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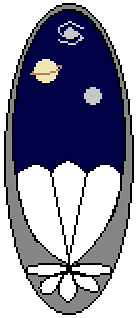
Introduction to e-MERLIN and MUST

Neal Jackson, Baltics Scientific Conference

With thanks to Rob Beswick (e-MERLIN),
Peter Wilkinson (MUST) for slides and comments



Outline

e-MERLIN – background & capabilities

Overview of on-going e-MERLIN key projects

The future – what next??

e-MERLIN

e-MERLIN (SKA-pathfinder) operating at cm-λ with μJy sensitivity and ~10-220km baselines

Key/integral part of the EVN - providing 'short' spacing baselines - Now becoming fully integrated

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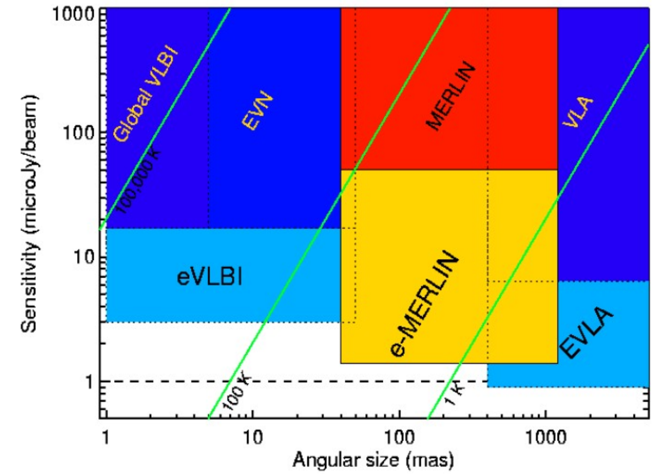
e-MERLIN



– Increase bandwidth to
  0.5 GHz (L-band)
  2 GHz (C-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; 600km leased (total ~700km)
– 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

Basic capabilities

150, 40, 10 mas **resolution**
~10 uJy **sensitivity** in typical runs
Order of mag 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

e-MERLIN

Unique instrument covering particular resolutions scales..

Basic Capabilities - See www.e-merlin.ac.uk for more details

	1.5GHz (L-band)	5GHz (C-band)	22GHz (K-band)	Notes
Resolution (milliarcseconds)	150	40	12	Uniform weight at central frequency
Field of View (FoV) (arcmin)	30	7	2	FWHM of 25m dishes; reduced when the Lovell Telescope is included
Frequency range (GHz)	1.25-1.75	4-8	21-24	Tuneable frequency range
Bandwidth (GHz)	0.5	2	2	Max bandwidth per polarisation; at C or K-band, 4GHz is possible using a single polarisation.
Sensitivity (μJy/bm) in a full imaging run	6-7	4	15	Performance depends on usable bandwidth and observing conditions. Figures are for e-MERLIN with the Lovell telescope at L and C-band.
Surface brightness sensitivity (K)	190	~70	~530	
ICRF astrometric performance (mas)	2	~1	~2	With respect to the ICRF (assuming a typical 3^{o} target-calibrator separation)
Astrometric repeatability (mas)	~0.5	~0.2	~1	Day-to-day repeatability using surveyed or in-beam sources, and assuming a full imaging run
Amplitude calibration (%)	2	1	10	Targets for day-to-day repeatability

Legacy & PATT Proposals

PATT proposals (aka PI-led proposals of all sizes)

- 6 monthly call cycle (spring/Autumn) – fully open
- Proposals accepted via Northstar proposals system

See www.e-merlin.man.ac.uk/observe/

- Online Simulator tools and exposure calculators available from e-MERLIN website
- Any use questions : **e-merlin@jb.man.ac.uk**

Existing Large Legacy projects

- Account for ~50% of available observing time
- Competitively allocated programme of 12 large projects
- Cover all science areas – planets to cosmology
- Long-term observing status – allowing large international teams to build resources and sustain projects.
- Opportunities for new projects will be available… soon!…

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Current e-MERLIN legacy programme:

Addressing the Key science challenges..

12 Large projects covering planet formation cosmology

Galactic Science :

- e∏ - Pulsar astrometry – Vlemmings/Stappers et al. 160hrs*
- PEEBLES – planet formation - Greaves et al. 172hrs
- 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

Extragalactic and cosmology :

- 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 - 1+deg^2 supercluster field - Battye et al 832hrs

* Additional allocations pending on-going reviews

e-MERLIN/VLBI Science

Pulsars, Gravity & Gravitational waves

Time-domain & Transient astrophysics

Planet & star-formation

Galaxy formation & evolution

Cosmic shear & Gravitational lensing

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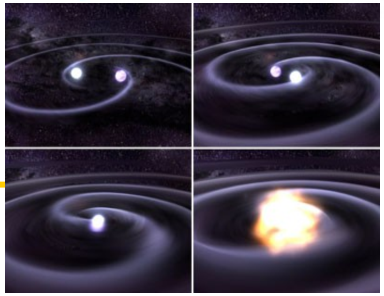
e-MERLIN

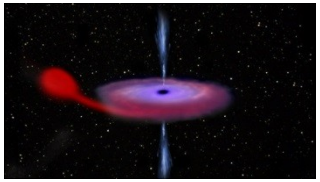
Time-Domain astrophysics

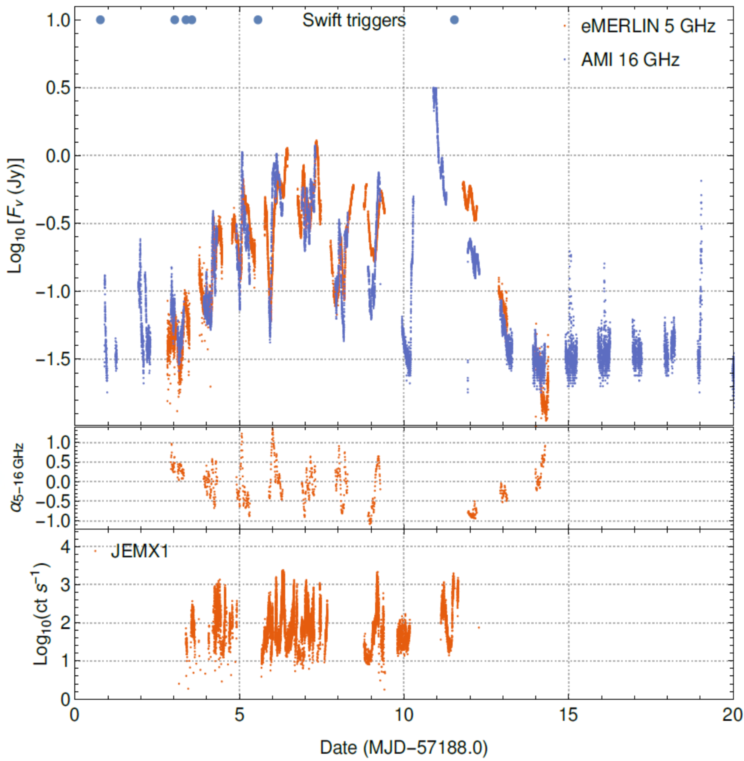
'rapid response, sensitivity and resolution'



e-MERLIN provides high sensitivity, temporal imaging, mas-astrometry
and monitoring of time variable objects.
Galactic objects such as XRB, novae through to SNe, TDEs, GRBs, FRBs etc

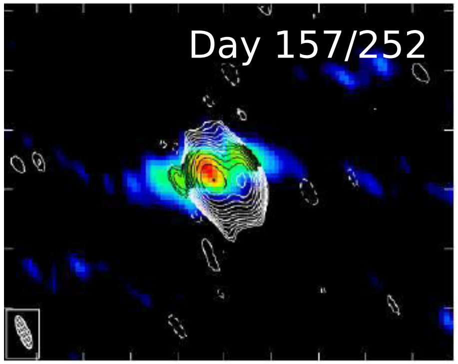
- Most energetic cosmic sources
- High energy particle accelerations
- Time-evolving structures

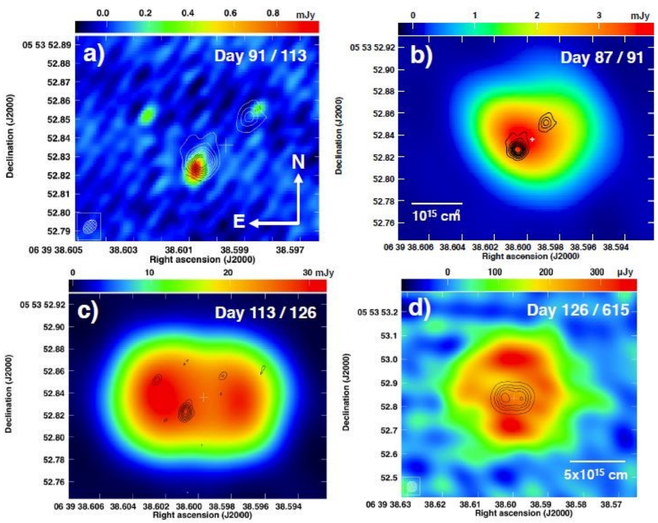




V404cyg 2015 outburst from stellar mass Black-Hole binary
- Unprecedented coverage of particle acceleration (Fender et al., in prep)

Evolution of the gamma ray nova (Nova mon)
EVN+e-MERLIN, jVLA
Chomiuk + 2014 Nature,
Healy+ 2017 MNRAS





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e-MERLIN/VLBI Science

Pulsars, Gravity & Gravitational waves

Time-domain & Transient astrophysics

Planet & star-formation

Galaxy formation & evolution

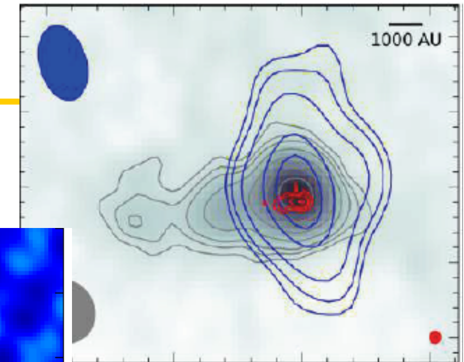
Cosmic shear & Gravitational lensing

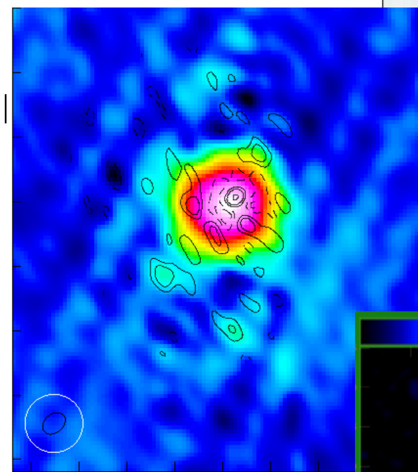
From stars to planets

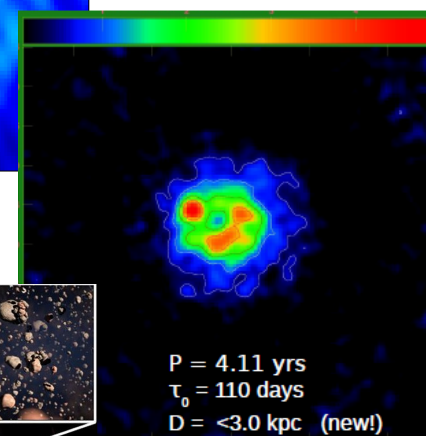
'sensitivity, resolution, spectral lines'

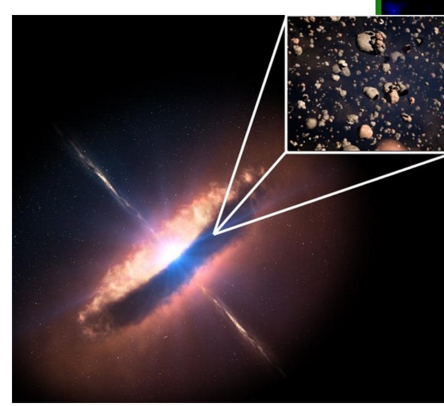
Probing full range of stellar evolution and planet formation

- cm-sized grain formation in pr
  disks
- YSOs to evolved stars to
stellar end-points
- Stellar outflows
- Stellar evolution
- Molecular astrophysics
- Magnetic fields
- Fundamental physics



