Australia's National Science Agency

Low-frequency VLBI

George Heald
with key contributions from Grant Hampson

ATUC Open Session, 8 November 2021

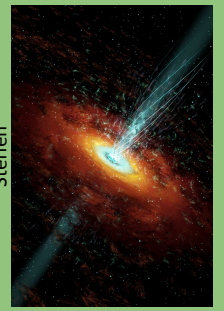
Outline

- Science case
  - Outline and external inputs
  - Community input and motivations
- Recap of Australian opportunity
  - ***LAMBDA***: Low-frequency Australian Megametre-Baseline Demonstrator Array
- Technical developments
  - Bluering developments
  - Test system
  - Site preparation at Narrabri
  - Observing plans and goals
- Upcoming “VLBI in the SKA Era” CSIRO Cutting Edge Symposium

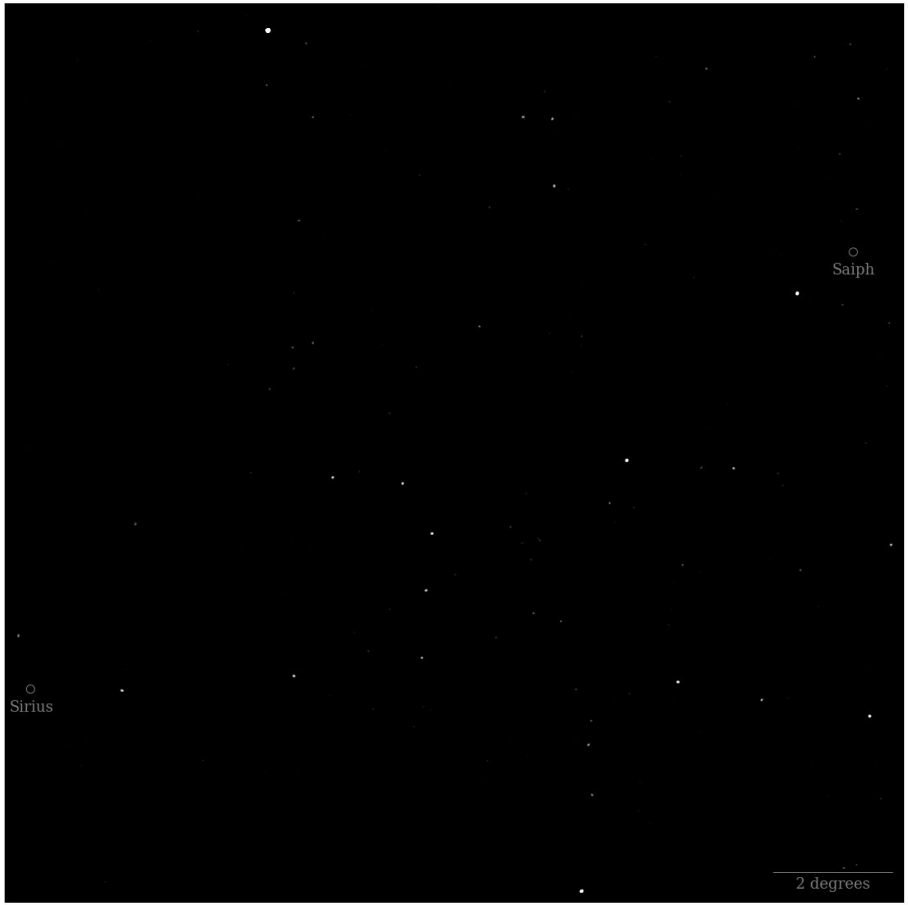
Science case

"Bread and butter" VLBI; increasing LBA capability
Unique/emerging science leveraging expanded frequency range
New capability from flexible/responsive/always-on observing

