Imaging Algorithms for the VLSS

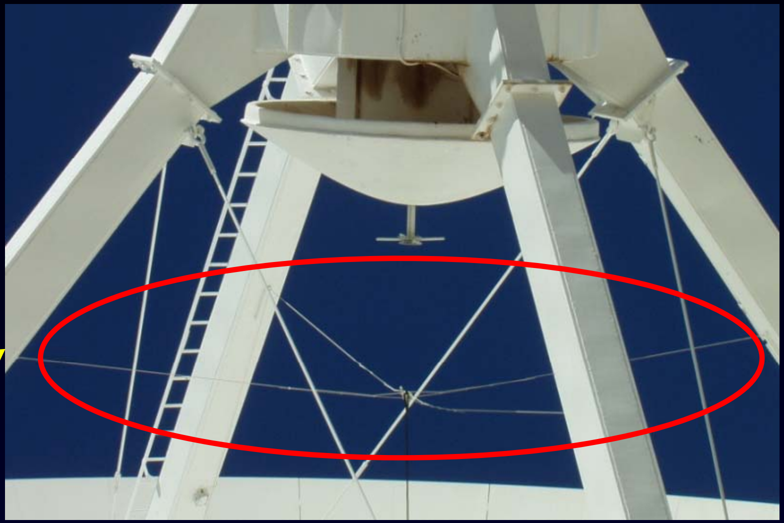
Aaron Cohen, Wendy Lane, Namir Kassim, Joseph Lazio
US Naval Research Laboratory

Richard Perley, William Cotton, James Condon
National Radio Astronomy Observatory

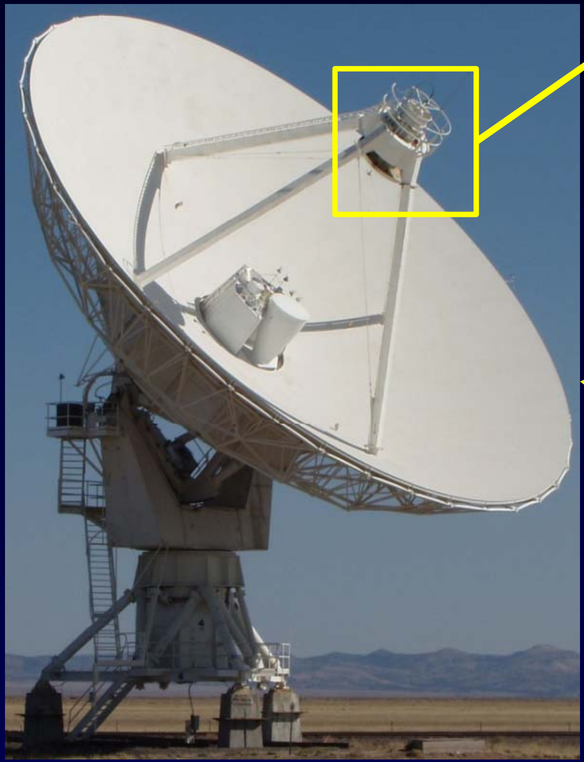
William Erickson
University of Tasmania

Low Frequency VLA

- 74 MHz receivers on VLA
  - Installed in 1998.
  - Very limited capabilities:
    - Low aperture efficiency.
    - Restricted to 1.5 MHz bandwidth.
  - Still the most powerful telescope operating below 100 MHz.