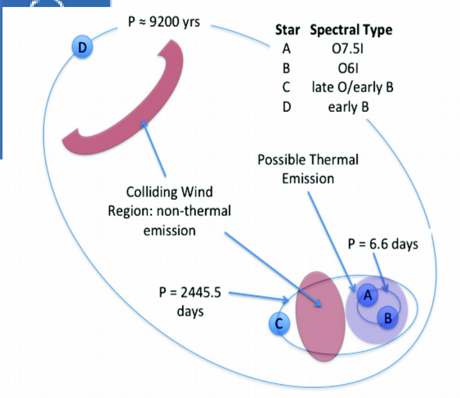


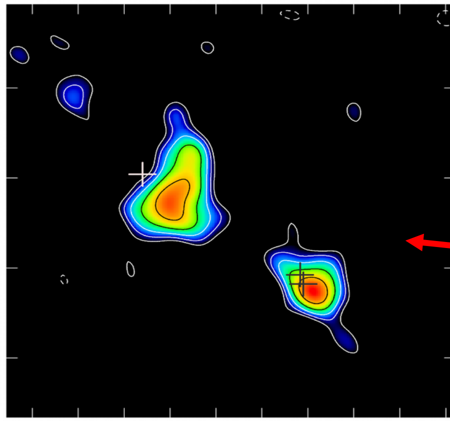




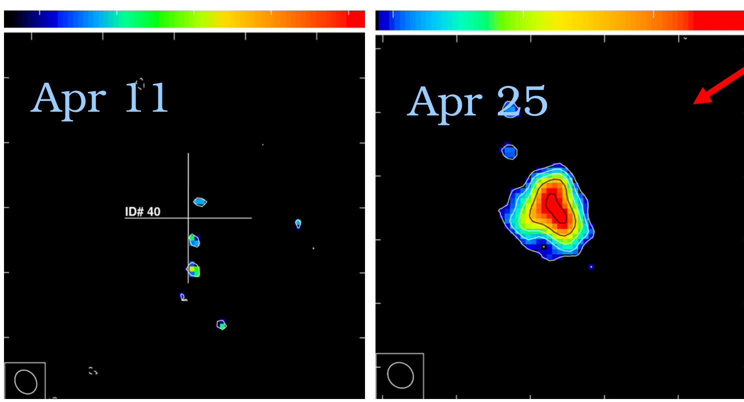
Multiple legacy programmes

Galactic Star-formation – deep fields

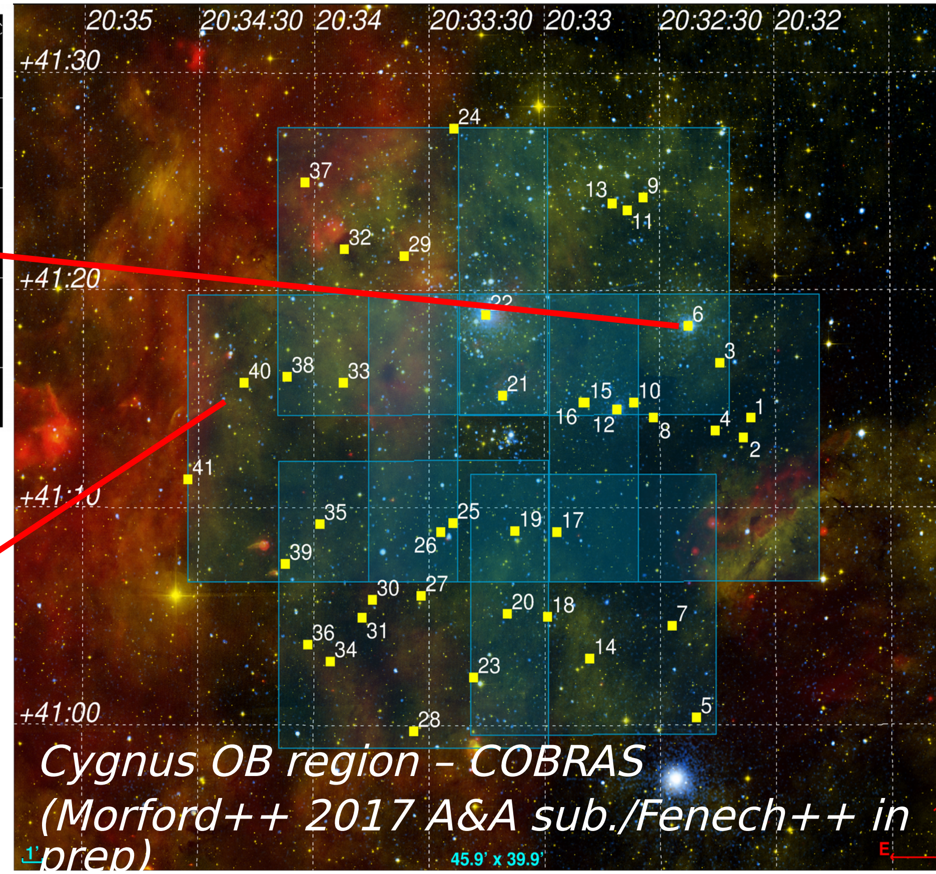




Quadruple star-system with colliding winds



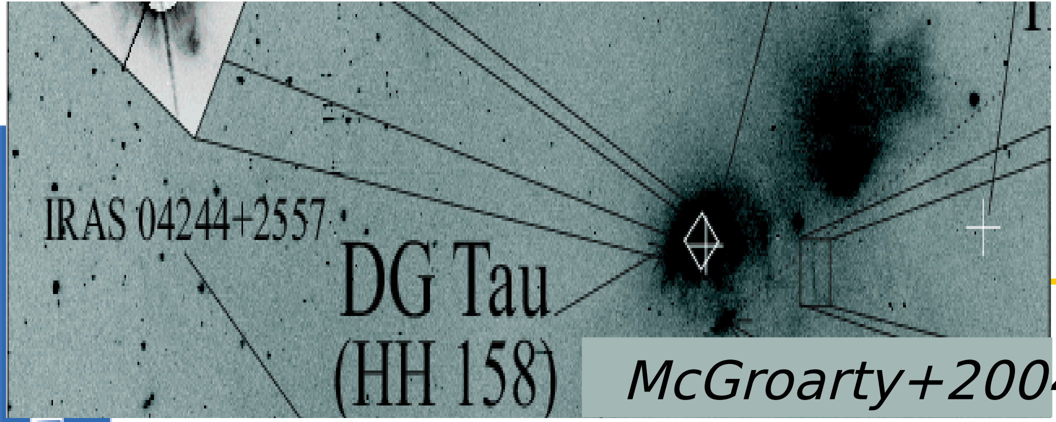
Previously unknown transient sources



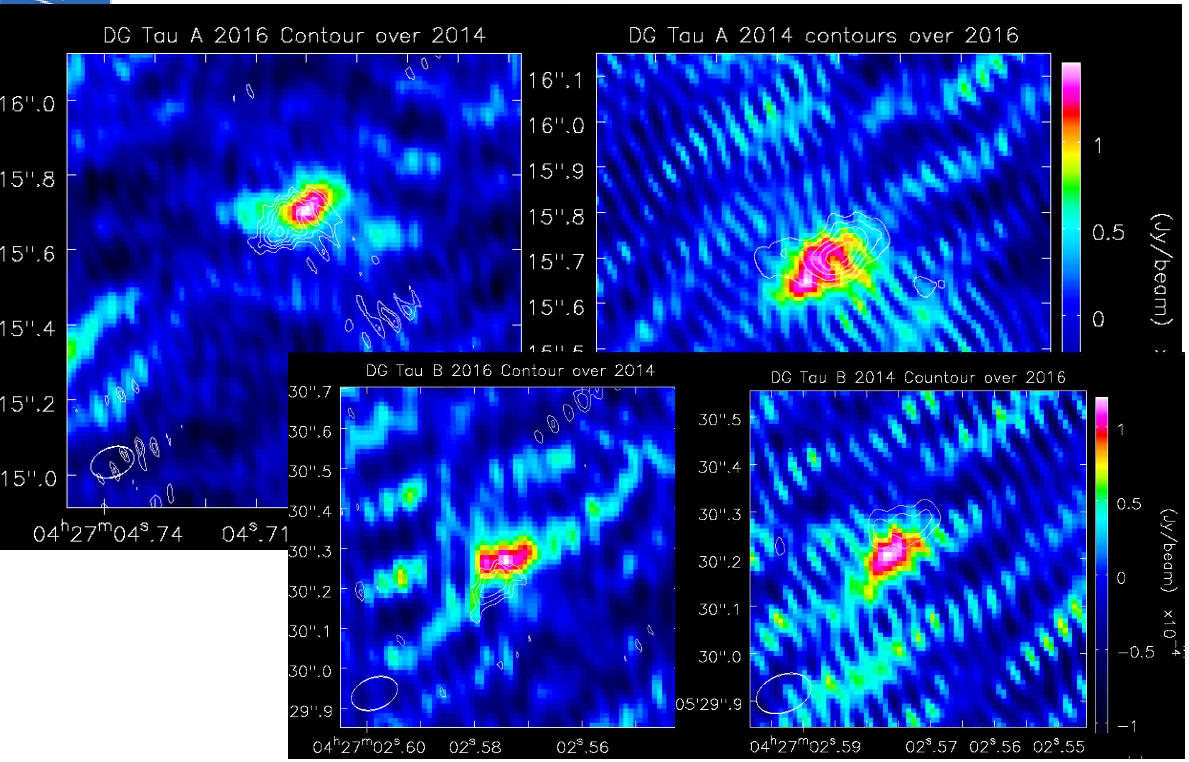
Lowest upper-limits of mass-loss rates for majority of these sources

CoBRAS legacy programme (Prinja et al)

Planet formation



McGroarty+2004



- Imaging protoplanetary discs
- DG Tau A (and younger B)
  - 2014 6.47 GHz
  - 2016 7.25 GHz
- Dusty discs detected
  - 10s au-scale
    - Resolve SED
    - Distinguish disc/jet

(Greaves et al. & Pebbles legacy project)

- More sensitivity, plus (new) X-band, 22 GHz will reveal any large grain clusters within few au of DG Tau A

PeBBLES legacy programme (Greaves et al)

e-MERLIN/VLBI Science

- Pulsars, Gravity & Gravitational waves
- Time-domain & Transient astrophysics
- Planet & star-formation
- Galaxy formation & evolution
- Cosmic shear & Gravitational lensing

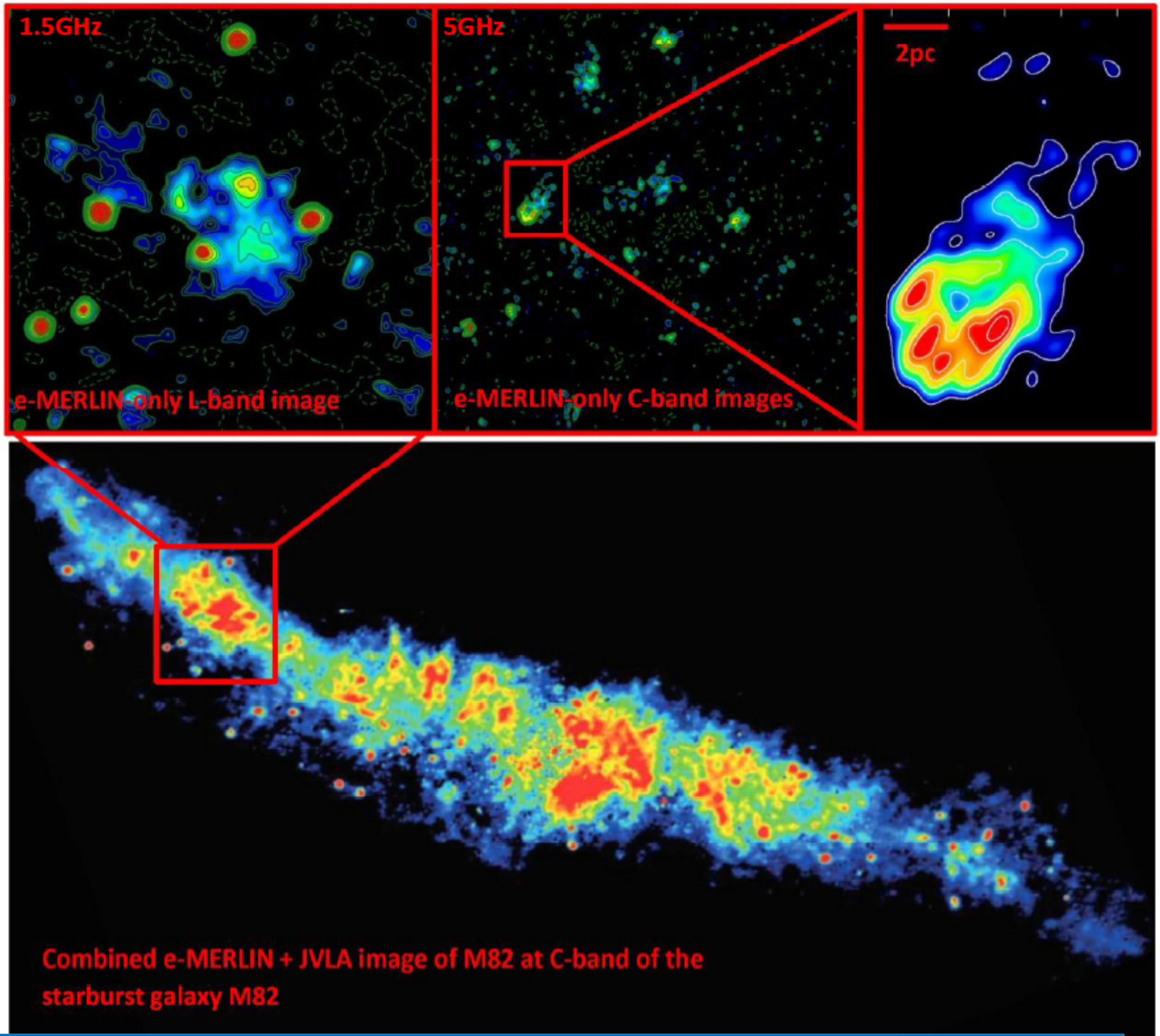
The Local Universe

Seeing through the dust

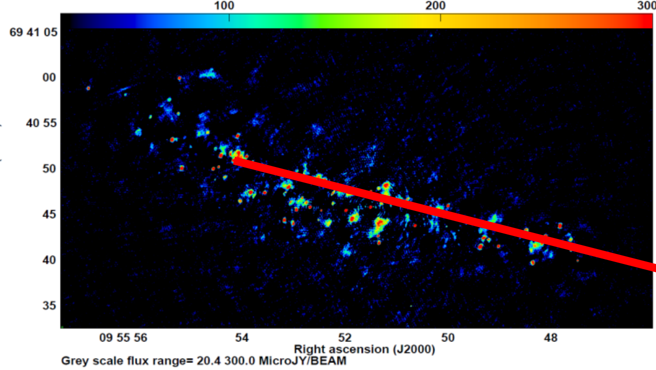
Decomposing individual galaxies into 100s of SF/accretion products – unique laboratories for galaxy evolution

Physics of SF/accretion on sub-pc scales.

