Heterogeneous Array Imaging with the CARMA Telescope

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• CARMA: 23-antenna array of 10.4, 6.1 and 3.5 m antennas,

• 1) Heterogeneous Array Mosaic Imaging.
  \( uv \) spacings from \( \sim 3.5 \) m to 2 km.
  Image a wide range of spatial scales.
  High quality short spacing data for aperture synthesis.
  Primary beam calibration, errors and image fidelity

• 2) Paired Antenna Calibration of atmospheric seeing.
  3.5 m antennas at \( \lambda \) cm calibrate \( \lambda \) mm observations
  Simultaneous calibration within a few degrees.
  0.15 arsec resolution in poorer atmospheric seeing.

• 3) Relevant for other aperture synthesis arrays
  mm/submm arrays: ALMA.
  cm/m wavelength arrays: SKA.
Figure 1: The CARMA 23-element interferometer at Cedar Flat.
1 INTRODUCTION

- Astronomical studies require observations wide range of spatial scales.
- 10 m antenna at $\lambda$ 1.3 mm has a field of view of $\sim 30''$.
- Extended sources require interferometer and single dish observations.
- Homogeneous arrays well studied (Cornwell, Holdaway & Uson, 1993).
- Image fidelity limited by pointing, and primary beam errors.
- Mosaic observations sample spatial frequencies around each $(u, v)$ point. (Ekers and Rots 1979)
- Homogeneous array depends heavily on single dish for spatial frequencies less than the antenna diameter.
2 CARMA

- Heterogeneous array of 10.4, 6.1, and 3.5 m antennas.
- OVRO, BIMA and SZA antennas merged on a new site at 2200 m.
- $\lambda$ mm aperture synthesis telescope.
- High spatial dynamic range: 3.5 m to 2 km.
- 10 arcmin to 0.15 arcsec resolution over a wide field of view.
- 8 GHz bandwidth in multiple subarrays.
Owens Valley Array

Figure 2: The OVRO array of 10m antennas.
Figure 3: The BIMA array of 6m antennas.
Moving 6m Telescopes from Hat Creek

Figure 4: Moving 6m antennas from Hat Creek.
Moving to CARMA
Antennas arrive at CARMA site
Figure 7: Re-building 6m antennas at CARMA
Moving 10m Telescopes from Owens Valley
Figure 9: Moving 10m antennas thro the narrows to CARMA
Figure 10: Re-building 10m antennas at CARMA
Figure 11: Building CARMA
Figure 13: M51 mosaic image combining 151 pointings of the CARMA 15-antenna array. (Koda et al., 2009, ApJ L700, 132)
3 HETEROGENEOUS ARRAY

- Adding 3.5 m antennas: Better sensitivity to large scale structures; Sample short $uv$ spacings.
- Large range of spatial frequencies with interferometer observations.
- Decouple the source from the primary beam illumination.
- Cross calibration of 3.5, 6.1 and 10.4 m antennas, for single dish and interferometer observations.
- Density of $uv$ samples doubled; improves image fidelity.
- Heterogeneous array produces better image fidelity than homogeneous array with the same number of antennas and collecting area.
- By historical accident, CARMA has about the right ratio of antenna sizes to produce good image fidelity for mosaics.
4 DATA SAMPLING

- Cross correlation of 10.4, 6.1 and 3.5 m antennas provides $uv$ data to deconvolve the synthesized and primary beam responses from the image.
- Sample rates are set by both the largest and smallest antenna diameter.
- Nyquist interval for the pointings, $\delta \theta = \lambda/2D_{max}$.
- Nyquist interval for the $uv$ data, $\delta uv = D_{min}/2\lambda$.
- Data are properly weighted in the imaging algorithms.
- 10 m antennas on longest interferometer baselines provides more uniform sensitivity and reduces the $uv$ sample rate.
- This mode produces the best image fidelity in practice.
5 PRIMARY BEAM PATTERNS

- Primary beam pattern for each pair of antenna types.
- Same pointing pattern for all antennas reduces number of primary beam types and minimizes primary beam errors.
- Mosaic observations with 10.4, 6.1 and 3.5 m antennas produce 6 primary beam types at each pointing center.
- Primary beam is the product of voltage patterns for each antenna pair.
- Complex valued PB if voltage patterns are not identical.
- Errors in voltage beam patterns degrade the image fidelity.
Table 1 lists the equivalent antenna diameter, primary beam FWHM and Nyquist sample interval at 230 GHz.