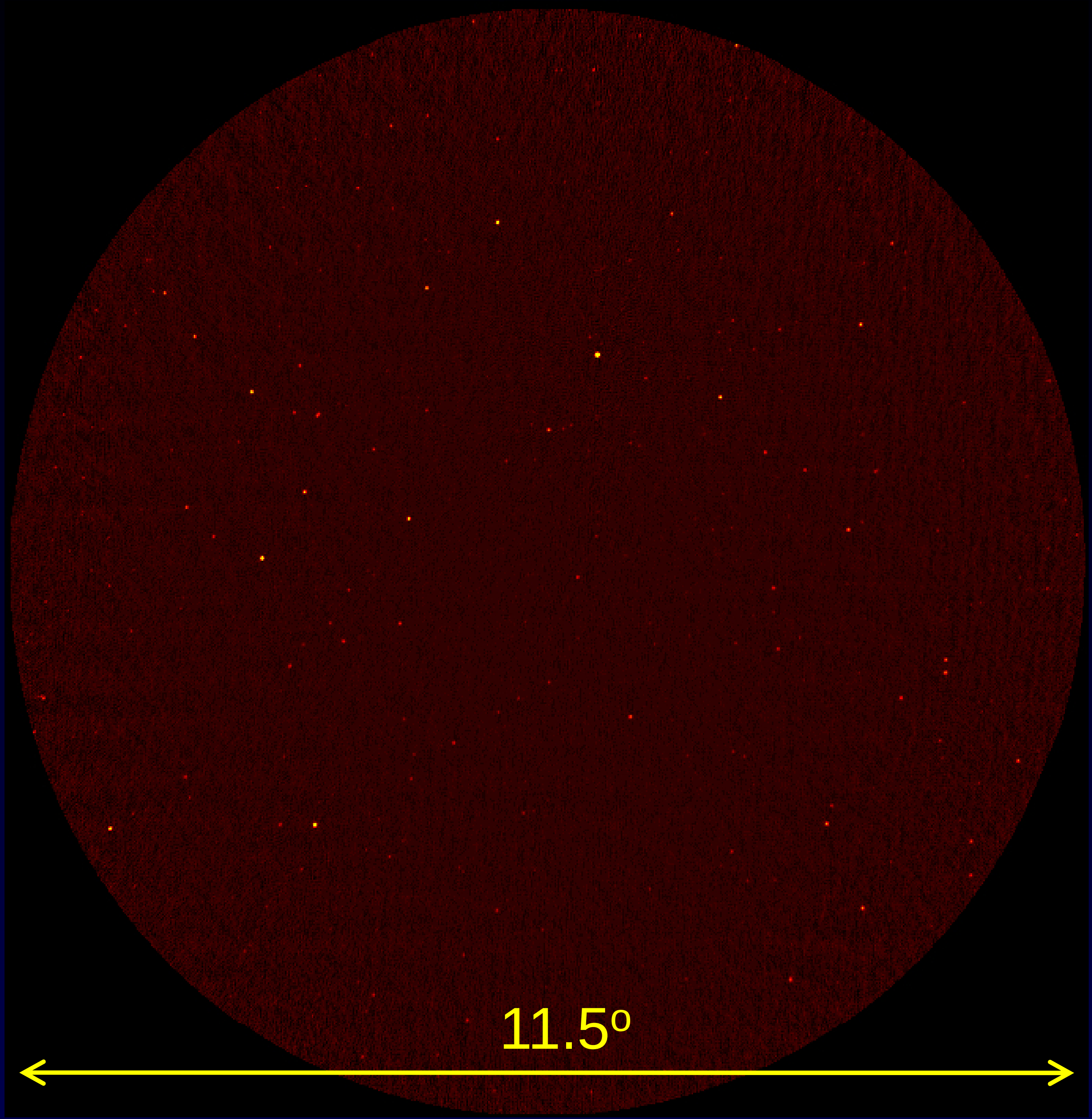


Crossed dipole suspended below sub-reflector by wires



74 MHz VLA Field of View

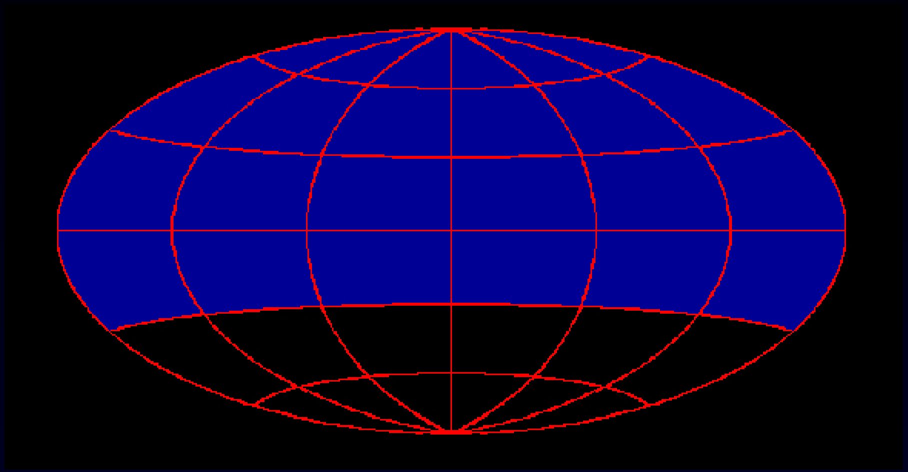
- <u>Field of View</u>
  - Diffraction limited by 25 m VLA dish.
  - ν = 74 MHz → λ = 4m.
  - FWHM ~ 11.5 deg.
  - Detects ~200 sources within the FOV.
  - Presents challenges for calibration and data reduction.
  - Low-frequency telescopes are very efficient at conducting large surveys.



Motivation for a 74 MHz Sky Survey

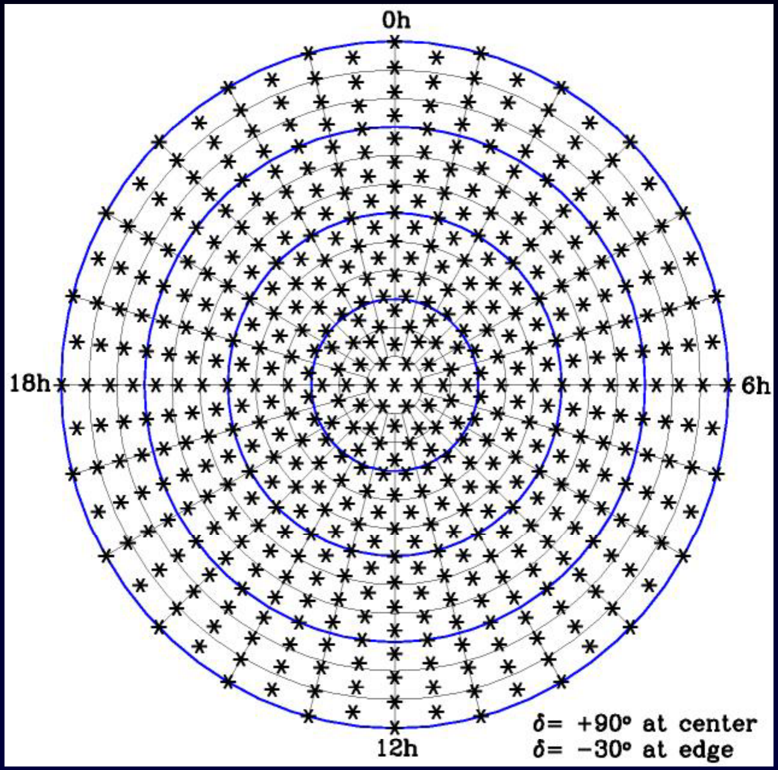
- Scientific
  - High z Radio Galaxies.
  - Cluster Halos and Relics.
  - Pulsars.
  - Absorption in SNRs.
  - Map HII regions over Galactic Plane.
  - Extend spectra to 74 MHz for ~105 sources.
  - Unexpected discoveries.
- Technical
  - Create low-frequency sky model and initial grid of calibrator sources for future low-frequency instruments.
  - Gain experience in low-frequency observing.
  - Develop automated routines for low-frequency data reduction.
  - Expand user base for low-frequency data.

VLSS: VLA Low-frequency Sky Survey



- <u>Survey Method</u>
  - 523 separate pointings
  - 1.25 hours per pointing
  - Automated pipelines for calibration, RFI excision, imaging, mosaicing and source detection.