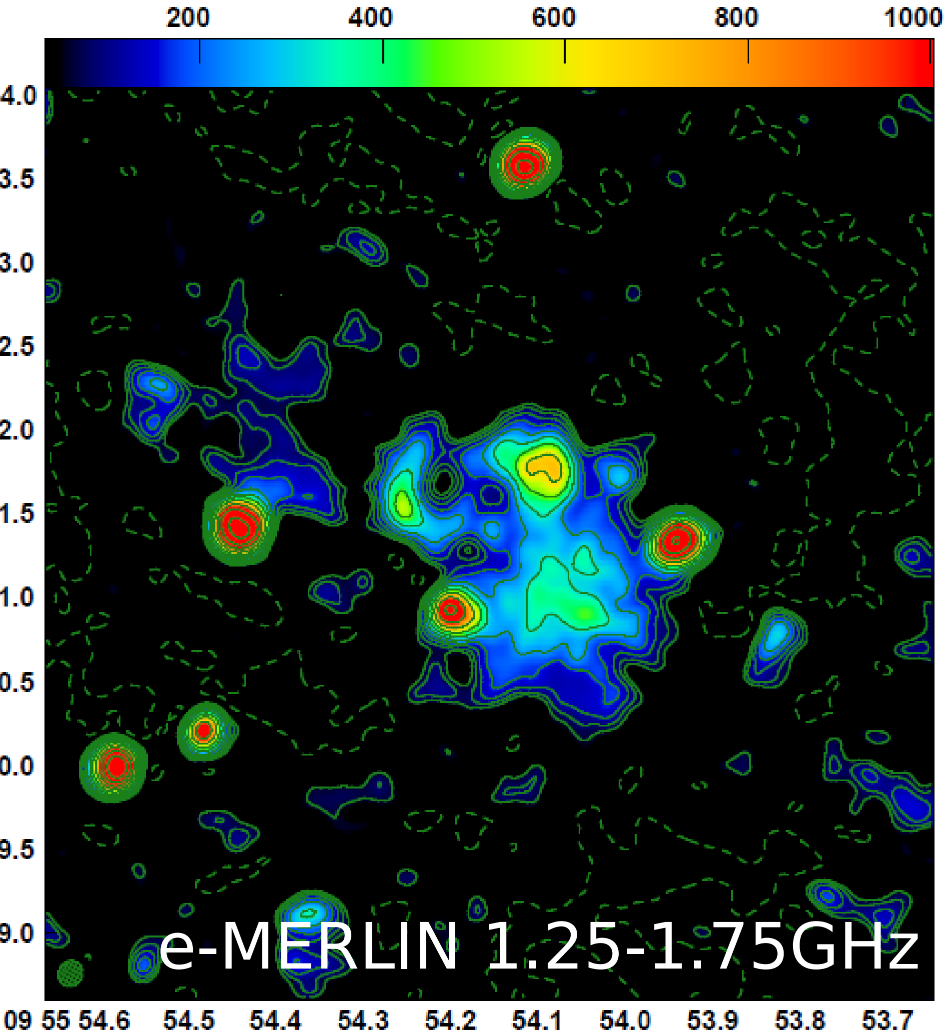
Galactic-style physics in galaxies of all environments and classifications

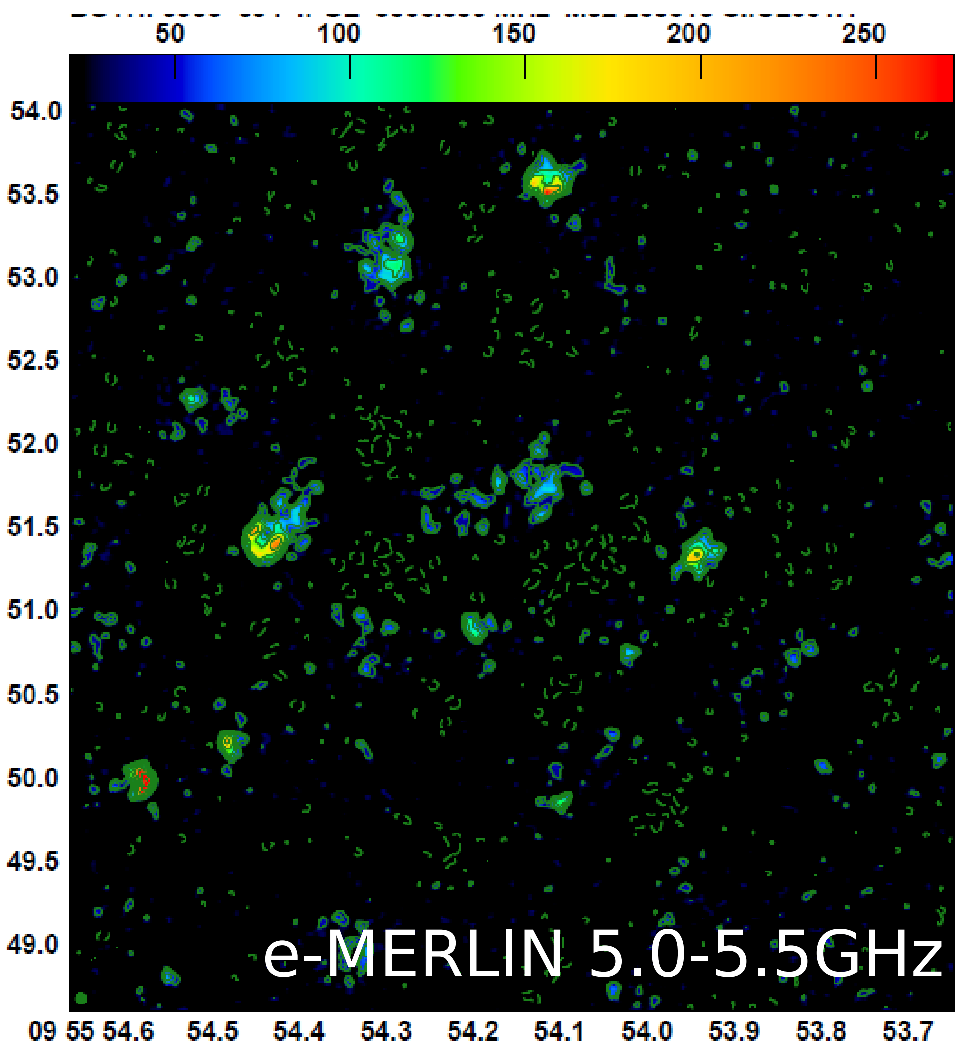


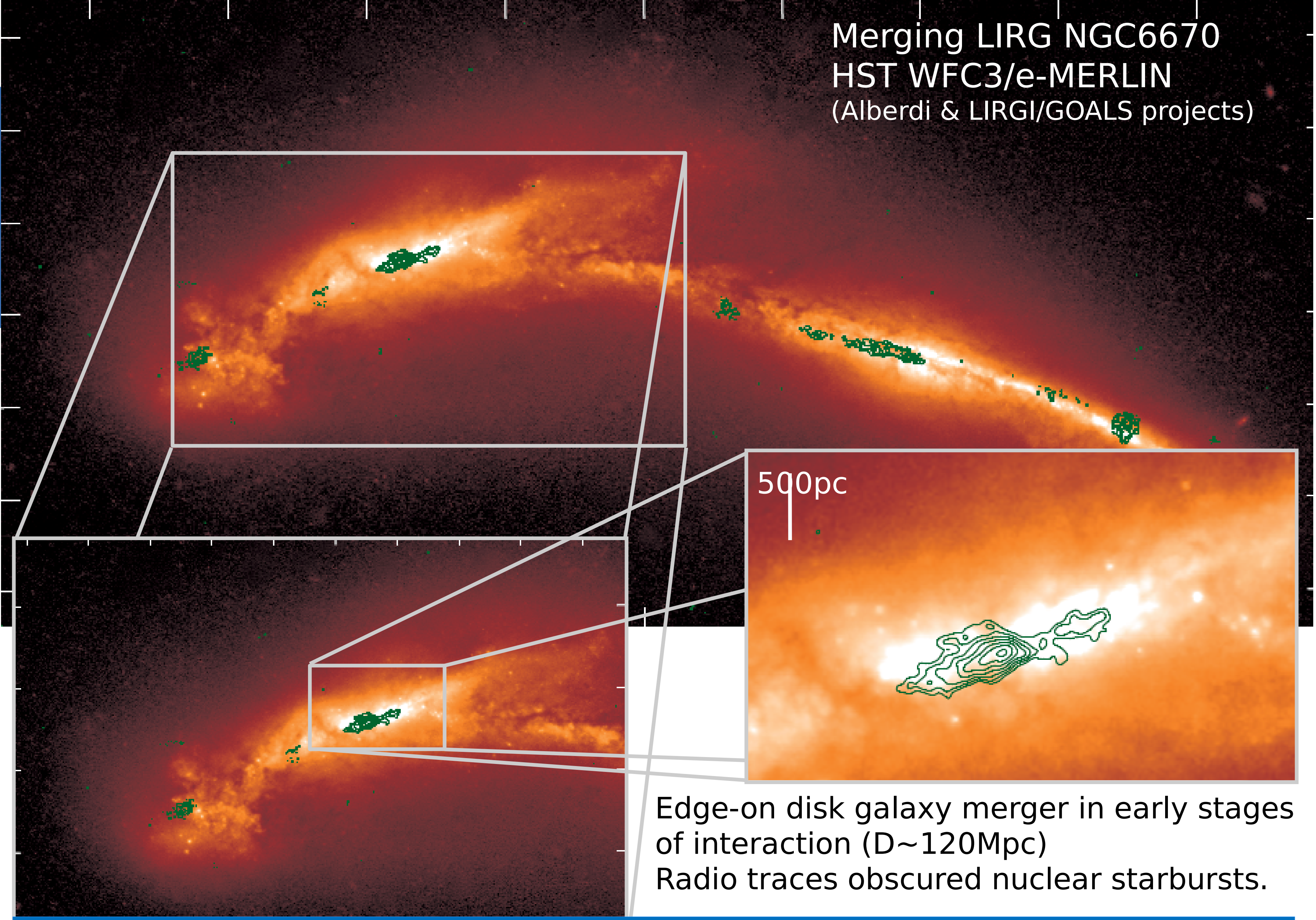
LeMMINGs legacy programme (Beswick/McHardy et al)



New SNR +
increasing fraction of HII regions
- Multiple SNR break-outs







Edge-on disk galaxy merger in early stages of interaction (D~120Mpc)
Radio traces obscured nuclear starbursts.

