e-MERLIN

Rob Beswick
(on behalf of e-MERLIN team)
- Major project to transform sensitivity & capabilities of old MERLIN
- 150 -10 mas resolution at L, C and K-band
- Increase bandwidth to 0.5/2 GHz → uJy sensitivity
- First semester of Legacy/Open time observations finished
The e-MERLIN Project

Goals
- Increase bandwidth to
  0.5 GHz (L-band)
  2 GHz (C & K -band)
- Include Lovell Telescope at C-band
- New telescope optics, feeds, receivers, IF, samplers
- Digital transmission system: 30 Gb/s from each telescope
- Dedicated optical fibre network
  - 100 km installed; 600 km leased
    (total ~700 km)
- H-maser freq (1 part in $10^{14}$) std over optical fibre network
- New correlator: wide field imaging; simultaneous line & continuum observations
- EVN recording/transmission for multiple telescopes

Capabilities
150, 40, 10 mas resolution
~3 uJy sensitivity in typical runs
20-30 x better than MERLIN performance
< uJy deep fields

Wide fields
[~7,27 arcmin]

Spectroscopy
Up to 16 sub-bands; >512 chan/pol;
(More with Recirculation)
Mix line and continuum

Much improved aperture coverage
Via frequency coverage

Spectral mapping
1.3-1.7; 5-7/4-8 GHz

Polarization (L,R → IQUV)

Astrometry
Goal is < 1 mas wrt ICRF
Data Transmission Network Solution

- 7tels * 30 Gb/s sustained data rate from each telescope
  - (=5M homes @ 10GB/month)
- Private fibre network to connect remote telescopes in rural locations
- Installed & tested 90km new fibre alongside minor roads to connect to...
- 600 km Dark Fibre trunks leased from UK telecoms providers
- Use e-MERLIN/JVLA/ALMA data transmission system
- Amplifiers/Regeneration at Peterborough, Nottingham, Birmingham, Crewe, designed and installed by JBO
Progress & Status

- Whole system complete & operational (except for 4 Gs/s boards – coming soon)
- Over the last couple of years...
  - Completed & commissioned 4-8 GHz (0.5 GHz b/w currently – expanding to 2GHz soon)
  - Completed & commissioned 1.25 – 1.75 GHz
  - Incorporated Lovell Telescope at L, C-band
  - Entire IF replacement
  - H-maser synchronisation over optical fibre
  - Complete new operational s/w
  - Successful e-VLBI tests with multiple telescopes
- Science continued at some level throughout development – *get scientists involved with early data*
- Started *Legacy* Programme observations
- Cycle-0 call & observations for open time (last year)
- Cycle-1 – commences in Autumn 2013
  - Oversubscribed ~3:1 (all time), ~6:1 (requests requiring Lovell telescope)
L-band performance

- Accessible band constrained by RFI
  - Radars etc below 1.2 GHz
  - Cell phones above 1.7 GHz

- High-performance filters → band (1.25 – 1.75 GHz)
  - Front ends & IF linear (8-bit sampling)

- Use narrower sub-bands than c-band
  - 8 x 64 MHz (512 ch/sub-band/pol)

- Auto-flaggers essential
  - SERPent (developed for e-MERLIN Peck & Fenech [UCL]) – see poster.

≈90% data useable is norm.
Interference from fixed links, CCTV camera, computers, wifi etc etc

- Typical image noise
  ≈ <10 uJy/beam, Lovell
Wide-field & wide-band imaging

- Default correlator configuration allows full primary beam imaging
- At L-band N(>2.5 mJy) ~ 15; 30% compact
  - SNR/tel ~ 10 in 100s using full 500 b/w
  - In-beam self-calibration routine at L-band
  - To achieve uJy sensitivity need to subtract these sources with DR ~10,000:1
  - Need detailed map/model of primary beam
  - Direction dependent calibration (ALBiUS)
  - 30% fractional bandwidth → MF deconvolution

N. Wrigley (part of his PhD)
Example Wide field imaging

- 9hrs on source (with LT) ~13uJy/bm noise
- ~300MHz band at L-band (older reduced b/w).
- Image multi-arcmin field.

