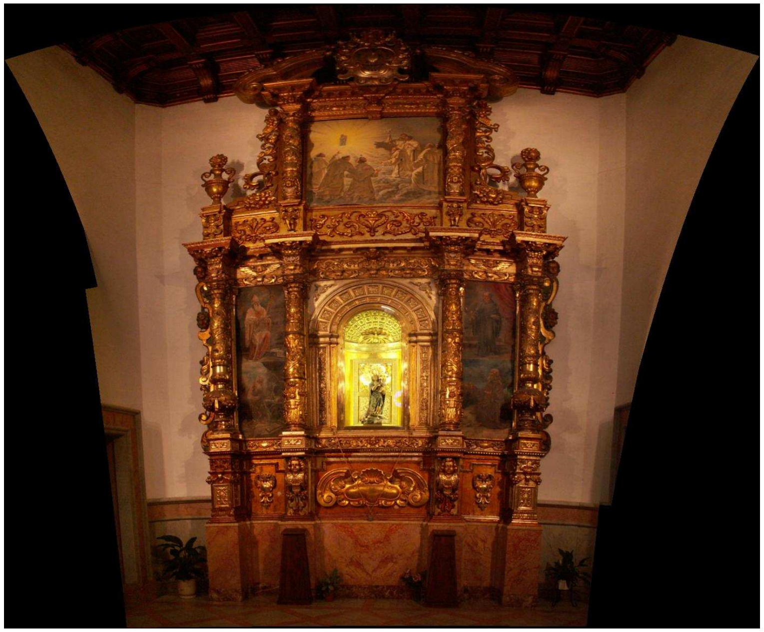
Wide-Field Imaging
Tom Muxlow

Wide-field imaging – not always as easy as it seems – things can get a bit distorted….

- Quick review of basic imaging – within AIPS – phase & gain calibration
- Non-coplanar baselines and multi-faceted images
- Wide-field combination imaging
- Bandwidth smearing (Chromatic aberration)
- Time-averaging smearing
- Primary beam response
- Confusion
- In-beam self-calibration



- Wide-field imaging: Multi-Frequency Synthesis – *e*-MERLIN and the EVLA
- Mosiacing – an example field from the GMRT at 610 and 1400 MHz
- High dynamic range imaging and implications for future instruments like the SKA

"Demonstration": How the GMRT 610 MHz field was made

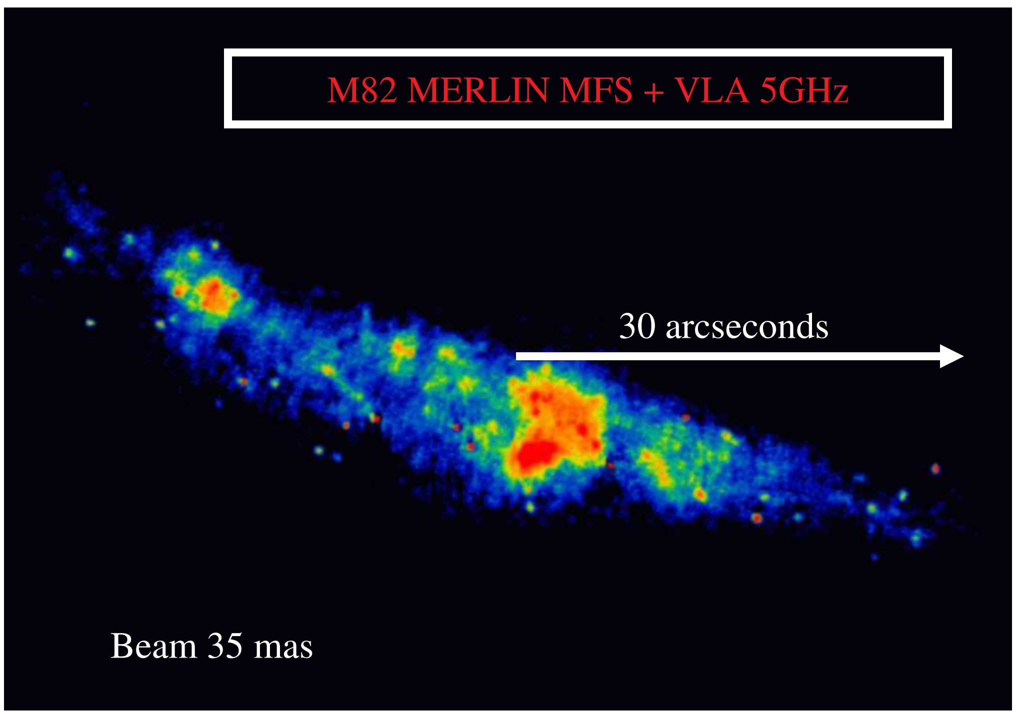
Wide-Field Imaging

- What do we mean by wide-field imaging?

Images with large numbers of resolution elements across them

Multiple images distributed across the interferometer primary beam

– M82 MERLIN MFS+VLA 5GHz image >1000 beams wide



- Wide-field images are subject to a number of possible distortions:

Bandwidth smearing

Time-averaging smearing

Primary beam response

Non-coplanar baselines

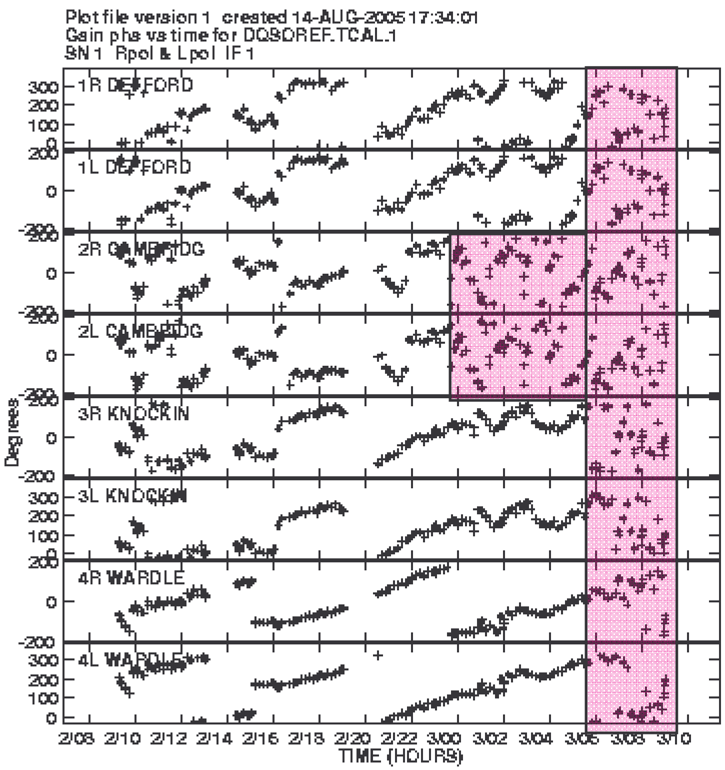
Wide Field Imaging

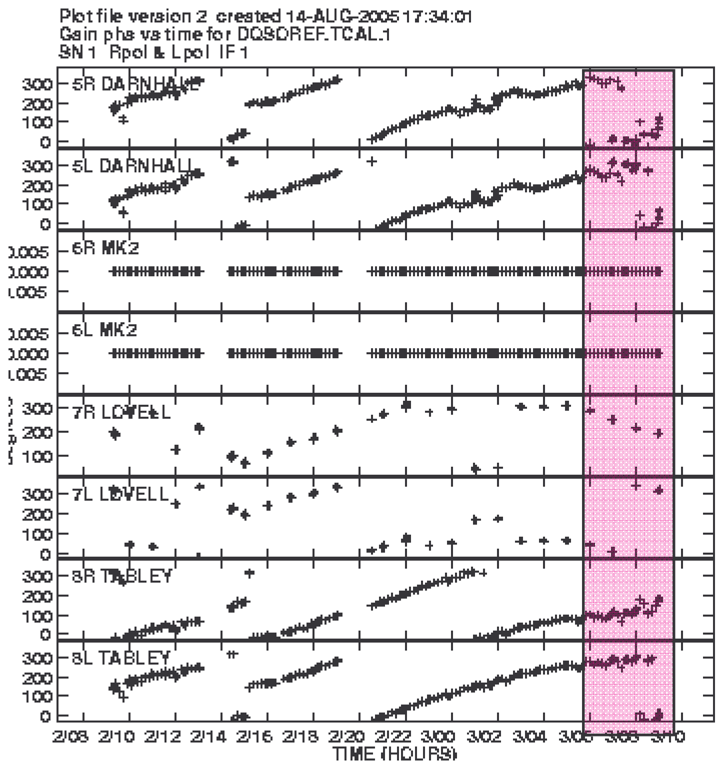
Conventional Imaging: Phase Calibration - 1

(As seen in the imaging demonstration)

- MERLIN is phase-stable (all telescope-generated LOs are locked to the Jodrell Bank Hydrogen maser standard) – but atmospheric delay must be calibrated by phase referencing to a nearby source. VLBI is less stable

- Ideally reference is a point – but can map out the object



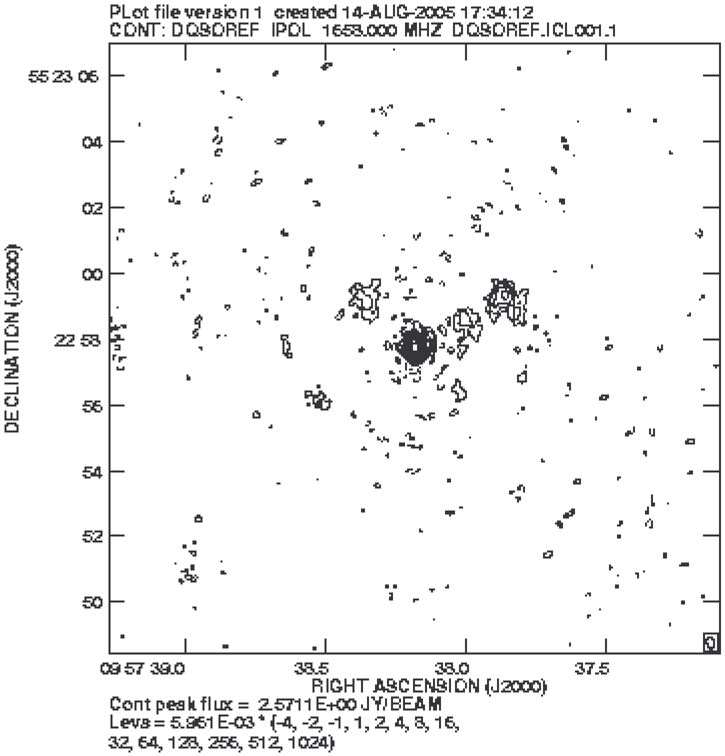


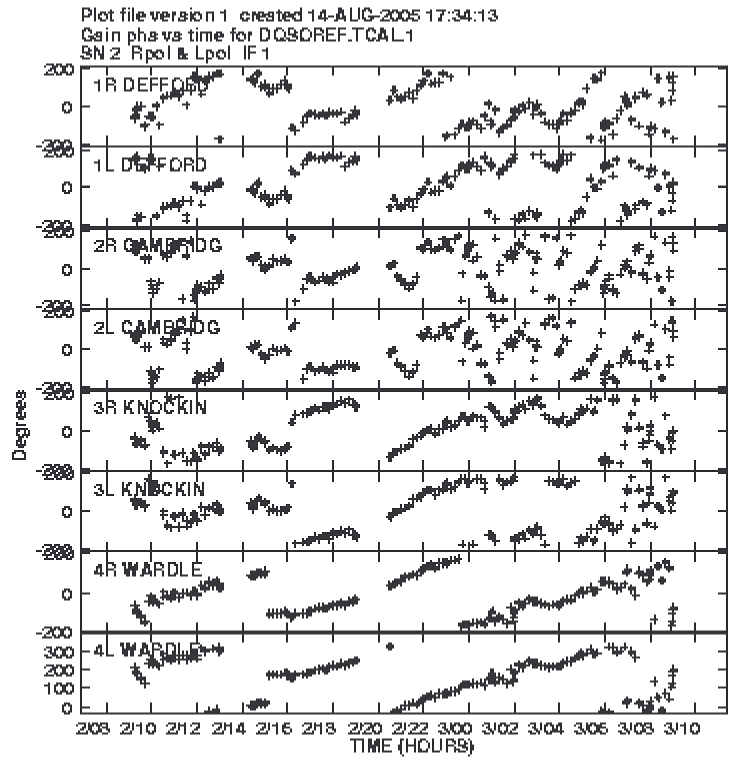
Phase-referencing cycle 7 mins – 3 mins with Lovell moving to the phase calibration source only every third scan – extends structural life by minimising total number of moves

Atmosphere less stable at end of run – also Cambridge has poor phase over the last six hours

Conventional Imaging: Phase Calibration - 2

- Initial phase solutions assume a point – first image of reference source may show structure.
- Use image clean components to refine phase solutions

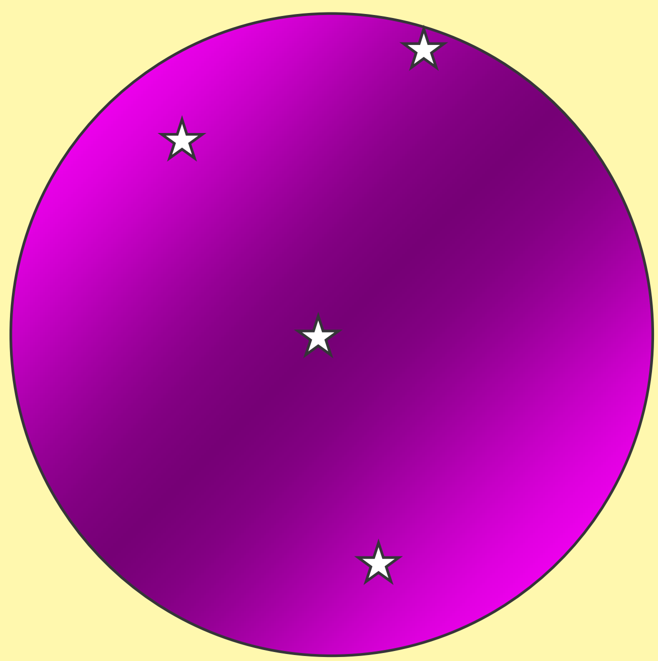




Conventional Imaging: Gain corrections

Wide-field Imaging:

Different parts of the primary telescope beam may have differing phase errors due to atmospheric non-isoplanicity or phase changes across the beam. Additional gain corrections will be required to account for the primary beam response.

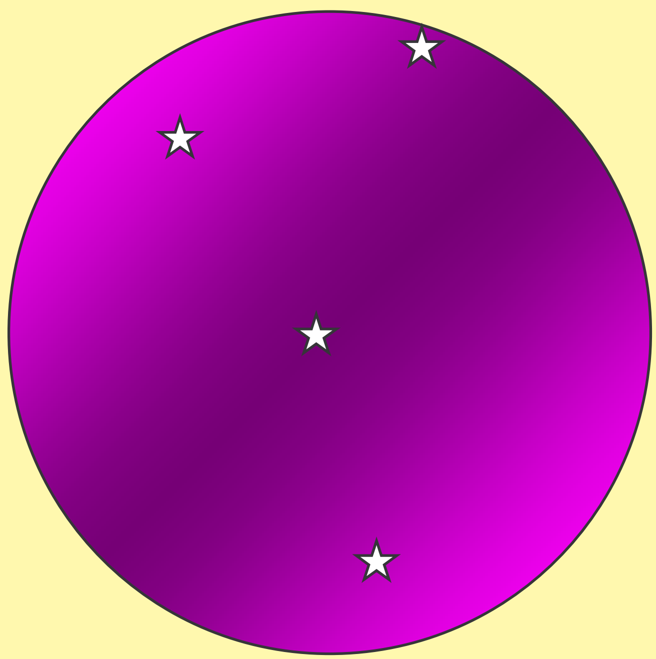


…more later

Conventional Imaging: Gain corrections

Wide-field Imaging:

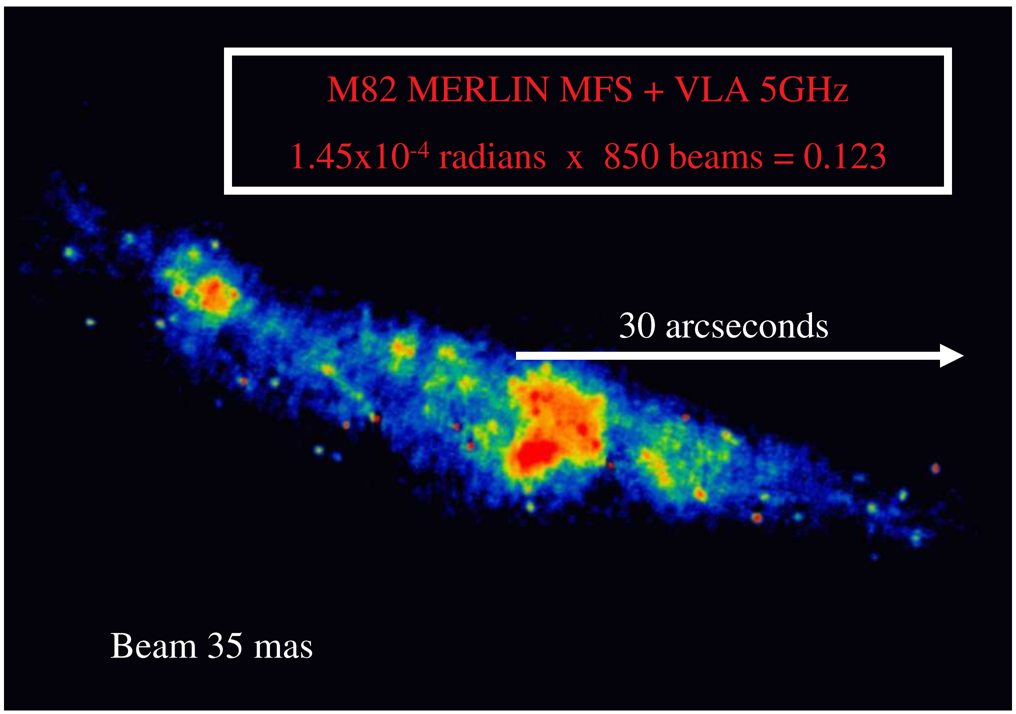
Different parts of the primary telescope beam may have differing phase errors due to atmospheric non-isoplanicity or phase changes across the beam. Additional gain corrections will be required to account for the primary beam response.



…more later

Wide-Field Imaging

Non-coplanar baselines



- Standard Fourier synthesis assumes planar arrays – only true for E-W interferometers
- Errors increase quadratically with offset from phase-centre
- Serious errors result if $\theta_{offset}(\text{radians}) \times \theta_{offset}(\text{beams}) > 1$
- Effects particularly severe for low-frequency VLA observations
- Need to account for a three-dimensional coherence function $V(u, v, w)$

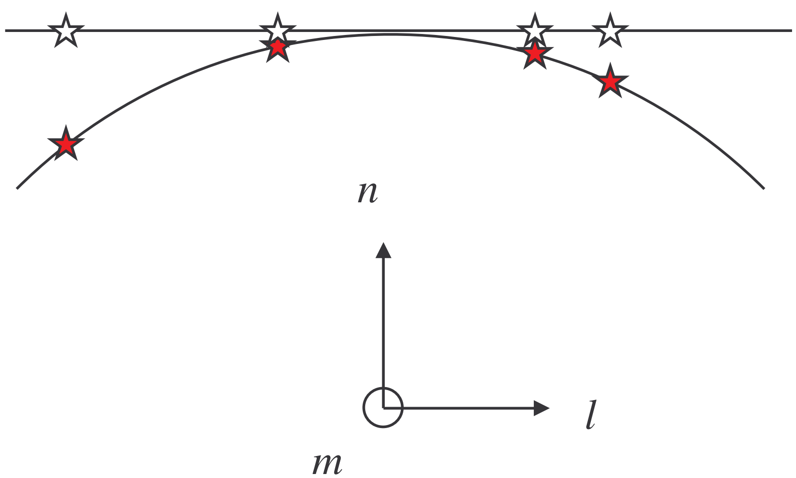
Wide-Field Imaging

Non-coplanar baselines

Wide Field Imaging

•Three-dimensional coherence function $V(u, v, w)$ can be Fourier transformed to a three-dimensional image volume $I(l, m, n)$ – this is not physical space since l, m, & n are direction cosines. The only non-zero values of I lie on the surface of a sphere of unit radius defined by $n = \sqrt{(1-l^2-m^2)}$.

