Characterizing Small-scale Ionospheric Fluctuations with Low-frequency Radio Interferometers

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New Project

- Seeking to expand on previous work by Jacobson & Erickson, Cohen & Rottgering, and Intema

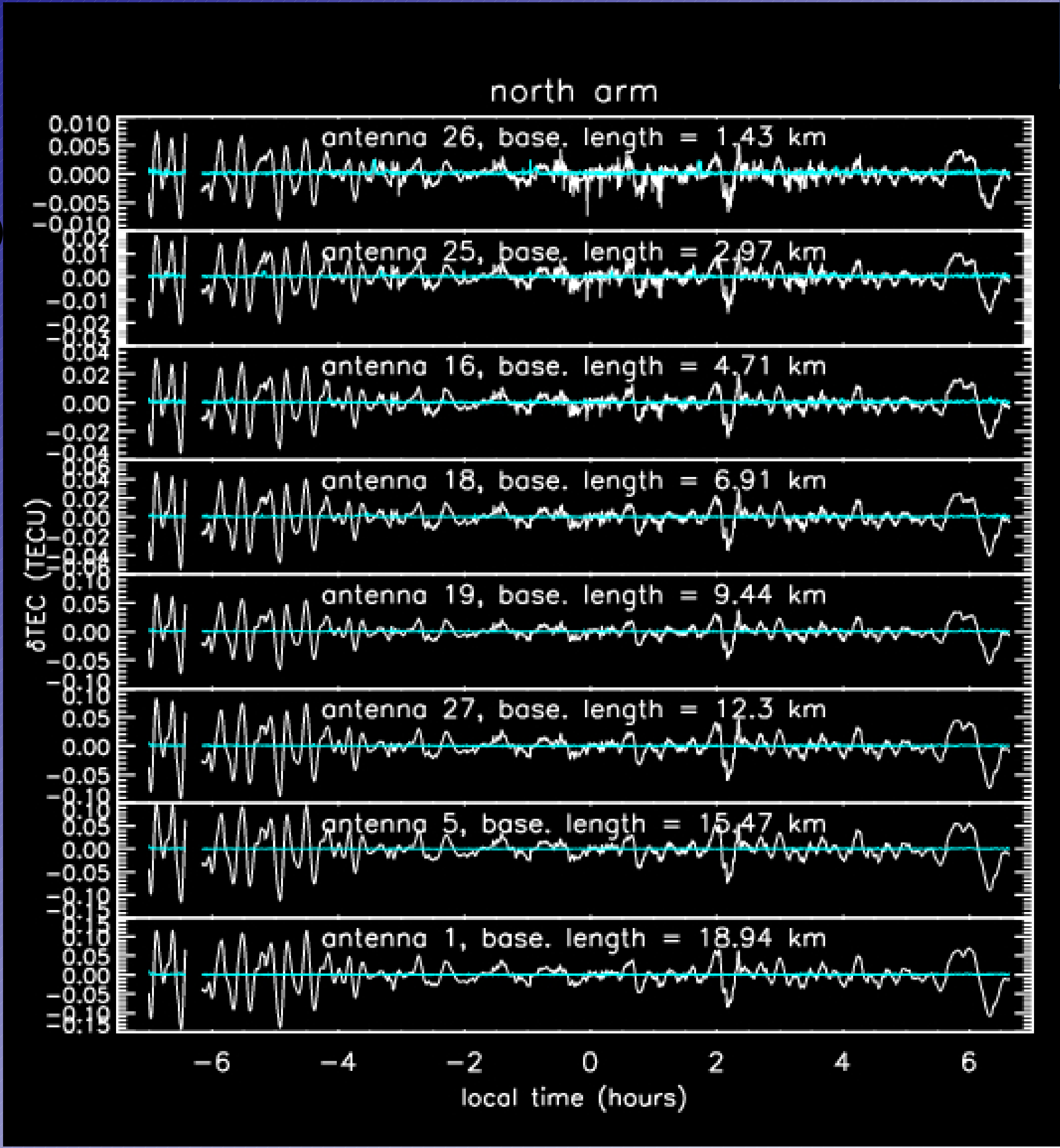
- Starting with a project focusing on long (>1 hour) observations of the brightest low-frequency sources (Cygnus A, Cassiopeia A, Virgo A, 3C98, 3C219, and 3C452) with the VLA 74 MHz/327 MHz system from VLA archives

- Starting with project ID AK570 containing one 12.8 hour scan and a shorter, 35 minute scan of Cyg A roughly spanning dusk to dawn at 74 and 327 MHz; using this data set to develop analysis routines and to explore properties of phenomena likely to see with other data sets

δTEC For Each Antenna

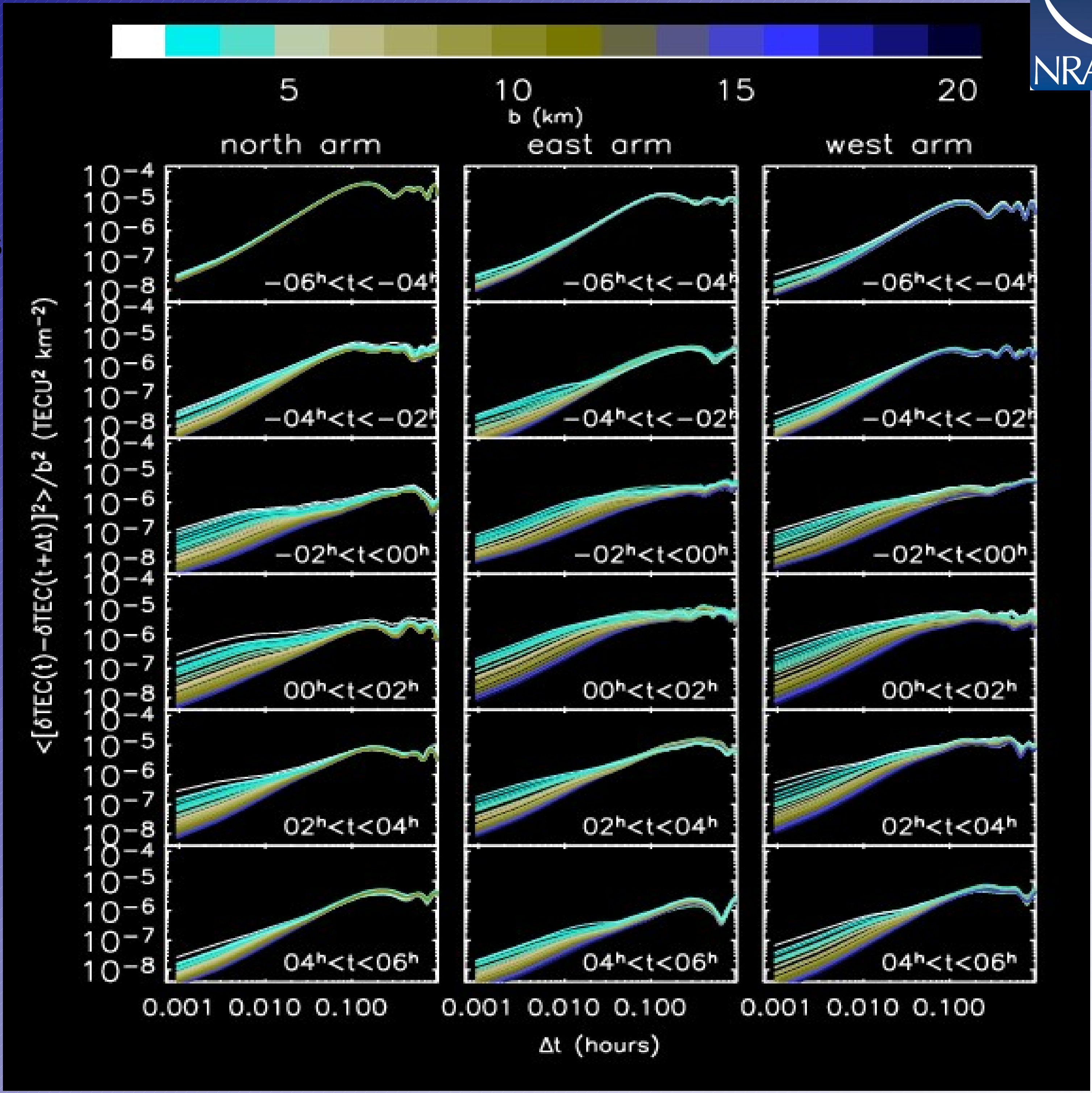
- Took median among 4 values (2 bands + 2 polarizations) to get final δTEC values after removing large time scale effects (instrumental phases, position offsets, etc.) with “continuum subtraction” process