LIRGI legacy programme (Perez-Torres/Conway et al)

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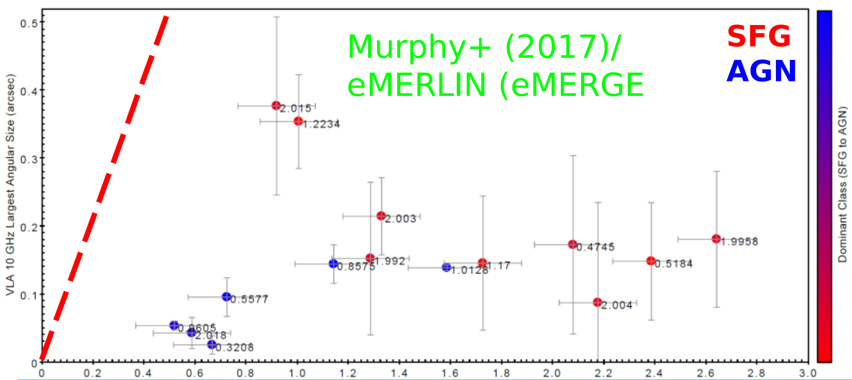
Star-formation across cosmic time: e-MERLIN deep fields

e-MERGE (e-MERLIN key science project deep field)
Extragalactic Deep field imaging

~200mas resolution separates SF and AGN activity and shows detailed feedback where present. SF galaxies dominate 1.5GHz number counts <100μJy

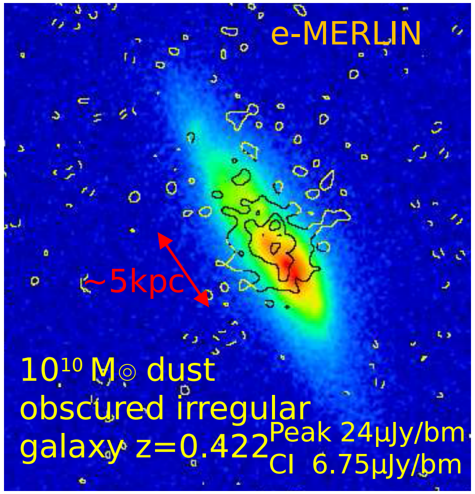
For z<0.5 – Extended starbursts aligned with major axis
For z>0.5 – Additional compact nuclear starburst components become more common

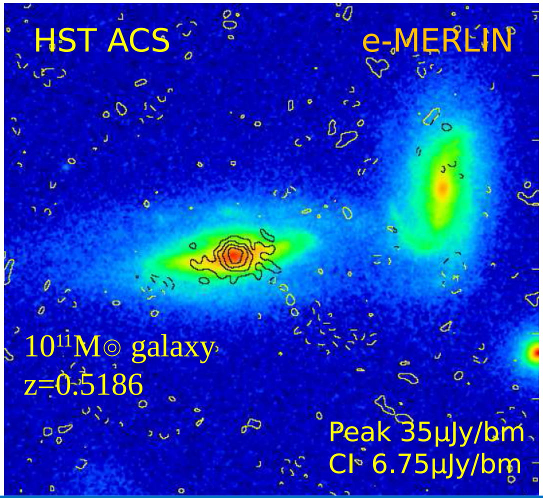
JVLA 10GHz (~200mas) show LAS up to x10 smaller



JVLA at 10GHz detects only the central nuclear starbursts in star-forming galaxies

- and the inner core-jet structures in





eMERGE legacy programme (Muxlow/Smail/McHardy++)

e-MERLIN/VLBI Science

Pulsars, Gravity & Gravitational waves

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Cosmic shear & Gravitational lensing

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Cosmic shear : radio weak lensing

Pioneering radio weak lensing surveys - aiming at first radio weak lensing detections. Pathfinder for SKA science

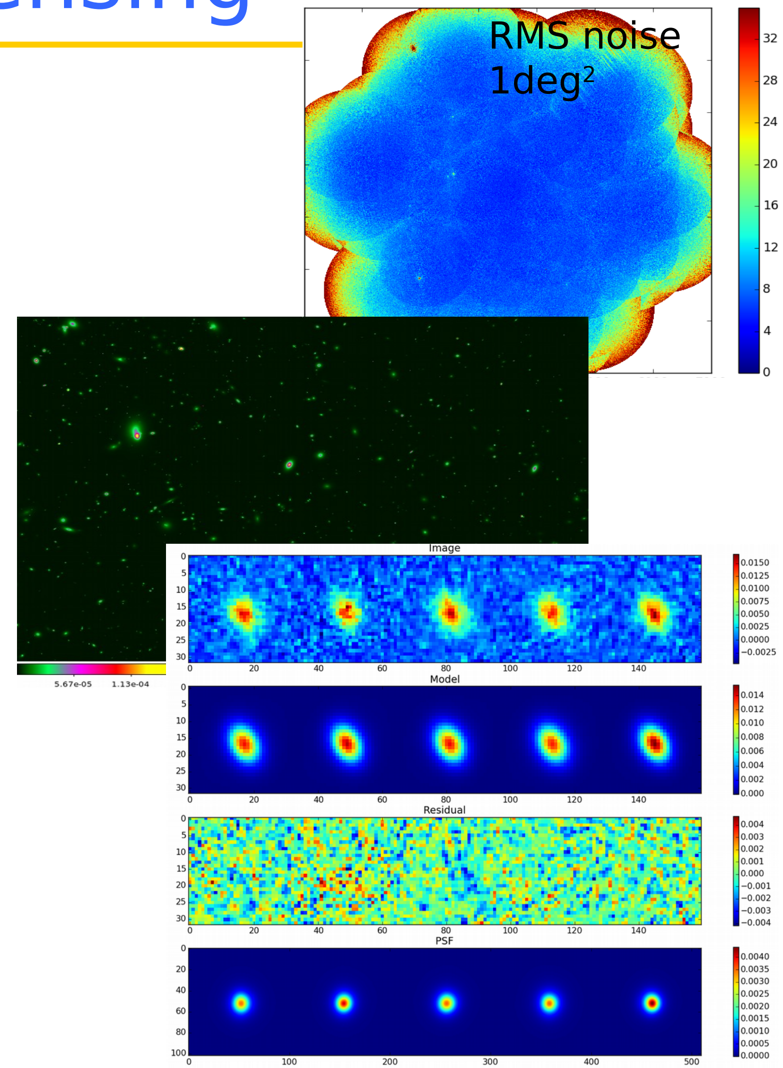
Exploiting e-MERLIN's unique ability to resolve high-z radio starbursts

- precisely defined, stable PSF

SuperCLASS field covering multiple supercluster fields

- combined Multi-λ programme

Radio + Optical weak lensing powerful complementary constraints.



SuperCLASS legacy programme (Battye et al)

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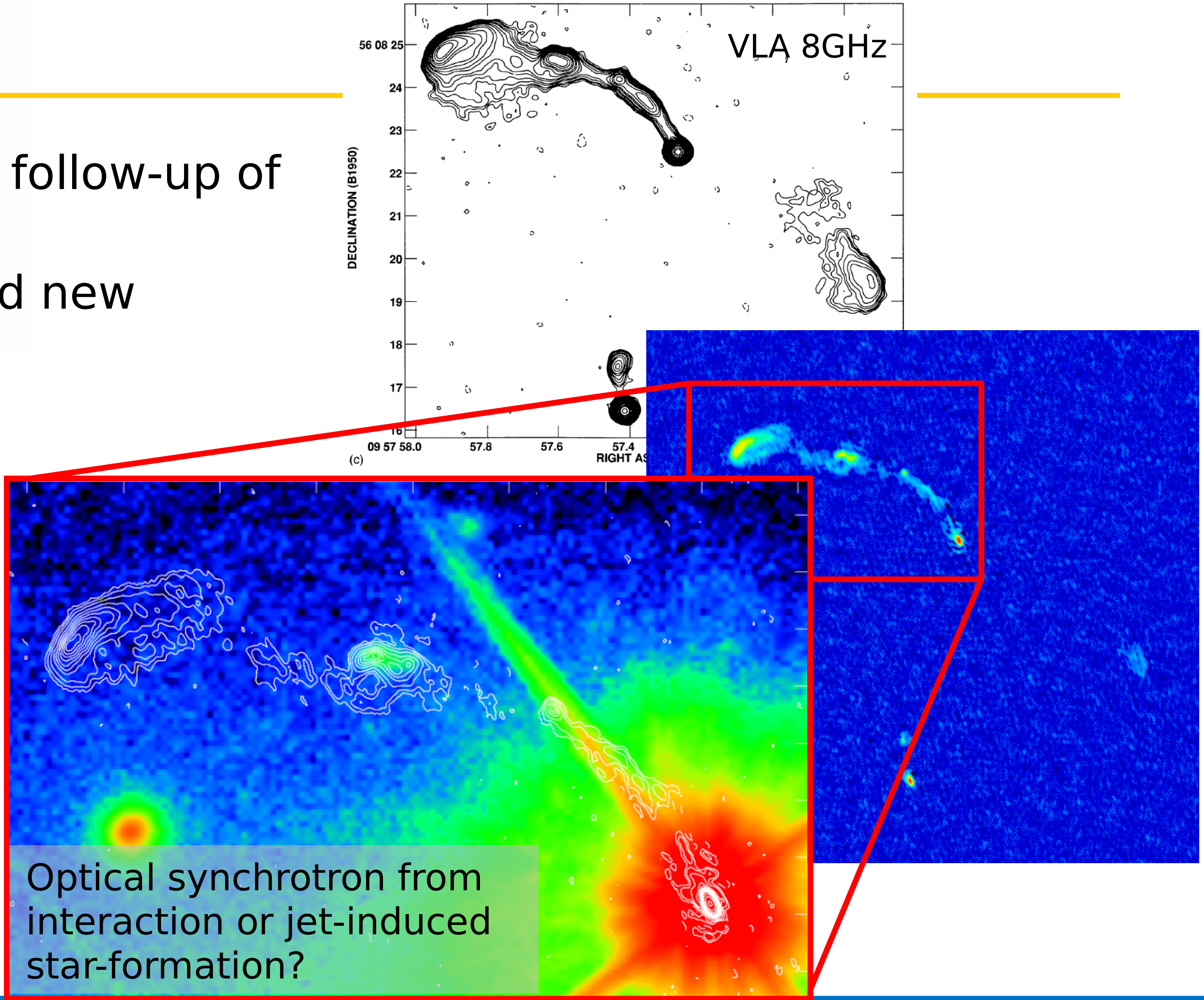
e-MERLIN

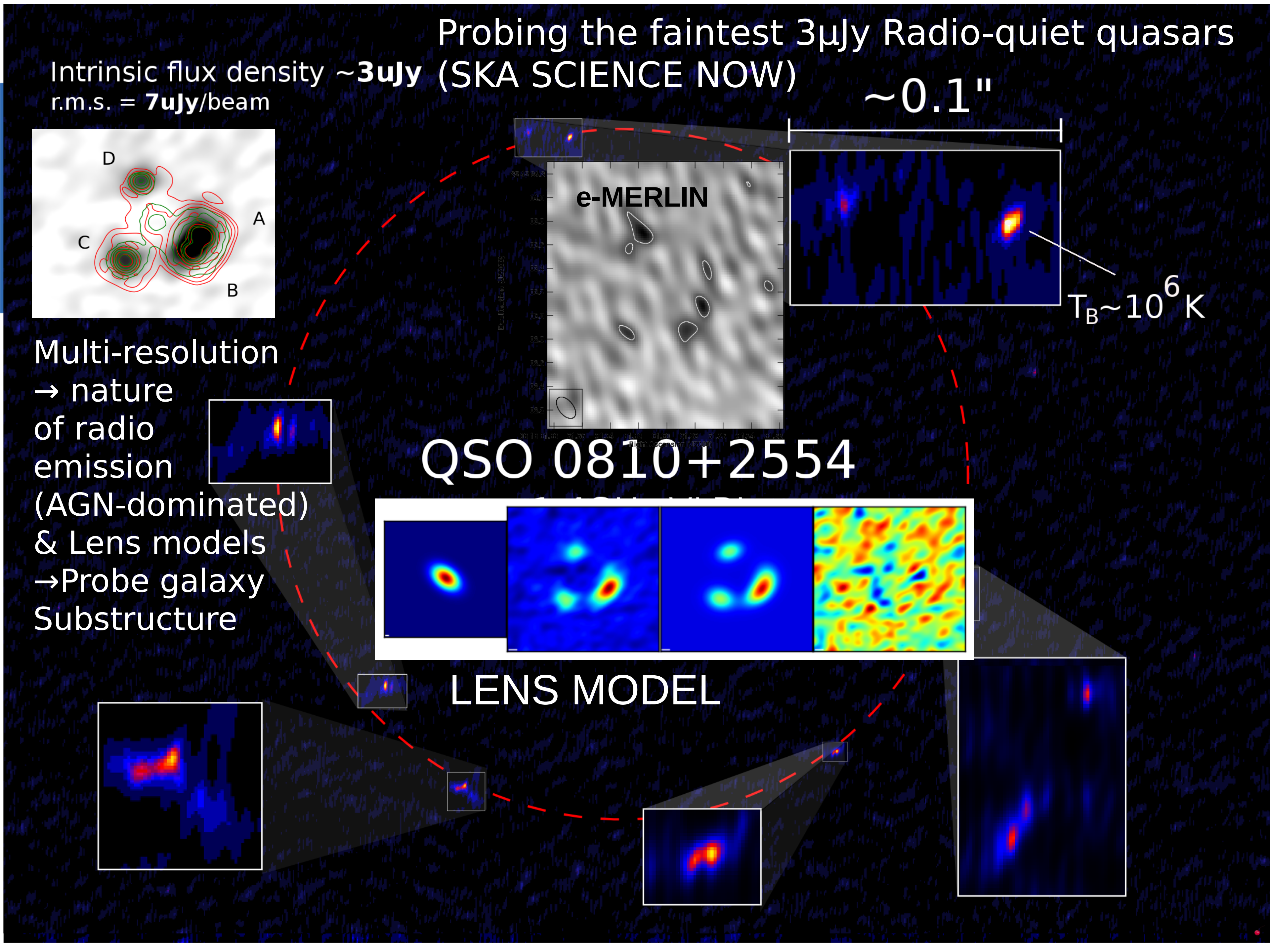
Strong lensing

On-going seep follow-up of lens

Known lens and new discoveries



Strong lens legacy programme (Jackson/Serjent++)


Probing the faintest 3μJy Radio-quiet quasars
(SKA SCIENCE NOW)
Intrinsic flux density ~3uJy
r.m.s. = 7uJy/beam
D
A
C
B
~0.1"
e-MERLIN
T_B~10^6 K
Multi-resolution
→ nature
of radio
emission
(AGN-dominated)
& Lens models
→Probe galaxy
Substructure
QSO 0810+2554
LENS MODEL

What next...?