•The sky brightness consisting of a number of discrete sources ★ is transformed onto the surface of this sphere.



•The two-dimensional image ☆ is recovered by projection onto the tangent plane

Wide-Field Imaging

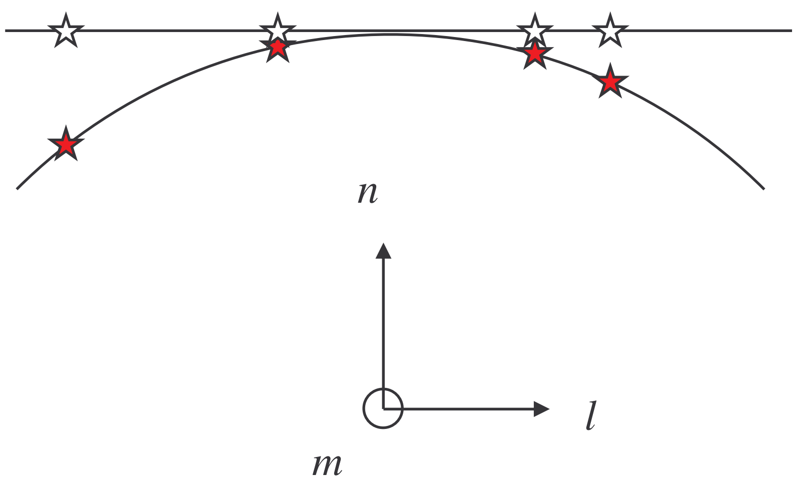
Non-coplanar baselines

- Three-dimensional direct Fourier transform of the coherence function $V(u, v, w)$ produces the three-dimensional image volume $I(l, m, n)$.

- Since the number of required planes in n is small compared with l and m, a gridded 3-D FFT is inappropriate since it will produce severe aliasing in the n dimension → must use a direct Fourier transform

- The instrumental response (dirty beam) is also three-dimensional.

- Accurate de-convolution requires three-dimensional beam subtraction.



- Full three-dimensional imaging is likely to be computationally expensive.

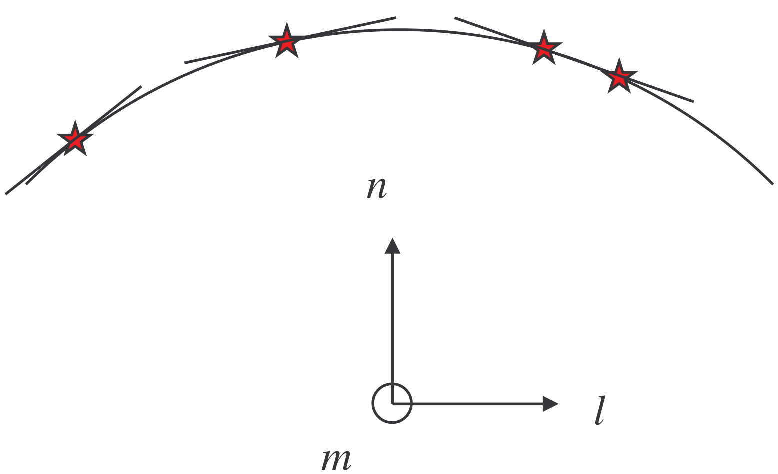
Wide-Field Imaging

Non-coplanar baselines

•A computational less expensive method of imaging is to adopt a faceted or small field approximation in which the image sphere is approximated by pieces of many smaller tangent planes. The centre of each sub-field is correctly positioned in the three-dimensional image plane.

•Within each sub-field fast two-dimensional FFTs may be used.

•Errors increase quadratically away from the centre of each sub-field, but these are acceptable if enough sub-fields are selected.



•Facets can be selected so as to cover known sources.

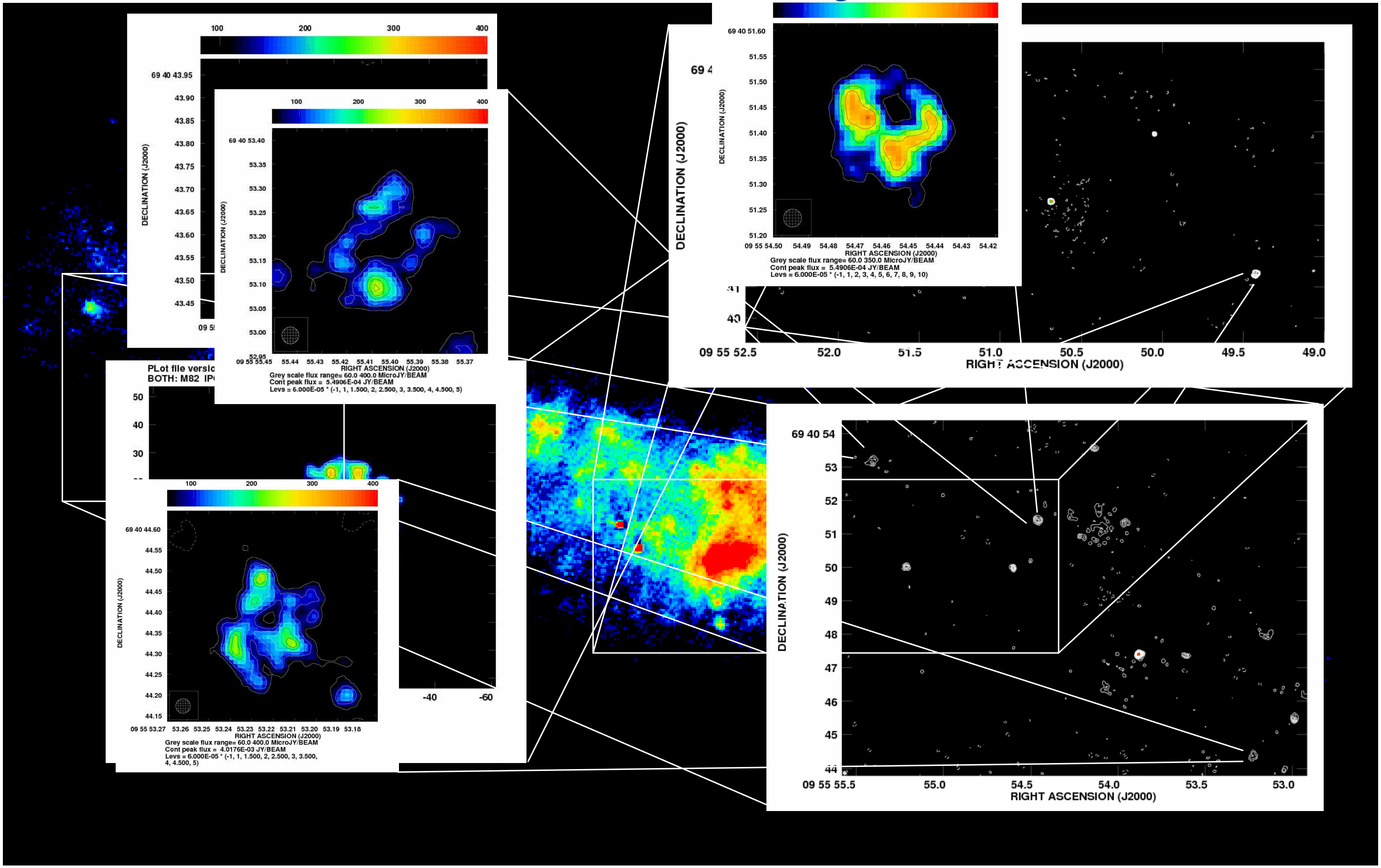
•Facets may overlap allowing complete coverage of the primary beam.

M82 Wide-Field Imaging: MERLIN+VLA 5GHz single image

EVN+MERLIN 1.7GHz multi-faceted image (Fenech et al)

Wide Field Imaging

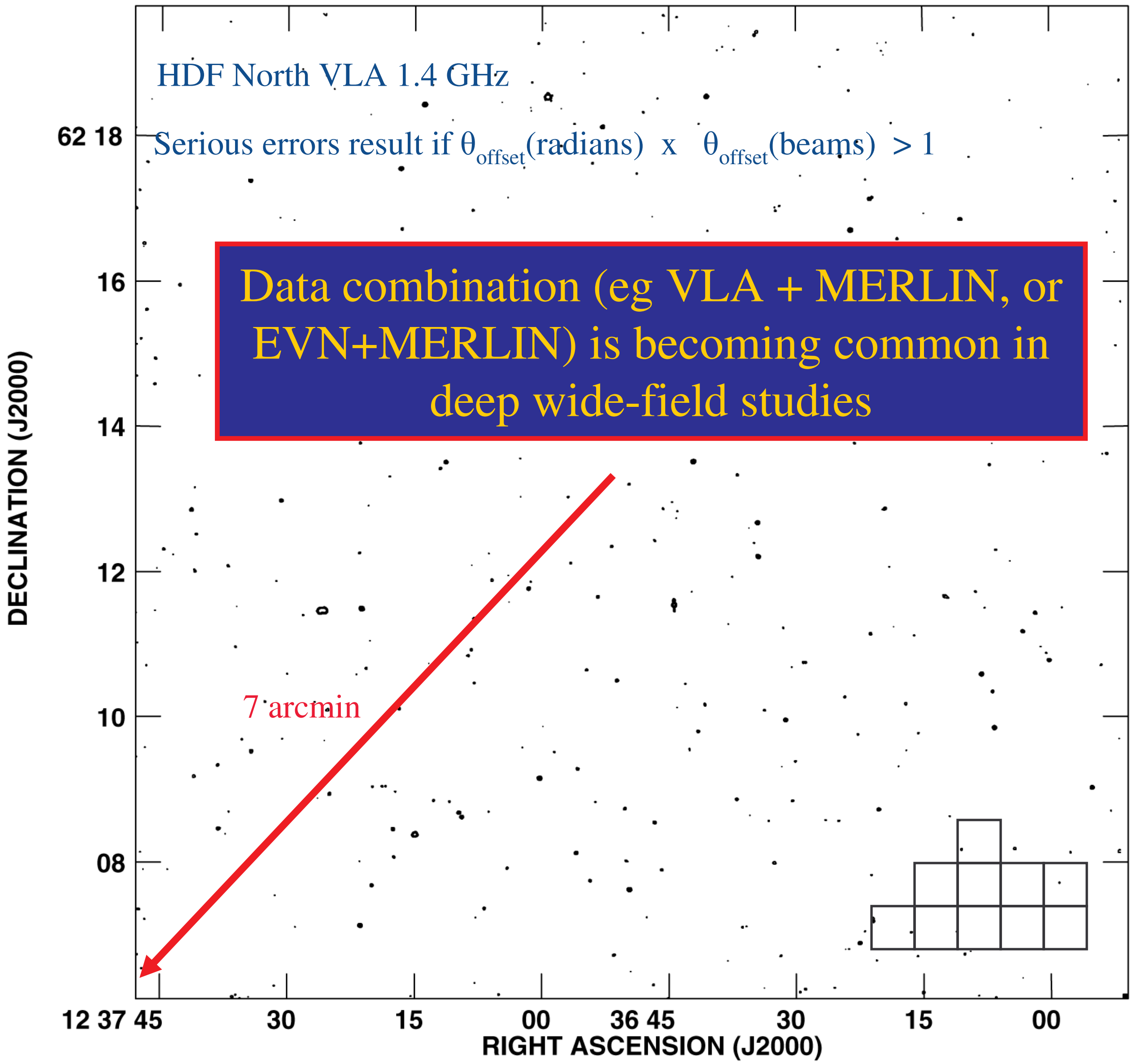
RadioNet



Wide-Field Imaging: Single or multi-faceted?

Wide Field Imaging

RadioNet



Corner of image 0.00206 radians from phase centre

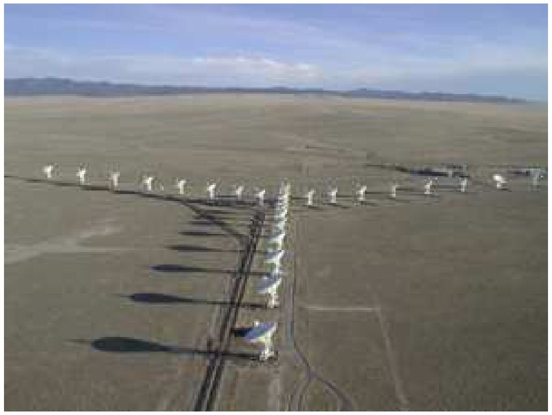
Beam = 2 arcsec – 212 beam offsets

212x0.00206= 0.437

OK!

- but not ok for VLA + MERLIN beam 200mas – need to mosaic with many smaller facets

Wide-Field Combination Imaging



Combination imaging or separate imaging ??

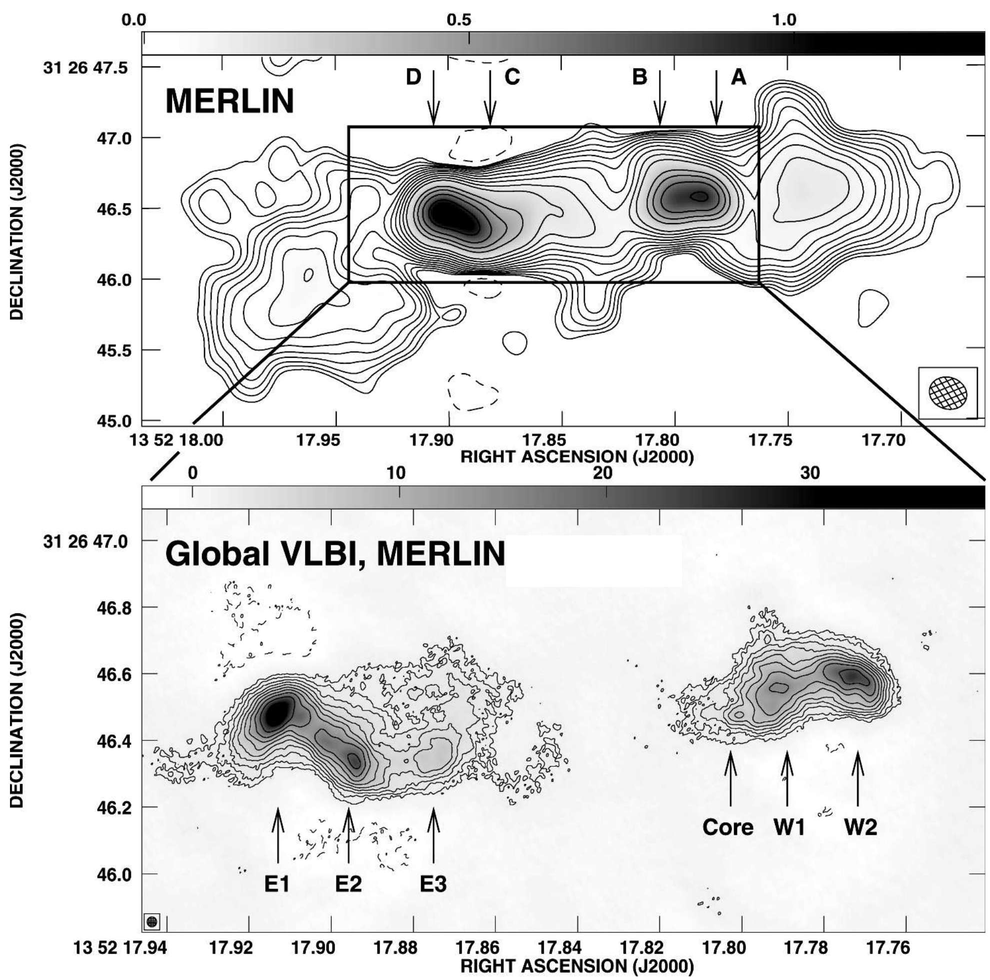
- Where surface brightness limitations do allow higher resolution imaging of extended structure, MERLIN will extend the resolution of the VLA, and VLBI extend that of MERLIN

- In VLA/MERLIN and MERLIN/VLBI combinations, the addition of the shorter-spacing data are required in order to provide otherwise missing spatial frequencies – they also stabilise the de-convolution procedure

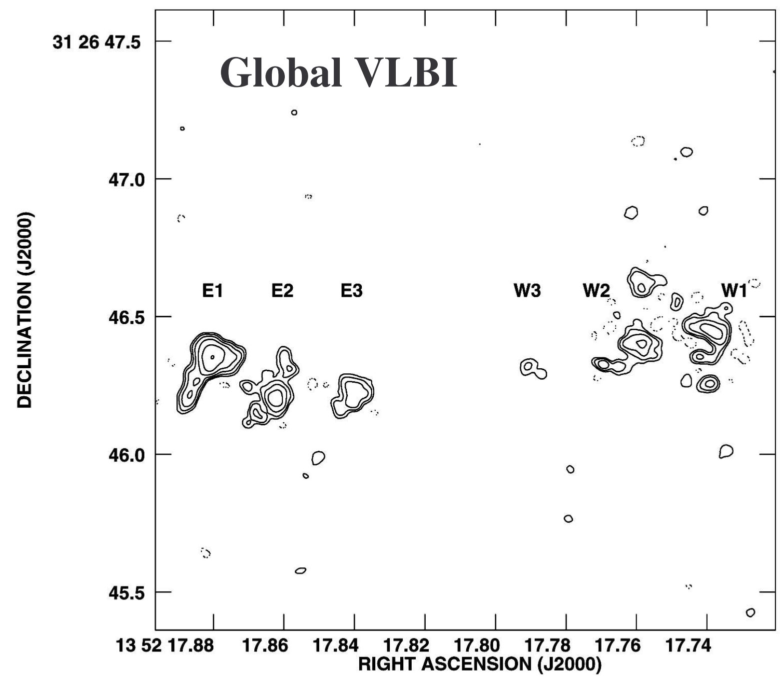
- Remember that the largest holes in the *u*-*v* coverage will always limit the size of extended region that can be imaged – MFS will fill spatial frequency coverage [*e*-MERLIN, EVLA]

Combination Imaging – stabilising de-convolution

3C293 Global VLBI + MERLIN (Beswick et al)

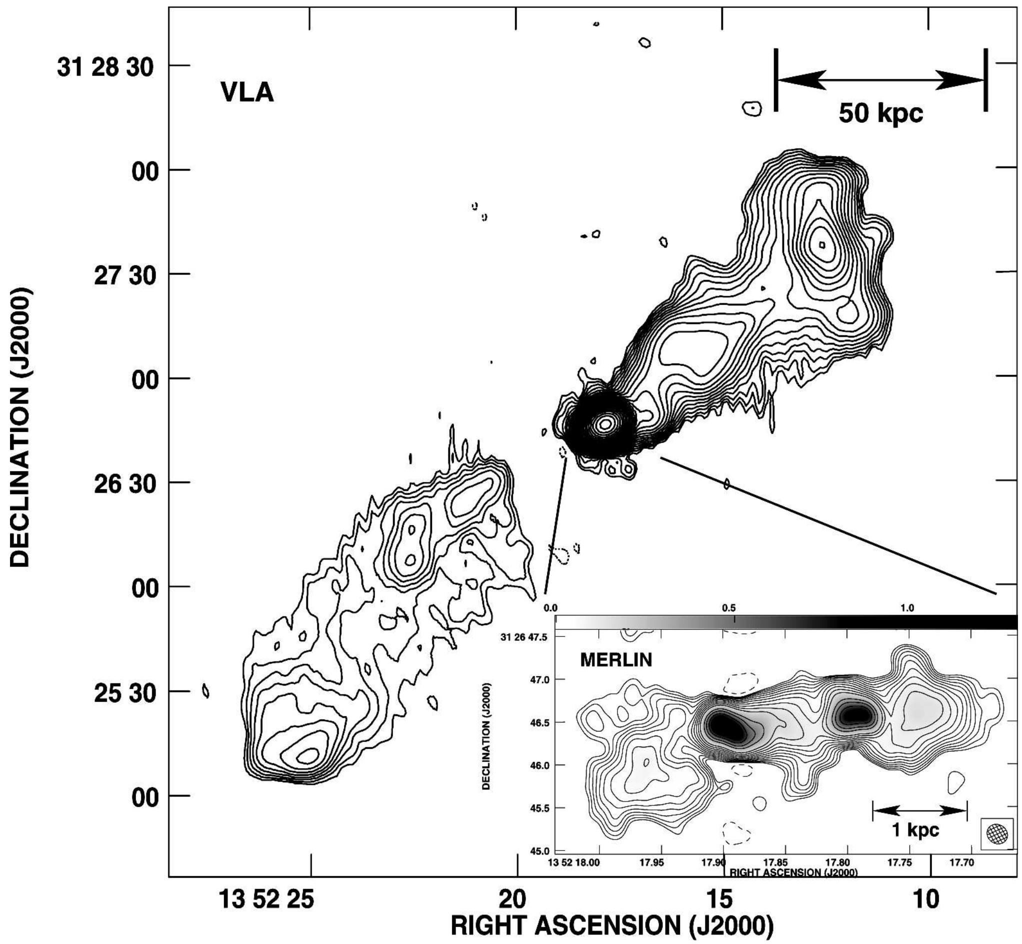


•MERLIN/VLBI combination stabilises the de-convolution of the VLBI-only image and permits high resolution imaging over extended components



