LAMBDA: Demonstrating Low-Frequency VLBI in the Southern Hemisphere for SKA-Low

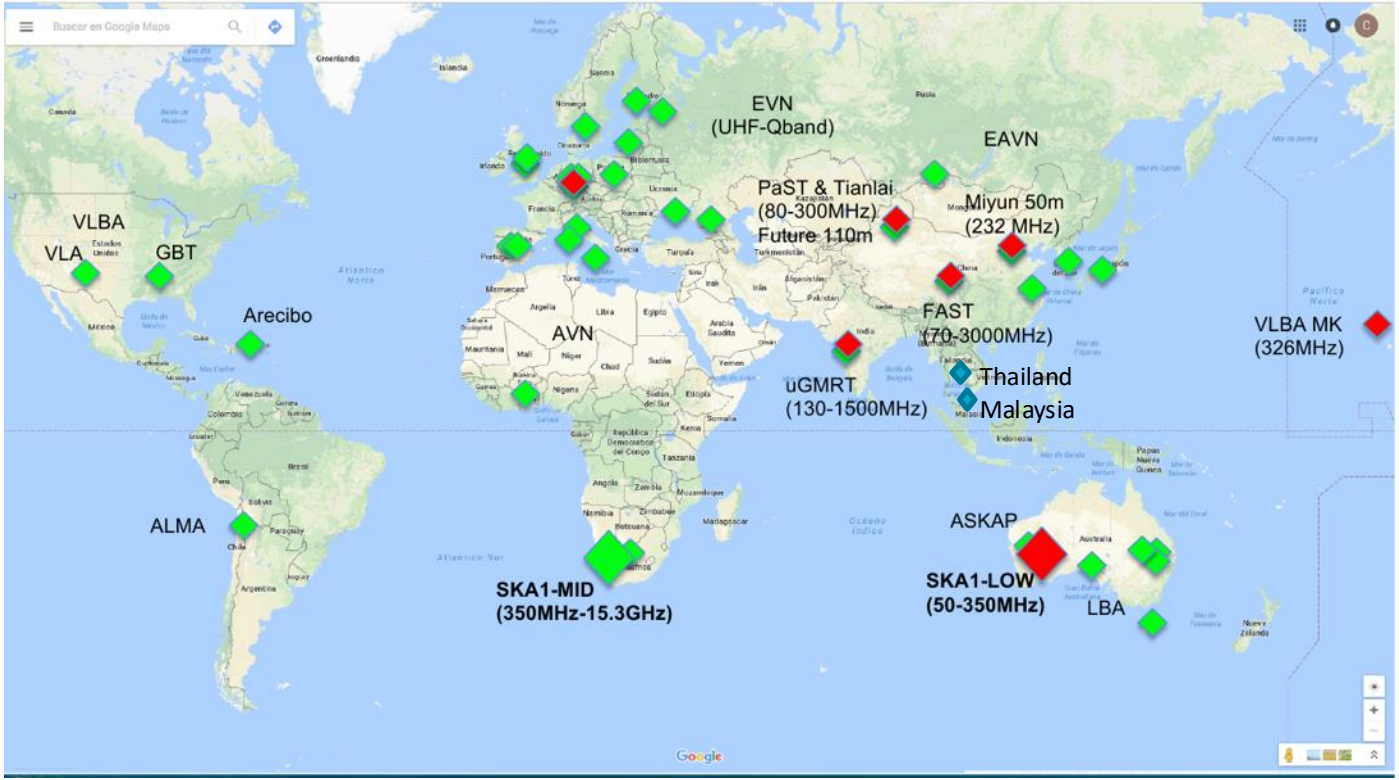
Tessa Vernstrom|Colearnium

Australia's National Science Agency

I would like to begin by acknowledging the Traditional Owners of the land that of the telescopes, and pay my respect to their Elders past and present.

‘Eternal Wisdom, Infinite Innovation’
artwork by Rachael Sarra, working with Gilimbaa.

SKA-VLBI Potential Elements



Green = SKA-Mid. Red = SKA-Low. Too few and not enough short baselines!

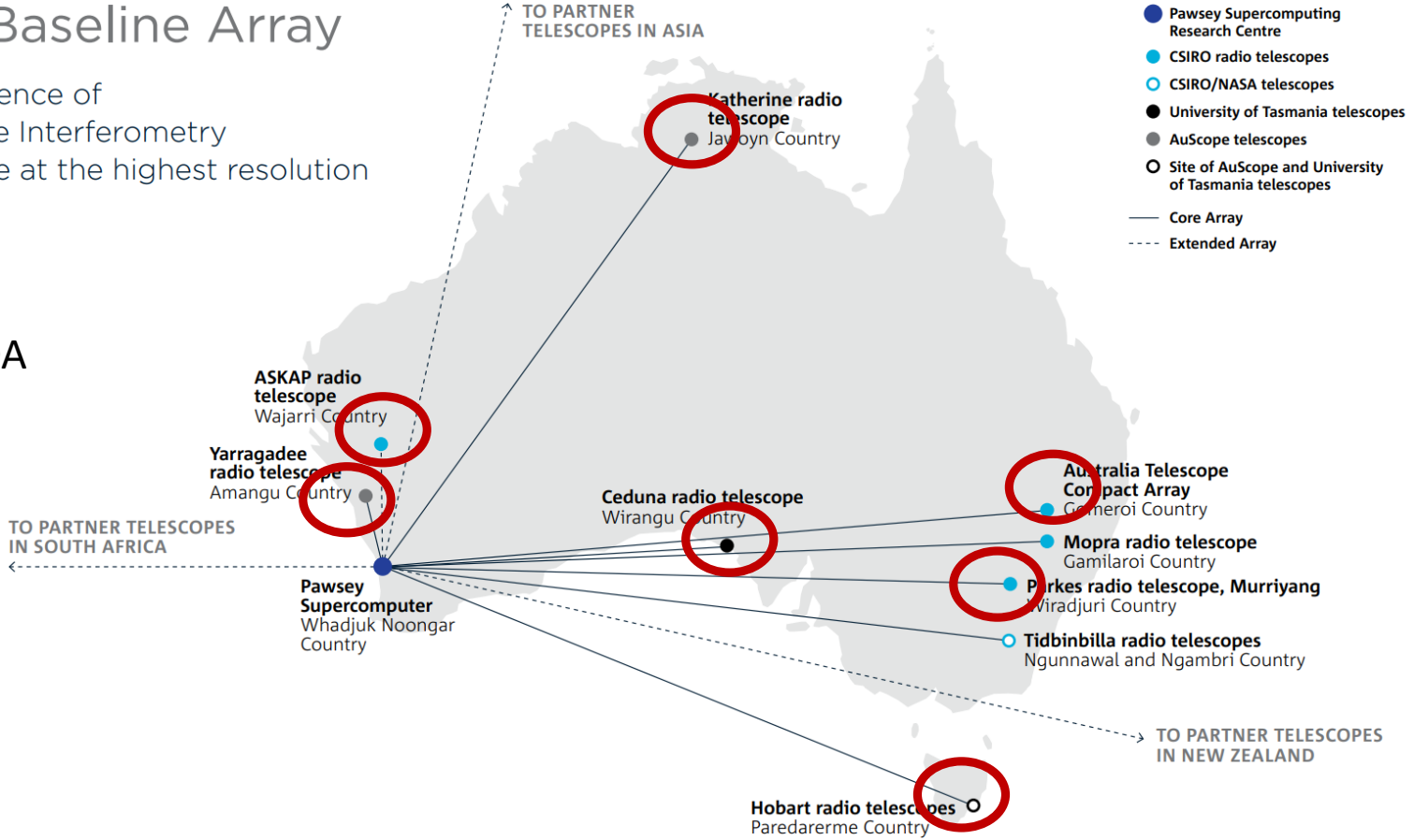
LAMBDA – Low-frequency Australian Megametre Baseline Demonstrator Array

- Goal: Demonstrate Feasibility of Long Baseline Science with SKA-Low
  - Provide evidence and motivation for SKAO to extend their baselines in next phase
- Low frequency antennas - SKALA
  - 256 dual polarization antennas
  - SKA-Low frequency range 50-350MHz
  - Locate at existing LBA observatories (or CSIRO sites)
  - Saves on site costs (power, network etc)
- Develop new backend – testbed for future SKA-Low upgrades
- Allows for commissioning of SKA-Low VLBI
- Not currently scoped as national facility

The Long Baseline Array

Harnessing the science of
Very Long Baseline Interferometry
to see our Universe at the highest resolution

Possible LAMBDA station sites



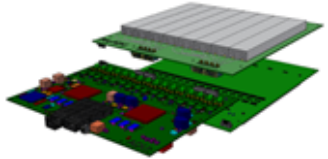
Approximate baseline distances (km)

	Ceduna	Hobart	Katherine	Narrabri	Parkes	MWA	SKA Low	Yarragadee	Warkworth, NZ
Ceduna		1708	1945	1512	1364	1759	1745	1798	3773
Hobart	1708		3475	1399	1090	3307	3291	3246	2430
Katherine	1945	3475		2509	2629	2111	2111	2373	4870
Narrabri	1512	1399	2509		322	3234	3221	3302	2424
Parkes	1364	1090	2629	322		3120	3106	3160	2440
MWA	1759	3307	2111	3234	3120		16	290	5528
SKA Low	1745	3291	2111	3221	3106	16		283	5514
Yarragadee	1798	3246	2373	3302	3160	290	283		5533
Warkworth, NZ	3773	2430	4870	2424	2440	5528	5514	5533	

Current Rollout Plan (subject to change):

- Narrabri
- Parkes
- Ceduna
- Yarragadee

Multi Stage λ Development



#0 → RF over Fibre → ADC → Filterbank (FPGA) → Station Beamformer → Network Switch → Correlator

#1 → ADC → Filterbank (Alveo) → Network Switch

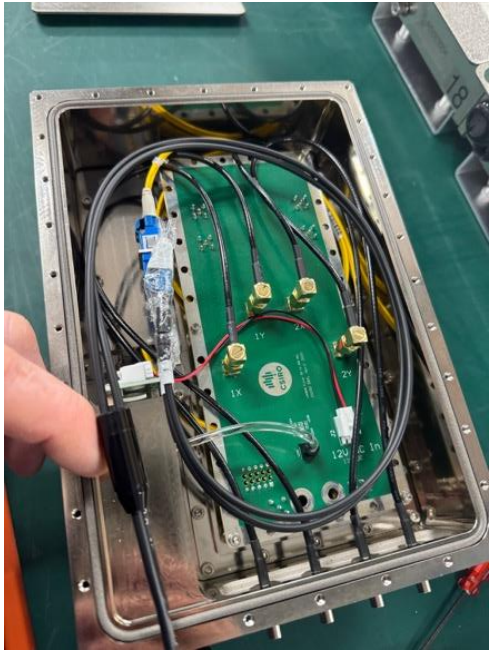
#2 → ADC → Filterbank (RFSoc) → Network Switch

#3 → ADC → Filterbank (ASIC) → Network Switch

Network Switch → Station Beamformer, Correlator, All-sky imager, etc.