<u>On-going</u> Operational upgrades

- Final commissioning of 2GHz bandwidths (C/K-band)
- Phasing up of array – superb PSR/transient instruments ~equivalent to 110m dish
- Inclusion of new dishes – Goonhilly + other? – More resolution, more coverage
- PAF on LT
- e-MERLIN fully in EVN baselines from 10 to 10,000s km

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eMERLIN

e-MERLIN Upgrades – science driven upgrades

Throughput	**SKA-based software pipelines**
Frequency coverage	**New Receiver Bands 2-4 & 8-16 GHz 1 ▯ 24 GHz**
Sensitivity	**New digital chain: 2x4, 2x8 GHz b/w**
PSR Beamforming	**Flexible correlator/beamformer**
Survey Speed	**PAF on Lovell**
Imaging quality	**New telescope at Defford**

Summary

- e-MERLIN provides a unique set of capabilities
  - Providing the frequencies and baseline lengths of SKA1-Mid now.. Perfect for (pre-SKA) science demonstration and development..
- e-MERLIN legacy programme covering a wide range of science goals
  - Current programmes first sets of results coming out now
  - New programmes will be considered in future rounds
- Exciting range of new capabilities being considered to further enhance instrument (~15M£ programme)
  - Great capabilities and complementarities
  - ~25% SKA1-mid…, new RXs 1-26GHz…, enhanced survey speeds etc… etc…

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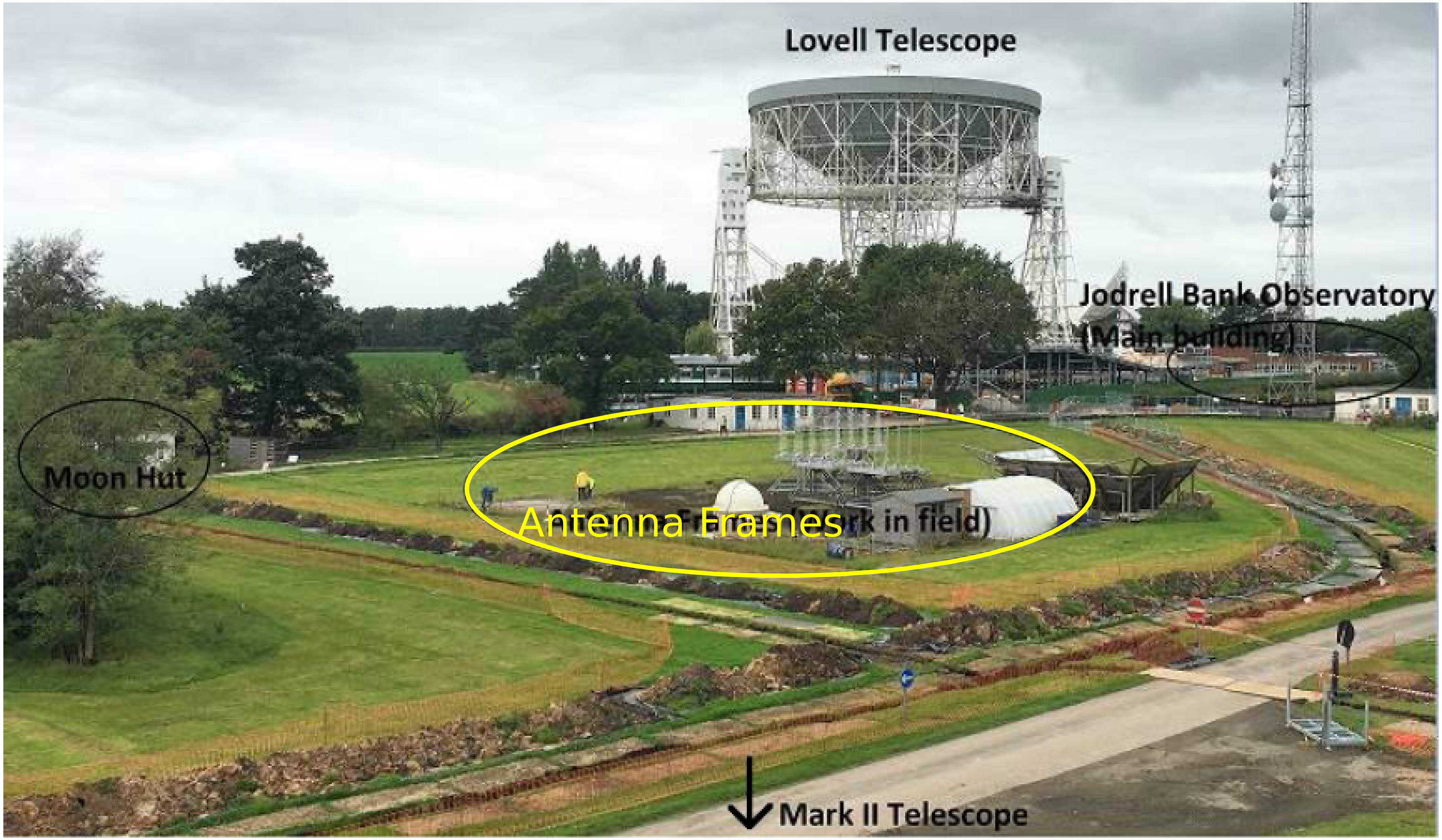
Manchester University Student Telescope MUST at the Jodrell Bank Observatory



The Manchester University Student Telescope: MUST

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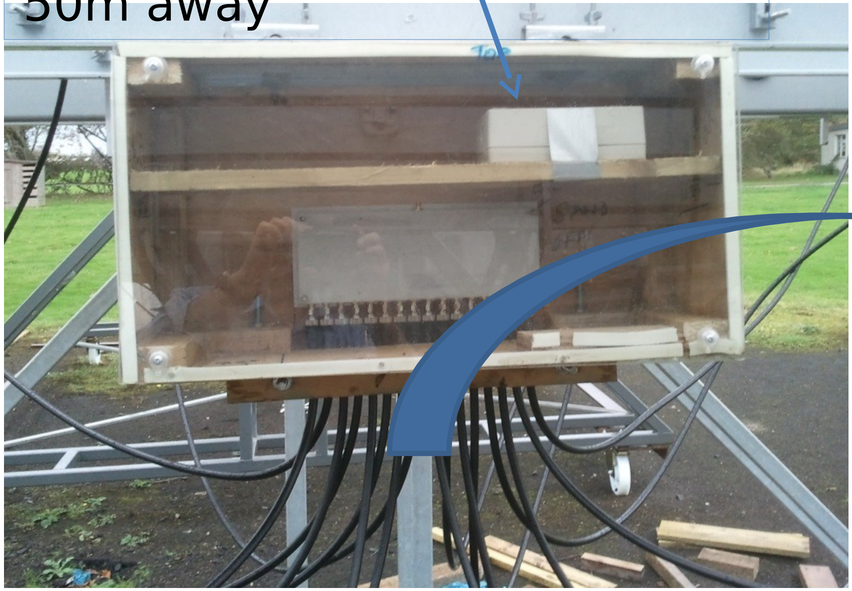
A single MUST frame

One of four flat frames each carrying 16 Yagi antennas as the collecting elements.

Low noise amplifier – then out to back-end receiver in a hut 50m away



Each Yagi is connected with an equal length of cable to a central combiner – the virtual focus of each frame.

Each frame array acts like a single dish antenna forming a single beam perpendicular to the plane of the frame

At the start of the BALTICS work programme with MUST the hardware was mostly assembled BUT……

- it had not been tested – individually or as a system
- the interferometer had not been made to work

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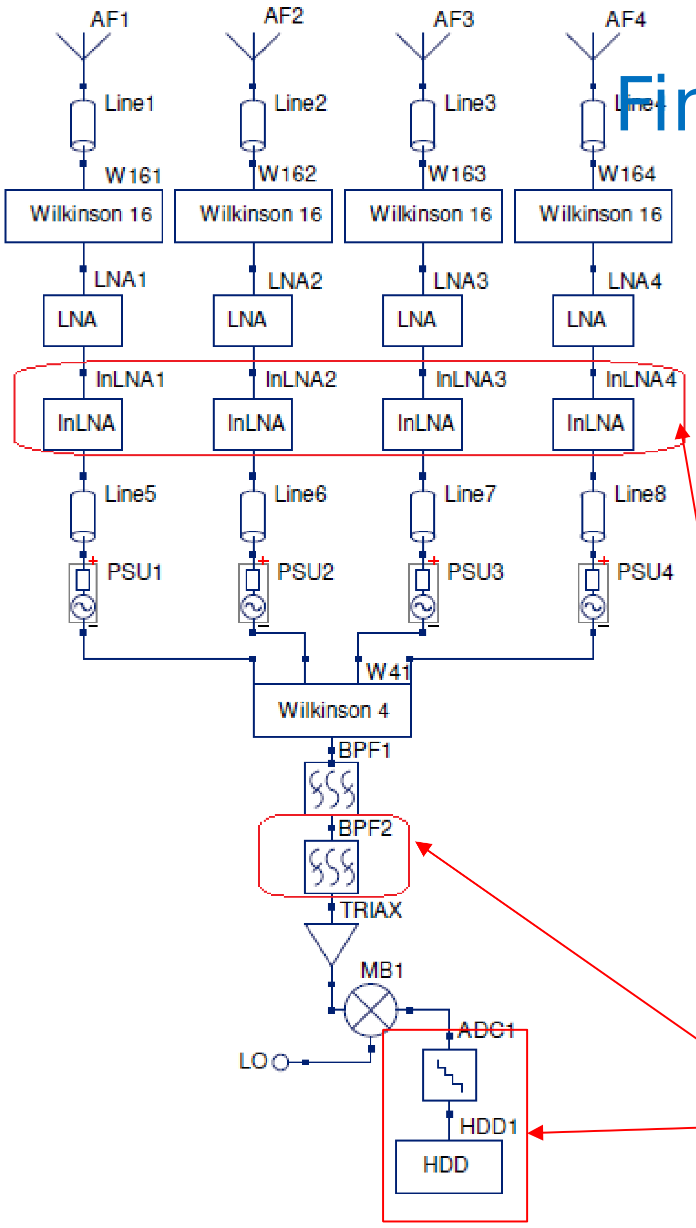
Initial capture of system

#	Block Name	Parameters
1	Antenna	Effective area: 0.52 m^2 (cable losses included) Flux: 10 Jy Bandwidth: 120 MHz
2	Wilkinson PC (No.1)	Inputs (Gain): 16 Bandwidth: 120 MHz Losses in total signal power: 0.5 dB
3	Cable (Wilkinson PC (No.1)-LNA) and S11	Bandwidth: 120 MHz Losses: 3.5 dB
4	LNA	Bandwidth: 120 MHz Gain: 23 dB k=1.38E-23 J/K T_0=290 K NF=0.7 dB
5	Cable (LNA- Inline Amp), attenuator and mismatch (characteristic impedances 50/75 Ω)	Losses: 4.5 dB
6	Inline Amp	Bandwidth: 120 MHz Gain: 20 dB k=1.38E-23 J/K T_0=290 K NF=2.3 dB
7	Central cable (Inline Amp-Wilkinson PC (No.2)) and mismatch (characteristic impedances 75/50 Ω)	Losses: 9 dB
8	Wilkinson PC (No.2)	Inputs (Gain): 4 Bandwidth: 120 MHz Losses in total signal power: 0.5 dB
9	Cable (Wilkinson PC (No.2)- BPF), attenuator and mismatch (characteristic impedances 50/75 Ω)	Losses: 4.5 dB
10	BPF	Bandwidth out: 50 MHz Bandwidth in: 120 MHz Losses: 1.5 dB (average value)
11	Cable (BPF- Amplifier: TRIAX #1) and mismatch (characteristic impedances 75/50 Ω)	Losses: 3.5 dB
12	Amplifier: TRIAX #1	Bandwidth: 120 MHz Gain: 30 dB k=1.38E-23 J/K T_0=290 K NF=0.4 dB
13	Cable (Amplifier: TRIAX #1- Mixer block) and mismatch (characteristic impedances 50/75 Ω)	Losses: 3,5 dB
14	Mixer block	Bandwidth: 50 MHz Gain: 12 dB k=1.38E-23 J/K T_0=290 K NF=12.5 dB
15	Cable (Mixer block-ADC) and mismatch (characteristic impedances 75/50 Ω)	Losses: 3.5 Db
16	ADC	Vpp: 0.2 V Rin: 50 Ohm Resolution: 8 bit Overload reserve: 6 dB Bandwidth: 50 MHz

