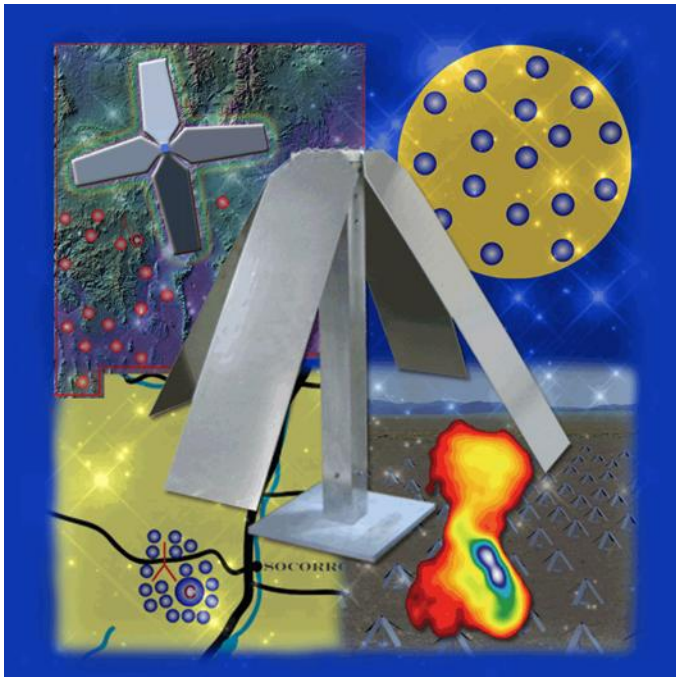
CEDAR-2012

Mesoscale Ionospheric Sensing Using Modern Radio Interferometers



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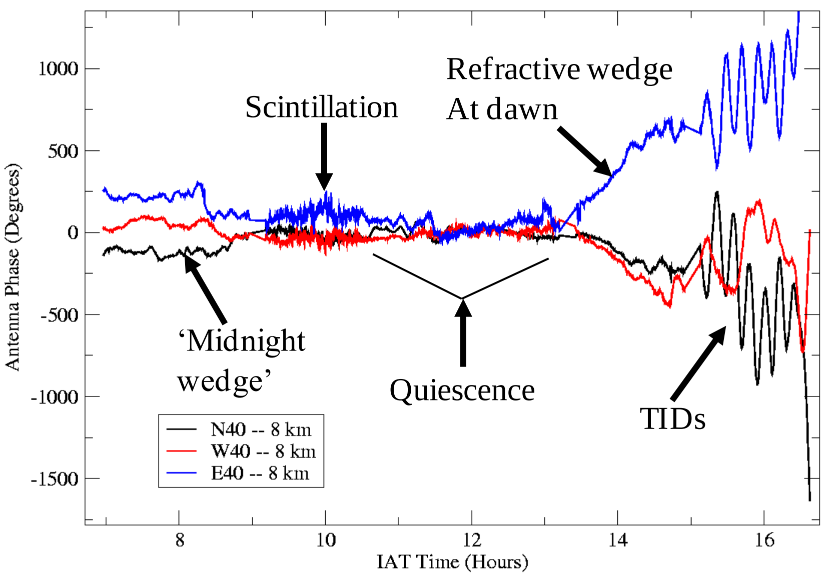
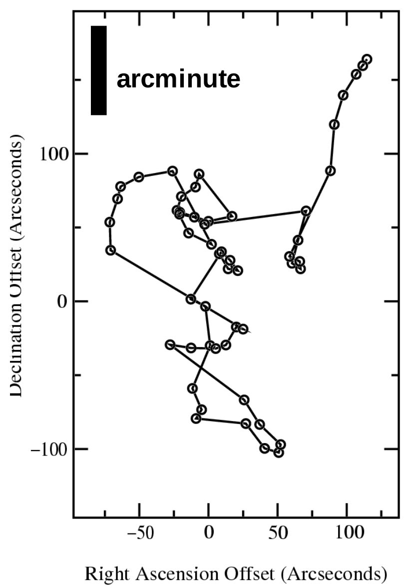
Overview

- Several next-generation astronomical radio interferometers are either operating or under construction
  - *Two northern hemisphere (EVLA/LWA, New Mexico, USA; LOFAR, Northern Europe primarily Netherlands)*
  - *Two proposed in the southern hemisphere (SKA, South Africa or Australia; MWA Australia)*
  - *Two equatorial (GMRT, India; ALMA, Chile)*
- Ionospheric effects including refraction, diffraction, scintillation, and Faraday rotation can affect astrophysical measurement quality
  - *Better ionospheric correction methods are needed to improve astrophysical imaging*
  - *However, the astrophysical observations can be exploited to better understand mesoscale ionospheric effects*
- Modern radio interferometers present new opportunities for ionospheric science

Ionospheric Effects on LF Astronomical Imaging

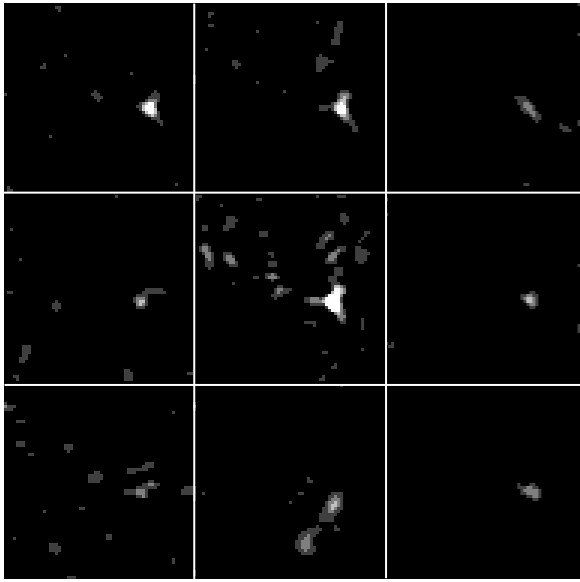
- Ionospheric effects are very important
  - *Correction is required to meet imaging goals*
  - *Ionospheric specification/measurement is a byproduct of ionospheric correction/calibration*





1 minute sampling intervals

9 sources showing refractive wander

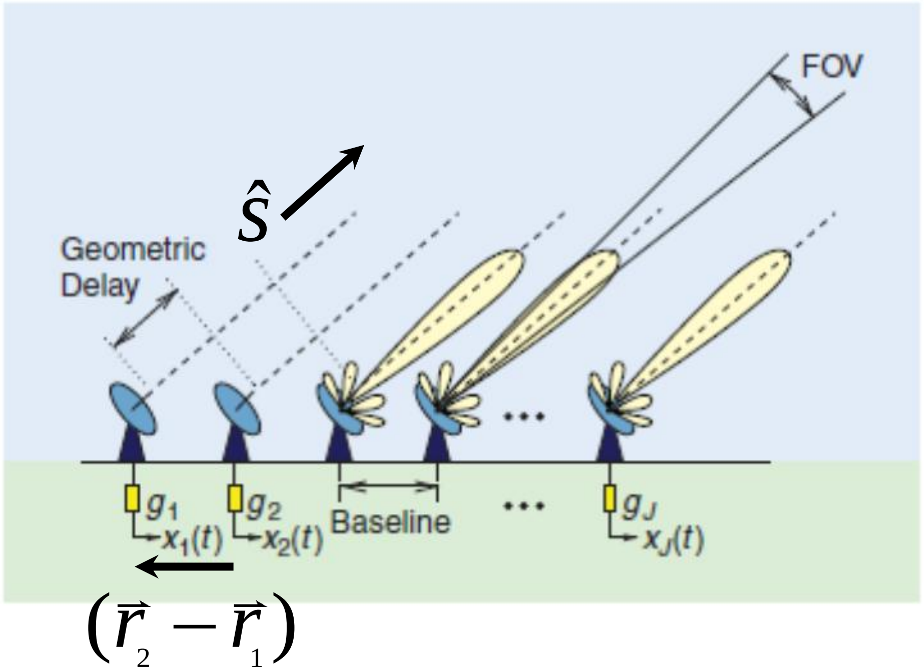


How Do Interferometers Work?

