Understanding Ionospheric Effects for the LWA

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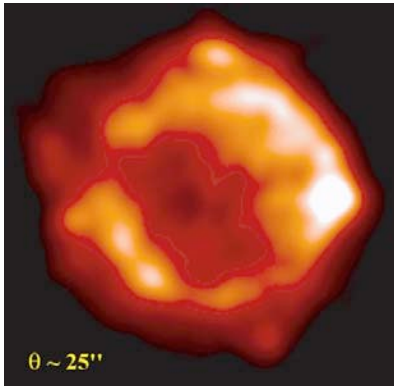
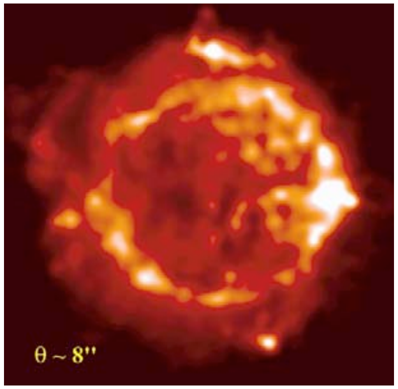
Long Wavelength Array

The LWA is an effort to advance radio astronomy and ionospheric physics by using inexpensive dipole antennas to build a very large aperture radio telescope to probe the universe at the **lowest frequencies that penetrate the Earth's ionosphere**.

- Frequency range 20-80 (12-88) MHz
  - One of the most poorly explored regions of the electromagnetic spectrum
- Large collecting area
  - Approaching 1 square kilometer at its lowest frequencies
  - Interferometric baselines up to at least 400 km





The galaxy Cassiopeia A mapped @ 74 MHz using the VLA in A configuration and VLA + Pie Town (making a much larger array), demonstrating increased resolution

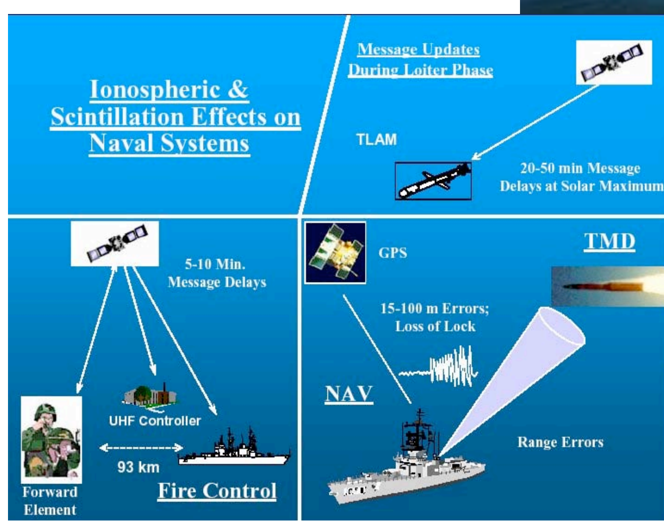
Learn more about the LWA project:

From Clark Lake to the Long Wavelength Array: Bill Erickson's Radio Science [ASP Conference Series, Vol. 345]

lwa.unm.edu

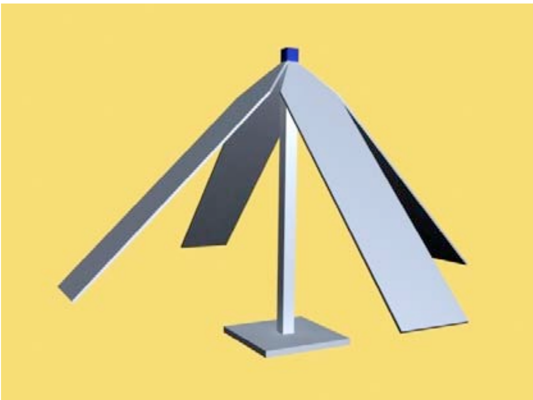
Space Weather Motivation for the LWA

- Ionospheric physics on fine spatial and temporal scales
  - Waves and turbulence
  - Coupling of ionosphere & neutral atmosphere
- Improvement of global data assimilation models
- Reliability of GPS & communications systems
- Space weather predictive capability for "events"
- The LWA is funded through the ONR
  - Ionospheric microstructure affects a wide variety of operations:
    - Communications
    - Navigation
    - Geolocation
    - Satellite operations



LWA: Far larger than the VLA

Primary Element Model



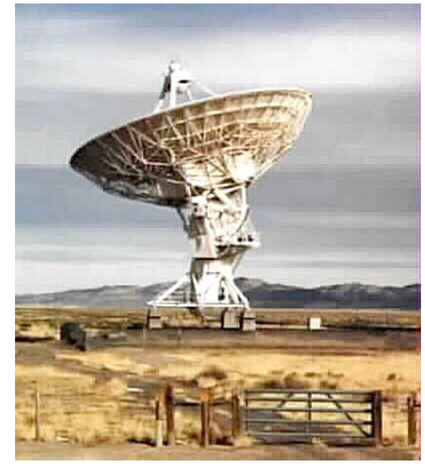
~3 m

~4 m

LWA Station (256 antennas)

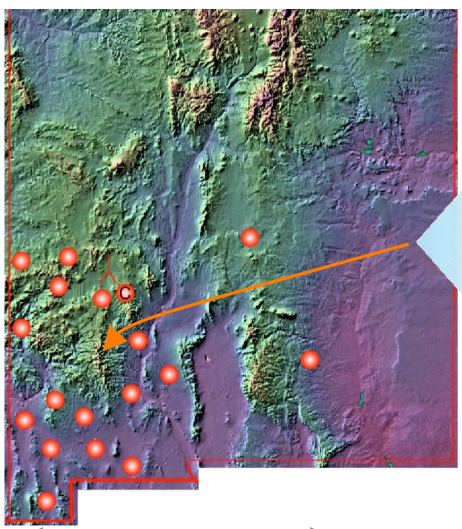
100 m

=



Each LWA station has a
Collecting Area of
>10 × Single VLA Dish
(at 74 MHz)