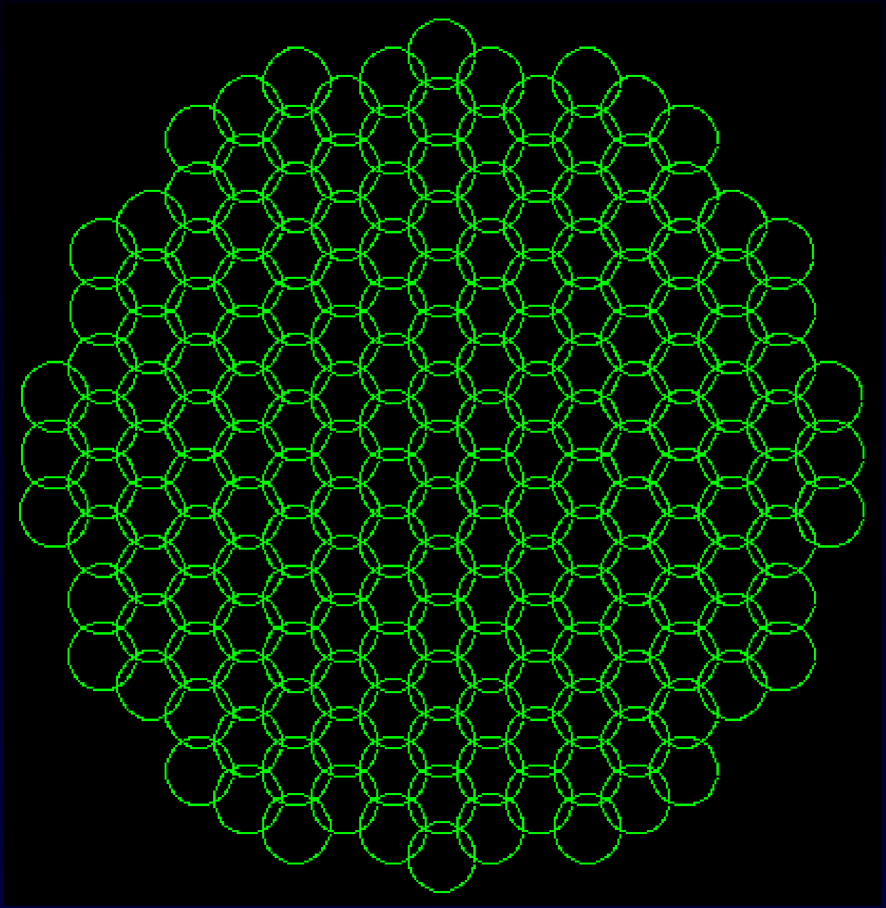
- <u>Survey Goals</u>
  - 74 MHz VLA in B-configuration
  - Map entire sky above $\delta > -30^o$



- <u>Further Information</u>
  - Cohen et al. 2007, AJ 134, 1245.
  - http://lwa.nrl.navy.mil/VLSS

Wide Field Imaging

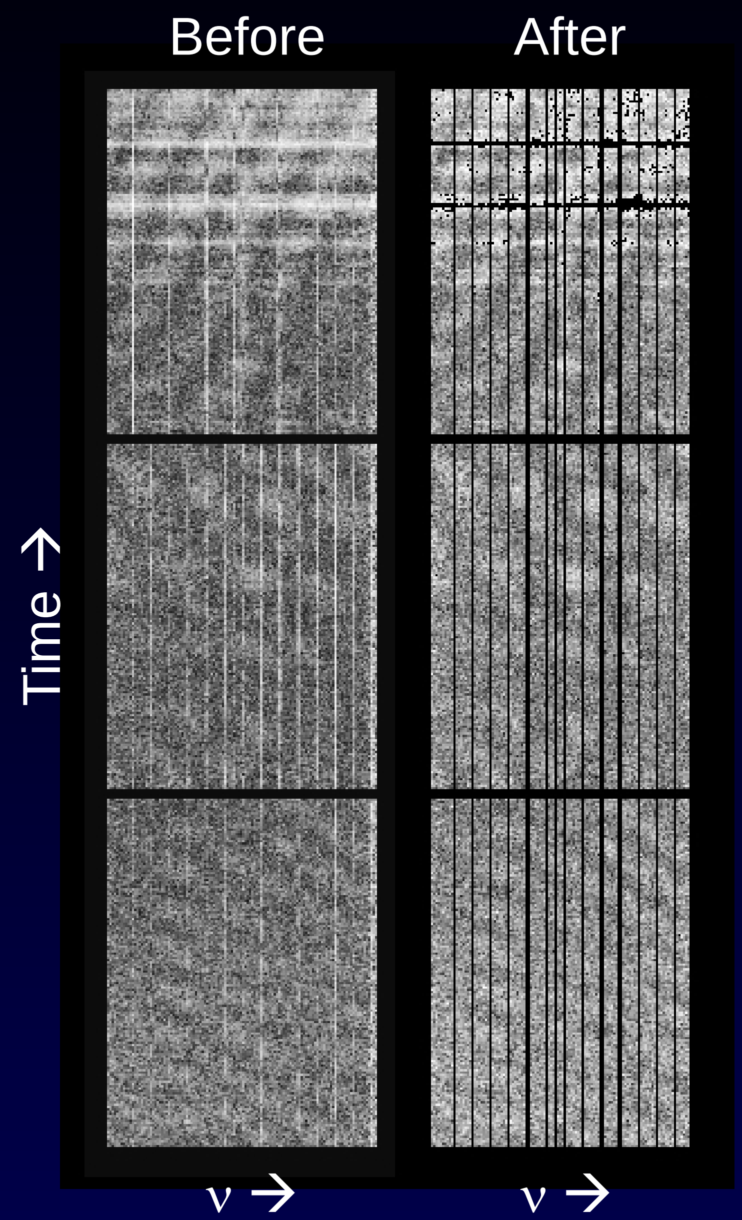
- Problem:
  - Synthesis UV coverage not co-planar: w-terms are significant.
  - A 3D Fourier inversion is required to map the full field of view.
  - Current algorithms only perform 2D Fourier inversion.
- Solution:
  - FOV is divided into many smaller “facets”.
  - Each facet is imaged with it’s own phase center.
  - The facets are combined in the image plane.



The full field of view is covered by a “fly’s eye” of smaller images or “facets”.

