Imaging of Ionospheric Irregularities via Observations of their Impact on the Plasmasphere

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Ionospheric Impact on Interferometers

Very Large Array (VLA): Array of 27 parabolic antennas, each 25-m in diameter. In central/western NM

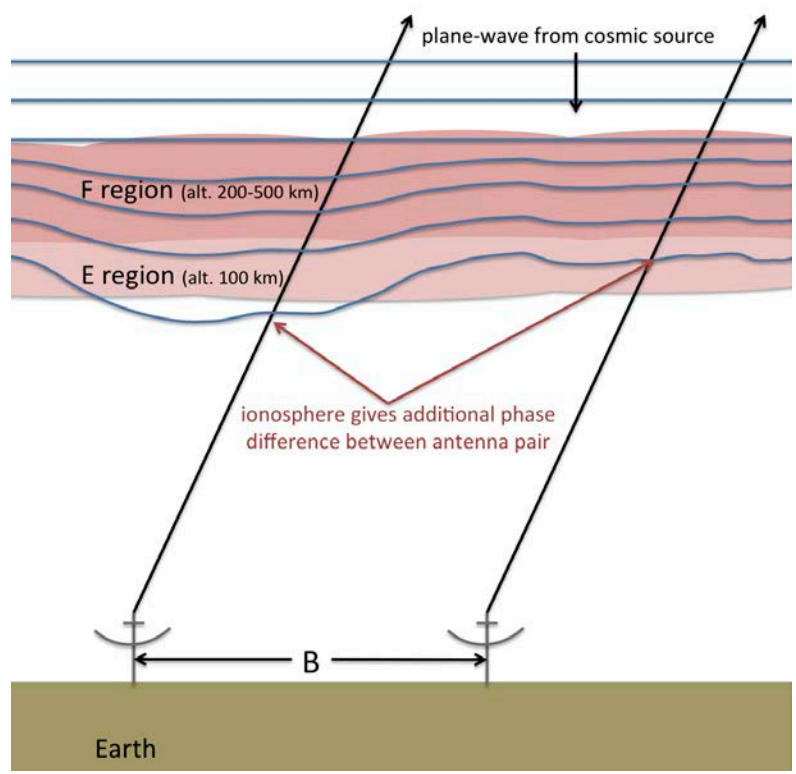
Observing through plasma

Simultaneously observe cosmic source and ionospheric structure

- Ionospheric delay proportional to total electron content (TEC) along line of sight times ν^{-2}.
- Gradients in TEC lead to additional baseline phase ~$\delta TEC \times \nu^{-1}$, so impact much larger at low frequencies (dominates over troposphere blow roughly 1 GHz).

Turning trash into treasure

- Methods to solve for/remove ionospheric phase provide extremely precise measurement of TEC gradient.
- With VLA low-band system (74 and 330 MHz), δTEC precision as good as 10^{-4} TECU (1 TECU = 10^{16} e^{-} m^{-2}), or gradient precision ~2×10^{-4} TECU km^{-1}.

