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Jodrell Bank Observatory

MANCHESTER 1824

e-MERLIN Development 2018-2023

Simon Garrington

JBO, e-MERLIN/VLBI National Facility

University of Manchester

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Motivation
Scientific potential

Productivity limited by processing

- Harder (RFI, calibration, wide-band, wide-field…)
- Data volume x 100

Key science is sensitivity limited

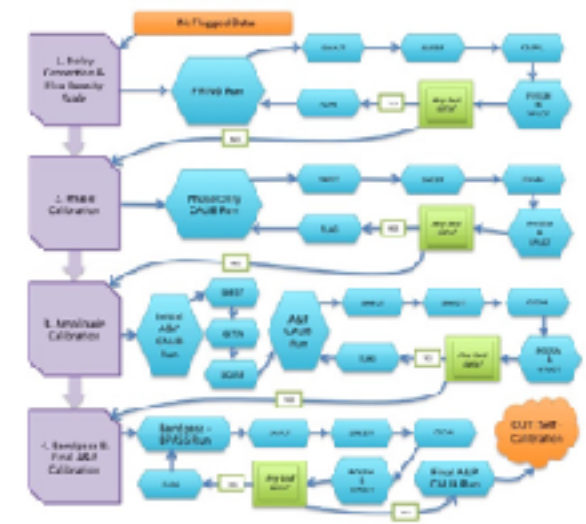
→Optimise frequency bands

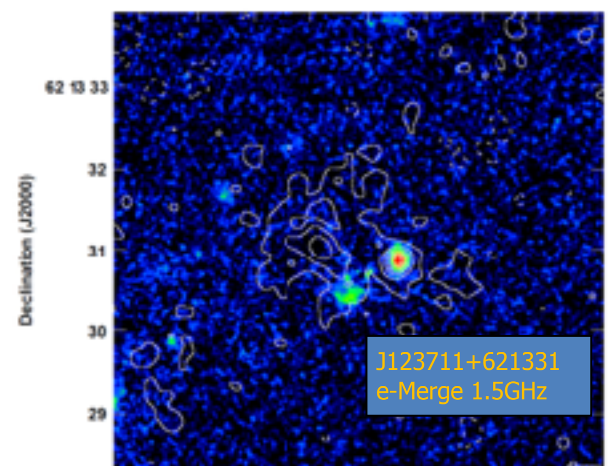
→Maximise survey speed

→Maximise bandwidth

→Optimise image quality

These are the issues to be addressed to bring e-MERLIN truly into the SKA-era





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→Optimise image quality

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WP2: Software

WP3: 2-4 GHz

WP4: 8-16 GHz

WP5: PAF

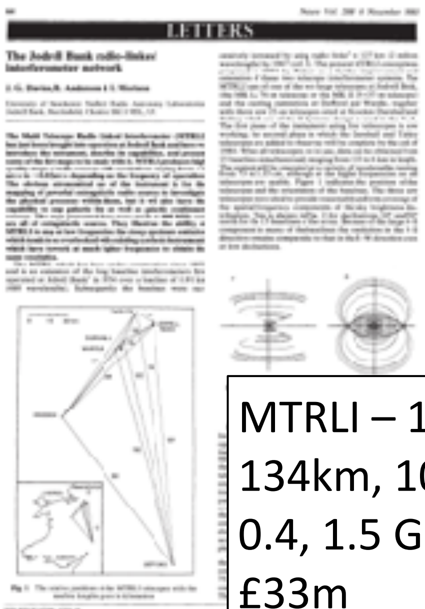
WP6: Bandwidth

WP7: Defford

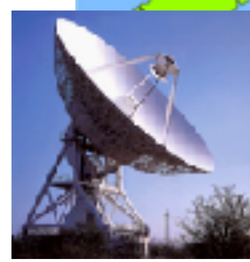
e-MERLIN Upgrades

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

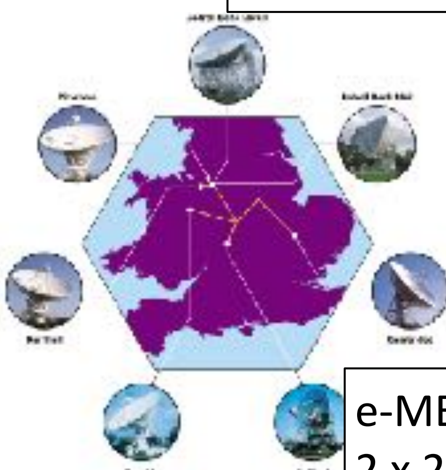
Transformation



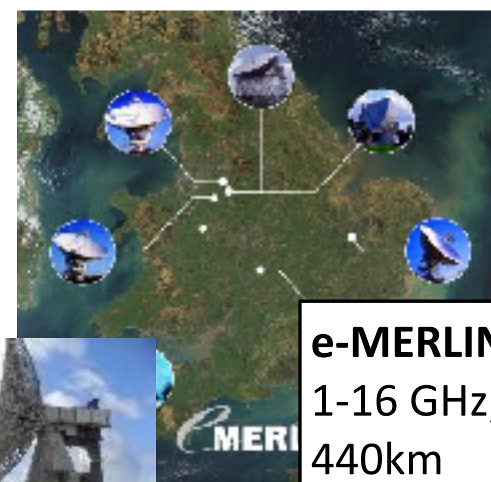
MTRLI – 1980
134km, 10 MHz
0.4, 1.5 GHz
£33m



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



e-MERLIN – 2009
2 x 2 GHz
£11m

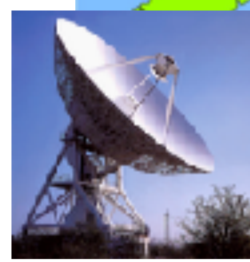


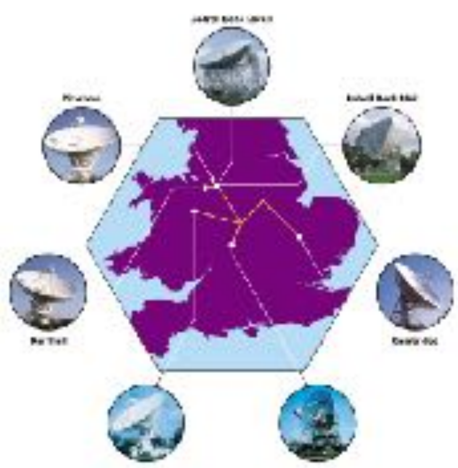
e-MERLIN – 2018
1-16 GHz; 2x8 GHz b/w
440km
£10m

Transformation


LETTERS

The Jodrell Bank radio-linked interferometer network





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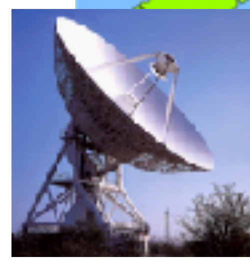
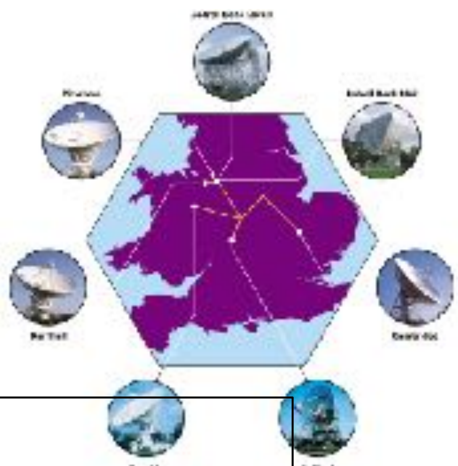
Transformation