Full LWA (~50 stations)

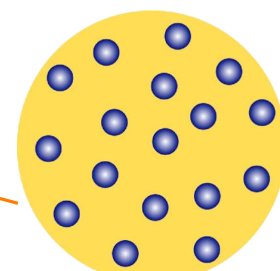


400 km

Central Array Overview

50 km

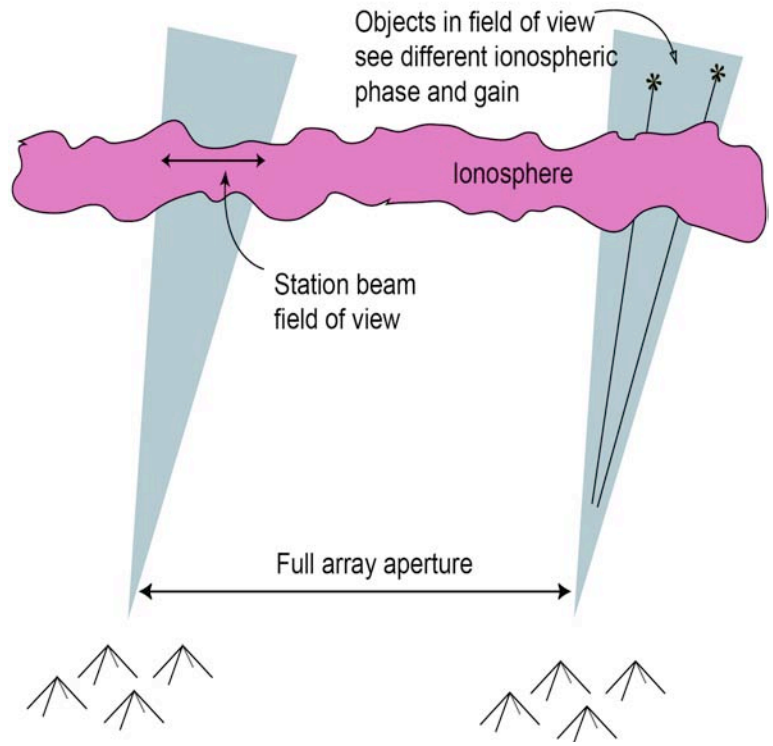
Core ~15 Stations



5 km

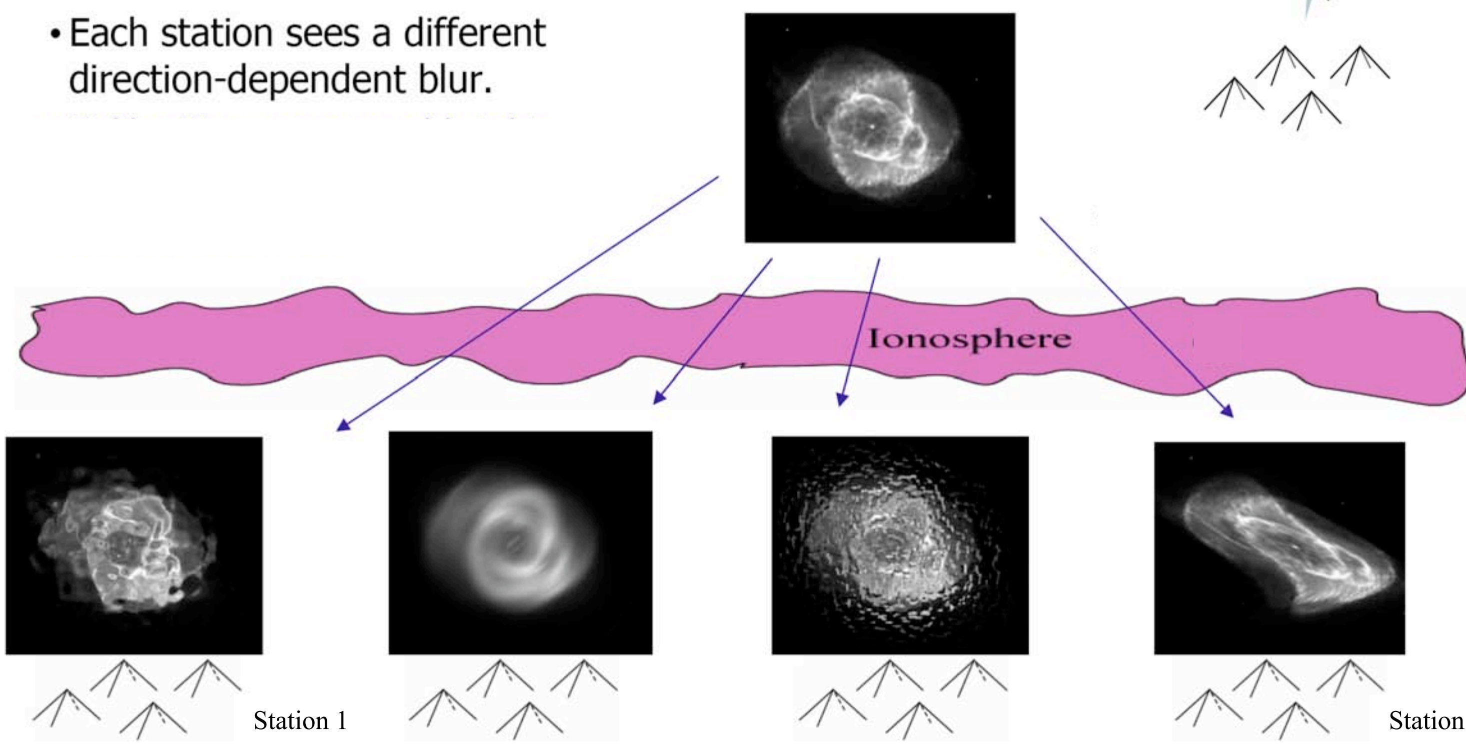
Ionosphere Opportunity using LWA

- Ionosphere severely limits resolution & sensitivity
  - Spatial and temporal variations in the ionosphere across each station beam distort the image
  - Large area means different stations view different ionosphere
- *The solution of these ionospheric problems presents an opportunity for ionospheric science*