- Use median absolute deviation (MAD) to estimate uncertainty (blue curves)



Structure Functions

- Computed structure functions for δTEC for all baselines along each arm
- Plotted here normalized by baselin length, b, squared to highlight presence of non-linear structures



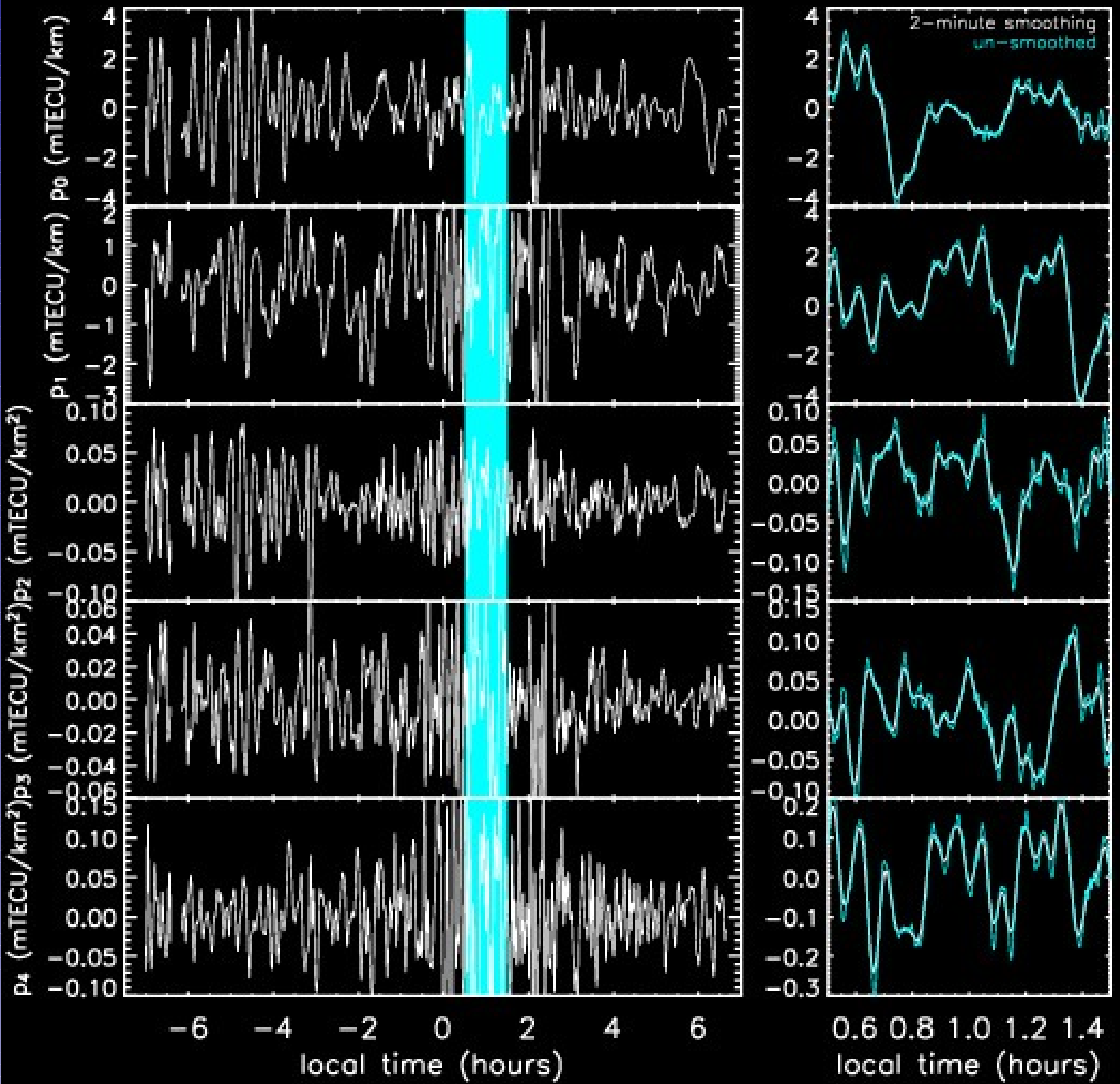
Polynomial Fits

- ✪ Simple plane across the array is not sufficient; instead, fit 2nd order Taylor series:

$$\delta TEC = p_0 x + p_1 y + p_2 x^2 + p_3 y^2 + p_4 xy + p_5$$

where +x=north, +y=east and p_5 is arbitrary

- ✪ Performed fits using all baselines. Added two-minute smoothing to force temporal coherence

