e-MERLIN: Past, Present & Future

Simon Garrington, Jodrell Bank

Long baseline interferometry at JBO (1953-1965)

The Birth of MTRLI (1973-1978)

MERLIN (1980-1991)

Extension to Cambridge (1992-2002)

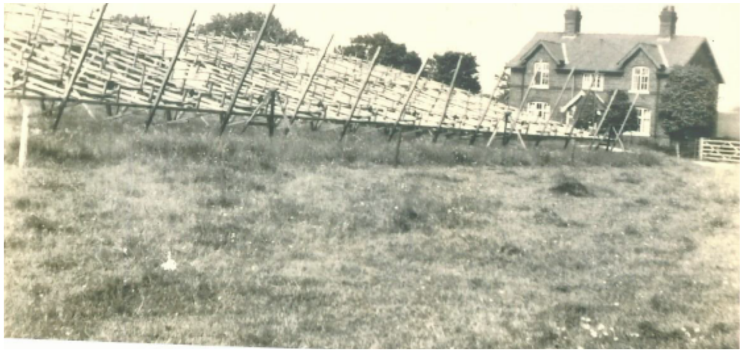
e-MERLIN (2002->)

Development & e-MERLIN in the SKA Era (2018+)

ACBL 'The Jodrell Bank Telescopes' (1985)
H Palmer 'High Resolution Studies in Astronomy' (1965)
Serendipitious Discoveries in radio Astronomy, NRAO, (1983)
George Miley talk at JIVE-ERIC Inauguration

Early Interferometry at Jodrell Bank

- Jennison & Das Gupta 1951-3: Cyg A
- Intensity interferometer 125 MHz
- Radio-linked - 10km
- Early multi-frequency synthesis!



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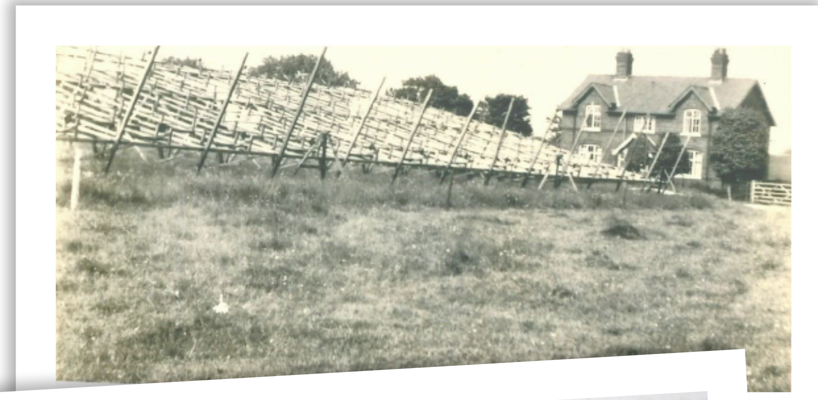

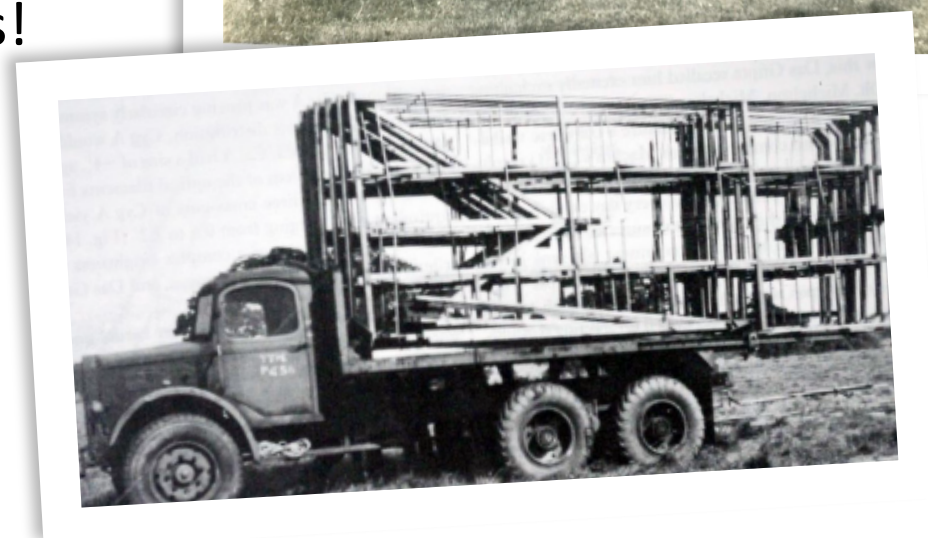

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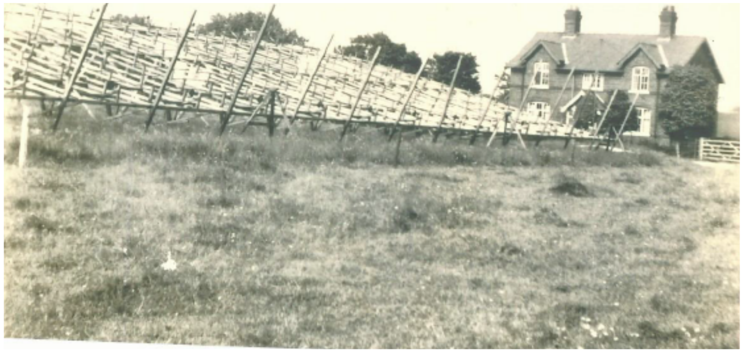

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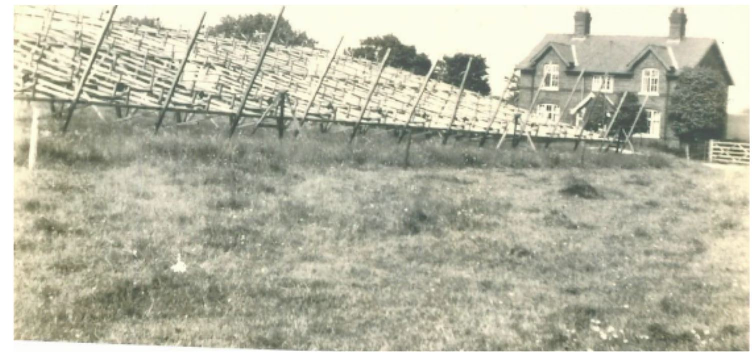

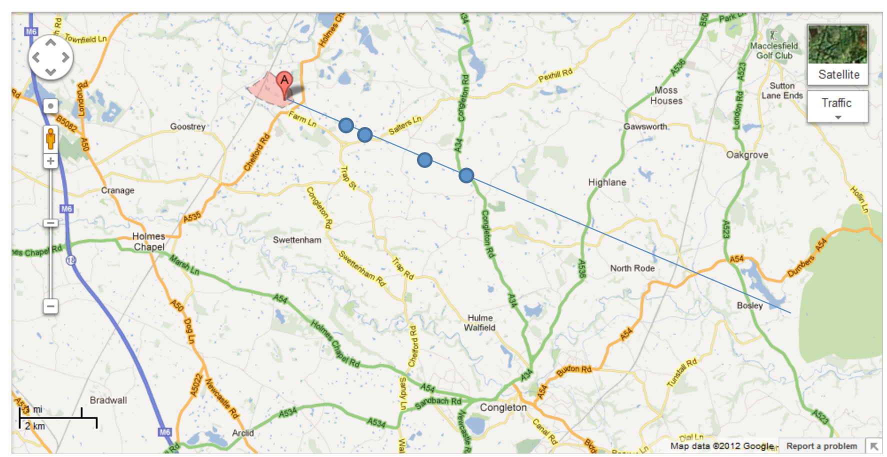

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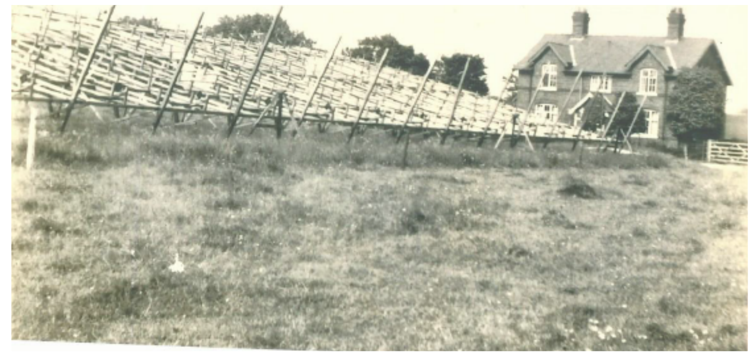
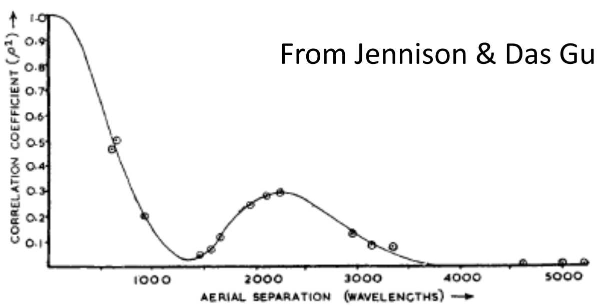


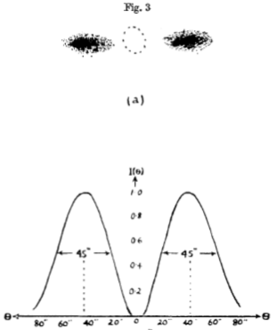
Fig. 1

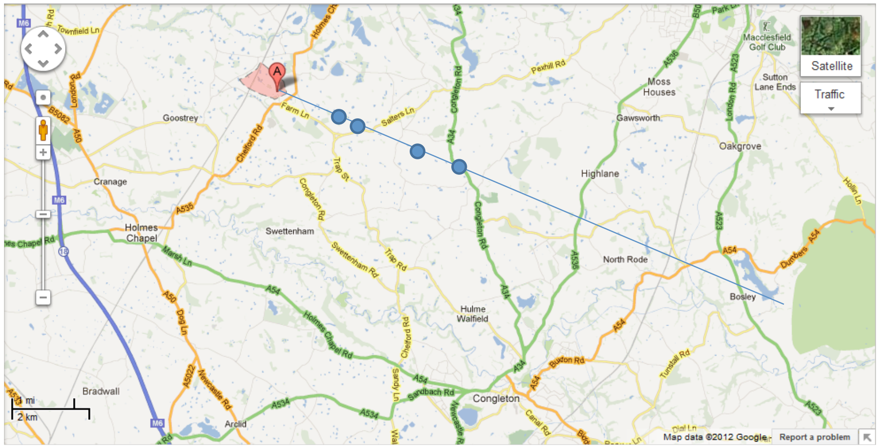


From Jennison & Das Gupta 1955

Variation of correlation coefficients with baseline for the intense radio source Cygnus I, measured in position angle 113° at a frequency of 125 Mc/s.

Fig. 3





The start of long baseline interferometry at Jodrell Bank

Henry Palmer’s group
158 MHz (Michelson): 218’ transit+36m^2 array
VHF radio link

1954: 0.9 km (Jodrell)
1955: 1.8 km (Lower Withington)
3.9km (Goostrey)
13 km (Congleton)
20km (Cat & Fiddle)
3 objects smaller than 12 arcseconds

Fig. 2. The remote station of the 158 MHz interferometer. Receiving equipment is in the two small trailers. The antenna on the pole at the left is the radio link back to the main station at Jodrell Bank. Circa 1954.