- High resolution ($\lesssim$kpc scale at all *z*) mapping of AGN and other radio sources detected with MWA, ASKAP
  - NB: EMU, POSSUM, FLASH, VAST all getting rolling now!
    2/3 of ASKAP sky inaccessible at low freq with long baselines
  - MWA science results have already prompted LBA proposals
- Pulsar astrometry, distances, proper motions, scintillometry
- Gravitational lens discovery / imaging


Steffen

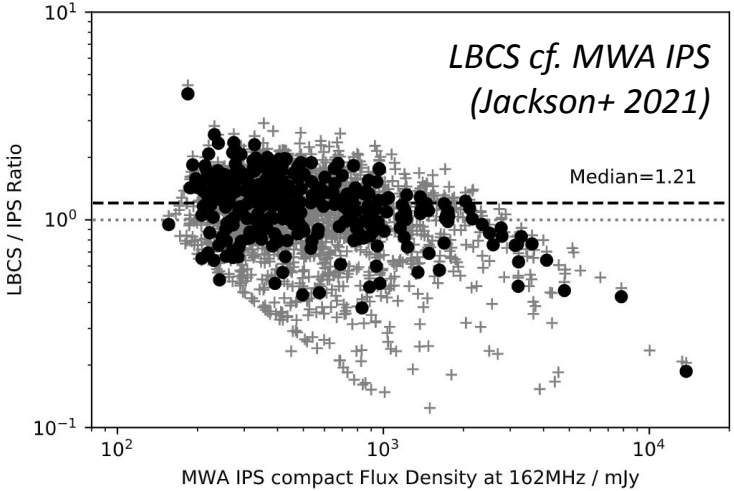
Sub-arcsecond resolution via IPS with MWA



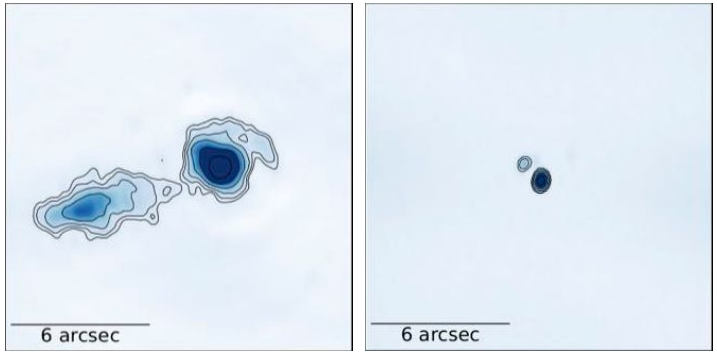
- Interplanetary scintillation with MWA selects source structure on ~0.3” scale
- About 10% of MWA sources scintillate
- Three source types identified: CSS, peak- and flat-spectrum (blazars)
- Deeper sample expected from GLEAM-X !

70x0.5s MWA images @ 162 MHz, Chhetri+2018

Imaging IPS sources



- International LOFAR provides ~0.3” imaging resolution at 150 MHz
- MWA IPS sources detected in LBCS, with consistent flux density
- Direct imaging at ~0.3” resolution supplements IPS analysis
- MWA as a clear candidate pathway
  - **Estimate**: All MWA IPS sources would be detected with excellent broadband sensitivity *per baseline* with LAMBDA
  - **Extrapolation** from S^3 simulation and IPS (Chhetri+ 2018): ~5 compact src / sq deg with high image S/N in imaging survey



Two LOFAR sources @0.3” resolution (Morabito+ 2021)

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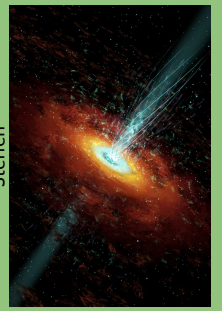
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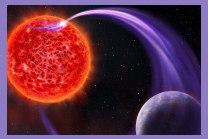
- Pulsar astrometry, distances, proper motions, scintillometry
- Gravitational lens discovery / imaging
- Resolving stellar systems, distinguishing planet from host star (e.g. Sun-Jupiter system to D ~ 50 pc)