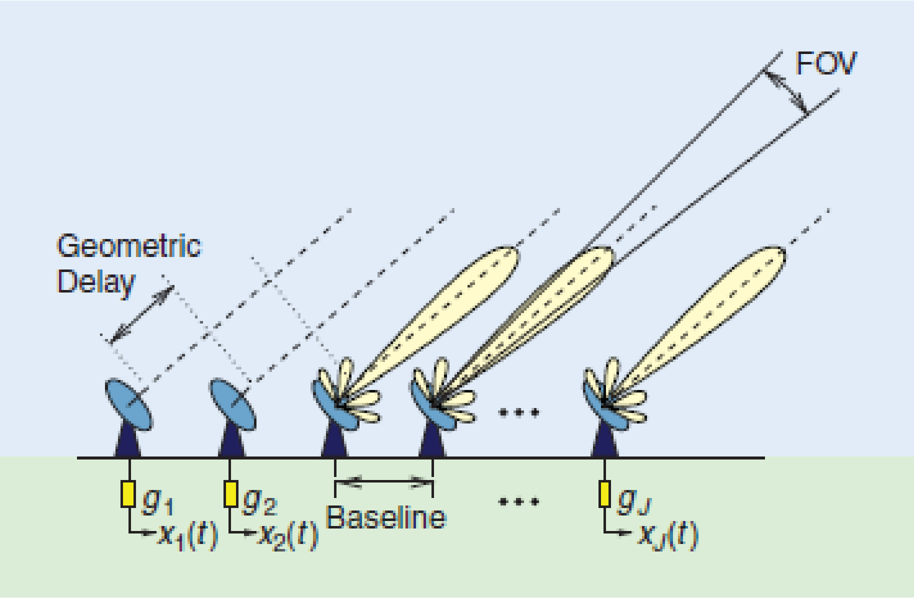
- Interferometers measure the quasi-monochromatic fringe visibility *V*
- *V* is the interferogram of sources visible within the beam of the interferometer
- The Visibilities and the Brightness (*B*) are a Fourier transform pair
- The Brightness is seen to be only a function of the baseline distance between the antennas
- The slow rotation of the Earth causes the dot product to vary with time effectively scaling the baseline distance
- This improves the coverage in the spatial frequency domain and improves the retrieved image quality

$$V_\nu\left(\vec{r}_1,\vec{r}_2\right) = \int B_\nu(\hat{s})\exp\left(-2\pi i\hat{s}\cdot(\vec{r}_2-\vec{r}_1)/\lambda\right)\, d\Omega$$

$$B_\nu(\hat{s}) = \int V_\nu\left(\vec{r}_1,\vec{r}_2\right)\exp\left(2\pi i\hat{s}\cdot(\vec{r}_2-\vec{r}_1)/\lambda\right)\, d\Omega'$$



Measurement Imperfections (1 of 2)



- But the interferometers are imperfect and instrumental and other artifacts creep into the measurements
  - *Geometric and antenna delays*
  - *Point spread function of antennas*
  - *Assumption that celestial sphere does not affect transmission of radio waves – ionospheric distortions violate this assumption*

Measurement Imperfections (2 of 2)

- These imperfections affect the measurement equation

$$V_\nu^M(\vec{r}_1,\vec{r}_2) = \int B_\nu(\hat{s}) g_1 g_2^* \exp\left(-2\pi i \hat{s}\cdot(\vec{r}_2-\vec{r}_1)/\lambda\right) d\Omega$$

- The antenna gain terms (g_1) are given by:

$$g_1 = P_\nu(\hat{s}) \exp(i(\phi_{Amb} + \phi_{Iono} + \phi_{Geom} + \phi_{Ant}))$$

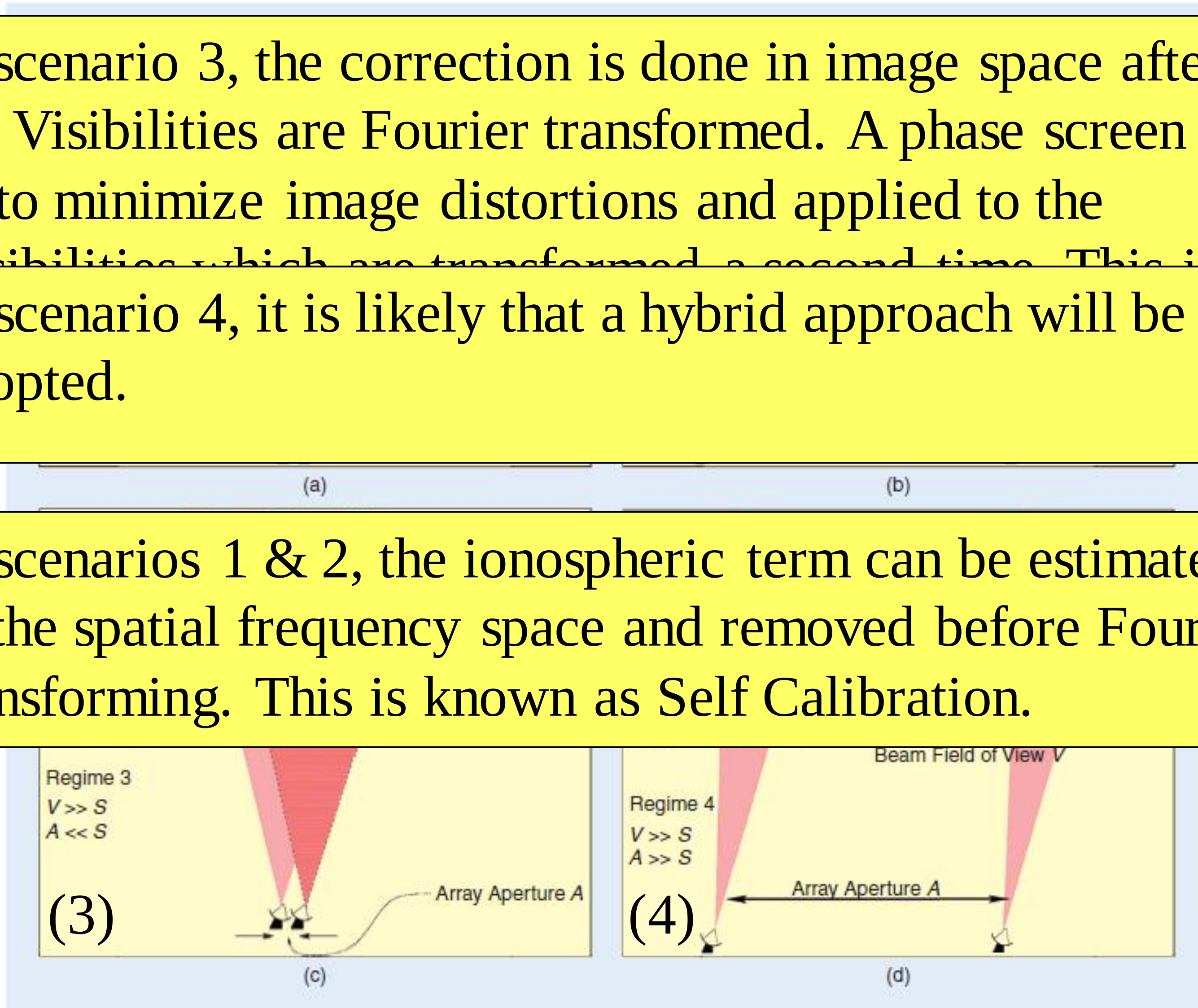
  - *P_s is the antenna point spread function*
  - *ϕ_{Amb} = 2π ambiguities*
  - *ϕ_{Iono} = ionospherically induced phase delay*
  - *ϕ_{Geom} = geometrically induced phase term (Earth's rotation)*
  - *ϕ_{Ant} = phase delay induced by antenna electronics*
- The ionospheric terms are what we are interested in
- The Visibilities are affected by the phase differences:
  - *$\Delta\phi = (-8.48 / \nu_{GHz})\, \Delta T_{TECU} \sim 0.0015$ TECU deg^{-1} (at 74 MHz)*

Ionospheric Distortion Scenarios

In scenario 3, the correction is done in image space after the Visibilities are Fourier transformed. A phase screen is fit to minimize image distortions and applied to the Visibilities which are transformed a second time. This is

In scenario 4, it is likely that a hybrid approach will be adopted.