λ Phase 1

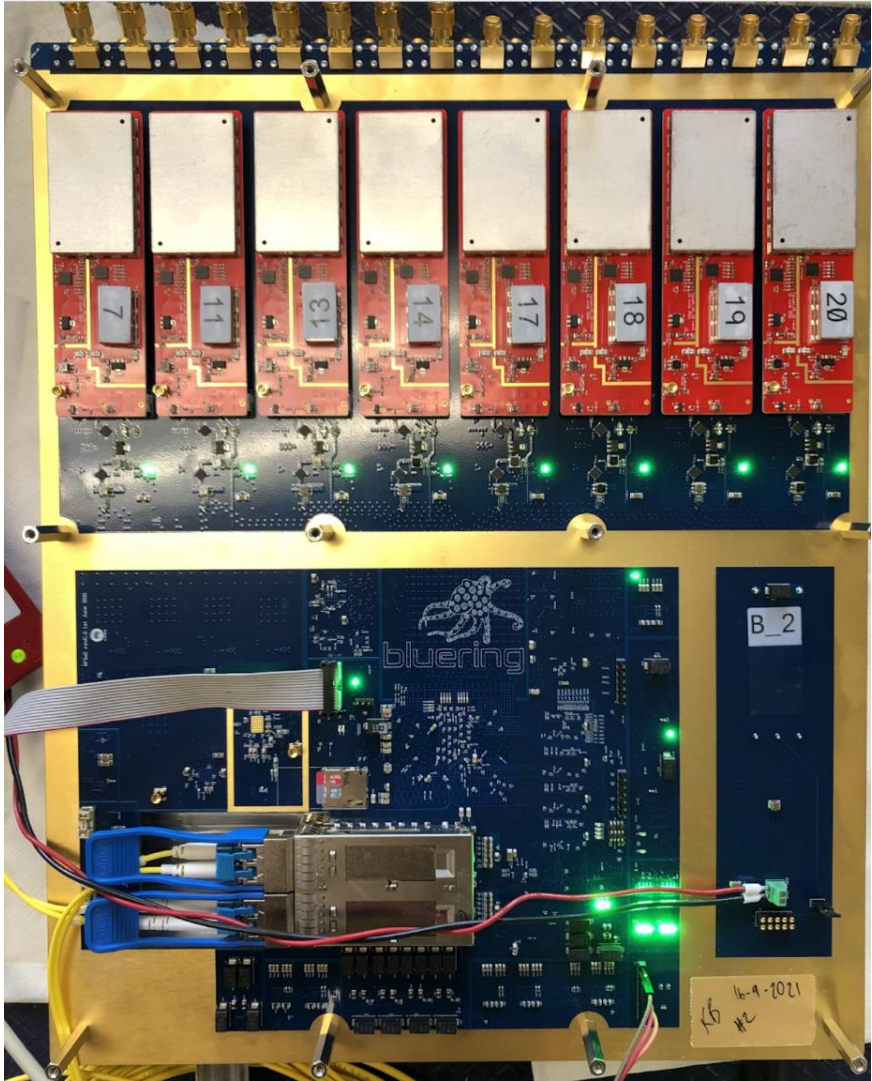
- 4 channel custom ADC module at antenna
  - JESD output
- Alveo U45N processing
  - Receive signals via PCIe interface
- Filterbank output via 2x100 GbE



λ Phase 2

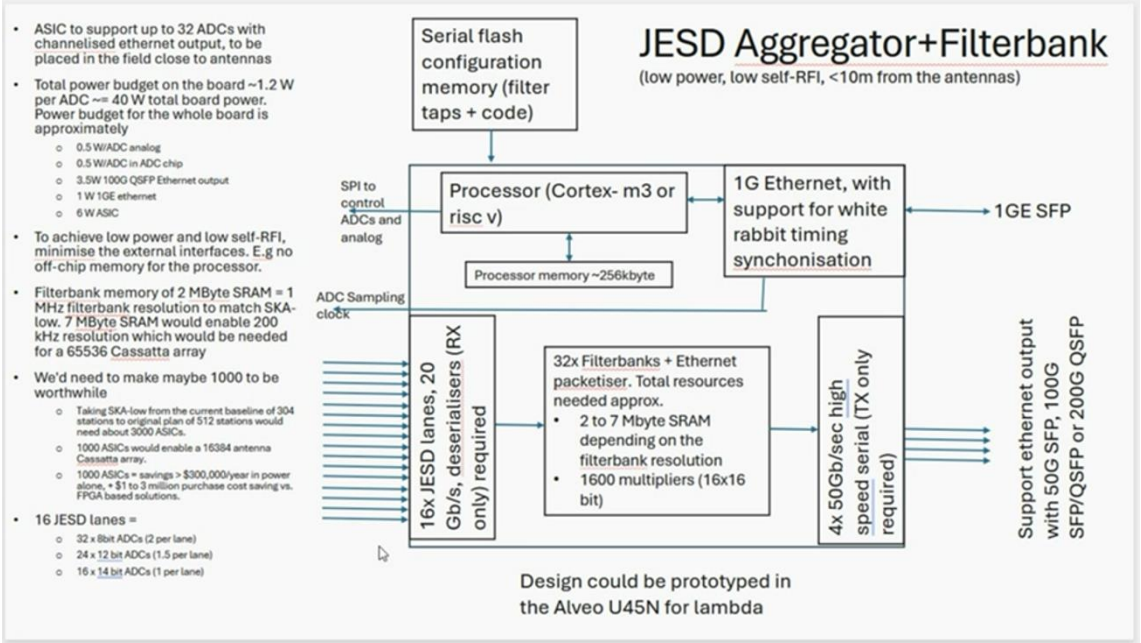
- 16 channel Xinlinx (AMD) RFSoc
  - “Bluering”
- 2x 100 GbE output
- < 1/3 power
- ~1/3 cost
- ½ fibres

- Also designing new LNA for higher noise environments



λ Phase 3

- ASIC design?
- Long lead time, large investment, high risk….

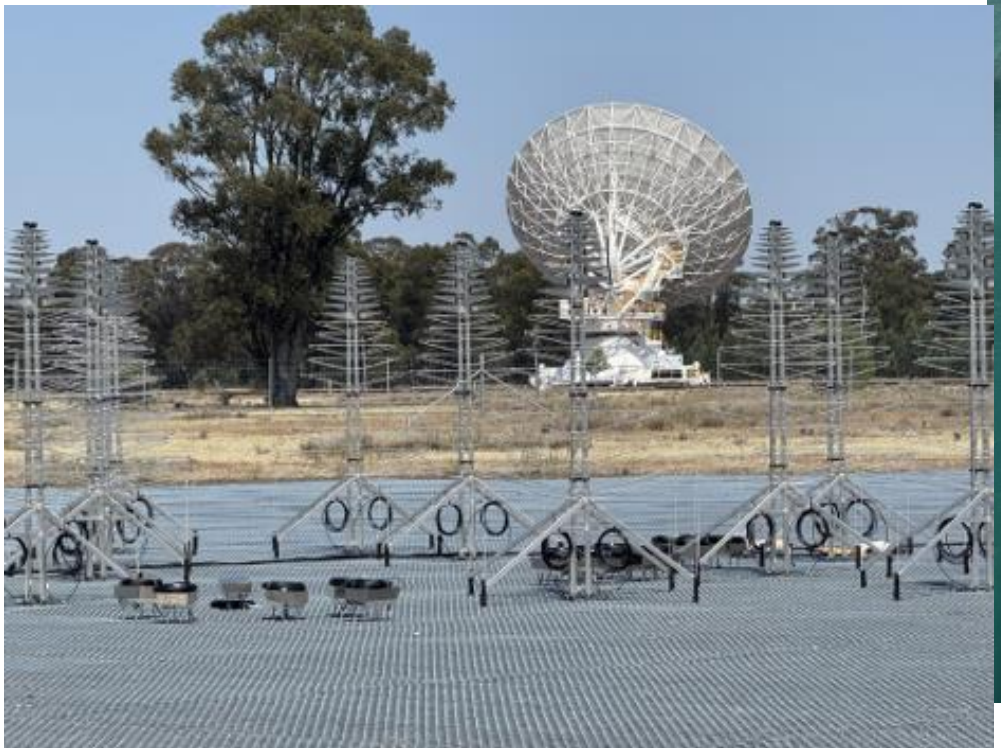


λ Backend

- Meant to be modular and scalable
  - Used with different antennas
  - Different frequencies
  - Optimising for lower power and for use in higher noise environments

Status

- Currently Deploying 36 antennas at Narrabri
  - Test signal chain before deploying full station