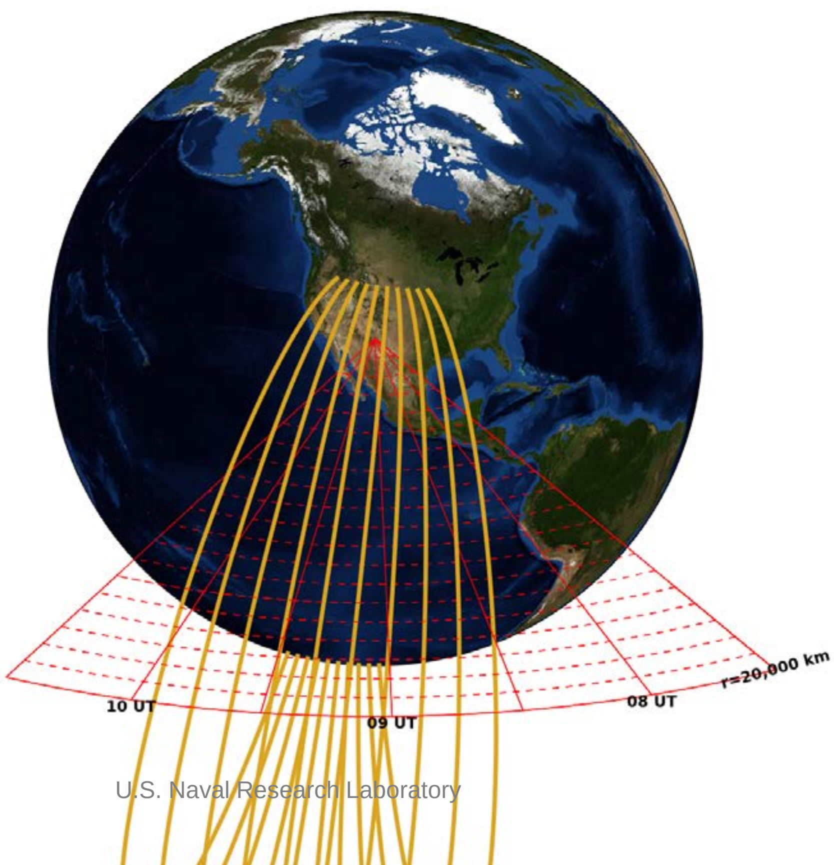


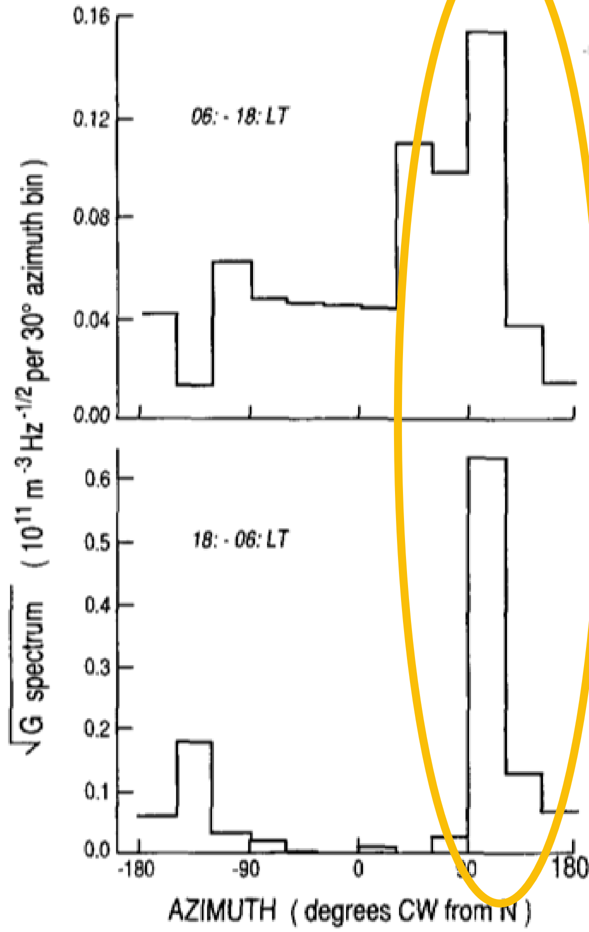
Ionospheric Studies with the VLA

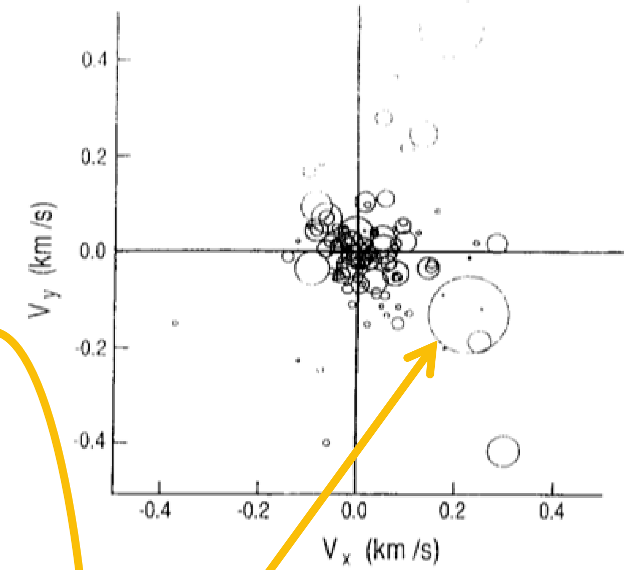
Looking for TIDs, finding flux tubes

Plasmaspheric irregularities

- Magnetic eastward-directed (MED) waves discovered with the VLA turned out to be field-aligned irregularities within the plasmasphere.
- Variations in density among flux tubes, combined with co-rotating nature of plasmasphere leads to appearance of wavefronts moving toward magnetic east.







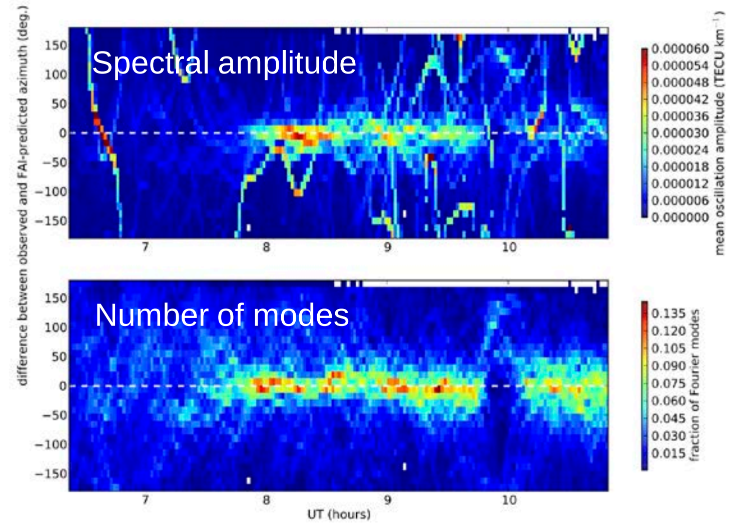
MED waves were prominent during Mar.-Sep. 1990 campaign; appear to move faster than other waves and more prominent at night (Jacobson & Erickson 1992).