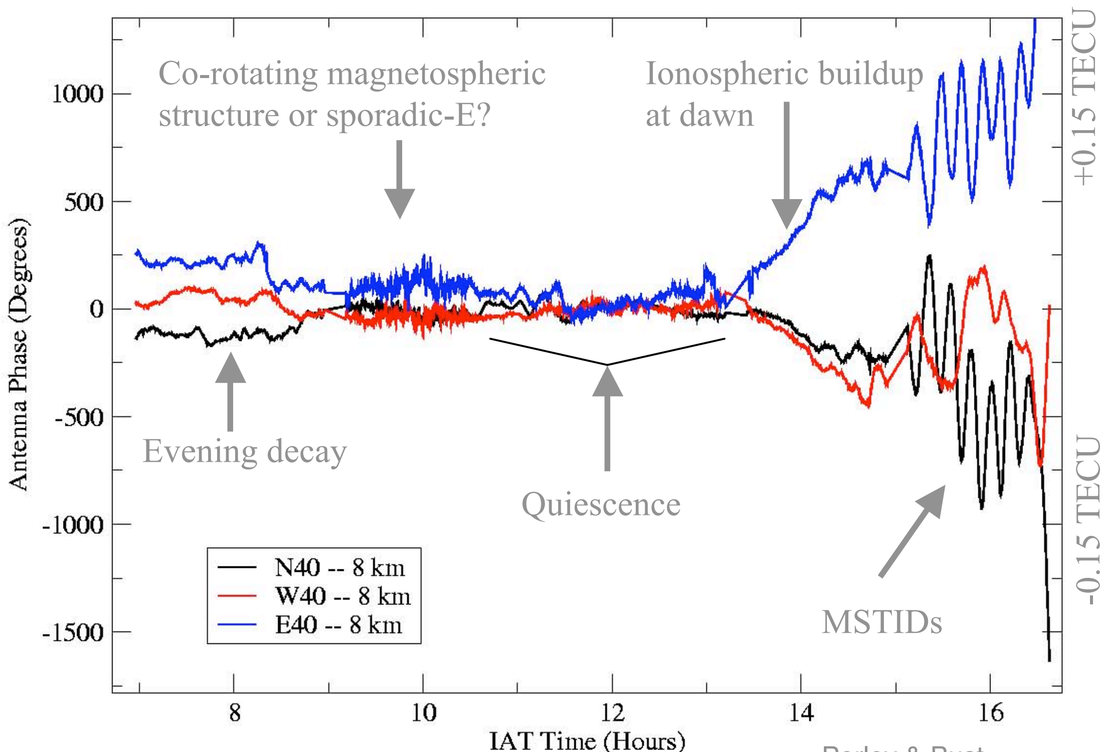
B Jeffs

- Each station sees a different direction-dependent blur.



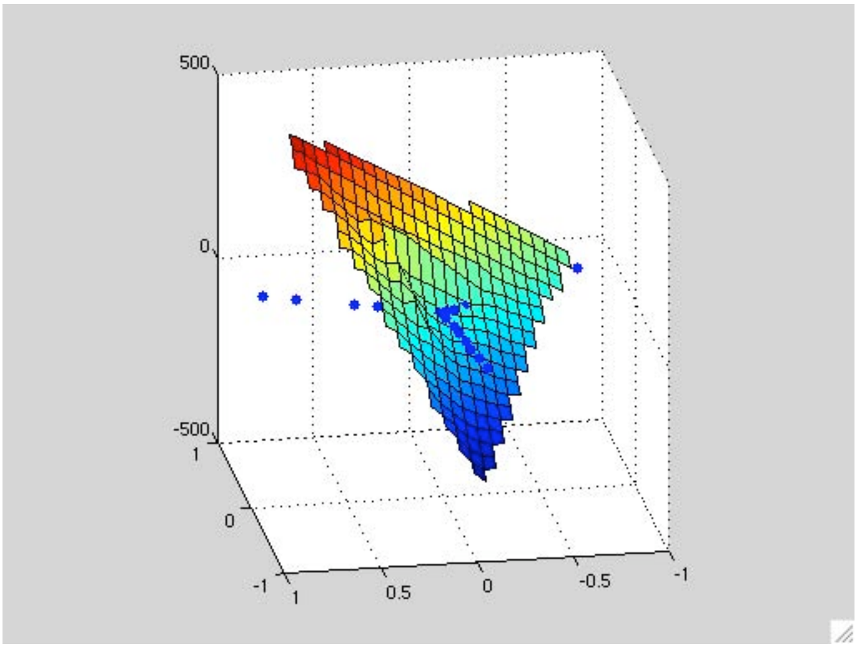
Ionospheric Phase Measurement

- Radio telescope arrays (e.g. the VLA) are extremely sensitive to ΔTEC
  - Current VLA has ΔTEC precision $\leq 10^{-3}$ TECU at 74 MHz
    [1 TECU $\equiv \int n_e dl \sim 10^{16}$ m^{-2}]
  - VLA probes ΔTEC variations to ~100 m, ~1 min, over 20° field of view