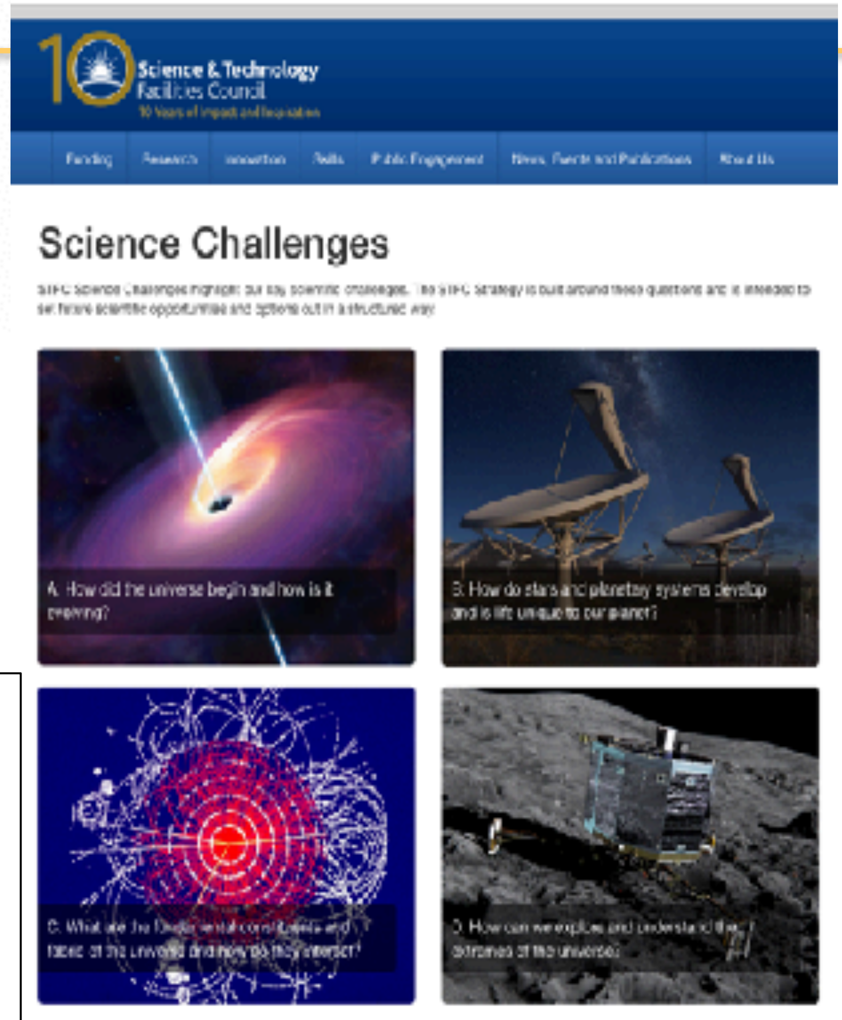
2000-2008:
£3.2m/yr
+ £120k LT↓



2009-2017: £2.0m/yr
£0k Lovell

2018: £2.3m/yr
+£400k Lovell

STFC Science Challenges



A: The Universe…
A1: early universe
A2: first structures
A3: roles of DM & DE
A4: first stars, gals, BH
A5:galaxy evolution
A6:stellar formation

B: stars & planets
B1: planetary systems
B2: influence of Sun
B3: life elsewhere

C: Fundamental physics
C1: particles
C2: space-time
C3: unified framework
C4: dark matter
C5: dark energy
C6: nuclear/hadrons
C7:matter-antimatter

D: Extreme physics
D1: physics in extremes
D2: high energies, GW
D3: ultra-compact obj

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e-MERLIN

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

Science Case:
Planet-forming disks

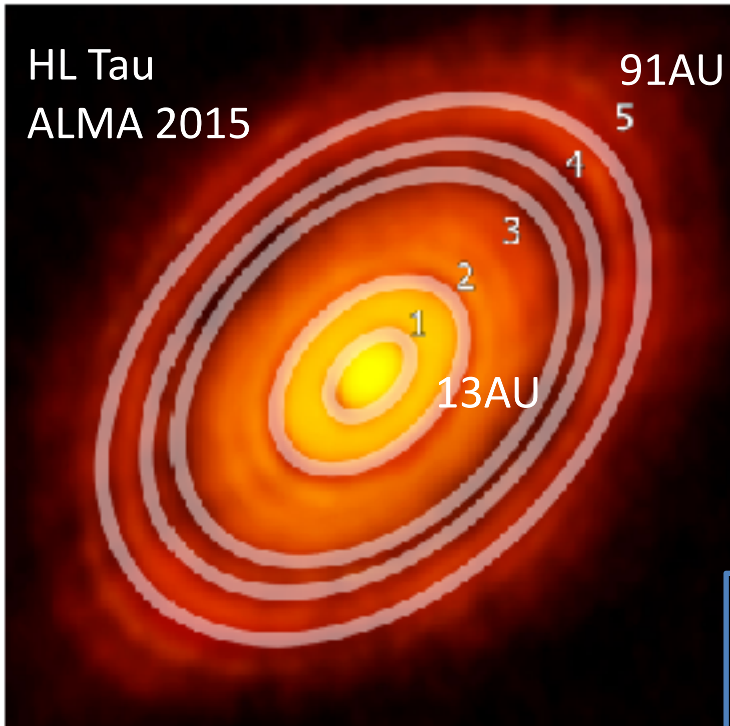


Figure 1. ALMA's 233 GHz continuum image of HL Tau (http://www.eso.org/public/news/eso1436), with white ellipses overlaid on the five most prominent dark bands and labeled 1 to 5. For scale, gap 5 lies ~ 91 AU from the central star.

Inner 10AU (Saturn) opaque to sub-mm

Need cm wavelengths

(1) see through dust &

(2) detect pebble material

At 1AU need >~ 3 cm

>200km baselines to reach inner (terrestrial) orbits

Jup: 40 mas, Mars 12 mas

→ e-MERLIN at 10 GHz (3cm) is ideal:

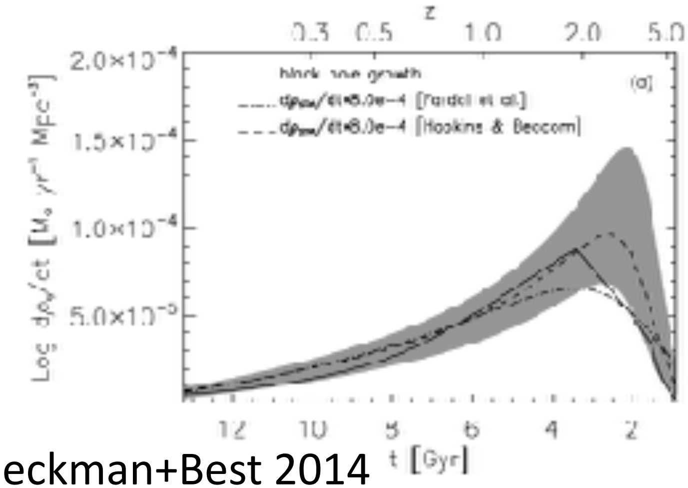
1 uJy/b = 15 K (τ=0.15 T=100K)

$S \sim \nu^{\alpha}$ $\alpha > 2$; win even for surf. brightness

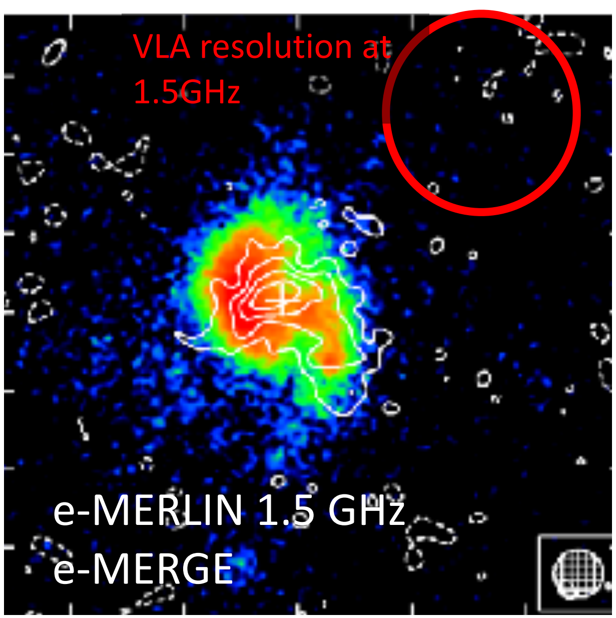
20 mas resolution

use 5 GHz, 22 GHz to untangle emission from thermal jets, disk winds, synchrotron

Science Case:
Galaxy evolution



Heckman+Best 2014



- Cosmic star-formation history
- Most star-formation obscured

-> radio (SNR, HII) or sub-mm (dust)

- Radio emission is very faint, steep spectrum, and extended ~ 1”

Where does star-formation occur?
AGN? Central star-formation?