A R Thompson, 1983

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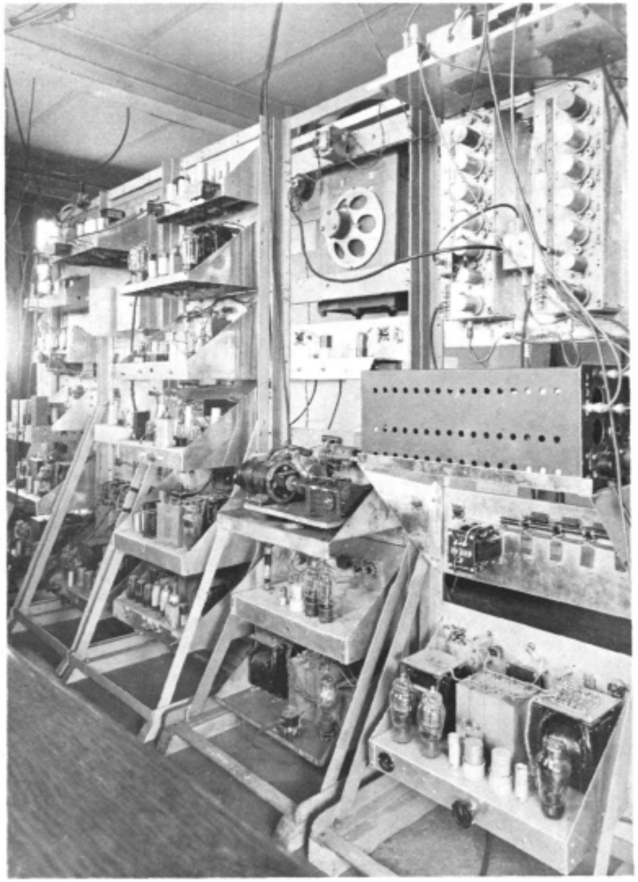

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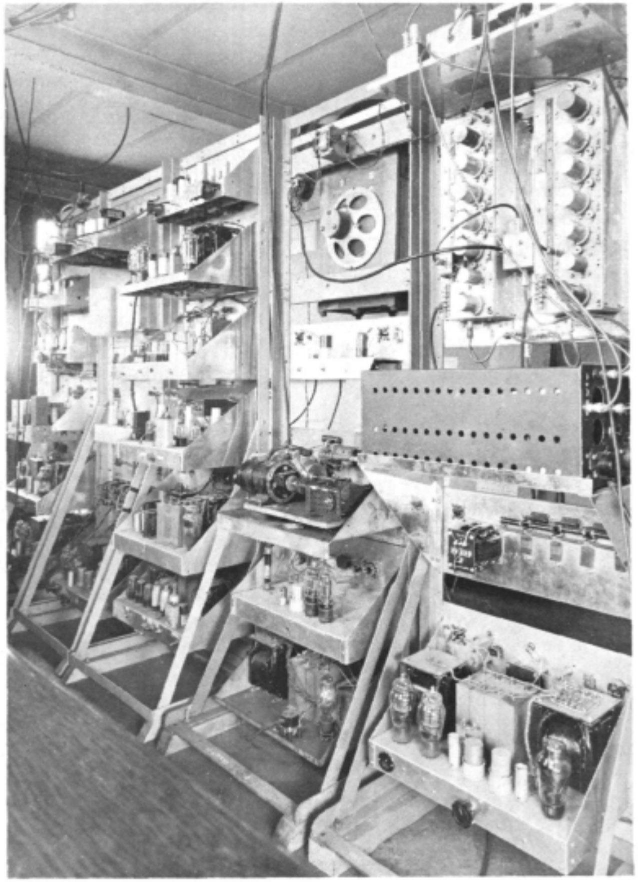

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NOTES FROM OBSERVATORIES

FIVE RADIO SOURCES OF SMALL ANGULAR DIAMETER

By D. Morris, H. P. Palmer, and A. R. Thompson
Jodrell Bank Experimental Station, University of Manchester

The measurements were made at 158 Mc/s with the rotating lobe interferometer which has been described elsewhere.[3] The aerials used were the 218 ft transit telescope at Jodrell Bank and a portable broadside array of aperture 36 m². The sources were observed with a number of different baselines, the greatest being 20 km.

For baselines greater than 1 km a VHF radio link was used to convey the signals from the distant station to the multiplier and recorder which were close to the transit telescope. The signals from the latter were delayed to achieve coherence with those from the distant station. The

Fig. 2. The remote station of the 158 MHz interferometer. Receiving equipment is in the two small trailers. The antenna on the pole at the left is the radio link back to the main station at Jodrell Bank. Circa 1954.

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The push to longer baselines

- 1958-9: Mk1 + 100m^2 cyl. parabola
- 1960: Holywell (60km W)
- 1961: Hemswell via Holme Moss
  115km E, 187 sources
  7 < 0.8 arcsec
  … discovery of quasars…
- 1964: Pocklington
  25' dish,134km, 408 MHz
  remote control, TV link
  3 quasars < 0.4 arcsec

Allen et al 1962
Anderson et al 1965

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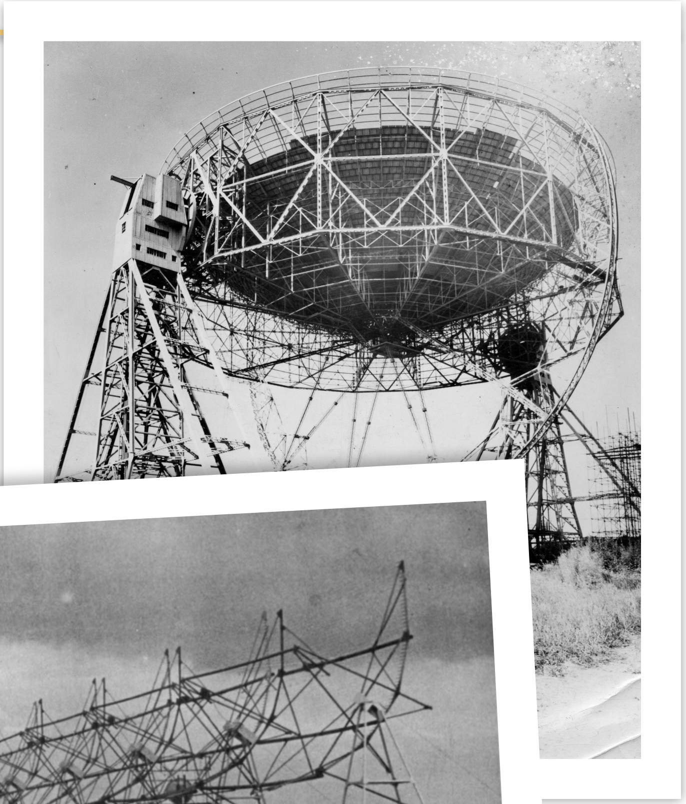

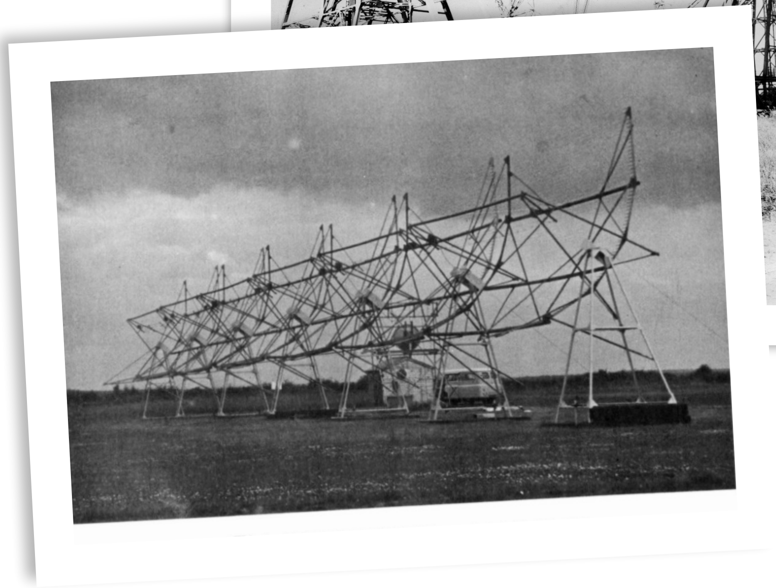

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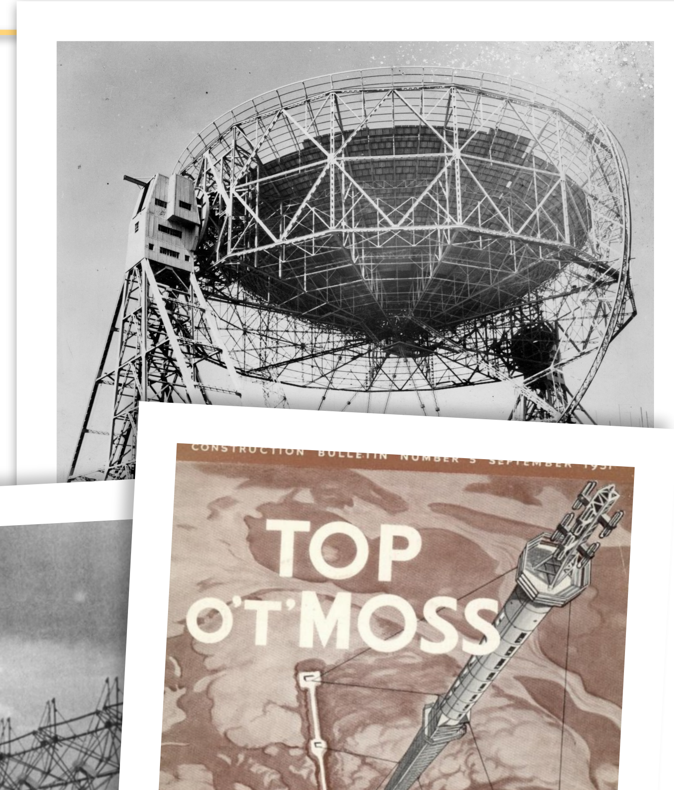

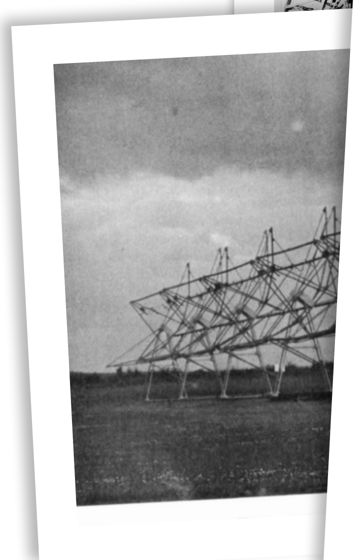

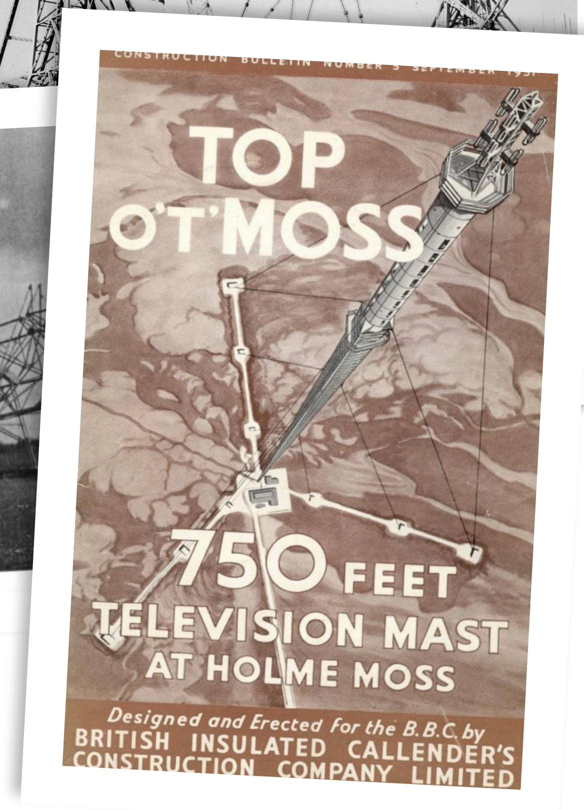


Pocklington
Hemswell
Holywell
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25’ dish by W Donaldson & B Anderson
at Pocklington, Yorks.