- Within 5% level, primary beam patterns are Gaussian.
- Clip primary beam model at $\sim 5\%$ to avoid errors at low levels.
- For best image fidelity use measured voltage patterns for each antenna.
Simulated observations with cross correlations between 3.5, 6.1, and 10.4 m antennas. 23-antenna configurations: EZ, DZ, CZ.

Model image of Saturn + rings ∼ 45″ diameter.

$uv$ data sampled from -2 to +2 hours: good azimuthal $uv$ coverage, and minimize antenna shadowing.

Hexagonal pointing pattern with 15″ spacing; ∼ 45″ diameter source lies within FWHM of 6.1 and 3.5 m antennas.

Large field mapped by 3.5 m antennas helps define extent of source.

Thermal noise, using receiver temperature 80 K and zenith opacity 0.26 at 230 GHz, was added to the $uv$ data.
• Maximum Entropy (MEM) deconvolution

• Three different MEM deconvolutions were used:
  i) Using interferometer data only with a total flux constraint.
  ii) Using single dish data as a default image.
  iii) Joint deconvolution of interferometer and single dish data.

• Resulting images were compared with model to measure image fidelity.
Figure 14: CARMA 23-element heterogeneous array. Left: uv data sampling at 100 GHz, DEC=30°. Yellow points: uv coverage for the CARMA 15-element array; blue points show the additional uv coverage when the 3.5-m antennas are used in the 23-element array. The dense uv sampling at short spacings shown in the inset, gives sensitivity to larger scale structure. Right: Simulated CARMA observations of Saturn show the increase in image fidelity for extended sources provided by the 3.5 m antennas.
7 SINGLE DISH DATA

- Using single dish data as a default image, provides a total flux estimate and low spatial frequencies unsampled by the interferometric mosaic.
- This gives higher image fidelity than just using the interferometer data with a total flux estimate.
- Best image fidelity using joint deconvolution of interferometer and single dish data.
- Extent to which single dish data can be deconvolved is limited by primary beam and pointing errors in the single dish data.
- Single dish data from 10.4 m antennas; noise 1% of the peak flux density, to include primary beam and pointing errors.
- Multiple 10.4 m antennas reduce pointing and primary beam errors.
• Giving higher weight to the single dish data, as in the joint deconvolution, improves the image fidelity, but a 1% error may be unrealistic.

• In practice, primary beam and pointing errors will limit image fidelity (Cornwell, Holdaway & Uson, 1993).

• Best image fidelity using cross correlations with 3.5 m antennas.
8 PRIMARY BEAM ERRORS

• Heterogeneous cross correlations provides additional $uv$ data to deconvolve the synthesized and primary beam responses from images.

• Errors in the voltage beam patterns which lie within the primary beam of smaller antennas corrupt images.

• If we do not determine the primary beam patterns well enough, the errors will degrade the image fidelity.

• Concentric pointing centers minimize uncertainties in the product of voltage patterns.

• Asymmetric primary beam patterns rotate on the sky.
9 USING MEASURED PRIMARY BEAM PATTERNS

- Primary beam pattern is complex valued if the antenna voltage patterns are not identical.
- Use measured voltage patterns to generate primary beam patterns for each antenna pair.
- Simulate mosaic observations using images of Cas A and Saturn scaled to different diameters as source models.
- Model $uv$ data for ALMA, ACA, ATA and CARMA telescopes.
- Standard MIRIAD software.
Figure 15: Scaled image of Cas A illuminated by ALMA 12 m antennas in a 19-pointing mosaic.
Figure 16: Scaled image of Cas A illuminated by ALMA 12 m antennas in a 19-pointing mosaic.
Figure 17: Scaled image of Cas A illuminated by ALMA 12 m antennas in a 19-pointing mosaic.
• Image fidelity calculated from difference between mosaic image and original image model convolved to the same resolution.

• Pointing and primary beam errors cause amplitude and phase errors in the \( uv \) data by changing the illumination pattern of the source.

• Pointing errors corrected on line during data acquisition.