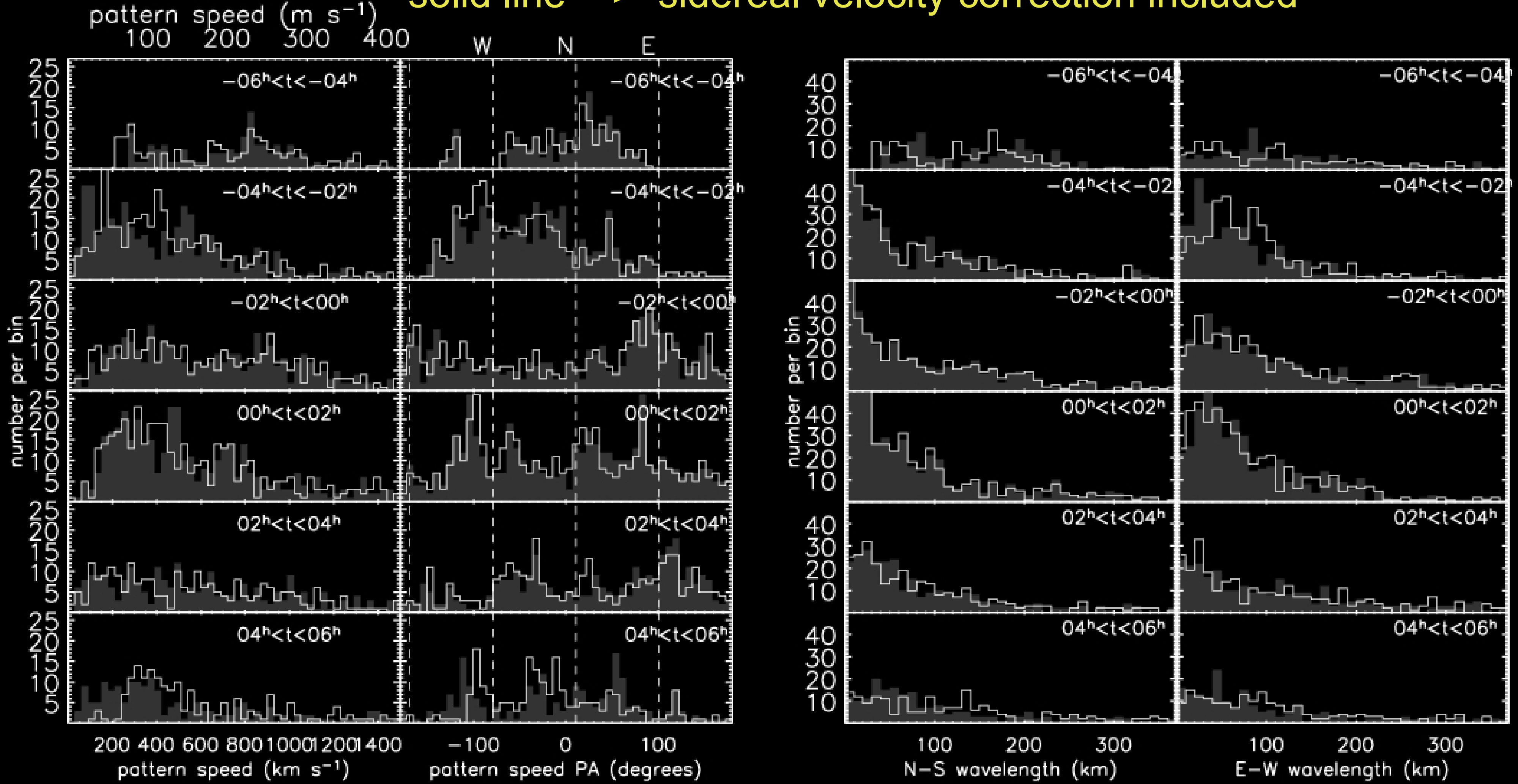


Wave Properties

✪ Tracked extrema of polynomial fits across the area of the VLA (r<20 km) to estimate pattern speed vectors

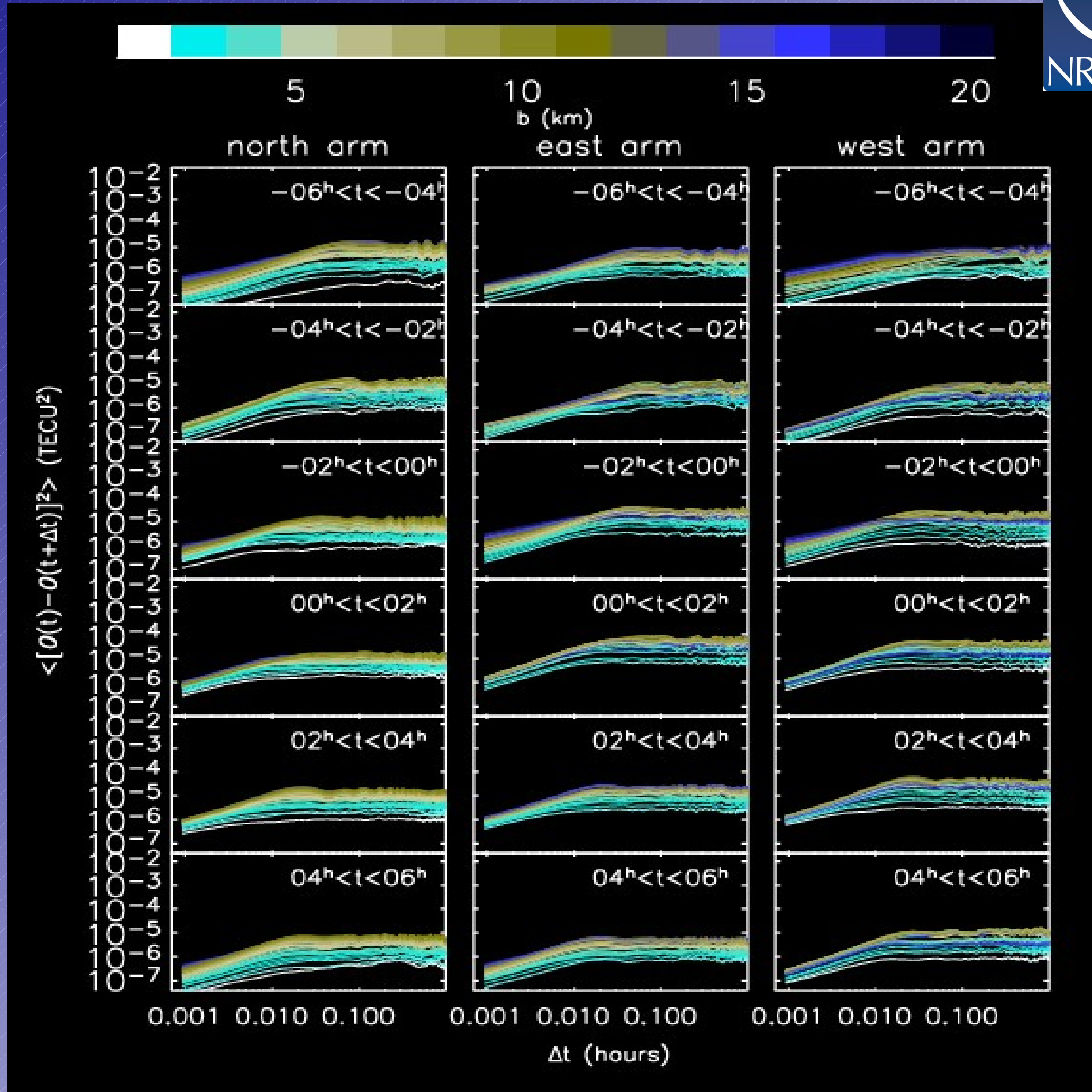
✪ Used peak/trough locations to measure oscillation frequencies; used these with velocities to get wavelengths