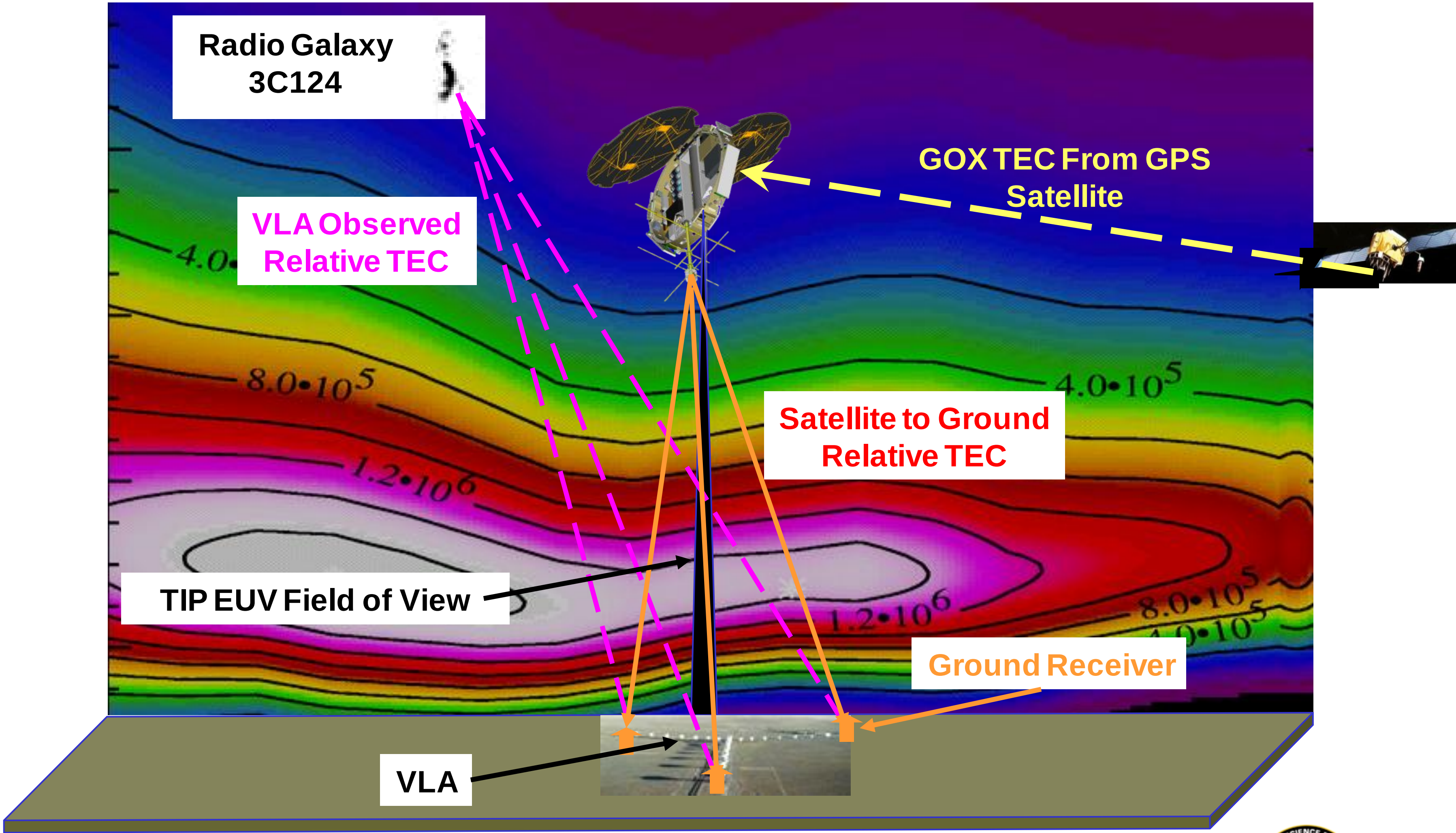
In scenarios 1 & 2, the ionospheric term can be estimated in the spatial frequency space and removed before Fourier transforming. This is known as Self Calibration.



Where Do We Go From Here?

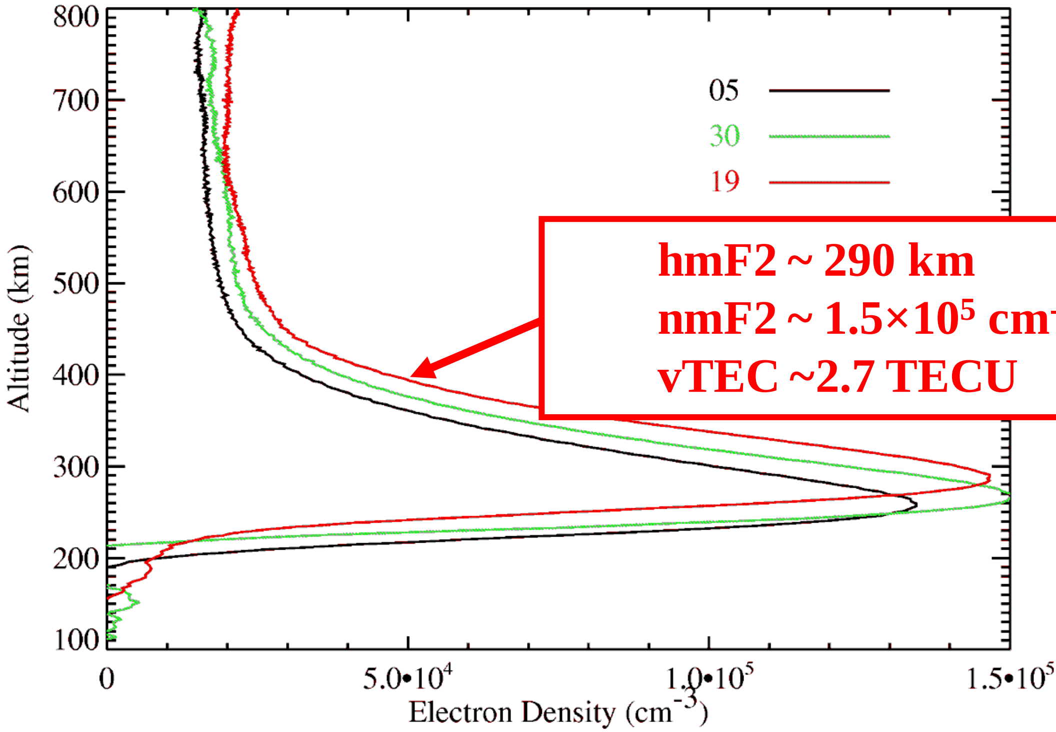
- Self Calibration: works for narrow fields of view and bright sources
- Field Calibration: works well for wider fields of view and for cases when the ionospheric coverage exceeds the array size
- Hybrid Calibration: a combination of self calibration and field calibration
  - *Peeling: Self calibrate on bright sources and then apply field calibration to remove the remaining distortion*
- Can we use ionospheric knowledge to produce a better approach?
  - *Data assimilation: Assimilate heterogeneous ionospheric measurements to create global/regional ionospheric specification*
  - *Phenomenological approach: identify ionospheric phenomena present in data and tailor correction*
- What phenomena are observable?