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Imagery ©2017 , Bluesky, DigitalGlobe, Getmapping plc, Infoter

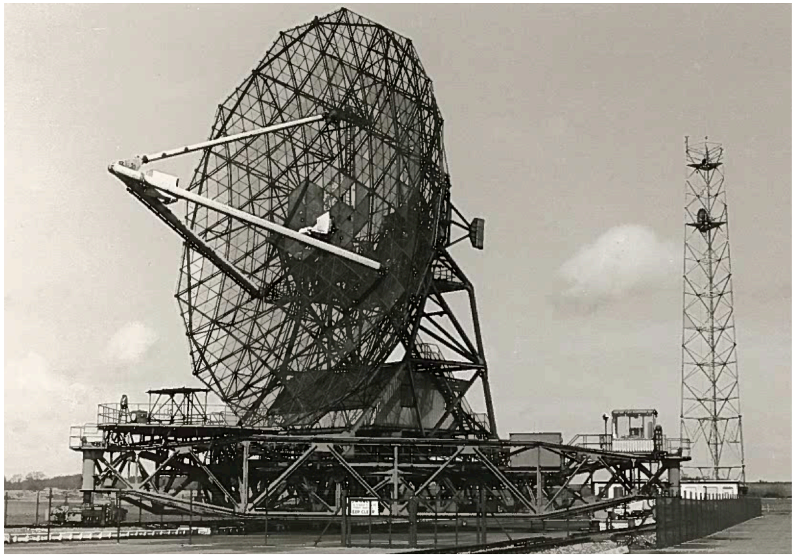
Defford

- 2 x 25m interferometer by JS Hey 1962
- 127 km baseline to JBO
- 1965: 1.4 GHz

  5 sources < 0.1 arcsec
- 1966: 5 GHz

  < 0.01 arcsec

VLBI takes over…



Palmer et al 1967; Miley et al 1967

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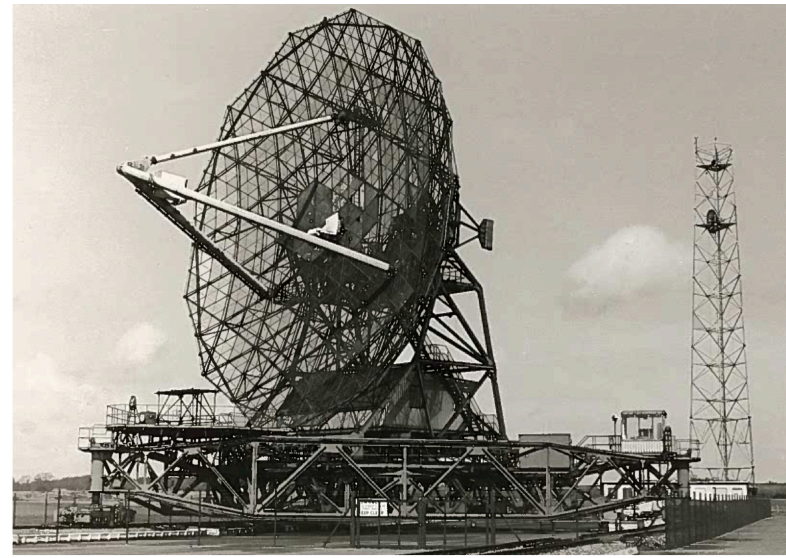

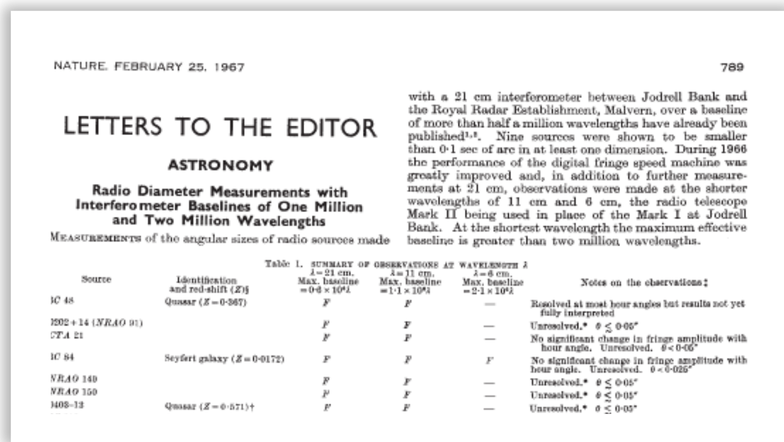

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LETTERS TO THE EDITOR

ASTRONOMY

Radio Diameter Measurements with Interferometer Baselines of One Million and Two Million Wavelengths

MEASUREMENTS of the angular sizes of radio sources made with a 21 cm interferometer between Jodrell Bank and the Royal Radar Establishment, Malvern, over a baseline of more than half a million wavelengths have already been published[1,2]. Nine sources were shown to be smaller than 0·1 sec of arc in at least one dimension. During 1966 the performance of the digital fringe speed machine was greatly improved and, in addition to further measurements at 21 cm, observations were made at the shorter wavelengths of 11 cm and 6 cm, the radio telescope Mark II being used in place of the Mark I at Jodrell Bank. At the shortest wavelength the maximum effective baseline is greater than two million wavelengths.

Table 1. SUMMARY OF OBSERVATIONS AT WAVELENGTH λ

Source	Identification and red-shift (Z)§	$\lambda = 21$ cm. Max. baseline $= 0{\cdot}6 \times 10^6\lambda$	$\lambda = 11$ cm. Max. baseline $= 1{\cdot}1 \times 10^6\lambda$	$\lambda = 6$ cm. Max. baseline $= 2{\cdot}1 \times 10^6\lambda$	Notes on the observations‡
3C 48	Quasar ($Z = 0{\cdot}367$)	F	F	—	Resolved at most hour angles but results not yet fully interpreted
0202+14 (*NRAO 91*)		F	F	—	Unresolved.* $\theta \lesssim 0{\cdot}05''$
CTA 21		F	F	—	No significant change in fringe amplitude with hour angle. Unresolved. $\theta < 0{\cdot}05''$
3C 84	Seyfert galaxy ($Z = 0{\cdot}0172$)	F	F	F	No significant change in fringe amplitude with hour angle. Unresolved. $\theta < 0{\cdot}025''$
NRAO 140		F	F	—	Unresolved.* $\theta \lesssim 0{\cdot}05''$
NRAO 150		F	F	—	Unresolved.* $\theta \lesssim 0{\cdot}05''$
1403–12	Quasar ($Z = 0{\cdot}571$)†	F	F	—	Unresolved.* $\theta \lesssim 0{\cdot}05''$

Wardle

- Designed as a low cost transportable dish based on MkII design (24 x 36m) (1961; comm. 1966; decomm. 1996)
- 24 km baseline
- Phase-stable link

  Warwick et al (1976)

  subsequently M Bentley, BA, RJD

  Founding technology of MERLIN

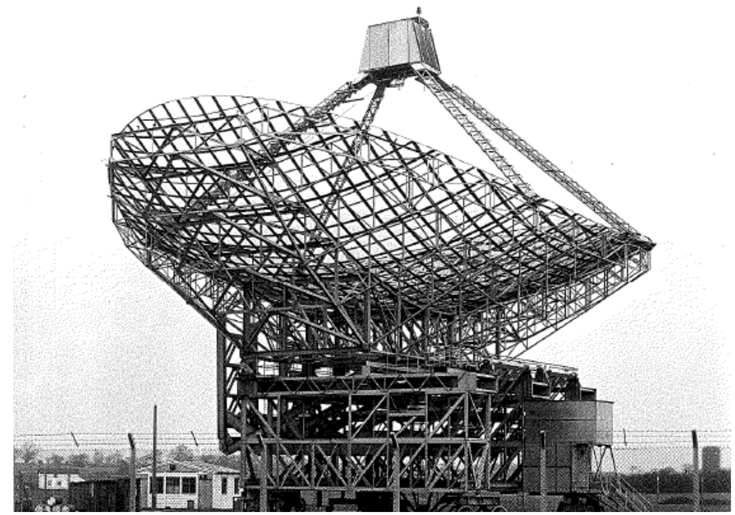
→ Industry of Jodrell single baseline component & polarization values (1970s)

  0.4km (MkII), 24km (Wa) & 127km (De)

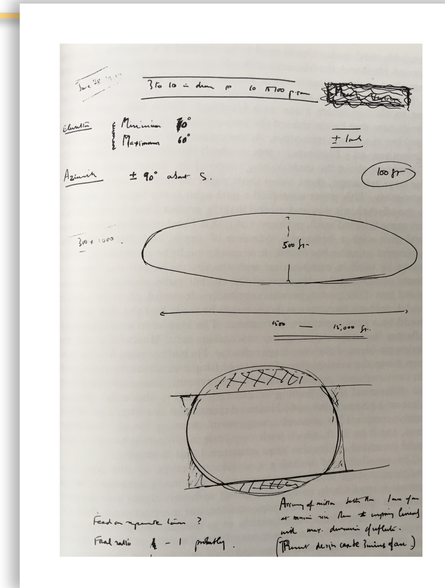
→ Depolarization Asymmetry (Laing+STG, 1988)

→ Extended emission around flat spectrum quasars

  Moore et al (1981) [Mk1-De 966 MHz]



MkV(A) & the birth of MERLIN



Lovell's grand plan 1960-1977
Big single dish

MkIV: 500x1,500-15,000'
MkV (1965-1970):400', £8m
MkVA (1971-1974: Cancelled): 375',£18-22m

'Reserve plan' to SRC for long-baseline interferometer network (MTRLI- H Palmer) in 1974:
JB, Defford, Wardle (127 & 24km), + 3 new dishes
  £3.6m for 3 VLA dishes, + links etc

Sep '74: reduced to 1 new dish (£1.9m) at Knockin
approved Jan 1975.
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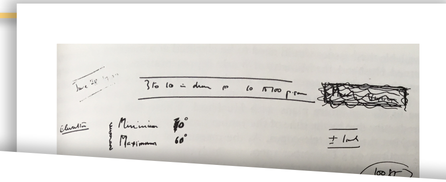

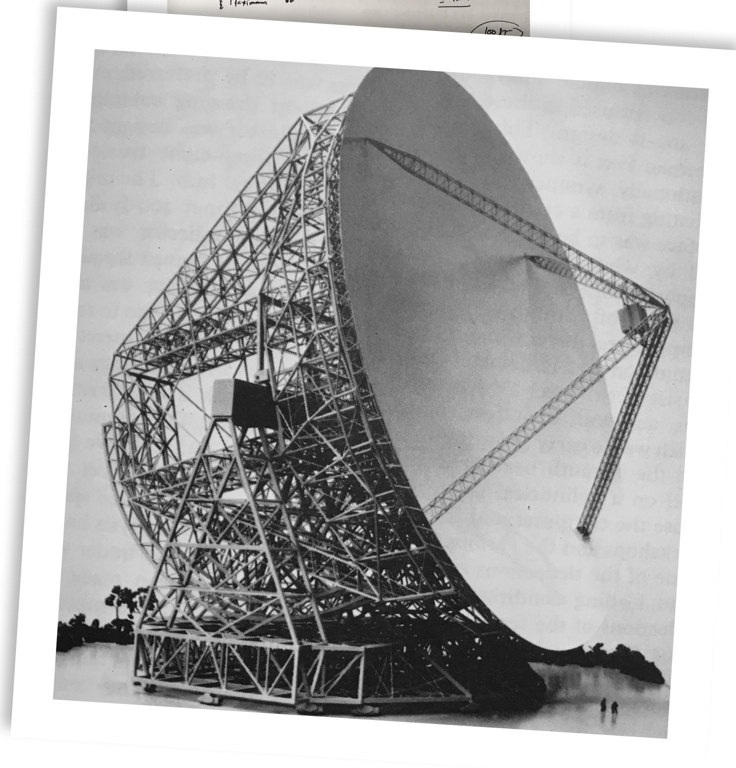

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One more hurdle…

- No source structure between 0.01 ~1”?
  (Cambridge, IPS)
- JB-Defford (127km) 13cm
  (Aug 1977: Tzanetakis, Spencer,+)
- Source separations down to 0.1”
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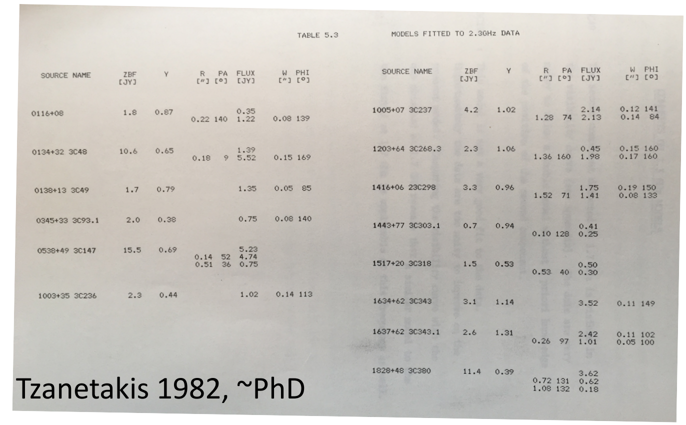
TABLE 5.3 MODELS FITTED TO 2.3GHz DATA