Combination Imaging – separate images

3C293 Global VLBI + MERLIN (Beswick et al)



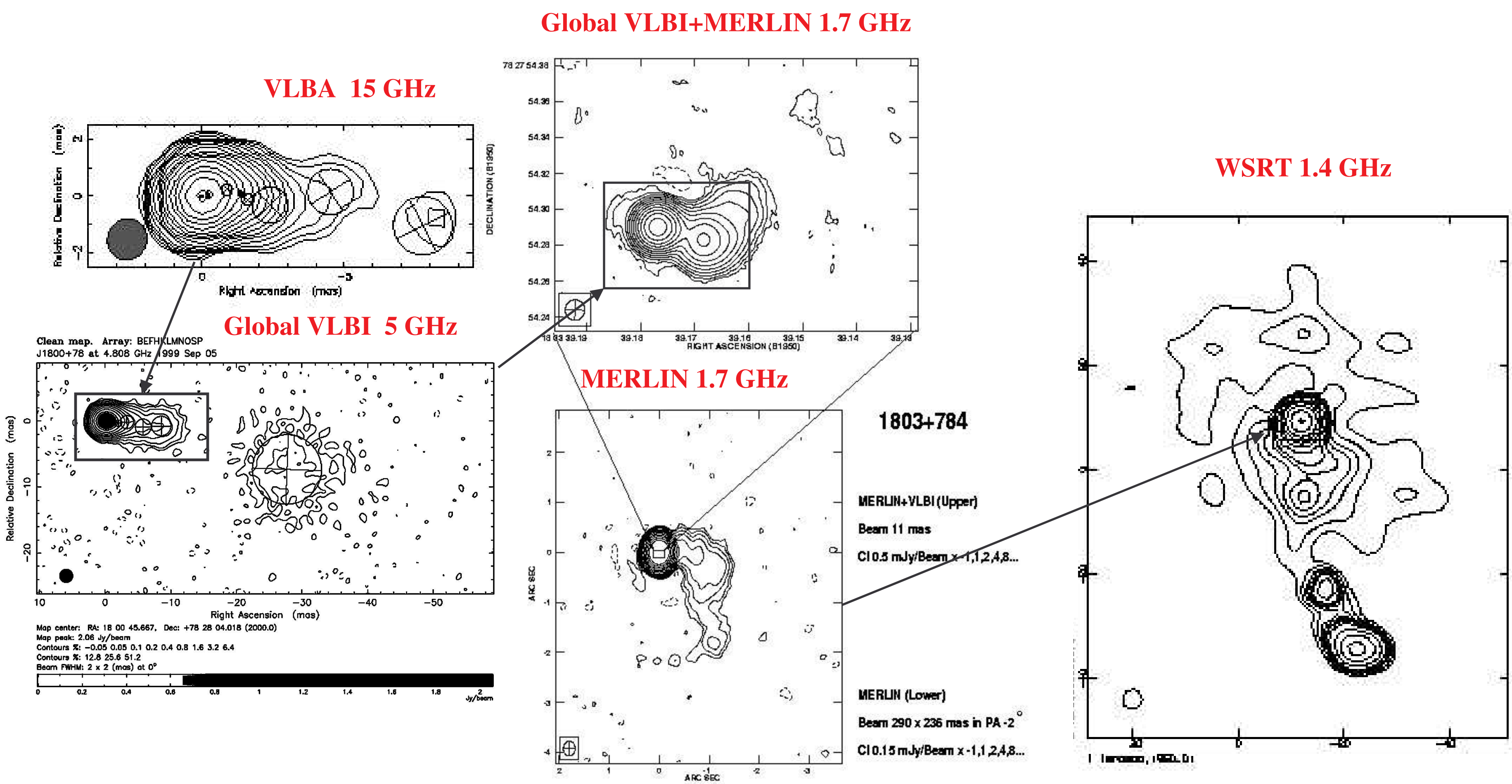
- •VLA image shows low surface brightness lobes which are too extended to be successfully imaged by MERLIN or VLBI
- •Separate images are appropriate to show the relationship between regions of low and high surface-brightness

Combination Imaging – combined/separate images

Wide Field Imaging

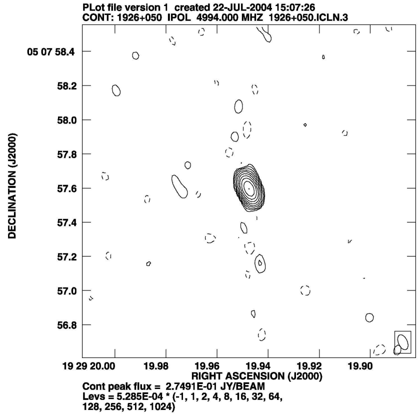
RadioNet

1803+784 Global VLBI + MERLIN (Britzen et al)



Combination Imaging

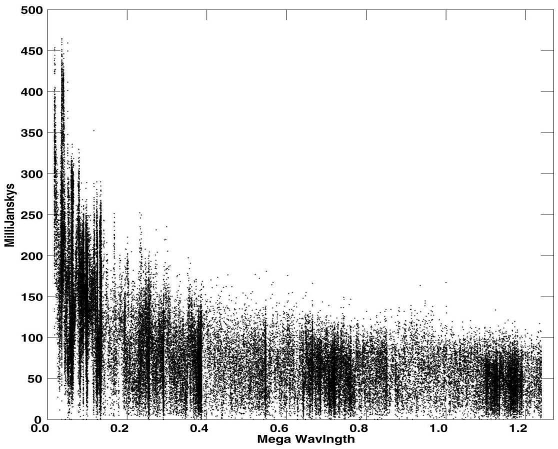
Are the data sets astrometrically aligned?



- Ensure that both data sets are either B1950 or J2000
- Beware early VLA data sets nominally observed in B1950 – the phase calibrator positions are quoted in equinox 1950, epoch 1979.9
- If the data sets have been phase-calibrated, check the assumed phase-calibrator positions
- Old data sets may suffer from poor phase-calibrator positions
- If the data sets have been self-calibrated only, they are almost certainly not aligned
- Make each image separately and convolve down the higher resolution image to that of the other and check the positions on a compact component within the overall source structure – beware blending

Data plane combination

•Use DBCON in aips to concatenate each single-source data set to a combination set



Positions:

•Provided each data set is astronomically aligned, different pointing centres can be accommodated within DBCON by shifting the pointing centre of the second data set to that of the first (DOPOS parameter)

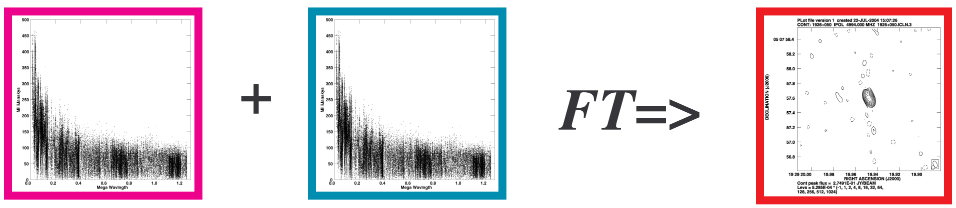
•If the data sets are not astronomically aligned, they can still be combined within DBCON and shifted to a single nominal pointing centre. However further cycles of self-calibration will be required in order to align the data set. It is usual to start with the high-resolution model for the first round of self-calibration

•Provided the data sets are single channel, all should be ok

•Multi-channel data can cause major problems unless they have the same characteristics – can cause radial smearing from wrongly gridded channels

Image plane combination

•Since the Fourier transform is a linear transform, one can make use of the equivalence principle which states that the transform of the sum of two distributions is equivalent to the sum of the separate transforms



Standard data-plane combination

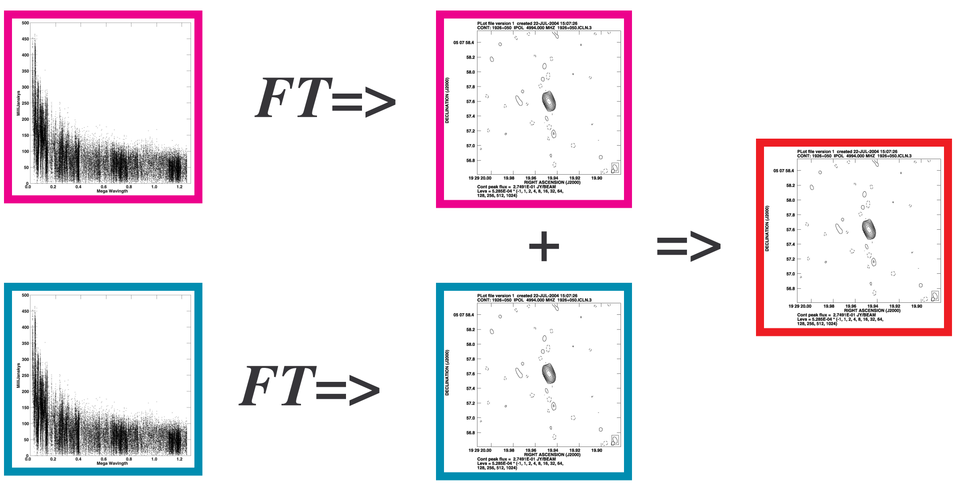
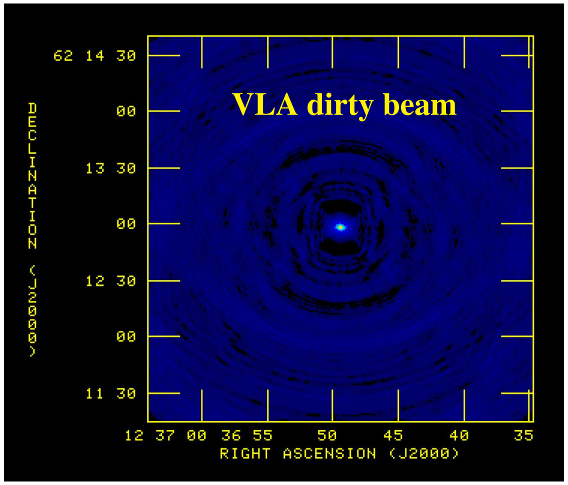
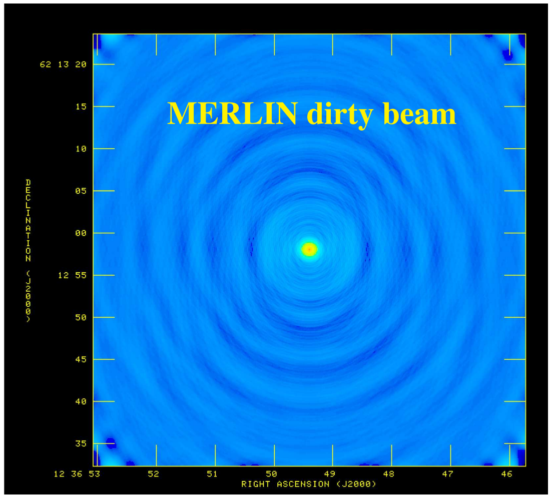


Image-plane combination

Image plane combination

- This is the standard method for deep field VLA+MERLIN combinations
- The VLA and MERLIN data sets are each Fourier transformed to separate dirty maps and dirty beams with appropriate image and pixel sizes
- The VLA dirty map and dirty beam are then re-gridded with HGEOM to the geometry of the MERLIN images
- Combination dirty maps and dirty beams are constructed with COMB prior to conventional de-convolution via an image-based algorithm





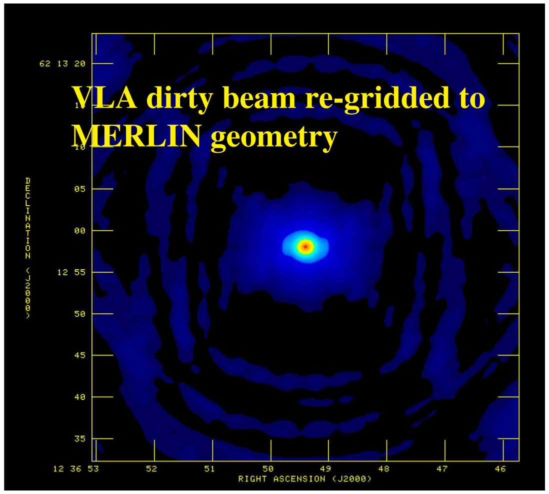


Image plane combination

•The sensitivity of the combination image may be maximised by altering the relative weighting in COMB to reflect the array sensitivities

•Test image performed from HDF-N field (Muxlow et al 2005) for 307μJy source J123649+620738, which lies 320 arcsec from field centre. Data rotated and averaged to single channel before imaging

•Test shows that images are the same for dynamic ranges ~300:1

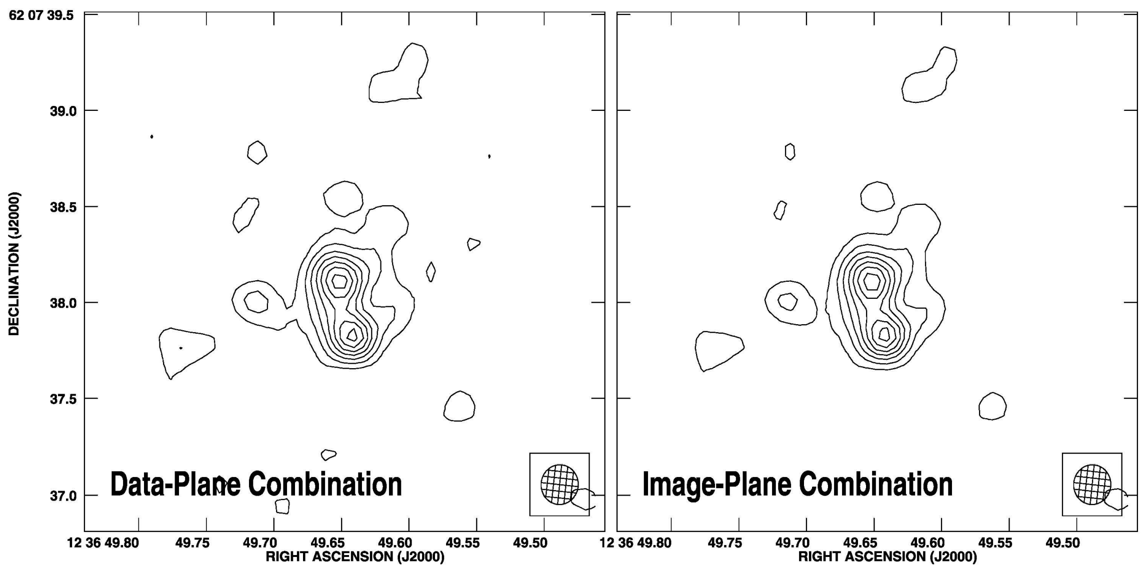
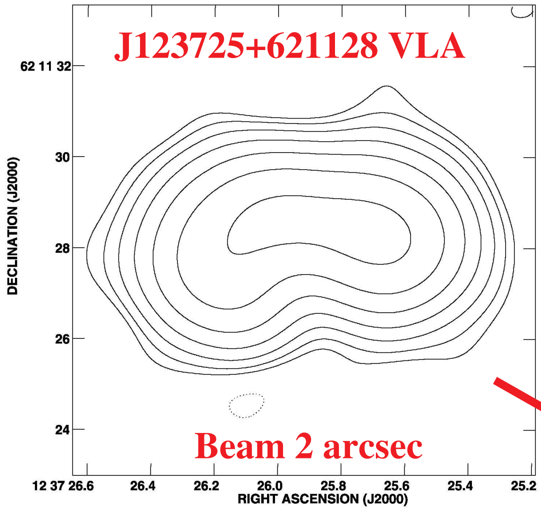
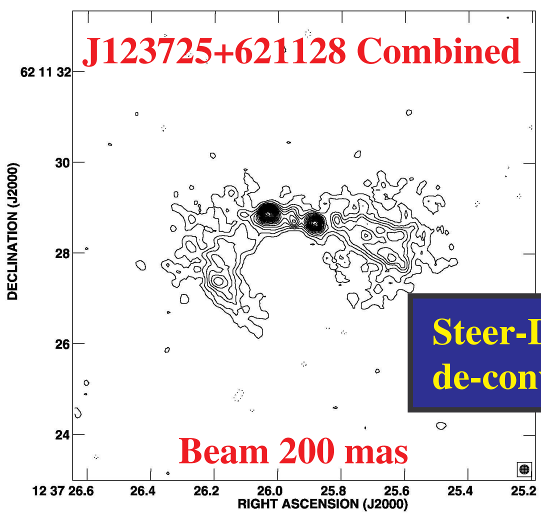


Image plane combination – GOODS North

- MERLIN – 18 days, 1 IF (1420 MHz, 31x0.5 MHz channels
- VLA – 42 hours, 2 IFs (1365&1435 MHz, 7x3.125 MHz channels