Array HPBW (top of band)
Array HPBW (bottom of band)
e-MERLIN observing

- e-MERLIN is open to all users
  - Open-time Cycle-0 observations (complete)
  - Cycle-0 period (3-way-split = open-time shared-risk/ongoing instrument commissioning/legacy test observations)
  - Cycle-1 starting Autumn 2013.
    - Oversubscribed ~3:1 (all time), ~6:1 (requests requiring Lovell telescope)
- Alongside open-time, 50% of time in first ~5 semesters is allocated to large ‘key’ science [Legacy] programmes.
  - Legacy projects targeting key science areas and provide long term legacy data products.
  - Large consortia teams.
- Legacy observations now underway (observing)
e-MERLIN legacy programme

- Defined key science programme before instrument ready

Large projects covering planet formation → cosmology

Full project proposals available http://www.e-merlin.ac.uk/legacy/

**GALACTIC PROJECTS:**

- eIT - Pulsar astrometry – Vlemmings/Stappers et al. 160hrs **
- PEEBLES – planet formation - Greaves et al. 72hrs **
- Feedback processes in Massive SF – Hoare/Vlemmings et al. 450hrs
- Thermal jets from low mass stars - Rodriguez et al 180hrs
- COBRaS – wide-field deep galactic survey - Prinja et al. 294hrs

**EXTRA-GALACTIC PROJECTS:**

- LEMMINGS – 300 nearby gals - Beswick/McHardy et al. 810hrs
- LIRGI – LIRGs/ULIRGs - Conway/Perez-Torres et al. 353hrs
- Extragalactic Jets – Laing/Hardcastle et al 375hrs
- AGATE – cluster fields - Simpson/Smail et al 330hrs
- e-MERGE – deep field - Muxlow/Smail/McHardy et al 918hrs
- Gravitational lenses – Jackson/Serjeant et al 228hrs **
- SuperCLASS - weak lensing 1.7deg² supercluster Battye et al 832hrs

** Remaining 830hrs to be allocated to these projects pending initial results**
First Science and early results

- **Legacy programme**
  - 12 projects
  - Proto-planets... Star-formation in distant galaxies
- **Open programme (PATT)** – 50% of observing time.

SNRs in M82

( Richards et al 2013 )
The e-MERLin Galaxy Evolution Survey

A tiered e-Merlin + JVLA Legacy project
- utilising e-Merlin step change in sensitivity & imaging ability

Tier 0 – Imaging radio emission from normal galaxies out to z ~ 5
Deep imaging around clusters to utilise amplification by lensing

Tier 1 – A very deep directed survey of the µJy radio source population
Deep imaging of the µJy radio source population in GOODS-N

The combination of these tiers will ensure a full sampling of the active and star-forming galaxy radio luminosity function out to z~5

Tier 0: Ian Smail [Durham], Tier 1: Tom Muxlow [Manchester] (Deep-narrow), Tier 2: Ian McHardy [Southampton] (Through PATT time) (Shallow-wide)

Tier 0 – 180hrs e-Merlin (L-band) + JVLA-A
Tier 1 – 360hrs e-Merlin+40hrs JVA-A (L-band)+ 378hrs e-Merlin+ JVLA A/B/C (C-band)
Tier 1: New Ultra-Deep Study of GOODS-N

e-MERLIN will match the depth of the existing (18 day) MERLIN image in just 24 hours of on-source integration.
L-band: Single pointing centre, ~20 days including 76m Lovell telescope.

Central 12 arcminute field
$1\sigma \sim 500\text{nJy/beam}$
(in combination with JVLA)
Outer 30 arcminute field
$1\sigma \sim 1\mu\text{Jy/beam}$
Tier 1: New Ultra-Deep Study of GOODS-N

e-MERLIN will exceed the depth of the existing MERLIN map in just 24 hours of on-source integration.