CRICKET Concept

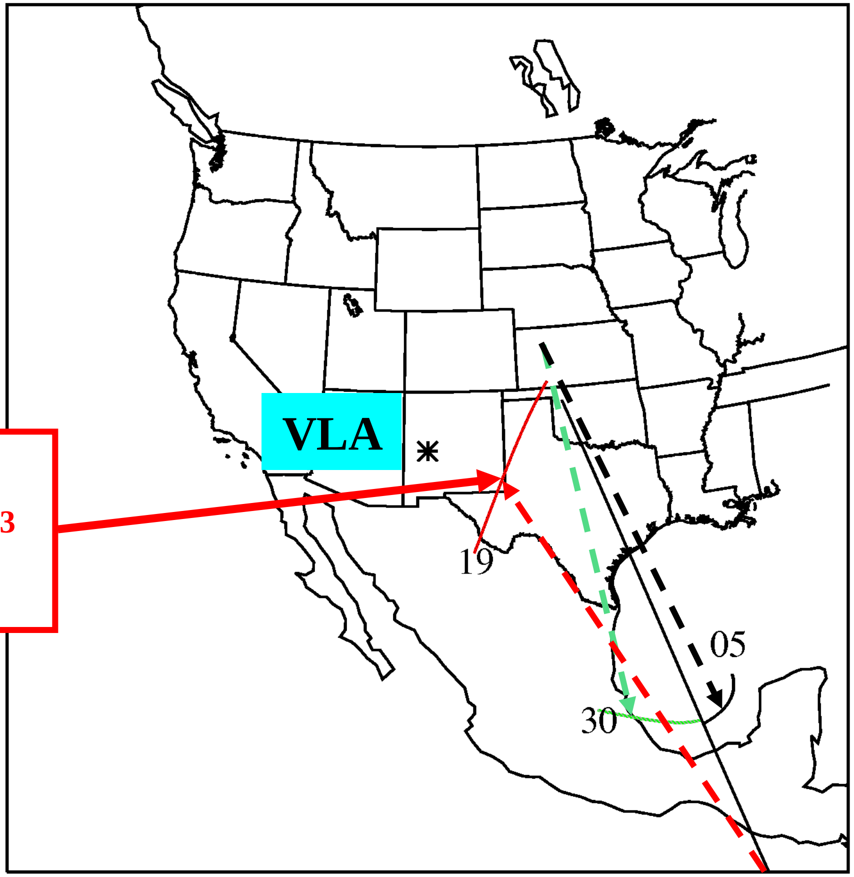


COSMIC-GOX: Electron Density Profiles

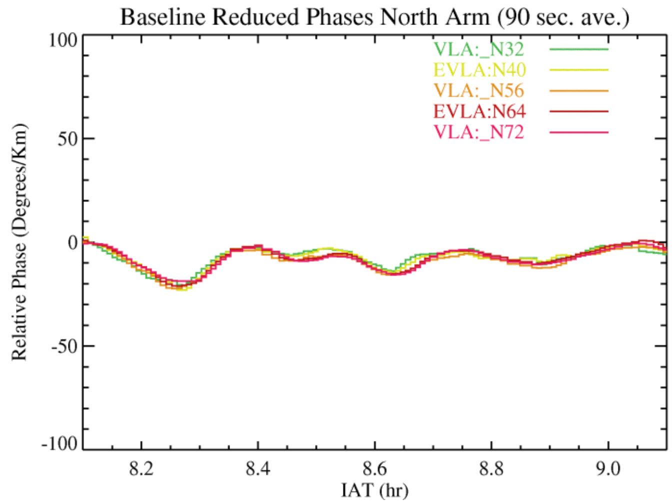
- Electron density profiles from three widely separated occultations indicated low gradients in the background ionosphere

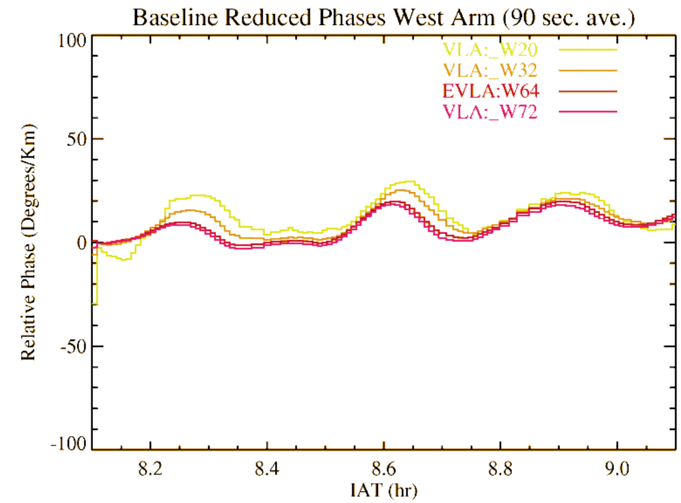


hmF2 ~ 290 km
nmF2 ~ 1.5×10^5 cm^{-3}
vTEC ~2.7 TECU

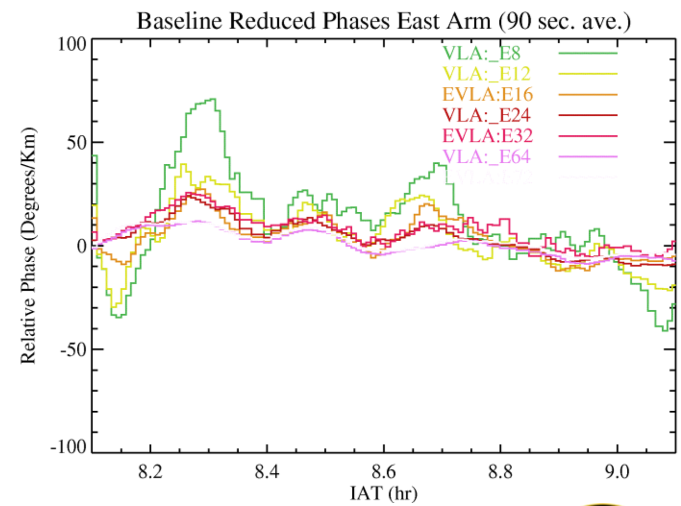


VLA Measurements





- The phases divided by the baseline length are shown
- West & North
  - *Phase/TEC gradients approximately proportional to the baseline length implying structures larger than the array dimensions*
  - *Phase structures along each arm are very similar*
  - *Phase progression indicating roughly North-to-South motion*
- East arm baseline scaling not as clear
- Taken together this indicates a large-scale wave traveling approximately perpendicular to the East arm (moving South-Southwest)



CRICKET Derived TID Parameters

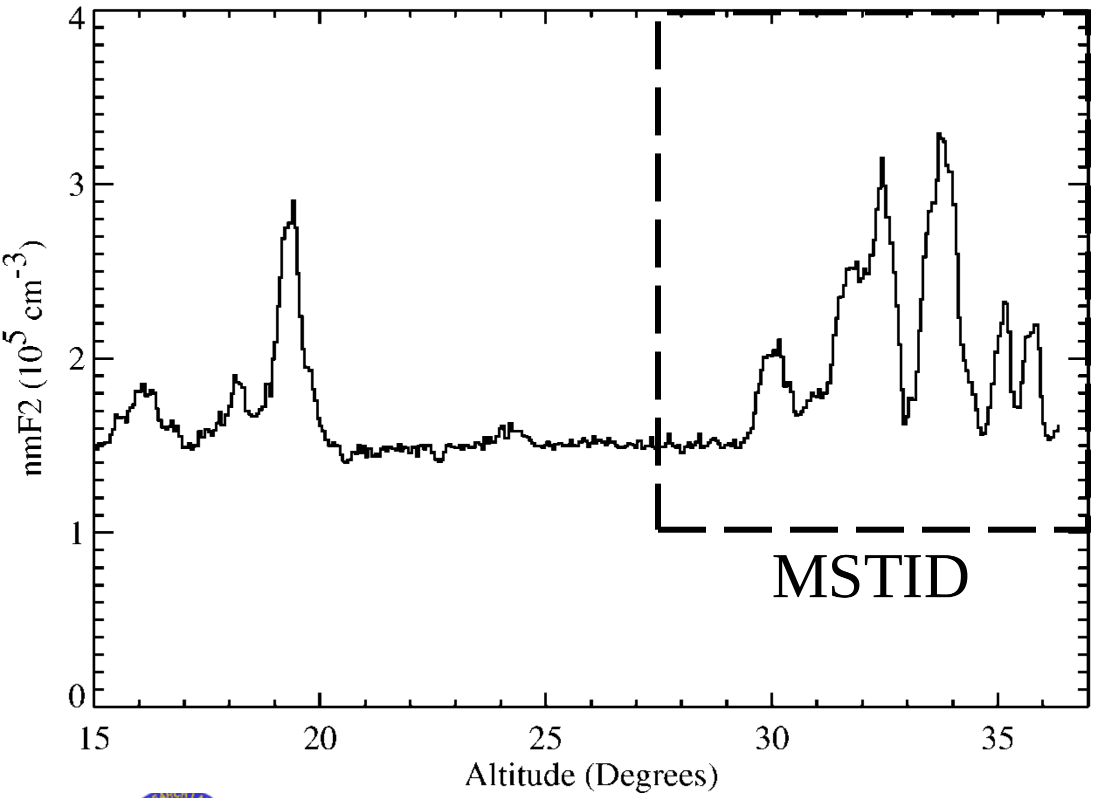
Period (min.)	Amplitude (TECU)	λ (km)	Azimuth (degrees)	Speed (m/s)	Projected λ(km)
95.33	0.010	91.2	186	16	100.7

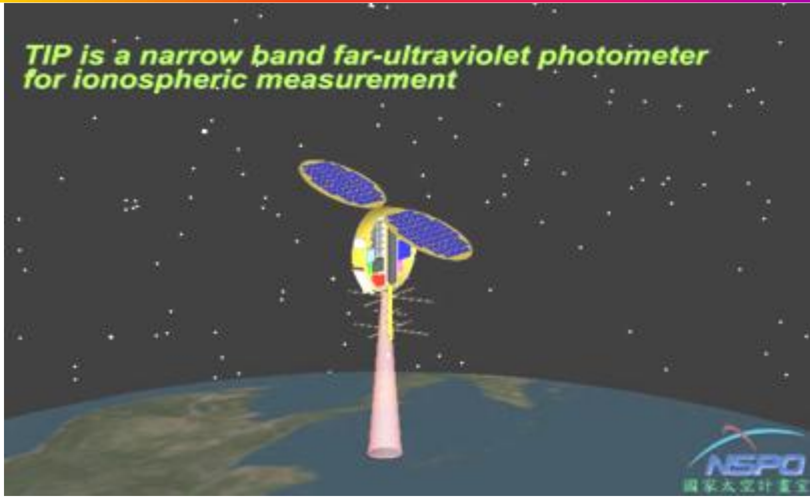
- Results are fairly typical for characteristics of MSTIDs seen over SW US
  - *Speeds typically ~100-200 m/s*
  - *Wavelengths typically 100-200 km*
  - *Periods 10-100 min.*
  - *Direction of propagation typically southwesterly – but not always*