• Measured deviations in primary beam patterns not well represented by pointing and focus errors.
• Real part of primary beam is close to the canonical Gaussian model.
• Imaginary part shows an asymmetric gradient caused by offset aperture illumination on some 10 m antennas.
• Image fidelity increased significantly by correcting this offset.
• Instrumental polarization response across the primary beam is also improved by reducing the imaginary part of the primary beam response.
Figure 18: Primary beam pattern for cross correlation between two 10m antennas 2 and 6. The red contours are the real part of the primary beam response. The blue contours are the imaginary part of the primary beam response. Contour levels = -.2, -.15, -.1, -.05, .05, .10, .15, .2, .3, .4, .5, .6, .7, .8, .9.
Figure 19: Amplitude of $uv$ data from the central pointing with antennas 2 and 6. Black points are the simulated $uv$ data. The red curve is the model visibility for the Gaussian model primary beam pattern used to generate the $uv$ data. The blue curve is the model visibility using the real part of the measured primary beam response. The green curve is the model visibility using the real and imaginary parts of the measured primary beam response.
Figure 20: Phase of uv data from the central pointing with antennas 2 and 6. Black points are the simulated uv data. The red curve is the model visibility for the Gaussian model primary beam pattern used to generate the uv data. The blue curve is the model visibility using the real part of the measured primary beam response. The green curve is the model visibility using the real and imaginary parts of the measured primary beam response.
We present a method for deconvolving the primary beam response from interferometric images of astronomical sources.

Measured $\sim 1$-5% deviations from canonical beam patterns can be devastating, reducing image fidelity from 8000 to 50 for a source which fills the primary beam FWHM.

The image fidelity is greatly improved by using the measured voltage patterns in the deconvolution.

The data are imaged using canonical primary beam patterns, and deconvolved using the measured primary beam voltage patterns.

The primary beam may be time variable, non axi-symmetric and different for each antenna.
• Subtract a model image from \textit{uv} data weighted by the measured primary beam patterns (MIRIAD:uvmodel).

• Residual \textit{uv} data are re-imaged to make an improved model image.

• Iterate until the residual \textit{uv} data are consistent with thermal noise and other residual instrumental errors.
11 PAIRED ANTENNA CALIBRATION SYSTEM

- 3.5 m antennas paired with 6.1 and 10.4 m antennas making science observations at $\lambda$ mm.
- 3.5 m antennas simultaneously observe calibration sources at $\lambda$ 1 cm.
- Wide field of view of the 3.5 m antennas allows us to find strong calibration sources within 1-3 degrees of the target source.
- 3.5 m antennas placed within $\sim$ 20 m of 6.1 and 10.4 m antennas so that the atmospheric phase fluctuations are correlated.
- Subtract the phase fluctuations at $\lambda$ 1 cm measured by 3.5 m antennas, scaled by frequency, to correct atmospheric phase on the target source.
- PACS allows us to make images at 0.15 arcsec resolution in a wide range of atmospheric seeing conditions.
- The PACS results are discussed elsewhere in these SPIE proceedings.
Figure 21: Paired Antenna Calibration System using 3.5 m antennas at 30 GHz. The 3.5 m antennas are paired with 6.1 and 10.4m antennas making science observations at millimeter wavelengths. The 3.5 m antennas simultaneously observe calibration sources in the 1 cm band. For calibration sources within a few degrees, the millimeter wavelength observations of the science target source, and the observations of the calibrator at 1cm, sample similar atmospheric phase fluctuations, allowing us to correct for the atmospheric phase fluctuations on long baselines at millimeter wavelengths.
Figure 22: Phase correction using Paired Antenna Calibration System. The thick (green) line plots the phase versus time measured between CARMA antennas 2 and 5 while observing the radio source 3C111 at 225 GHz. The large phase fluctuations are caused by atmospheric turbulence on the long baseline between antennas 2 and 5. The dashed (blue) line plots the phase between two 3.5 m antennas which are close to CARMA antennas 2 and 5, but observing at 30 GHz. The 30 GHz phase multiplied by 7.5 (225/30), closely follows the 225 GHz phase allowing us to correct the 225 GHz phase. The thin (red) line shows the 225 GHz phase, corrected for atmospheric phase fluctuations.
Paired Antennas 6m + 3.5m
Paired Antennas 10m + 3.5m
Antenna-Based Phase Correction –

3C273 - selfcal 15 min instr/0.03 min atm - best fit coeff=2.96/used=3.09

Antenna phase (deg)

Time (hrs)

CARMA5 before (RMS=48.5 deg)

CARMA5 after (RMS=13.7 deg)
Figure 26: PACS: Orion KL before atmospheric phase correction.

