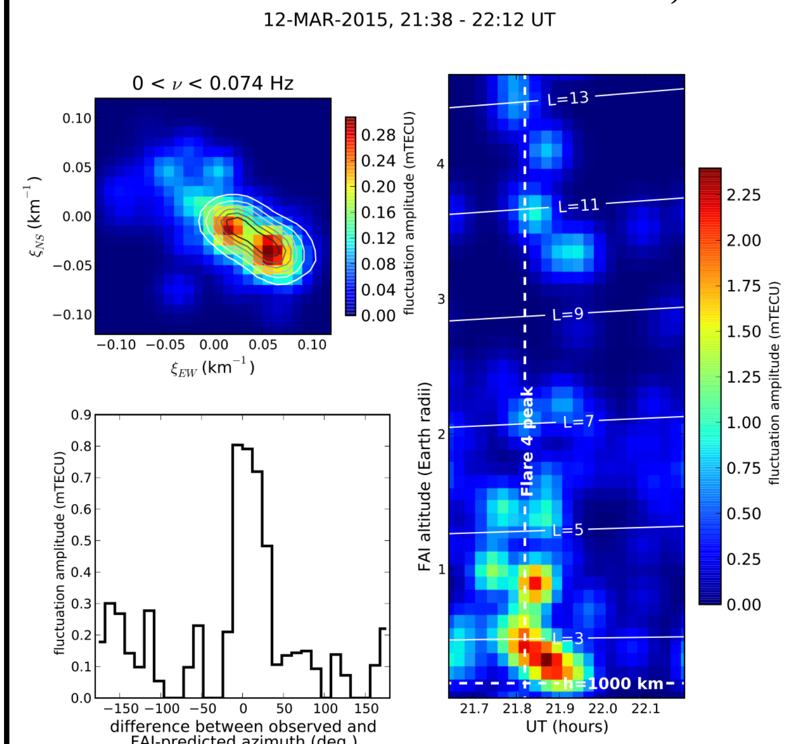


Polynomial fit converts δTECs to antenna-based TEC gradients.

(d) **Fluctuation spectra**

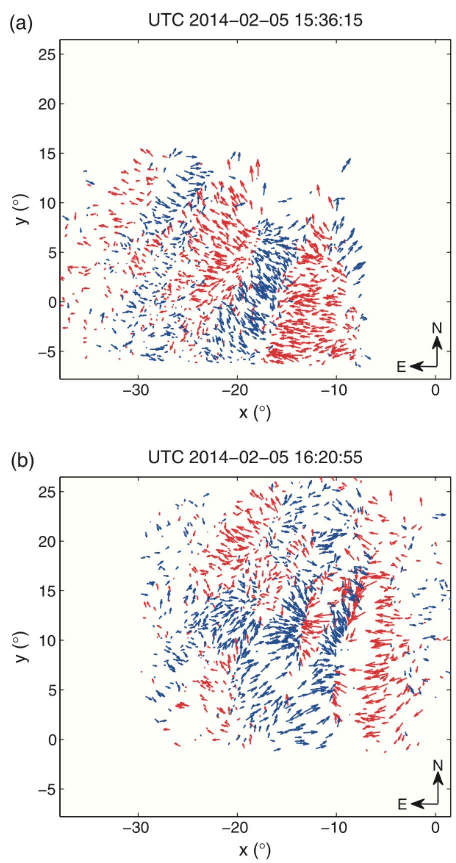


On 12 Mar. 2015, had series of VLITE observations of 3C84 during solar flare; found plasmaspheric FAIs associated with it (Helmboldt et al. 2015).



Imaging Ionospheric Irregularities with MWA

- Wide field of view of MWA requires monitoring position shifts of moderately bright sources for ionospheric corrections ➔ allows for “imaging” of ionospheric structures over large area.