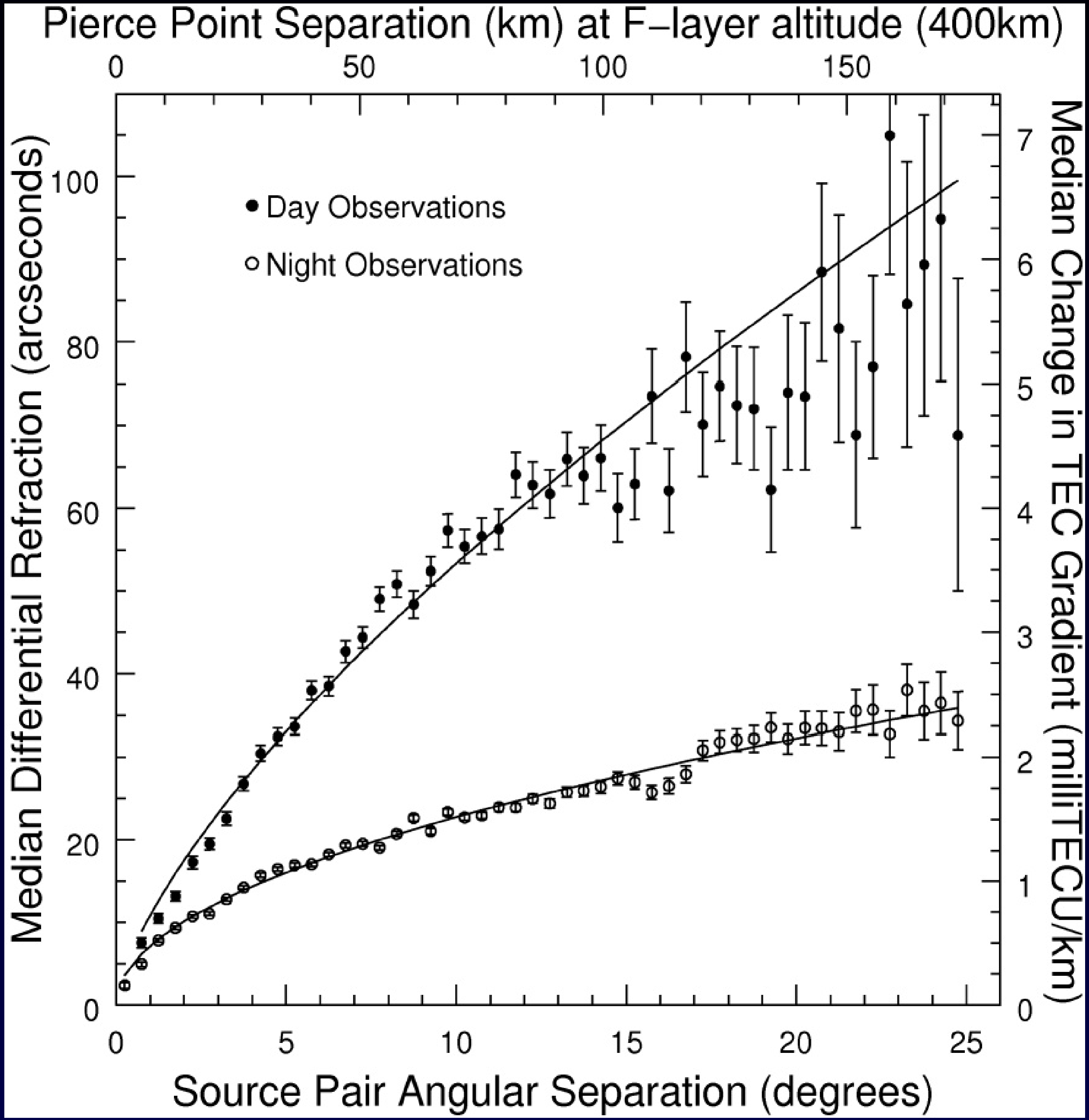
Radio Frequency Interference (RFI)

- Coping with RFI
  - The 74 MHz VLA is limited to a small, protected 1.5 MHz bandwidth.
  - Even within the protected region, RFI is significant.
  - When data is taken in spectral line mode, RFI can be isolated and removed.
  - The most effective method for RFI removal remains human editing, but this is not always practical.
  - For the VLSS, we developed an automated routine that performed statistical fits to determine which data are likely contaminated by RFI.



Median Differential Refraction

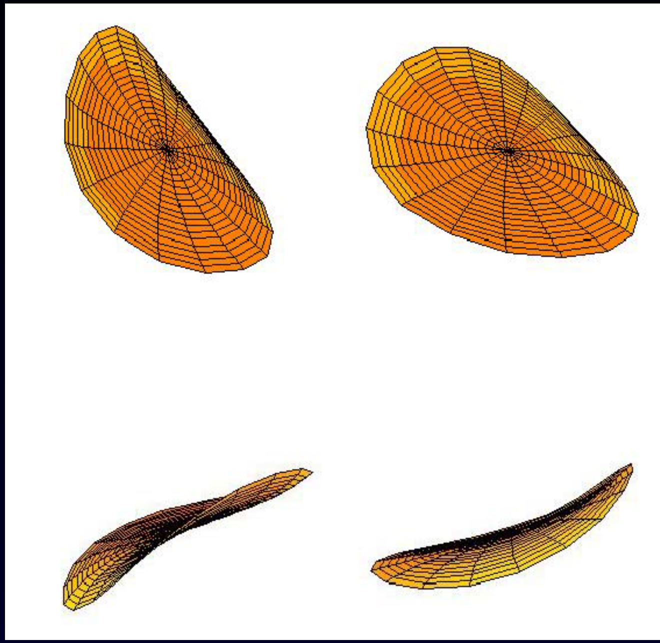
- Median Differential Refraction
  - This is the difference between the ionospheric refraction of two sources in the same field of view.
  - Is analogous to the atmospheric "seeing" of optical telescopes.
  - This measures the magnitude of the ionospheric distortions that can be expected in future instruments.