Final block diagram of system



AF1 - AF4: Antenna Array, CF 593 MHz
Line1 - Line4: Signal Cable, 2.2 meters
W161 - W164: Wilkinson PC, 16-input, 0.5 dB
LNA1 - LNA4: Low Noise Amplifier, 24 dB
InLNA1 - InLNA4: Low Noise Amplifier, 20 dB
Line5 - Line8: Signal Cable 74.2 meters, 8.5 dB
PSU1 - PSU4: Power Supply Unit, 12 V, 0.5 dB
W41: Wilkinson PC, 4-input, 0.5 dB
BPF1 - BPF2: Band Pass Filter, 591 – 595 MHz, 0.5 dB
TRIAX1: Amplifier, 0.5 dB
MB1: Mixer
LO: Local Oscillator, 590 MHz
ADC1: Analog-to-Digital Converter
HDD1: Hard Disk Drive

Red boxes indicate where major changes
were made by BALTICS staff

Summary of the technical programme

In the lab – quantitative characterisation of:
- All active electronic components
- All passive RF components

In the field - quantitative characterisation of:
- Performance of the Yagi antennas
- Performance of the “frame arrays” of Yagi antennas

Some changes/additions made:
- Fixed various faults !
- “Frame array” configuration simplified for practicality
- Front-end RF amplifiers modifiedbetter noise performance
- RF filters retuned *as a pair* avoid broadcast TV
- Software written for N.I. ADC to produce “fringes”

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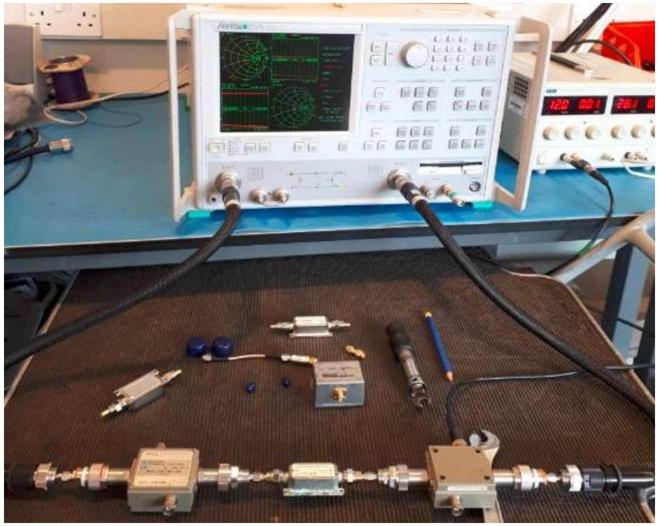
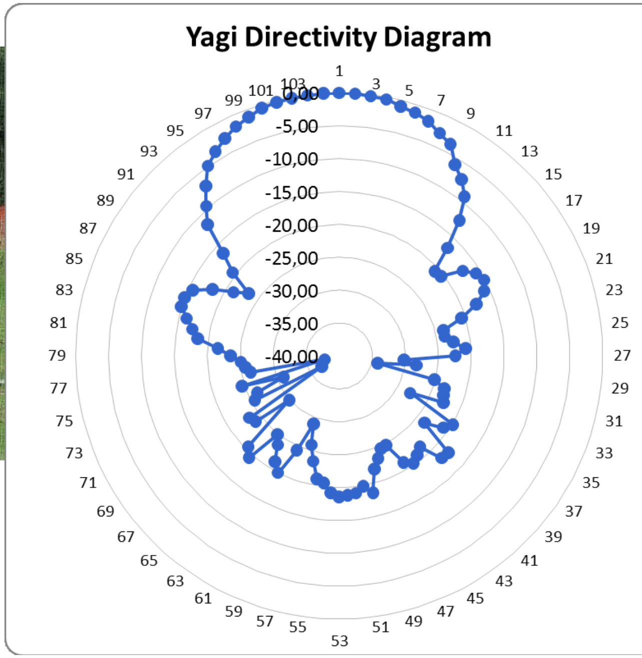
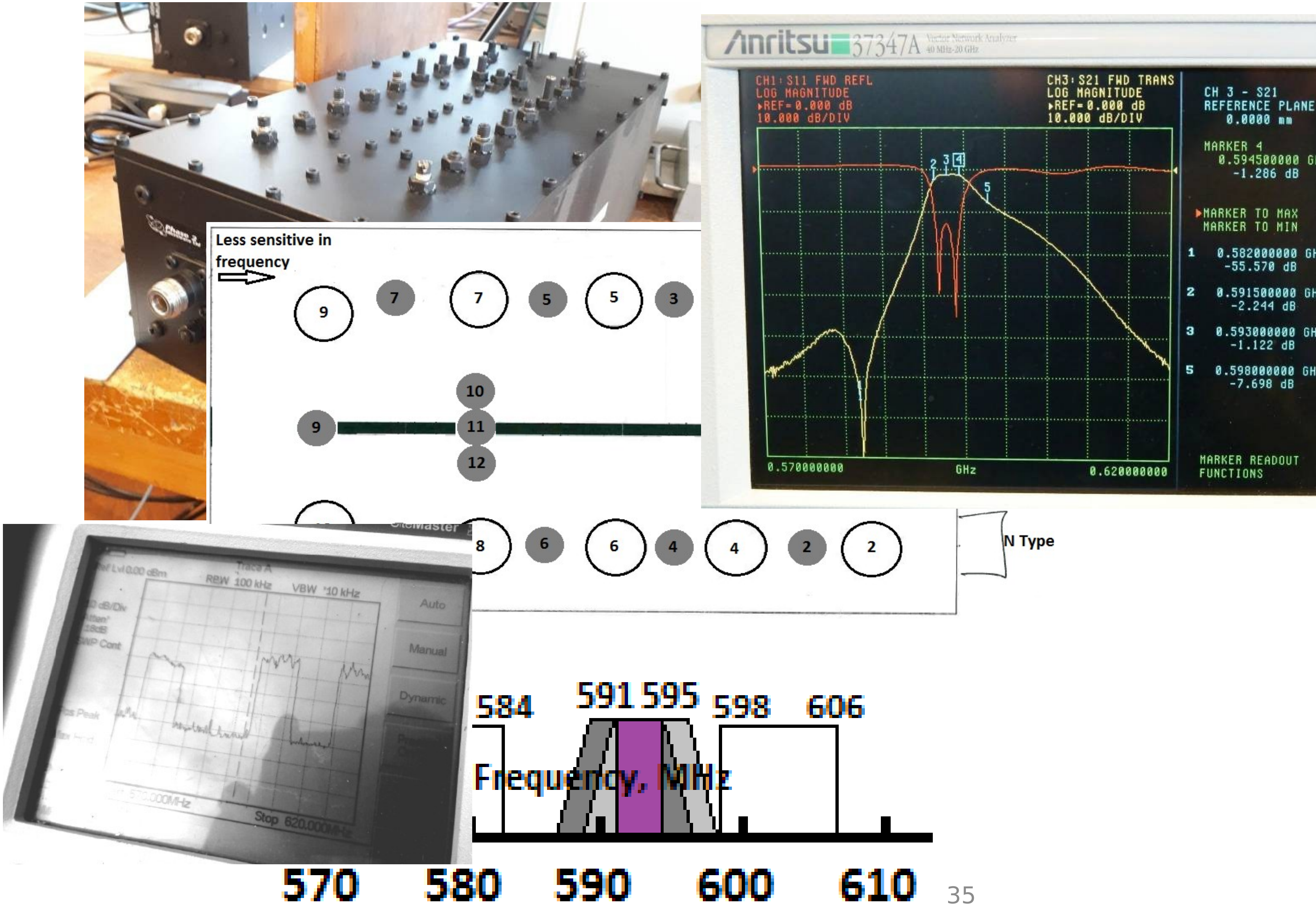





Less sensitive in frequency
9
7
7
5
5
3
10
9
11
12
8
6
6
4
4
2
2
N Type
Anritsu 37347A
CH1: S11 FWD REFL
LOG MAGNITUDE
REF= 0.000 dB
10.000 dB/DIV
CH3: S21 FWD TRANS
LOG MAGNITUDE
REF= 0.000 dB
10.000 dB/DIV
CH 3 - S21
REFERENCE PLANE
0.0000 mm
MARKER 4
0.594500000 GHz
-1.286 dB
MARKER TO MAX
MARKER TO MIN
1 0.582000000 GHz -55.570 dB
2 0.591500000 GHz -2.244 dB
3 0.593000000 GHz -1.122 dB
5 0.598000000 GHz -7.698 dB
0.570000000
GHz
0.620000000
MARKER READOUT
FUNCTIONS
RBW 100 kHz
VBW 10 kHz
Auto
Manual
Dynamic
Stop 620.000MHz
584
591 595
598
606
Frequency, MHz
570
580
590
600
610