Perley & Bust

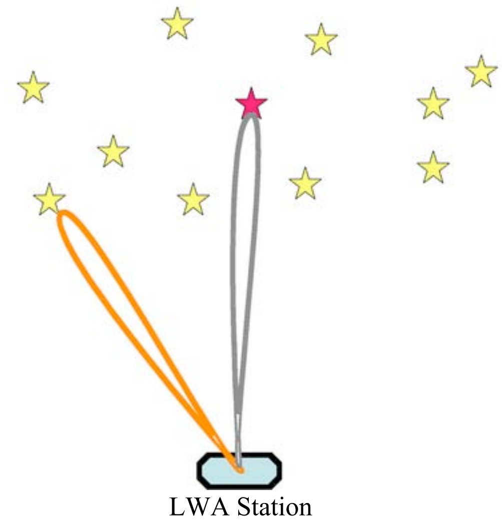
Δ phase over VLA



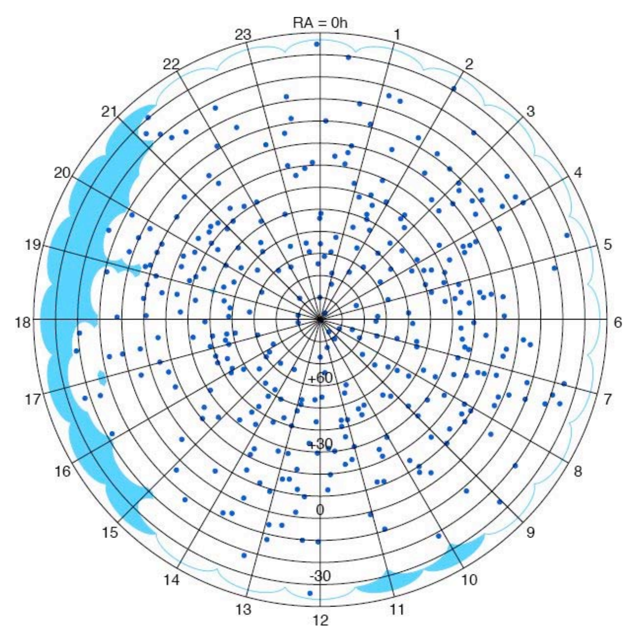
19 Jan 2001, Mike Montgomery

LWA Calibration Strategy

- Rapidly cycle 1 synthesized beam among known bright sources
  - Other beams can observe astro sources of interest
- ~ 100 calibrator sources visible @ any time
  - Sources isolated, so only one in ~3° beam
  - Source brightness dominates beam intensity
- Phase difference within 8MHz band can give absolute TEC
- Yields >5000 chords through ionosphere over ~75,000 km^2 area
  - Compare to GPS, ~10 chords/receiver -> 500 receivers
  - GEONET has 1200 receivers over Japan (same area)
- Required cycle period estimated to be 10s

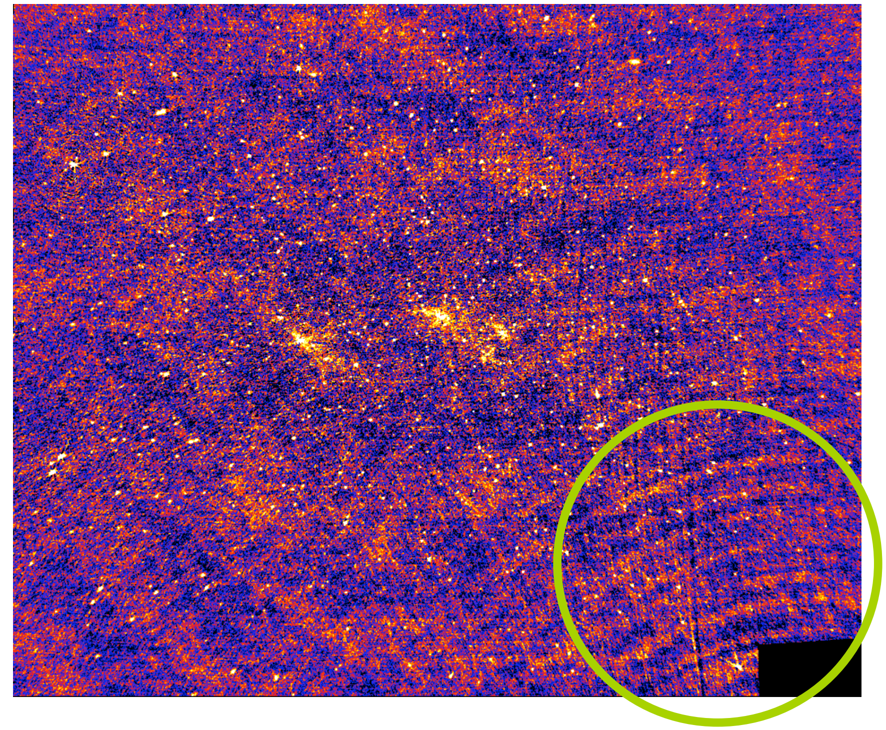


All 362 Calibrator Sources for LWA



Supplemental Ionospheric Correction

- High density GPS receiver network near each LWA station
  - Multiple pierce points for high resolution TEC measurements
  - Use other beacon satellites, too
- Passive "radar" from RFI sources
  - FM and TV stations
- Self-calibration methods (proposed by other radio telescopes LOFAR, MWA)
  - Peeling algorithm: successive calibration on brightest source
  - Direct least-squares: using all bright sources
- Ionospheric Modeling
  - GAIM & IDA3D incorporate data