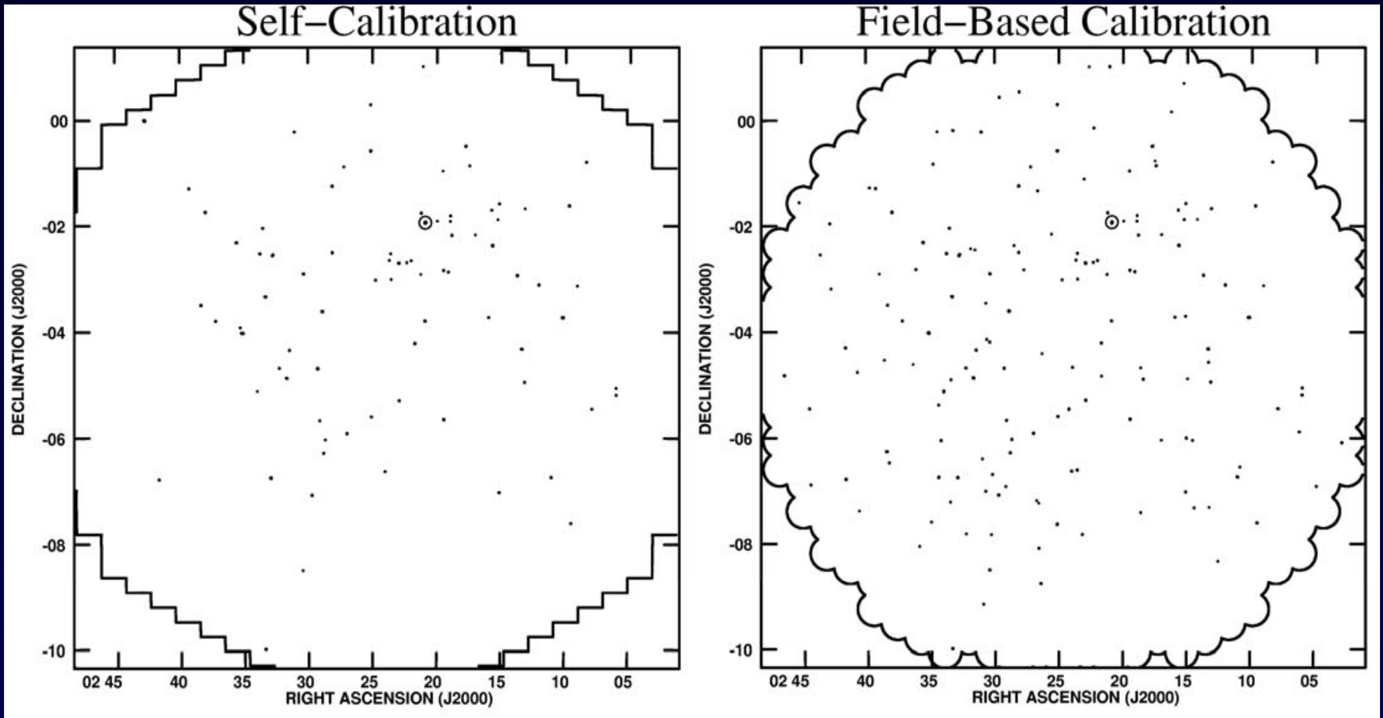
Cohen & Rottgering, in prep.

Field-Based Ionospheric Calibration

- <u>Problem</u>
  - At 74 MHz, phase distortions vary across the field of view.
- <u>Solution</u>
  - Take snapshot images of bright sources in the field of view and compare to NVSS positions.
  - Fit a 2nd order Zernike polynomial phase delay screen for each time interval.