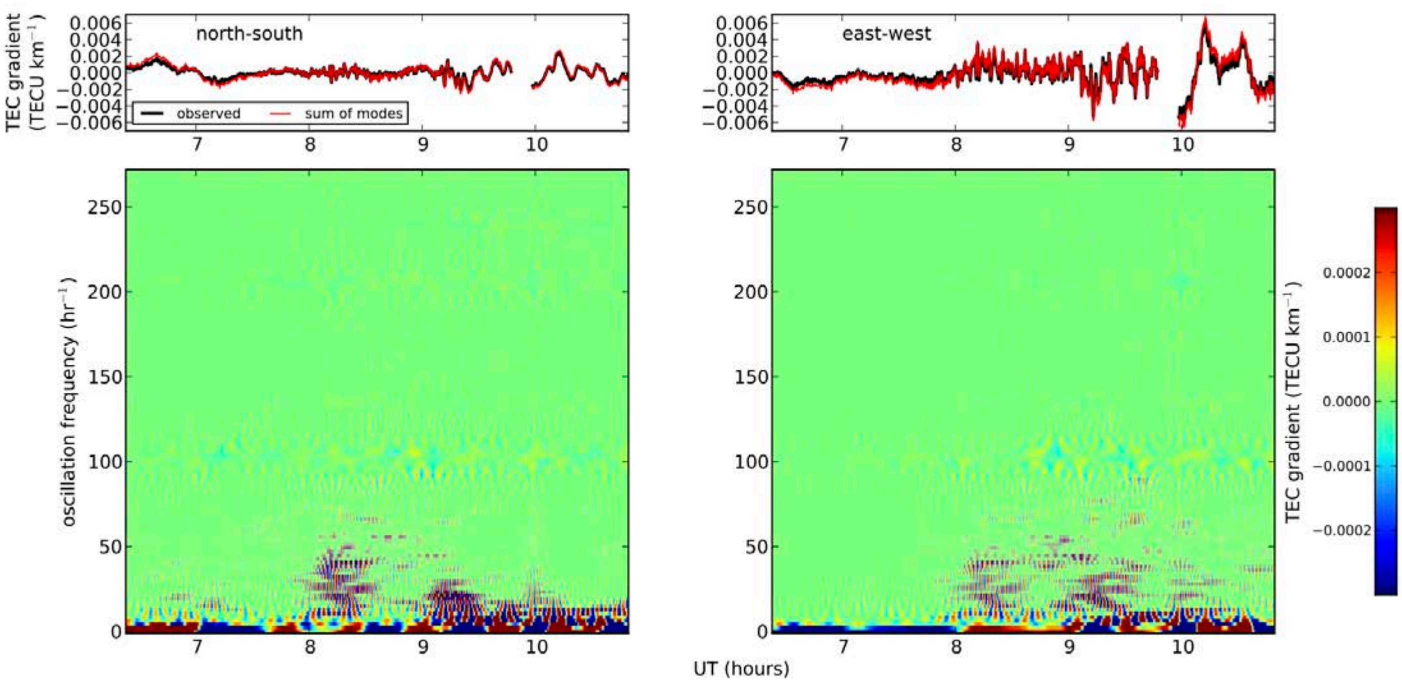
Radial Profile Retrievals

Imaging flux tubes

Quasi-tomographic spectral decomposition (QTSD)

- Can exploit co-rotation to reconstruct radial profiles of N_e gradient.
- Apparent phase speed of co-rotating flux tubes is proportional to distance from telescope.
- First step in QTSD process is to decompose time series into modes with Fourier transform (FT) and sliding window.
- Use spatial variation to measure wavenumber vector perpendicular to line of sight; yields distance estimate.
- Isolate those with wavenumber vectors consistent with flux tubes.





01 March 2001 Virgo A observation with VLA at 74 MHz. *Left*: First step in QTSD, spectral decomposition. 1st order TEC spatial derivatives shown, but 2nd order terms analyzed, too. *Above*: Step 2, find those modes with speeds/distances consistent with expected orientation for co-rotating flux tubes.

Radial Profile Retrievals

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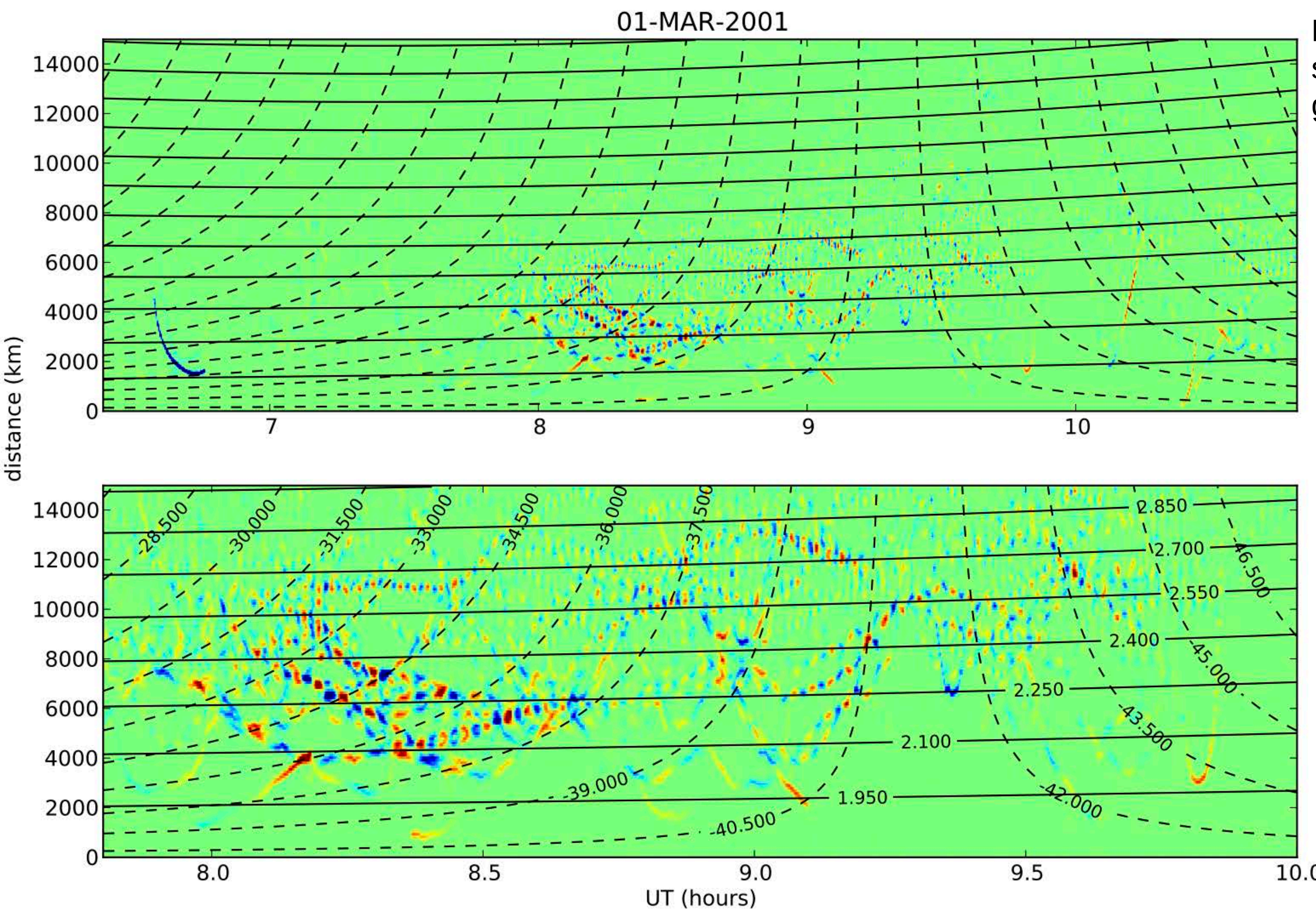
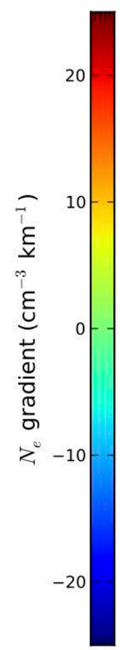
Imaging flux tubes