L-band: Single pointing centre, ~20 full tracks.
Central 12 arcminute field $1\sigma \sim 500\text{nJy/beam}$
Outer 30 arcminute field $1\sigma \sim 1\text{µJy/beam}$

e-MERLIN will image $\sim850$ individual starburst and AGN with an angular resolution of $\sim170$ mas, complete to $\sim3\text{µJy}$
($>10$ times deeper than the 2005 study)

In the surrounding 800 square arcmins, e-MERLIN will image $\sim2500$ star-forming galaxies and $\sim1200$ AGN brighter than $\sim6\text{µJy}$

$>5000$ sources in 0.2 square degree field
Tier 1: New Ultra-Deep Study of GOODS-N

New C-band image: 7 pointing centres
Mosaic pattern set for Lovell - 25m beam
JVLA will provide short spacings
Inner 6' $1\sigma \sim 500\text{nJy/beam}$
6-12' $1\sigma \sim 700\text{nJy/beam}$
Resolution $\sim 40$ mas

Separate and disentangle the AGN and starburst components of emission

Study the role that the AGN play in controlling star-formation via feedback - on sub-kpc scales for several hundred galaxies

JVLA C-array 7 pointing mosaic – for addition to B & A-array data + e-MERLIN
Resolution $\sim 5$ arcsec, $1\sigma$ noise $5.5\mu\text{Jy/bm}$
Recent L-Band e-Merlin test taken and now being processed.  
Test data: 26 hours on target → $1\sigma$ noise $\sim 6.6\mu$Jy/bm

Full spatial frequency coverage: → Superb image fidelity – from just 7 (6) antennas - 1230 MHz – 1740 MHz (34%)  
Even reference field deep enough to image interesting confusing sources  
– $\sim 20\text{mJy FR-I}$  
– 8’ offset  
– Peak $\sim 926\mu\text{Jy/bm}$  
$\sim 3\text{mJy}$ unresolved flux density within central 12 arcmin field is sufficient for $\phi$ self-calibration
Tier 1: New Ultra-Deep Study of GOODS-N

Test e-MERLIN L-band data: 26 hours on target $\rightarrow$ 1$\sigma$ noise $\sim$6.6$\mu$Jy/bm
Core-jet AGN at nucleus of 11" N-S FR-I (Total 5.96mJy)

HST ACS: $I=20.9^{\text{mag}}$ red elliptical $z=1.050$
Tier 1: New Ultra-Deep Study of GOODS-N

Test e-MERLIN L-band data: 26 hours on target \( \rightarrow \) 1\( \sigma \) noise \( \sim 6.6 \mu \text{Jy/bm} \)

Extended steep-spectrum \( (\alpha = 0.74) \) starburst (Total 230\( \mu \text{Jy} \)) ISO detection
\n\[ L_{1.4} = 4.1 \times 10^{24} \text{ W/Hz} \] \( \rightarrow \) Star-formation rate \( \sim 960 \text{ M}_\odot/\text{yr} \) (0.1-100\( \text{M}_\odot \) assuming Salpeter IMF)

HST ACS: \( I = 22.3 \text{mag} \) Scd galaxy \( z = 1.219 \)

J123634+621241 Starburst
Lowest contour 20\( \mu \text{Jy/bm} \)
Tier 1: New Ultra-Deep Study of GOODS-N

AGN Wide-angled tail radio galaxy  (Total 1.3mJy)
Tier 1: New Ultra-Deep Study of GOODS-N

AGN Wide-angled tail radio galaxy (Total 1.3mJy)

HST ACS: $I=22.9^{\text{mag}}$ galaxy $z=1.2653$
Tier 1: New Ultra-Deep Study of GOODS-N

Ide-field data allows imaging to the edge of the outer field:
62mJy FR-II imaged (test data) – 10.4 arcminutes from field centre

L-band: Single pointing centre, ~20 days including 76m Lovell telescope.
Central 12 arcminute field $1\sigma \sim 500\text{nJy/beam}$ (in combination with JVLA)
Outer 30 arcminute field $1\sigma \sim 1\mu\text{Jy/beam}$

Target of field source count statistics free from sample variance, over small but deep region
Tier 1: New Ultra-Deep Study of GOODS-N

30' field $\sim 0.2 \text{ deg}^2$ – Complete to $6\mu\text{Jy} \rightarrow$ source count scatter imposed by sample variance $\sim 5\%$ of the mean & sources $\sim$ unresolved to JVLA

L-band: Single pointing centre, $\sim 20$ days including 76m Lovell telescope.
Central 12 arcminute field $1\sigma \sim 500\text{nJy/beam}$ (in combination with JVLA)
Outer 30 arcminute field $1\sigma \sim 1\mu\text{Jy/beam}$