Futselaar

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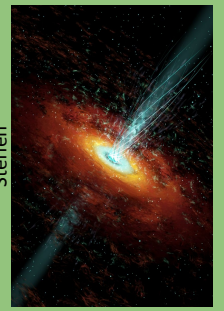
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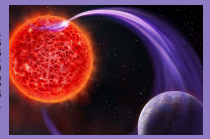
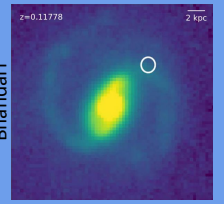

Futselaar

- FRB followup and host imaging with optical resolution
- Single-/multi- station mode: pulsar monitoring/timing, determination of high-precision ISM properties, SETI



Bhandari

Plans for direct community input

- Elements of science case, technical and operational requirements will be discussed at the upcoming “VLBI in the SKA Era” symposium, hosted by CSIRO and sponsored by SKAO
- Symposium will include discussion time targeted toward topics of direct relevance to our developing plans in Australia for VLBI with SKA1-LOW, and Global VLBI
- Specific plans coming soon for LAMBDA science case workshop (likely one-day event, preceding SKA-VLBI symposium)
- Discussions welcome to plan toward LIEF bid for pathfinder project delivering LAMBDA capability - contact me!

Motivation to go beyond current LBA

- SKA1-LOW (Bmax=65 km) will be limited to angular resolution $\gtrsim$3-20” but capable of participating in VLBI networks

- Low-frequency VLBI is feasible (e.g. LOFAR): typical isoplanatic patch ~ 1° and coherence timescale ~ 1-2 min (at 140 MHz; LBCS)
  - Intermediate baselines are essential for imaging work

- Australia is well situated to develop this capability for the Southern hemisphere (~ 4000 km E-W extent, existing VLBI network, home of MWA and SKA1-LOW)
  - Potential to link to NZ, uGMRT, FAST, Japan, South Africa, ...

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Community motivation: LOFAR, JUMPING JIVE

Astronomy & Astrophysics

- Special issue of A&A this year
- Press release with international coverage (including ABC News)
- 8 papers, including completion of Long Baseline Calibrator Survey (LBCS), high resolution imaging of radio galaxies and LIRGs, grav lenses

Report on SKA-VLBI Key Science Projects

JUMPING JIVE
Project ID: 730884

JUMPING JIVE
Project ID: 730884

WP10: VLBI with the SKA

- Report of 2019 SKA-VLBI meeting includes specific call to add low-freq capability to existing LBA locations
- Seven SKA-LOW VLBI science cases elaborated, ranging from YSOs, pulsars, exoplanets to AGN, HI absorption