SOURCE NAME	ZBF [JY]	Y	R [″]	PA [°]	FLUX [JY]	W [″]	PHI [°]
0116+08	1.8	0.87			0.35		
			0.22	140	1.22	0.08	139
0134+32 3C48	10.6	0.65			1.39		
			0.18	9	5.52	0.15	169
0138+13 3C49	1.7	0.79			1.35	0.05	85
0345+33 3C93.1	2.0	0.38			0.75	0.08	140
0538+49 3C147	15.5	0.69			5.23		
			0.14	52	4.74		
			0.51	36	0.75		
1003+35 3C236	2.3	0.44			1.02	0.14	113
1005+07 3C237	4.2	1.02			2.14	0.12	141
			1.28	74	2.13	0.14	84
1203+64 3C268.3	2.3	1.06			0.45	0.15	160
			1.36	160	1.98	0.17	160
1416+06 23C298	3.3	0.96			1.75	0.19	150
			1.52	71	1.41	0.08	133
1443+77 3C303.1	0.7	0.94			0.41		
			0.10	128	0.25		
1517+20 3C318	1.5	0.53			0.50		
			0.53	40	0.30		
1634+62 3C343	3.1	1.14			3.52	0.11	149
1637+62 3C343.1	2.6	1.31			2.42	0.11	102
			0.26	97	1.01	0.05	100
1828+48 3C380	11.4	0.39			3.62		
			0.72	131	0.62		
			1.08	132	0.18		

Tzanetakis 1982, ~PhD

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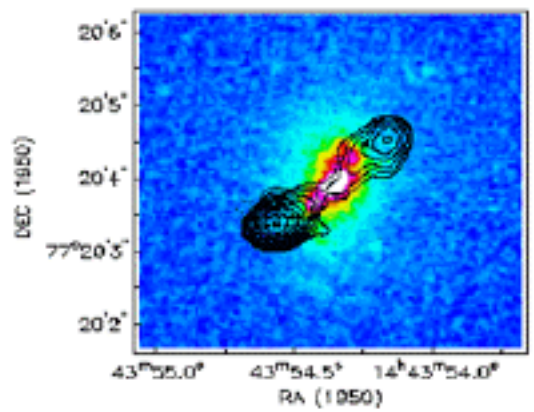
0138+13 3C49	1.7	0.79			1.35	0.05	85
0345+33 3C93.1	2.0	0.38			0.75	0.08	140
0538+49 3C147	15.5	0.69	 0.14 0.51	 52 36	5.23 4.74 0.75		
1003+35 3C236	2.3	0.44			1.02	0.14	113
1005+07 3C237	4.2	1.02	 1.28	 74	2.14 2.13	0.12 0.14	141 84
1203+64 3C268.3	2.3	1.06	 1.36	 160	0.45 1.98	0.15 0.17	160 160
1416+06 23C298	3.3	0.96	 1.52	 71	1.75 1.41	0.19 0.08	150 133
1443+77 3C303.1	0.7	0.94	 0.10	 128	0.41 0.25		
1517+20 3C318	1.5	0.53	 0.53	 40	0.50 0.30		
1634+62 3C343	3.1	1.14			3.52	0.11	149
1637+62 3C343.1	2.6	1.31	 0.26	 97	2.42 1.01	0.11 0.05	102 100
1828+48 3C380	11.4	0.39	 0.72 1.08	 131 132	3.62 0.62 0.18		

Tzanetakis 1982, ~PhD

O’Dea et al 3C 303.1



CSS galaxy

Fig. 1 (online colour at: www.an-journal.org) Contours of VLA 8.4 GHz image from Akujor & Garrington (1995) on HST/WFPC2/F702W image showing the emission lines along radio axis.

MTRLI/MERLIN: 1980-1990

- 25-m E-systems telescopes at Tabley, Darnhall 1979
- Complete array Dec 1980
- Excelled at high resolution imaging 0.1-1" resolution, complemented VLA
  - Extended emission around quasars
    -> unified schemes (Orr & Browne, +…)
  - Quasar Jets, CSS sources, Seyferts
  - Gravitational lenses
  - OH Shells
- Technical development
  - Remote operations (real time, synchronous modems, TV, autonomy)
  - Phase transfer on 100+km baselines
  - Self-calibration & hybrid mapping

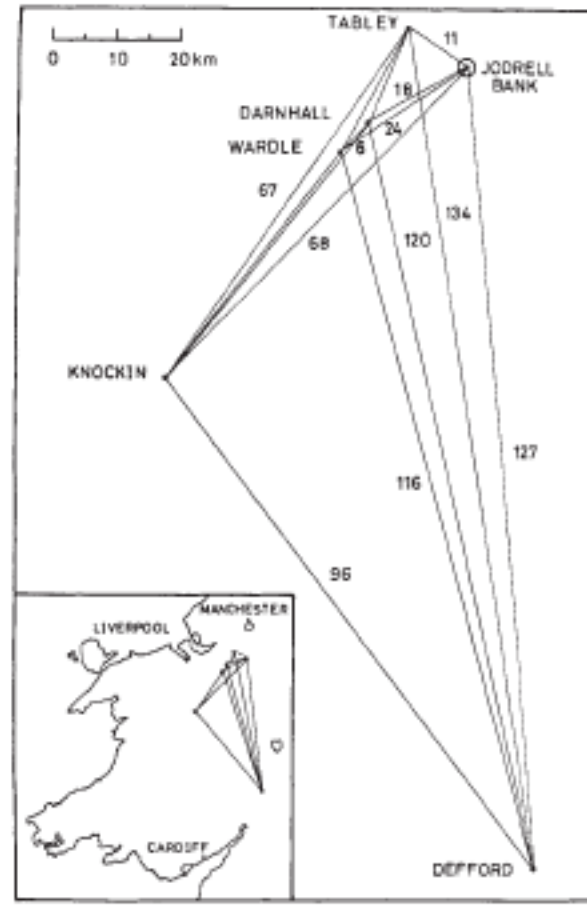
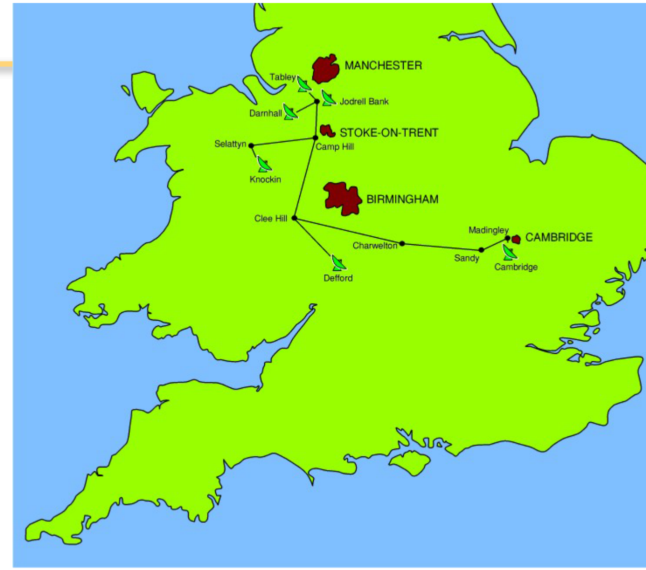


Fig. 1 The relative positions of the MTRLI telescopes with the baseline lengths given in kilometres.

MERLIN2: Extension to Cambridge 1992-2002



- 32-m at Cambridge: 217km
- 10 MHz -> 2 x 16MHz dual pol
  (new AM links; 40 MHz correlator)
- 1.4/1.7, 5 & 22 GHz receivers
- 150 - 15 mas resolution; 30-50 uJy/b rms
- High-quality imaging; deep fields; thermal sources
- phase referencing, astrometry, polarimetry, spectroscopy

MERLIN Imaging

Luedke, STG et al

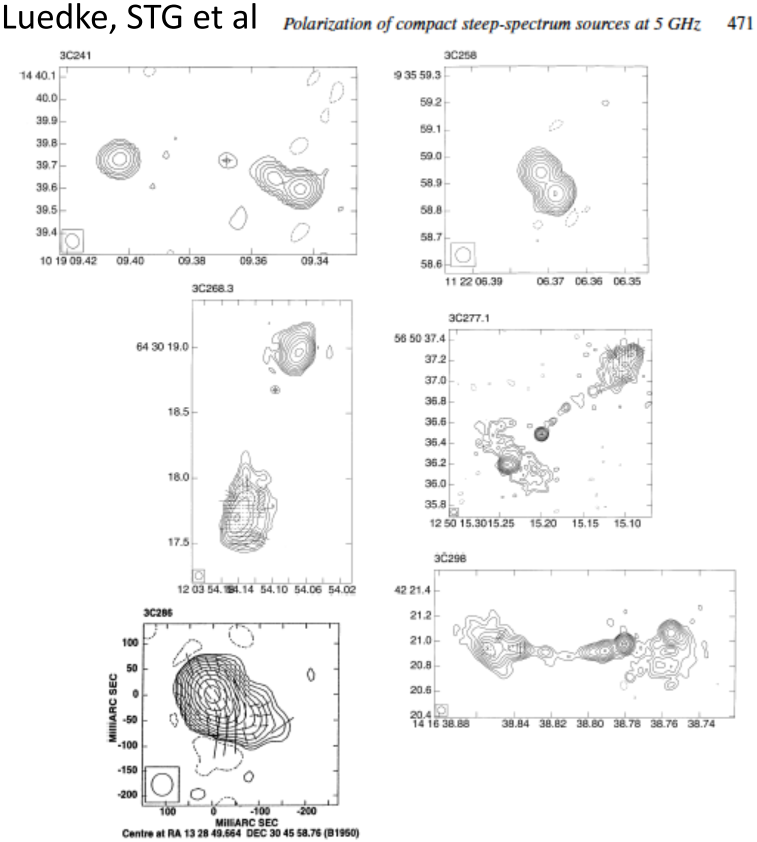
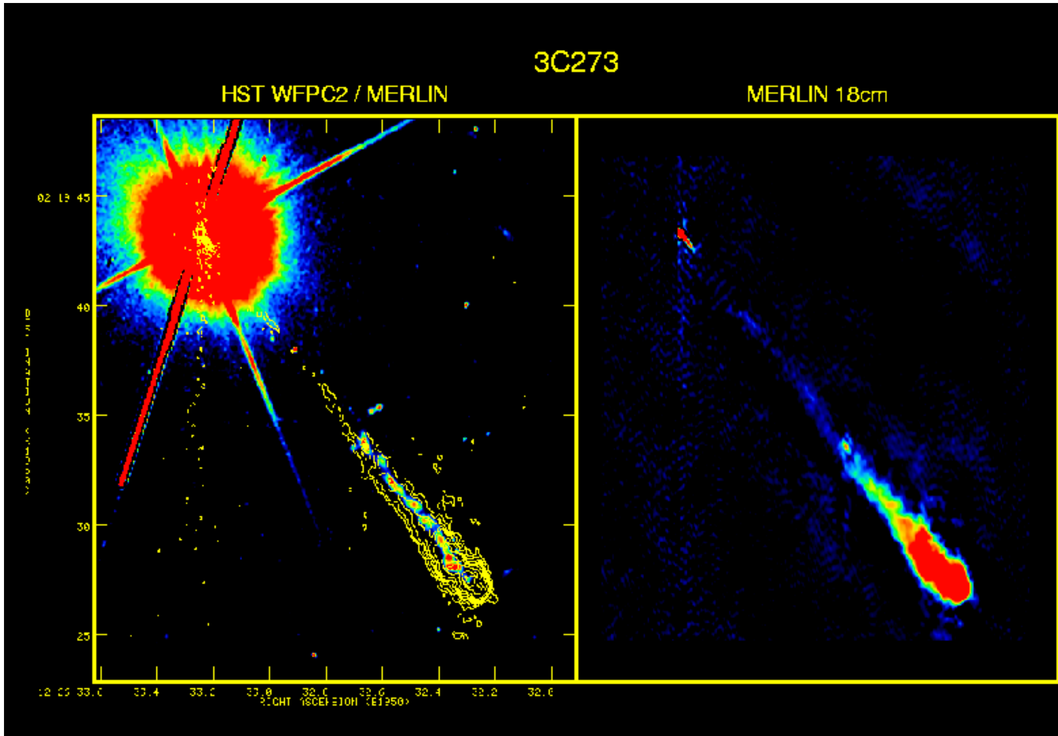
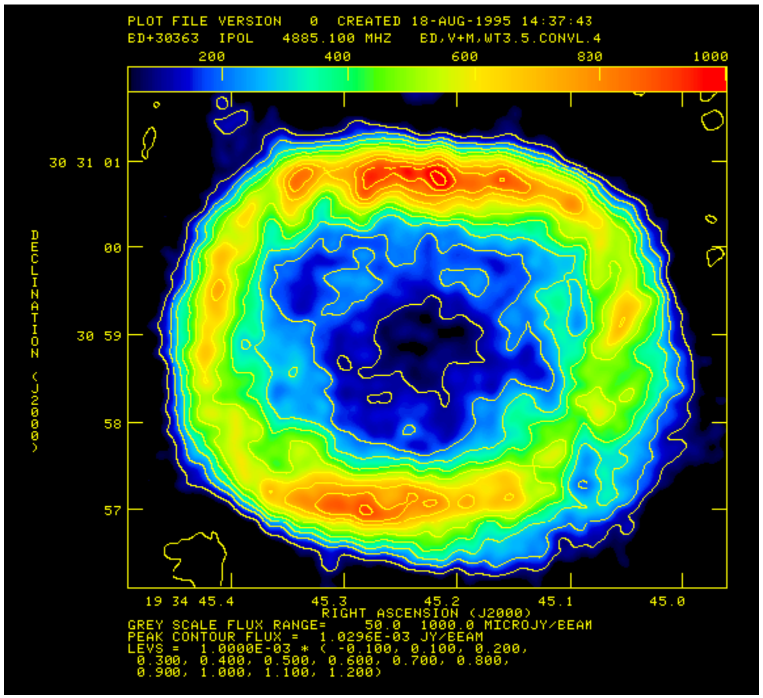