solid line => sidereal velocity correction included



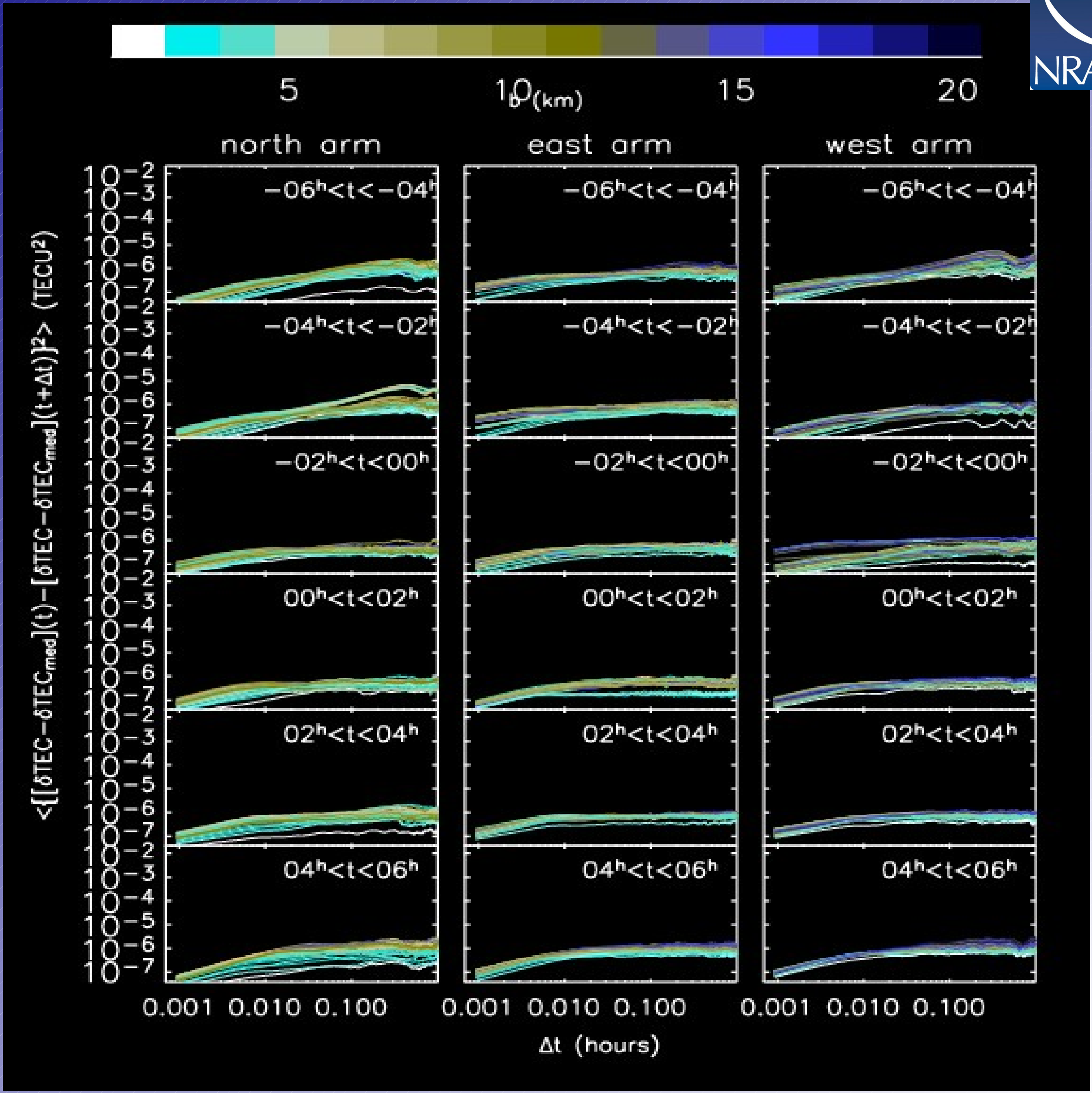
More Structure Functions

- ✪ Structure functions for the polynomial fit residuals



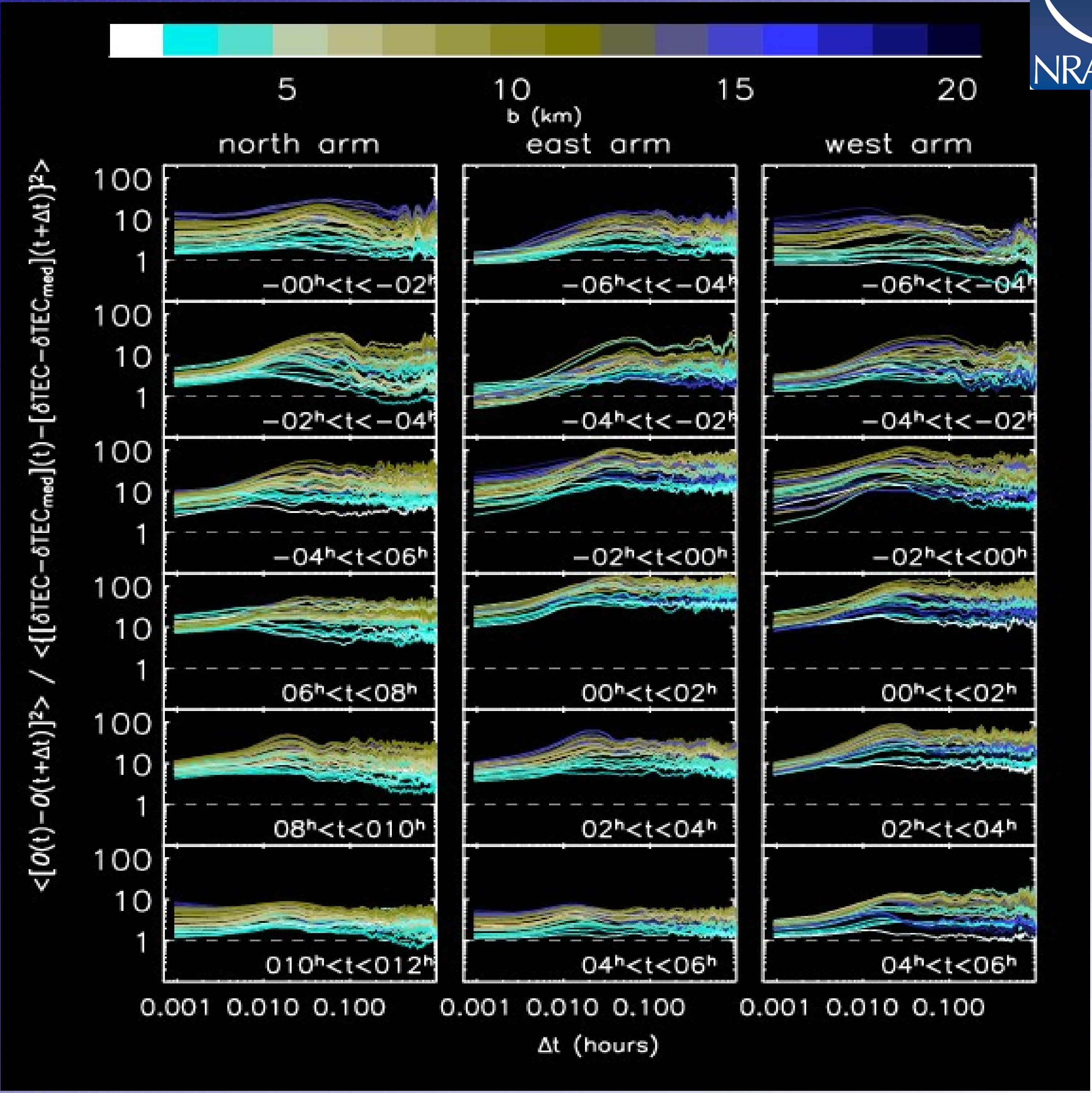
More Structure Functions

- ✪ Structure functions for the uncertainties in δTEC



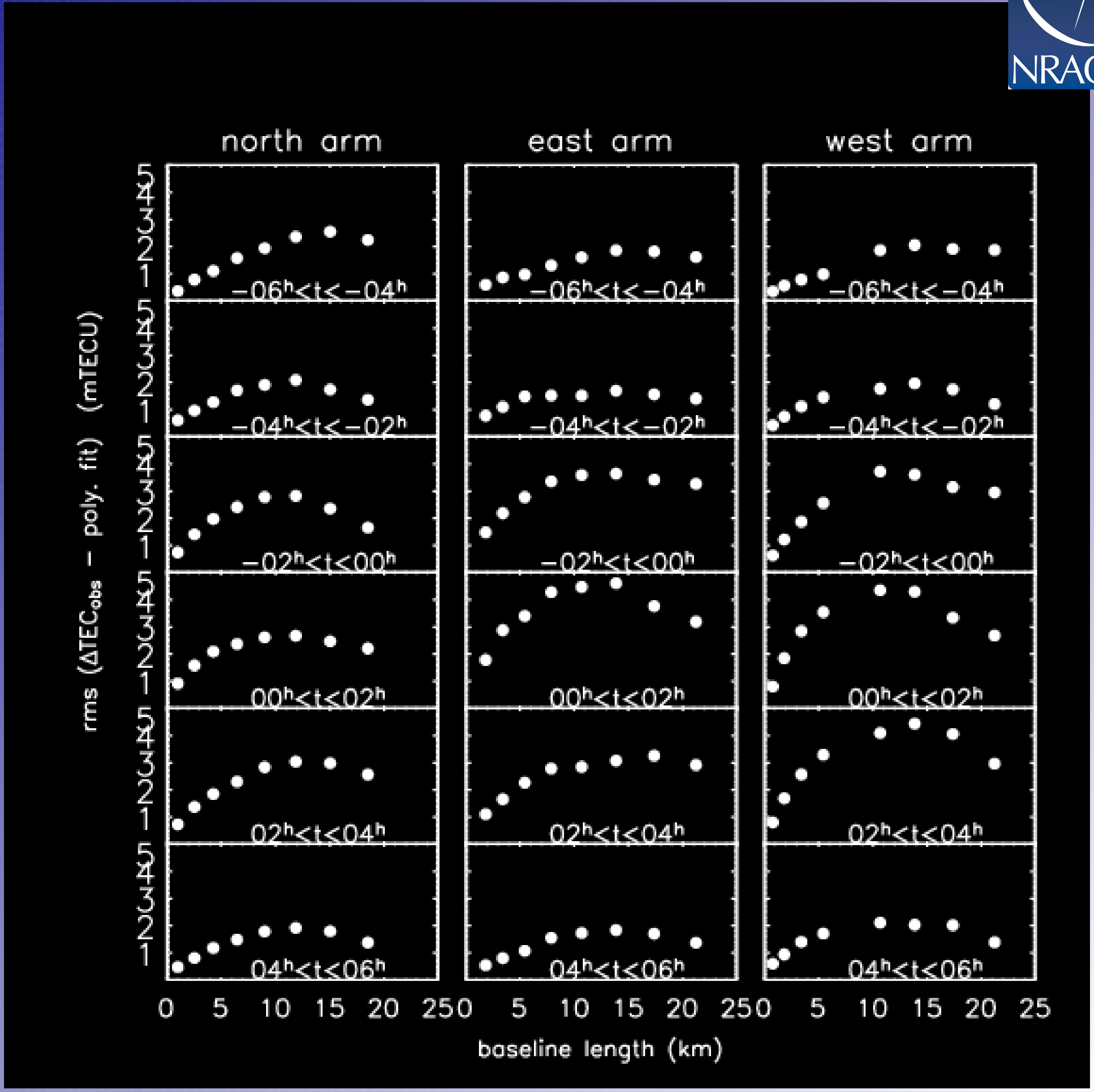
More Structure Functions

- ✪ Ratios of the structure functions in the previous 2 slides

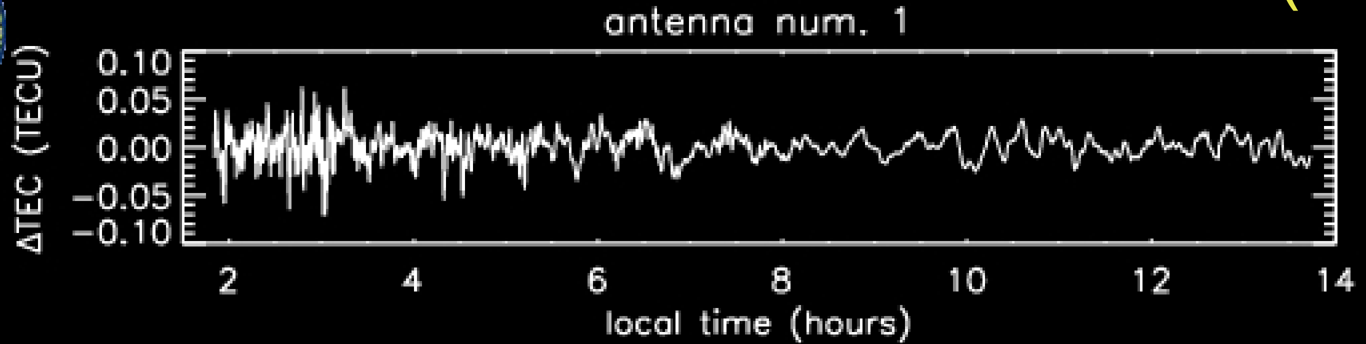


Size of Small-scale Structures

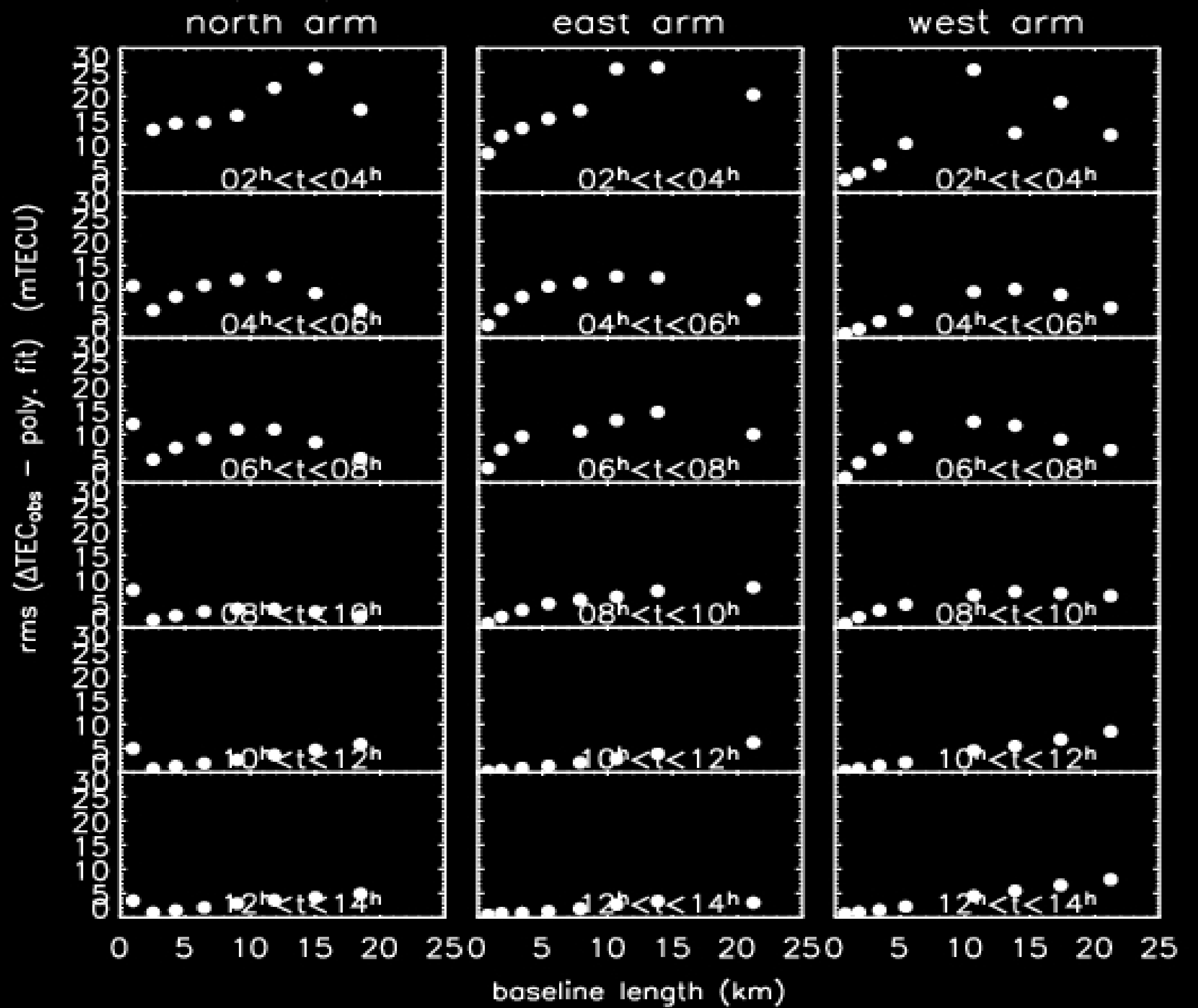
- ✪ rms of fit residuals within two-hour bins as functions of baseline length; some cases, see definite peak around 10-15 km, so, possibly incoherent across the array



Size of Small-scale Structures (cont.)



✪ weak small-scale structures maybe weaker versions of some instances of scintillation; here are some preliminary results on a similar dataset with detected scintillation