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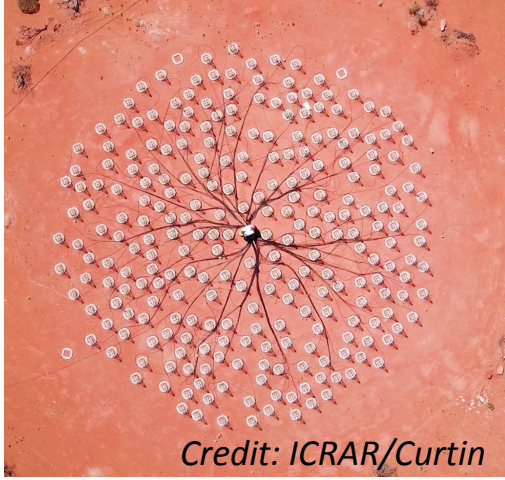
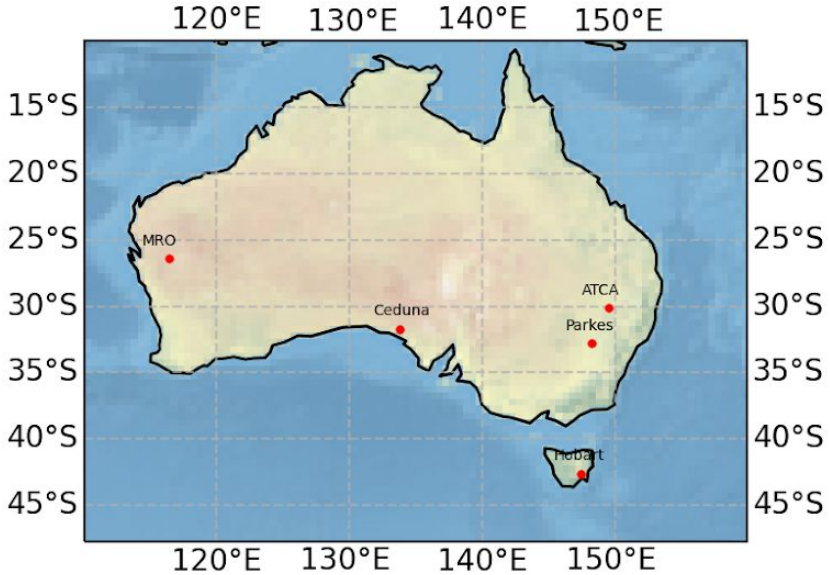
What would it take to get started?

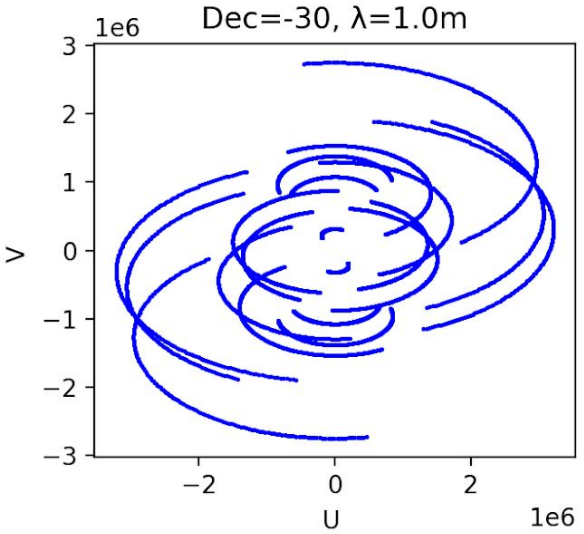

Credit: ICRAR/Curtin

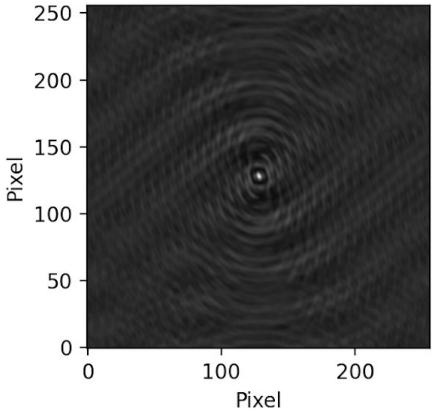
- A minimally useful demonstrator array would comprise:
  - Phased-array stations of proven antennas (flexible, well understood, and robust)
  - Flexible backend system to deliver station beam data (correlation either in real time over network, or from recorded data)
  - Sufficient number of stations for useful uv coverage (at least 4, ideally 6, at established sites)
  - Large enough stations to ensure sufficient calibration (estimates from Curtin's EDA: scale of SKA1-LOW stations is sufficient, using knowledge from LOFAR LBCS; Jackson+ 2016)
- A small number of large stations, using existing infrastructure
- Emphasis on flexibility and scalability

LAMBDA project - indicative uv coverage

Initial locations selected to coincide with existing LBA sites for power, network







Plots courtesy of Cormac Reynolds (CSIRO) and Yun Yu (SHAO)

Example uv coverage: 70 mas @ 300 MHz

LAMBDA project - future expandability

Future locations: follow fiber backbone in WA / across Australia?