Figure 1 – continued

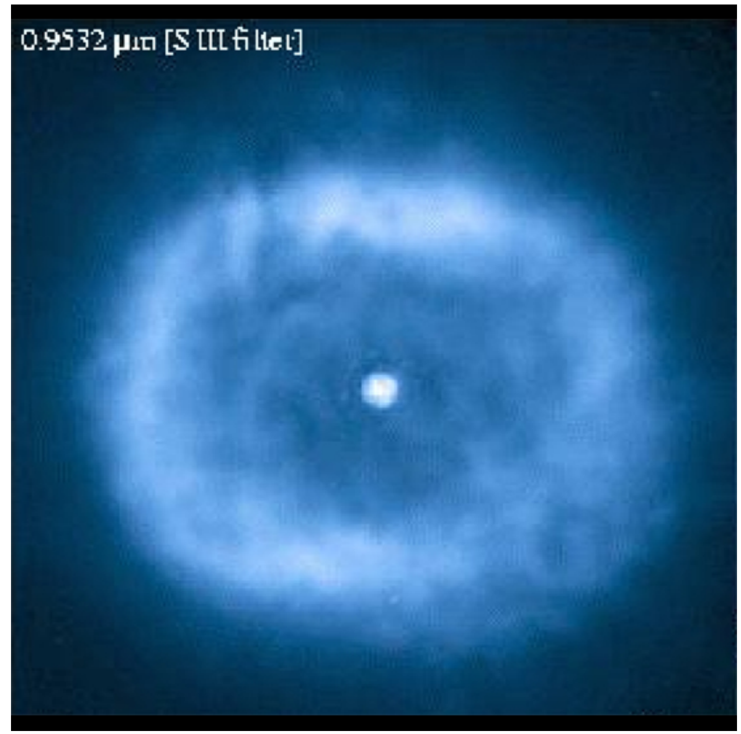


Bahcall, Muxlow,STG et al

MERLIN Imaging

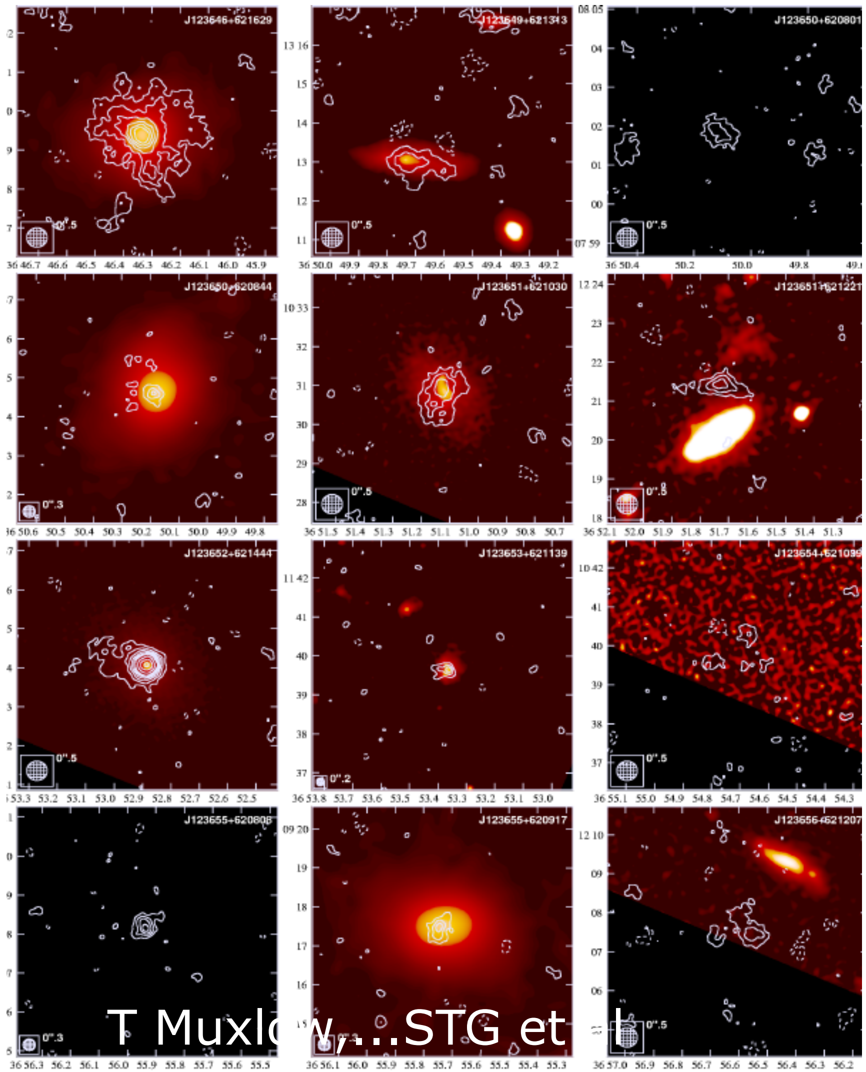


MERLIN (Bryce et al)



Hubble Space Telescope

MERLIN Imaging



MERLIN+VLA Observations of HDF-N
1986 (Muxlow et al 2005)
94 sources in 10' sq. rms 3 uJy/b
150-300 mas:
sizes to 1"; structure 100 mas scales
star-formation vs AGN

The University of Manchester
Jodrell Bank
Observatory

eMERLIN

The birth of e-MERLIN

- RJ Cohen (1995) - 'MERLIN Phase 3'
  - New high frequency bands, replace Defford (tried as Phase 1)
  - Up to 1 GHz b/w, optical fibres?
- New Director (Diamond), many reviews, detailed design concept 2000 (except for data transmission…)
- Funding package mostly from local development/ Manchester University, + UMIST, Cambridge 2002
- Budget evolution:
  - £16m -> £11m -> £8.6m -> £7.6m
  - … of which £5.2m (non-staff) for:
  - National fibre network, optics, receivers, IF, samplers, transmission, correlator ,…

MSC(95)15.1

IN CONFIDENCE
19 December 1995

PARTICLE PHYSICS AND ASTRONOMY RESEARCH COUNCIL
MERLIN STEERLING COMMITTEE

MERLIN PHASE 3 – OUTLINE CASE FOR BROADBANDING
R. J. Cohen

1. Introduction

Increases in sensitivity invariably lead to advances in science. This has been widely appreciated by the optical community with their drive to increase sensitivity by a factor of 4 by going from 4m to 8m diameter telescopes. In radio astronomy developments in technology mean that similar advances can be made by increasing bandwidths. This drive for higher sensitivity radio imaging through increased bandwidth is the force behind several developments which are underway or planned worldwide. Typical bandwidths being considered are 1-GHz. For example the VLBA can already operate at up to 256 MHz in "burst mode" (with two tape recorders going), for short periods of time. The European VLBI network (EVN) is in the process of building the next generation of taperecording system, the MkIV system, which has 500 MHz of bandwidth. The VLA is planning a major upgrade for the turn of the century which will include a 1GHz bandwidth capability. MERLIN uniquely fills the baseline coverage between the VLA and the VLBI networks (50-200 km). Therefore it is obvious that for MERLIN to remain competitive in this role it will need a radical increase in bandwidth from its current 32 MHz to about 1-GHz. This will increase the sensitivity by almost an order of magnitude at one stroke. The following sections describe the new science which will be addressed by the wideband MERLIN Phase 3, and how it may be achieved technically.

eMERLIN

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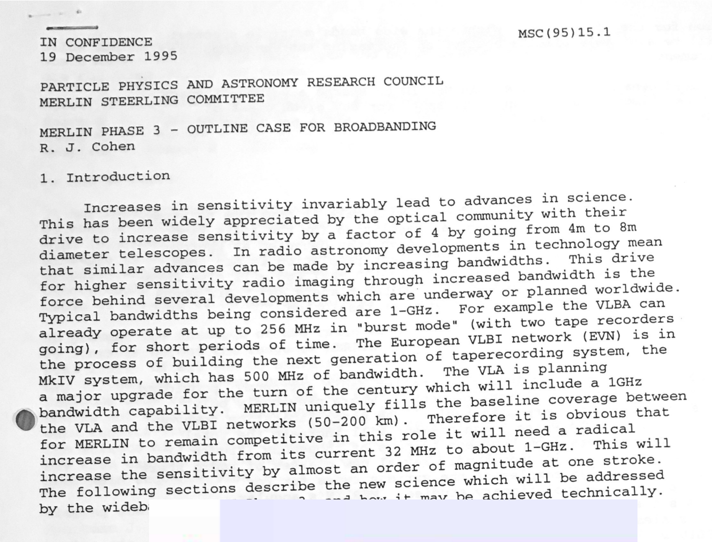
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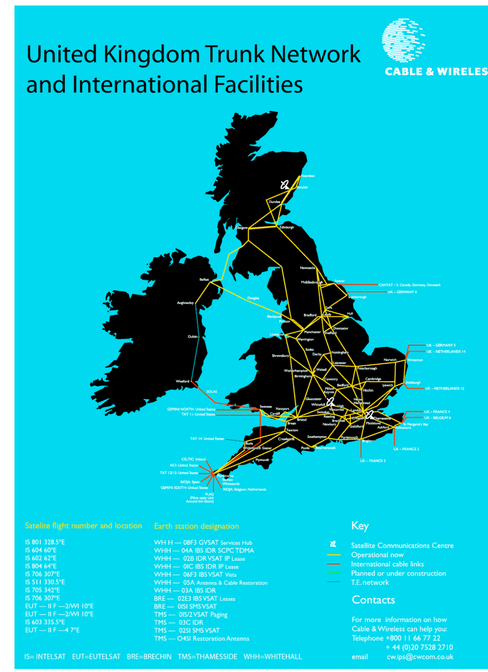
e-MERLIN: Design & Implementation