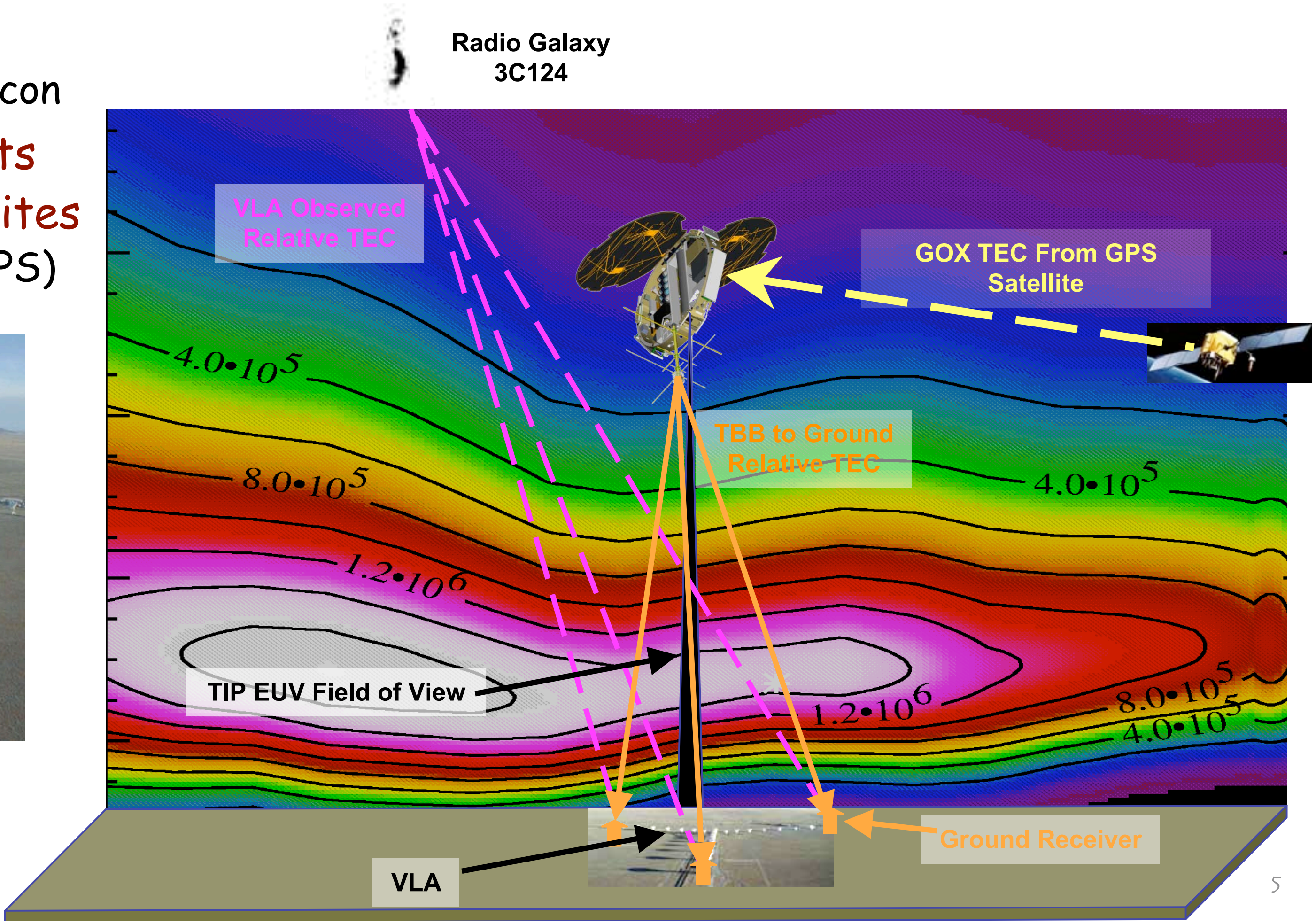


Stippling due to poor ionospheric correction

Ultimate goal:
$\Delta t \sim 10$ ms, 10 m resolution

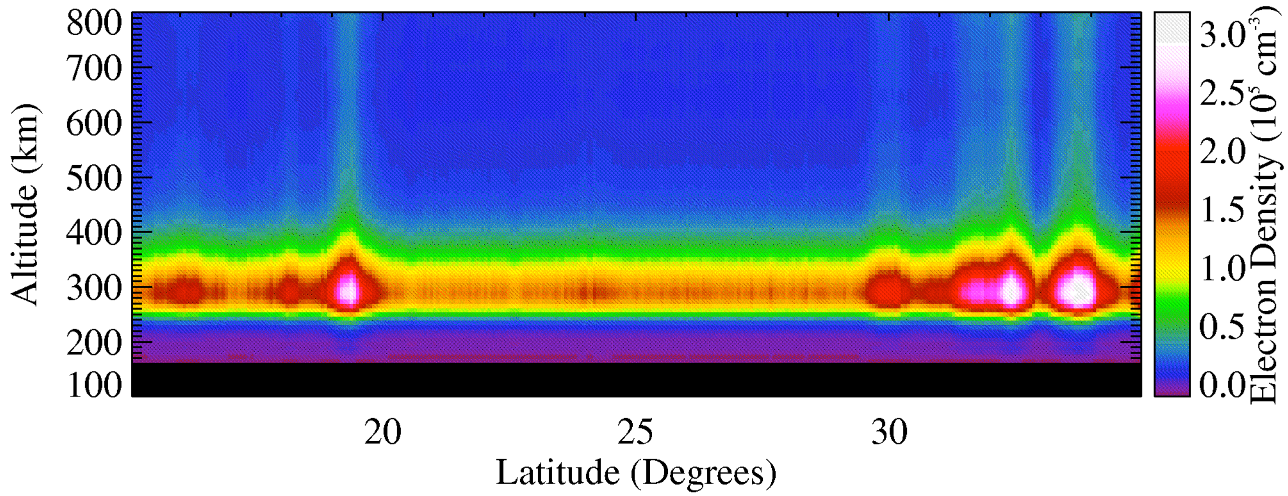
The CRICkET Project with the VLA

- CRICkET (Combined Radio Interferometry and COSMIC Experiment in Tomography):
  - Develop 3D ionosphere reconstruction tools with radio telescope & satellite beacons
  - Use Very Large Array (VLA) as surrogate for LWA
- VLA detects astro source at 74MHz
  - Extremely sensitive to changes in ionospheric electron content (ΔTEC)
- COSMIC can study the ionosphere using
  - GOX: GPS occultation
  - TIP: UV photometer
  - TBB: Tri-band radio beacon
- Tri-band receiver detects many radio beacon satellites
  - Sensitive to TEC (like GPS)