Period (min.)	Amplitude (TECU)	λ (km)	Azimuth (degrees)	Speed (m/s)	Projected λ(km)	
13.62	0.065	78.7	223	96	165.3	TIP
11.92	0.141	178.6	121	250	233.4	TIP
10.59	0.137	196.1	159	309	196.2	TIP

TIP Measurements

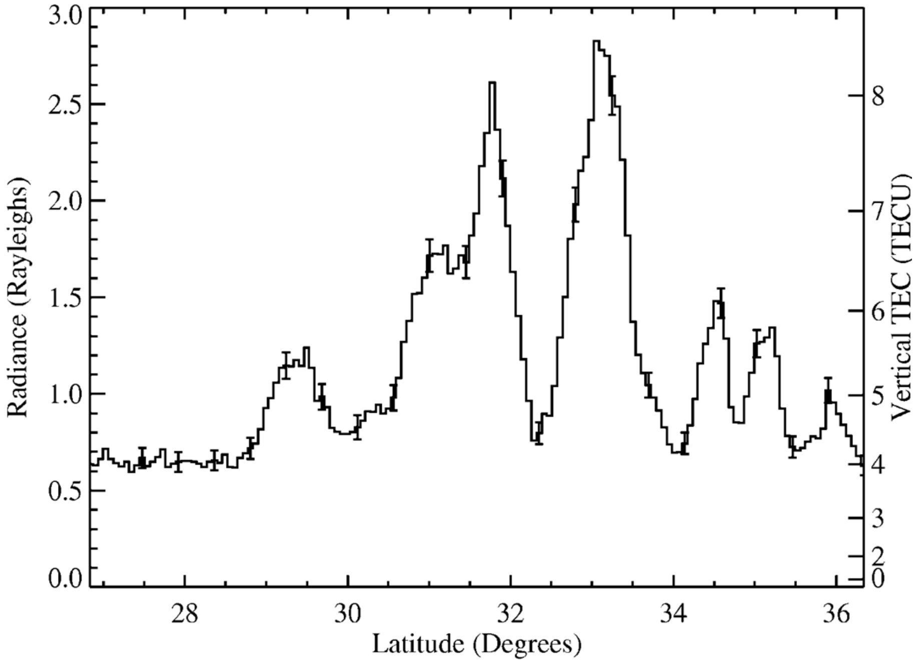
- TIP measures the UV radiance at 135.6 nm
  - *$O^+ + e \rightarrow O + h\nu$ (135.6 nm)*



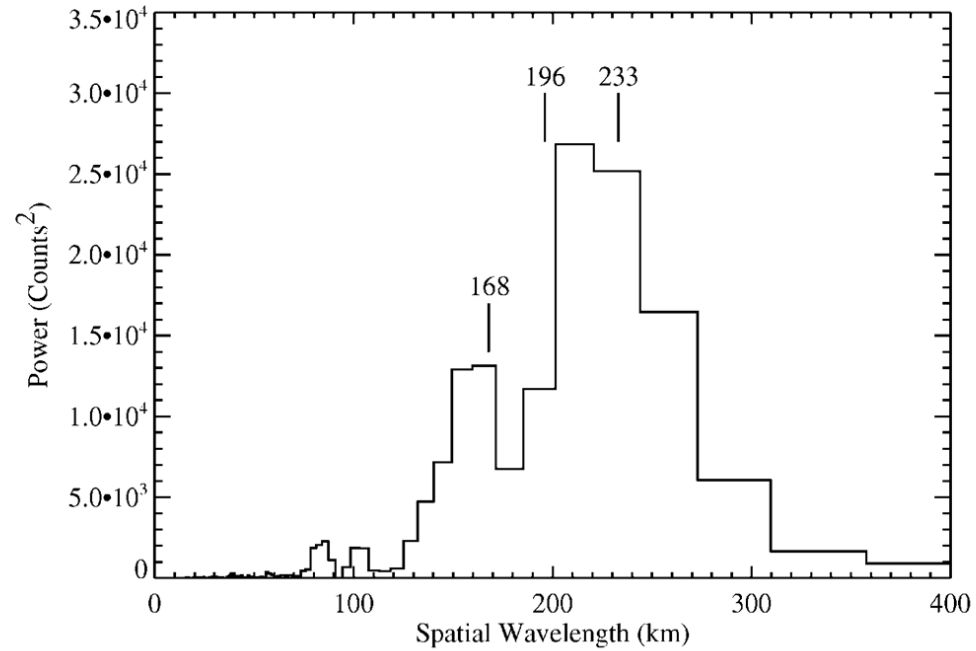


TIP Measurements

TIP Radiance & TEC



Fourier Transform of TIP Data

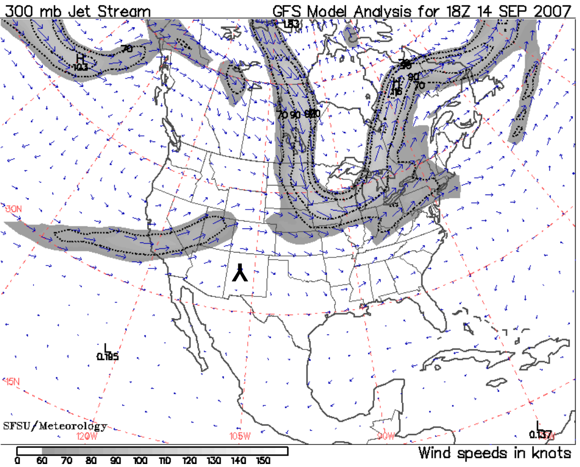


Three wavelengths seen in TIP data consistent with VLA measurements.

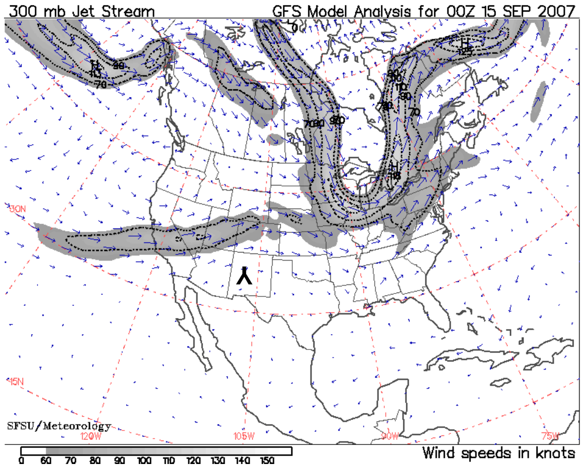
Where did it/they come from?

- Some MSTIDs are thought to originate from turbulence near jet streams
- The jet stream over the central US was changing dramatically on Sept 15, 2007
- This is a possible explanation for their origin