Fibre network & correlator were key challenges

- Correlator: DRAO/NRAO WIDAR
  - Excellent fit, flexible design
  - < 10% of EVLA WIDAR
- Fibre network:
  - 2x2 GHz = 30Gb/s per tel (min)
  - Nationwide network at time of dotcom bust/boom + deregulation

    10x UK internet traffic (at tender,2004)

    -> Dark fibre network + ALMA/EVLA DTS
  - 'Last mile' = 100km
    - significant dig across private land, along roads, under motorways, canals,... 2004-5
  - 600km leased from 3 providers



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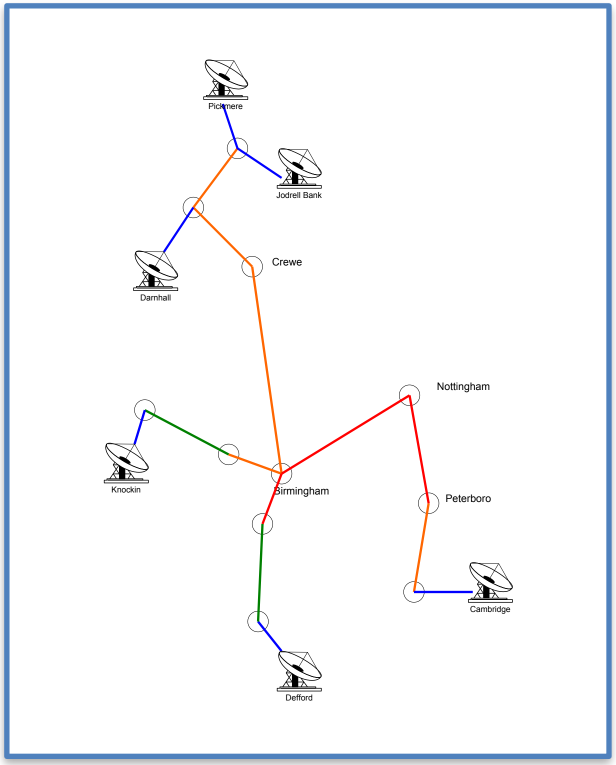
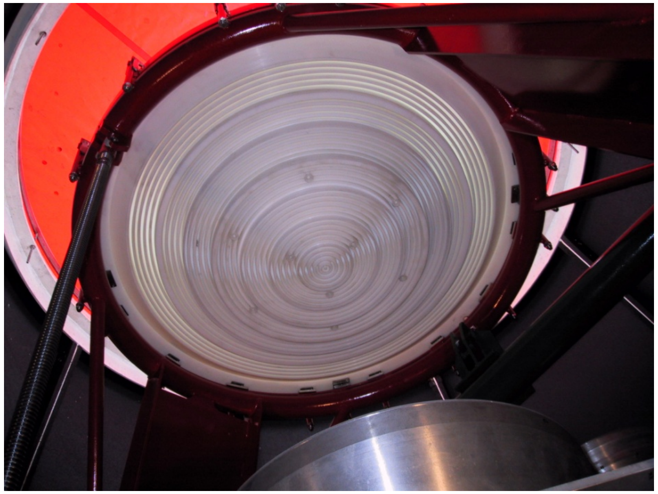


e-MERLIN: Implementation

Entire system replaced:
Telescope drives, control, optics
Receivers, IF, LO, samplers, transmission
Correlator, data acquisition & control s/w
Frequency std distribution over optical fibre network

Key decisions:
Early focus on fibre network :)
Bought-in correlator DRAO, Penticton:)
Upgrade where possible :)
No compromise on 2 x 2 GHz b/w :)
Optical phase transfer using MERLIN modulation :)
Beg & borrow designs :|
Piecemeal improvement in tel. control :(



Time & Budget:
On-budget :) … some work deferred to operations
On-time:
fibre network; receivers
Some delay…
IF/digital: manpower-limited
Correlator: complexity

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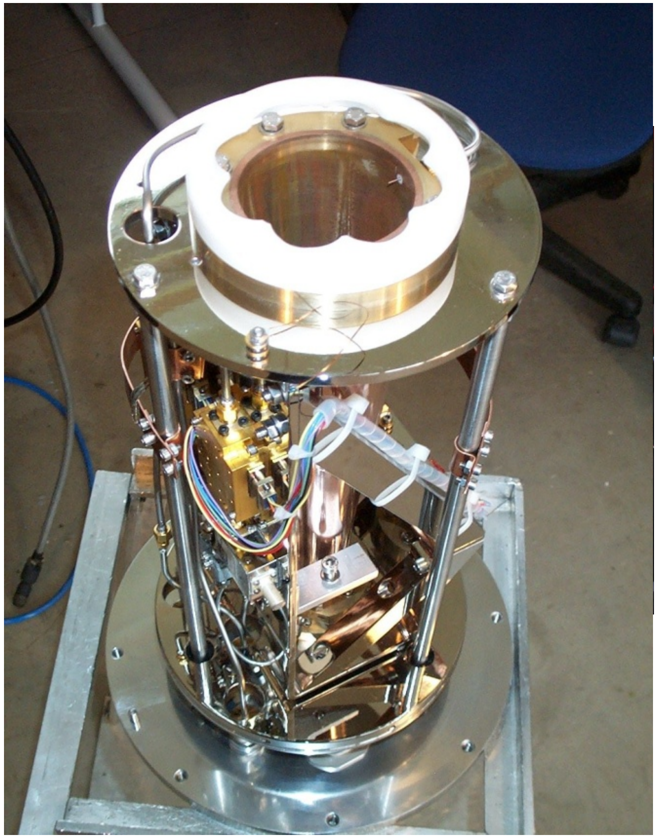

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Bumps in the road

- 2008 was difficult for everybody … incl STFC
- Strong support from public & scientific community
- KSP programme (Legacy) instrumental in demonstrating breadth & depth of science, mobilising community

From The Times
March 6, 2008

Britain's window on the stars faces closure in funding row

Jodrell Bank has been responsible for some of the most important astronomical discoveries of the last 50 years

Lewis Smith, Science Reporter

The network of seven giant astronomy dishes that has made this country a leader in the study of stars and planets is to be axed under plans to save £2.5 million a year.

EXPLORE SCIENCE NEWS
- CRIME NEWS
- EDUCATION NEWS
- HEALTH NEWS
- SCIENCE NEWS

TIMES RECOMMENDS
- Britain's window on the stars faces closure
- Battle for tycoon's £10m costs Tories
- 3,000 chauffeur-driven cars for 'green' Games

SCIENCE NEWS

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From The Times
July 9, 2008

Deal to rescue Jodrell Bank helps Britain see its future in the stars

Lewis Smith, Science Reporter

Jodrell Bank, Britain's window on the stars, has been saved from closure and is to keep searching for answers to Man's place in the Universe.

The future of the institution was secured with an agreement to reinstate funding for e-Merlin, the observatory's key research project.

The Science and Technology Facilities Council had planned to cut money for e-Merlin but reversed its decision after The Times revealed that it would mean the closure of the Jodrell Bank Observatory.

Funding has now been promised to cover the £2.5 million annual operating costs for the next three years and the deal means that Jodrell will play a leading

Jodrell Bank was threatened with closure

TIMES RECOMMENDS
- We are at a deeply significant turning point'
- Baikal: the gangsters' gun
- Band emerges from Dragon's Den with the cash

MARS PHOENIX MISSION

NASA spacecraft beams back pictures of Mars
Slide Show

SCIENCE NEWS

First Light

- Huge effort!
- 1st single tel. ’analogue light’ to 1st fringes: 24 days (T0+6yr)
- 1st fringes to 1st images: 8-16 months
- 1st fringes to production:

2 yrs (RTS rule! 8 yrs after funding)

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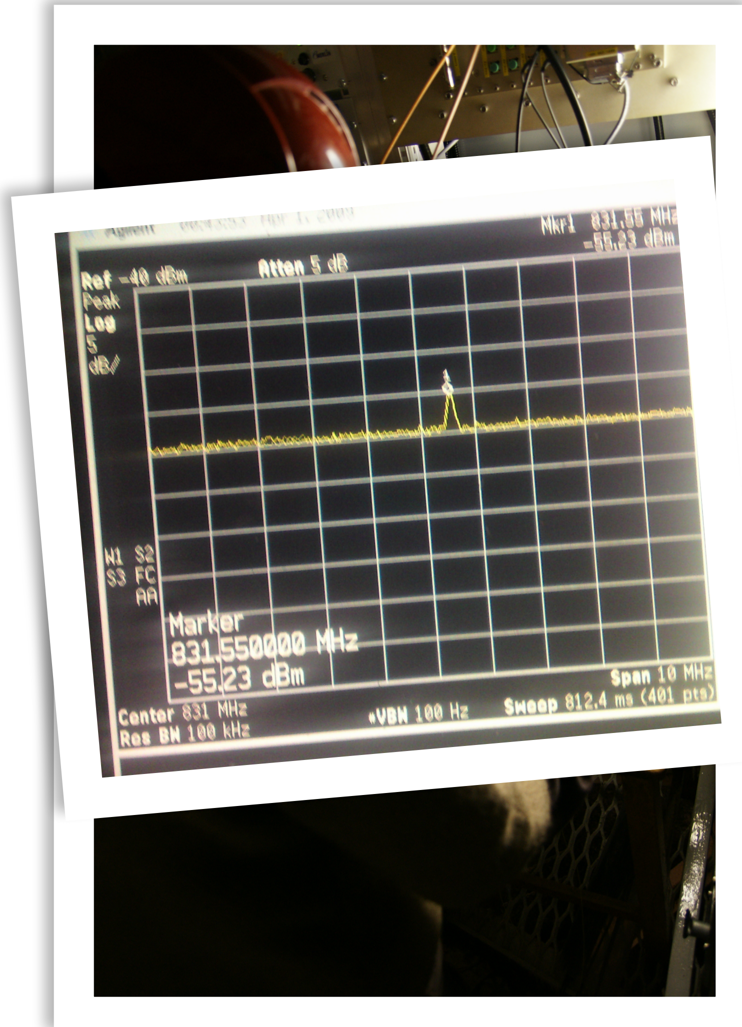