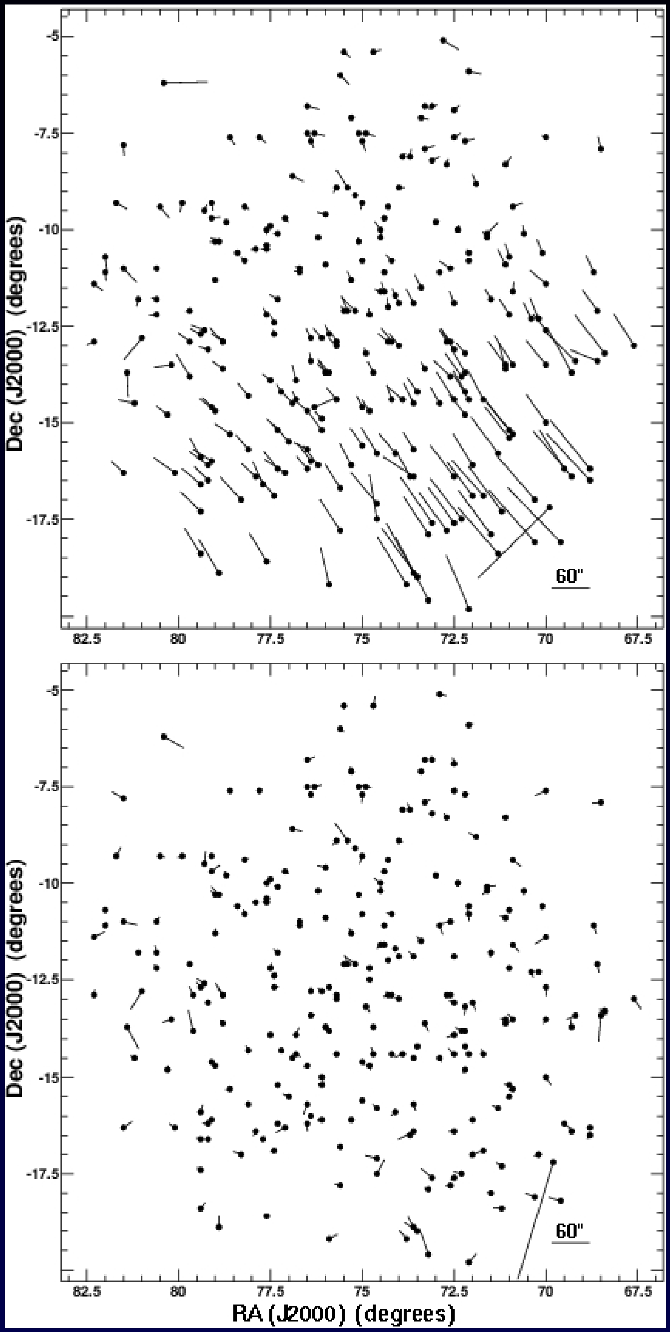


Phase screen examples

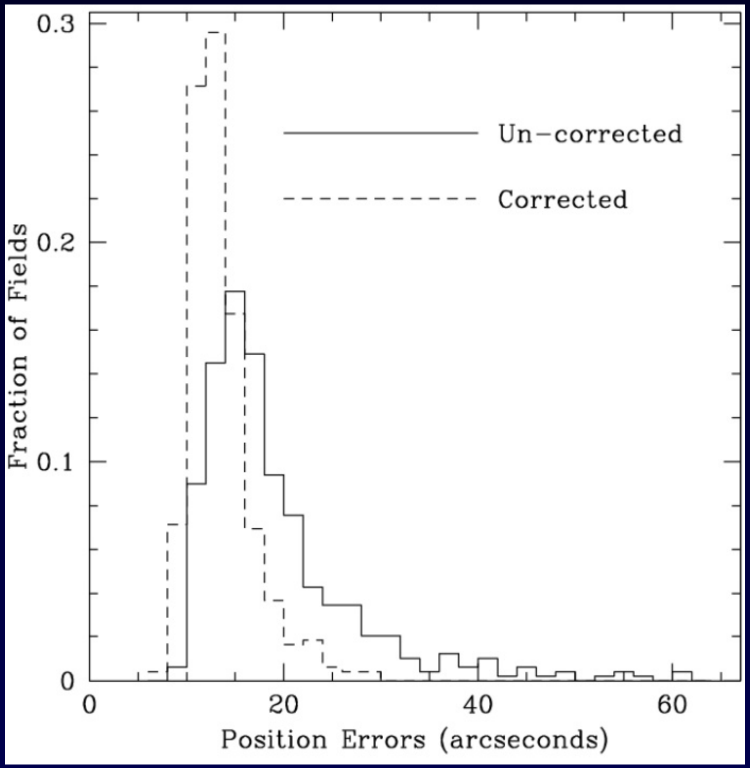


Field-based algorithms developed by W. Cotton and J. Condon.
For more information, see
Cotton et al. 2004

Residual Ionospheric Corrections

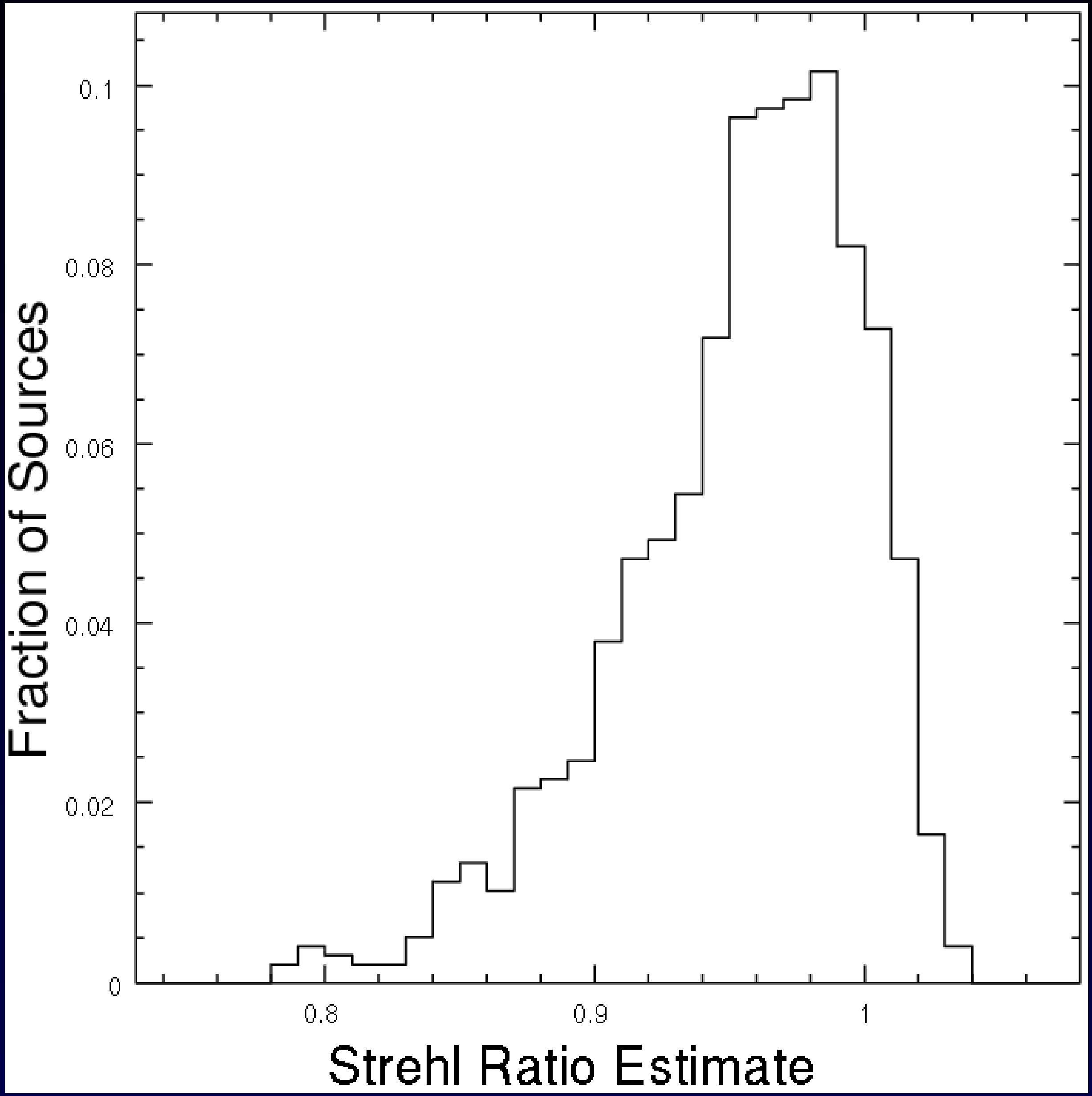


- Additional Ionospheric Correction:
  - Image produced from full time integration is compared to NVSS.
  - More accurate 4th order Zernike polynomial phase screen is determined to correct for residual time-invariant errors.
  - VLSS astrometry is significantly improved.