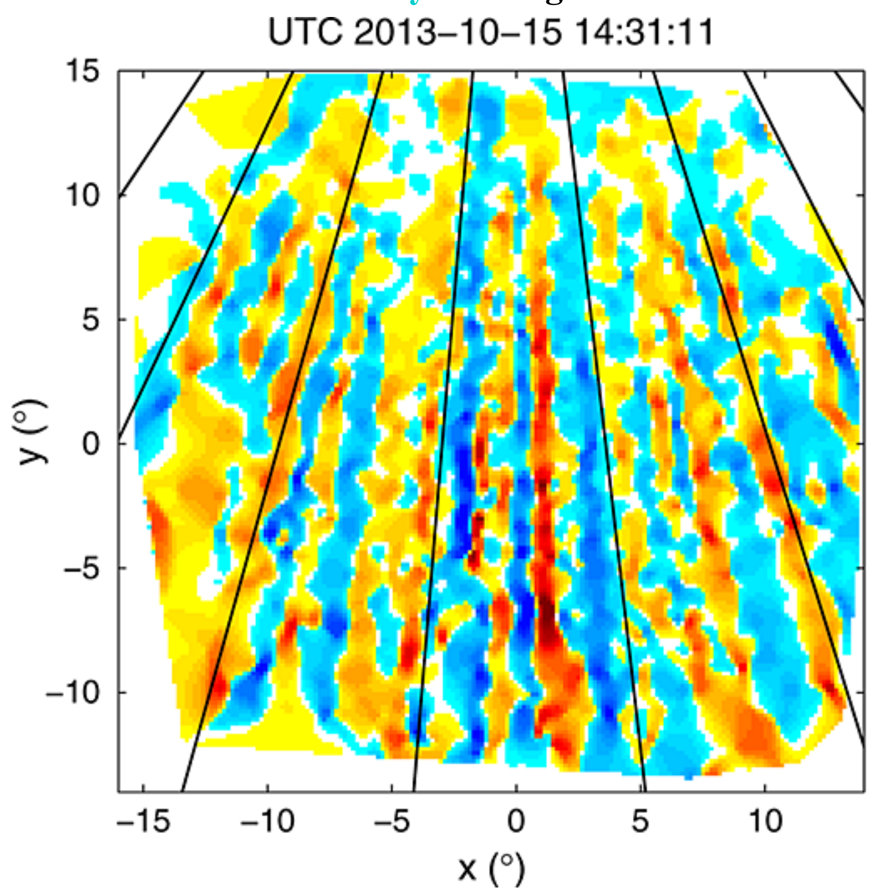


From Loi et al. (2015), position shifts (relative to mean) @183 MHz from individual 2-minute snapshots.

red = eastward, blue = westward.

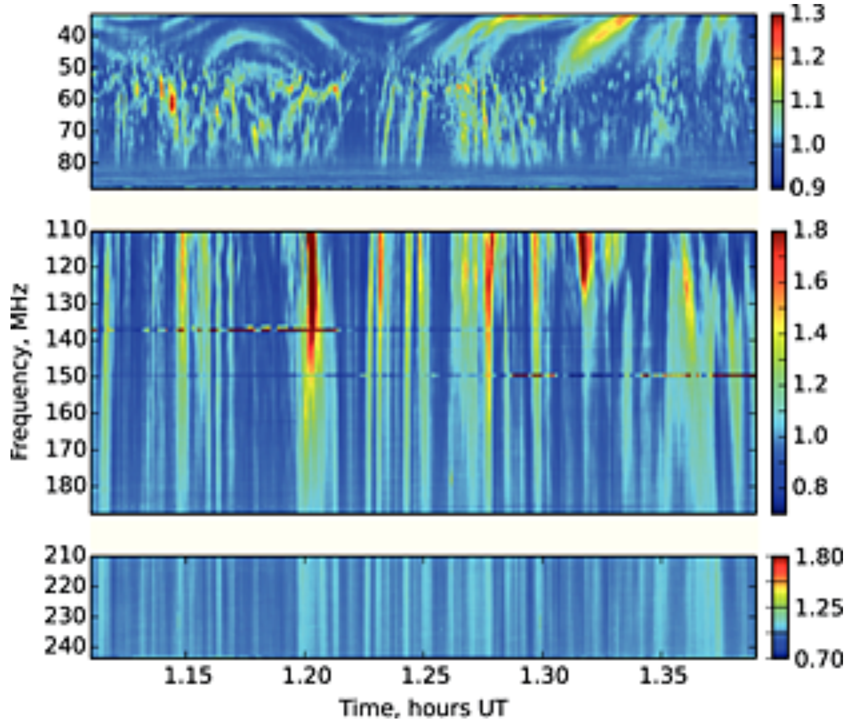
MWA snapshot of plasmaspheric FAIs. Image shows position shift divergence for one 183 MHz, 2-minute snapshot.

