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Wide field observations from the *e*-MERGE survey: First high-res LAS distribution at L-band.

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Sources in the Hubble Deep Field (North) have been observed in the past at 1.4 GHz using the original MERLIN radio interferometer network of telescopes based in the UK, yielding 92 positive detections over a 10 arcmin wide region. The subsequent data reduction and analysis took considerable time due to the high resolution and large imaging area. To enable rapid imaging of 26 hours of new *e*-MERLIN data collected for the *e*-MERGE survey, a method presented here uses a modified technique originally conceived to image VLBI fields contiguously. The 'Fast Wide Field Imaging' methodology is expanded to wide-band imaging of observations taken by the new *e*-MERLIN array of the same GOODS-North region demonstrating a considerable speed increase. The incorporation of a primary beam model, the ultimate limiting factor to the instrument's field-of-view corrects the flux and crucially allows modification to synthesised cleaning beams taking into account the induced spectral index. It demonstrates that the usable field of view of the *e*-MERLIN + JVLA imaging extends to 7.5 arcmin from the pointing centre. The results enable a tentative first analysis of the largest angular scales of high resolution source sizes within the HDF-N at L-band, yielding a median size of 1.3 arcsec. 90 percent complete to 20 μJy. This figure is expected to increase to 100 percent as the *e*-MERGE survey matures. As well as yielding useful evolutionary indicators, angular size distributions are also an important consideration in the design of future radio telescope array configurations.

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1. Fast Wide Field Imaging

Imaging wide-band *e*-MERLIN data required the development of customised tools to allow production of maps within a reasonable timeframe, due the size of the data and comparative computational constraints. This article describes the methodologies developed to correctly generate the images for the *e*-MERGE survey [1], particularly overcoming the following issues:

- The primary beam of the telescope array causes attenuation across the field.
- The primary beam causes induced spectral index across the band.
- The curved sky *w*-projection effect restricts imaging size.
- The dataset is large - imaging takes excessive amount of time even on modern workstations.

Each of these problems is mitigated in the method described here, modified from a technique originally devised for imaging VLBI data [3]. The process, called *fast wide-field-wide-band-imaging*, involves a hierarchical approach to averaging the *uv* data down in both time and frequency dimensions to create small facets which locally overcome the *w*-projection or curved-sky problem. Synthesised beam scaling compensates for the induced spectral index caused by the primary beam as well as attenuating confusing sources that give rise to *ripple noise*. The result is a technique that produces images at a speed up to two orders of magnitude faster than the standard CLEANing.

2. Primary Beam Correction

Whilst correct flux scales are derived for the pointing centre during standard calibration, the effect of the beam of each telescope in the array contributes an increasing amount of attenuation as a function of angular displacement from the centre. The antennas comprising the *e*-MERLIN array can be approximated as being equal to a 25m diameter aperture with two exceptions - the Cambridge telescope (32m) and the Lovell telescope at Jodrell Bank (76m). A semi-empirical model was developed to determine the amount of attenuation as a function of angular displacement from the pointing centre based on sensitivities of each telescope, and permitted flux corrections to be determined as a function of spectral window whilst providing the framework for a derivation of an optimal sensitivity weighting scheme as a function of frequency.

2.1 Hierarchical Averaging and Multi-Faceting

To circumvent the *w*-projection problem, whilst at the same time reducing the image processing time significantly and incorporating the induced spectral index compensation, fast wide-field wide-band imaging techniques are utilised. These are incorporated in the *e-MERLIN* pipeline. The calibrated and isolated target *uv* dataset is first phase rotated (using UVFIX) to four new phase centres, pre-determined by the required field of view. Each of the new visibilities is then averaged in time by a factor of two (i.e. 1 second averaging becomes 2 seconds etc) and also in frequency (i.e. 128 channels become 64 channels). The resulting *uv* files are each now 1/4 of the size of the original, but time and bandwidth smearing at the extremities have increased correspondingly. However, this effect is mitigated by an equal amount because the field of view is reduced by the same factor. The procedure is repeated for the new averaged files by rotating each one four times and averaging. The process is illustrated in Figure 1. The result is 64 facets spread over the primary beam area down to the predicted HPBW of the array.

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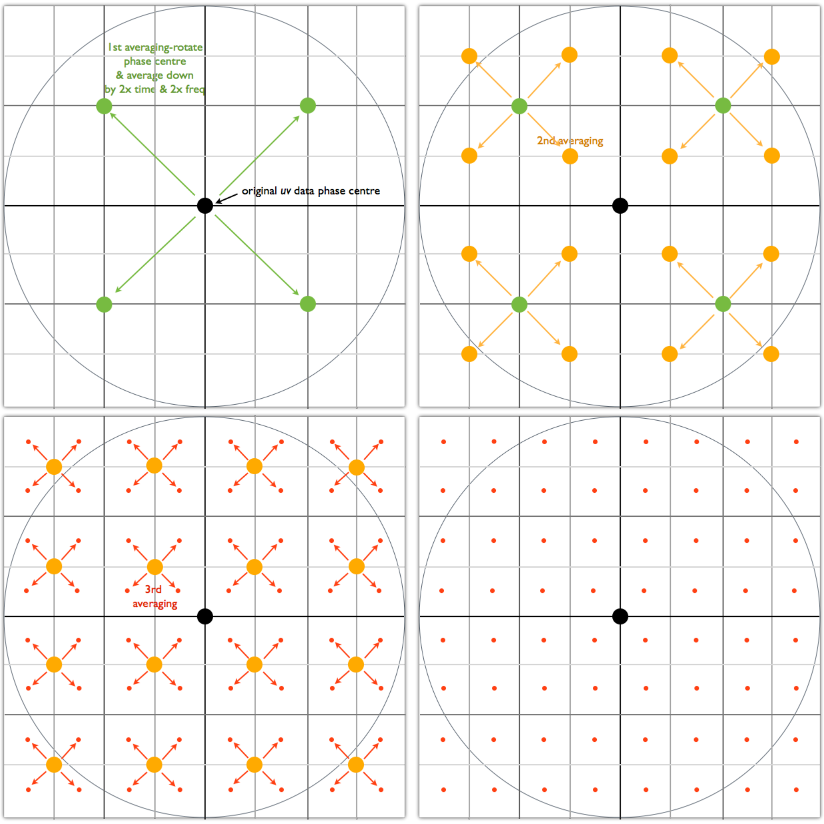