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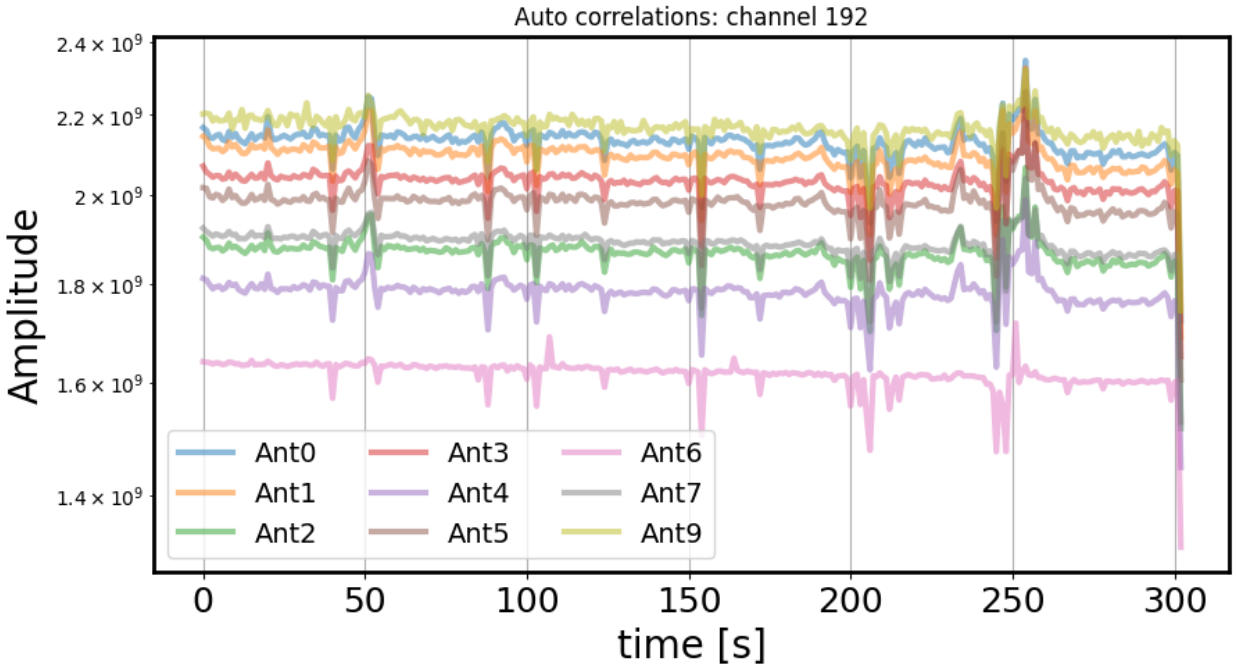
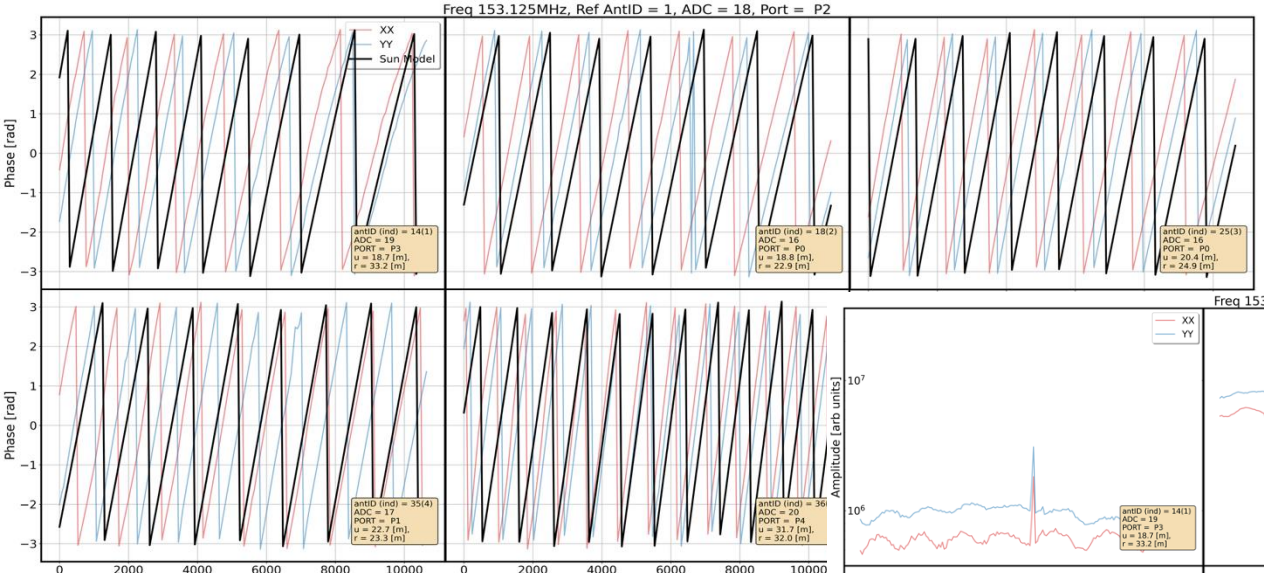
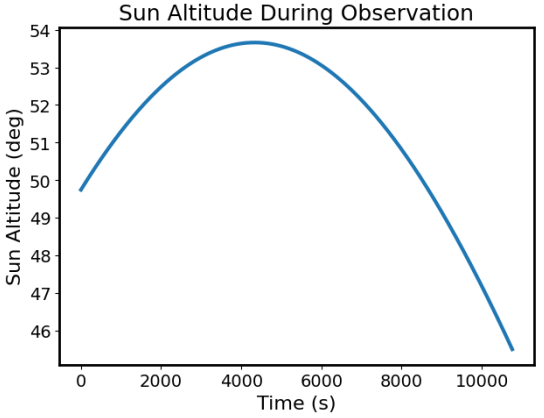
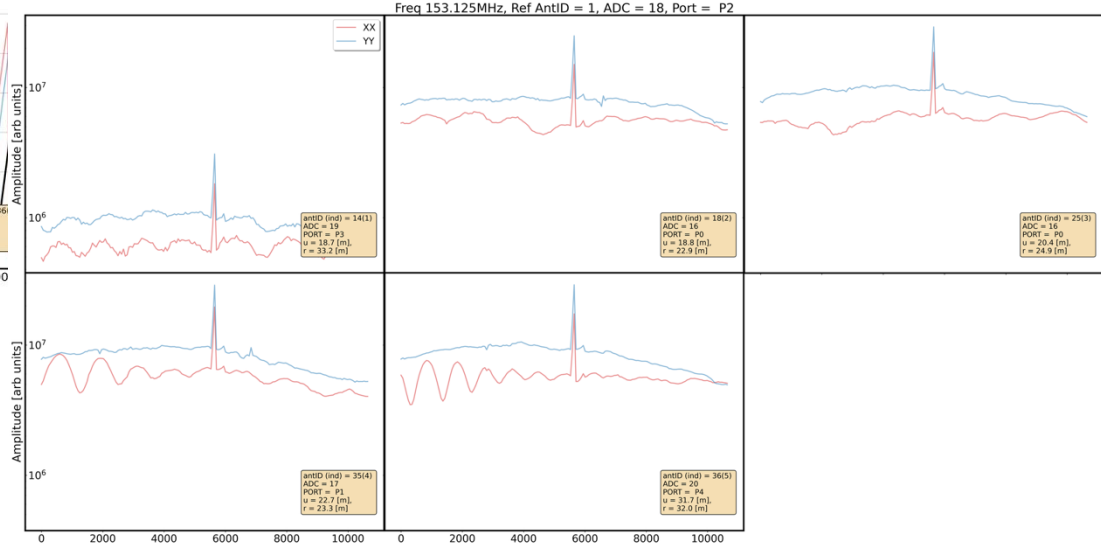
First correlation visibilities
5 minutes of time
150-155.47MHz



Status


Freq 153.125MHz, Ref AntID = 1, ADC = 18, Port = P2
XX
YY
Sun Model
Phase [rad]
antID (ind) = 14(1)
ADC = 19
PORT = P3
u = 18.7 [m],
r = 33.2 [m]
antID (ind) = 18(2)
ADC = 16
PORT = P0
u = 18.8 [m],
r = 22.9 [m]
antID (ind) = 25(3)
ADC = 16
PORT = P0
u = 20.4 [m],
r = 24.9 [m]
antID (ind) = 35(4)
ADC = 17
PORT = P1
u = 22.7 [m],
r = 23.3 [m]
antID (ind) = 36
ADC = 20
PORT = P4
u = 31.7 [m],
r = 32.0 [m]
0
2000
4000
6000
8000
10000


Sun Altitude During Observation
Sun Altitude (deg)
Time (s)
54
53
52
51
50
49
48
47
46
0
2000
4000
6000
8000
10000


Freq 153.125MHz, Ref AntID = 1, ADC = 18, Port = P2
XX
YY
Amplitude [arb units]
10^7
10^6
antID (ind) = 14(1)
ADC = 19
PORT = P3
u = 18.7 [m],
r = 33.2 [m]
antID (ind) = 18(2)
ADC = 16
PORT = P0
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PORT = P0
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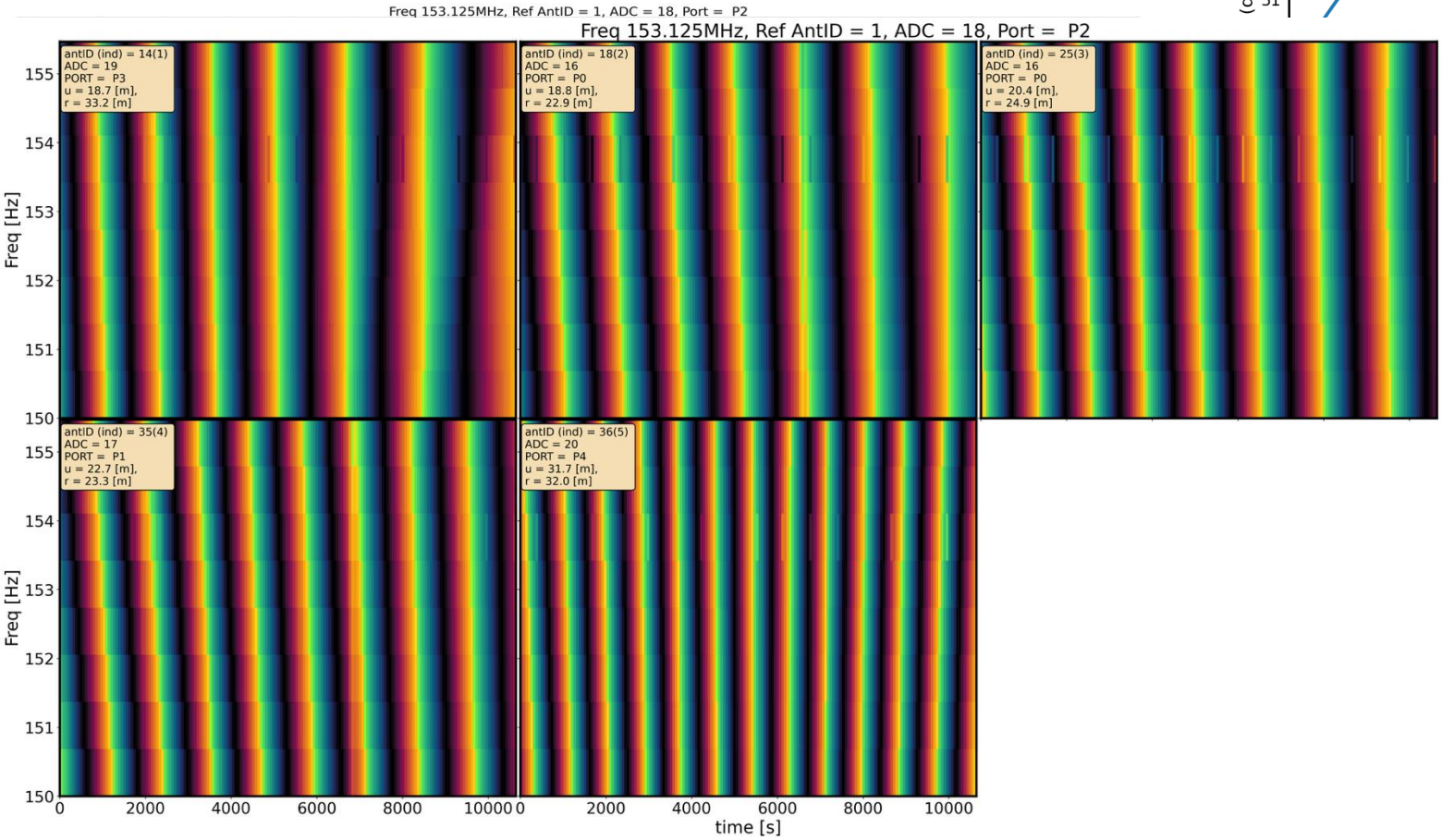
antID (ind) = 35(4)
ADC = 17
PORT = P1
u = 22.7 [m],
r = 23.3 [m]
antID (ind) = 36(5)
ADC = 20
PORT = P4
u = 31.7 [m],
r = 32.0 [m]
0
2000
4000
6000
8000
10000