red/yellow = positive
blue/cyan = negative

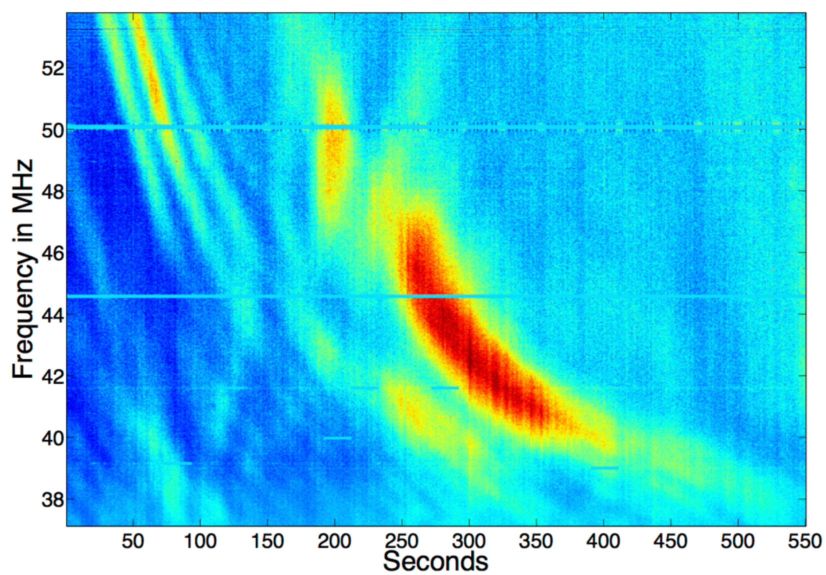


Compact/Phased Arrays

- Compact, usually dipole-based arrays can be powerful tool for exploring fine scale ionospheric structures.
- Dipole-based HF/VHF radars have been used for decades (e.g., Jicamarca); potential benefits of all-sky sensitivity of arrays designed for astronomy just starting to be realized.



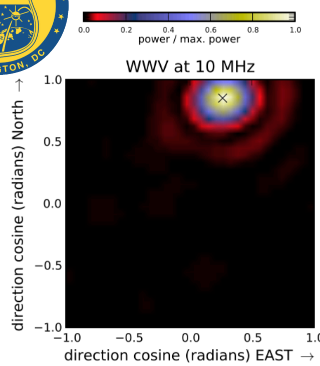
Dynamic spectrum of Cygnus A from the LOFAR KAIRA station from 26 Sep. 2012 (Fallows et al. 2014); shows significant spectral structure of scintillations at northern latitudes.

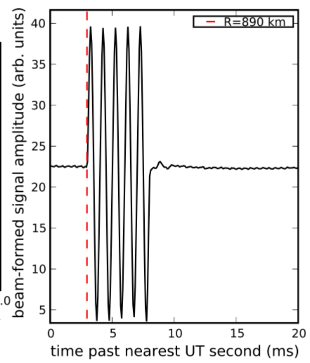


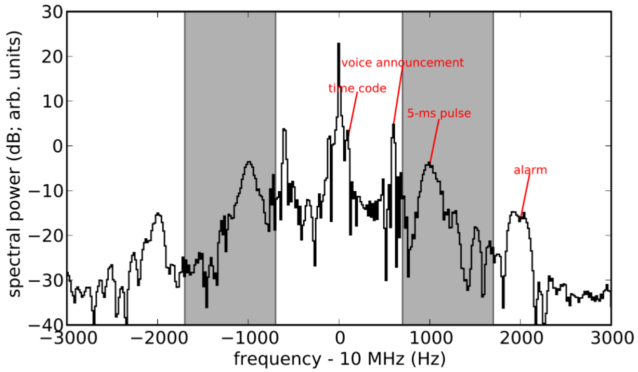
Similar variations (shown on smaller time/frequency scales) seen with LWA1 toward 3C252 (made by K. Obenberger); "banana" shape resembles dispersed pulse with DM = 190 pc cm^{-3}.

Passive Radar

❖ "All-sky" transient buffer modes allow for useful radar-based studies, esp. when paired with a "free" transmitter.