→ Need ~0.1” resolution
→ 2-4 GHz band ideal
JVLA preferred band
4 x bandwidth, less RFI
0.1” for e-M + JVLA
→ Addition of Goonhilly

Science Case:

Galaxy evolution

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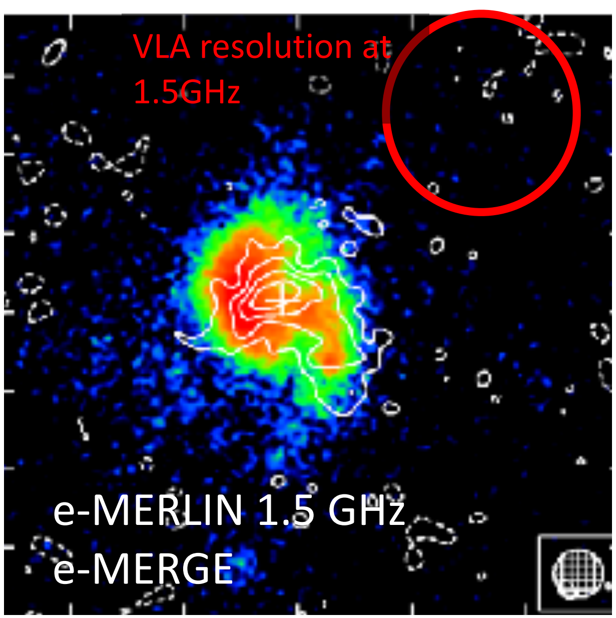

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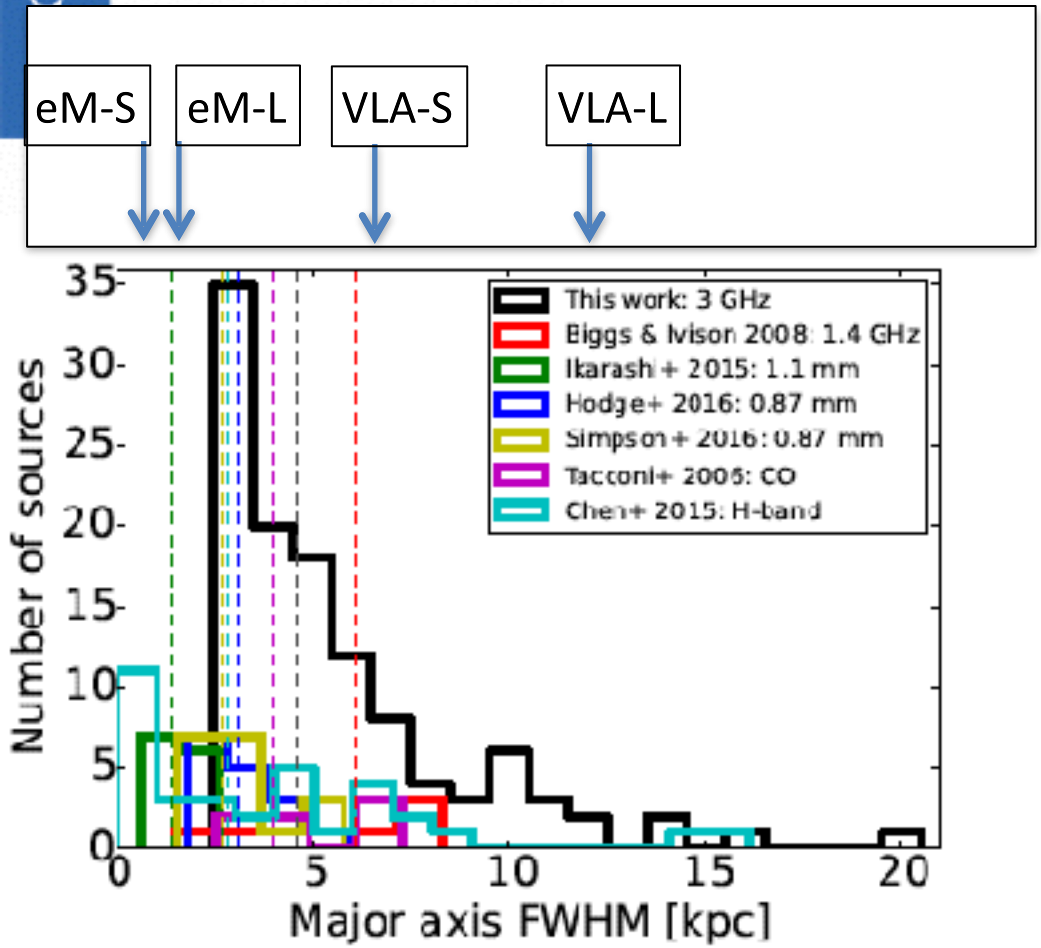
Science Case:
Galaxy evolution



ig. 9. Distributions of the SMG sizes (major axis FWHM) measured in adio, dust, CO, and stellar emissions. The black histogram shows the izes of our COSMOS ASTE/AzTEC SMGs as seen at ν_{obs} = 3 GHz.

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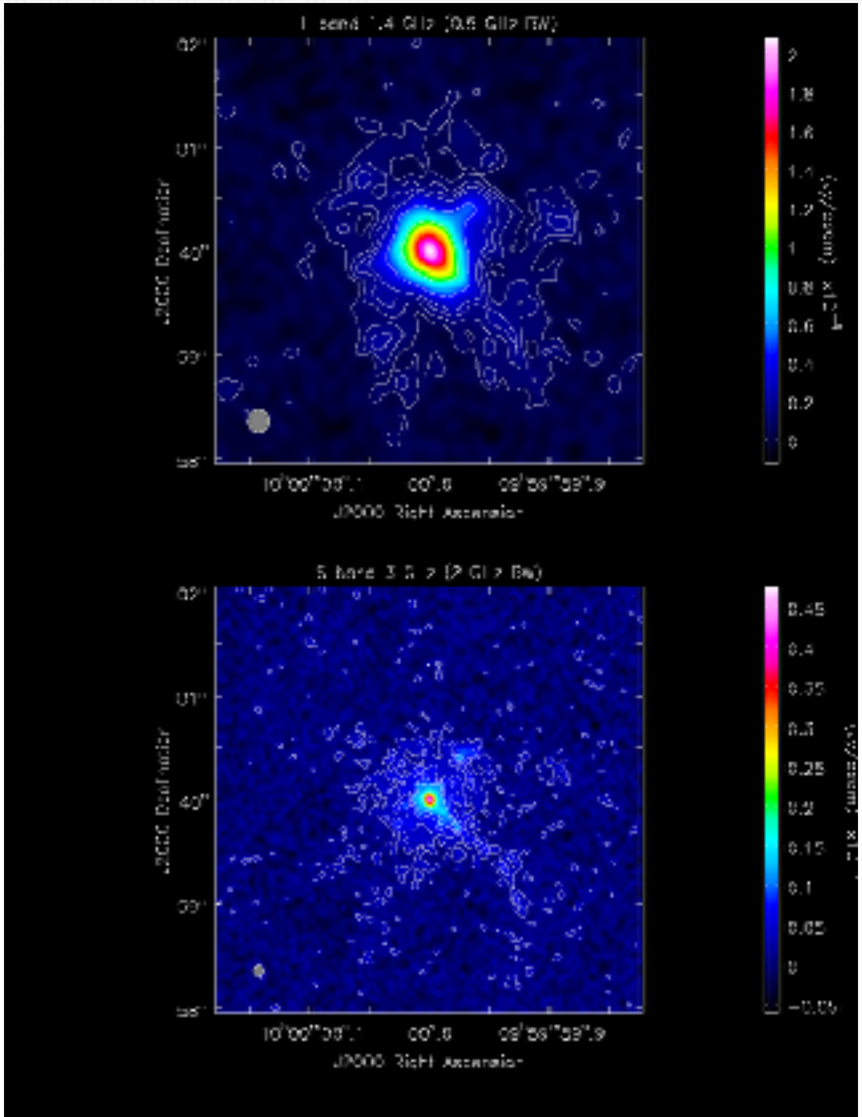
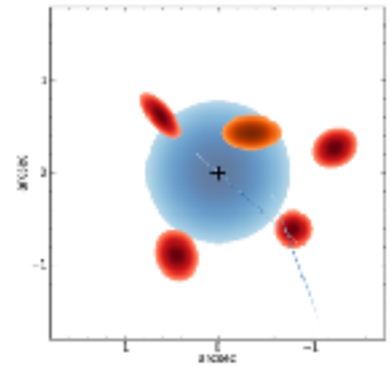
S-band (2-4 GHz) simulations

Javier Moldon (e-MERLIN/JBO)

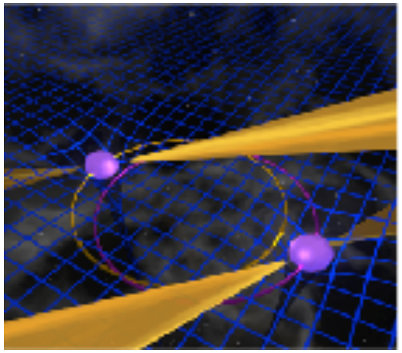




- Higher resolution
- Maintain sensivity to diffuse emission
- Distinguish & separate the components & processses:
- star-forming knots, nucleus, jet etc

Science Case:

Gravity, Gravitational Waves & Utilising Pulsar Clocks.