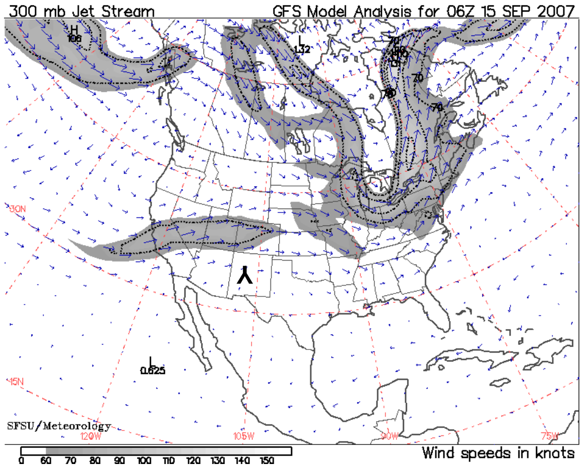
14 Sept, 18 UT



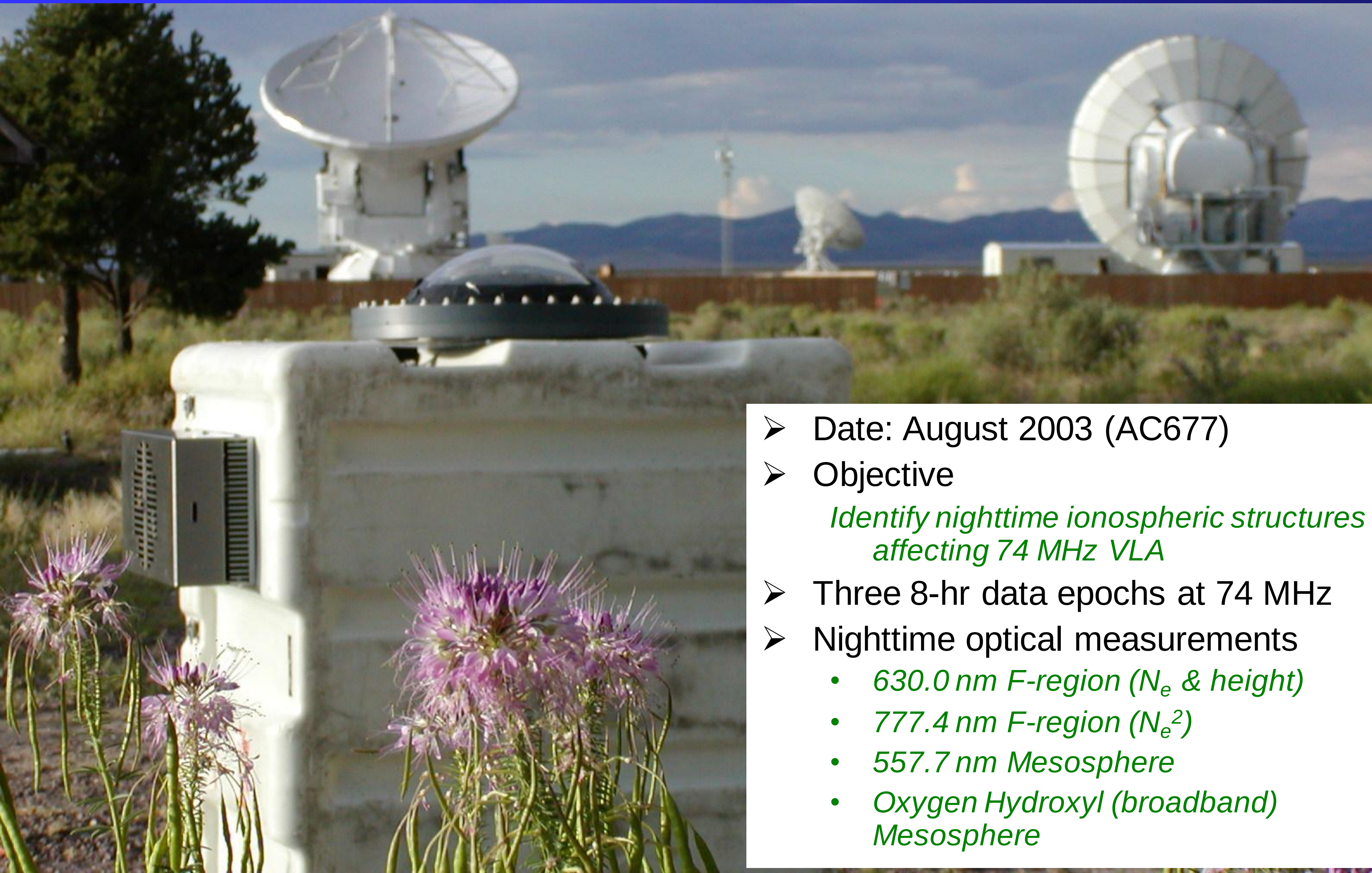
15 Sept, 0 UT



15 Sept, 6 UT



Simultaneous Radio and Optical Observations (Campaign 1)

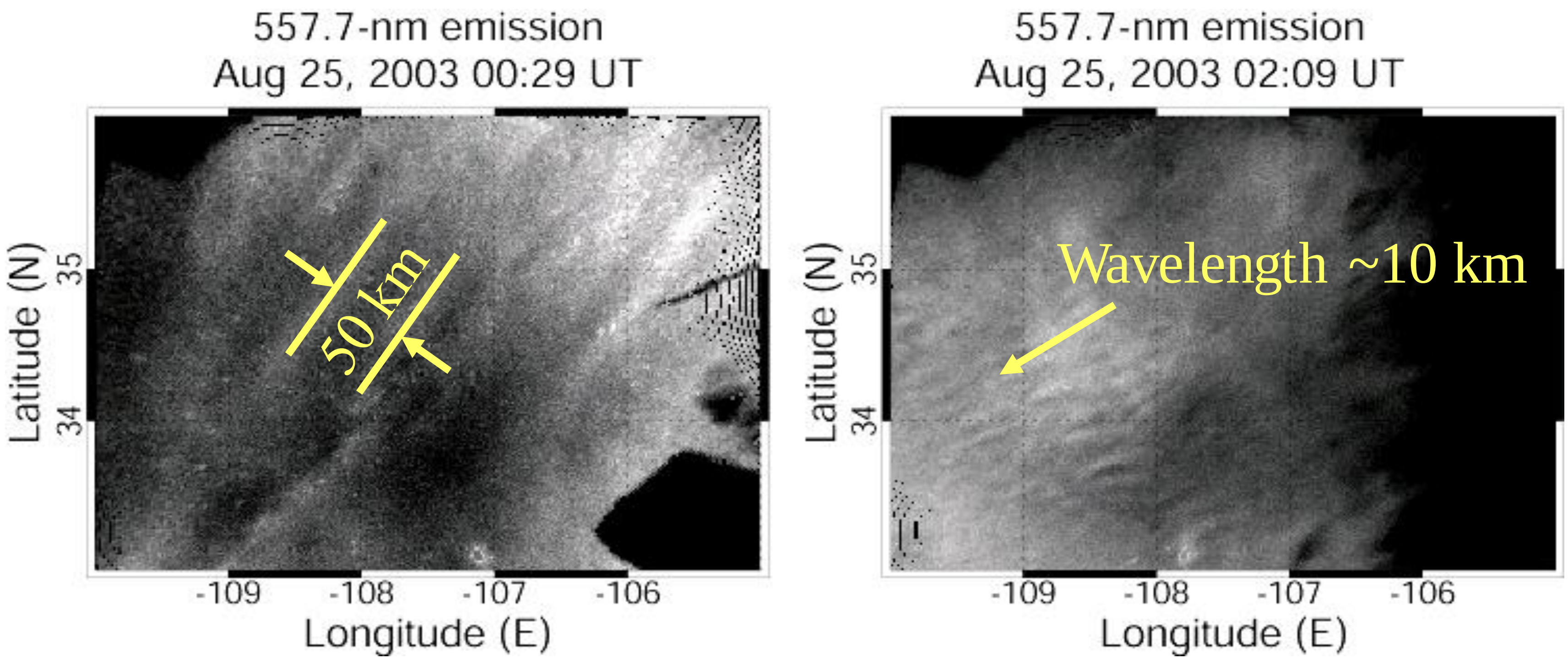


- Date: August 2003 (AC677)
- Objective
  - *Identify nighttime ionospheric structures affecting 74 MHz VLA*
- Three 8-hr data epochs at 74 MHz
- Nighttime optical measurements
  - *630.0 nm F-region (N_e & height)*
  - *777.4 nm F-region (N_e^2)*
  - *557.7 nm Mesosphere*
  - *Oxygen Hydroxyl (broadband) Mesosphere*

Mesospheric Waves

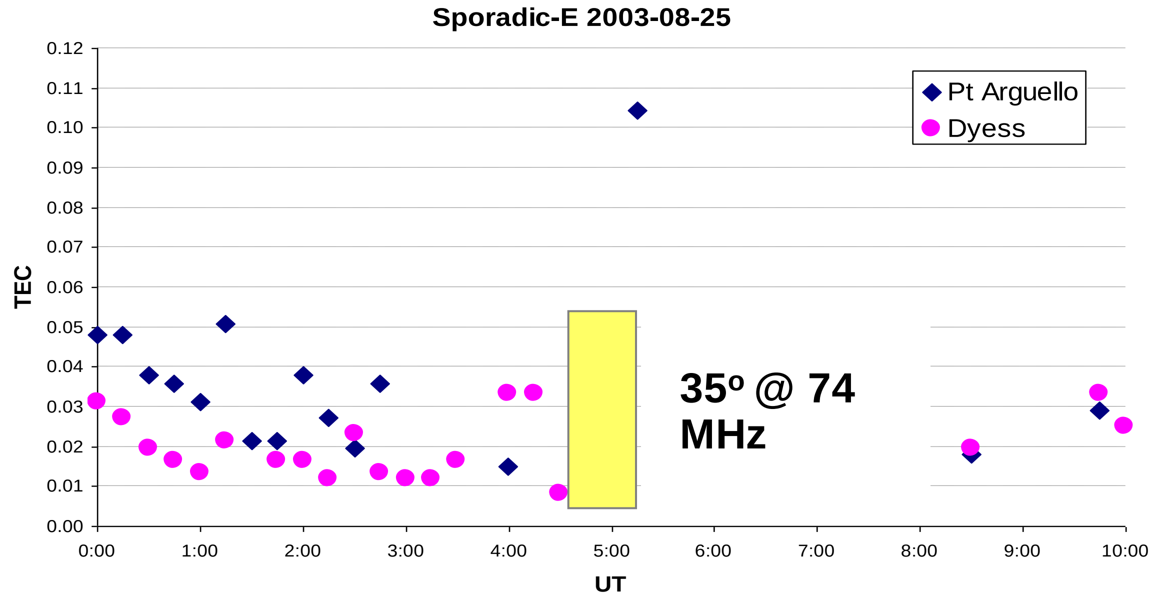
- Complex mesospheric waves observed by optical camera
- Mesosphere – neutral atmosphere, 50–85 km altitude
- Turbulence driven by atmospheric gravity waves