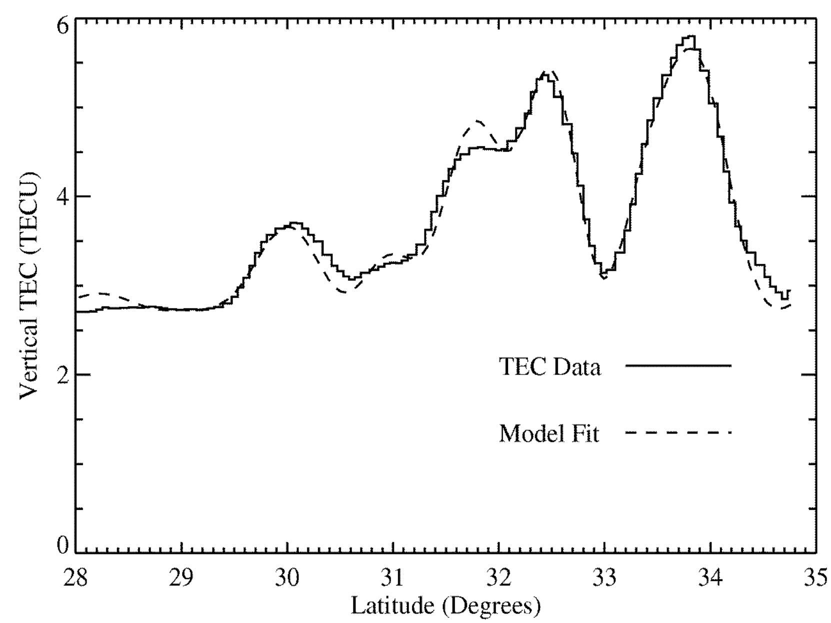
Initial Analysis of CRICkET

- Ionosphere density profile derived from TIP and GOX (cut @ 90°W)



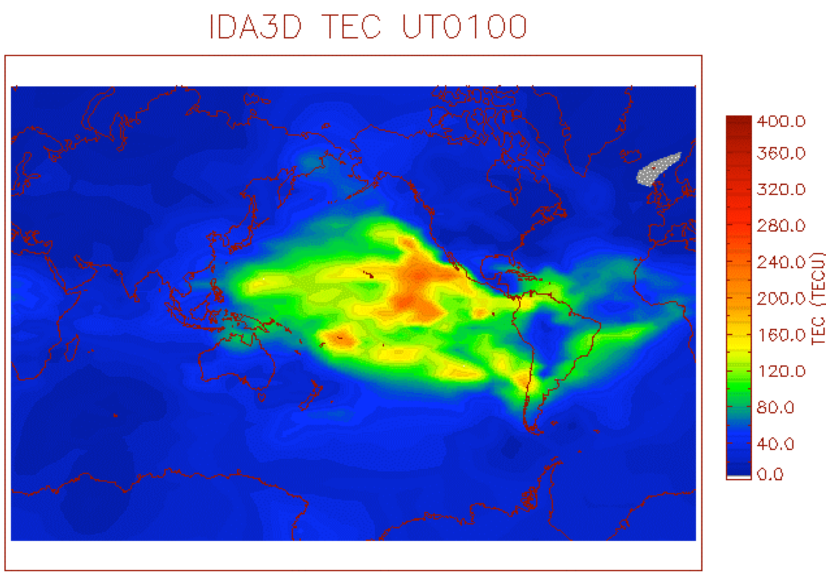
- VLA and the TIP data show evidence of the TID wavepacket
  - Rare type consisting of a pair of waves
  - Localized over Texas; traveling south-southwest

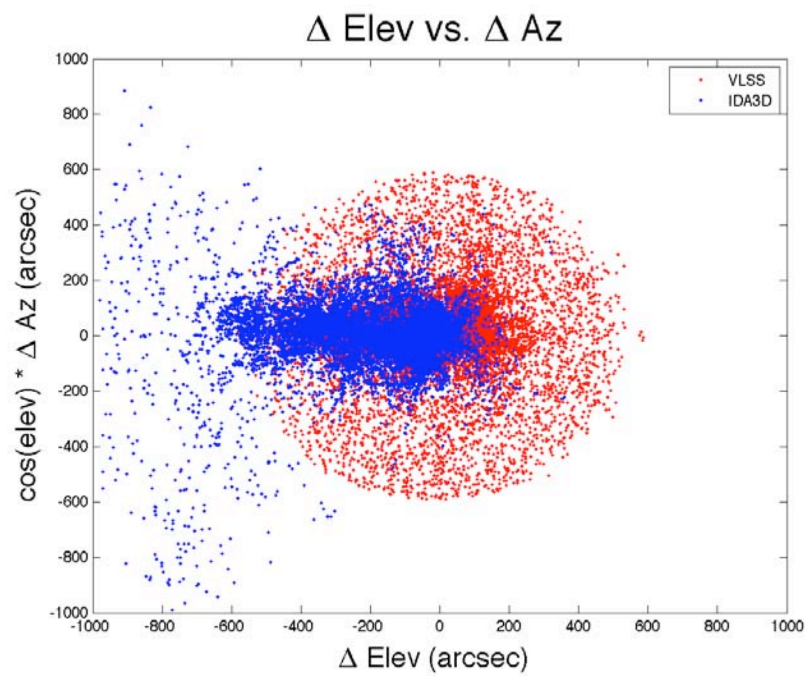
- Analysis Parameters:
  - Wave 1:
    - Amplitude: 1.6±0.02 TECU
    - Wavelength: 205.6±2.0 km
    - Peak Location: 378.3±6.6 km
    - FWHM: 382.2±11.6 km
  - Wave 2:
    - Amplitude: 3.4±0.1 TECU
    - Wavelength: 170.4±1.4 km
    - Peak Location: 172.6±1.4 km
    - FWHM: 280.0±5.2 km