Figure 1: Fast Wide-field Imaging - first, second rotation and averaging (top), third and final rotation and averaging (bottom). The result is 64 small *uv* files that can be cleaned independently.

2.2 Spectral Cleaning Correction

The effects of the changing primary beam-width as a function of frequency have undesirable effects when using the standard CLEAN/APCLN algorithm within AIPS. Sources at the centre of the field (i.e. at the pointing centre) are not affected by the primary beam effects, however those some distance from the centre will experience significantly more attenuation at the higher frequency end of the band than at the lower. Consequently those sources will appear fainter in higher frequency IFs than in lower IFs. This *induced spectral index* emulates a source of very high spectral index and leads to poor beam deconvolution and hence amplitude errors.

Therefore, to more completely deconvolve sources towards the edge of the primary beam, the dirty beam should be modified to *better represent* the true integrated dirty beam, i.e. biased for those beams in the lower IFs. This can be achieved by instructing AIPS to create dirty beams for each frequency (at some localised region) and amplitude scaling the result according to the primary beam prediction (from the PB model). Once scaled, the dirty beams are averaged together and normalised to yield a single dirty beam, which is applicable to only that region. This is used for cleaning with the AIPS task 'APCLN' and results in minimal amplitude errors. The process is carried out within each of the 64 facets (in the example here a total of 10 million iterations are used) before being flattened and beam corrected using PBCOR parameters derived from the model. The resulting high resolution map measures over 300 megapixels.

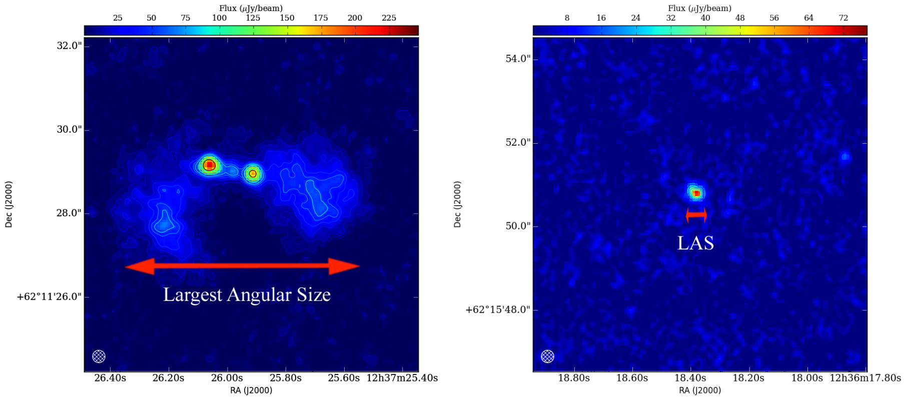

Figure 2: Left: A Wide-Angled-Tail source generated using the fast wide-field wide-band imaging illustrating an estimated Largest Angular Size (LAS) measurement. Right: An AGN source with comparative LAS.

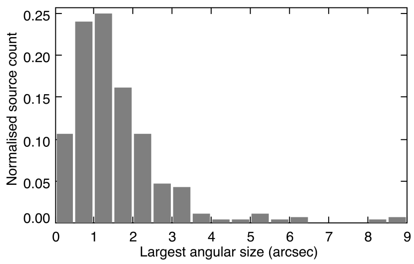

Figure 3: Largest Angular Size distribution obtained from 90 percent of the 339 sources within the GOODS-N region. The median galaxy size measured 1.3 arcsec (down to 20μJy).

3. Images

The results of the these preliminary e-MERGE observations are combined with JVLA data and legacy MERLIN observations [2] to yield the deepest high resolution map of the GOODS-North region to date, with a restoring beam size of 0.3 arcsec and a minimum rms noise under 2.7μJy/bm at the pointing centre. Postage stamp cutouts of selected sources are shown in Figure 2. A total of 339 sources were identified within the GOODS-N field at L-band from historical VLA data down to 20μJy. The Largest Angular SIze (LAS), which describes only greatest spatial extent of each object regardless of the number of components, was estimated for each of these sources using gaussian fitting and visual inspection. Of the sources 33 were not distinguishable from noise and were rejected. The remaining 90 percent are included in this analysis - see Figure 3. The median galaxy size was determined to be 1.3 arcsec.

References

[1] Muxlow, Smail and McHardy 2011. *The e-MERGE Survey: e-MERLIN Galaxy Evolution Survey.*

[2] Muxlow et al. 2005 *High-resolution studies of radio sources in the Hubble Deep and Flanking Fields.*

[3] Wucknitz, O. 2010. *Efficient wide-field VLBI imaging. POS (10th EVN Symposium).*