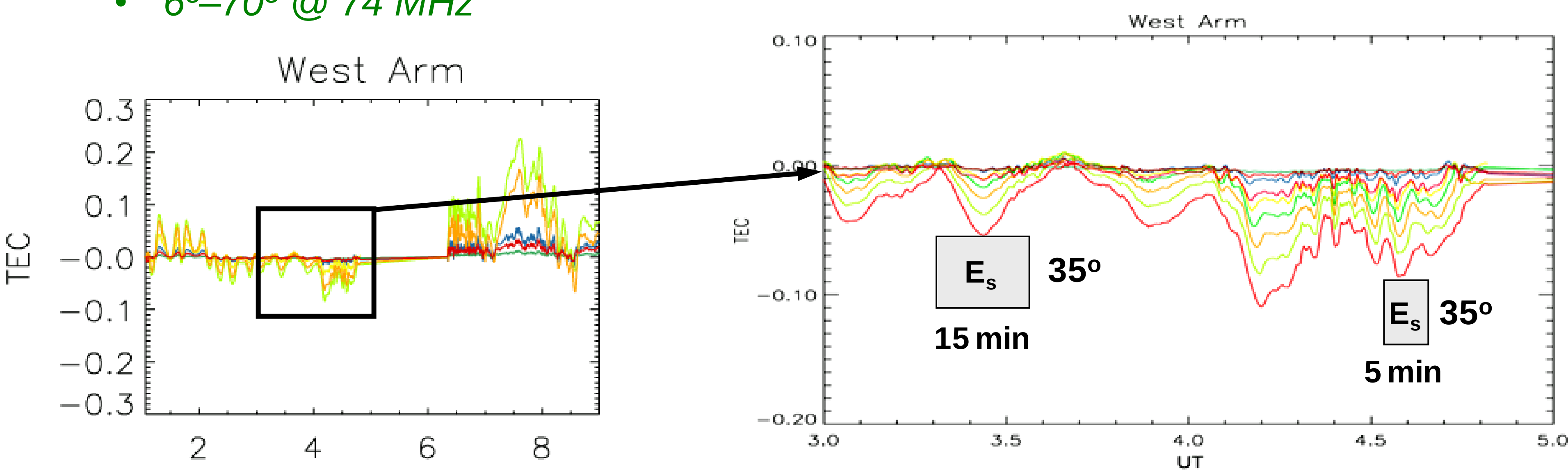
Turbulence suggests the possible existence of Sporadic-E plasma clouds near 100 km altitude



Sporadic-E Observations

- Top panel: Off-site Ionosonde observations of sporadic-E
- Estimated VLA Es scale sizes match fluctuations in August 2003 VLA data
    - *50 km horizontal scale*
    - *50–150 m/s speed*
    - *5–15 min fluctuations*
    - *6º–70º @ 74 MHz*



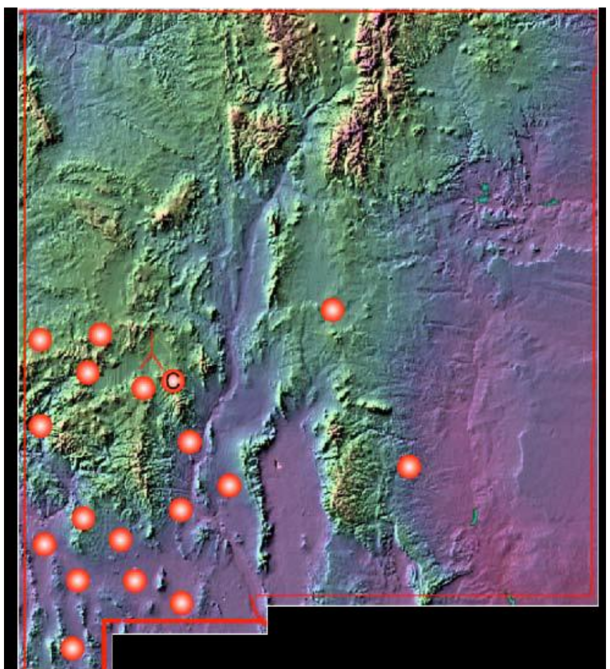


LWA Overview

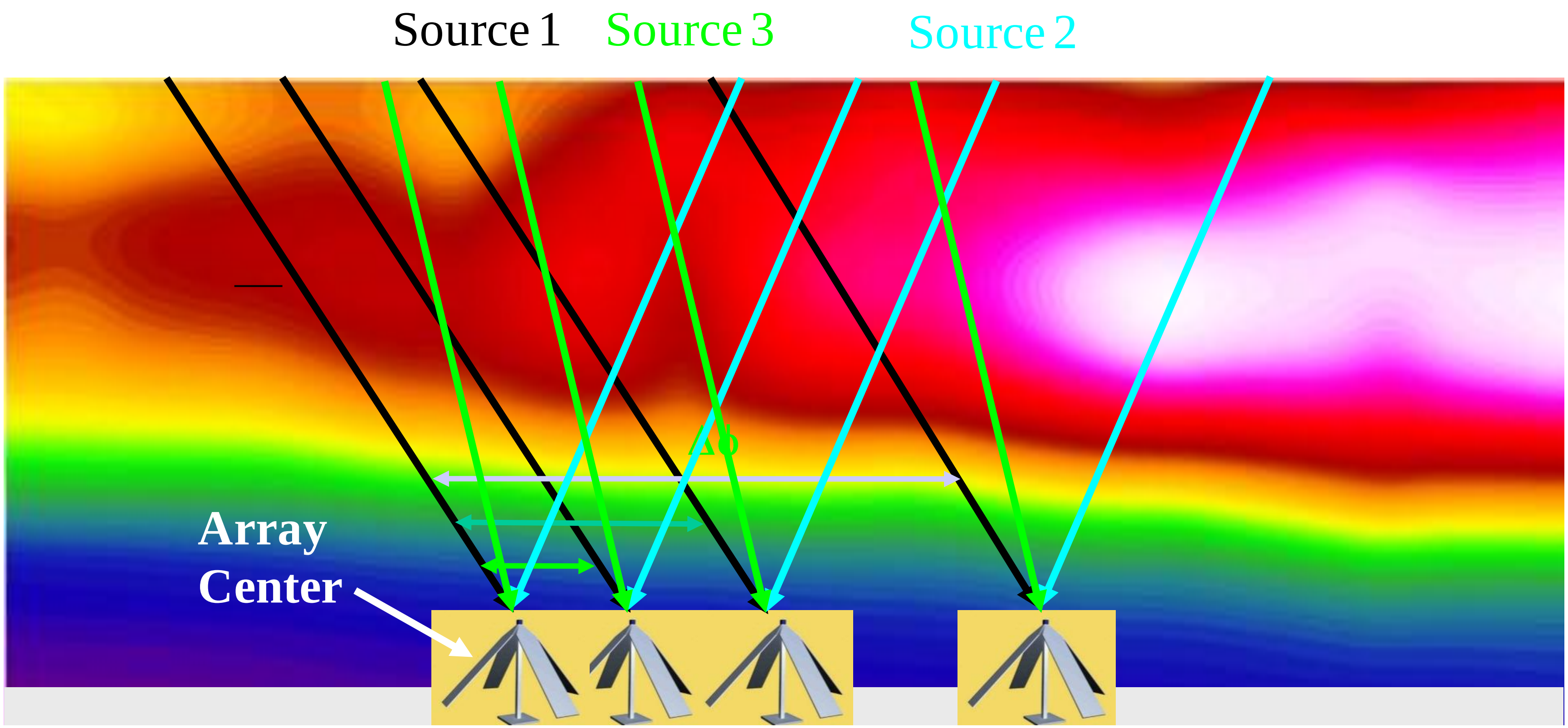
- 52 Stations spread over New Mexico (bottom panel)
- Each station consists of sets of phased array antennas
  - *Operates from 20-88 MHz*
  - *Computer controlled beam steering*
- Upper Panel at right LWA station 1
- Lower left panel shows antennas at LWA 1
- First station: 256 antennas, 2.8° Beam width at 75 MHz