Status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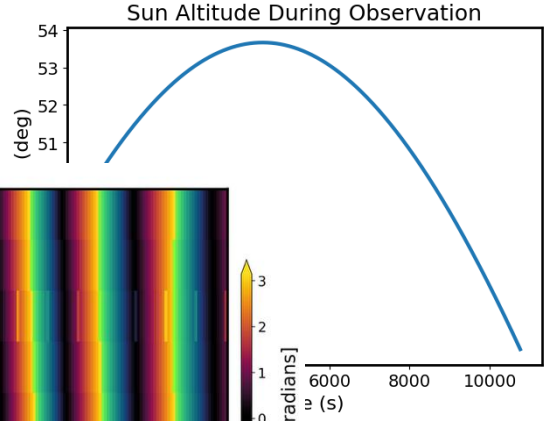
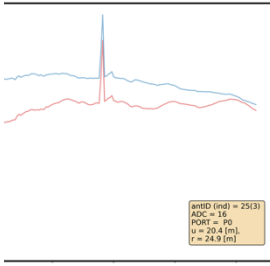
ADC = 20
PORT = P4
u = 31.7 [m],
r = 32.0 [m]
Freq [Hz]
Phase [rad]
time [s]
Phase [radians]


Sun Altitude During Observation
(deg)
54
53
52
51
6000
8000
10000
e (s)



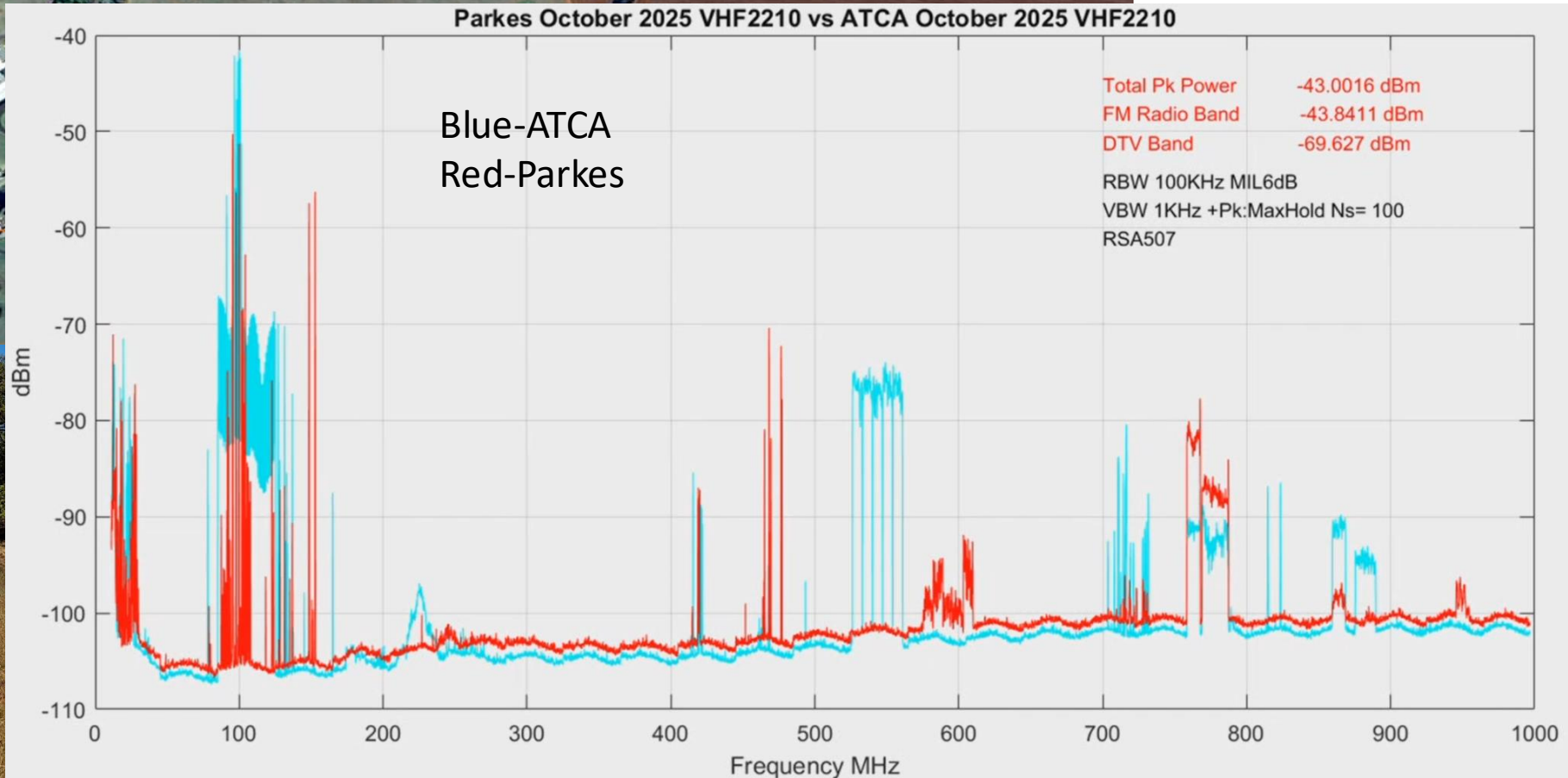
Timeline & Next Steps

- Currently Deploying 36 antennas at Narrabri
  - Test signal chain before deploying full station
  - Develop station calibration pipeline
  - Work to get first single station images (next few months maybe next week?)
  - Goal of first fringes with SKA-Low (or GMRT,MWA, etc) (~ mid/late this year ?)
- Stage 2
  - Rollout of two half stations (128 antennas) at Narrabri and Parkes
    - Order of 256 antennas in progress
    - Earthworks beginning at Parkes soon
    - Improved remote control and monitoring
    - Implement low-powered RF System on a Chip (RFSoC)

Parkes Site


New Fibre Conduit - 450m
New Power Conduit - 425m
Option 5
Existing Fibre Conduits

Parkes Site


Parkes October 2025 VHF2210 vs ATCA October 2025 VHF2210
Blue-ATCA
Red-Parkes
Total Pk Power -43.0016 dBm
FM Radio Band -43.8411 dBm
DTV Band -69.627 dBm
RBW 100KHz MIL6dB
VBW 1KHz +Pk:MaxHold Ns= 100
RSA507
dBm
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
Frequency MHz

Science cases

Single station
Single baseline
Longer term – requiring more baselines
International Baselines

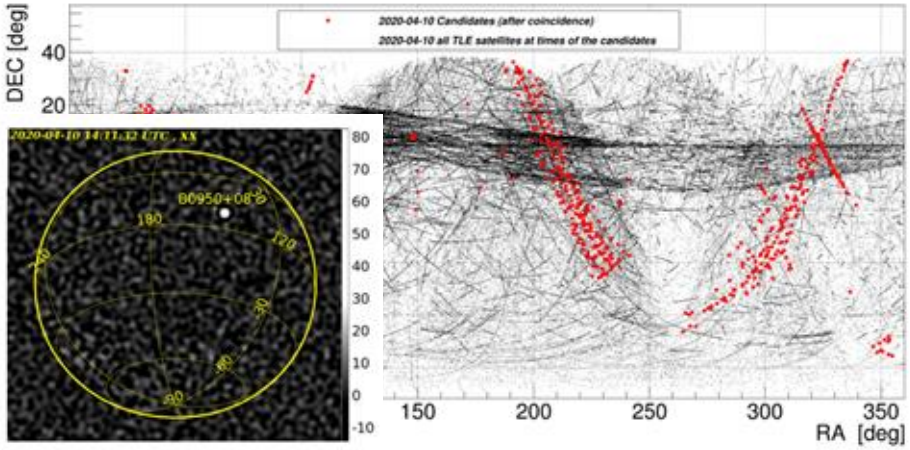
- Technosignature Searches (SETI)
- Ionosphere and Space Weather
- Transient / sky-monitoring
- Pulsar astrometry
- AGN core identification
- Pulsar distances, proper motions, scintillometry (minimum 3 baselines)
- FRB follow-up and host imaging with optical resolution (minimum 3-4 baselines)
- Long period transient localisation (minimum 3-4 baselines)
- High resolution (sub-kiloparsec scale at all redshifts) mapping of AGN
  - Requires more short to mid baselines
- Young stellar objects and Supernova Remnants in our Galaxy
- Redshifted HI
  - Baseline distribution depends on redshift
- Resolving stellar/planetary systems, distinguishing planet from host star
  - e.g., Sun-Jupiter system to D ~ 50 parsecs – would require international baselines
- Unknown → high resolution ultra-low frequency one of the least explored parameter spaces in all of astronomy, leaves the door open for new and exciting science