Conclusions

- ✪ Larger waves appear around dusk; smaller waves more dominant during the night => makes wide-field calibration better during the day/twilight (already known; see VLA Summer School book).

- ✪ Small-scale structure apparent at all times appears quite localized => will be a limiting factor in sensitivity of low-frequency wide-field image

- ✪ Because of this, we are planning large study with archival data of small-scale structures to see how their properties vary (if at all) with time of day, time of year, solar activity, etc.

More developments

- ✪ Calibration phase corrections often shows evidence of time lag between antennas, strongly suggesting the presence of traveling, quasi-constant patterns

- ✪ Some basic parameters of these traveling patterns could be measured (at high accuracy) and cross-checked with ionospheric physics literature

- ✪ Time coherence may / should be utilized to improve ionospheric calibration for low-frequency radio observations

- ✪ Several studies in '90s literature using radio telescopes (e.g., Jacobson & Erickson with VLA, van Velthoven with WSRT)

- ✪ Recent & new LF telescopes offer great opportunity for studies of ionospheric transient effects

Experimental setup (1)

- ✪ When a single dominant pattern (like a TID) is traveling over a reasonably dense 2D array, the collection of time lags between phase pattern measured between different baseline pairs should give us a pattern speed and direction

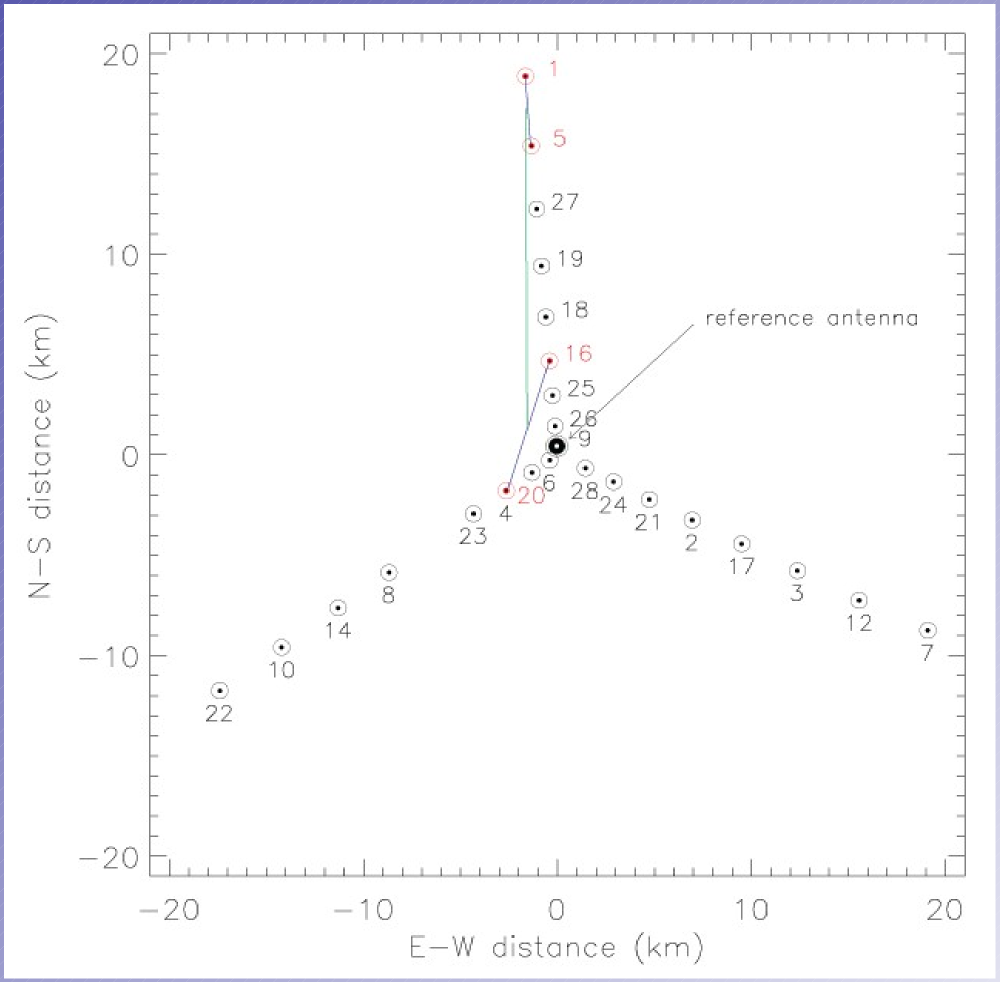
- ✪ Using time correlations to determine the time lag requires little assumptions on the actual shape of the traveling phase pattern