LWA Station 1 Layout

LWA Layout



RASCAL Concept



Rapid All-Sky CALibration (RASCAL) technique proposed to perform ionospheric measurements & calibration

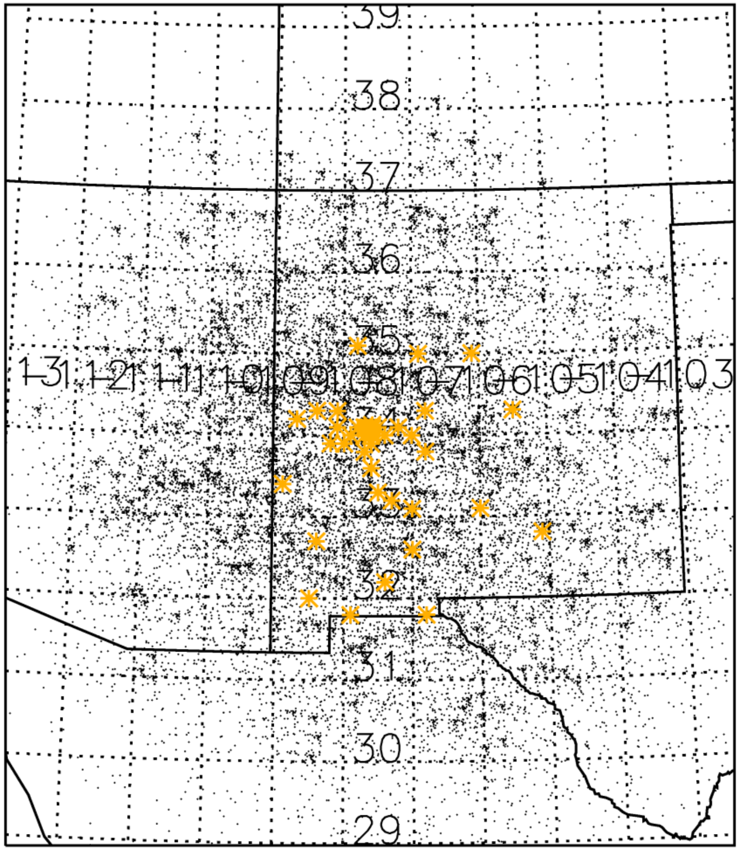
- Uses the VLSS sky survey for source selection

RASCAL technique will scan all visible sources with ~10 second cadence

- Current implementation: ~100 sources, 1 station, 50 msec dwell, ~6-7 sec scan

RASCAL Simulation

- VLSS sky catalog contains:
  - *16612 sources*
  - *Flux > 1 Jy*
- Midnight local time on 3/21/2010
  - *52 LWA stations (yellow stars)*
  - *Minimum source elevation 30°*
  - *339 sources visible with fluxes > 10 Jy*
    - Given current operating constraints – 50 ms dwell and 20% switching overhead – ~20 sec required to sample sources
  - *For 17628 total lines-of-sight!*
    - High sampling density
  - *Ionospheric height 300 km*



Summary & Conclusions

- Modern array interferometers are extremely sensitive to the ionosphere
  - *Measure the TEC difference between array elements to extremely high precision*
  - *However, they are insensitive to the absolute TEC*
- High temporal resolution ~10 seconds
  - *Good for studying traveling structures: TIDs, Sporadic-E, Ionospheric Gradient Evolution…*
- High spatial resolution ~10 km
  - *Good for mesoscale ionospheric studies*
- New ionospheric correction techniques are required providing opportunities for young researchers
- Also, new measurement and calibration techniques promise new ionospheric measurement types

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Backup Slides

Interferometer Measurements (1 of 2)

- Maxwell's Equations tell us that:

$$\vec{E}(\vec{r}) = \iiint P_\nu(\vec{R},\vec{r})\vec{E}(\vec{R})dxdydz$$

- Assume that the celestial sphere is empty

$$\vec{E}(\vec{r}) = \iint \vec{\mathcal{E}}(\vec{R}) \frac{\exp\left(2\pi i\nu\left|R-r\right|/c\right)}{\left|R-r\right|} dS$$

- Actually we are interested in the fringe visibility, which is proportional to the expectation value of square of the electric field

$$V_\nu\left(\vec{r}_1,\vec{r}_2\right) = \left\langle \iint \mathcal{E}_\nu(R_1)\mathcal{E}_\nu^*(R_2) \frac{\exp\left(2\pi i\nu\left|R_1-r_1\right|/c\right)}{\left|R_1-r_1\right|} \frac{\exp\left(-2\pi i\nu\left|R_2-r_2\right|/c\right)}{\left|R_2-r_2\right|} dS_1 dS_2 \right\rangle$$

Interferometer Measurements (2 of 2)

- The source is assumed to emit incoherently, so the integral is zero except when $R_1 = R_2$ and the order of the integrations can be reversed:

$$V_\nu(\vec{r}_1, \vec{r}_2) = \iint \left\langle \left| \mathcal{E}_\nu(R) \right|^2 \right\rangle |R|^2 \frac{\exp(2\pi i\nu |R - r_1| / c)}{|R - r_1|} \frac{\exp(-2\pi i\nu |R - r_2| / c)}{|R - r_2|} dS$$

- Assuming that R>>r, expanding the exponentials retaining first order terms, and substituting:

$$I_\nu(\hat{s}) = \left\langle \left| \mathcal{E}'_\nu(\hat{s}) \right|^2 \right\rangle |R|^2$$

- We get finally the Measurement Equation ($\hat{s}$ is a unit vector pointing toward the source):

$$V_\nu(\vec{r}_1, \vec{r}_2) = \int I_\nu(\hat{s}) \exp\left(-2\pi i\nu \hat{s} \cdot (\vec{r}_2 - \vec{r}_1)/c\right) d\Omega$$

Total Electron Content Sensitivity (1 of 2)

- For a plane parallel ionosphere:

$$\Delta T_{2,1} = T_2(\vec{r}_2, \hat{s}_2) - T(\vec{r}_1, \hat{s}_1)$$
$$= \int_0^\infty n(x_2, y_2, z_2) \, dz_2 / \mu_2 - \int_0^\infty n(x_1, y_1, z_1) \, dz_1 / \mu_1$$

- Assuming a small spatial extent for the array and expanding in a Taylor series:

$$\Delta T_{2,1} \approx \int_0^\infty \left[n(x_1, y_1, z)\mu_1 + \mu_1 \vec{\nabla}_{x,y} n(x_1, y_1, z) \cdot (\vec{r}_2 - \vec{r}_1) - n(x_1, y_1, z)\mu_2 \right] \frac{dz}{\mu_2 \mu_1}$$

- In a plane parallel atmosphere: $\mu_1 = \mu_2$

$$\Delta T_{2,1} \approx \int_0^\infty \left[\vec{\nabla}_{x,y} n(x_1, y_1, z) \cdot (\vec{r}_2 - \vec{r}_1) \right] \frac{dz}{\mu}$$

- *The interferometer is sensitive to the gradient of the TEC*

Total Electron Content Sensitivity (2 of 2)

- For ionospheric physics purposes, interferometer *sensitivity to phase changes* and *insensitivity to absolute phase* implies that:
  - *Interferometers are insensitive to laminar ionospheres*
  - *Determination of "large scale" phase screens is an under-determined problem*
    - Constant TEC terms are lost
  - *Also, ionospheric tomography using intereferometers is under-determined – due to absolute phase insensitivity and due to insufficient vertical resolution*
    - Similar to Computerized Ionospheric Tomography which measures TEC relative to some position (usually the point of closest approach)
    - But instead of a few bias terms ~ number of stations – tomography would require thousands of bias terms ~ number of sources the number of stations!
- But interferometers are very sensitive to TEC changes to ~0.001 TECU/deg phase (at ~80 MHz)
  - *Great for measuring and monitoring gradients and their time variation*
  - *Great for detecting traveling structures*
  - *Maybe use frequency dependence to provide additional information?*