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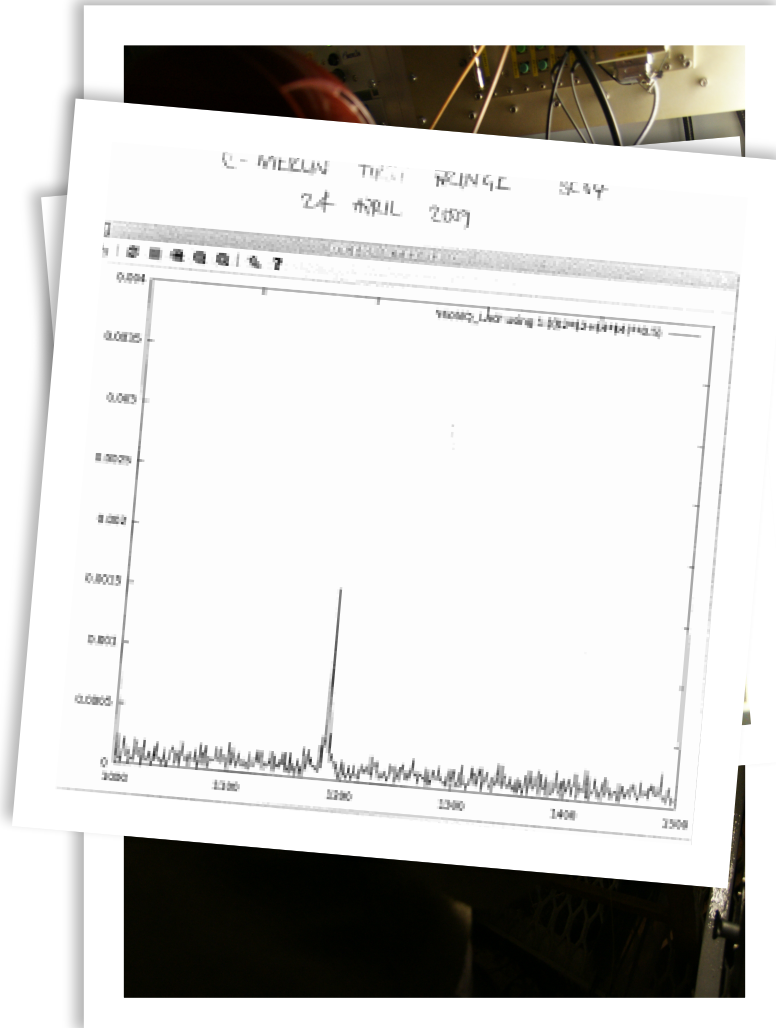

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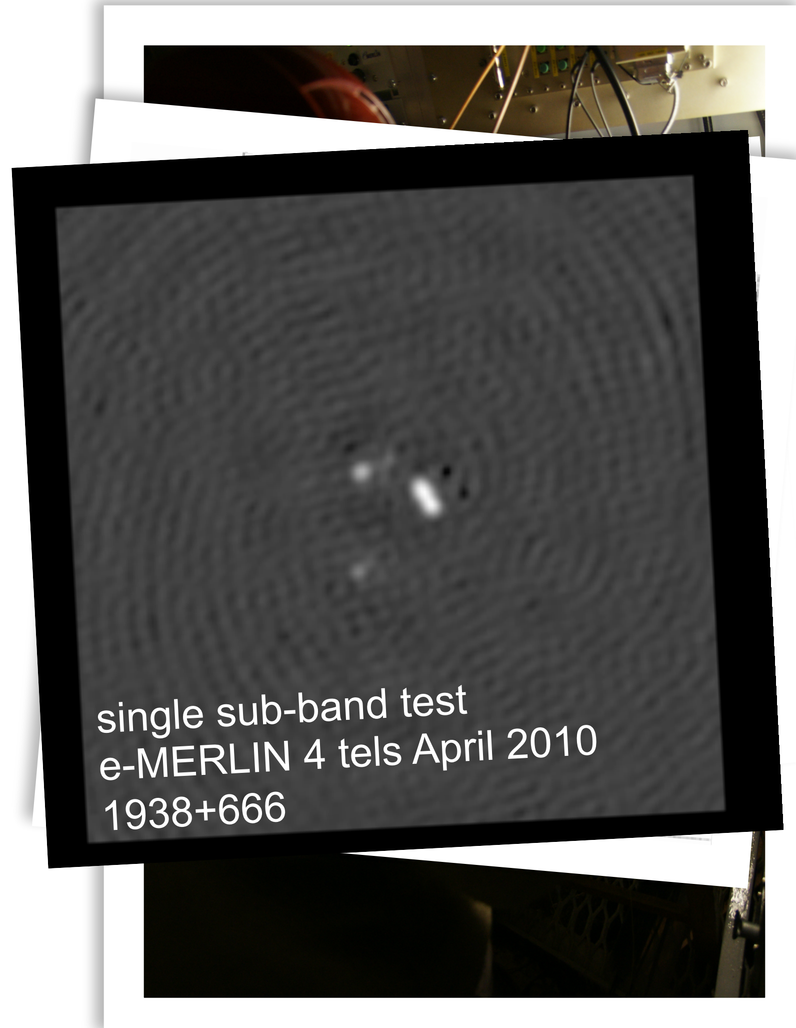

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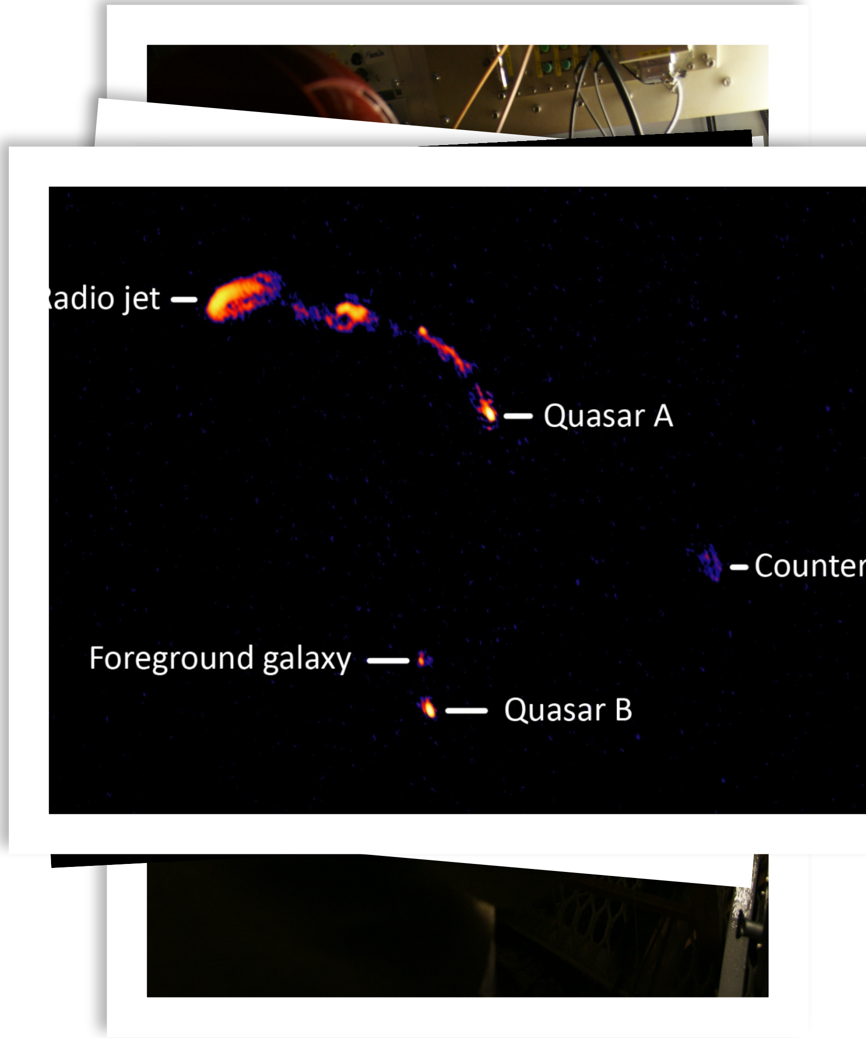
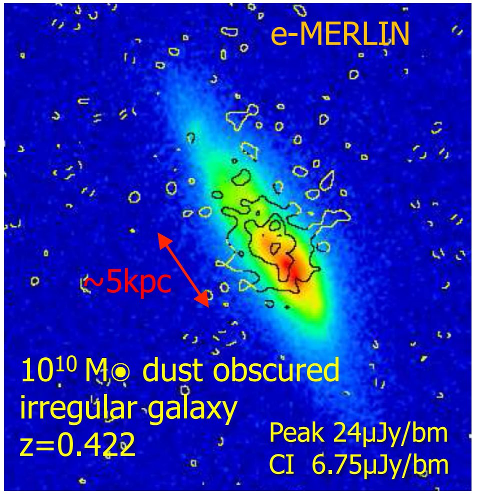
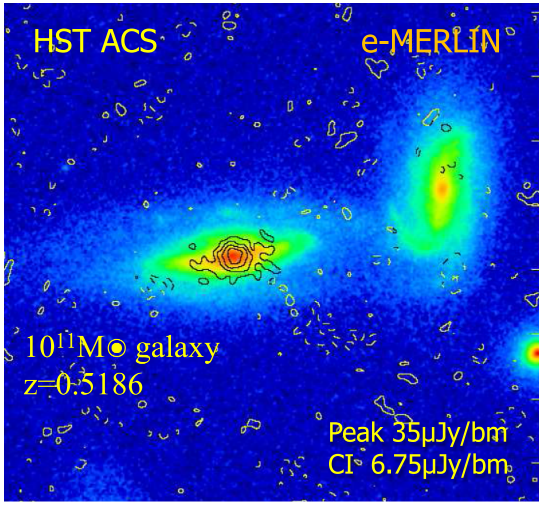


e-MERLIN: Performance & Current Science

- High-sensitivity (2uJy/b) high-resolution (0.15”) wide fields, eg GOODS-N
  - AGN/SFGs; where is star-formation?
- Mosaiced Surveys:
  - galactic (Cyg OB)
  - weak lensing

e-MERGE Consortium:
Muxlow, Beswick, Smail. STG,+…





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COBRaS: Morford, Prinja, Fenech+…
Cyg OB Association Survey

A&A proofs: manuscript no. morford_2017

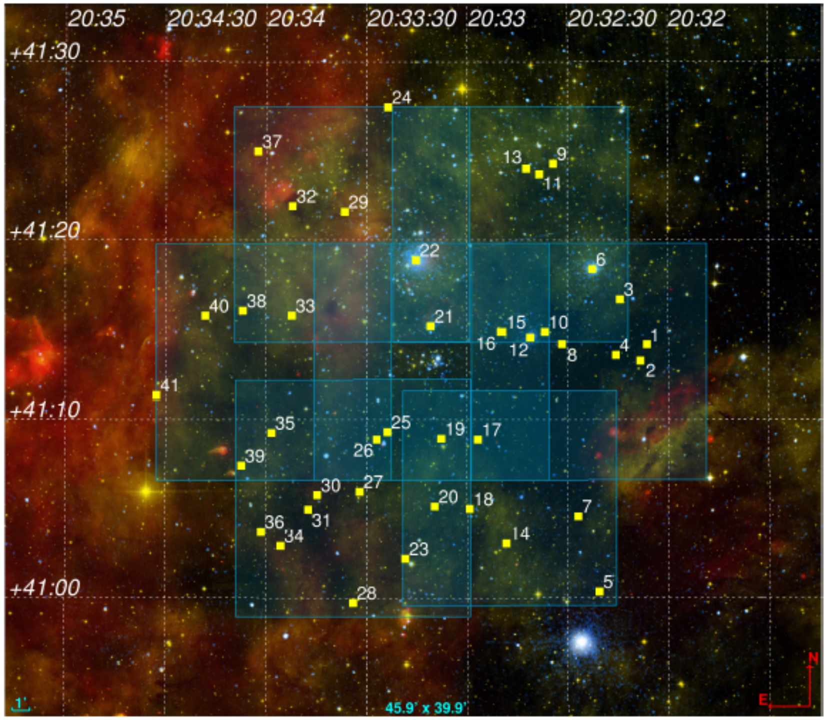

Fig. 5: The positions of the 41 sources (shown as yellow squares) in the CLASC, overlaid onto the areas as marked by the seven COBRaS L-band pointings. The background shows a composite of images from Chandra X-ray (NASA/CXC/SAO/J.Drake et al), Isaac Newton Telescope (Optical: Univ. of Hertfordshire/INT/IPHAS) and Spitzer IR (NASA/JPL-Caltech) observations.