CARMA map
1mm
0.3'' resolution
CARMA map
1mm
0.3'' resolution
Ori KL source I and BN after atmospheric phase correction.
Heterogeneous arrays have some advantages:

- Smaller antennas allow a larger range of spatial frequencies to be sampled by interferometer observations.
- Heterogeneous beam patterns decouple the source brightness distribution from the primary beam illumination.
- Short $uv$ spacings; less dependence on single dish observations.
- Large overlap in spatial frequencies to cross calibrate single dish and interferometer observations.
- Excellent cross calibration of the 3.5, 6.1 and 10.4 m antennas.
• The 3.5 m antennas effectively sample a guard band around the source brightness distribution. This helps the mosaic algorithms to define the extent of the source. Imaging a guard band without having to make observations at extra pointing centers was an unexpected bonus.

• Pointing and primary beam errors cause amplitude and phase errors in the measured $uv$ data by changing the illumination pattern of the source.

• Complex valued primary beam results in polarization errors.

• Instrumental polarization across the primary beam is significantly improved by reducing the imaginary part of the primary beam which arises from asymmetries in the aperture illumination.
• Image fidelity improved by using the measured voltage patterns in the deconvolution.
  
  i) subtract the best estimate of the sky brightness distribution weighted by the measured primary beam pattern from $uv$ data.
  
  ii) residual $uv$ data re-imaged to provide an improved model of the sky.
  
  iii) iterate until the residual $uv$ data consist of thermal noise and other instrumental errors.

• These results are relevant to all aperture synthesis arrays, including $\lambda$ mm/submm arrays like ALMA, and cm/m wavelength arrays like SKA.

• The results are especially relevant for aperture arrays where the primary beam is time variable.
• At millimeter wavelengths, the voltage patterns can be measured using strong astronomical sources, or a transmitter to obtain sufficient signal to noise.

• If the primary beam voltage patterns can be characterized as a function of elevation, temperature etc, then these data can be used to correct the $uv$ data.

• At cm/m wavelengths, the sky brightness model itself may provide the best voltage patterns measurements.

• The problem is a self-calibration determining sky brightness and primary beam models which are consistent with the $uv$ data in the sense that when the final model of the sky brightness, weighted by the primary beam patterns is subtracted, the residual $uv$ data are consistent with thermal noise or other residual errors. (e.g. LOFAR calibration)
• Alignment of antenna surface, subreflectors, and receiver feeds, feed leg blockage and reflections on the antenna structure all contribute to offsets and asymmetries in the aperture illumination.

• The magnitude and stability of these alignments will determine how well we can correct the data for primary beam characteristics.

• For phased array station beams, geometric projection and atmospheric path fluctuations make the complex valued station beams time variable.

• Even for clean voltage patterns with low level sidelobes, the complex sidelobe patterns vary with time due to pointing errors, which cause a time varying illumination of the sky brightness distribution.
CONCLUSIONS

- Primary beam errors are present in all aperture synthesis arrays and limit the image fidelity. At some level all arrays are heterogeneous.
- Primary beam and pointing errors dominate the image errors in mosaic observations of large sources.
- Precision antennas with stable primary beam patterns require fewer parameters which must be determined to calibrate the data.
Figure 29: Mosaic Image of Cas A using VLA Image as model observed using 19-pointing mosaic with ALMA config10 64-antenna configuration.
Figure 31: Radial distribution of the Fourier transform of Saturn Images. The solid black line shows the Saturn model. The amplitude shows a characteristic Bessel function from the disk and ring system. The red dashed line plots the Fourier transform of the MEM image, before convolving by a restoring beam. The radial distribution is plotted over the range of $uv$ spacings sampled by the CDZ configuration. The lower two curves show the difference images between the MEM images and the original model image both convolved by the restoring beam.
Figure 32: Mosaic Image of Cas A model scaled to 128″ diameter observed with the CARMA 15-antenna D configuration using a single pointing center at an observing frequency 100 GHz. The grey scale pixel image shows the maximum entropy deconvolution using the three standard truncated Gaussian primary beam models for 10m-10m 10m-6m and 6m-6m antenna pairs. The contours show the residual image when the measured voltage patterns for just one antenna pair, antennas 1 and 8, is used instead of the truncated Gaussian model. Contour intervals: -.004,-.003,-.002,.001,.002,.003,.004 Jy.
14 REFERENCES


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