Modeling Ionospheric Effects on VLA

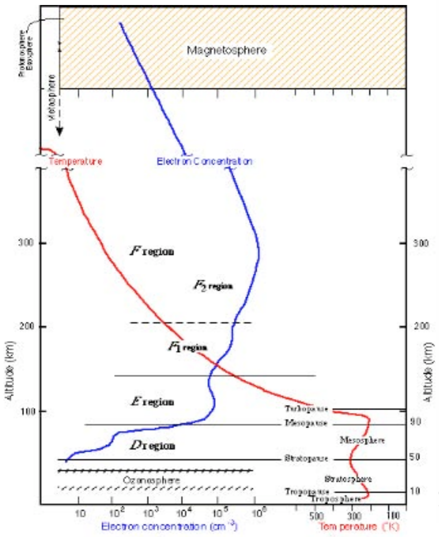
- TEC data used to predict position deviation seen by VLA
  - Work at ARL by Munton, *et al.*
- IDA3D used to reconstruct ionosphere
  - Assimilative model incorporates data from GPS, GPS occultation (GOX), over-satellite electron content (OSEC)
- Use ray tracing through ionosphere to obtain position of shift of astro sources
- Compare with known positions
  - Model does a reasonable job of predicting deviations. (<1/3° maximum deviation)
  - Daytime and low elevation sources show poorer predictability
  - *VLA data can potentially "correct" the model*

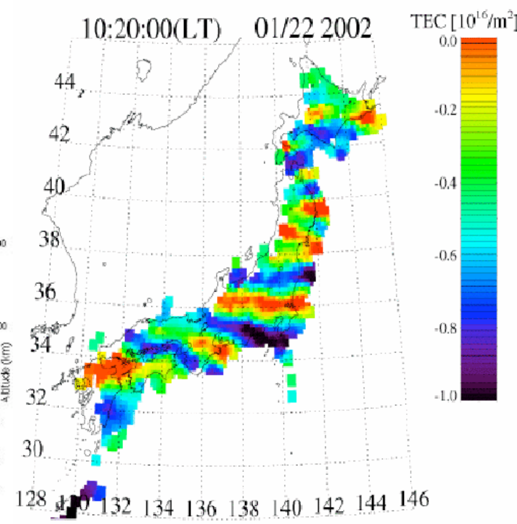


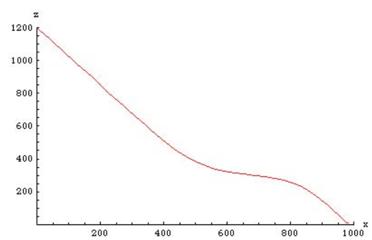


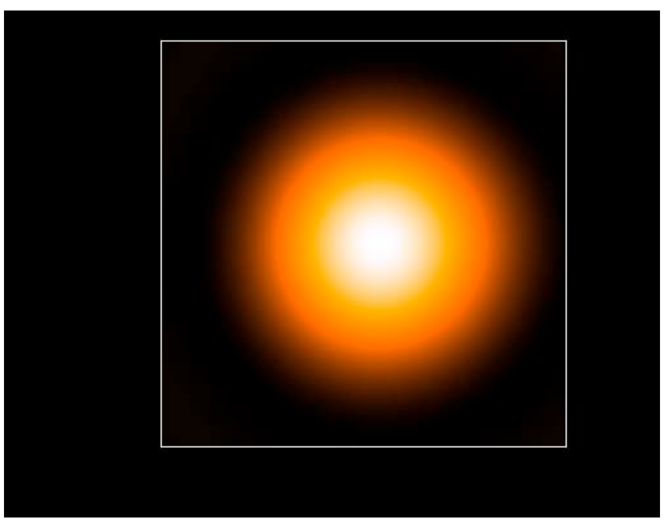
VLA measured (red) and IDA3D Predicted (blue) deviations