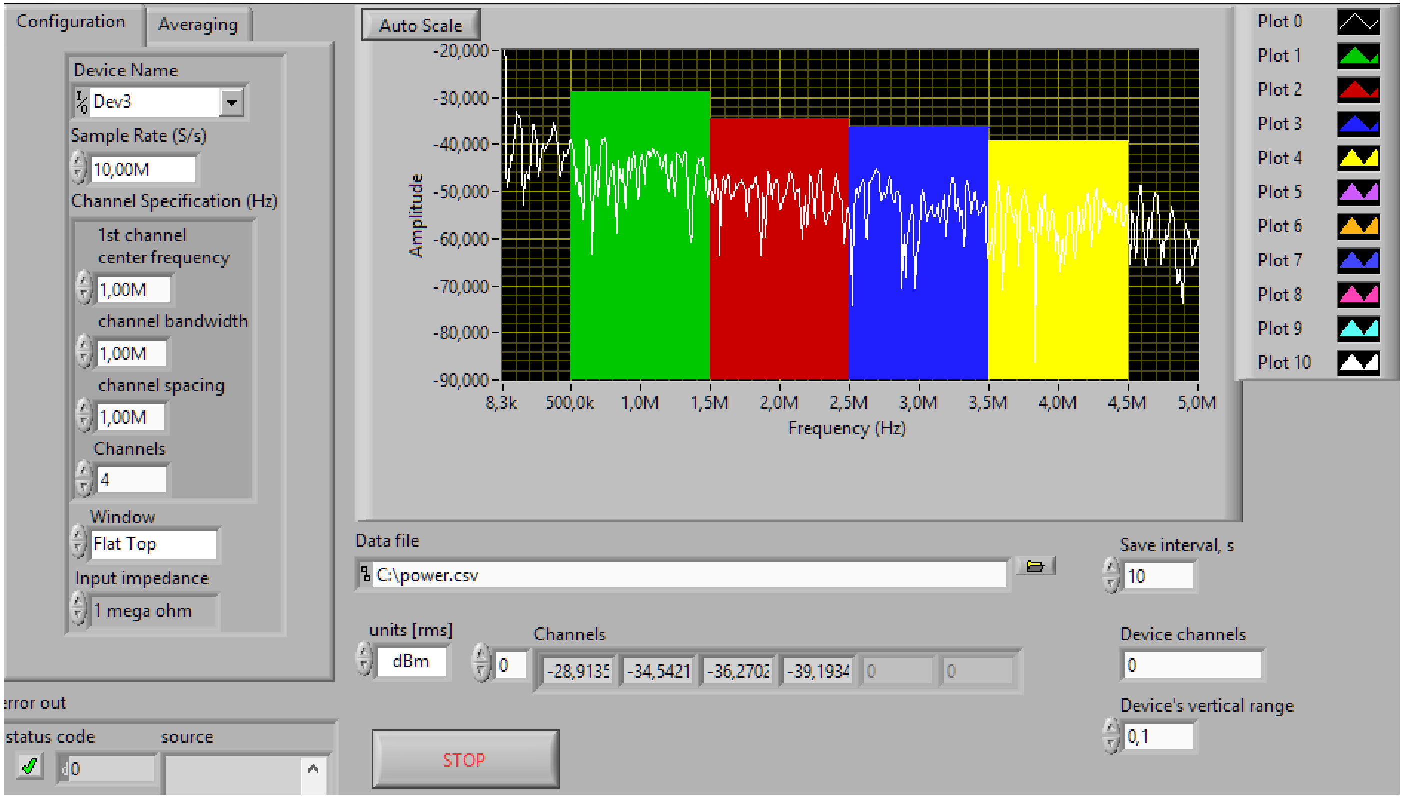
The back-end system

Analogue part

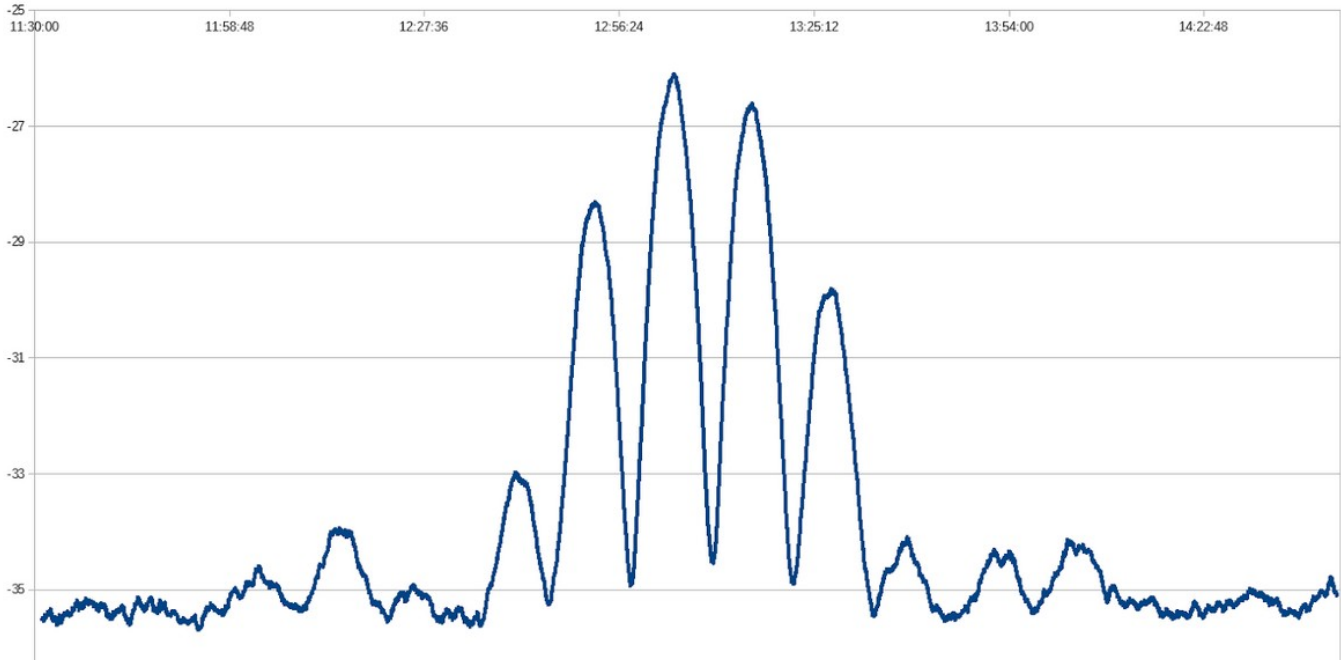
Pair of gang-tuned UHF filters

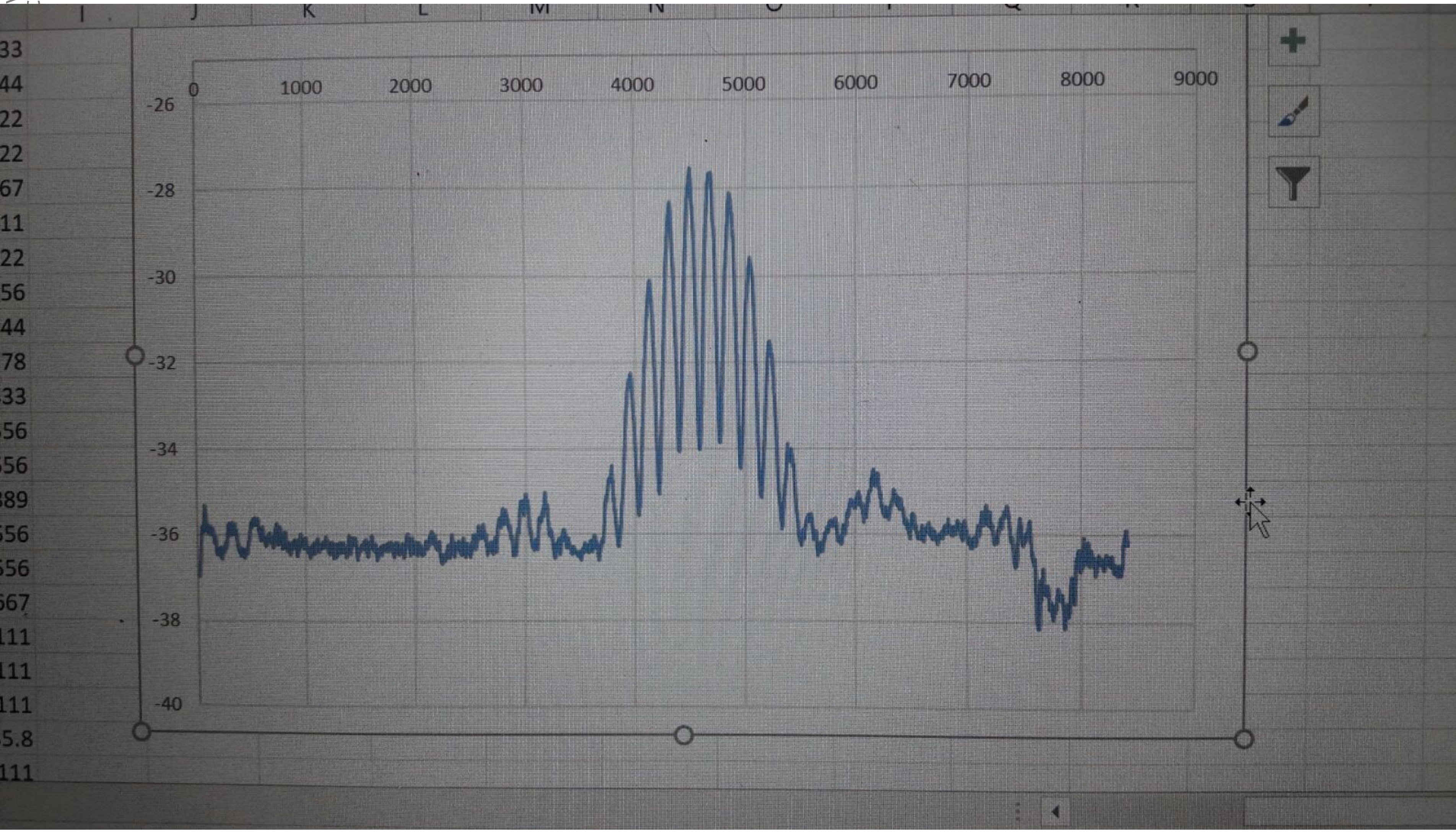
Digitizer and PC

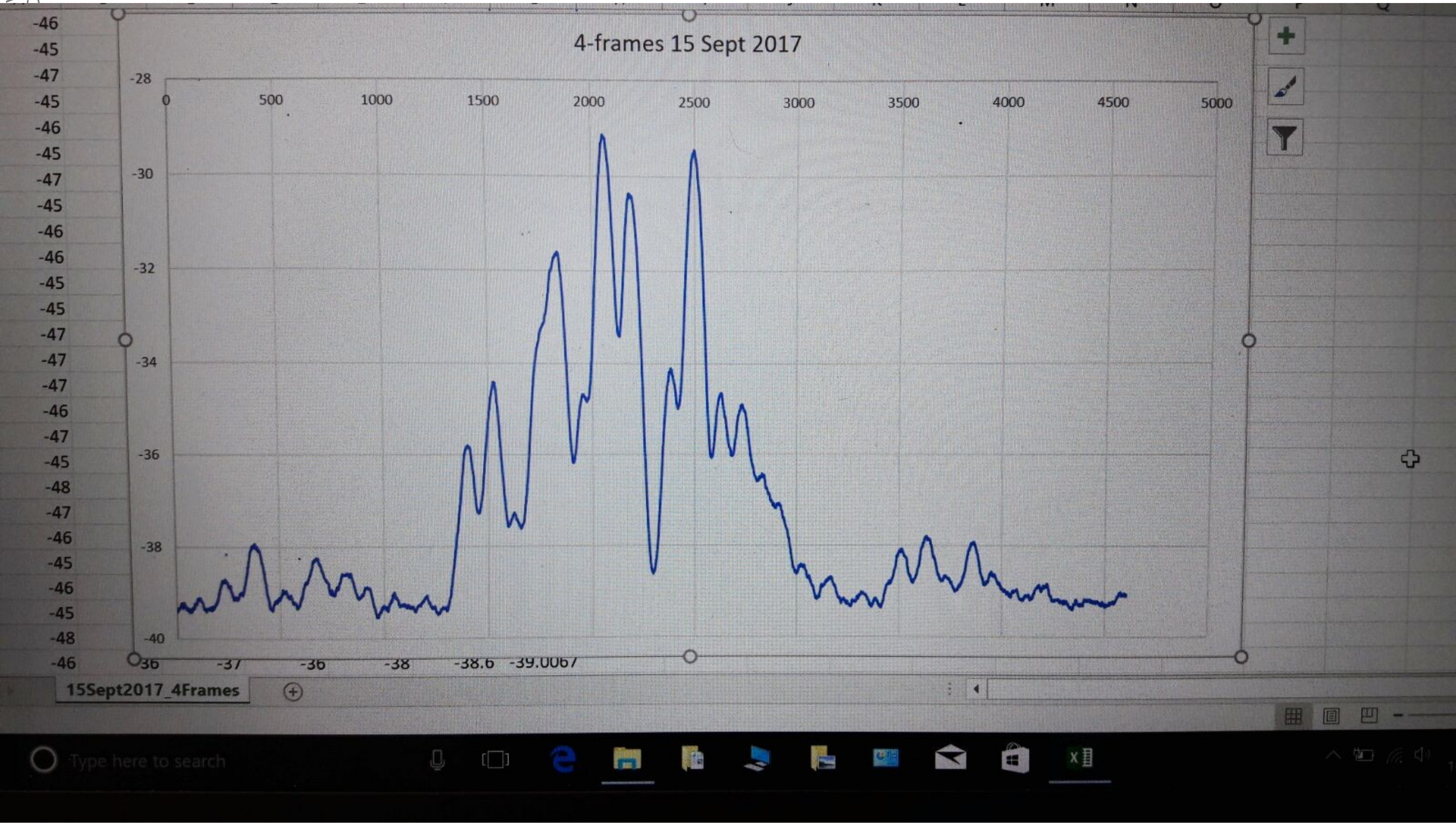
GUI for National Instrument Digitizer

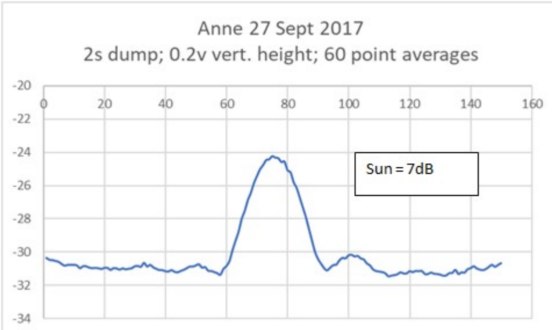


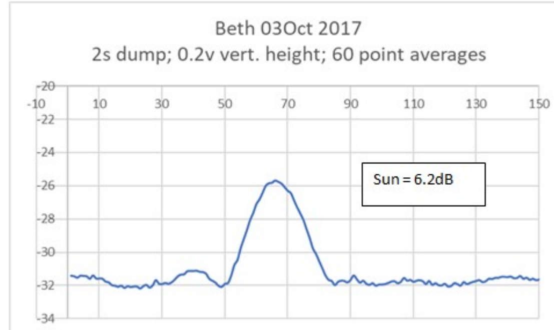
GUI and data acquisition software written by BALTICS team

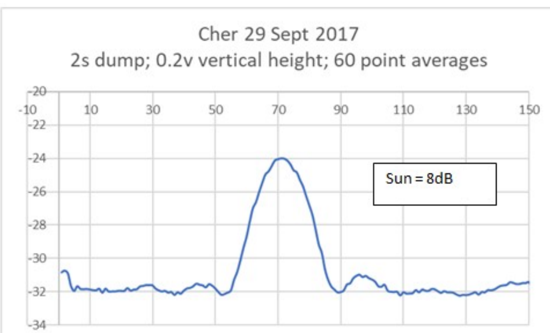

-25
-27
-29
-31
-33
-35
11:30:00
11:58:48
12:27:36
12:56:24
13:25:12
13:54:00
14:22:48