Steer-Dewdney de-convolution

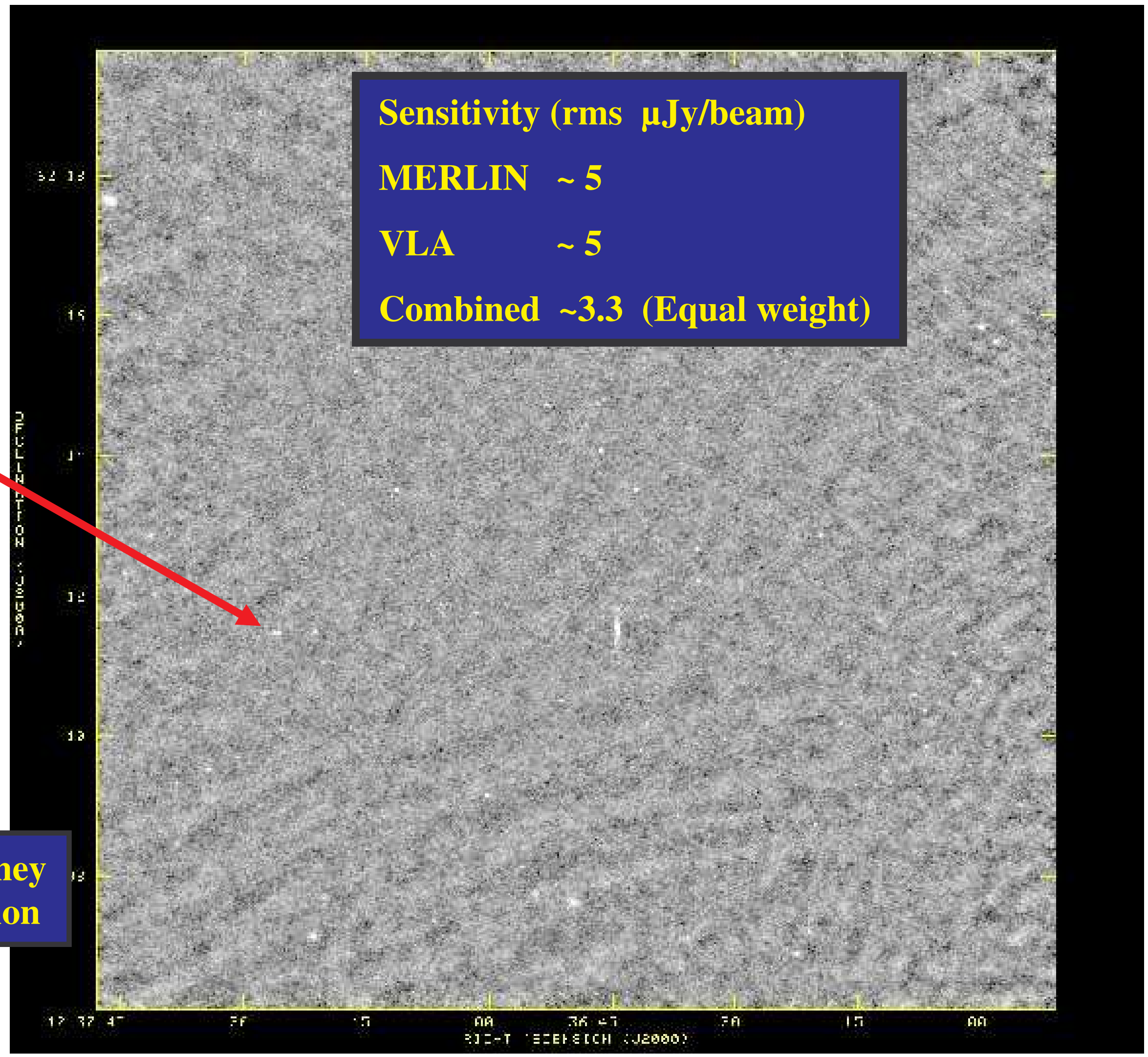
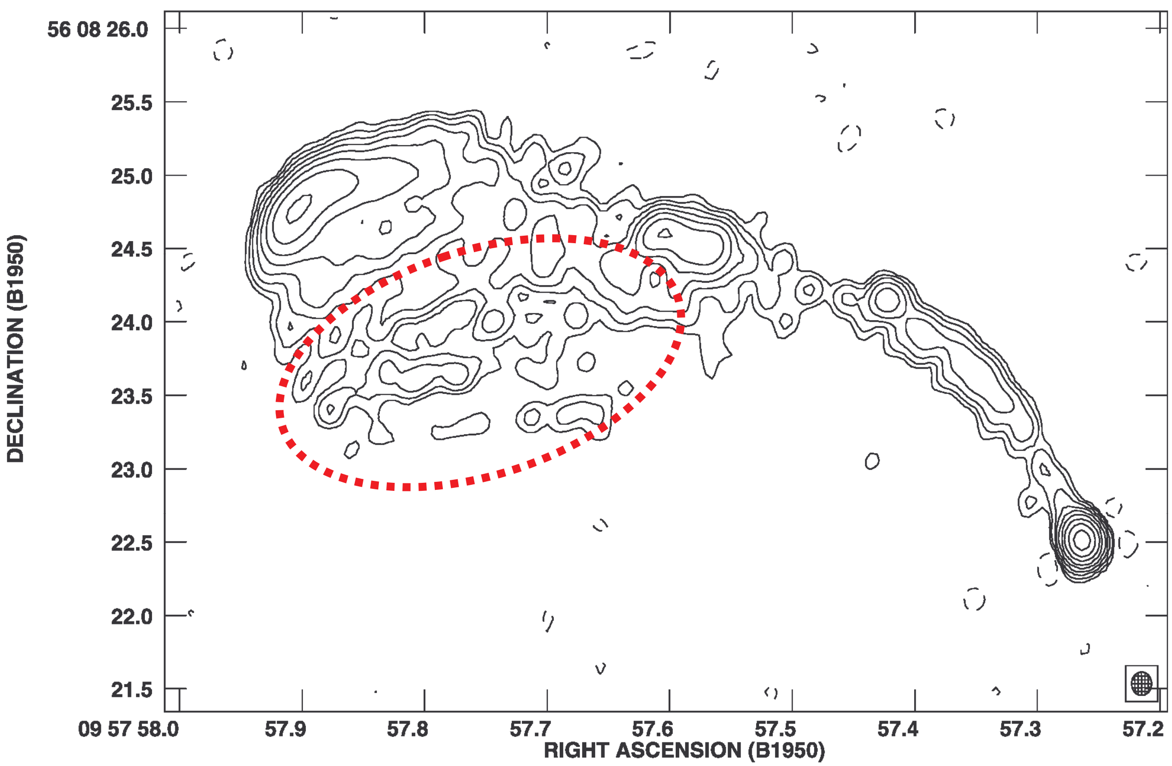


Image De-convolution – Extended Emission

Wide Field Imaging

-not so wide-field imaging…

•Low surface brightness extended structure, can be subject to fragmentation during de-convolution – especially for arrays with sparse *u-v* coverage



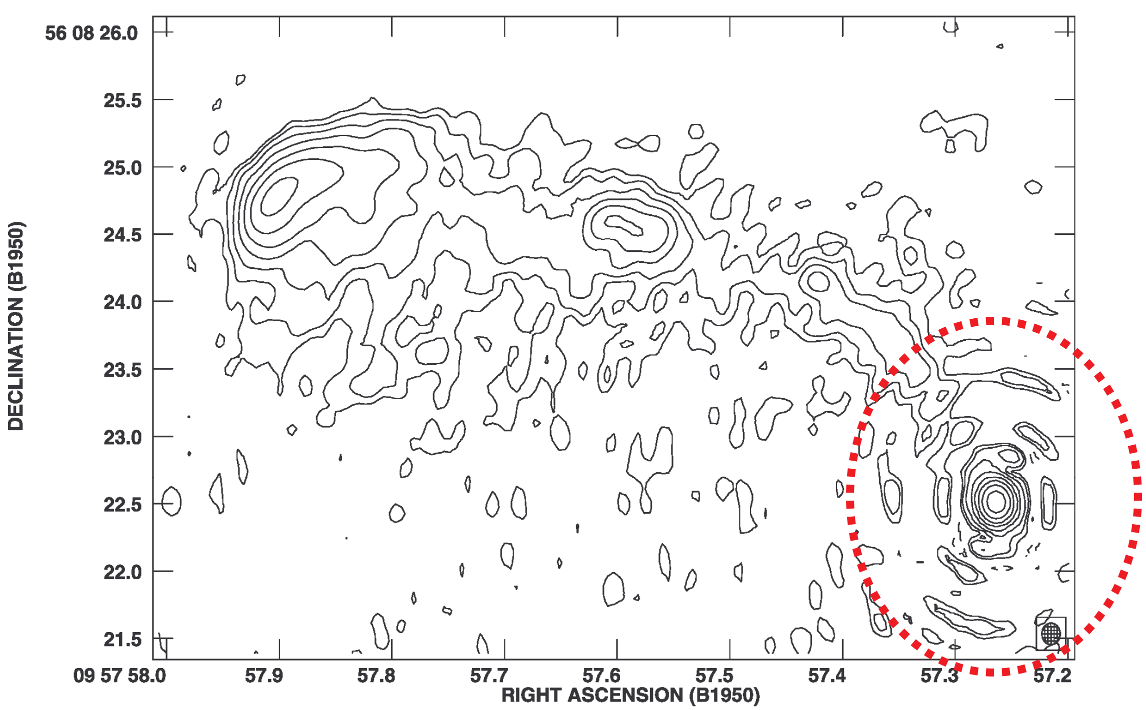
•Can be partially alleviated in conventional cleaning algorithms by setting a low loop gain and using 'Prussian Hat' beam modifications

•SDCLN (Steer-Dewdney) avoids ripples produced by standard cleaning by selecting all pixels above a certain threshold

Image De-convolution – Extended Emission

-not so wide-field imaging…

•Maximum entropy de-convolution will produce smoother images in regions of low signal:noise



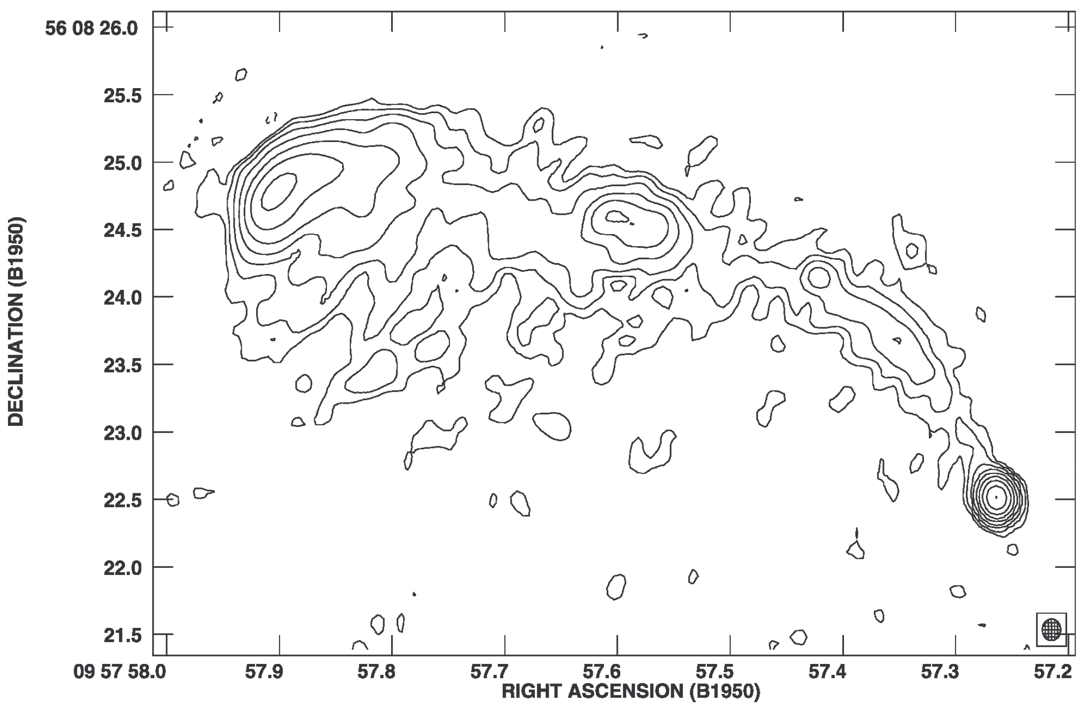
•VTESS algorithm will produce the maximum entropy image convolved with the fitted beam + residuals

•VTESS does not deal well with bright points in the image – residual side-lobes are common

Image De-convolution – Extended Emission

-not so wide-field imaging…

- Maximum entropy can be used in combination with conventional cleaning to alleviate residual side-lobes from bright points whilst still producing a smoother solution in areas of low surface-brightness



Multi-scale clean as developed in CASA and imagr may supersede this….

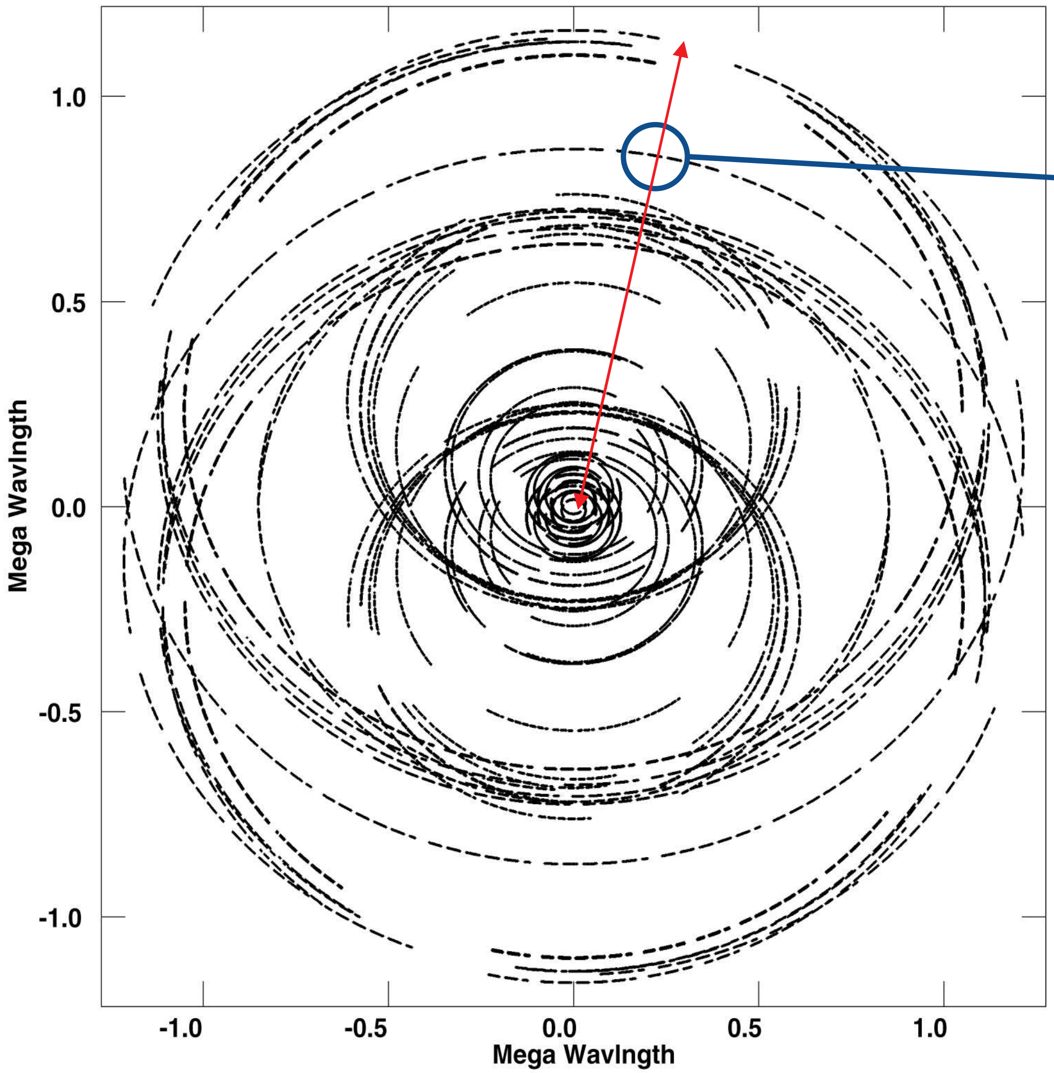
- Image is initially cleaned to subtract the bright points and clean components are not restored

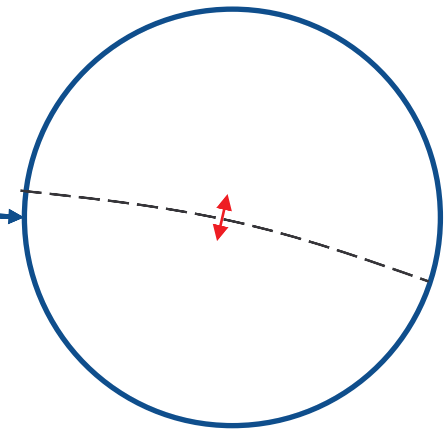
- VTESS is run on the residual image

- RSTOR restores the subtracted clean components to the smoothed maximum entropy image

Wide-Field Imaging

Bandwidth smearing (chromatic aberration)





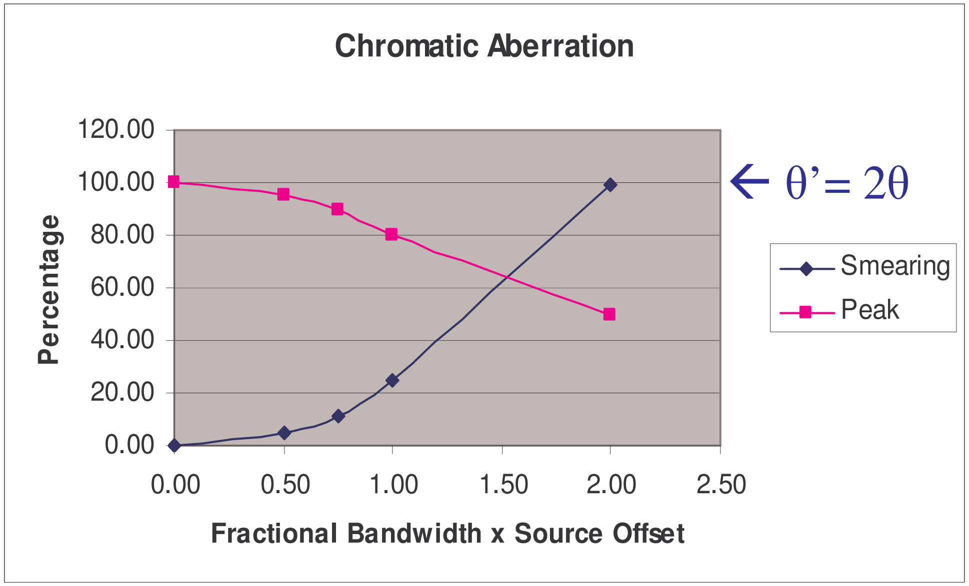
- Thus far we have considered monochromatic visibilities.
- Finite bandwidth averages the visibility data radially producing a radial smearing in the image plane.
- Smearing increases with distance from the pointing centre.

Wide-Field Imaging   Bandwidth smearing

•Bandwidth smearing (chromatic aberration) will produce radial smearing and reduction in source peak

•Parameterized by the product of the fractional bandwidth and the source offset in synthesised beamwidths

$$\boxed{\delta \upsilon / \upsilon_0 \;\; x \;\; \theta / \theta_{HPBW}}$$



•Can be alleviated by observing and imaging in spectral line mode with many narrow frequency channels gridded separately prior to Fourier inversion – reduces $\delta\upsilon$

•Detailed form of response depends on individual channel bandpass shapes.

Wide Field Imaging

Wide-Field Imaging Bandwidth smearing

•VLA outlier (confusing source) in the outer part of the telescope primary beam. GOODS HDF North field

•Distant classical radio galaxy 27.2 arcmin (1631 arcsec) from field centre.

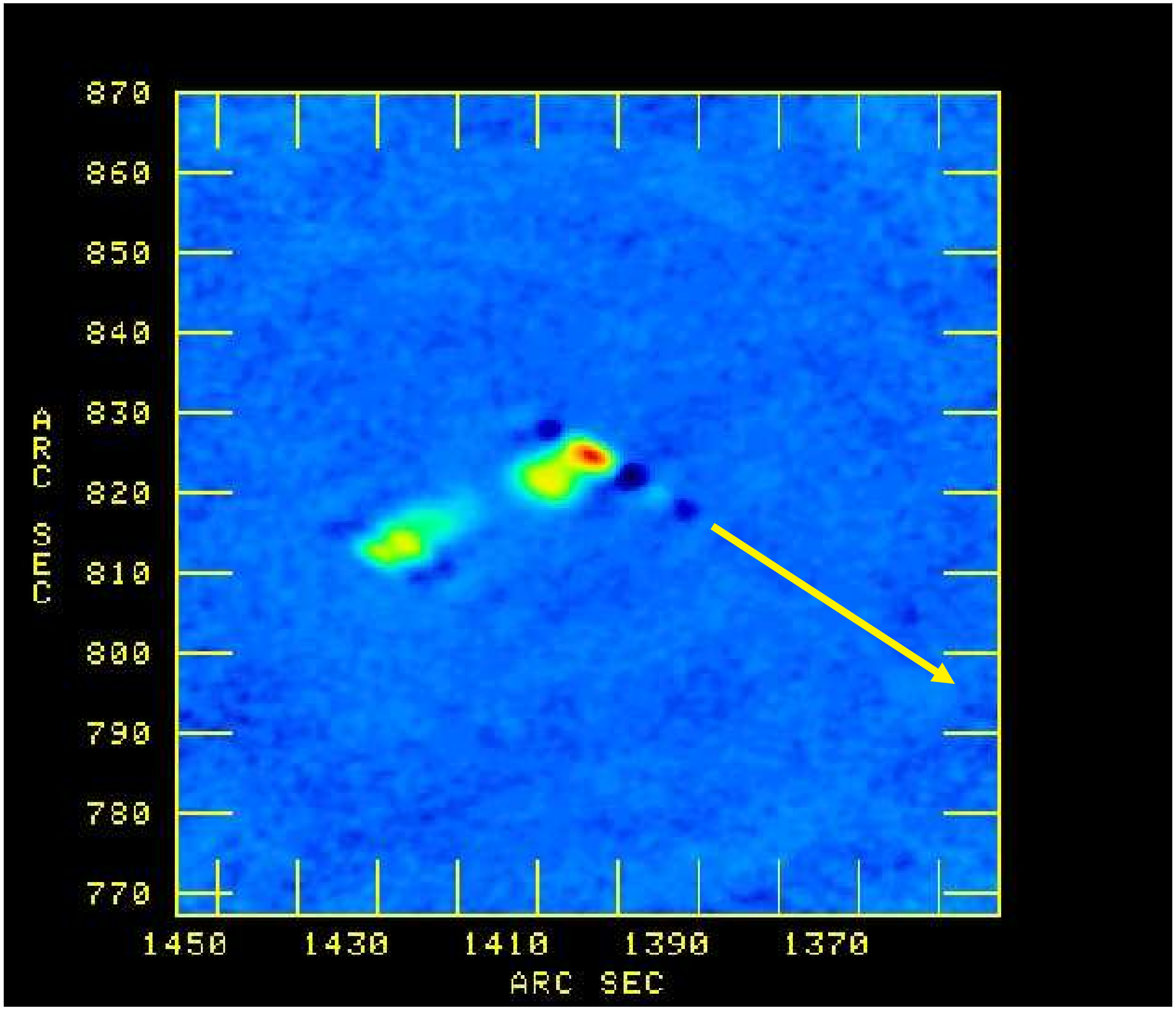
•θ_{HPBW} = 2 arcsec

•υ_0 = 1400MHz

•δv = 7MHz

$$\boxed{\delta\upsilon / \upsilon_0 \ \ x \ \ \theta/\theta_{HPBW}}$$

→ 4.1 Very Smeared!