- ✪ Assume phase pattern length larger than baselines selected → baseline measures spatial derivative of phase pattern, still allows for same time lag determination

- ✪ Bandpass filtering of phase solutions restricts temporal frequency range and removes instrumental offsets

Experimental setup (2)

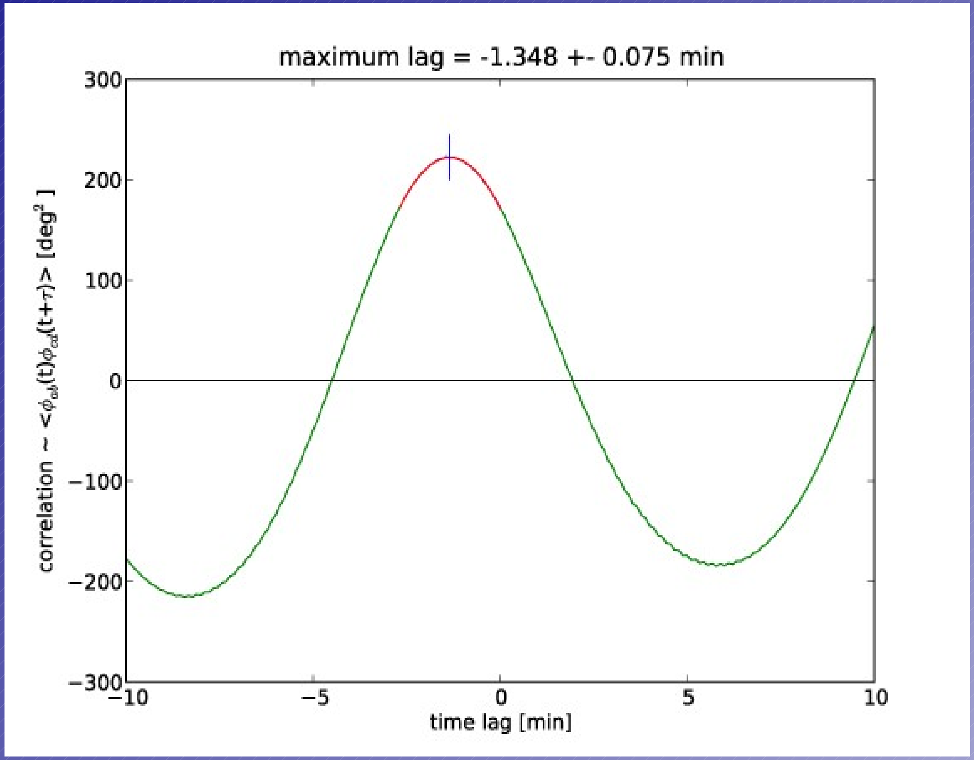
- Baselines pairs were chosen to roughly align with separation line
- Baseline lengths were chosen to be relatively short w.r.t. separation
- Ad-hoc choice of bandpass time range (3-20 min)
- Ad-hoc choices of time window (15 min) and time lag range (-10 to 10 min) for calculating correlations
- Several ad-hoc criteria to reject data with ill-behaved correlation functions