(Note importance of intermediate-scale baselines for good imaging quality)

aarnet

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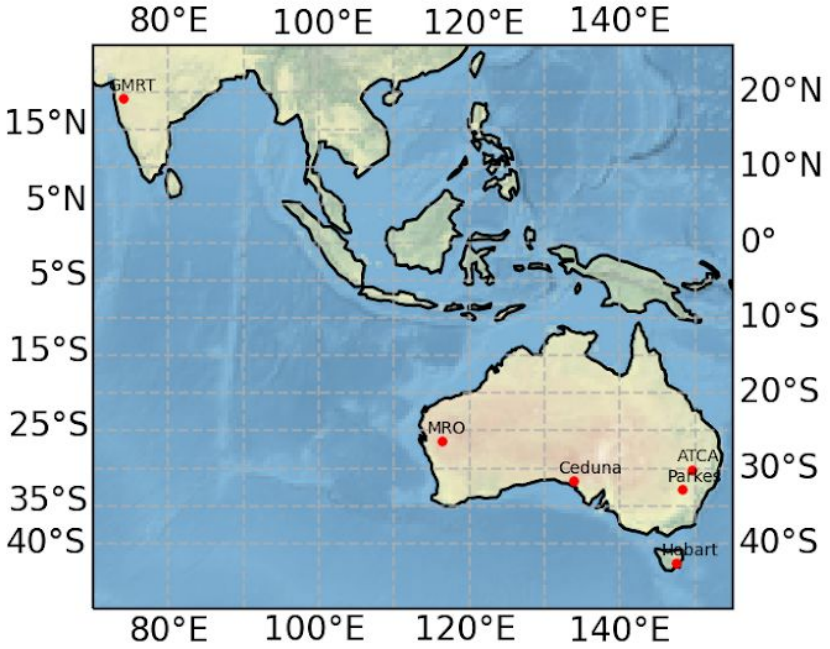
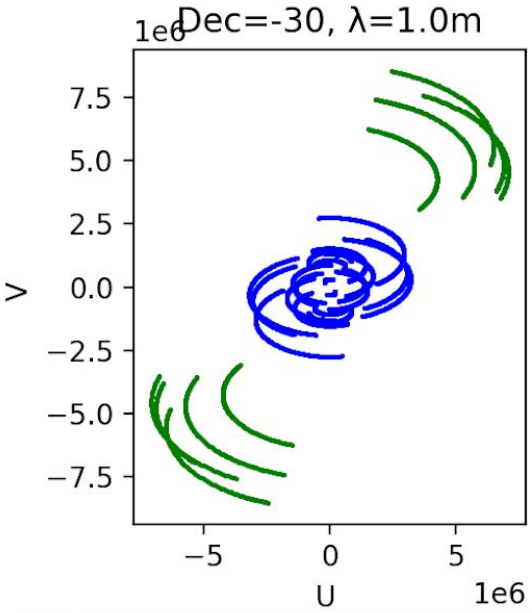
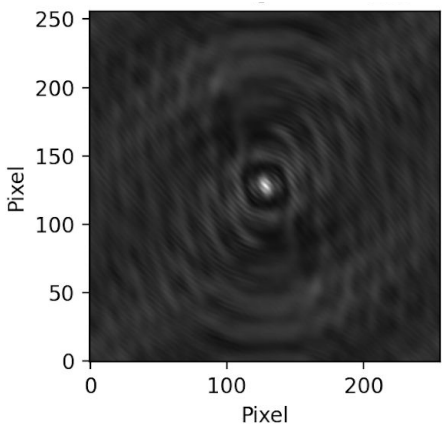
LAMBDA project - as part of Global VLBI

Potential to link with uGMRT, East Asian VLBI Network, ...