Wide-Field Imaging

Bandwidth smearing

•MERLIN outlier (confusing source) in the outer part of primary beam

•Galactic microquasar 987 arcseconds from field centre.

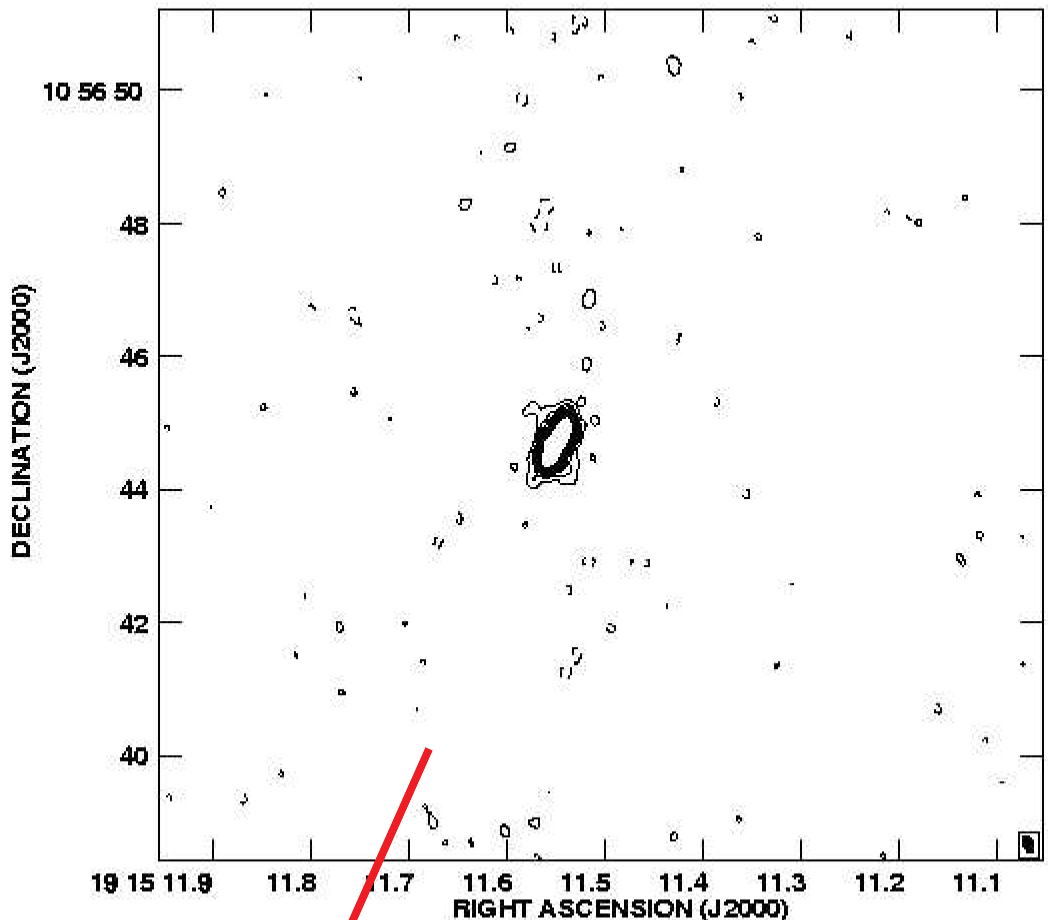
•θ_{HPBW} = 0.22 arcsec

•υ_0 = 1658MHz

•$\delta\upsilon$ = 1MHz

$$\boxed{\delta\upsilon / \upsilon_0 \;\; x \;\; \theta / \theta_{HPBW}}$$

→ 2.7 Very Smeared!



Wide-Field Imaging

Bandwidth smearing

•MERLIN outlier (confusing source) in the outer part of primary beam

•Galactic microquasar 987 arcseconds from field centre.

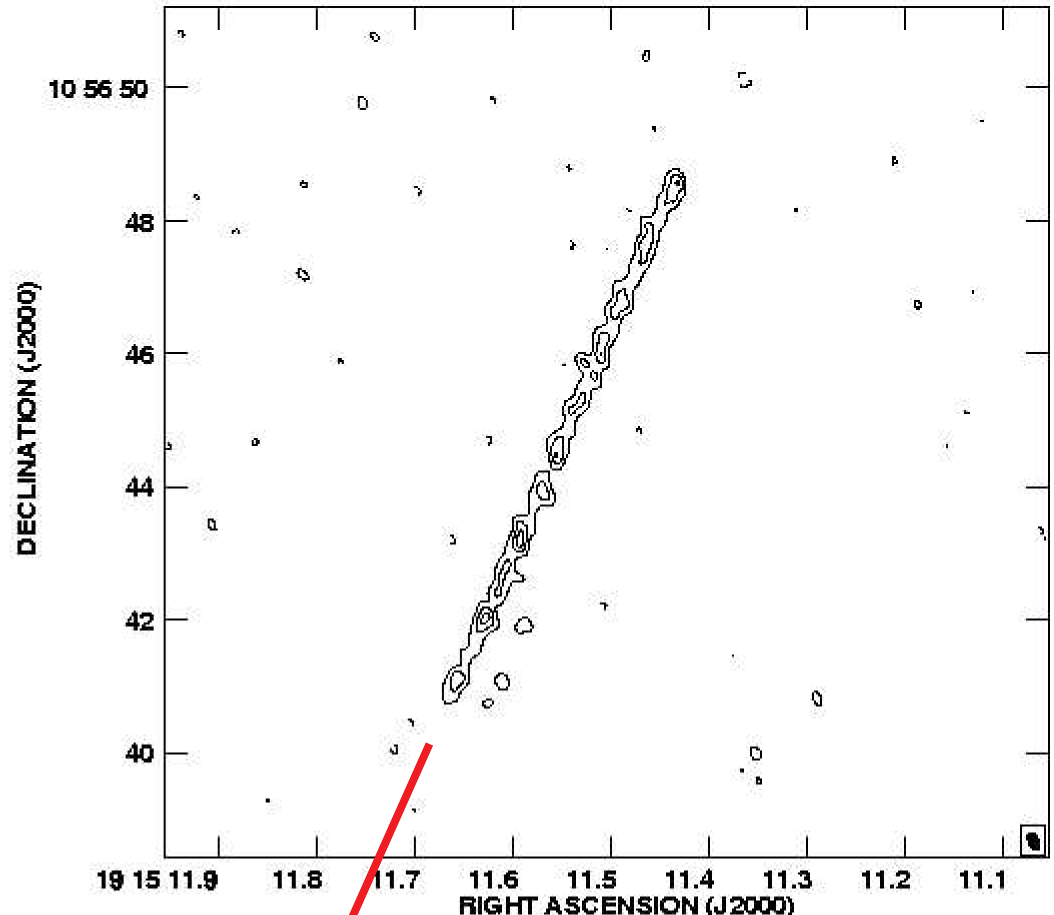
•θ_{HPBW} = 0.22 arcsec

•υ_0 = 1658MHz

•$\delta\upsilon$ = 15MHz

$\boxed{\delta\upsilon / \upsilon_0 \;\; x \;\; \theta/\theta_{HPBW}}$

→ 41 !!!!



Same data averaged to 1x15 MHz instead of 15x1 MHz frequency channels

Wide-Field Imaging Time-averaging smearing

•Time-average smearing (de-correlation) will produce tangential smearing

•In general cannot be easily parameterized. At Declination=+90° a simple case exists where the effects can be parameterized by the equivalent product:

$$\boxed{\omega_e \delta t_{int} \;\; x \;\; \theta/\theta_{HPBW}}$$

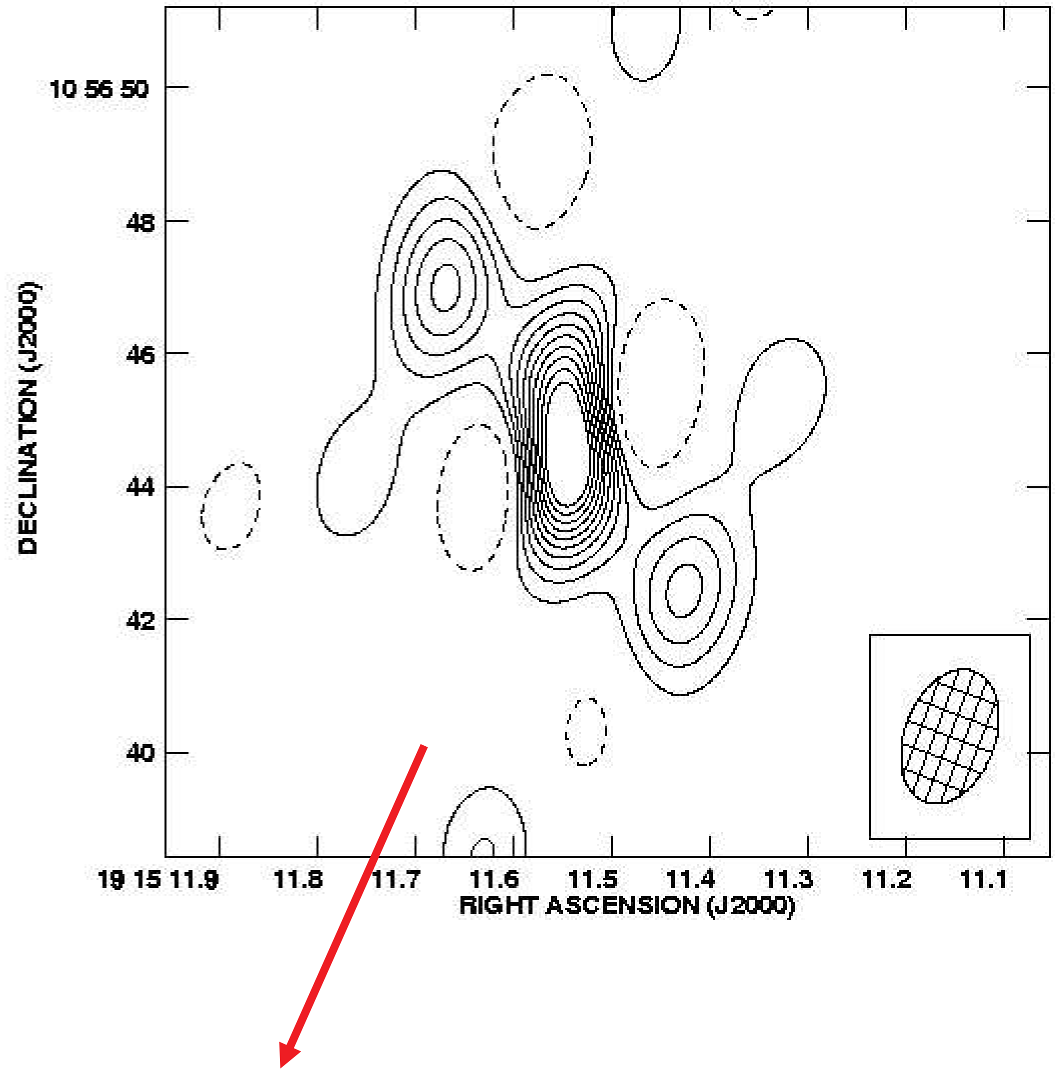
Where $\boldsymbol{\omega_e}$ is the Earth's angular rotation rate and $\boldsymbol{\delta t_{int}}$ is the integration time interval in the dataset

•For other Declinations the effects are more complicated. However they can be alleviated by ensuring that $\boldsymbol{\delta t_{int}}$ is small enough such that there at least 4 samples per turn assuming a maximum rate of $\boldsymbol{\theta/\theta_{HPBW}}$ turns in 6 hours

Wide-Field Imaging

Time-average smearing

- MERLIN outlier (confusing source) in the outer part of primary beam



- Galactic microquasar 987 arcseconds from field centre.

- Data averaged to 2 minutes integrations.

- Source heavily de-correlated on longer spacings

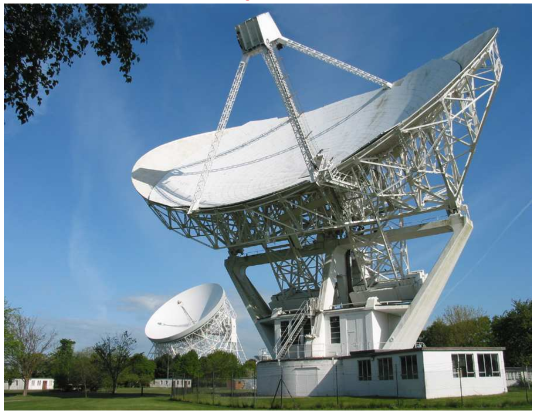
- ~5000 turns in 6 hours→ one turn in ~5 sec. Need τ~1 sec.

- Strong tapering reveals tangential smearing

Wide-Field Imaging

Primary beam response

•The ultimate factor limiting the field of view is the diffraction limit of the individual antennas. For an antenna of diameter ***d*** metres an approximate formula for the full width at half power in arcminutes is given by: $\theta_{HPBW} = 1125 / (d\, \nu_{GHz})$



•AIPS routines exist to correct for primary beam effects (PBCOR for existing images and frequency dependent beam corrections within IMAGR when cleaning)

•For mixed arrays, beams for interferometer pairs are simply the voltage polar diagram of one multiplied by that of the second.

•In the limit where one dish is much larger than the other, the beam is determined by the voltage pattern of the large telescope. (Strom 2004, astro-ph/0412687) – at 1.4 GHz Lovell HPBW beam ~10.4’, Knockin beam ~30’ – but Lovell-Knockin beam ~14’

•The overall correction will also depend on the relative weighting and the data distribution between telescopes. Detailed solutions are usually empirical and are derived from measurements on offset sources of known strengths.

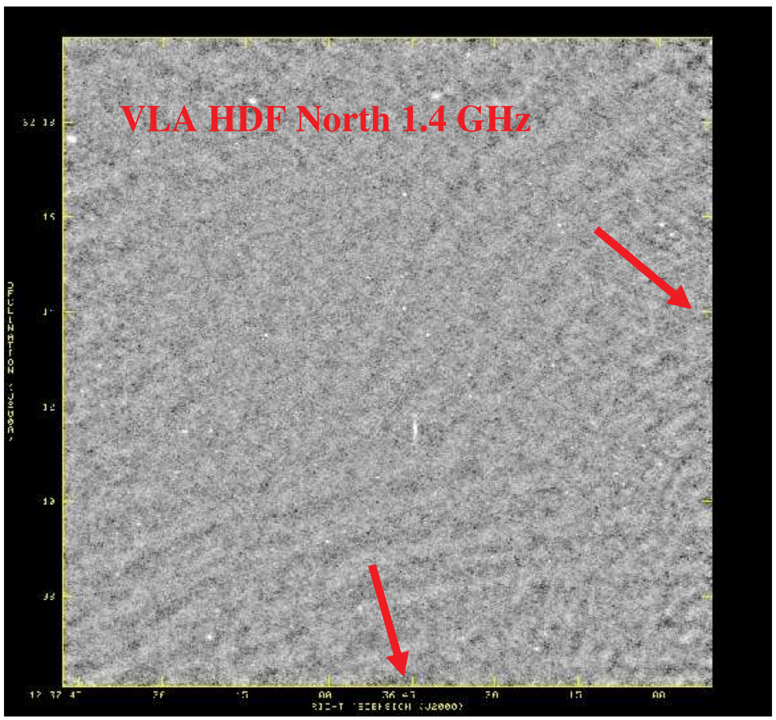
Wide-Field Imaging

Confusion

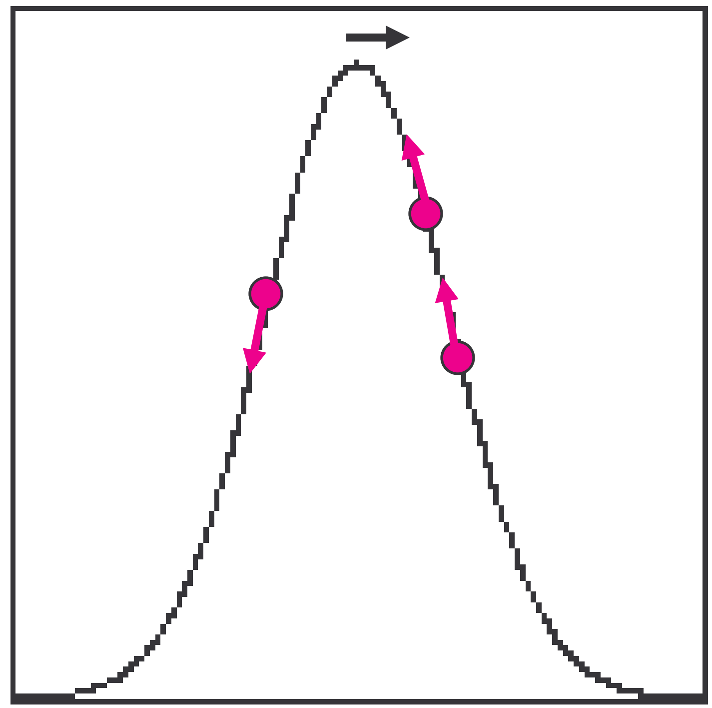
•Strong sources on the edge of the primary beam can give rise to ripples in the centre of the field of view

•The primary beam size is spectrally dependent, so image subtraction should include such corrections and be performed in full spectral-line mode

•Pointing errors will introduce gain and phase changes on the edge of the primary beam. If severe, the apparent source structure may change – attempt multiple snapshot subtraction on timescales comparable with pointing error changes



See Ian Stewart's talk on Thursday



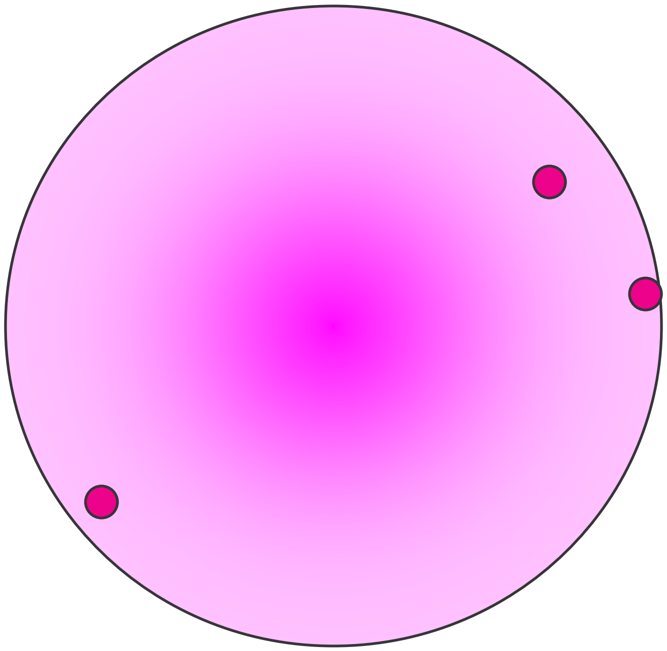
Wide-Field Imaging Pealing off Confusion

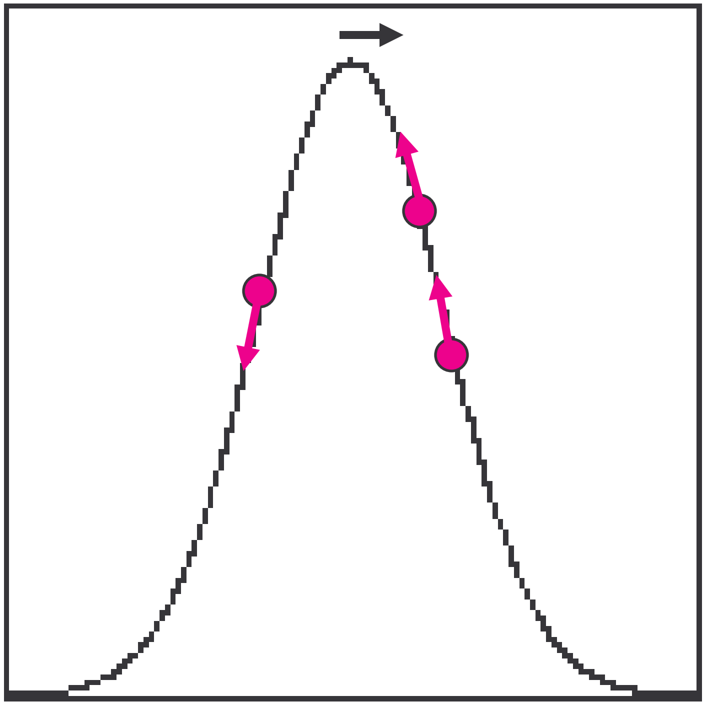
•After phase calibrating the data, perform self-calibration for the brightest confusing source – then subtract it out