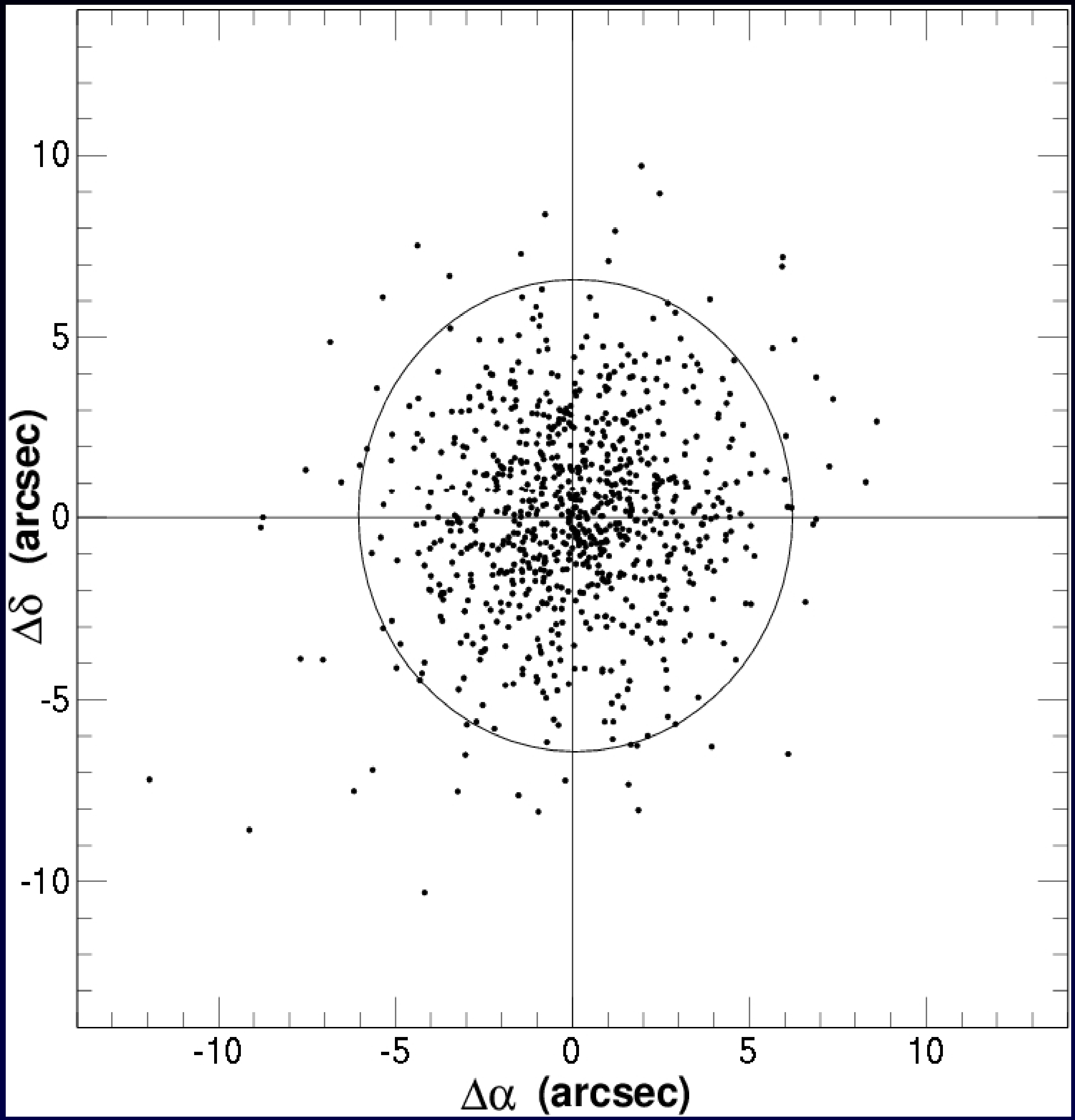
Strehl Ratios for VLSS Sources

- Test for Residual Ionospheric "Smearing"
  - Strehl ratio is ratio of resolution element to measured source size.
  - Strehl ratios measured for sources with:
    - High flux density
    - Isolated
    - Compact in NVSS
    - Not bright enough to be used as a calibrator
  - The median Strehl ratio for the VLSS = 0.96 or "seeing" of ~7 arcsec.