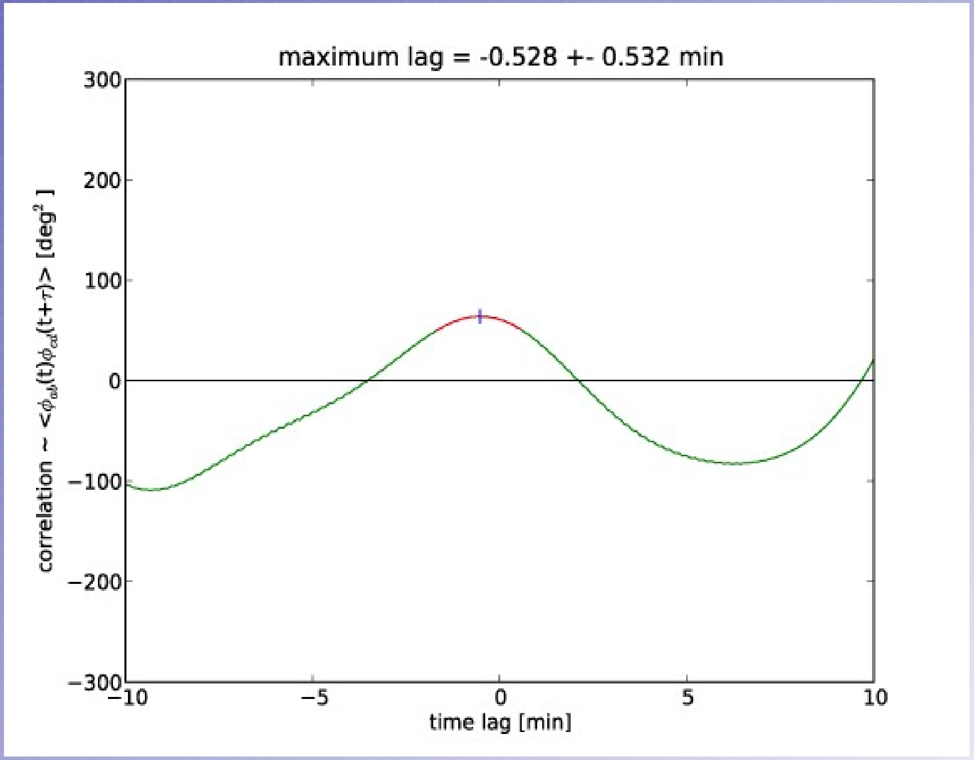
Time correlation examples

- Example on 74 MHz VLA data of Cyg A, 6.67 sec time resolution

Baselines 1-5 and 4-8

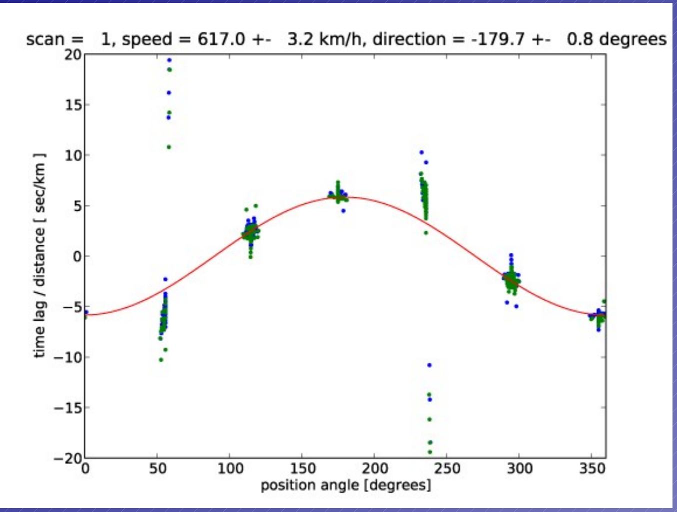


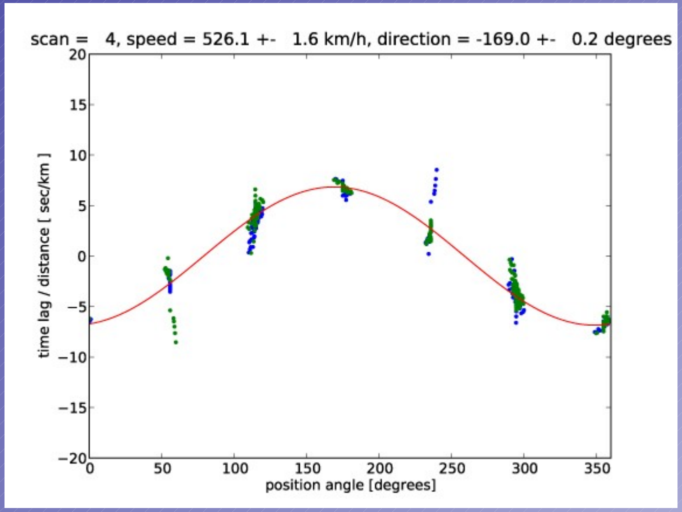
Baselines 2-4 and 3-7

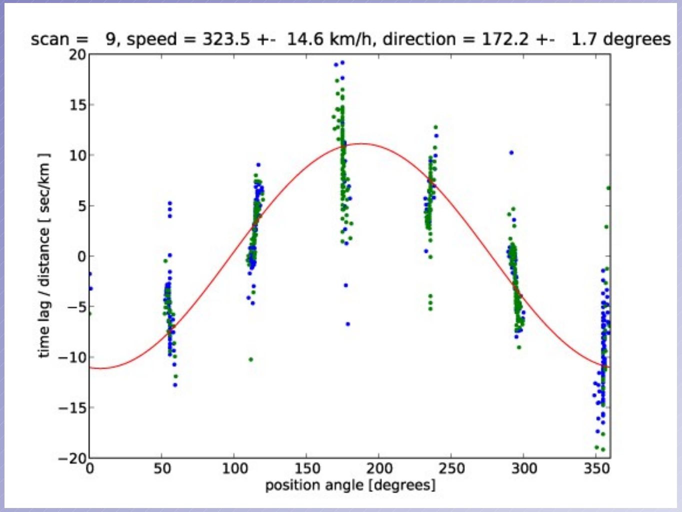


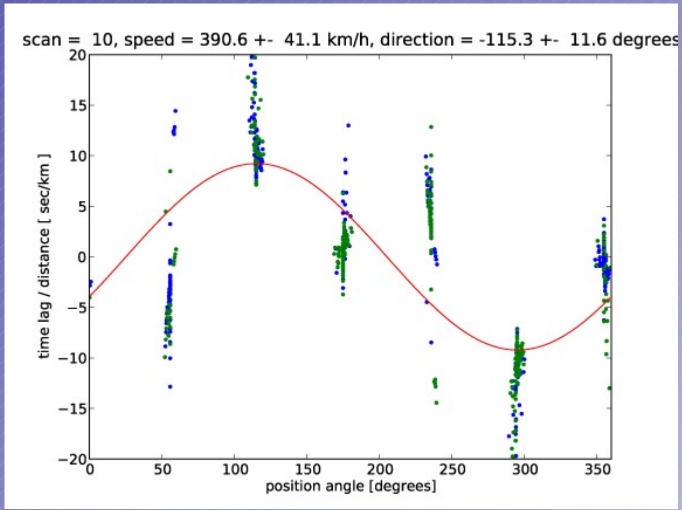
Velocity determinations for several time ranges

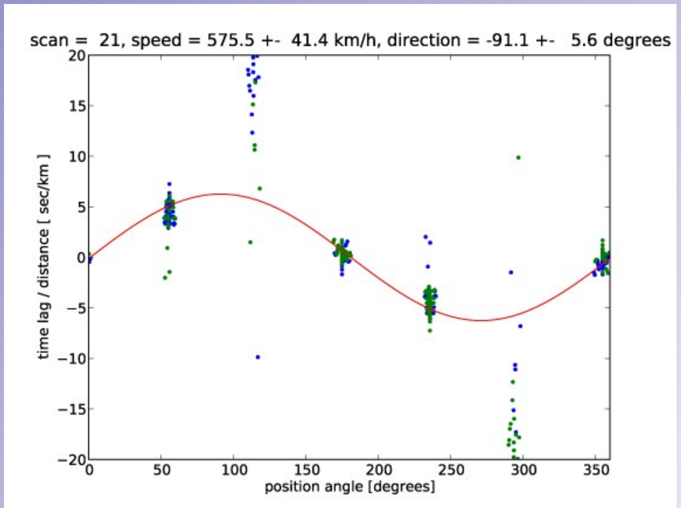
- Weighted fit of cosine to: time lag / separation = cos(direction) / speed
- For several time ranges, fits give reasonable numbers for velocity, for other times it gives bad results











Summary and future work

- During certain time ranges, there is evidence of traveling quasi-stationary patterns in the ionosphere

- Determination of basic pattern velocity parameters seems possible, but needs great care.

- Subset of well-determined speeds is in agreement with ionospheric literature

- First step towards using time axis to increasing available information for fitting ionospheric models to correct LF radio observations

- Obviously needs more work, but results look promising

- How to solve for superposition of multiple traveling patterns?

- Attempt to better understand smallest-scale fluctuations