•Delete phase solutions derived for previous confusing source ❶

•Move to next brightest confusing source, perform self-calibration/imaging cycles – then subtract that source from the dataset ❷

•Perform ❶and ❷ until all confusing sources are subtracted. Delete all self-calibration solutions and image central regions



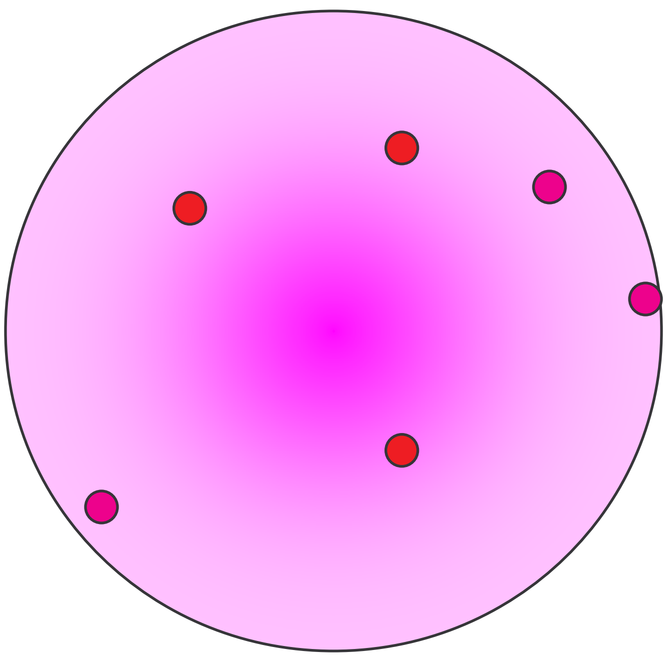


Wide-Field Imaging   In-beam self-calibration

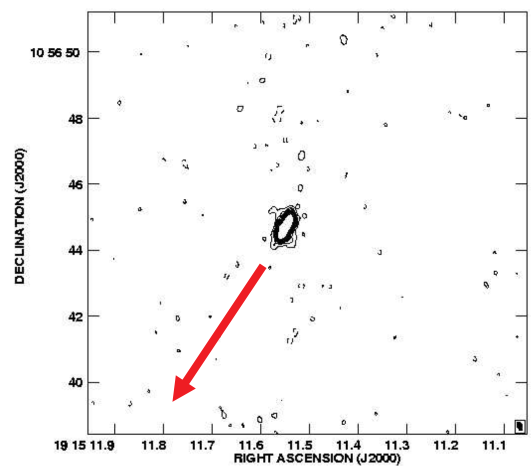
•After pealing off confusing sources ●, other sources may lie within the central areas of the primary beam ●

•Provided these are compact and bright enough, they can be used to self-calibrate the target dataset provided they lie within the isoplanatic region of the image.

•For non-isoplanatic situations (eg VLA D-array at low frequencies, LOFAR) one can attempt to solve for the telescope errors across the beam – provided there are enough sources to adequately sample the beam (work in progress)

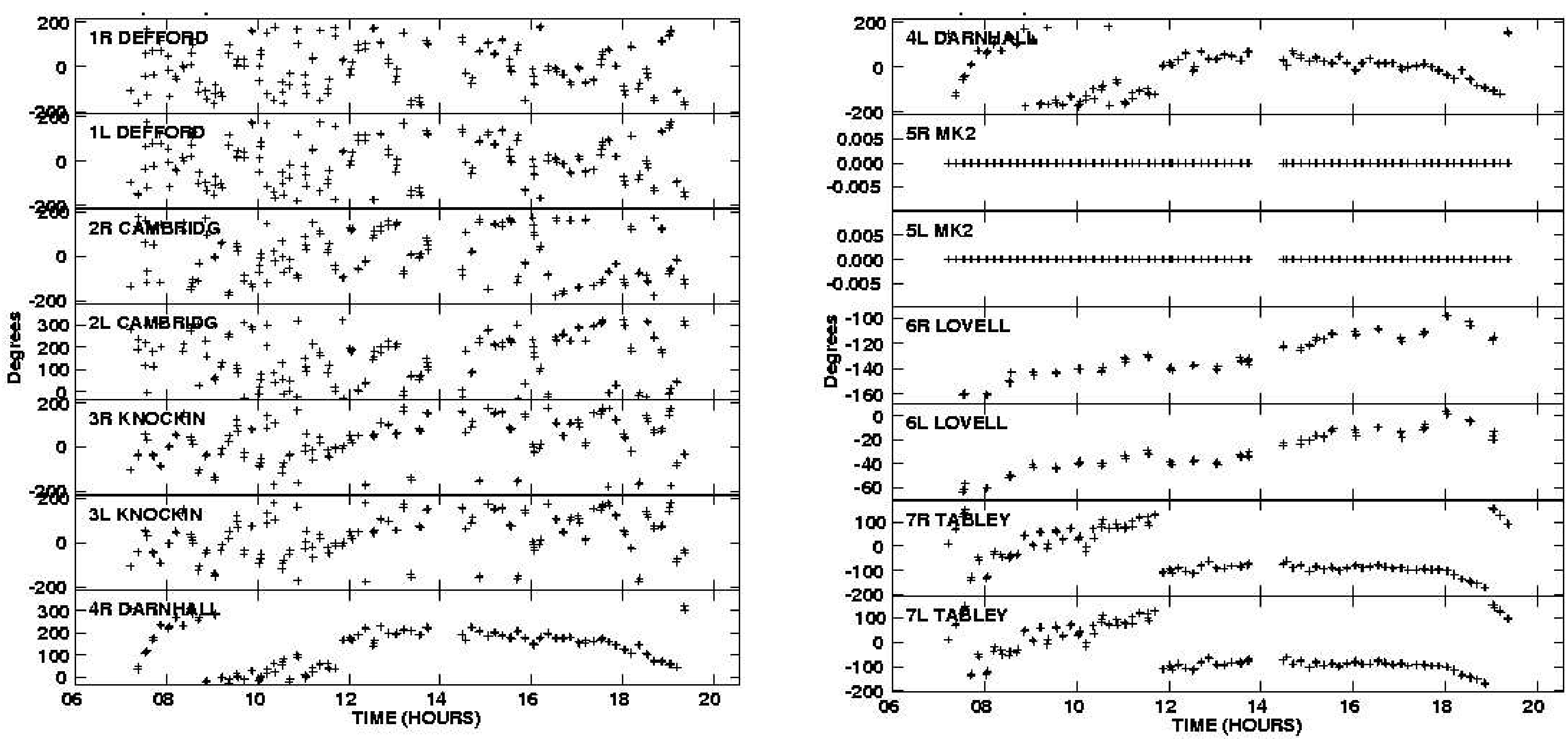


•For example – MERLIN source 987 arcsec from pointing centre can be used to self-calibrate data



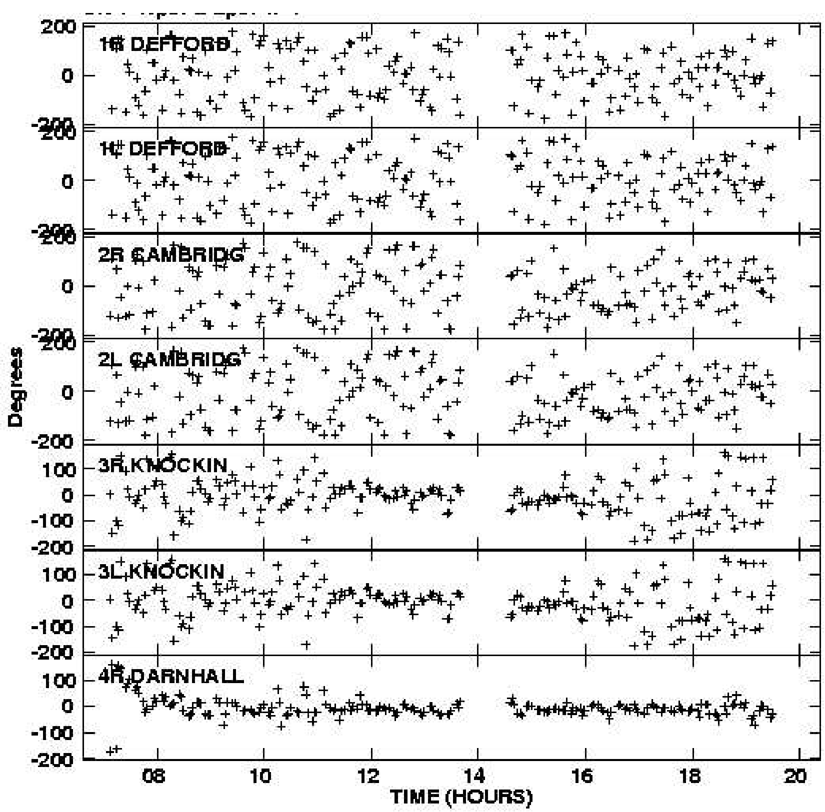
Wide-Field Imaging In-beam self-calibration

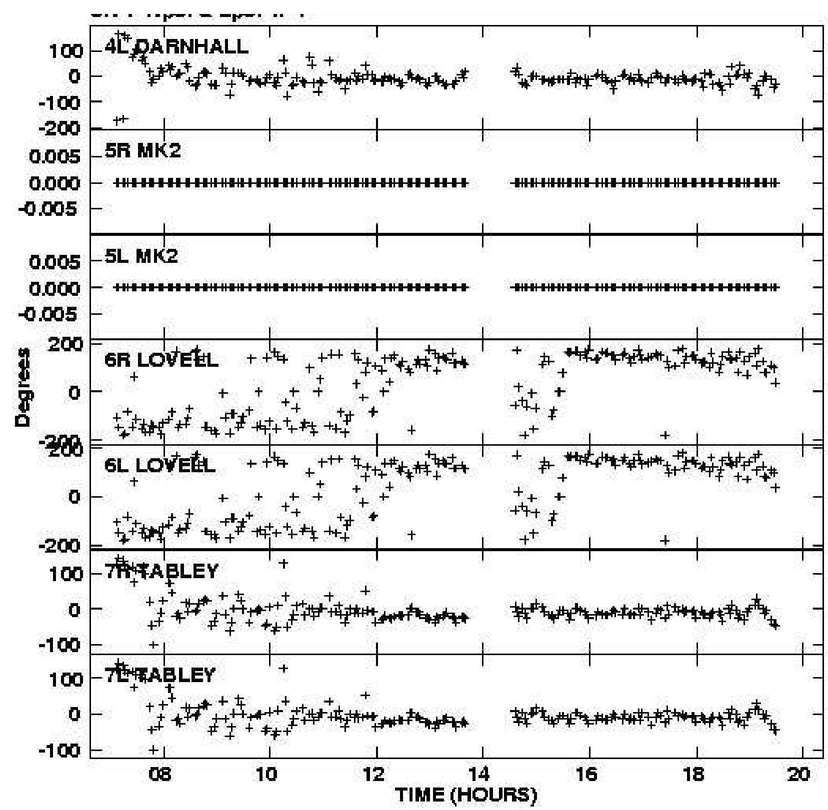
- Initial external phase calibration suffered from poor ionosphere with resulting unrecoverable high phase rates
- Dataset contained Lovell telescope for sensitivity – Galactic microquasar lies within the primary beam for most MERLIN telescopes – but not for the Lovell.
- Initial phase solutions for external reference source – reference antenna Mk2.



Wide-Field Imaging In-beam self-calibration

- Microquasar can be used for self-calibration even though it is heavily smeared radially
- Mk2 is still the reference antenna – high phase rate solutions on more distant telescopes. Lovell solutions show phase solutions from side-lobe response and are valid for the microquasar, but not the target at the pointing centre

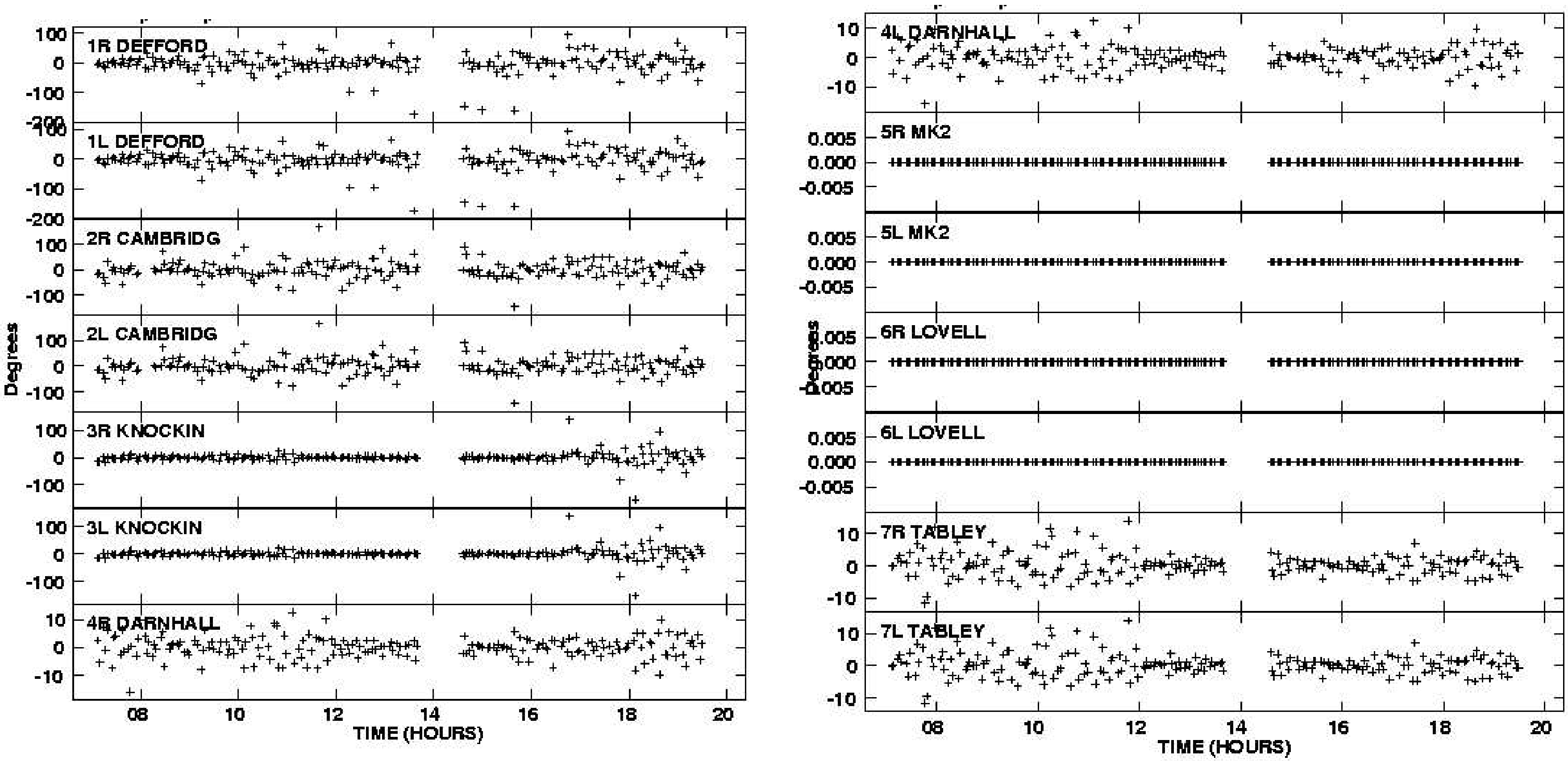




Wide-Field Imaging In-beam self-calibration

•Subsequent self-calibration cycles show convergence

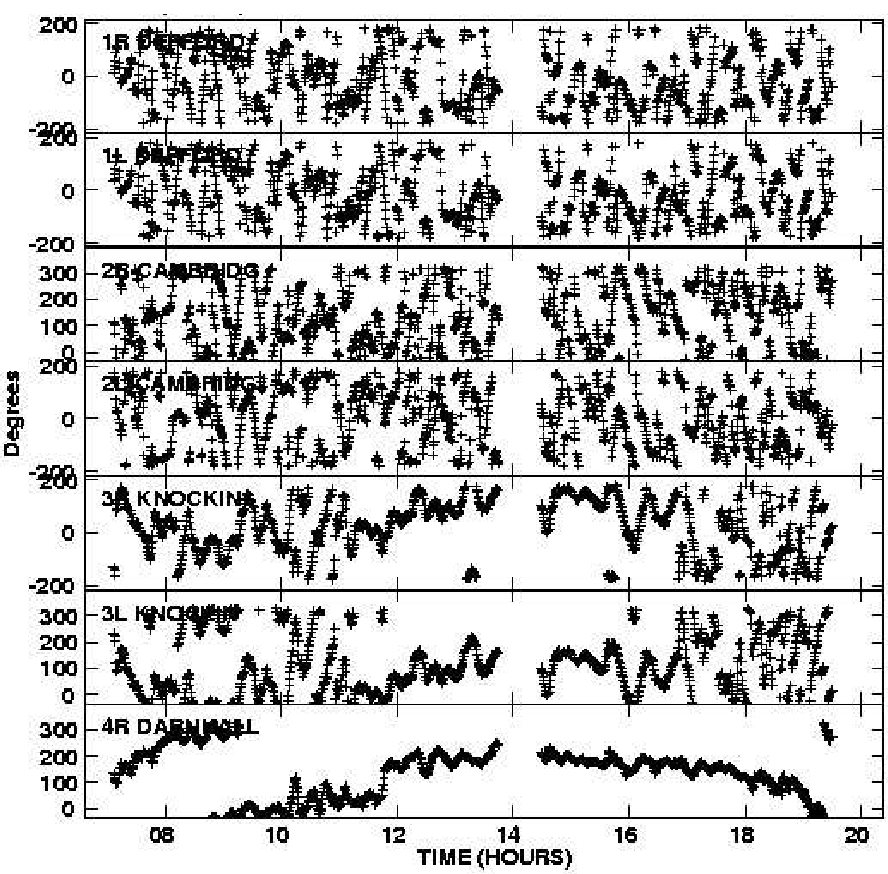
•Solutions retained for all telescopes except Lovell – these are overwritten with 0 by routine SNCOR so as to use the original external phase calibration solutions which are valid since Mk2-Lovell is very short and has very low phase rates

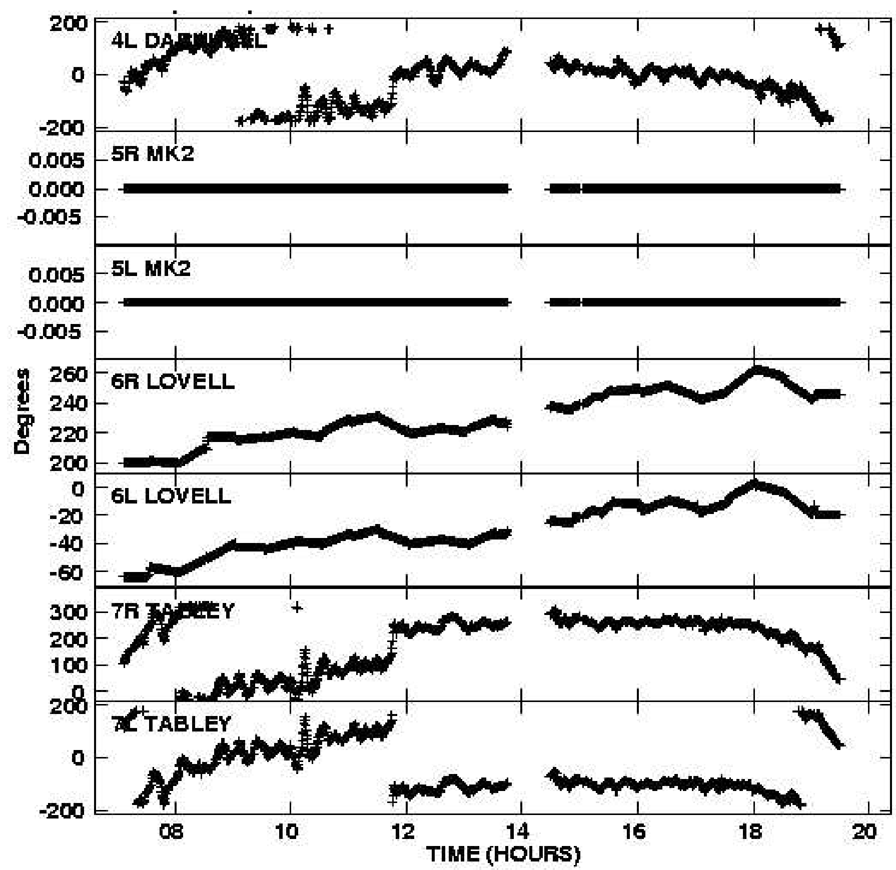


Wide-Field Imaging In-beam self-calibration

•Combination of initial external calibration + subsequent in-beam self-calibration has successfully recovered errors