Heywood, Jarvis, & Condon 2013

Field source count statistics free from sample variance
Star-formation History of the Universe - from Starburst Luminosities


L-Band results from the eMERGE survey will provide data for several thousand more sources

Star-formation from GRB studies – Kistler et al 2009
Tier 0: Imaging sub-\(\mu\)Jy galaxies

A single L-band pointing on a strongly lensing cluster A2218 (\(z=0.18\)).

e-MERGE will characterise the \(\mu\)Jy & sub-\(\mu\)Jy radio source population

\[ \Rightarrow \text{the target population for the SKA in future high redshift SF studies} \]

Measure faint radio counts
May include SF galaxies with SFR\(\sim\)200\(M_\odot/\text{yr}\) to \(z\sim5\)
Summary

• e-MERLIN is full operational
  • Unique capabilities of uJy and sub-arcsecond imaging
  • Simultaneous spectral line modes
  • Wide range of science
  • Wide-ranging key-science programme
    – driving science & operational developments.
  – Further developments coming soon
    • 2GHz b/w at C-band, improved 22GHz sensitivity  .....  

• Few hundred km baseline SKA pathfinder.
  – Resolution key for much of e-MERLIN astrophysics & continuum science.
  – Typical moderate redshift galaxy size is ~<1arcsec

• Communications with users critical.
  – Early science helps keep users involved & contributing
Stacking of deep MERLIN data: GOODS – ACS data

- \( \sim 13030 \) galaxies above mag 28.3 mag in z-band (just in 8.5 arcmin\(^2\) field)
- ACS images aligned with MERLIN radio image to <0.05 arcsec rms.
Radio census of ACS sources

- Radio flux within 0.75 arcsec of all z-band optical galaxies.

(Note excluding all bright radio sources (>20µJy at any pixel))

Median values are not statistically different from means implying that of the ~2700 galaxies brighter than Z=24mag, around 1400 will have radio flux densities of ~4µJy or greater (~8σ for a deep e-MERLIN/EVLA image)
Radio source sizes:
very weak (sub-20uJy) radio sources

Average source sizes range from $r \approx 0.75$ arcsec (21.25 mag $[\sim 12\mu$Jy]) to

Above 40uJy
Average images of starbursts in the HDF-N.

Radio flux density contained within an annulus of radius 0.75 arcseconds centred on the position of each of 13000 catalogued galaxies in the region of overlap between the ACS and MERLIN/VLA image binned by Z-band magnitude. Control sample incorporates a random 7 arcsecond offset.

Composite of emission from 1710 24 +/- 0.5 magnitude HDF-N galaxies.

Radio RMS=74nJy
Capabilities

- 150, 40, 10 mas resolution at L[20cm], C[6cm], K[1.3cm]
- ~2 uJy sensitivity in typical runs
  - <uJy in deep fields
  - ~30 uJy in ~1 min
- Wide fields
  - Out to HPBW of 25-m [7.27 arcmin]
- Spectroscopy
  - 16 placeable sub-bands; >512 channels/pol; recirculation
  - Can mix/trade bandwidths; no. of channels, polarisations
- Much improved aperture coverage
  - Via frequency coverage
  - May help snapshots too
- Spectral mapping
  - 1.3-1.7; 5-7/4-8 GHz
- Polarization (L,R → IQUV)
- Astrometry
  - Goal is < 1 mas wrt ICRF:
    using GPS measurements of troposphere delay
    (5cm error -> 5mm); closer calibrators
C-band Performance

- C-band – on telescope
  - Tsys: ~34K over 512 MHz
    ~38K over 2 GHz
  - SEFD (25-m) 300, 340Jy
- C-band noise measurement
  - 10-15% higher (low elevation)
- Image noise measurement
  ~15 uJy/beam, 512 MHz, no Lovell
- RFI – time consuming
  - Groups working on auto-flaggers
  - Not a major impact on C-band performance
Optical fibre synchronisation

- Single H-maser at Jodrell Bank
- 2-way transmission system
- Local frequency standard at telescopes
- Now fully implemented on optical fibre network on separate fibre or additional DWDM wavelengths
- Improved short term stability
- Diurnal drifts – incorporated into delay model