Key Questions

- Physics in extreme conditions
- Testing theories of gravity, detection of GW

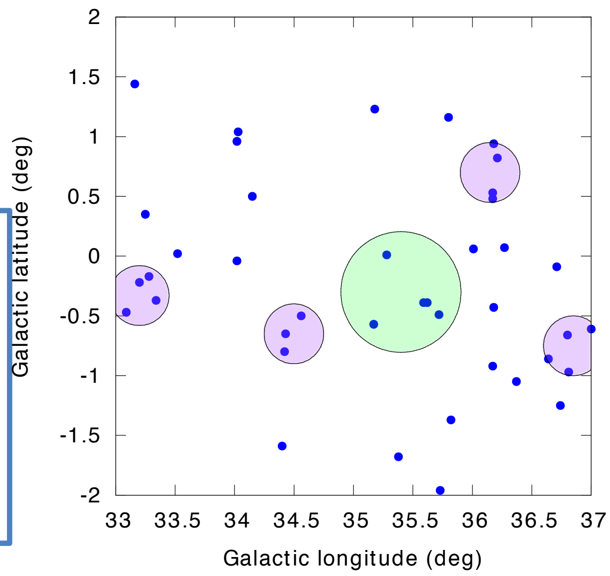
Requirements

- **Sensitivity, cadence, survey speed, accuracy**

Benefits of Lovell + e-MERLIN

- 2x sensitivity for pulsar observations
  (=Largest steerable telescopes in N Hemisphere)
- Increased sensitivity for LEAP, Pulsar Timing Arrays

Simultaneous multi-pulsar observing with e-MERLIN and/or PAF



- PAF: increased survey speed & cadence
- S-band: increased accuracy
  - Larger bandwidth
  - Reduced dispersion (λ^2) and scattering (λ^4)
  - → S-band will be band of choice for PSR timing, GW

Design & Implementation Summary

WP2: Software: P Alexander (Cambridge),A Scaife

WP3: 2-4 GHz receivers: M Jones (Oxf), S Garrington,

WP4: 8-16 GHz Rx: M Jones

WP5: LT Phased Array Feed: M Keith

WP6: Digital Upgrade: K Grainge

WP7: New dish at Defford: S Garrington

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WP2: Software

P Alexander (Cambridge) & A Scaife

- Current pipelines still a hurdle…
- Early adopter of SKA-SDP?
- Leverage large UK and international investment
- Trial SDP on real data, similar configuration to SKA1-mid
- Head-start on configuring and using SDP pipelines: train & develop UK SKA community

- Early implementation of SDP pipeline
- follow SDP development cycle
- Workshops, schools etc
- Parallel development and implementation of algorithms for e-MERLIN issues:
  - RFI recognition & flagging
  - Calibration and imaging
  - PAF + single feeds

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WP3: S-band (2-4 Rx)

S Garrington & M Jones (Oxford)

- **Science motivation**: galaxy evolution, feedback (jets), cosmology (shear), PSR timing
- **Technical motivation**:
  - 4x bandwidth, 2x resolution compared to L-band (1.5 GHz)
  - JVLA band of choice for galaxy surveys
  - Plug-in upgrade: retrofit receivers to telescopes: same downconversion, samplers,…
  - Less interference

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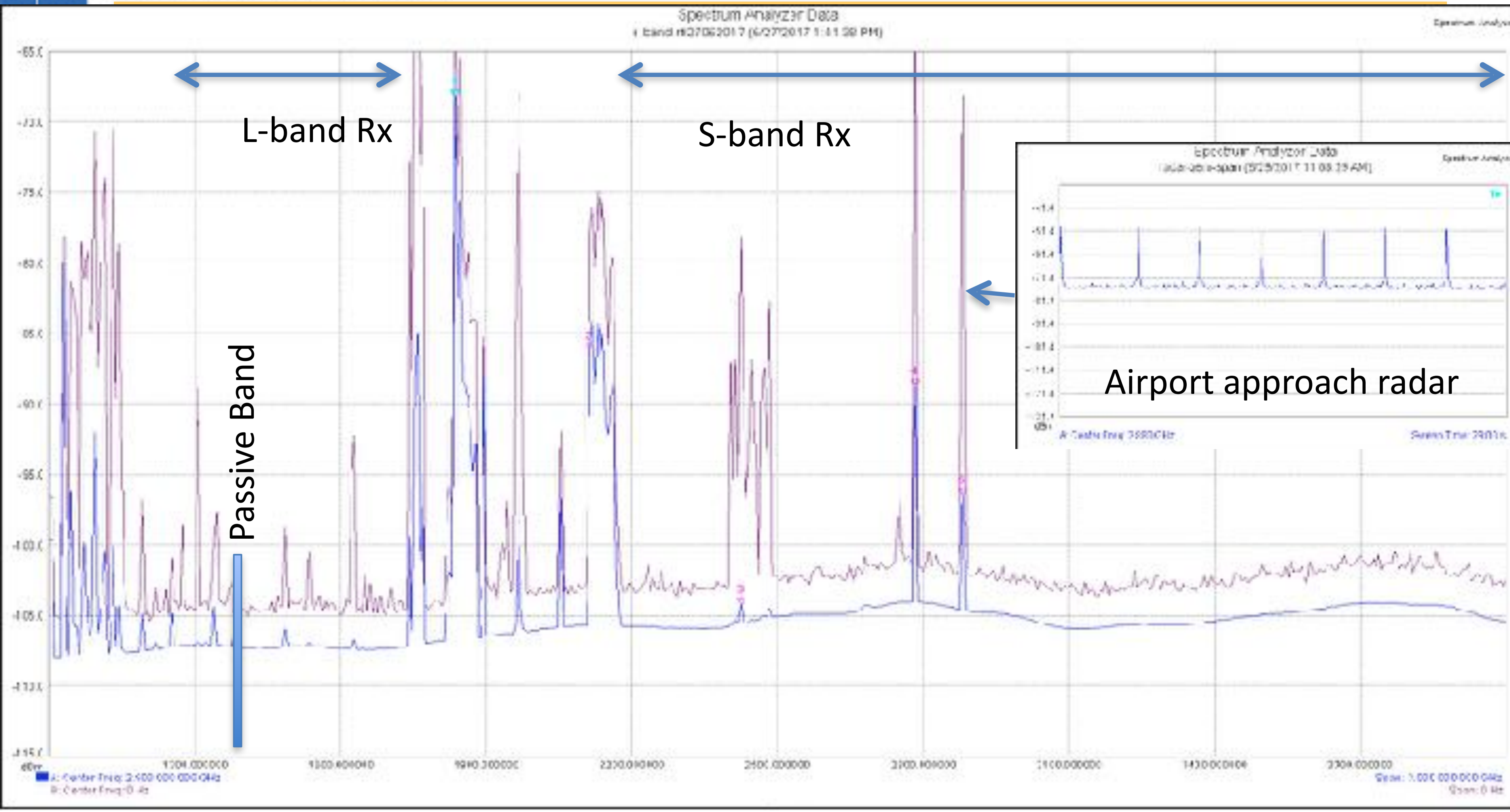
1-4 GHz Terrestrial Spectrum

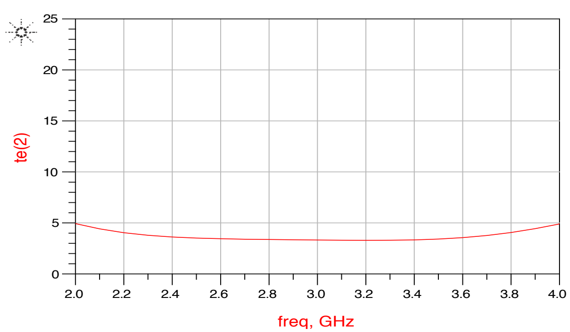


2-4 GHz Receiver Components

- Feed horns
  - Large horns for Cassegrain
  - External/internal lens?
  - Small feeds for prime (Mk2, De, LT)
- OMT
- LNA

Figure 1. S-band feed horn

Figure 2. Range testing of S-band feed horn at UATR



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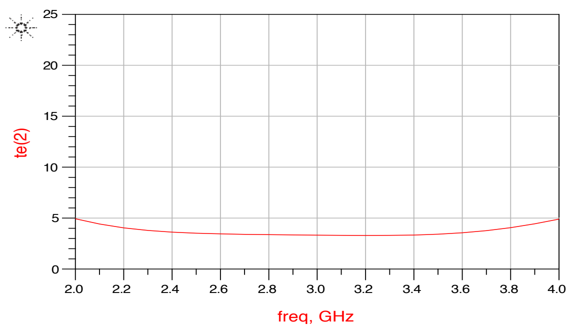

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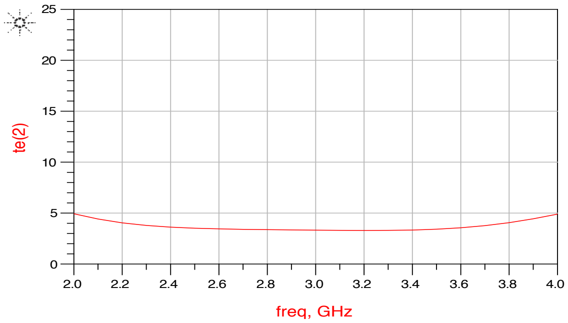

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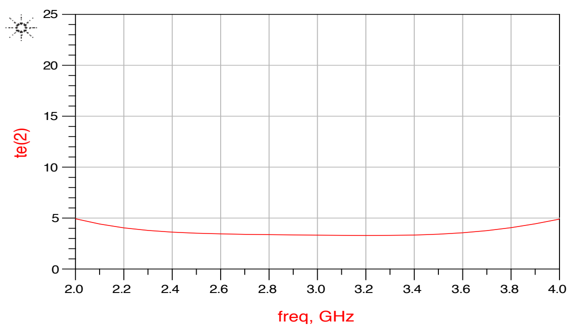