Slant range/time images

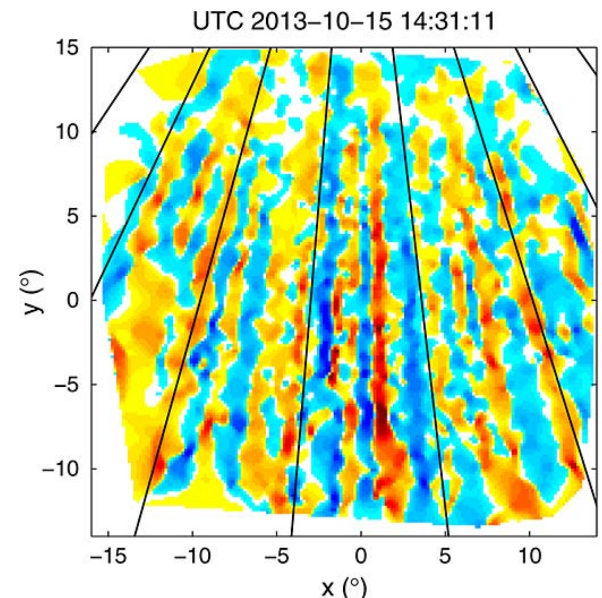
- Final step in QTSD is to group modes consistent with co-rotating flux tubes by distance/slant range.
- Summing within slant-range bins and dividing by bin width gives mean N_e gradient profiles as function of time.
- Complementary to method used with Murchison Widefield Array (MWA) in Australia; images flux tubes over large area of sky using position shifts of many sources at ~200 MHz as tracers of TEC gradient in ~2-min. snapshots.





Final image for 01 March 2001 Virgo A observation shown in previous slide. Dashed lines are geomagnetic longitude; solid lines are L-shells.

MWA snapshot of plasma ducts; analyzing data taken in binocular mode estimates height at ~600 km (Loi et al. 2015)



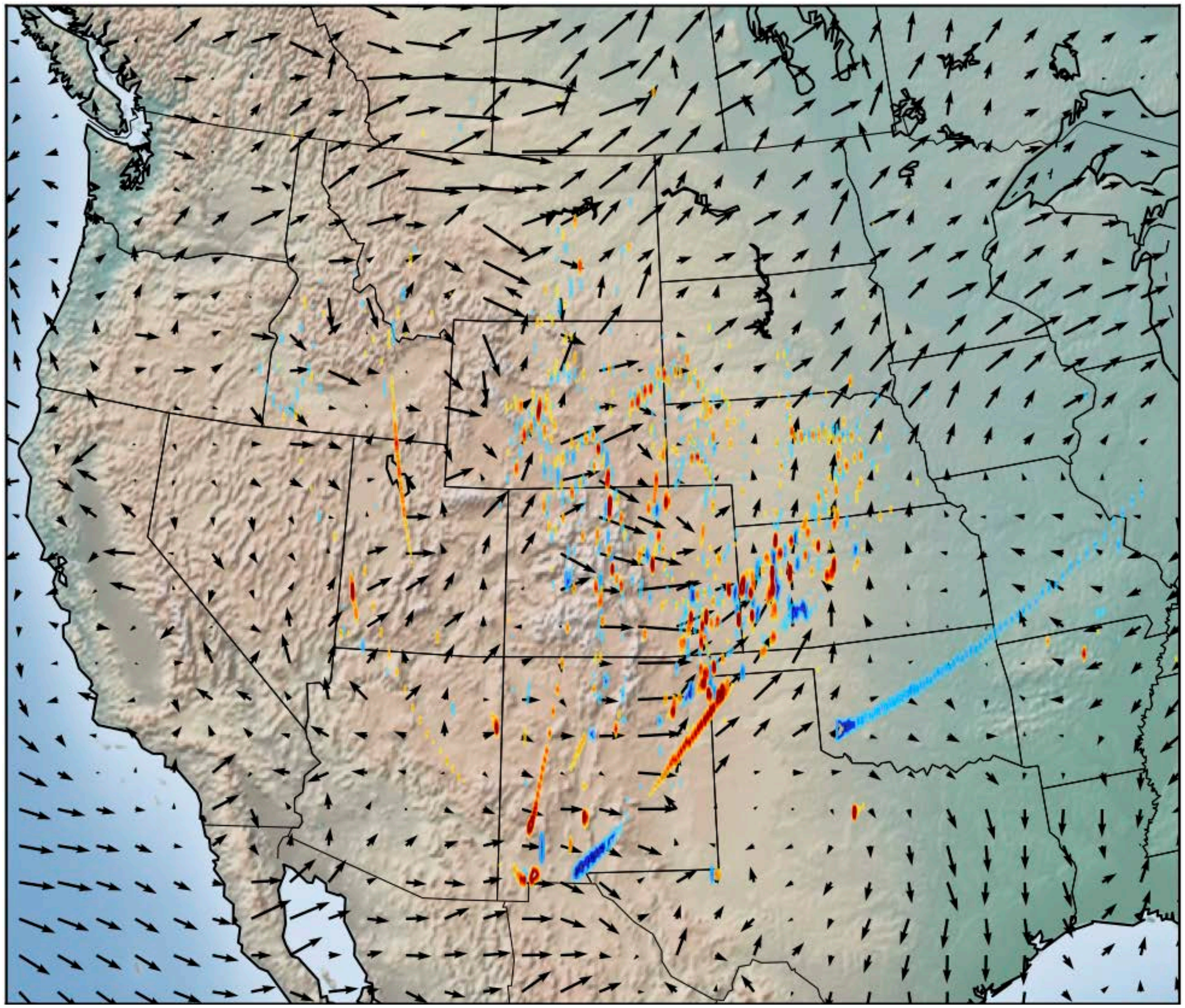
Ionospheric Connection

Mountain waves in space

Flux tubes modified from below

- Tracing disturbed flux tubes from QTSD map to locations where intersect the ionosphere (300 km altitude) reveals likely origin.
- Located on or to lee side of Rocky Mountains; implies variations in ion pressure from mountain waves (possibly standing waves) in ionosphere responsible for observed density gradient fluctuations in plasmasphere above.
- Note, relatively complex spatial structure implies integrated measurement (e.g., GPS-base TEC) not ideal (recall original time series).