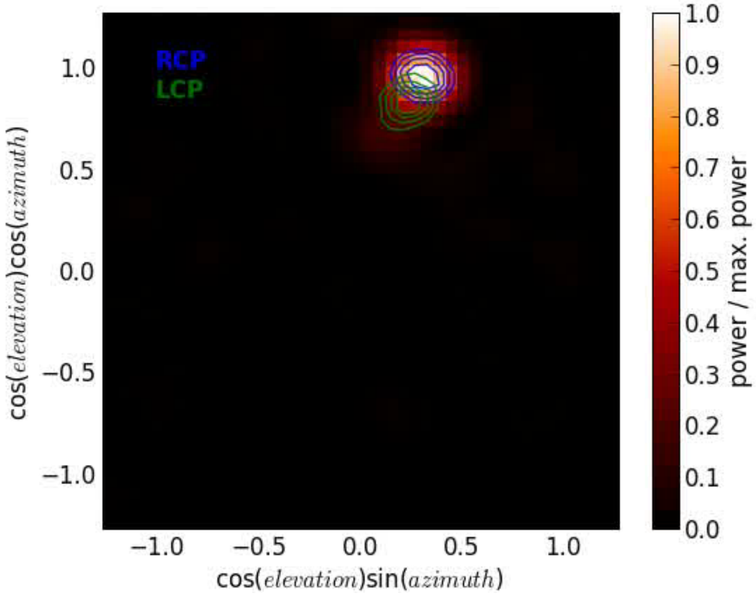


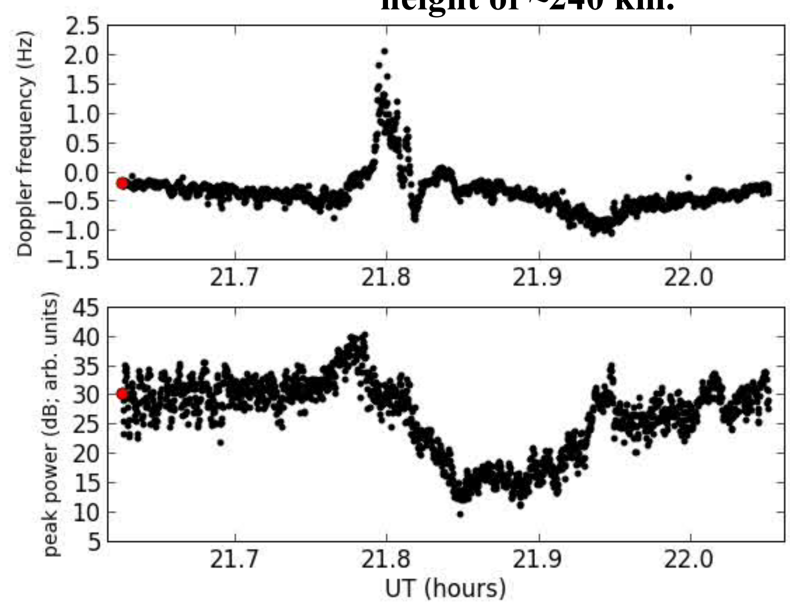




"Skywave" at 10 MHz of the WWV radio station near Ft. Collins, CO from an LWA1 TBW capture.

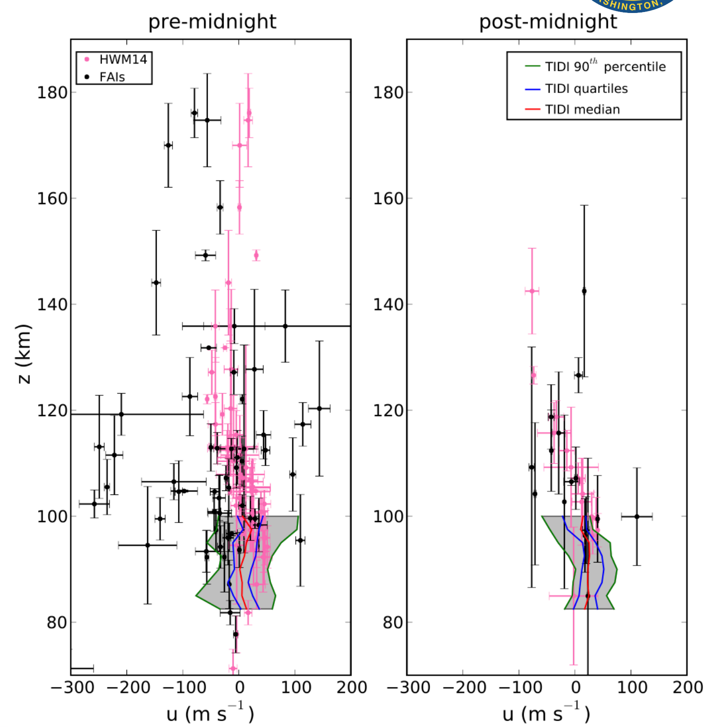
All-sky images of WWV 10 MHz carrier skywaves with time series of Doppler and power before/during/after M-class solar flare (@21.8 UT); pulse timing gives "reflection" height of ~240 km.