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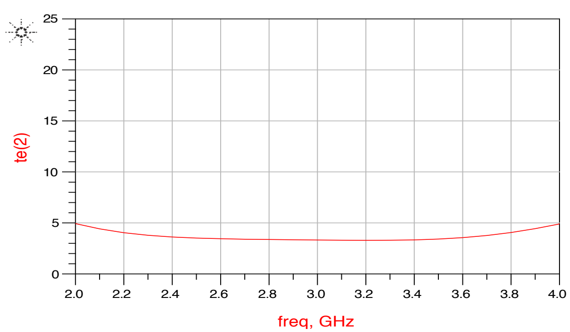
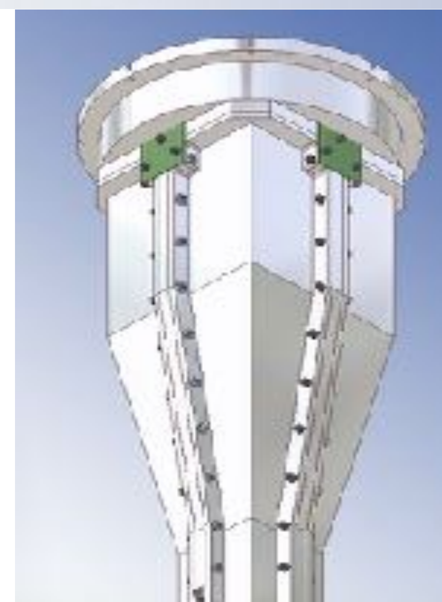


EVLA OMT Design



WP4: X-band (8-16 GHz)

M Jones (Oxford)

- Scientific Motivation:

  Few AU resolution and ~10K sensitivity for planet-forming disks

  + star-formation, low-luminosity AGN,+…

- Technical Motivation:
  - High-performance, low-cost receivers for SKA
  - Up to 8 GHz bandwidth

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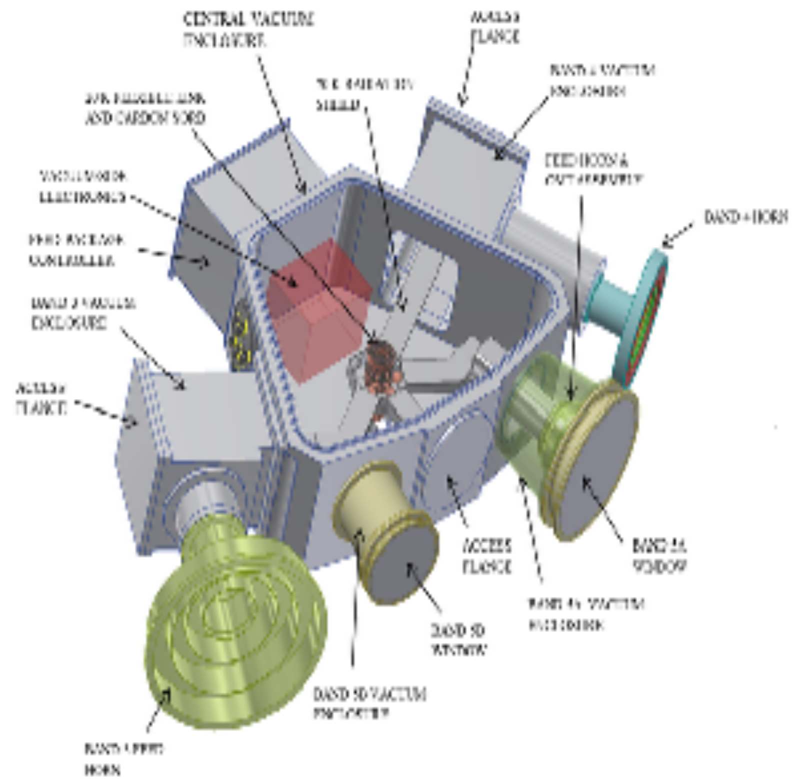
SKA1-mid receiver package

- SKA Band 3/4/5 receivers being designed at Oxford
- Provides up to 5 bands on SKA-mid antennas
  - 1.6 – 3 GHz
  - 3 – 5 GHz
  - 4.6 – 8.5 GHz. *
  - 8.3 – 15.3 GHz *
  - 15 – 24 GHz

  *first-light bands
- eMerlin X-band receivers will be much simplified version, using same electronics, LNAs etc. Feeds/OMTs rescaled to eMerlin band and cryostat simplified for single feed.



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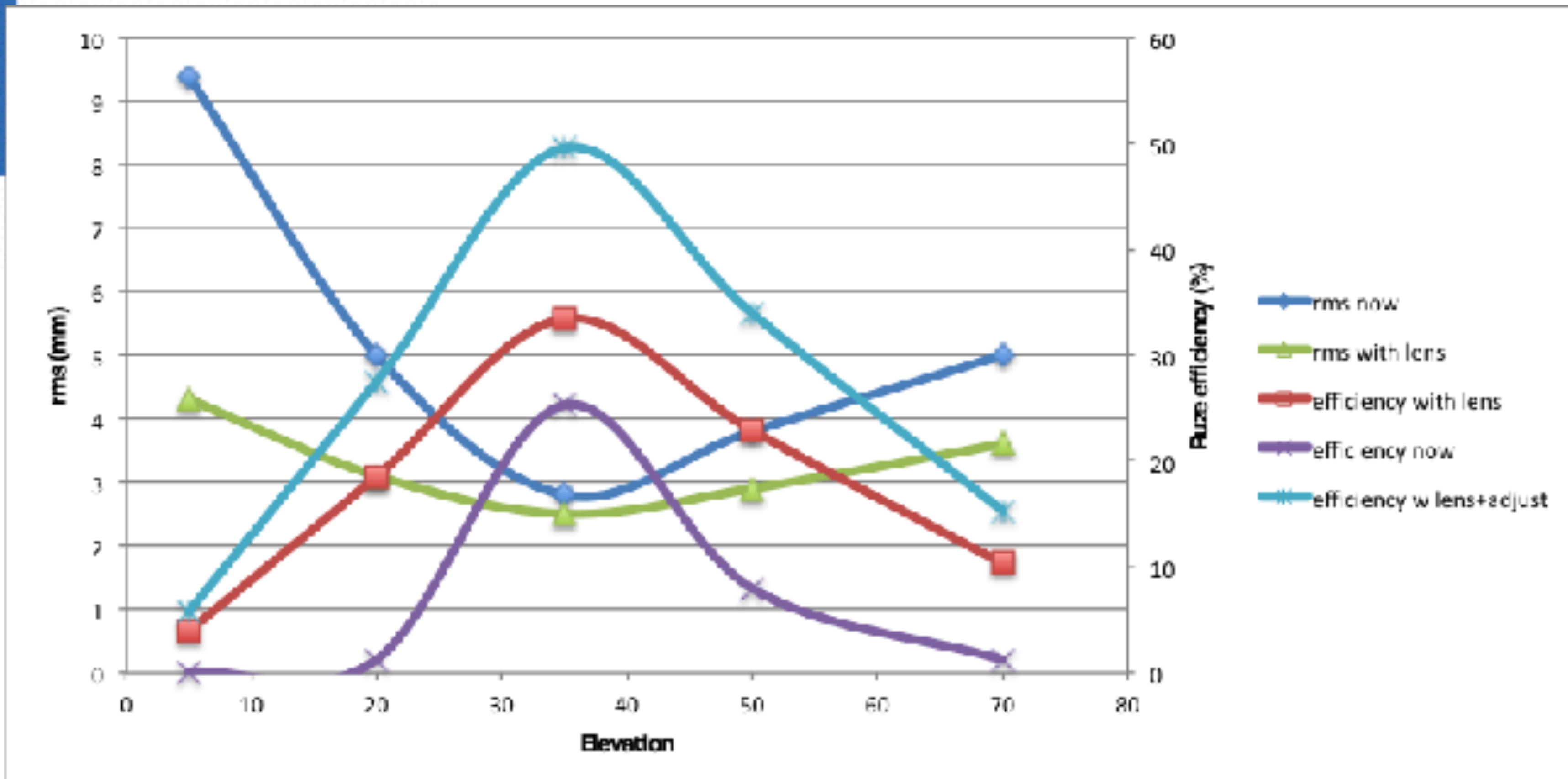
The Lovell Telescope at X-band

eMERLIN

Lovell performance at 10 GHz

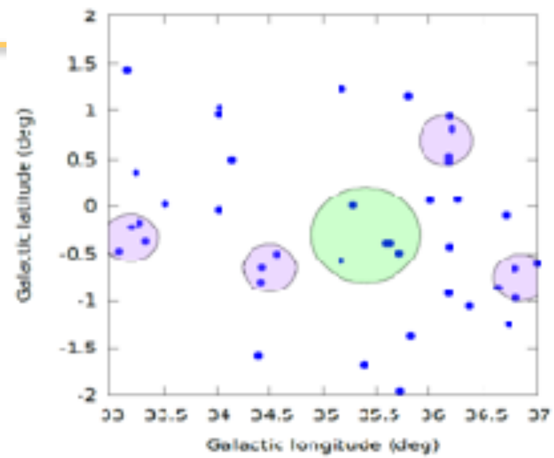


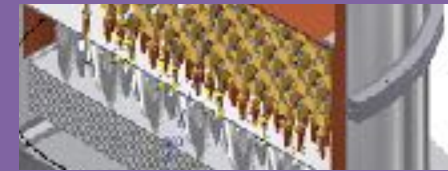
WP5: Phased array feeds

M Keith

- Science motivation
  - Survey speed at L-,S-band for galaxy evolution, weak lensing (also phase referencing)
  - Field-of-view for transients
  - Pulsar observing efficiency
  - Antenna efficiency/surface correction
- Phased project development
  - UoM purchasing ASKAP PAF 2017
    - Uncooled; ~250 MHz b/w; 2 x 96 eleme
  - STFC grant for cooled PAF R&D (2016-18)