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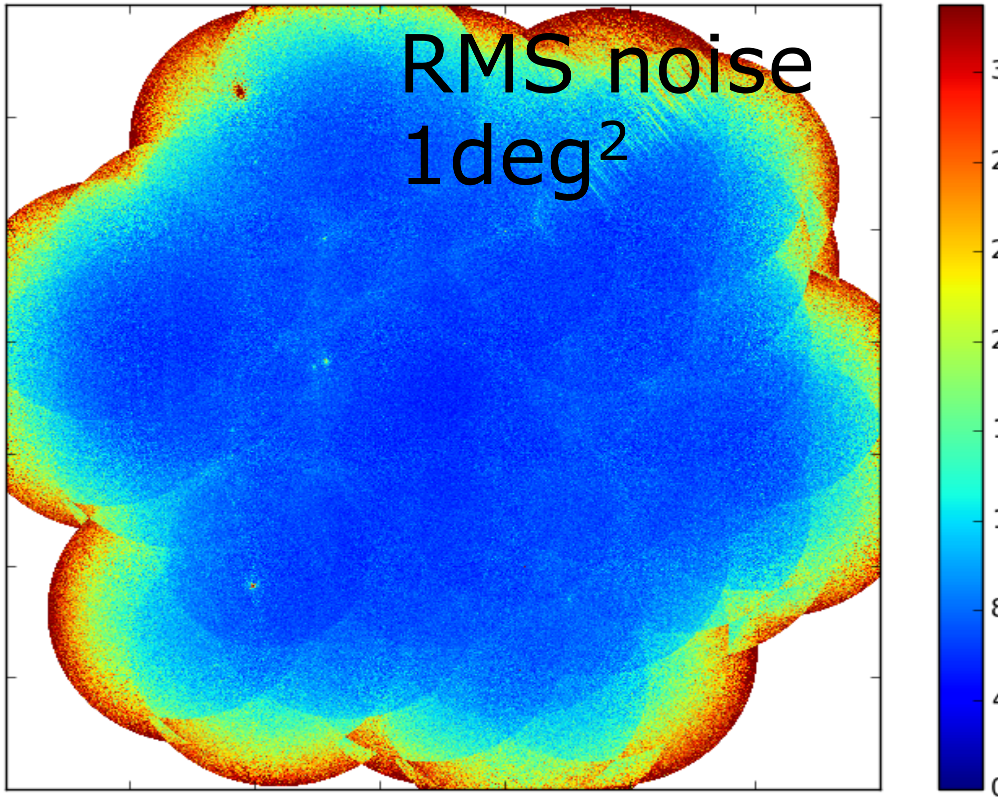
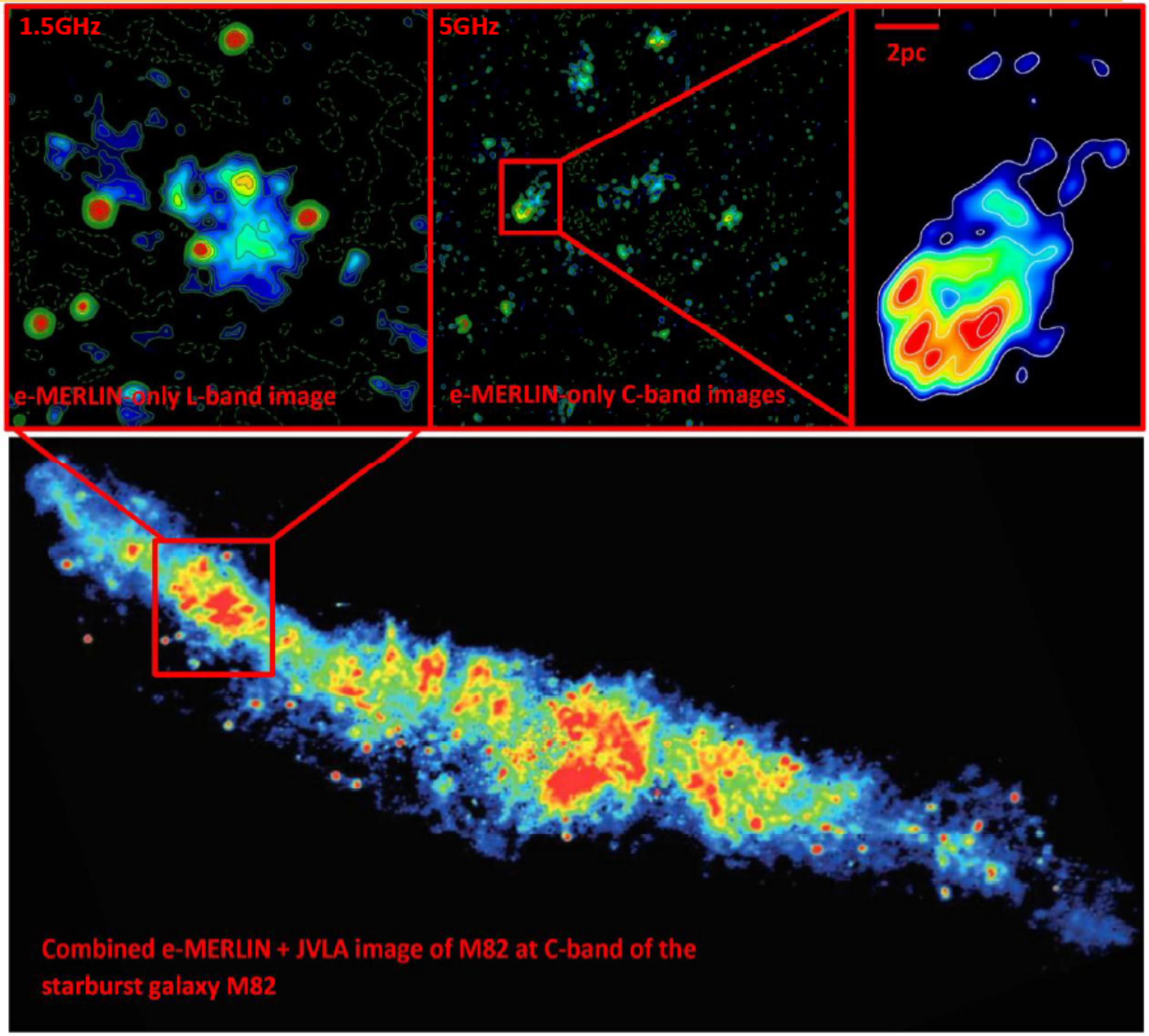
SuperClass Weak Lensing Survey
Battye, Brown,…STG et al



e-MERLIN: performance & current science

- Detailed imaging of M82
- Beswick + LEMMINGS consortium



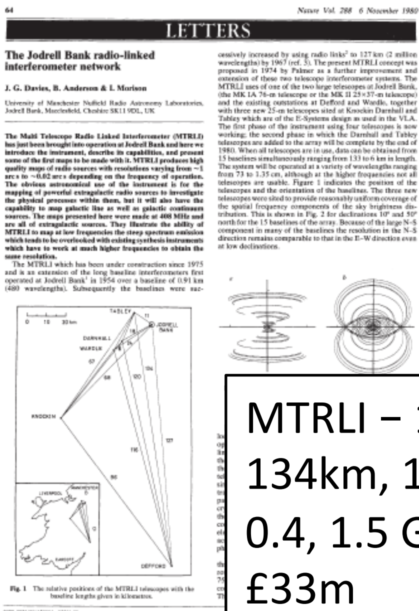
e-MERLIN: future development

- Proposal submitted for operations and development
- Aim to improve
  - productivity (s/w)
  - frequency coverage
  - bandwidth/sensitivity
  - survey speed
  - imaging quality
- Modest cost (£10m), non-disruptive
- Competitive & complementary to SKA1-mid … bring e-MERLIN to SKA Era
- Support development of SKA community

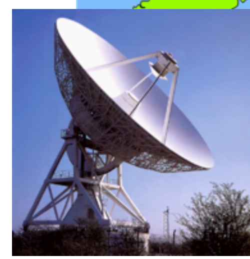
e-MERLIN Upgrades

Throughput	**SKA-based software pipelines**	✔SKA-level performance
Frequency Coverage	**New Receiver Bands 2-4 & 8-16 GHz**	✔Full coverage 1-24 GHz
Sensitivity	**New digital chain: 2x4, 2x8 GHz b/w**	✔max available b/w
PSR Beamforming	**Flexible correlator/ beamformer**	✔max area for pulsars
Survey Speed	**PAF on Lovell**	✔4x survey speed
Imaging quality	**New telescope at Defford**	✔all tels at all bands

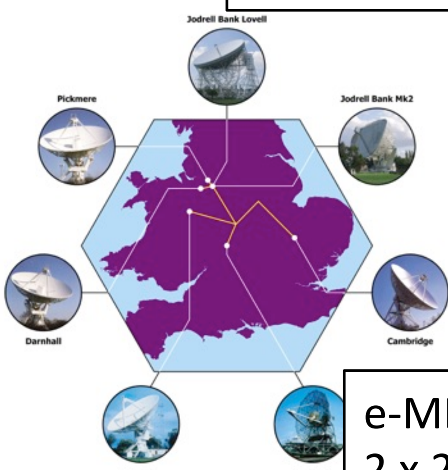
Transformation



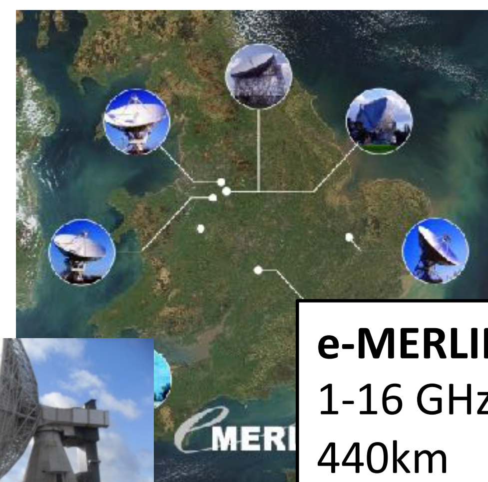
MTRLI – 1980
134km, 10 MHz
0.4, 1.5 GHz
£33m



MERLIN – 1991
217km, 2x15 MHz
0.15,1.5,5,22 GHz
£14m



e-MERLIN – 2009
2 x 2 GHz
£11m



e-MERLIN – 2018
1-16 GHz; 2x8 GHz b/w
440km
£10m

Key Science Goals

- Planet-formation
- Star-formation & evolution
- Galaxy evolution & role of black holes
- Fundamental & extreme physics with pulsars
- Gravitational waves (nHz) using pulsars
- Dark matter & dark energy using gravitational lensing
- Compact objects & relativistic particle jets from AGN

Bandwidth
8-16 GHz
Defford
2-4 GHz
PAF
Digital upgrade

2-4 GHz
Defford

Key figures

- Henry Palmer & group, esp Barrie Rowson
- MRTLI & MERLIN pioneers: Bryan Anderson, JG, Mike Bentley, Roger Noble, Peter Thomasson, Ian Morison, Richard Davis, Ralph Spencer, Tom Muxlow
- e-MERLIN Team:

  M Anderson, M Asif, J Bartle, A Bayley
  M Bentley, R Beswick, T Blackburn, E Blackhurst
  P Burgess, D Clarke, P Clarke, J Cullen, R Dickson
  J Edgley, A Galtress, S Garrington, A Gunn, J Hamilton
  B Hancock, P Harrison, A Holloway, A Howson, L Invernon
  A Johnson, C Jordan, J Kitching, J Lapi, A Linton, R McCool, C Mance
  I Manfield, F Manning, J Marshall, S Morris, T Muxlow
  R Noble, L Parry, M Roberts, C Shenton, S Smith, P Stanway
  M Stubbs A Williams

Summary

- MERLIN was inspired & justified by early long-baseline interferometry at JBO
- Established several key technologies
- Plenty of excellent science at 0.1”!
- e-MERLIN delivers the sensitivity required
- To reach full potential needs modest upgrade
    - Frequency coverage (1-24 GHz); bandwidth
    - PAF, imaging quality, SKA s/w
- SKA technologies; SKA science & skills preparation
- Small arrays of big telescopes: develop future technologies