Potential Single Station Science with LAMBDA36 & 256

Southern-Hemisphere all-sky radio transient monitor

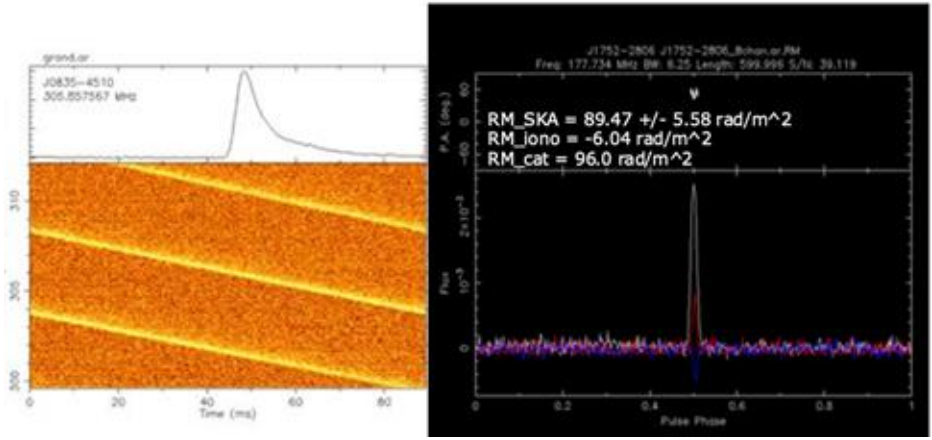
See Sokolowski+21 with EDA2/AAVS2

- Difference images to detect transients



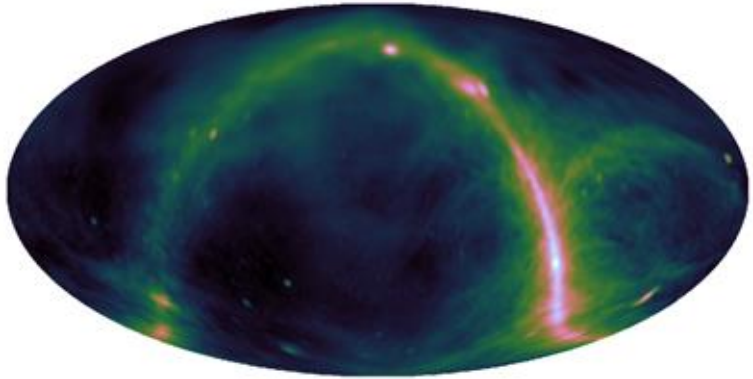
Pulsars

From SKA-Low commissioning team



M-mode Transit All-sky Imaging

Imaging EDA2 all-sky



LAMBDA Partners

- Successful Proposal from South Korea (KAIST) to build LAMBDA station and form “KAIST–ATNF Joint Research Center for Low-Frequency VLBI” (PI: Junhan Kim, KAIST)
  - Approximate ~7500 km baseline From South Korea to SKA-Low

Possible Intl Baselines

- Baseline estimate:
  - Narrabri to India ~ 9,700km (6500km to WA)
  - Narrabri to Korea ~ 7800km
  - Narrabri to Japan ~ 7900km
  - ~25-50 mas resolution
- Long Baselines good for higher resolution (stellar and exoplanet studies!)

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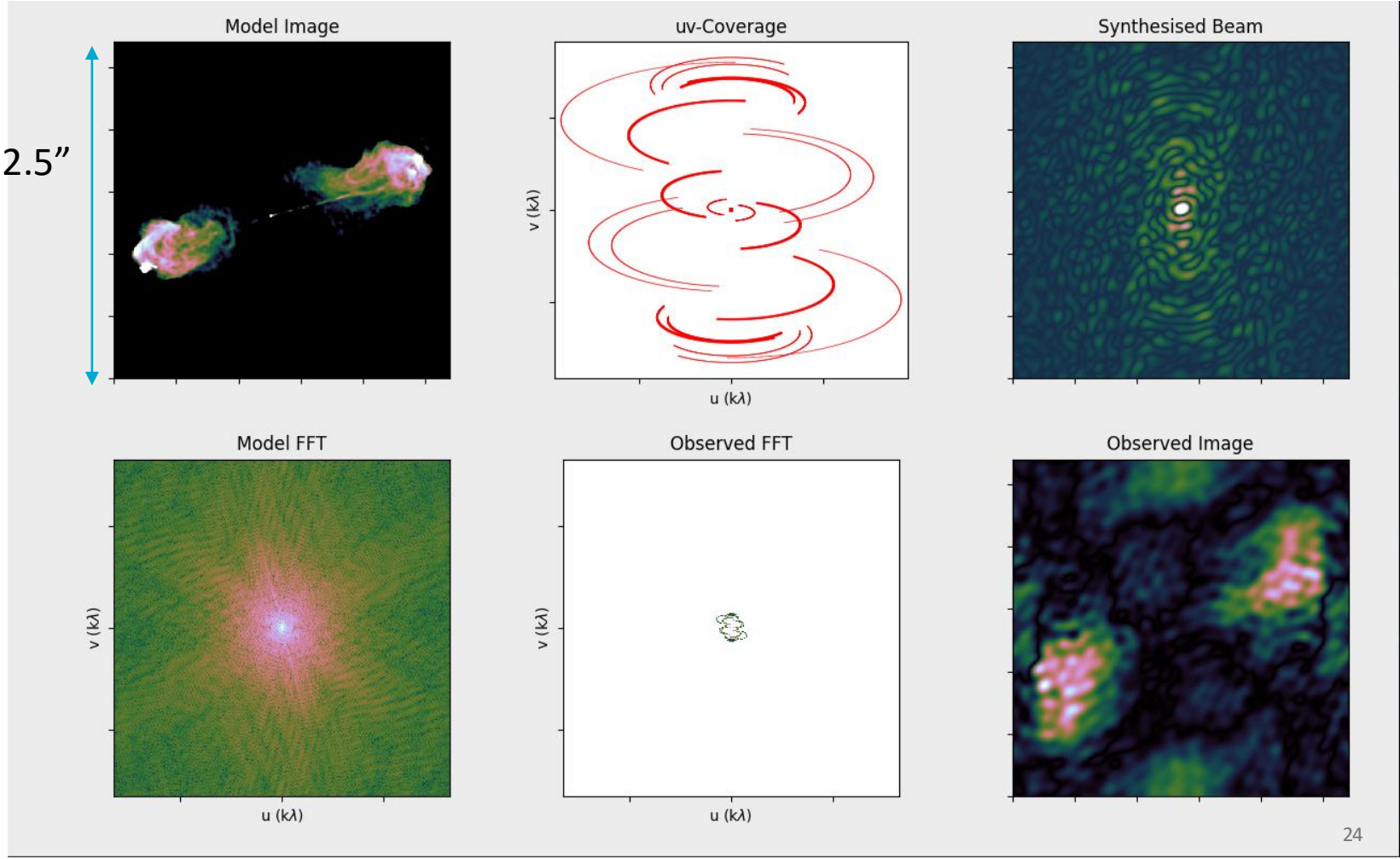
- Long Baselines good for higher resolution (stellar and exoplanet studies!)
- Potentially problematic for co-observing → low elevation →degraded performance