•Target imaging should now be of high quality – however astrometric positioning is dependent on initial phase solutions and is likely to be poor

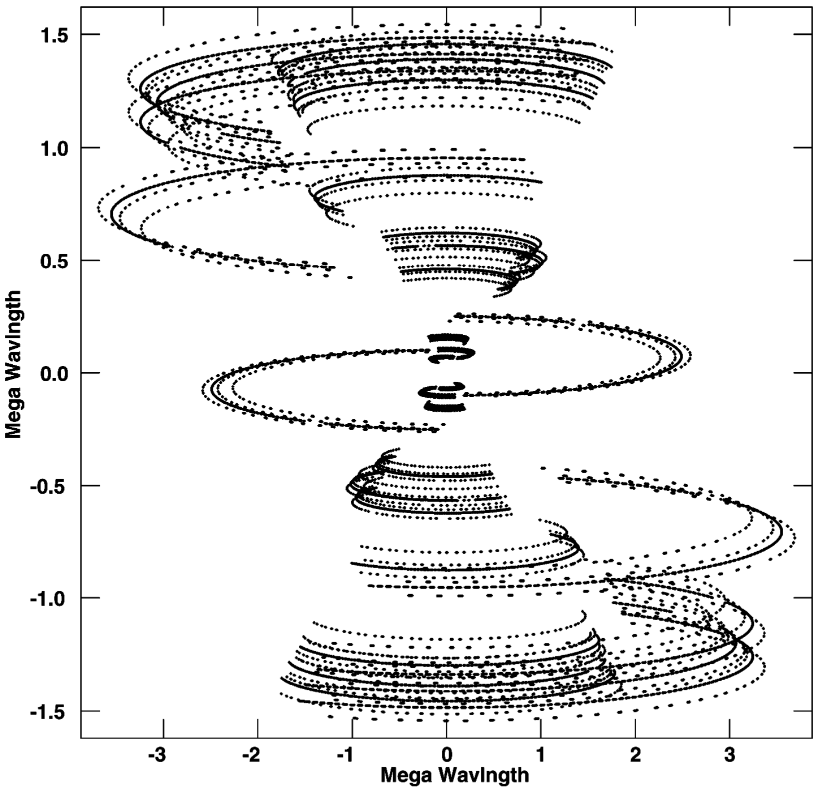




Multi-Frequency Synthesis

- Spatial frequency coverage for continuum imaging may be significantly improved by Multi-Frequency Synthesis observations where data are taken at several frequencies – MERLIN $\delta\nu$ ~13–15%

MERLIN 3C459 MFS 4546 / 4866 / 5186 MHz



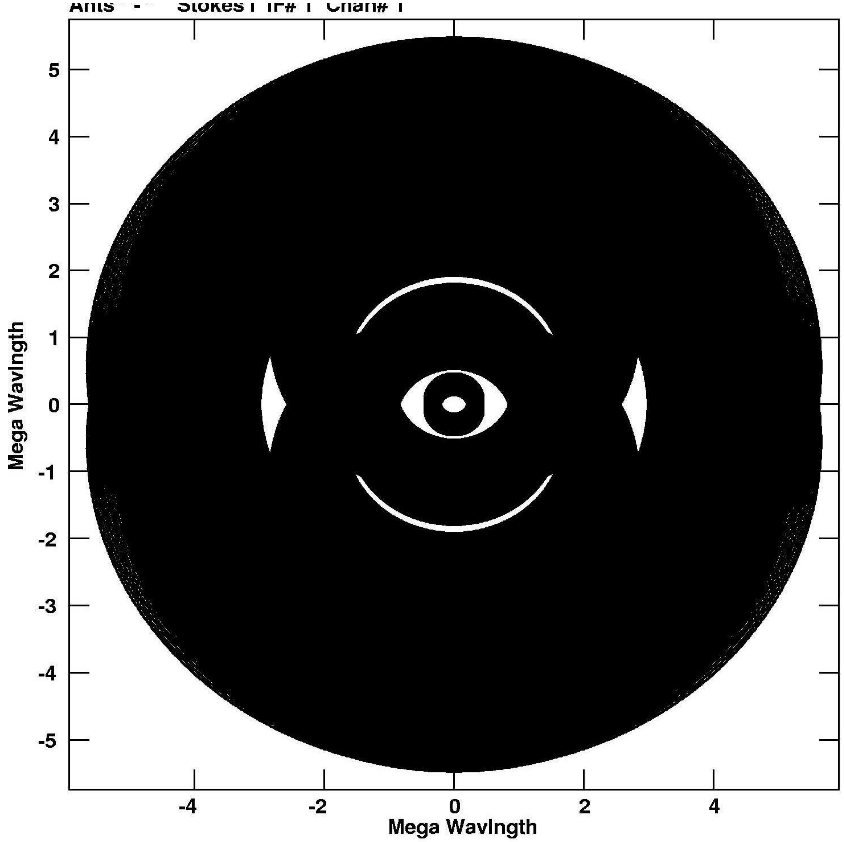
- Spectral changes across the source structure must be addressed if high dynamic ranges are required

- Overall spectral index accounted for in IMAGR – but discrepant components (flat-spectrum cores) may need separate subtraction from each frequency dataset – restoring a single central frequency average value

Multi-Frequency Synthesis

•New wide-band upgrades (*e*-MERLIN, EVLA1) will require a spectral solution in addition to the radio brightness at each location in the image

e-MERLIN MFS *u*-*v* Coverage 4–8 GHz at Declination 30°



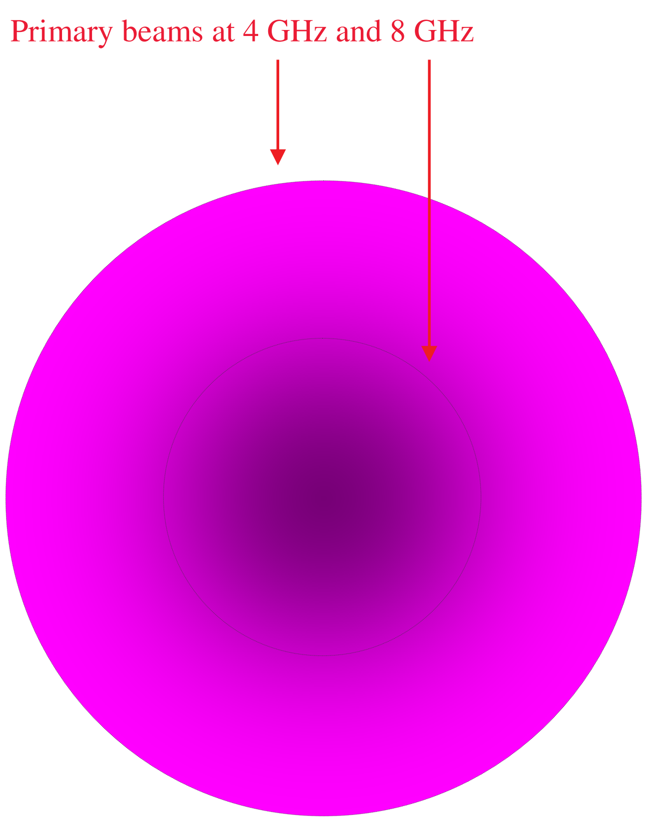
•MFS provides massively increased bandwidths together with improved image fidelity

•New algorithms have been developed/are under development to solve for spectral index (or full spectral fitting) in addition to radio brightness pixel by pixel

•Miriad software package already does this routinely for ATCA datasets

Multi-Frequency Synthesis

•For MFS observations at C-Band, the fractional bandwidth is likely to be substantial: eg 5 – 7 GHz, or even 4 – 8 GHz.



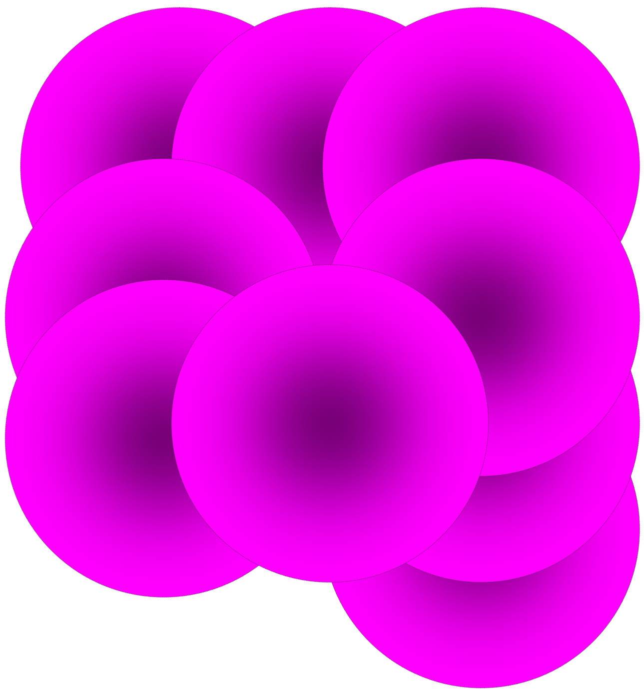
•The size of the primary beam scales as 1/observing frequency

•Full MFS imaging will be restricted to the primary beam as defined by the highest frequency

•High dynamic-range confusion subtraction from outer parts of the primary beam is likely to be a challenging problem – will need 'pealing' in spectral-line mode, possibly in multi-snapshot mode.

Mosaicing

•Ultra-wide fields of view can be built up by mosaicing with multiple pointing centres



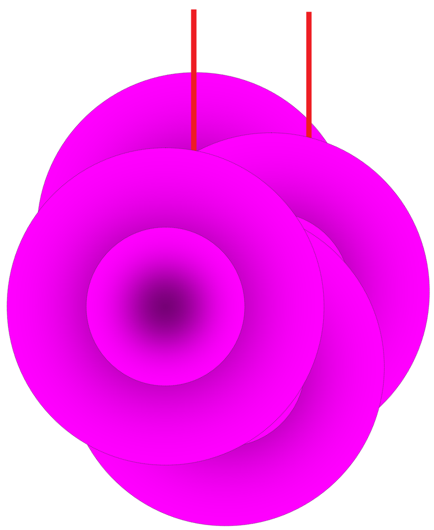
•Each pointing centre must contain some degree of overlap.

•Overlap optimisation depends on desired consistency in sensitivity across the mosaiced image and speed of observation.

•For arrays with a single type of element, this is relatively straightforward – a typical compromise is with a beam throw of ~70 %

Mosaicing

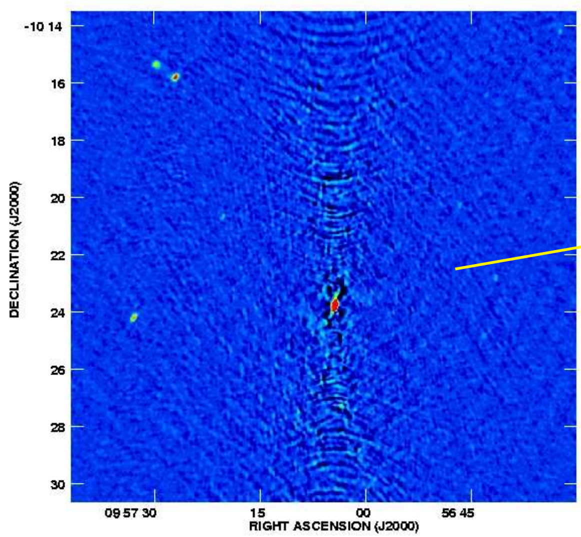
- For mixed arrays (eg *e*-MERLIN including the Lovell telescope), similar principles apply, but now each position will have a final image made from both sensitive Lovell and less sensitive non-Lovell pointings

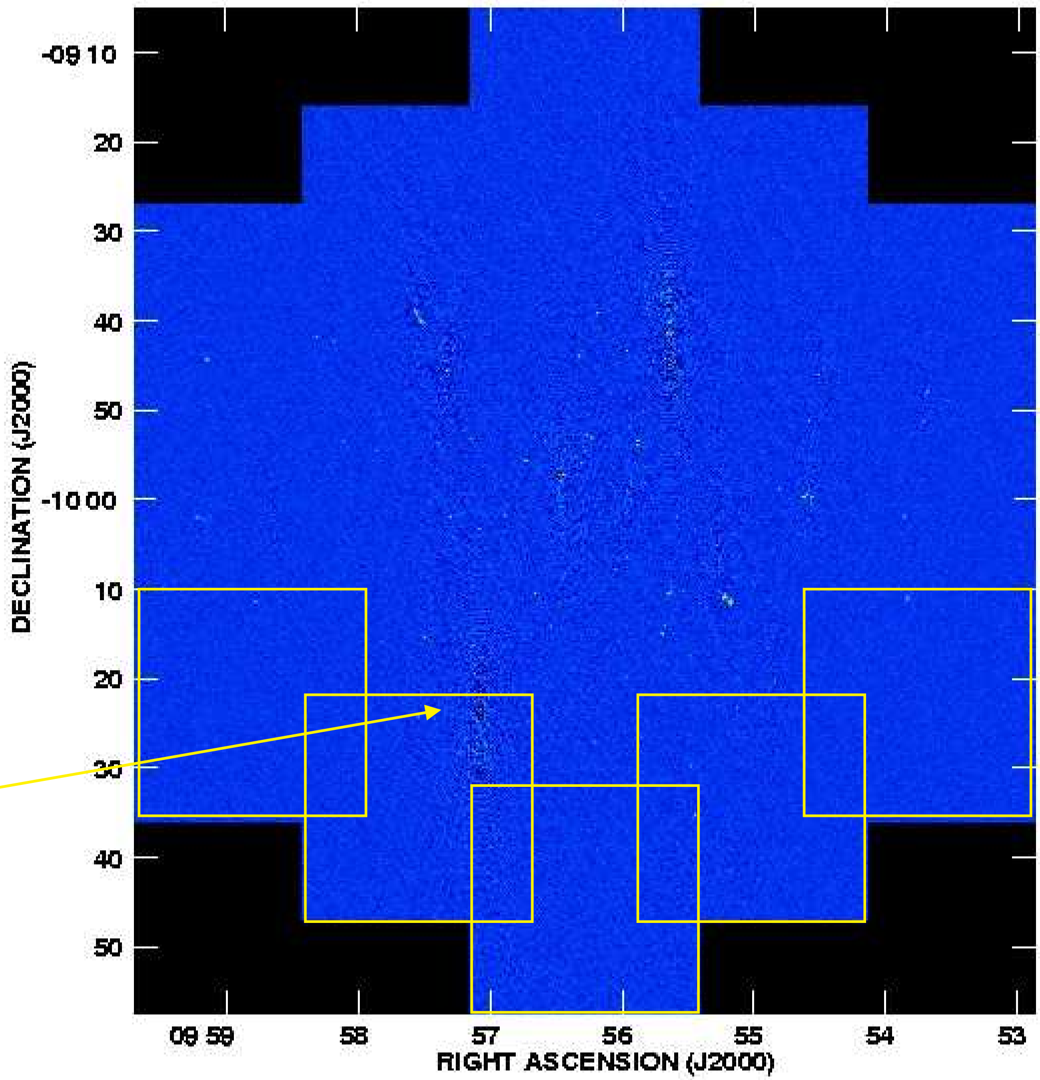


- Optimisation will depend on chosen data weighting schemes and established MFS performance
- Initial investigations will be from existing MERLIN deep field data
- Further investigations planned using MFS data taken with the prototype correlator
- Including EVLA will complicate matters further – watch this space……

Mosaicing within the primary beam

- GMRT observations of cluster Abell 901 - 610 MHz
- 19 facets used – projected to a flat image of a curved sky with correct positions by aips routine FLATN
- Close to thermal noise only away from bright sources

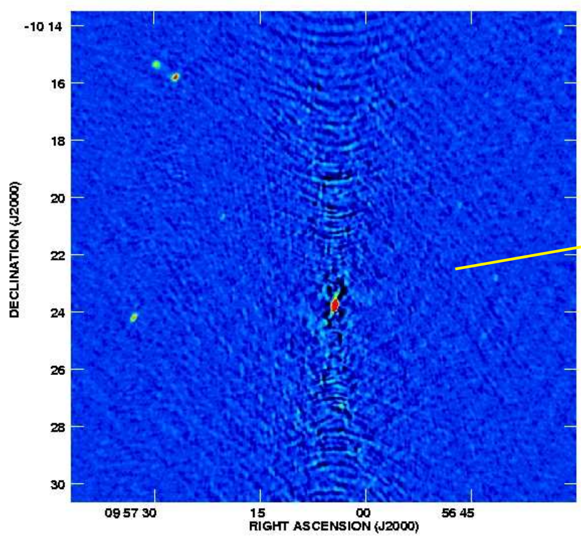


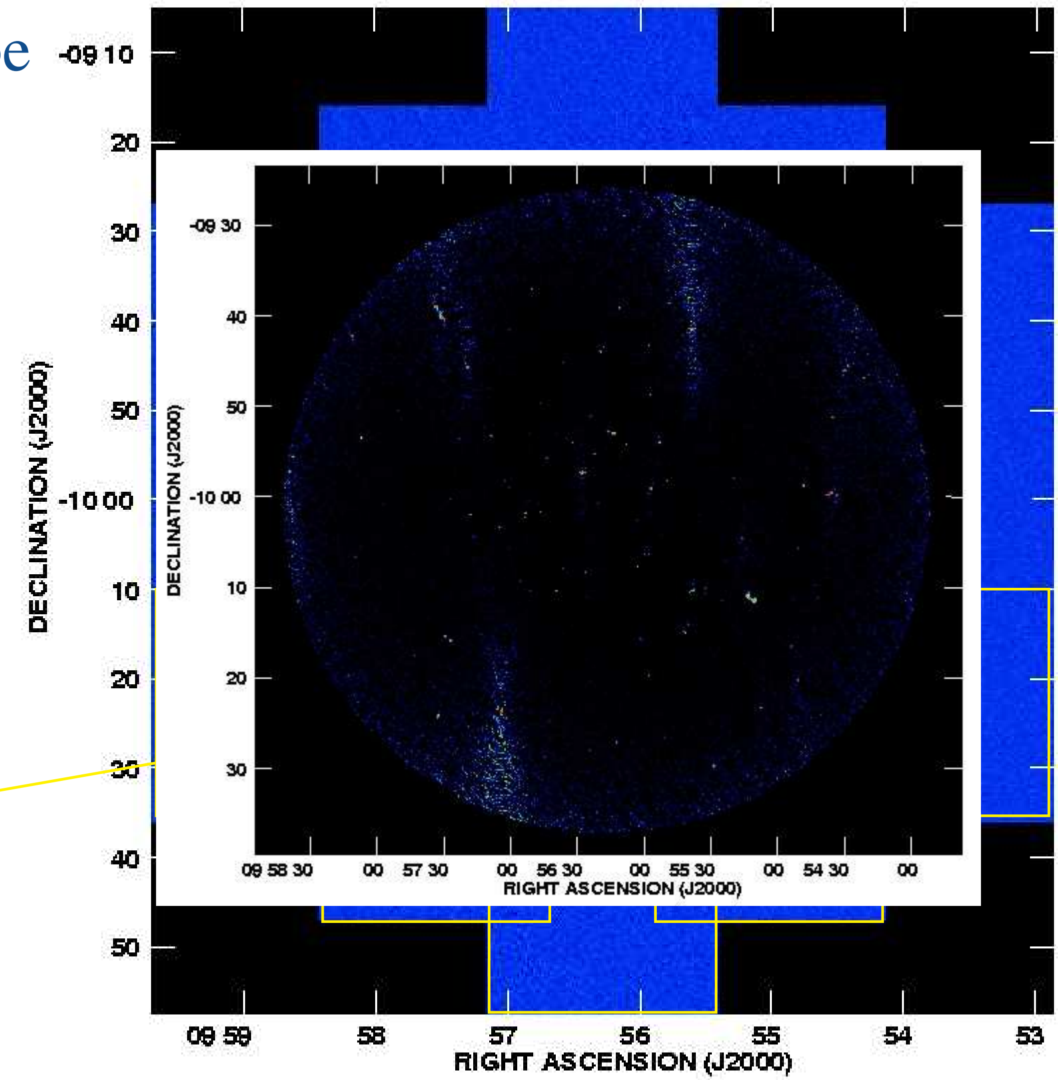


Beswick et al 2007 (In preparation)