01-MAR-2001



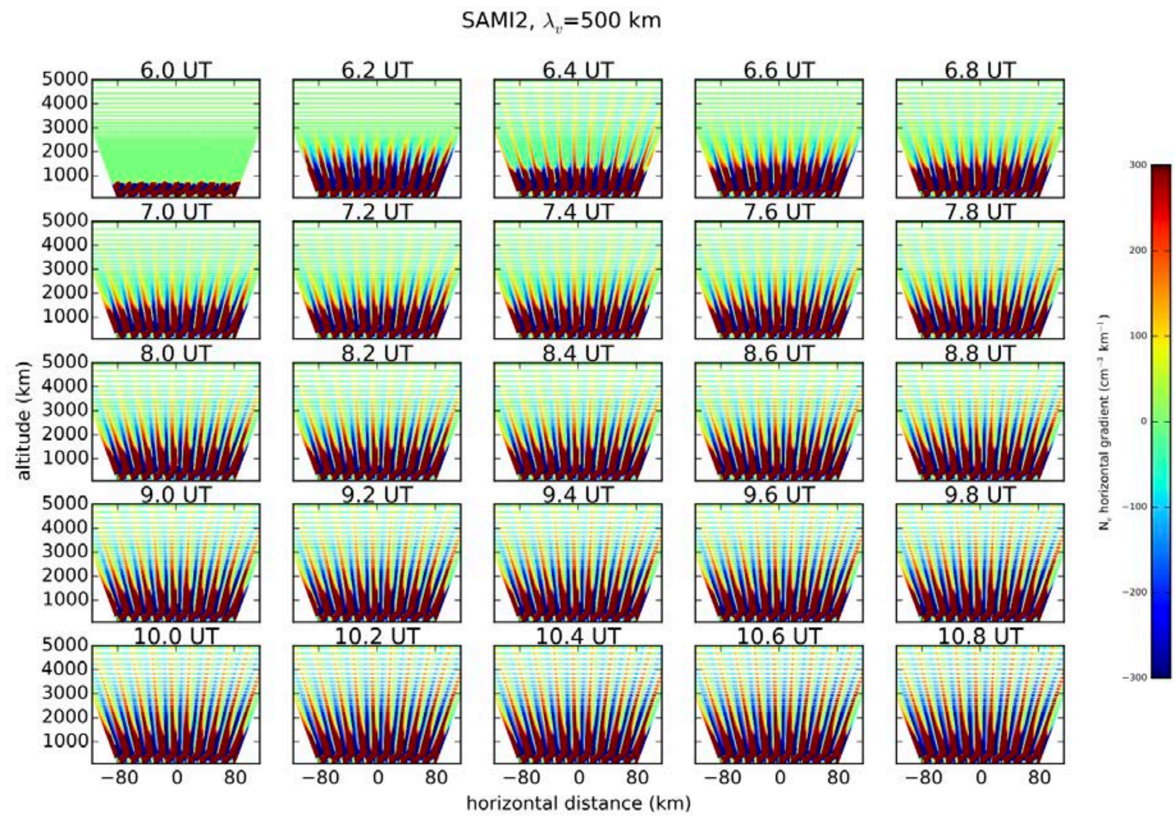
Arrows show surface wind vectors from NOAA North American Regional Reanalysis (NARR).

Synergy with Simulations

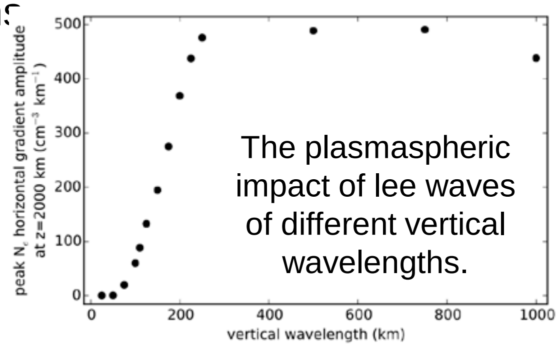
Modeling MED waves

SAMI2

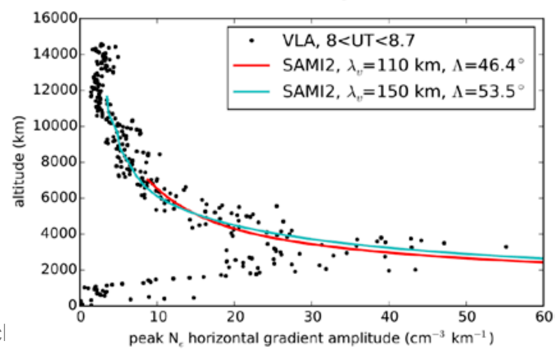
- SAMI is a model developed by NRL that combines ion production/transport with empirical models for neutral temp./wind and E×B drifts.
- There are 2-D and 3-D versions.
- 2-D version is open source; have modified it to incorporate simple lee wave model to check mountain wave hypothesis for MED wave origins.



Time series of electron density horizontal gradient from SAMI2 simulation of one field line per longitude (horizontal wavelength set to 16 km).



The plasmaspheric impact of lee waves of different vertical wavelengths.