4 SKA-Low + Narrabri + SK + Japan+ GMRT

If SKA-Low unavailable Parkes-Narrabri would be only “short” baseline

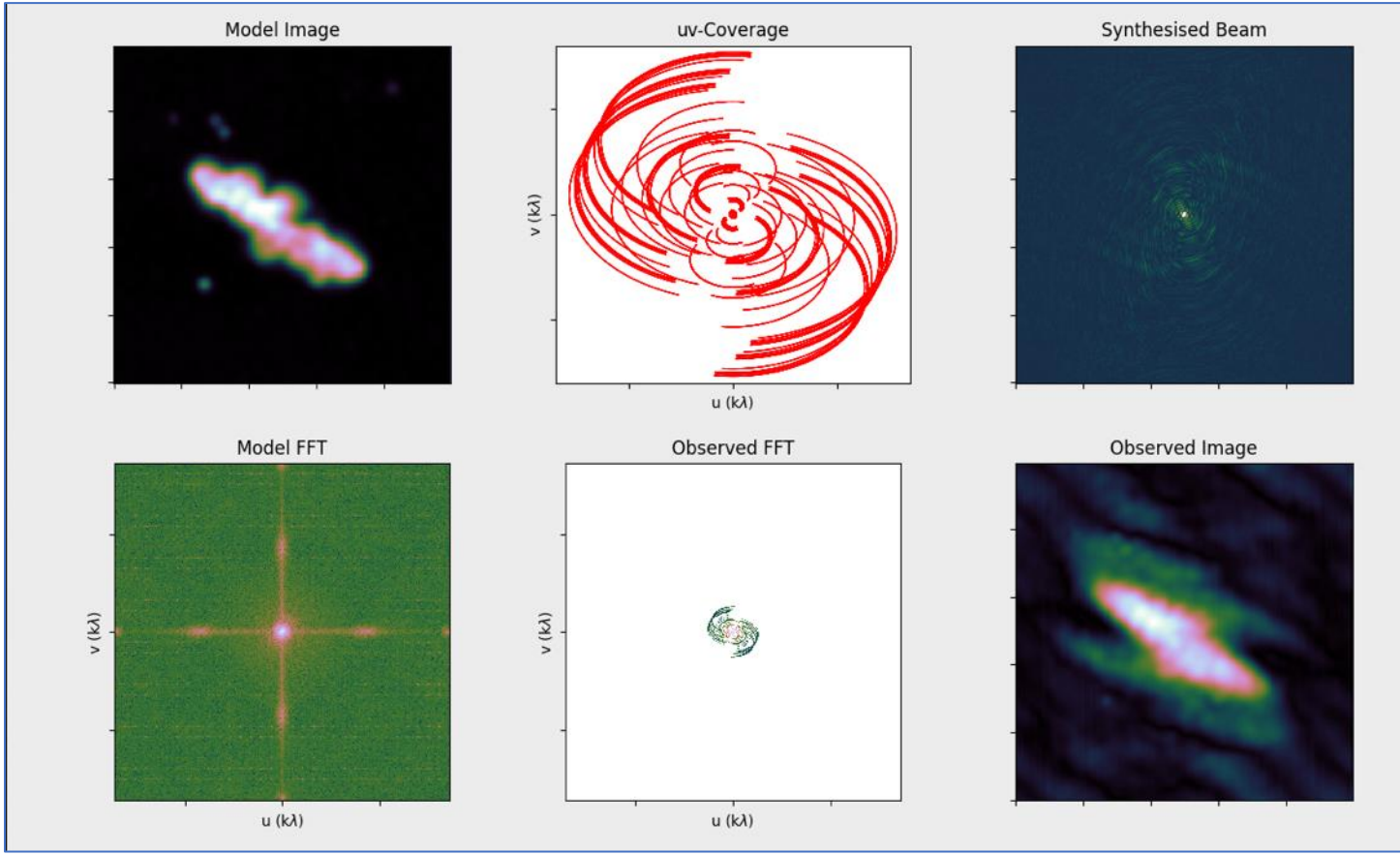


VLBI with SKA-Low

- SKAO says 4 (8) VLBI beams for Low
  - Lots of flexibility
  - On-sky beams and or sub arrays -- > limit is data
  - Could phase up entire core plus on each of the spiral arms
    - Or have multiple phased up stations within the core
  - Weighting need to be ajdusted per science case
  - Unlikely the widefield images like LOFAR (which does not phase up the core)

Baselines

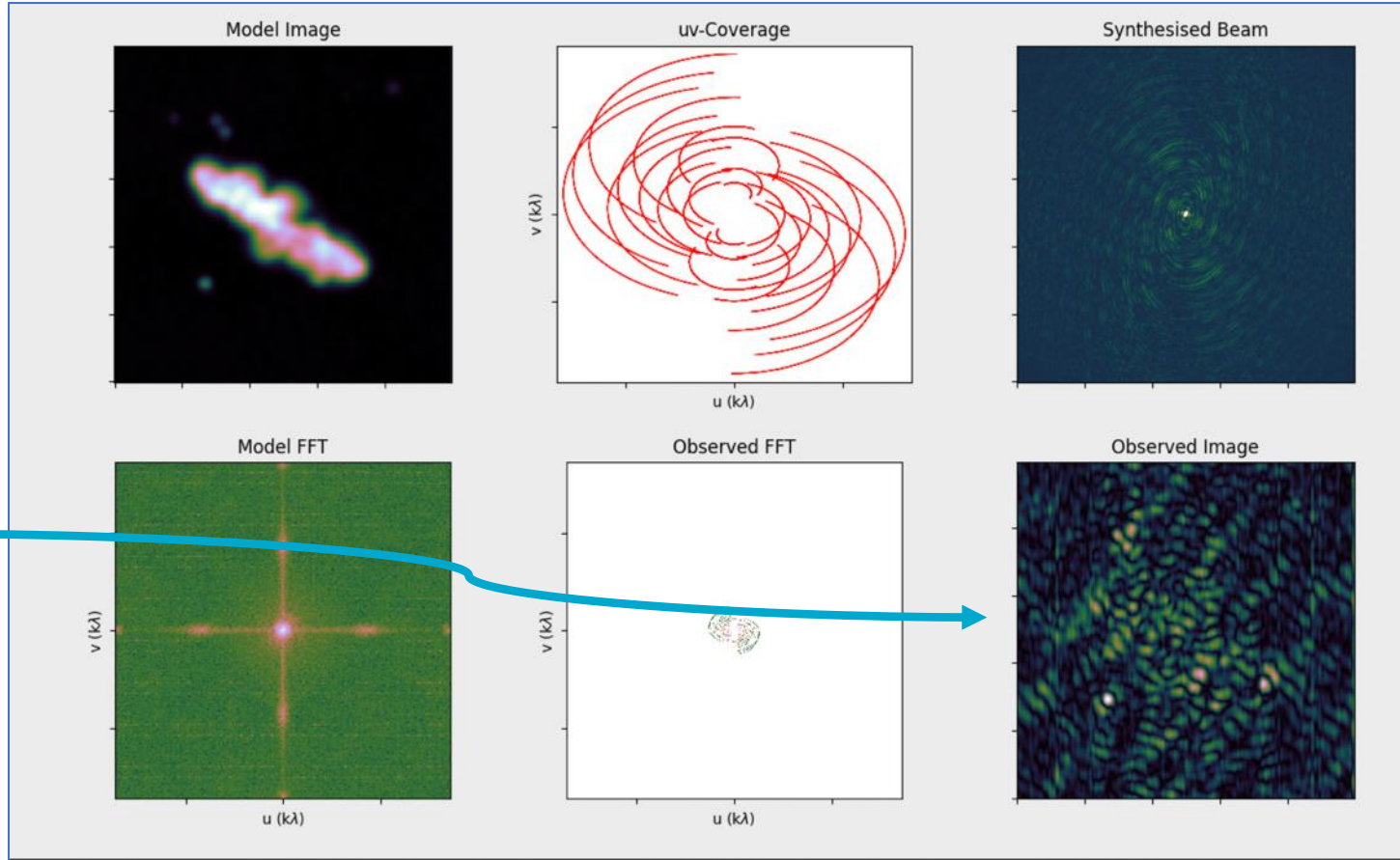
Mock – 10 hour observation 6 stations + 4 SKA-Low “stations” – model image 4 arcsec across



Short(er) Baselines

Mock – 10 hour observation 6 stations + **NO SKA-low stations**– model image 4 arcsec across

Yikes! Need intermediate and short baselines



Summary

- LAMBDA looks to test low-frequency VLBI with the SKA-Low
  - First fringe test hopefully 2026 with LAMBDA36
- Would be the only VLBI array at low-frequencies in Southern hemisphere
- New technologies being developed
- Currently building in Narrabri and soon to be South Korea & Parkes

Thank you

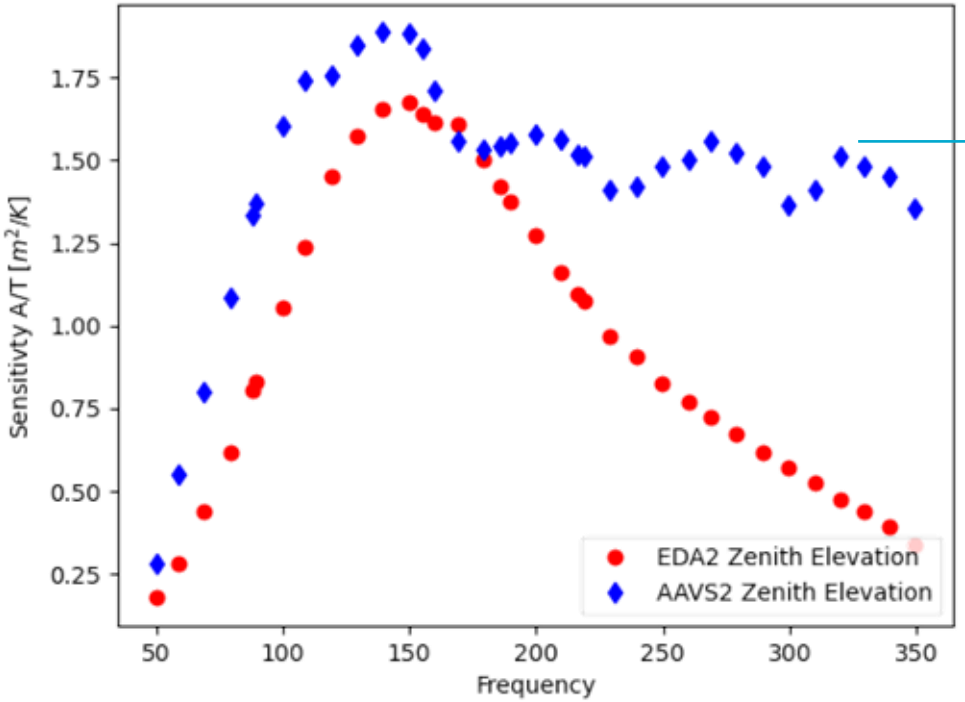
CSIRO Space and
Astronomy
www.atnf.csiro.au

Vanessa Kelly, VLBI, 2019

LAMBDA Intl baselines

- SKALA vs CRAB for low-elevation – from SKA-Low sensitivity calculator from Marcin Sokolowski using EDA2 and AAVS2

Blue – SKALA Antenna
Red –MWA style antenna



~SEFD 2000 Jy

SKA-Low stations reaching this

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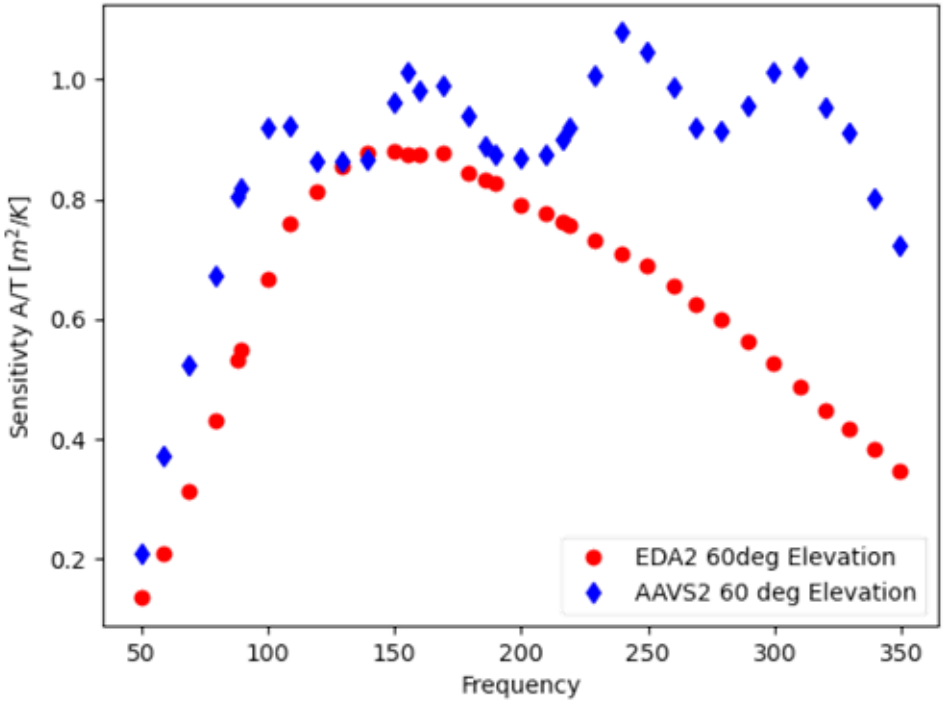