Modeling Ionosphere's Effect on LWA







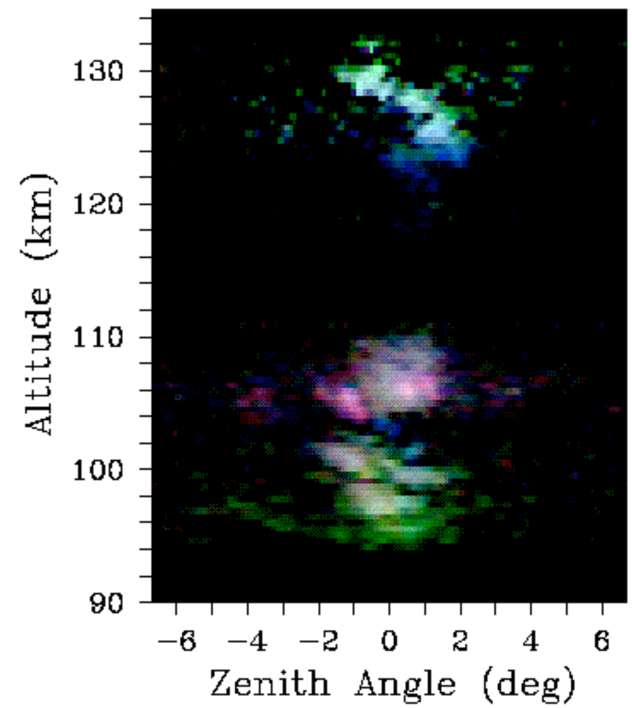


- Lower frequency -> More severe effects
- Use ray tracing code to understand ionosphere effect on beam pattern
  - Cold plasma model with magnetic field
  - Refractive and Faraday rotation effects
- Initial code check:
  simple laminar ionosphere
  - No effect on Station beam pattern
  - Note: ray @ 10MHz travels ~300 km horizontally
  - Nonuniformities & curvature will cause significant distortion
  - 2D "phase screen" won't work
- Add TID
  - Parameter mimic VLA measurements at 74 MHz
  - Significant beam deviation and distortion
  - ± 1° shift in beam direction (worst case)
  - Beam asymmetry depending on wave phase

LWA Ionospheric Research Contributions

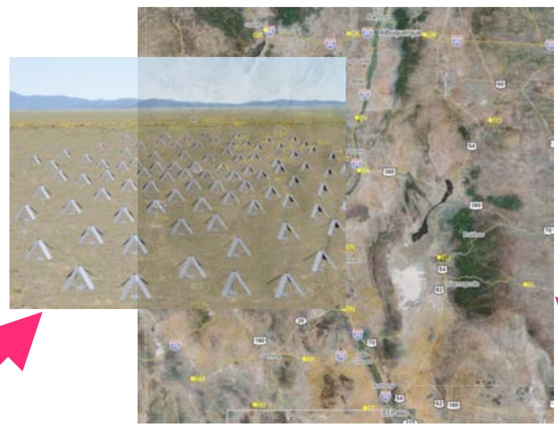
- LWA will provide unprecedented spatial & temporal ionospheric data
  - ΔTEC Measurements with extraordinary accuracy
    - Electron density 0.0003-0.003 TECU (Angular resolution/point accuracy)
    - Temporal resolution Δt ~ 1 msec
    - B along path ~ 1% (Faraday rotation (1°))
  - Spatial resolution comparable to highest density GPS networks
  - Continuous monitoring (not limited to night)
- Science contributions
  - Fine scale structure
  - Coupling of neutral atmosphere & ionosphere
  - Wave formation & attenuation
  - Evening collapse of F-region & onset of depletions & enhancements (bubbles)
  - Ionospheric response during solar & geomagnetic storms

Jicamarca high resolution image



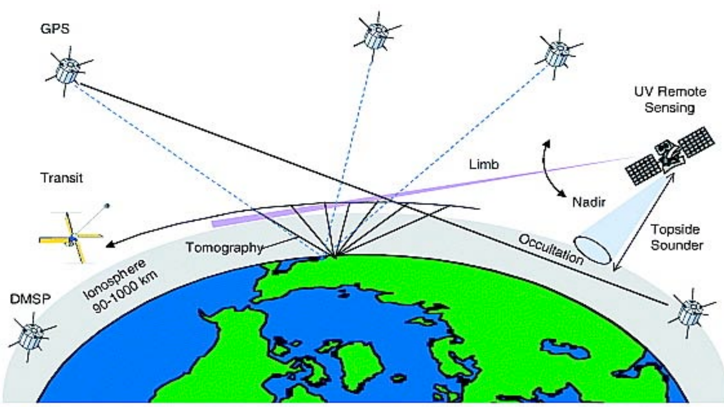
Summary

- Astronomy's obstacle is ionospheric science's opportunity
- Success will require multifaceted approach
  - LWA self-calibration using astrophysical emitters
  - GPS and related instrumentation
  - LWA use of coherent and incoherent sources (FM, scatter radar)
  - Modeling
- Astronomers and ionospheric physicists must work closely together from the start

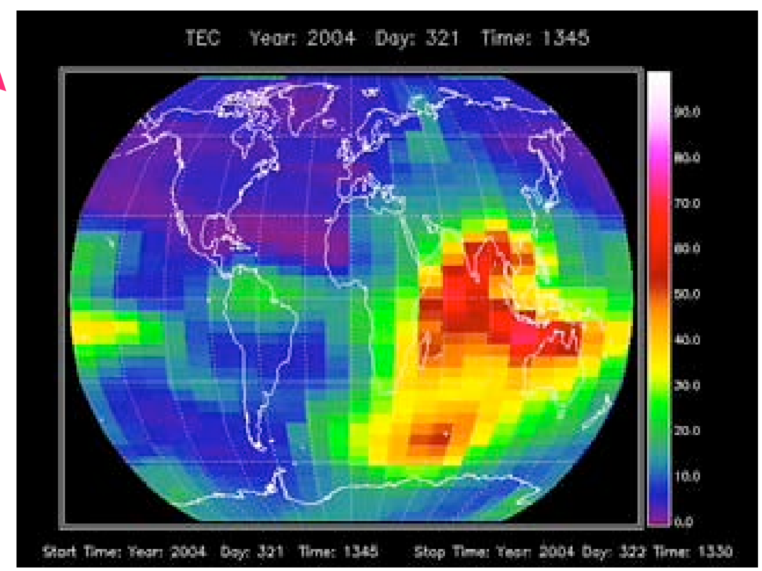


Long Wavelength Array

More input from ionospheric community needed!



Multiple sensor input to modeling



GAIM dynamic TEC model