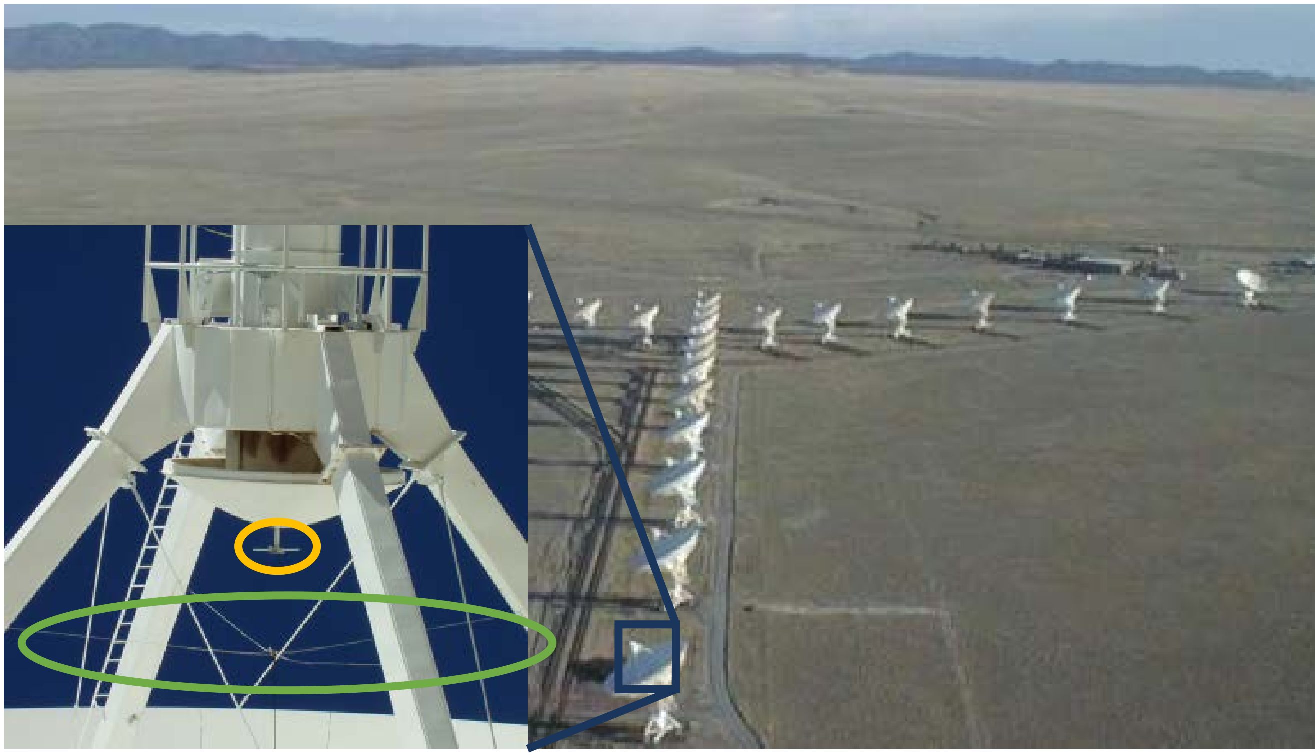
Comparison of observed and model plasmaspheric perturbation amplitudes for different field lines and vertical wavelengths.

VLA Low-band Ionosphere and Transient Experiment (VLITE)

VLITE

Piggybacking on the VLA

- VLITE is dedicated backend on 10 VLA antennas (soon to be more).
- Takes advantage of P-band optics to continually stream 320—384 MHz band to dedicated software correlator (DiFX).
- Each scan output separately; real-time ionospheric pipeline automatically processes these as they arrive.
- Science operations started in Nov. 2014 and still going . . .



P-band feed
4-band feed (no longer used)

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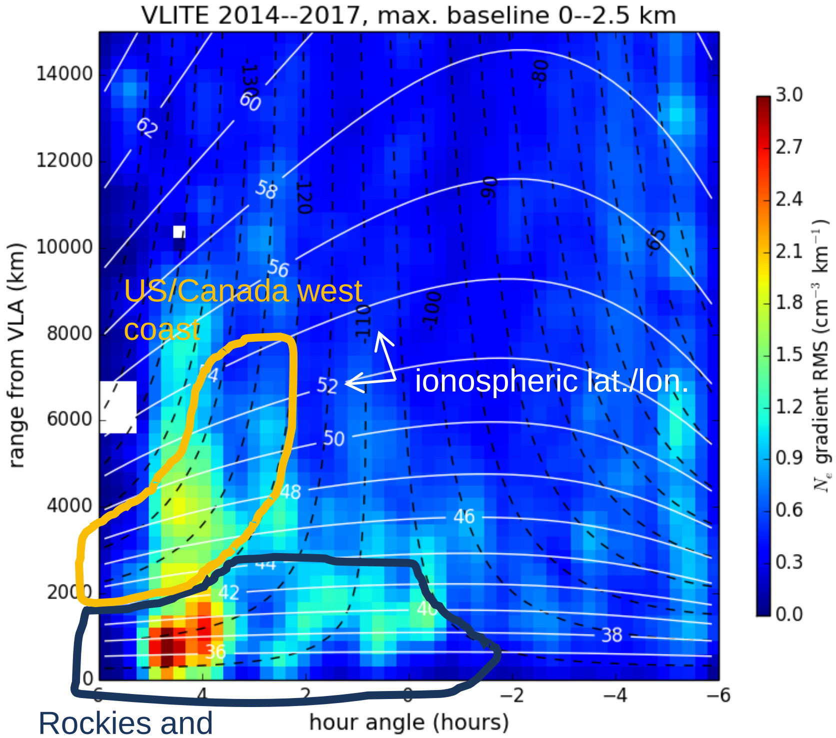
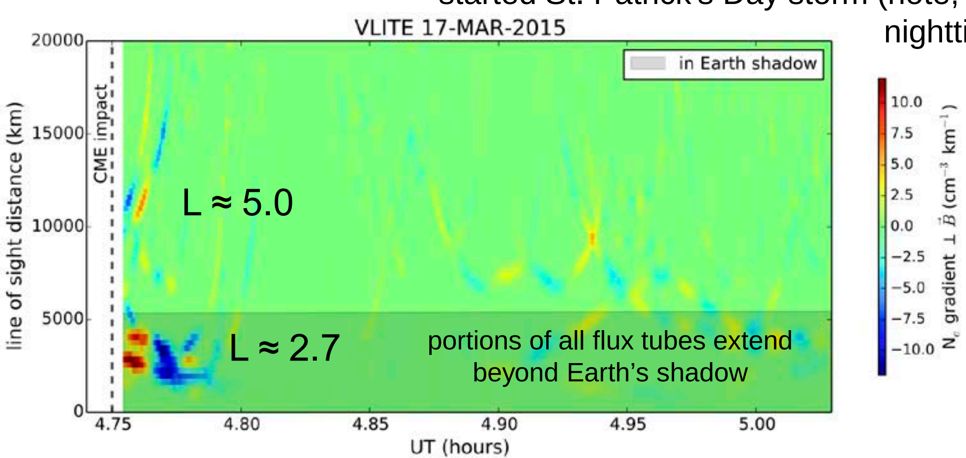
VLITE QTSD Analysis