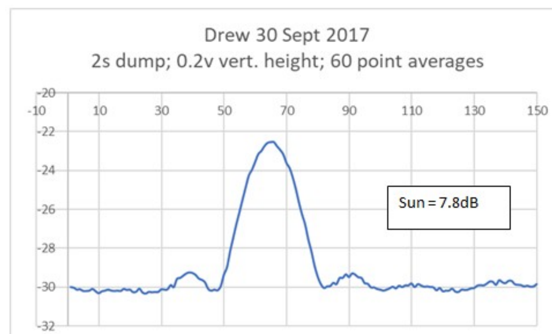

0
1000
2000
3000
4000
5000
6000
7000
8000
9000
-26
-28
-30
-32
-34
-36
-38
-40

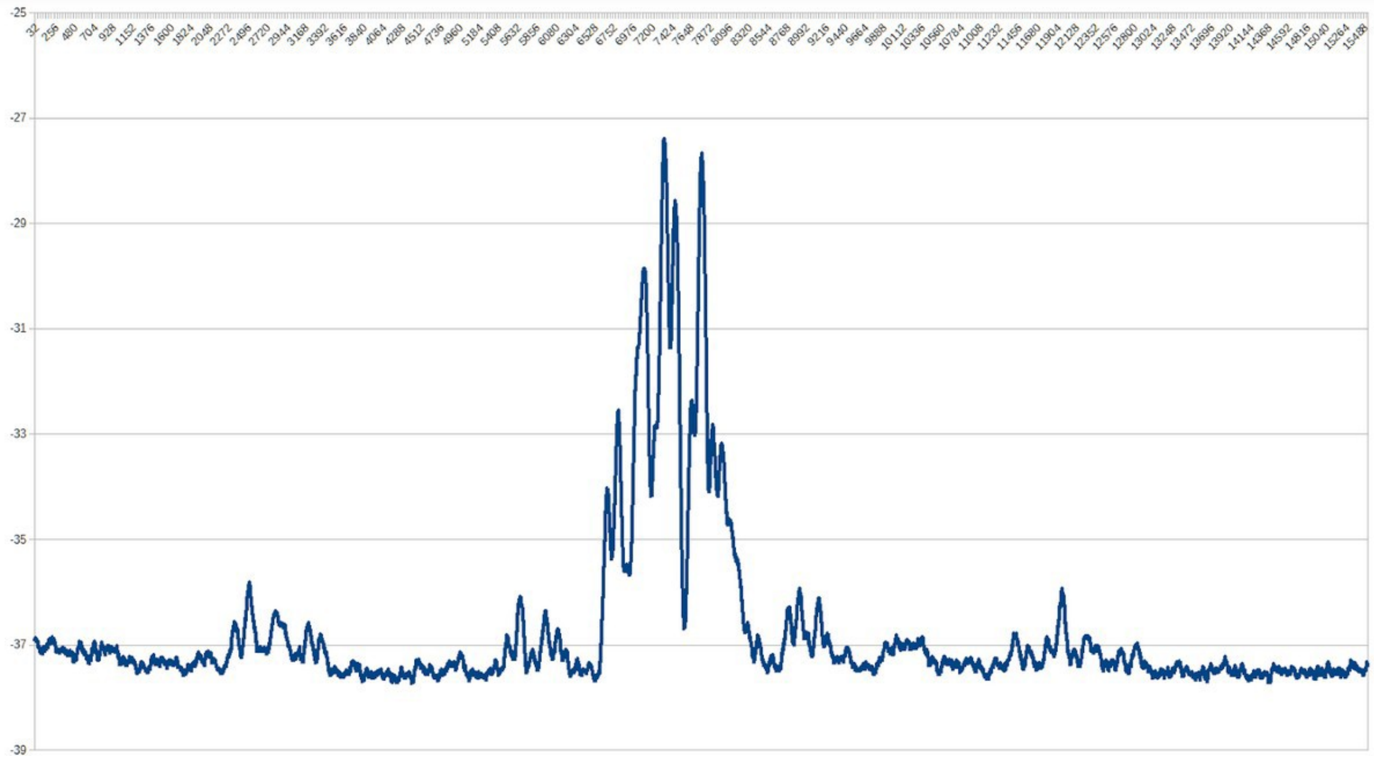

4-frames 15 Sept 2017
15Sept2017_4Frames


Anne 27 Sept 2017
2s dump; 0.2v vert. height; 60 point averages
Sun = 7dB
-20
-22
-24
-26
-28
-30
-32
-34
0
20
40
60
80
100
120
140
160


Beth 03Oct 2017
2s dump; 0.2v vert. height; 60 point averages
Sun = 6.2dB
-20
-22
-24
-26
-28
-30
-32
-34
-10
10
30
50
70
90
110
130
150


Cher 29 Sept 2017
2s dump; 0.2v vertical height; 60 point averages
Sun = 8dB
-20
-22
-24
-26
-28
-30
-32
-34
-10
10
30
50
70
90
110
130
150


Drew 30 Sept 2017
2s dump; 0.2v vert. height; 60 point averages
Sun = 7.8dB
-20
-22
-24
-26
-28
-30
-32
-10
10
30
50
70
90
110
130
150


-25
-27
-29
-31
-33
-35
-37
-39
32
256
480
704
928
1152
1376
1600
1824
2048
2272
2496
2720
2944
3168
3392
3616
3840
4064
4288
4512
4736
4960
5184
5408
5632
5856
6080
6304
6528
6752
6976
7200
7424
7648
7872
8096
8320
8544
8768
8992
9216
9440
9664
9888
10112
10336
10560
10784
11008
11232
11456
11680
11904
12128
12352
12576
12800
13024
13248
13472
13696
13920
14144
14368
14592
14816
15040
15264
15488

MANCHESTER
1824

The University
of Manchester

At the end of the BALTICS work programme with MUST the hardware was fully assembled AND……

- it had all been tested – individually and as a system
- the interferometer system was working

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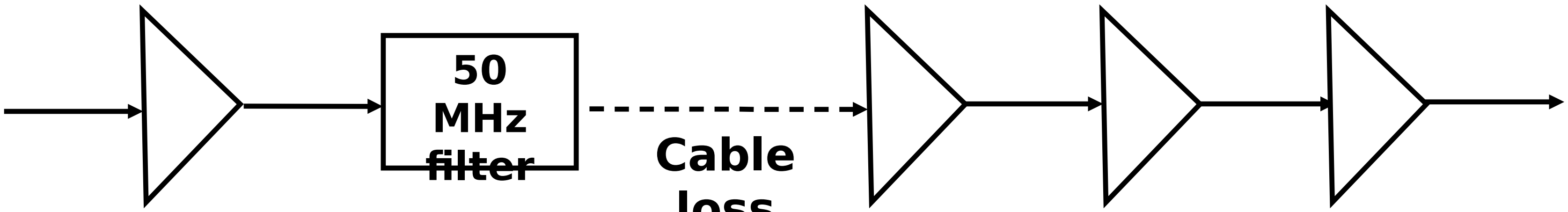
The University
of Manchester

The University of Manchester

RF Amplifier Chain



LNA 23 dB
NF 0.4dB

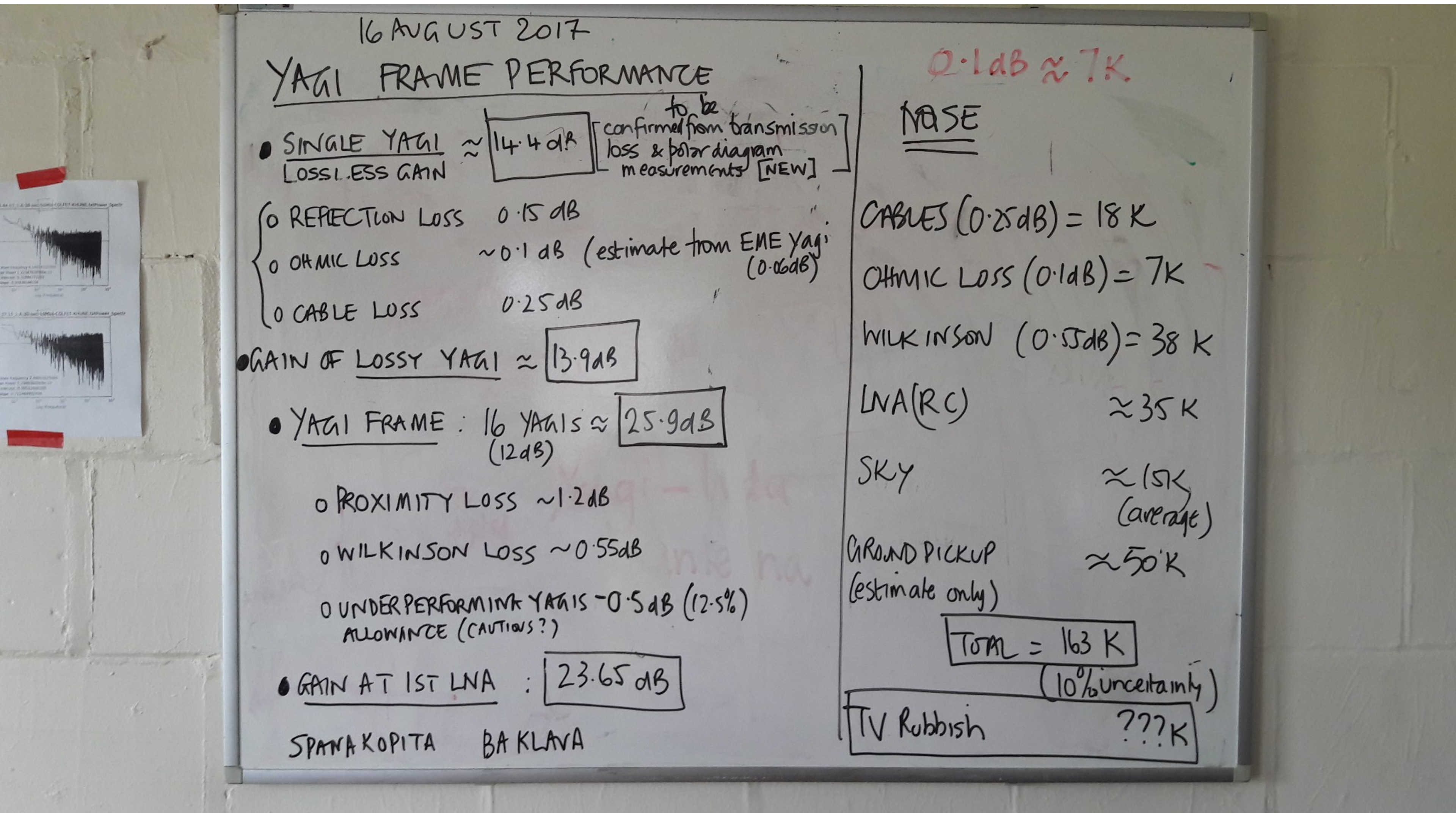
Cable loss ~8 dB (See below)

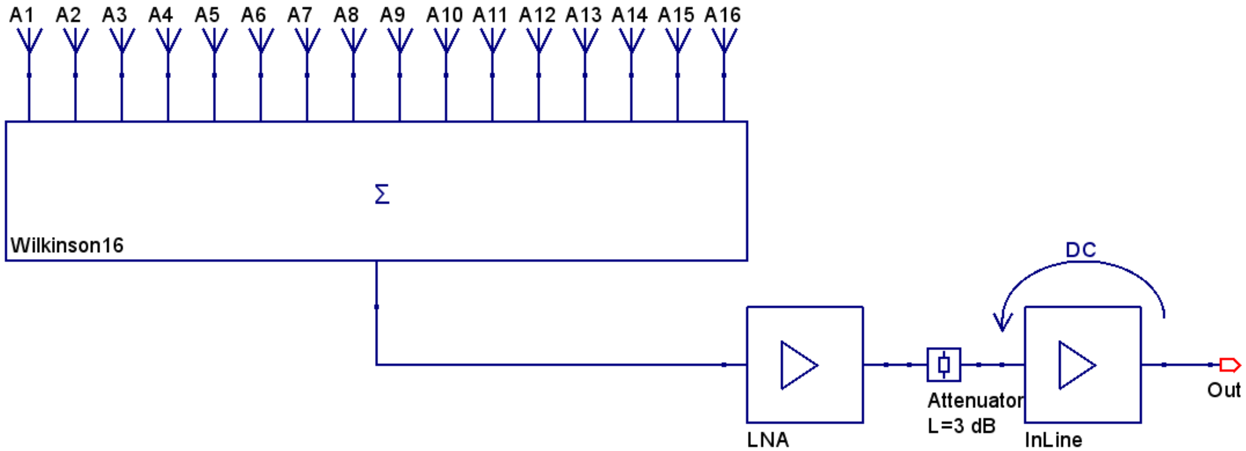
3 x Triax TFMV34W TV Masthead 30-34dB NF 1.8dB

23-8+34+34+34=118 dB

i.e. some margin available

ommercial mast-head amplifiers – but not yet tested
ee if 100dB gain at same frequency will cause oscillation


16 AUGUST 2017
YAGI FRAME PERFORMANCE
• SINGLE YAGI LOSSLESS GAIN ≈ 14.4 dB
[to be confirmed from transmission loss & polar diagram measurements [NEW]]
o REFLECTION LOSS 0.15 dB
o OHMIC LOSS ~0.1 dB (estimate from EME yagi (0.06dB))
o CABLE LOSS 0.25 dB
• GAIN OF LOSSY YAGI ≈ 13.9 dB
• YAGI FRAME : 16 YAGIS (12dB) ≈ 25.9 dB
o PROXIMITY LOSS ~1.2 dB
o WILKINSON LOSS ~0.55 dB
o UNDERPERFORMING YAGIS -0.5 dB (12.5%) ALLOWANCE (CAUTIOUS?)
• GAIN AT 1ST LNA : 23.65 dB
SPANAKOPITA BAKLAVA
0.1dB ≈ 7K
NOISE
CABLES (0.25dB) = 18 K
OHMIC LOSS (0.1dB) = 7K
WILKINSON (0.55dB) = 38 K
LNA (RC) ≈ 35 K
SKY ≈ 15K (average)
GROUND PICKUP (estimate only) ≈ 50 K
TOTAL = 163 K (10% uncertainty)
TV Rubbish ???K



A1 A2 A3 A4 A5 A6 A7 A8 A9 A10 A11 A12 A13 A14 A15 A16
Σ
Wilkinson16
DC
LNA
Attenuator
L=3 dB
InLine
Out