Plots courtesy of Cormac Reynolds (CSIRO) and Yun Yu (SHAO)

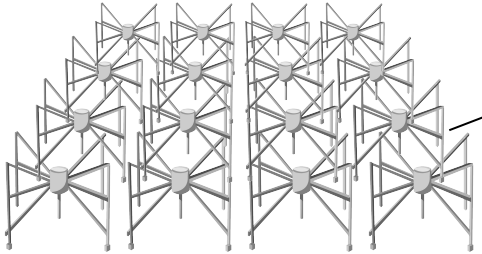
Example uv coverage: 20 mas @ 300 MHz

Bluering developments

Work by G. Hampson, W. Cheng, D. Humphrey, J. Bunton, P. Roberts, K. Bengston, R. Beresford, Y. Chen, R.Chekkala, G. Babich (... total ~ 1 FTE for this project)

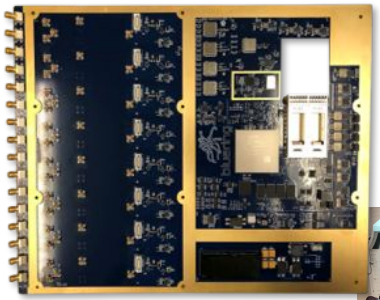
- Key strengths of this approach: scalability and flexibility
- Designed 18-layer Razorback PCB containing a 16 x 2GSPS RFSOC along with all the support circuitry integrated (clocks, power, memory)
  - System can be used for any array of antennas
  - Potential for on board 300MHz beamforming, pulsar folding, and correlation
- Designed Taipan RF module for MWA like antennas
- Written firmware for filterbanks and 100G packetisation
- Designed liquid cooling solution which duals as RFI shield (close to SKA spec)
- Written embedded software to control and monitor Razorback board
- Capture server built, software yet to be written to write to memory/disk
- Commencing integration of all the parts
- Learning tool - engineers/students access to sky signals - RFI

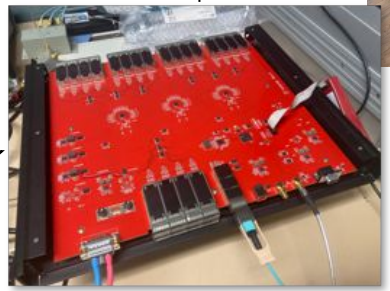
Test system



- 4x4 tile of MWA dipoles
- Dual-pol, 16-bit digitisation
- Located near ATCA posts
- Mesh ground plane

Razorback





Irukandji
(timing, also used for CryoPAF)

1 PPS & 10 MHz reference signal from ATCA system

Bluering server
- 64 cores (@2.3 GHz)
- 768 GB RAM
- 32TB SSD storage

Data written as CODIF
Post processing on server

Site prep at Narrabri

Work by Ron Beresford (Marsfield) & Brian Madden + Peter Mirtschin (Narrabri)

- Slab for rack with multiple access conduits for mains and fiber cable
- Power distribution panel with RCD protection and buried conduit to slab.
- Available vacant station post with 4 SM fibers, can be EW or NS spur but avoids vehicle traffic.
- Aiming for first-light in January 2022

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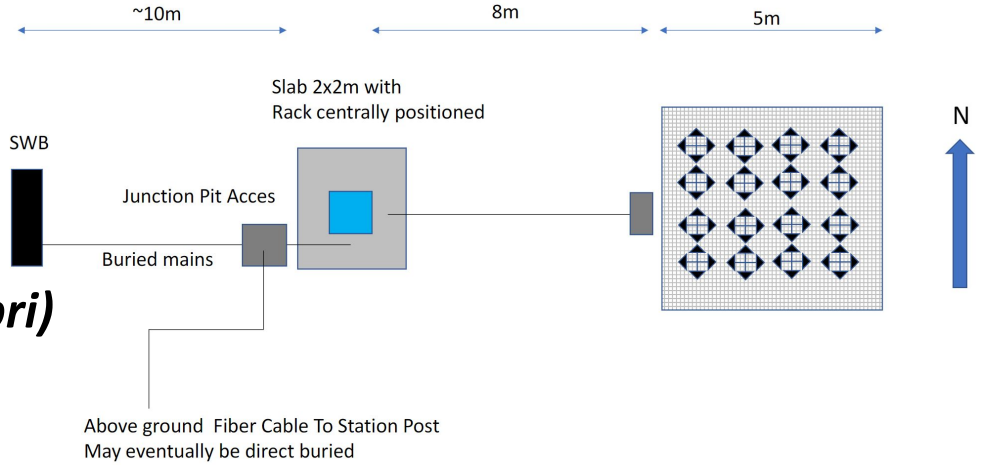