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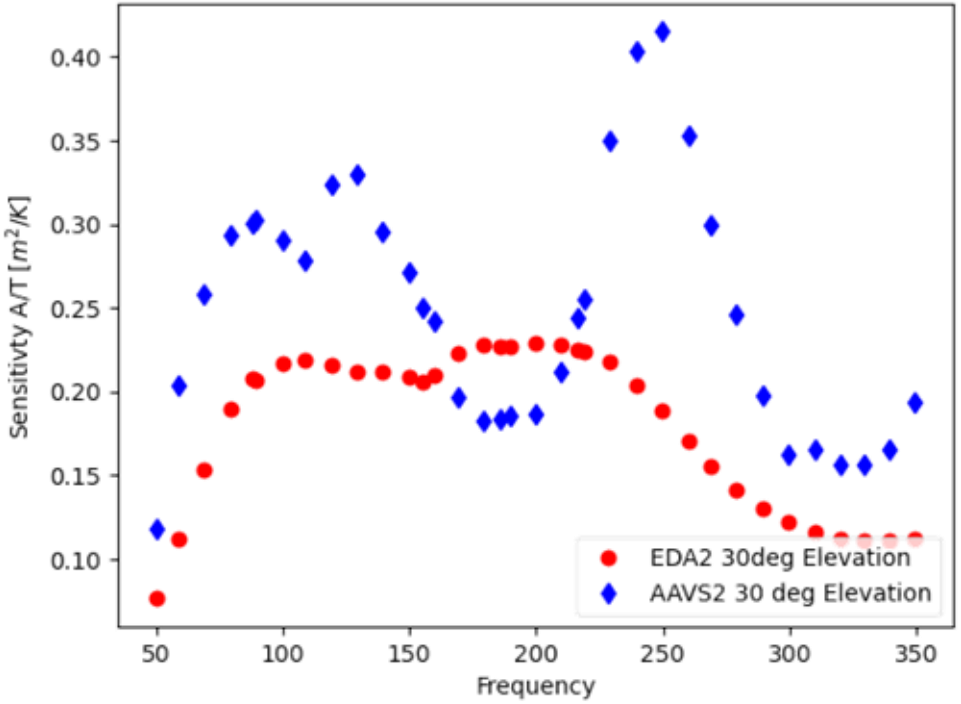


Basically both bad at low elevation !!

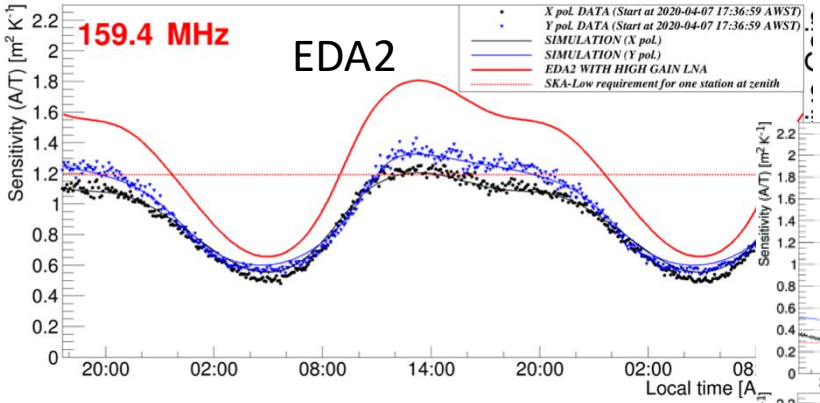
SKALA degrades faster

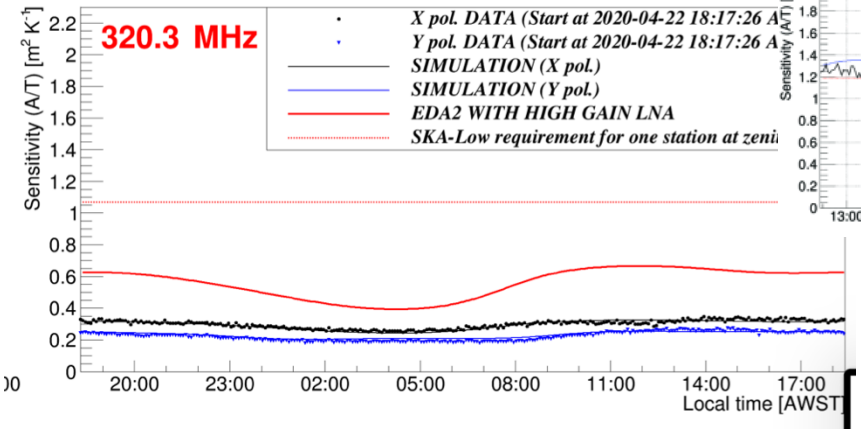
Elevations For Narrabri to SK

Declination δ	Narrabri h_{max}	South Korea h_{max}	Note
+30°	30°	~84° (very high)	AU suffers (low elev)
+10°	50°	~64°	both decent
0°	60°	~54°	both good
–10°	70°	~44°	KR getting low
–29° (Galactic Centre)	~89°	**~25° (low)**	KR very low
≤–54 (e.g., LMC/SMC)	visible from AU	**not visible from KR**	no overlap

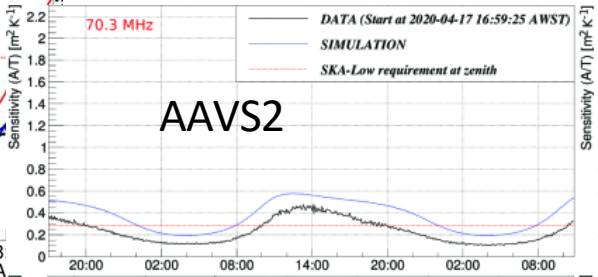
Elevations for Narrabri to Pune

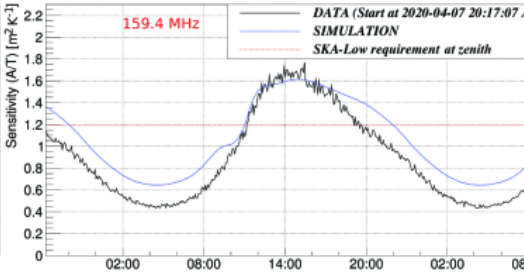
Declination δ	Narrabri h_{max}	Pune h_{max}	Note
+30°	30°	79°	AU low, IN high
+20°	40°	89°	AU modest, IN near zenith
+10°	50°	81°	both good
0°	60°	71°	both very good
−10°	70°	61°	excellent overlap
−20°	80°	51°	excellent overlap
−29°	89°	42°	AU near zenith; IN moderate (Galactic Centre)**
−40°	80°	31°	IN getting low
−50°	70°	21°	IN low (penalties likely)
−60°	60°	11°	IN very low (marginal)
−70°	50°	1°	IN essentially at horizon

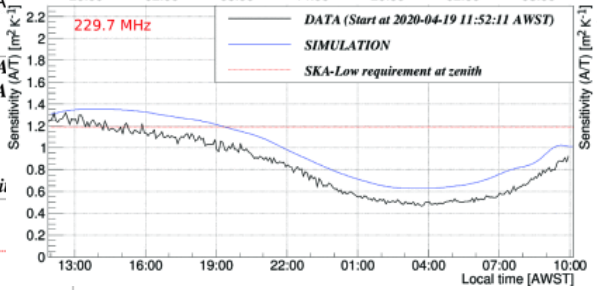

159.4 MHz
EDA2
X pol. DATA (Start at 2020-04-07 17:36:59 AWST)
Y pol. DATA (Start at 2020-04-07 17:36:59 AWST)
SIMULATION (X pol.)
SIMULATION (Y pol.)
EDA2 WITH HIGH GAIN LNA
SKA-Low requirement for one station at zenith
Sensitivity (A/T) [m² K⁻¹]
Local time [A

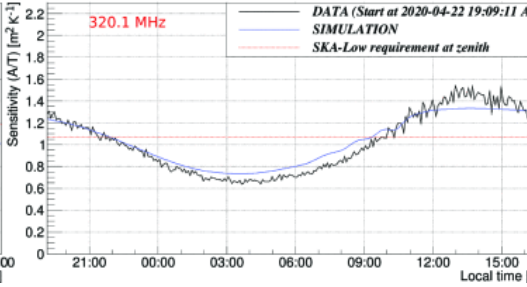

320.3 MHz
X pol. DATA (Start at 2020-04-22 18:17:26 A
Y pol. DATA (Start at 2020-04-22 18:17:26 A
SIMULATION (X pol.)
SIMULATION (Y pol.)
EDA2 WITH HIGH GAIN LNA
SKA-Low requirement for one station at zeni
Sensitivity (A/T) [m² K⁻¹]
Local time [AWST]