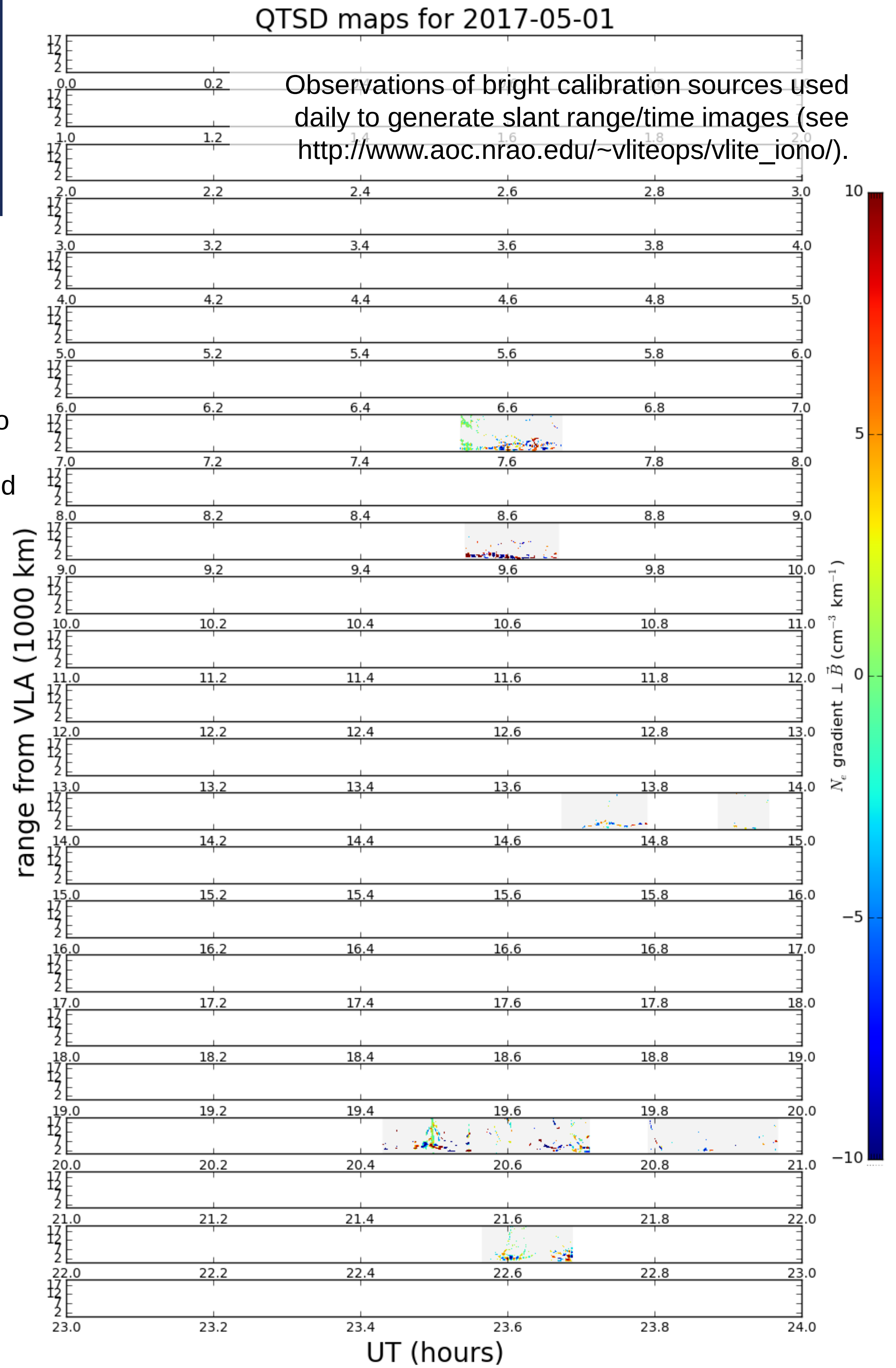


Rockies and western mountain ranges

Statistics from compact VLA configurations consistent with mountain wave hypothesis; also see features farther north and on both coasts.

Ionosphere/gravity waves not always to blame; map below shows impact of 17 March 2015 CME that started St. Patrick's Day storm (note, local nighttime).