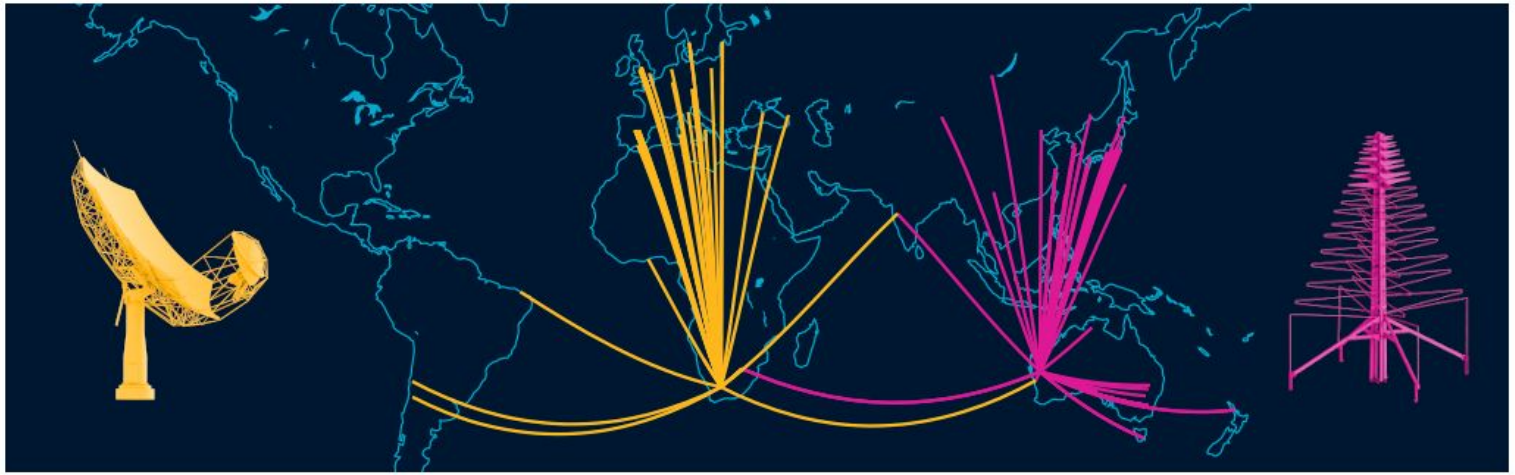
Observing plans and goals

- Observe for 64sec “snapshot” (fill 512 GB RAM buffer)
  - ~50 MHz bandwidth
- Record voltages to processing server (~4-5 min dump time)
- Repeat ~64x (fill 32 TB SSD storage array) - observe for about 5h
- Frequency band can be flexibly adjusted between snapshots
  - Opportunity for 4 50-MHz bands, possibly rotate through these 16x
  - Experimenting with RFI avoidance / filtering / suppression
- **Primary practical outcome**: Verification that post-processing leads to pulsar detections via beamformed time series
  - Expecting to be able to detect ~20+ known pulsars with this system
- Pave the way for expanded / enhanced system later on
- Possible publication describing system and illustrating data

CSIRO

VLBI in the SKA Era

14-18 February 2022



#SKAVLBI2022

Website and registration: https://whova.com/web/vlbis_202111/

Abstract deadline: 19 November 2021