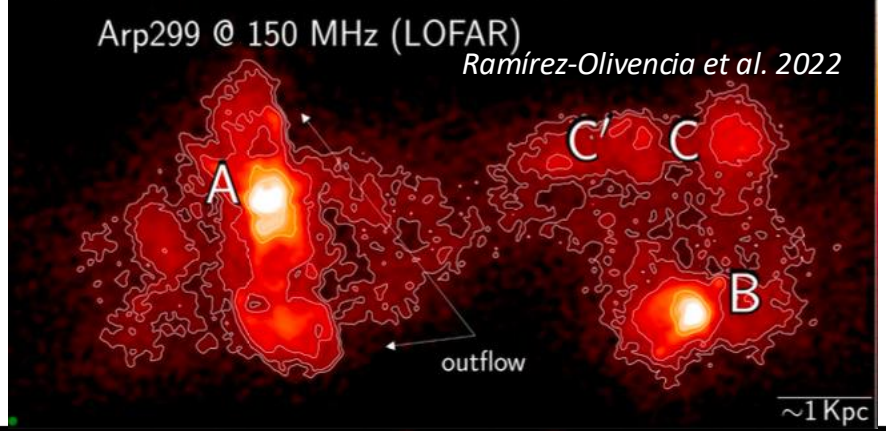
AAVS2

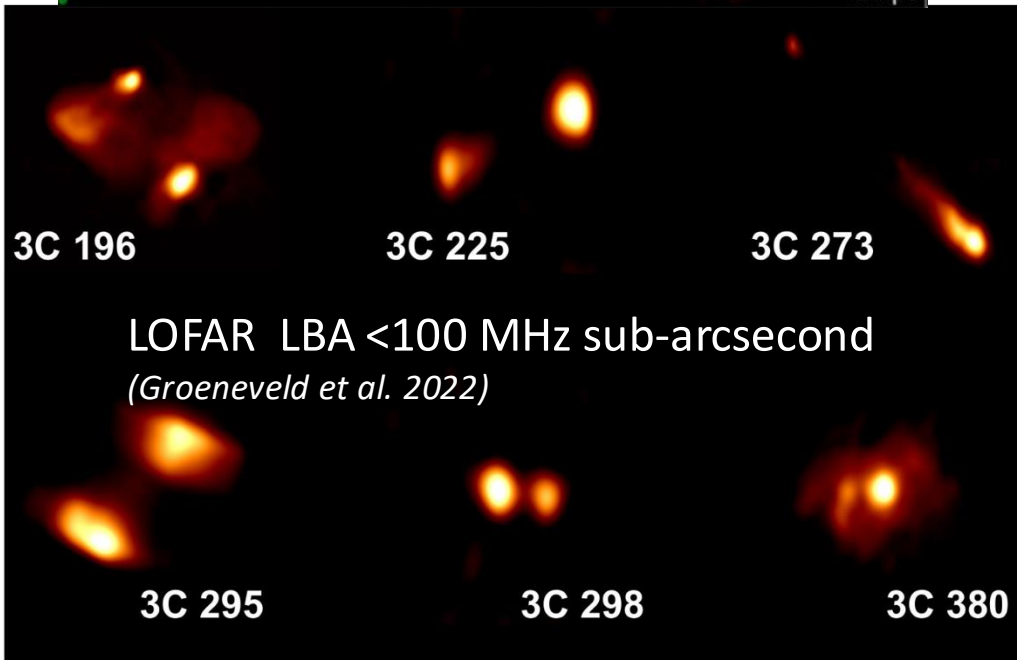

70.3 MHz
DATA (Start at 2020-04-17 16:59:25 AWST)
SIMULATION
SKA-Low requirement at zenith
Sensitivity (A/T) [m² K⁻¹]

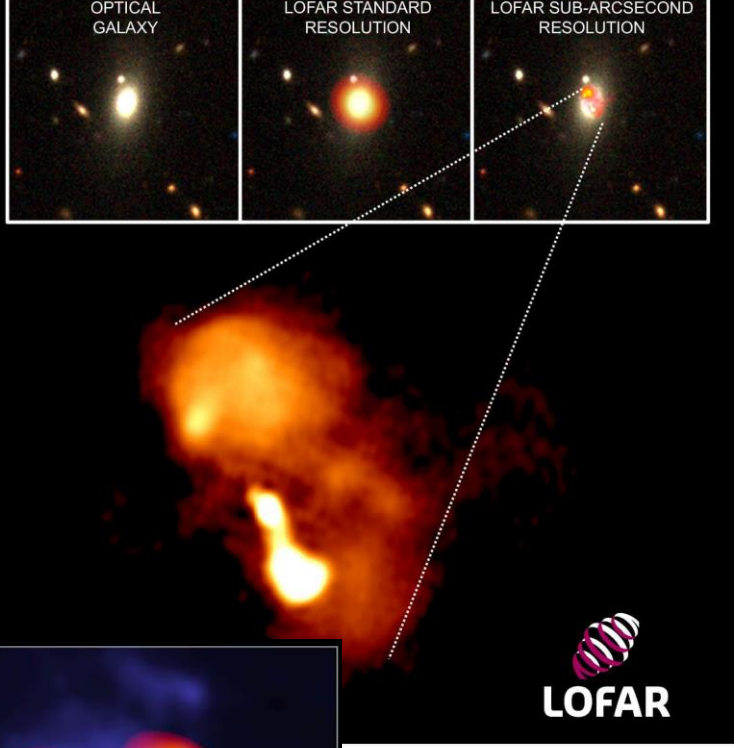

159.4 MHz
DATA (Start at 2020-04-07 20:17:07
SIMULATION
SKA-Low requirement at zenith
Sensitivity (A/T) [m² K⁻¹]


229.7 MHz
DATA (Start at 2020-04-19 11:52:11 AWST)
SIMULATION
SKA-Low requirement at zenith
Sensitivity (A/T) [m² K⁻¹]
Local time [AWST]

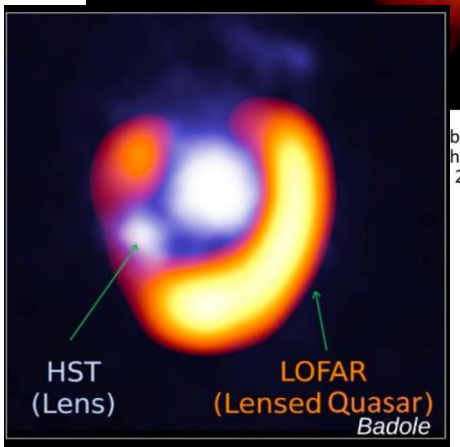

320.1 MHz
DATA (Start at 2020-04-22 19:09:11 A
SIMULATION
SKA-Low requirement at zenith
Sensitivity (A/T) [m² K⁻¹]
Local time



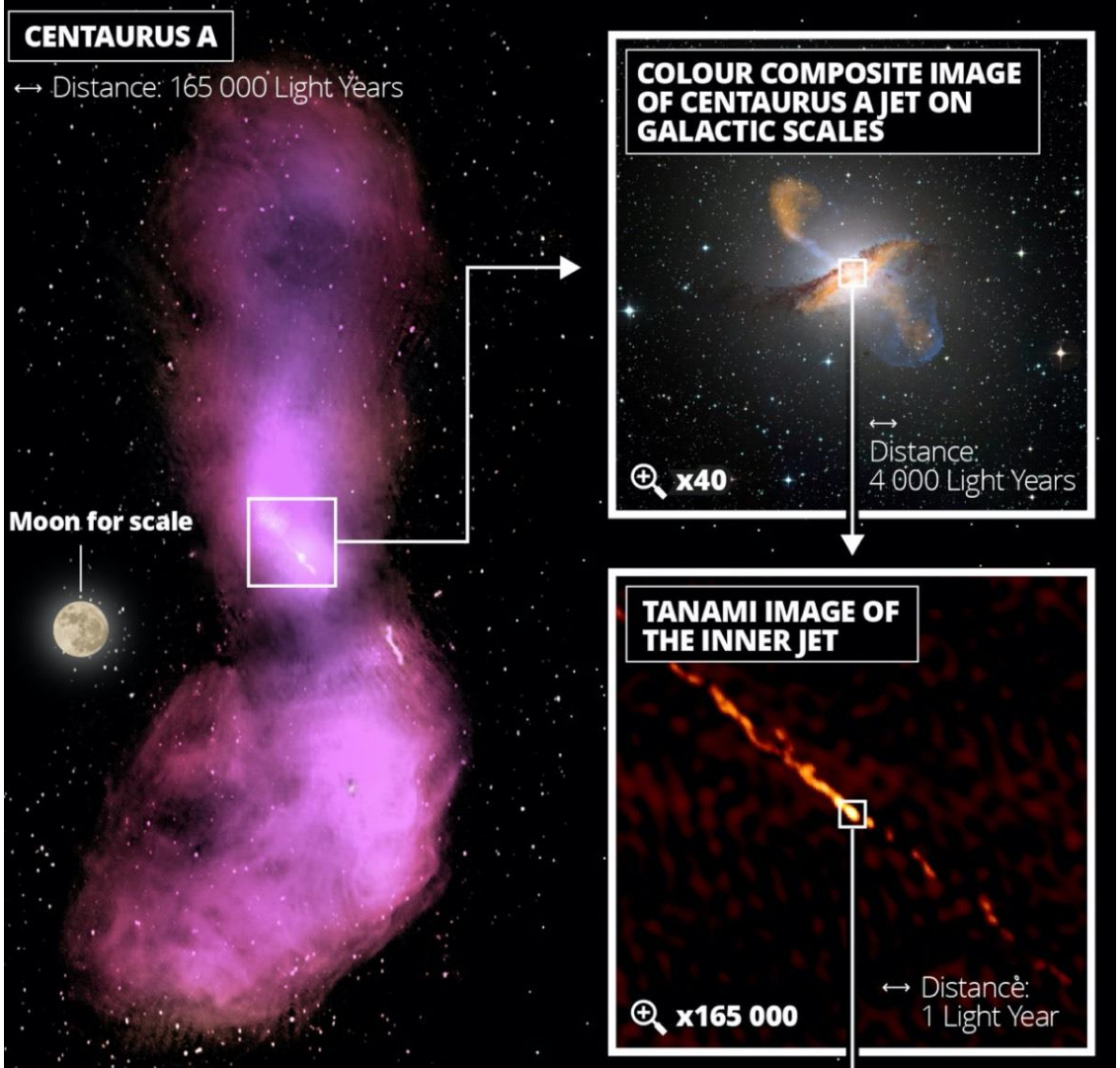




by new calibration techniques
he International LOFAR Telescope"
2022, A&A, 658)



CSIRO



Credit: Radboud University; CSIRO/ATNF/; ESO/WFI; MPIfR/ESO/APEX; NASA/CXC/CfA/; TANAMI

10s of mas

LAMBDA resolution ~100 mas

- Exoplanet emission
  - Expected at lowest frequencies
  - *Need* LONG baselines