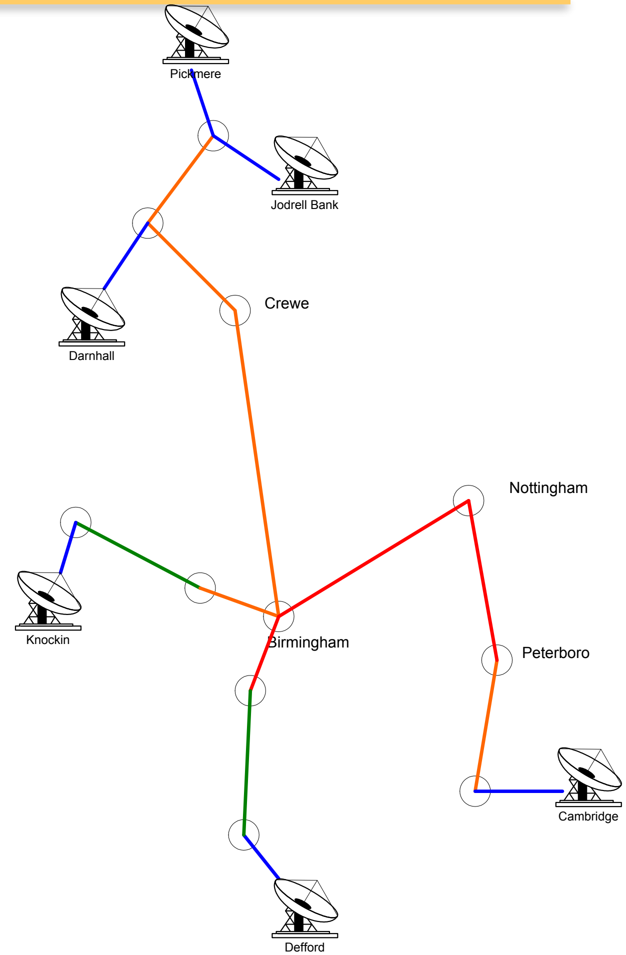
→ Cooled, broad-band L&S-band (1-4 GHz)



WP5: PAF	PHAROS	CSIRO PAF	2-4 GHz Cryo PAF
			
Frequency	4-8 GHz	1.2-1.8 GHz (plus 0.70-1.1 GHz)	2-4 GHz (plus 1.4-1.8 option)
Cooling	Cryogenic	Room temperature	Cryogenic
Project status	Testing of prototype	Integration of production system	Design and prototyping
Number of elements	220 (24 in prototype)	188	188 (~24 in prototype)
Element technology	Vivaldi	Chequerboard	TBD
Beamforming	Analogue (Upgrading to digital)	Digital CSIRO Beamformer	Digital CSIRO Beamformer
eMerlin development support requested	N/A	Interface between beamformer and eMerlin systems	Development of full-scale instrument (+same interfaces as CSIRO PAF)

WP6: Digital Upgrade

K Grainge

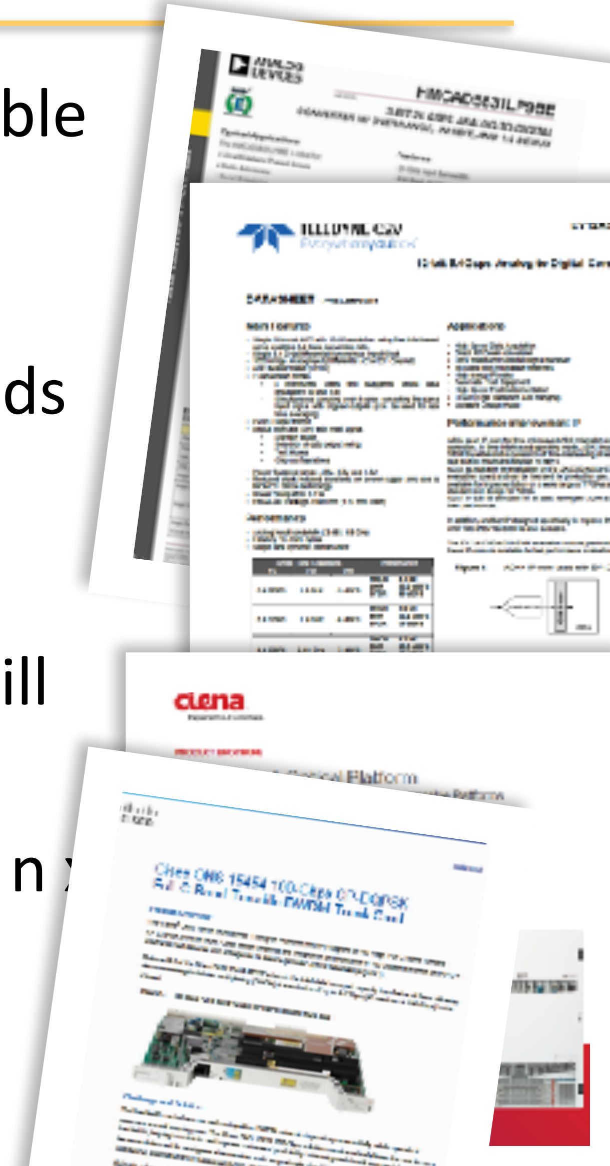


- Motivation
  - Sensitivity: Maximum bandwidth in C(4-8GHz) and X(8-16GHz) bands

    Currently 2 x 2 GHz
  - Upgradeable SKA technologies
    - 100 Gb/s links, standard network, flexible correlator/beamformer
- Project elements
  - Data acquistion (samplers)
  - Data Links (optical network)
  - Correlator

WP6: Digital Upgrade
Data acquisition & links

- Range of 5-26 Gs/s digitisers now available (e2v, TI, Analog Devices)
  - JESD204 Standard interfacing to FPGA
- Options of direct sampling for L,C,S-bands & 4,8 GHz IF for X (&K)
- DAQ boards in design by Oxford/AASL
- 100 Gb/s transmission now standard; will be used for SKA
- Convert existing network to n
  100 Gb/s ethernet



WP6: Digital Upgrade Correlator

- Last generation of big ASIC correlators
- Range of new options
  - FPGA, GPU, CPU
- Expect to use hybrid