Mosaicing within the primary beam

- GMRT observations of cluster Abell 901 - 610 MHz
- Aips routine PBCOR can be used to select the useable diameter of the primary beam and correct for sensitivity across the beam

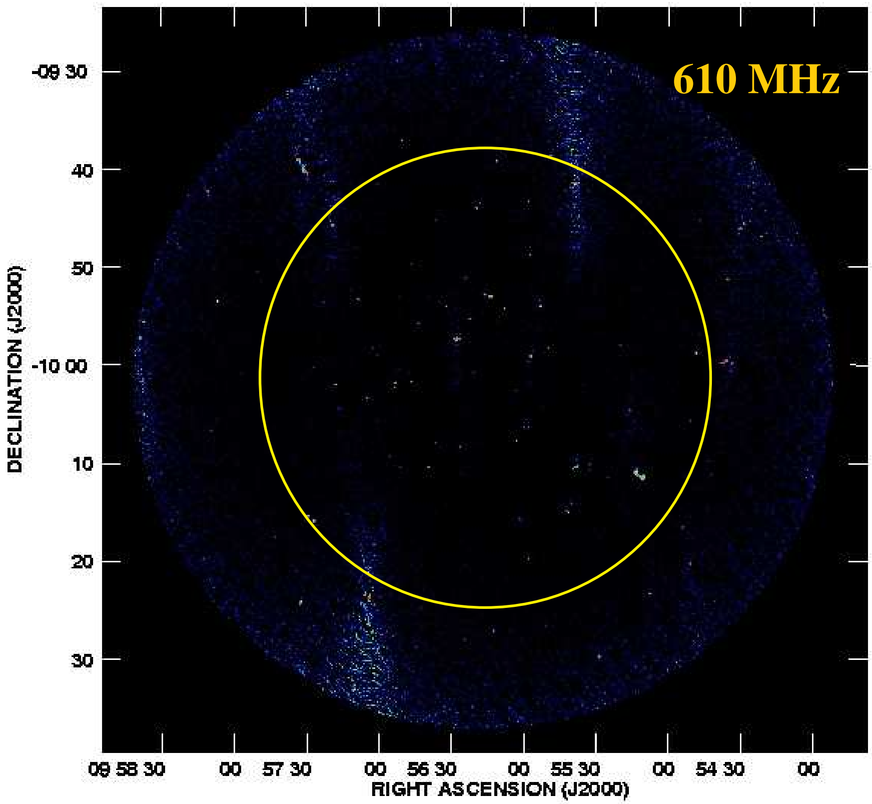




Beswick et al 2007 (In preparation)

Mosaicing within the primary beam

- GMRT observations of cluster Abell 901 - 1400 MHz
- Again a FLATNned multi-faceted image over a smaller primary beam with fewer dynamic range problems



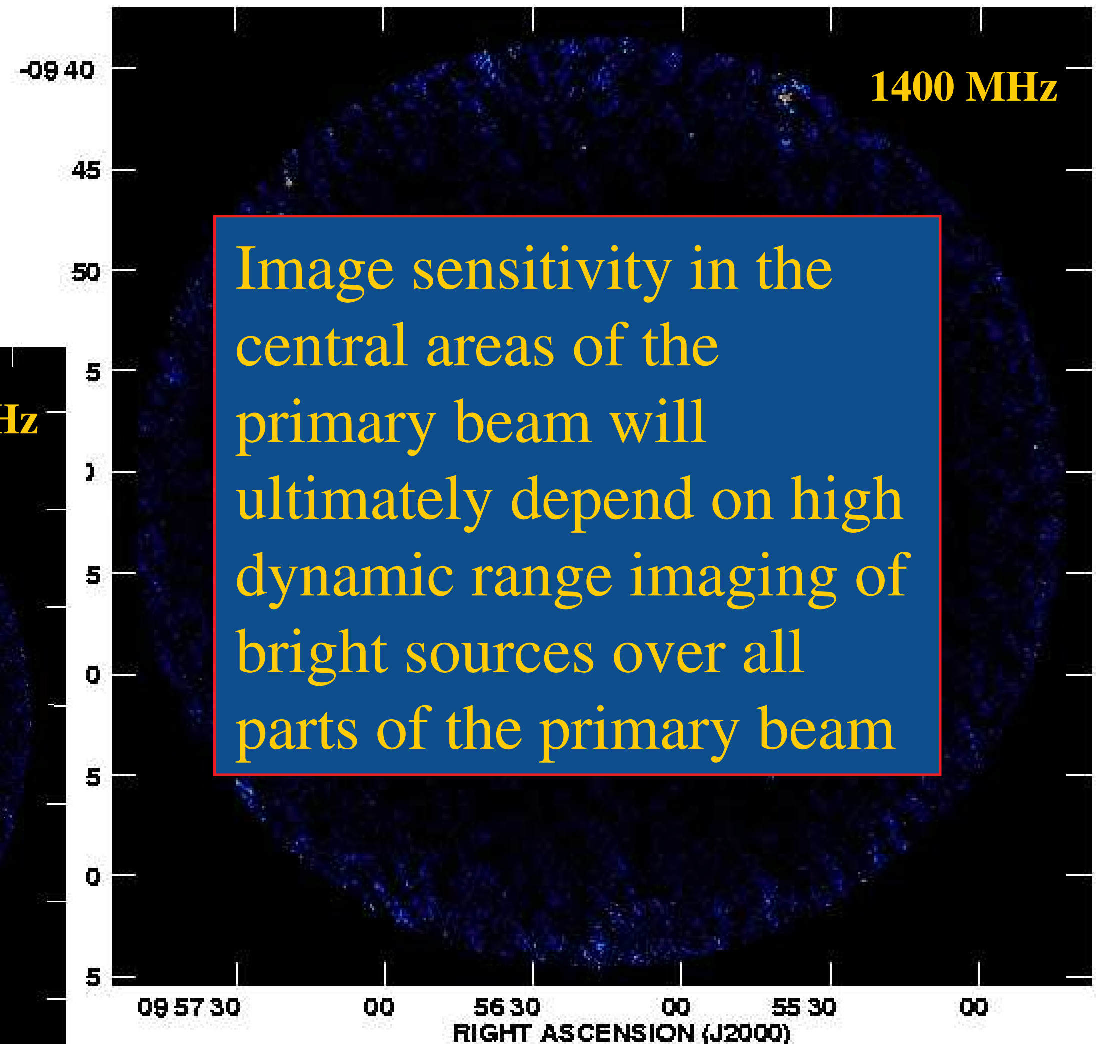


Image sensitivity in the central areas of the primary beam will ultimately depend on high dynamic range imaging of bright sources over all parts of the primary beam

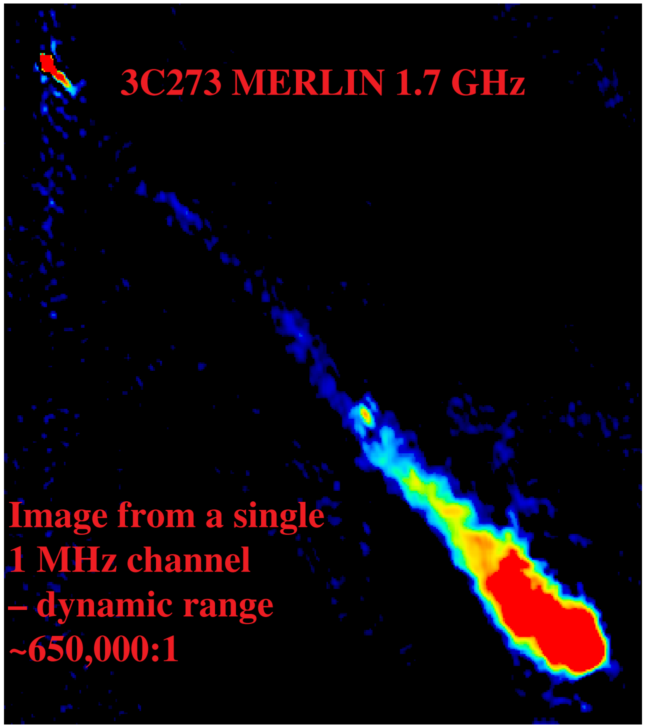
Beswick et al 2007 (In preparation)

Wide Field Imaging

High Dynamic Range Imaging

Present dynamic range limits (on axis):

- Phase calibration – up to 1000:1 → improve with self-calibration
- Non-closing data errors – continuum ~20,000:1 line >100,000:1
- After baseline calibration (BLCAL) ~10,000,000:1
- Non-closing errors thought to be dominated by small changes in telescope pass-bands on short timescales
- Spectral line data configurations are the default for all new wide-band radio telescopes
- In order to subtract out confusion we will need to be able to image with these very high dynamic ranges away from the beam centre



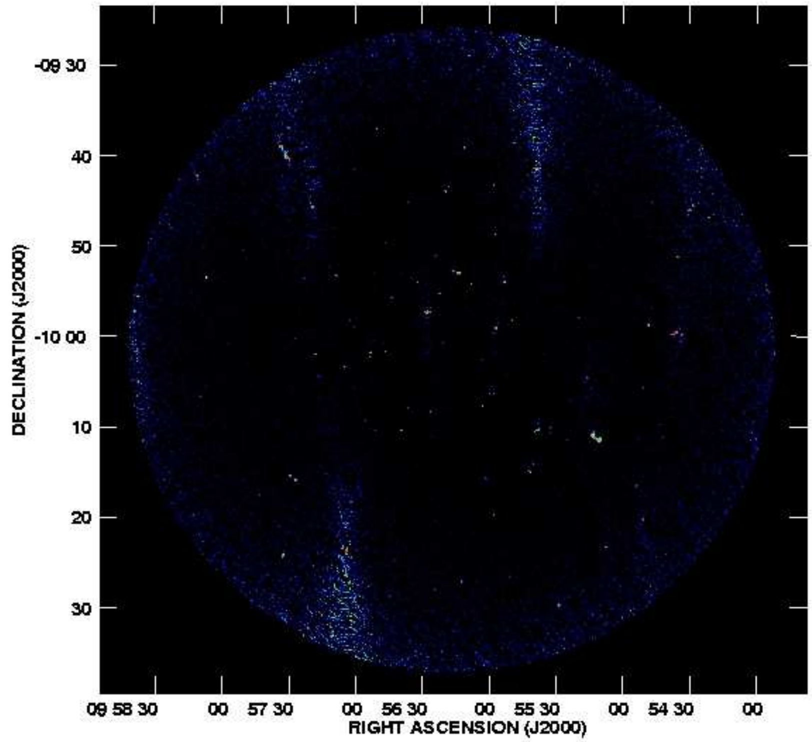
High Dynamic Range Imaging

Achieving high dynamic range off axis:

•It is vitally important to monitor and calibrate your spectral line data for dynamically changing spectral band-pass effects and pointing errors.

•You must understand the primary beam response to very high precision well into the near side-lobes

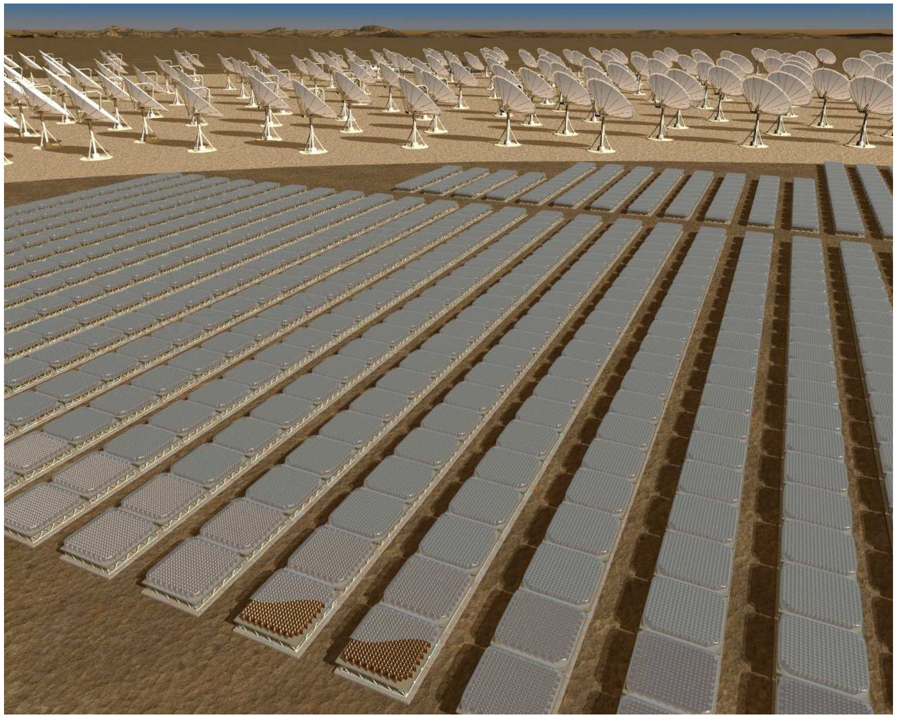
•Tests with ATCA data have successfully achieved high dynamic ranges off axis….



..by establishing an accurate primary beam model over a field of a few degrees and by mosaicing out to the 3rd or 4th sidelobe of the primary beam with the well-calibrated voltage pattern model.

High Dynamic Range Imaging

Achieving high dynamic range off axis for SKA:



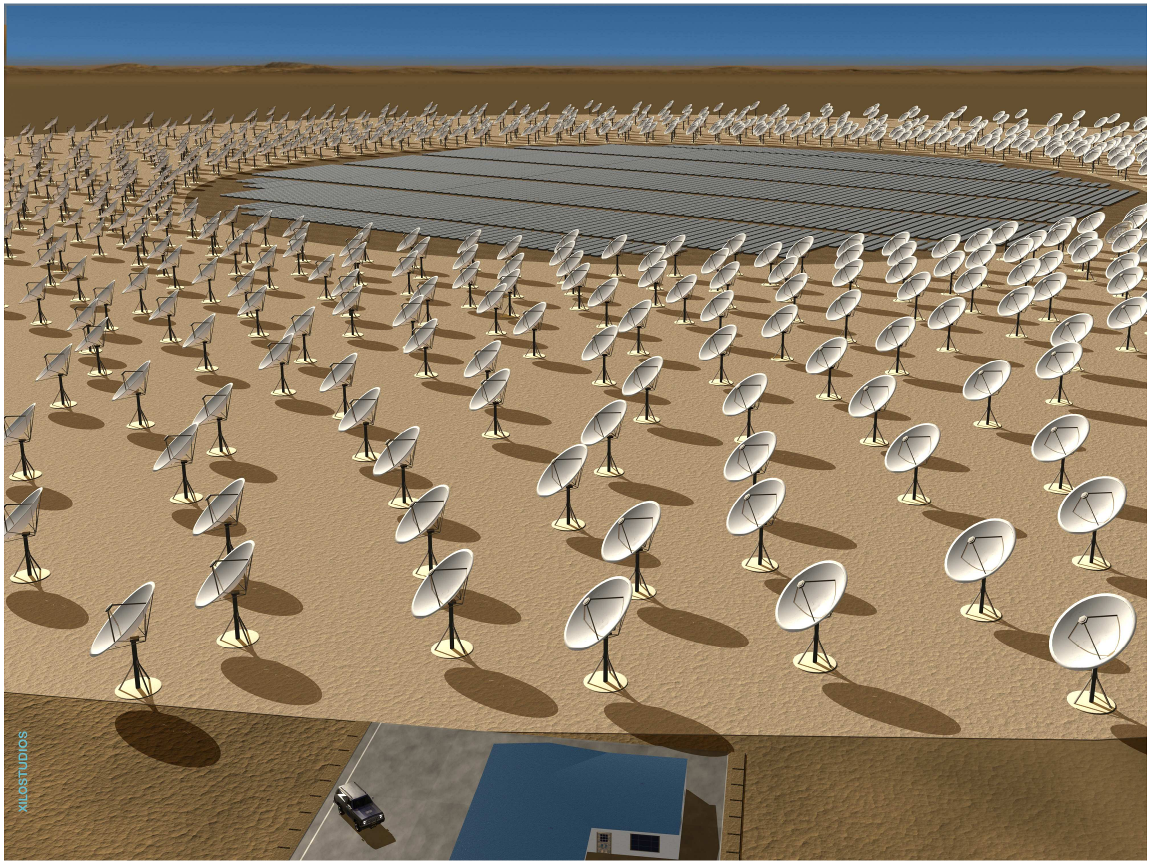
- A challenge !!
- Some elements may have a well determined and stable primary beam, but others may change with position on the sky
- Dynamic reconfiguration to provide multiple beams may introduce difficulties in achieving the required levels of calibration.
- The SKA pathfinder projects, LOFAR, and others, will prove invaluable in establishing the optimised configurations that will help to deliver both the desired levels of performance and flexibility.

Wide Field Imaging

RadioNet

High Dynamic Range Imaging

Achieving high dynamic range off axis for SKA:

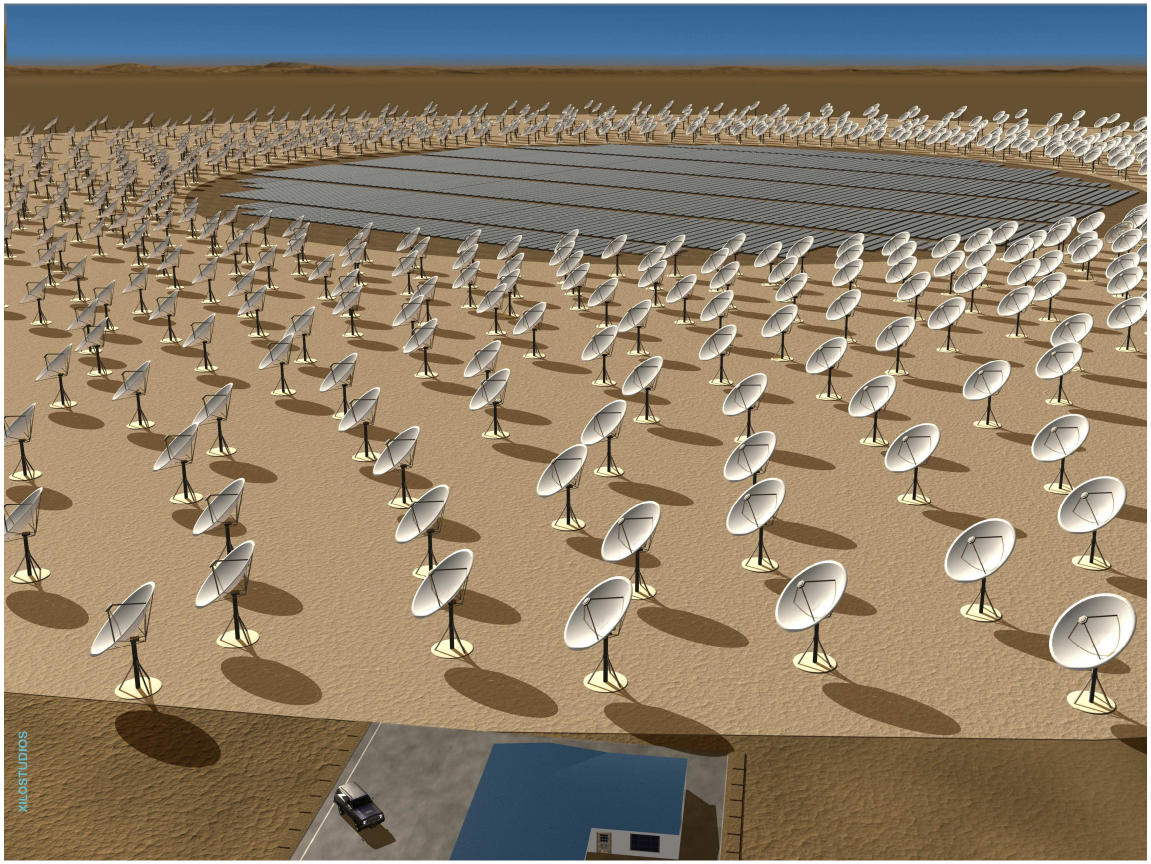


•Whatever configurations are chosen, the computational effort to make it work are likely to be very substantial……

RadioNet

High Dynamic Range Imaging

Achieving high dynamic range off axis for SKA:



…but as they say – It's only computing……………