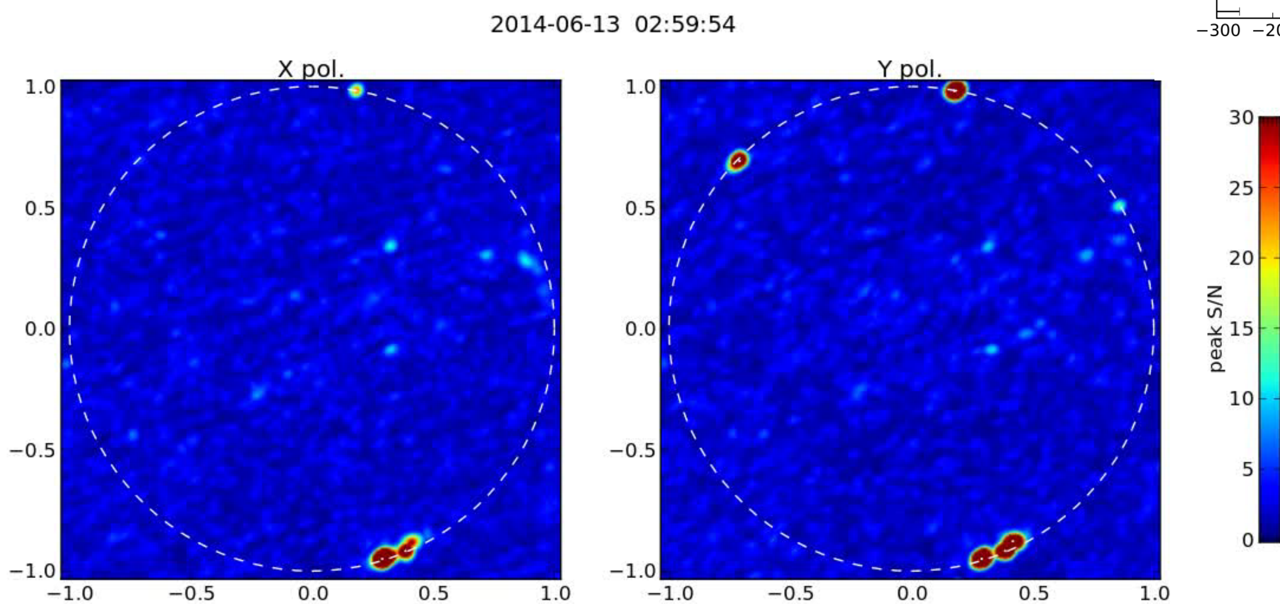




Passive Radar (cont.)

- Narrow-band video carrier of Channel 2 in Juarez (55.25 MHz) also useful; get returns from airplanes (not so useful), meteor trails, and FAIs.
- Can compute distance to FAIs with sky position, known Tx and Rx locations, and magnetic field model.
- All-sky tracking of FAIs associated with sporadic-E where ion motions largely wind driven provide new method for wind measurements up to ~150 km altitude or higher.





Left: **All-sky movie from LWA1 at 55.25 MHz; FAIs along arc to the north.** ***Above***: **Zonal winds from 75 different groups of FAIs found within 18 one-hour observations; compared with TIDI satellite measurements and HWM14 empirical model.**

Summary

- Low-frequency, interferometric telescopes are useful tools for studying the fine-scale dynamics of ionosphere/plasmasphere system.

- Much work has been done, but still have barely scratched the surface.

- Commensal systems like VLITE real-time ionosphere pipeline greatly increase chances of catching events like solar flares, sudden stratospheric warmings, earthquakes, and large explosions that impact via forcing from below and above.

- In turn, a better understanding of the physics behind ionospheric/ plasmaspheric disturbances on scales to which interferometers are sensitive will allow for construction of better models for calibration and imaging of low-frequency cosmic sources over wide fields of view, and with longer baselines.