  FPGA -> GPU cluster

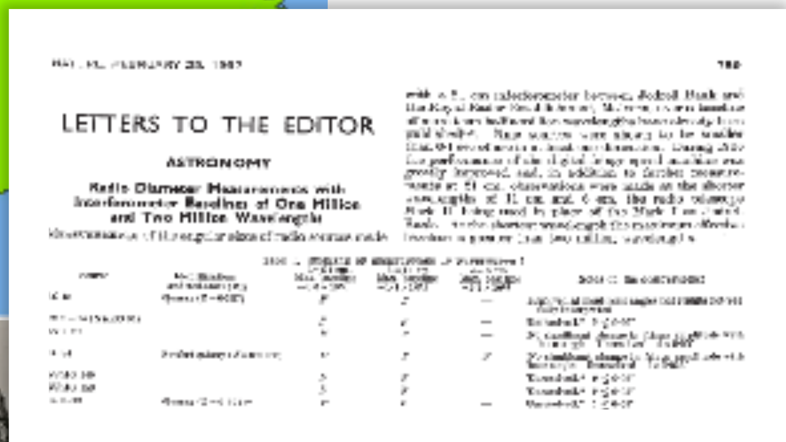
  Re-use Wilkes Cluster

WP7: Defford

S Garrington

WP7: Defford

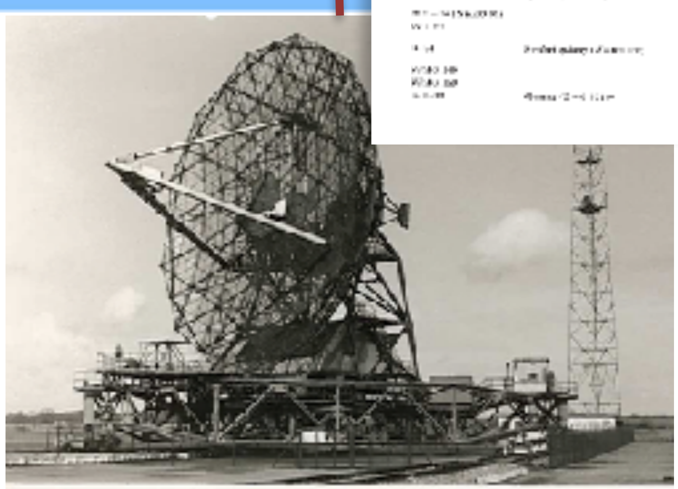
S Garrington



LETTERS TO THE EDITOR

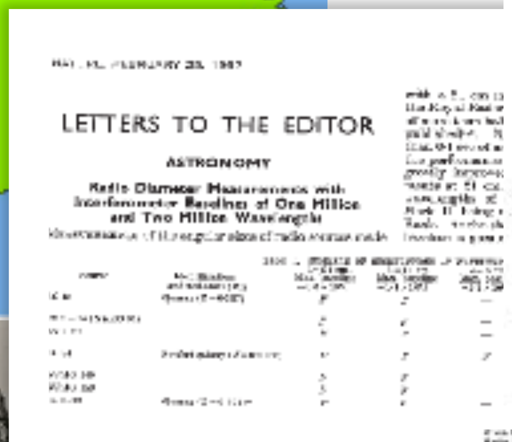
ASTRONOMY

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



WP7: Defford

S Garrington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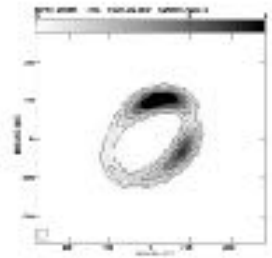

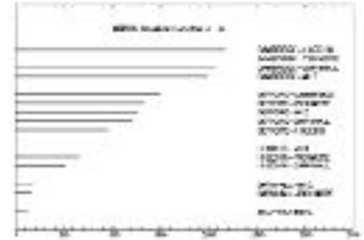

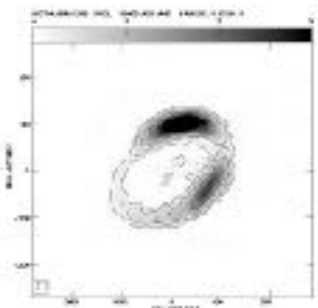

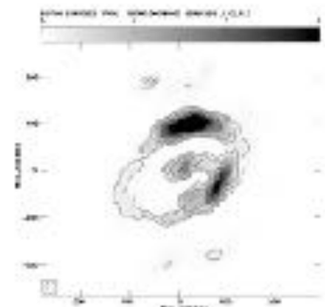

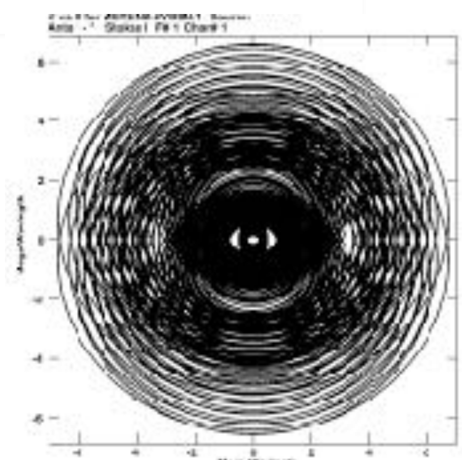

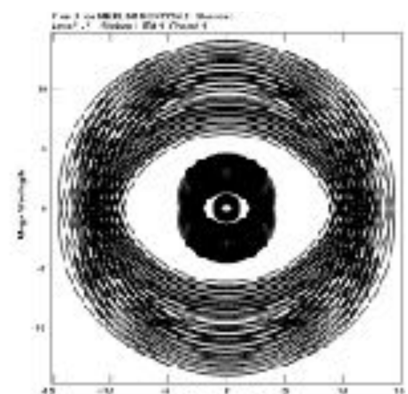

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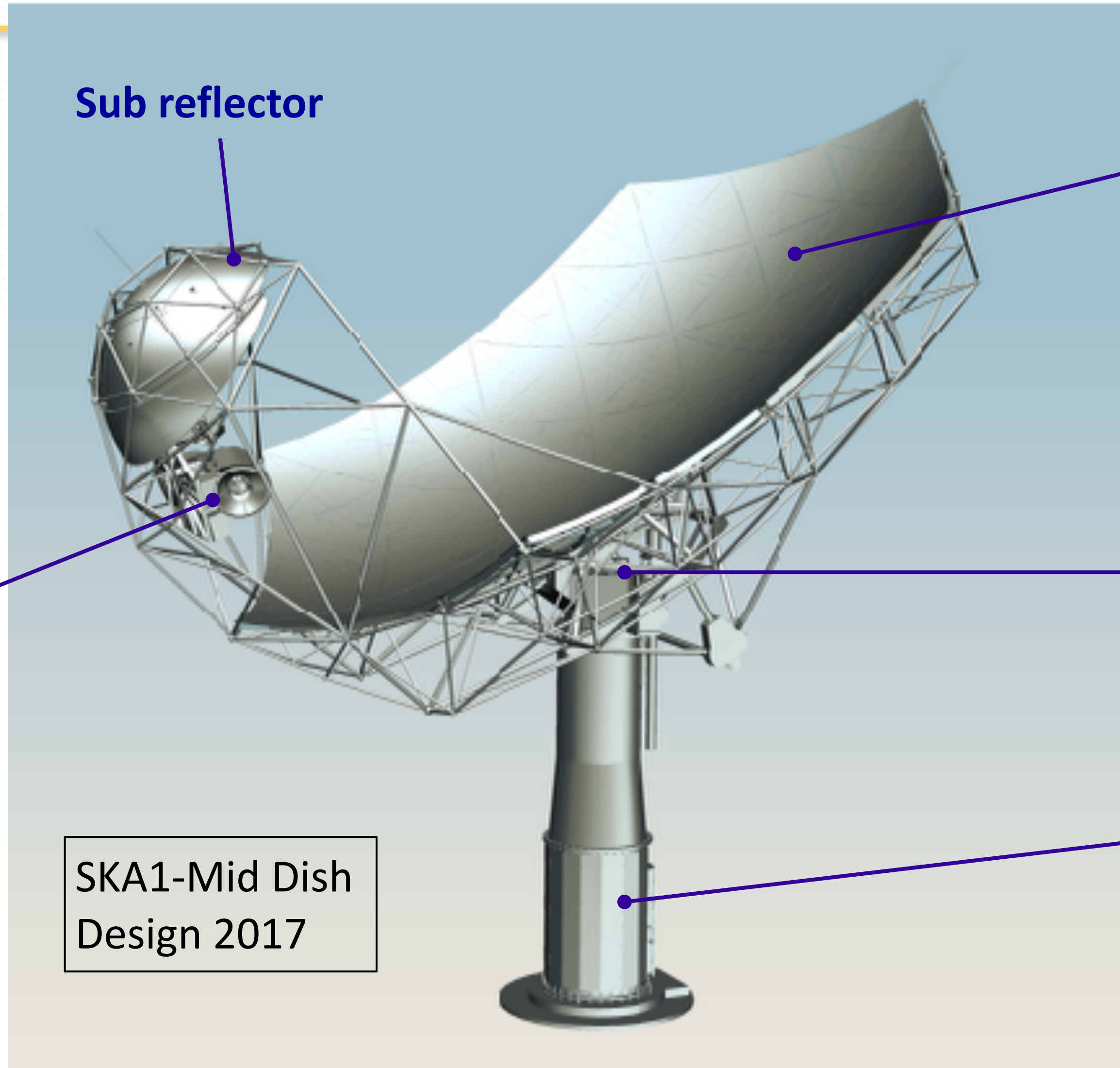
WP7: New dish at Defford