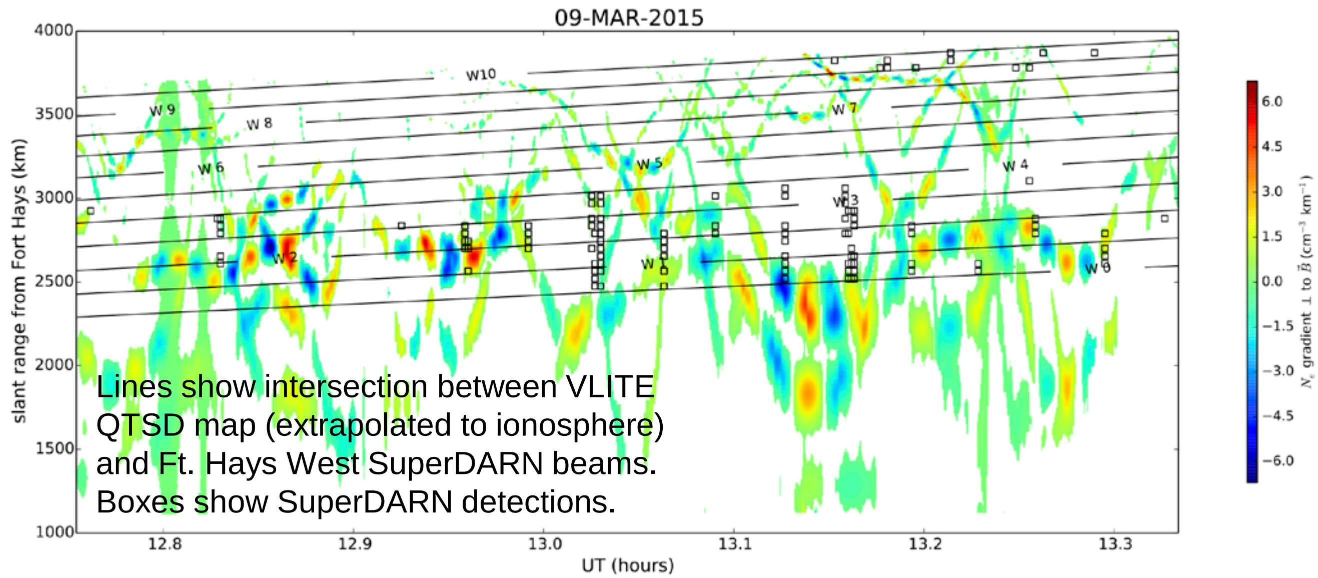
Observations of bright calibration sources used daily to generate slant range/time images (see http://www.aoc.nrao.edu/~vliteops/vlite_iono/).

Moving Forward

The future

Synergy with other platforms

- Beginning to look at overlap with data from other platforms, e.g., coherent backscatter radar (SuperDARN), HF Doppler sounder (LWA1+WWV).
- Could use some help *(**subtle hint to grad students/potential postdocs in audience**).*

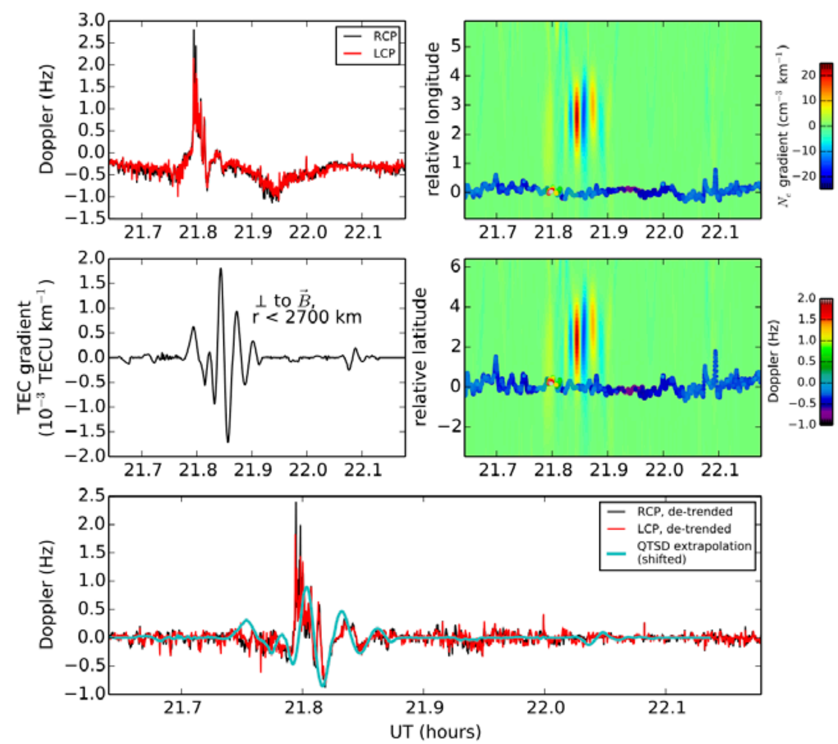


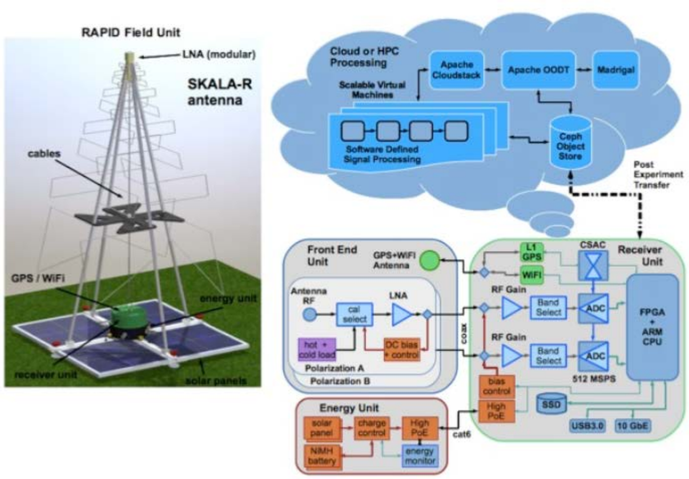
Lines show intersection between VLITE QTSD map (extrapolated to ionosphere) and Ft. Hays West SuperDARN beams. Boxes show SuperDARN detections.

Moving to other platforms

- Exploring development of re-locatable array with low-gain antennas to work in VHF regime where dishes are not needed.

Comparison of VLITE TEC gradients and HF (10 MHz) Doppler data. In bottom panel, VLITE gradient converted to Doppler by multiplying by phase speed, correcting for differing viewing angles/radio frequencies, and scaling according to steady-state/equipotential model (and International Reference Ionosphere).





Schematic of MIT's RAPID system (Lonsdale 2013).