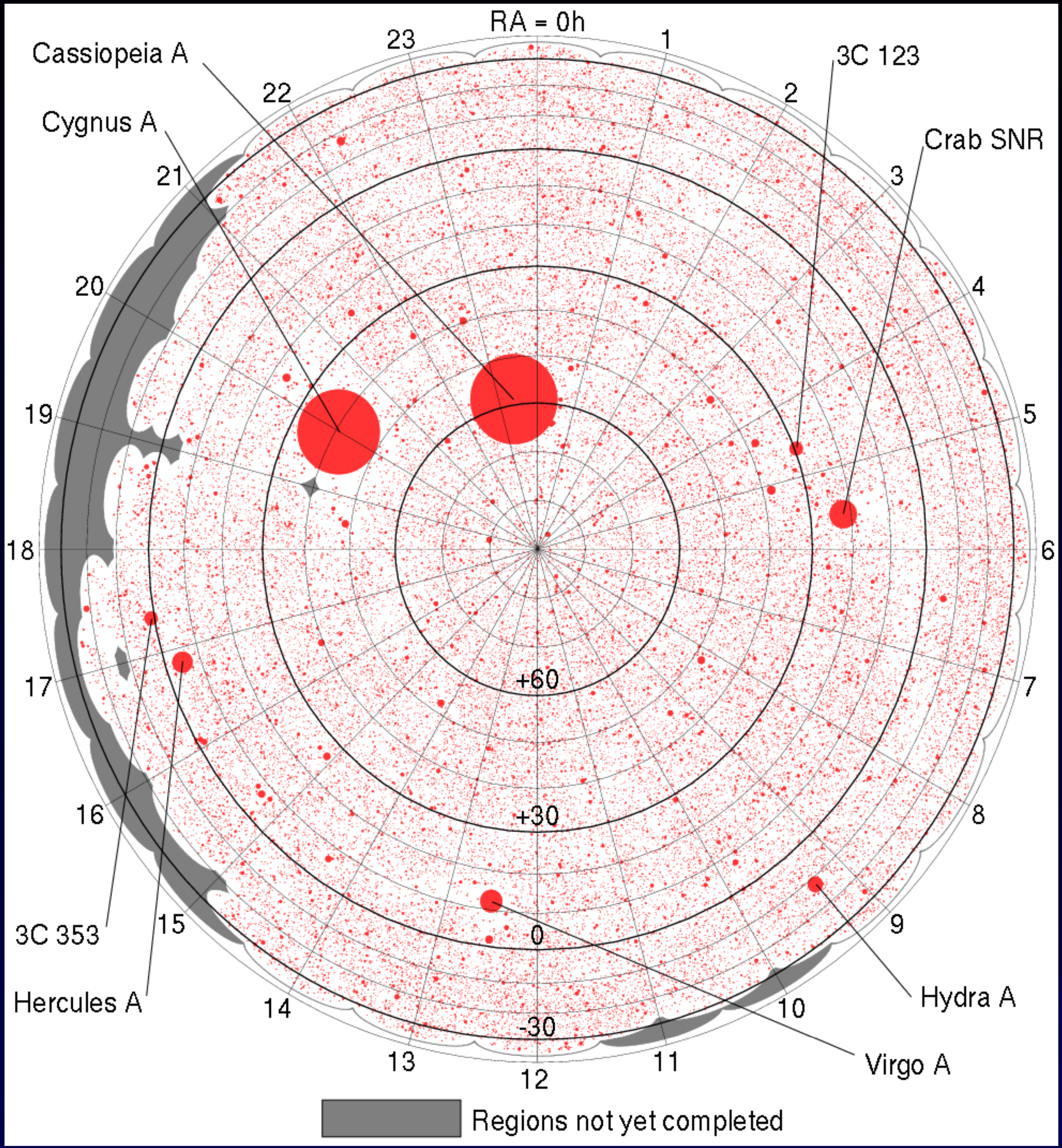
Astrometric Accuracy

- <u>Test for Astrometric Accuracy:</u>
  - Measured positions of sources with:
    - High flux density
    - Isolated and compact
    - Not bright enough to have been used as a calibrator
  - Positions were compared with NVSS
  - RMS deviation is about 3'', a small fraction of the 80'' synthesized beam.

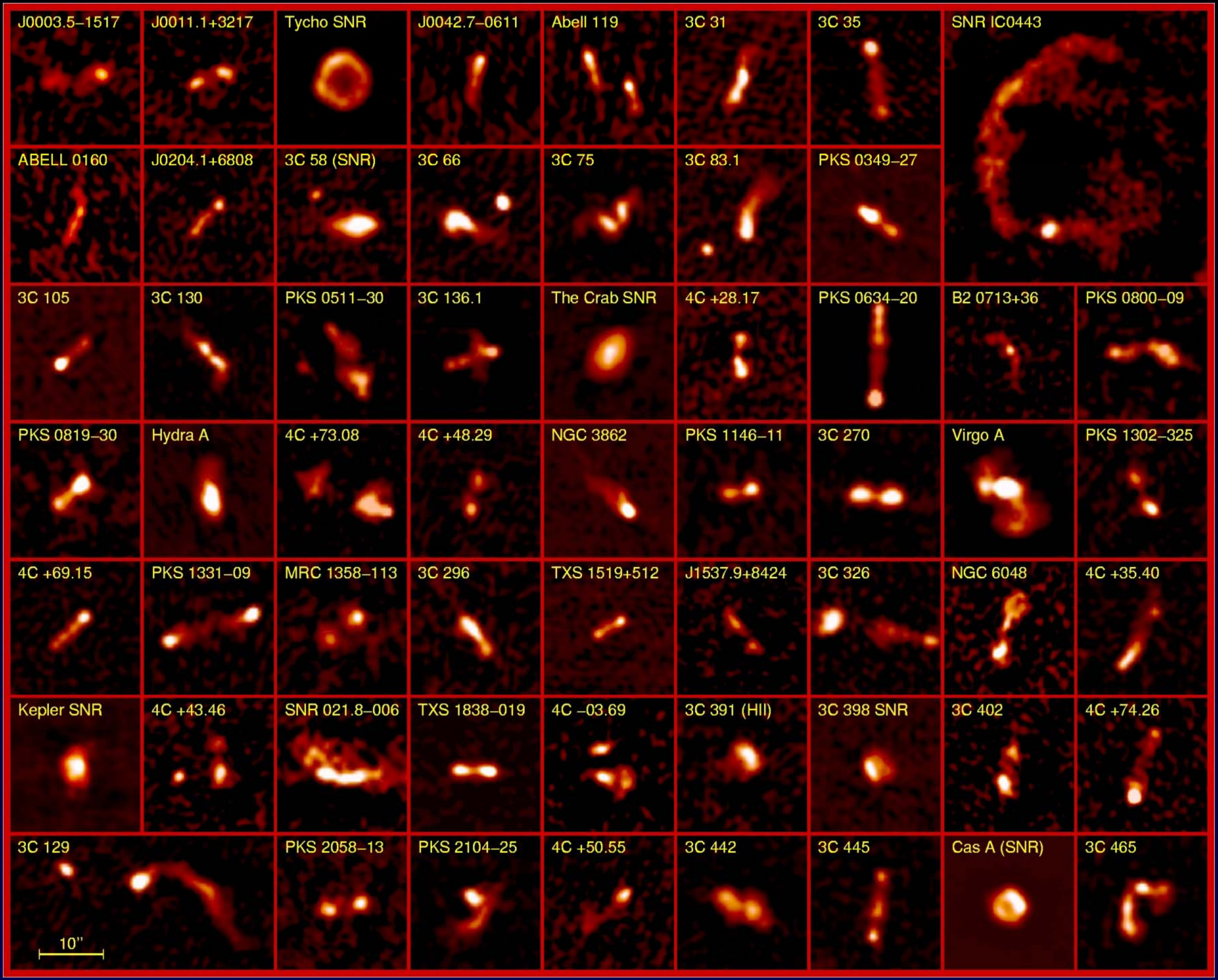


Radio Sources Detected by the VLSS

- <u>VLSS Sources</u>
  - Over 90% of survey region is now completed.
  - Equivalent to 70% of the entire sky.
  - About 67,000 radio sources have been detected at 5σ level.
  - Sources are plotted with red circles.
  - The area of each circle is proportional to its flux density.



Large Sources in the VLSS



Software Platforms Used

- AIPS – publicly available:
  - Bandpass calibration.
  - Amplitude gain calibration.
- AIPS – tasks written “in house” for 74 MHz needs:
  - Automated RFI flagging.
  - Instrumental phase gain calibration.
  - Field based ionospheric calibration and imaging.
  - Image mosaicing.
  - Automated source finding.
- OBIT:
  - Residual ionospheric corrections.
  - Error analysis (simulations to determine completeness and clean bias).

Conclusions

- <u>Conclusions</u>
  - We have developed and demonstrated data reduction algorithms that can reliably produce 74 MHz images at a resolution of 80’’.
  - This is only a first step towards what will be required for future instruments with higher dynamic range and resolution.
  - Future instruments will require much more sophisticated data reduction algorithms than currently exist.
  - We have gained valuable experience calibrating and measuring ionospheric distortions which can be used to guide future LF telescope designs and data reduction algorithms.
  - Having a common platform for low-frequency data reduction will make life easier for all low-frequency projects.
  - We (the VLSS team) have PLENTY of raw low-frequency data available for initial testing of any new software.