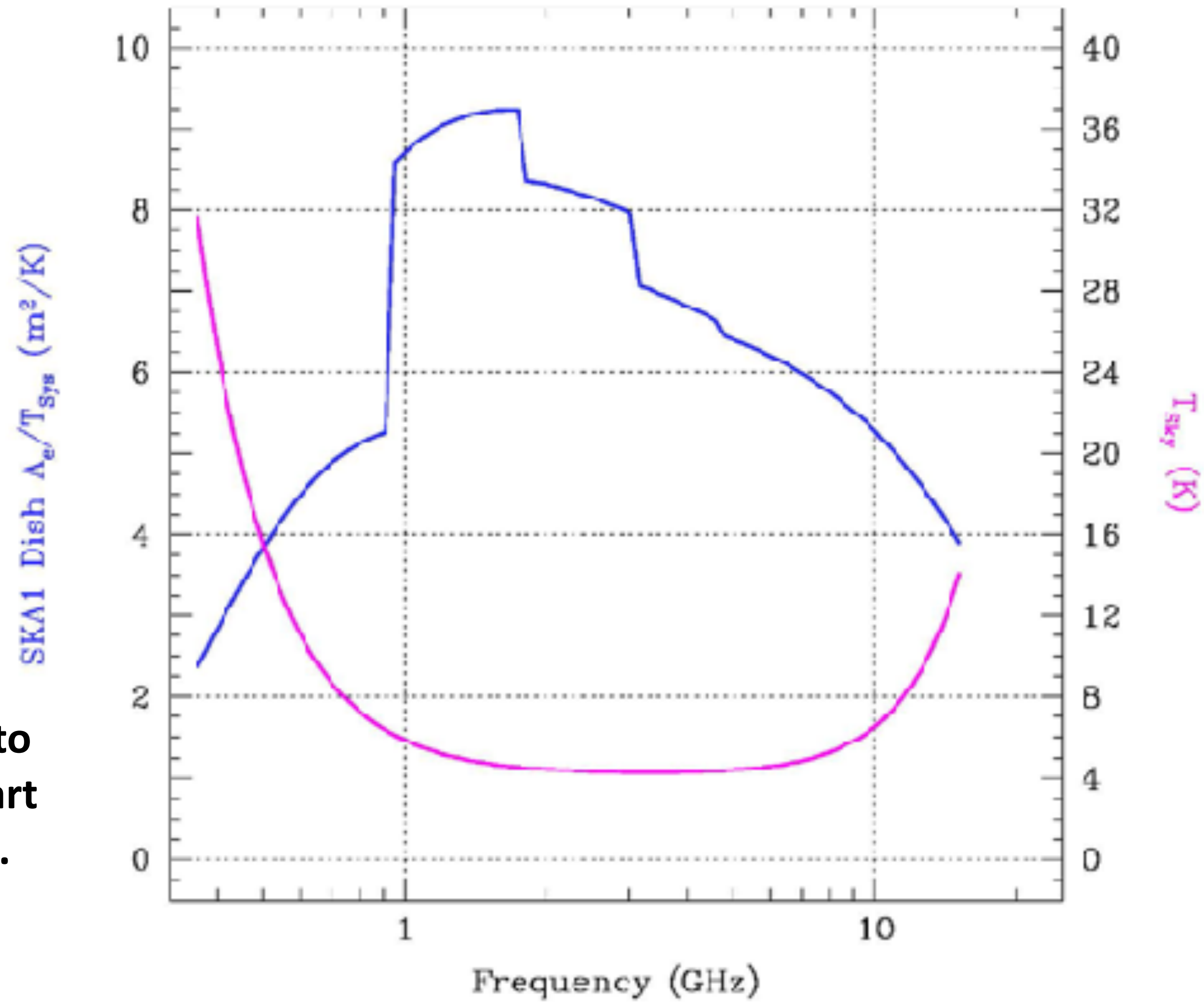


SKA1-mid Dish performance

Single Pixel Feed Band

- 1: 350 -1050 MHz
- 2: 950 -1760 MHz
- 3: 1.65 -3.05 GHz
- 4: 2.8 -5.2 GHz
- 5a: 4.6 - 8.5 GHz
- 5b: 8.3 – 15.3Ghz
- 5c: 14.8-24Ghz

Bands 3, 4 and 5c, are not to be fitted as they are not part of SKA1 initial deployment.



Work Package Costs

WP	Cost (to RC)	Benefits
2: Software	£1.5m	**Science throughput**, community engagement **Impact: s/w development**
3. S-band (2-4 GHz)	£1.0m	**Science: galaxy evolution, PSR timing, AGN feedback**
4. X-band (8-16 GHz)	£1.2m	**Science: planet & starformation, compact objects,…**
5. PAF	£2.3m	**Science: galaxy surveys, PSR, weak lensing (DM, DE)** **Impact: SKA technology**
6. Digital upgrade	£1.8m	**Science: sensitivity for planet formation etc** **Impact: SKA technology**
7. New Defford tel.	£1.7m	**Science: imaging quality at C,X-band (stars & planets)** **Impact: SKA technology**
8. Management	£0.5m	**Project management** **Impact: industrial engagement**

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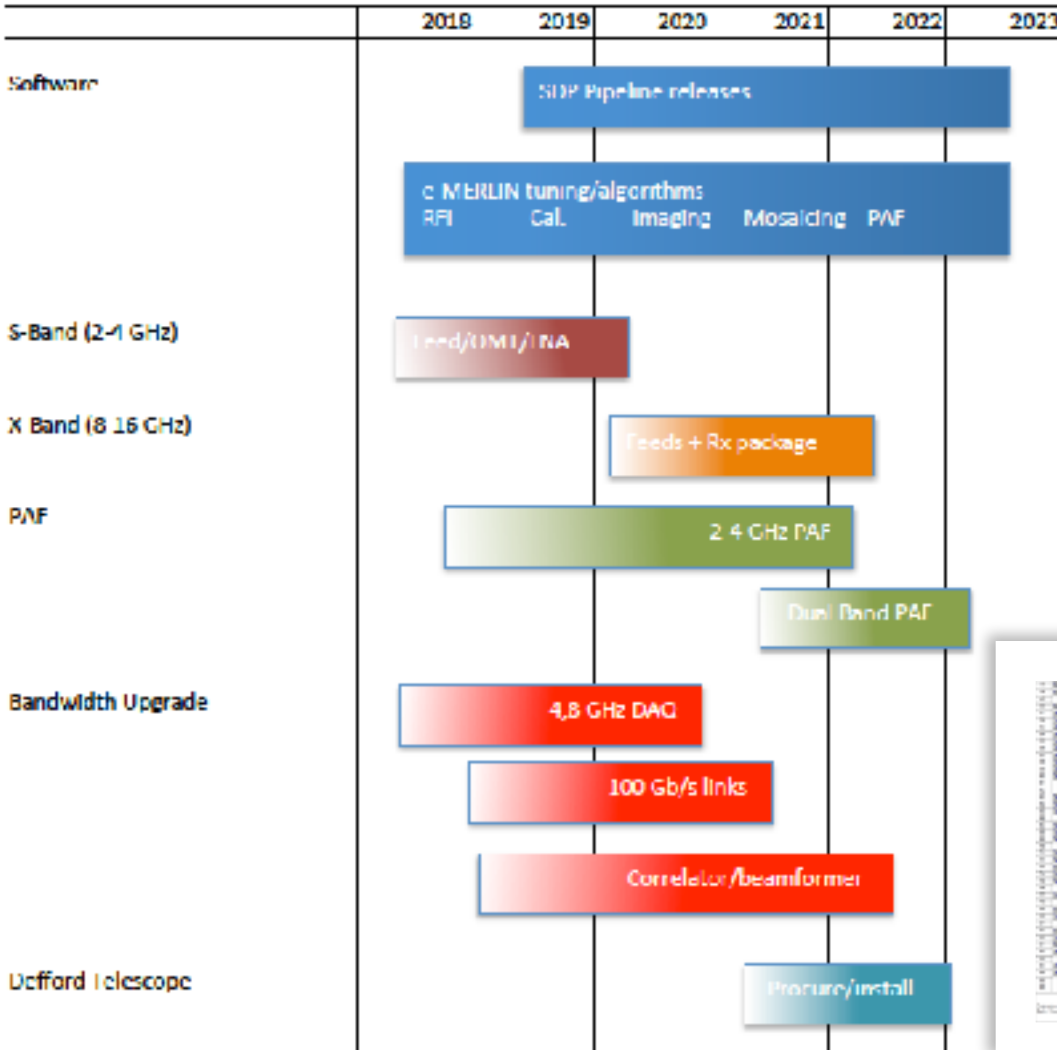
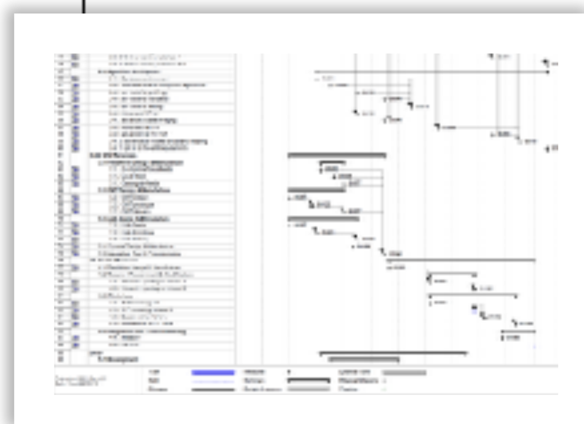
Schedule





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