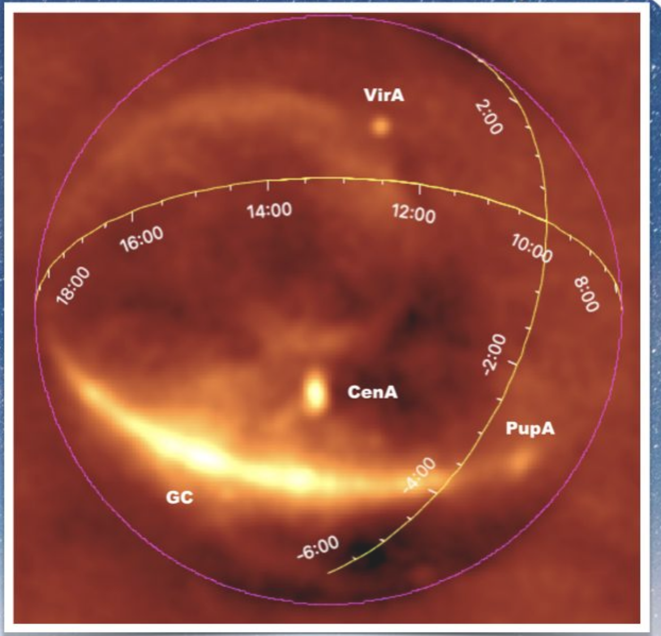
Observations with the SKA-low prototype station AAVS2: the INAF contribution towards science commissioning



The 4th National Workshop on the SKA Project

2023/11/27 - 12/1, Catania

Giulia Macario - INAF Arcetri Astrophysical Observatory

INAF AAVS observations team

Main roles (inside the team)

G. Macario, G. Pupillo, G. Bernardi, G. Comoretto:

observing plans, data acquisition, processing, analysis and interpretation, science commissioning

P. Bolli, P. Di Ninni:

antenna and station EM simulations

J. Monari, F. Perini, A. Mattana, M. Schiaffino:
support on receivers/signal chain, data acquisition and station monitoring

INAF OA Arcetri


G. Macario


P. Di Ninni


P. Bolli


G. Comoretto

INAF IRA Bologna and Medicina

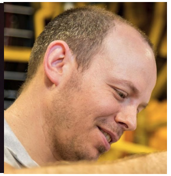

G. Bernardi


G. Pupillo


J. Monari


A. Mattana


F. Perini


M.Schiaffino

<u>In collaboration with</u>: **M. Sokolowski, R. Wayth, R. Subramanhyan** (*ICRAR Curtin*); **S. Asayama, R. Laing** (*SKAO*)

Aperture Array Verification Systems (AAVS's)

History of AAVS's (see Monari's talk)

Now: 2 *full*-size stations of 256 SKALA4.1al

- **AAVS2** (pseudo-random)

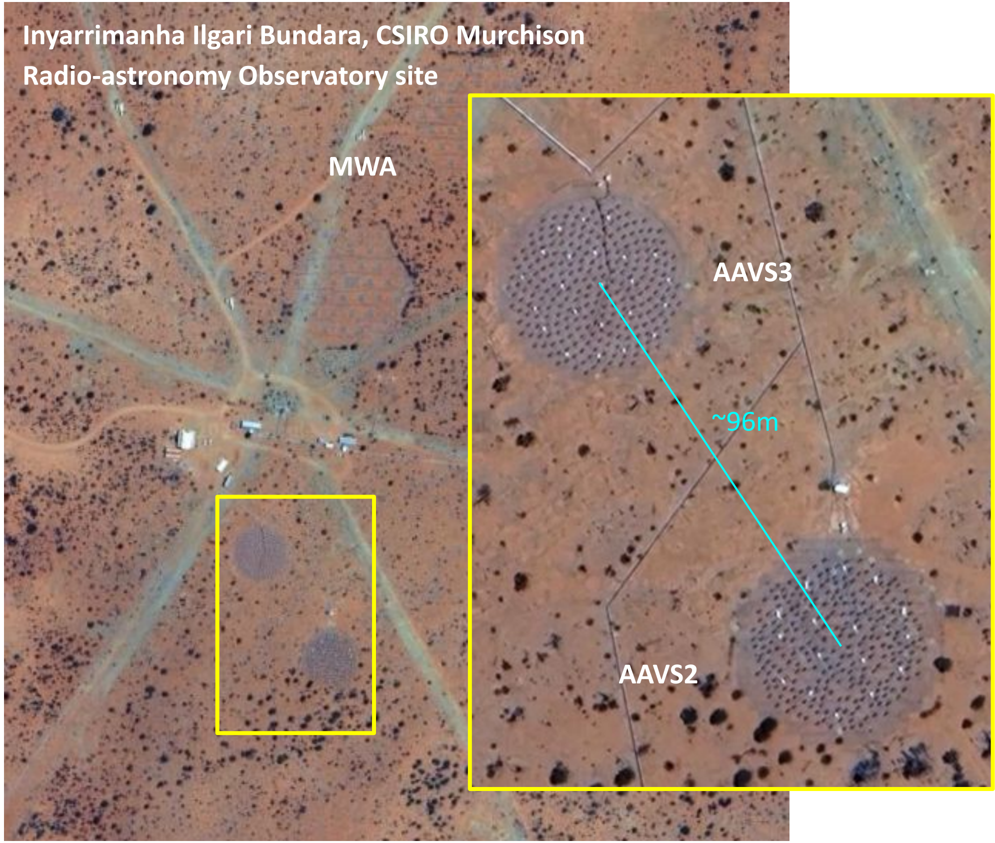
  2019-2024

- **AAVS3** (Vogel)

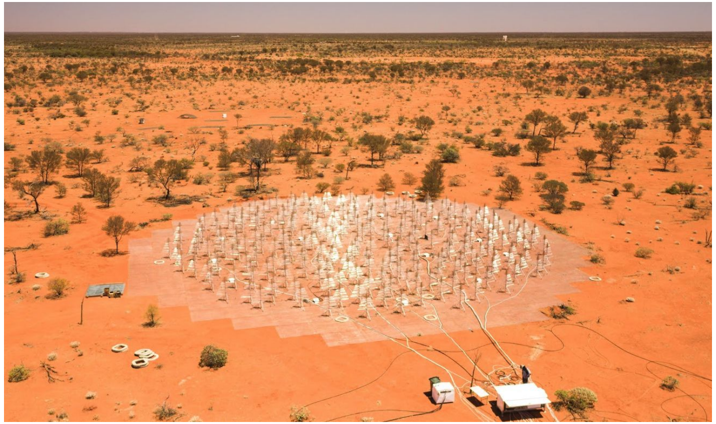
  Nov 2023 - March 2024

<u>Purpose</u>: station validation in preparation to **Array Assembly (AA) 0.5**: first 6 SKA-Low Stations under construction, expected 2024.

→ start of SKA-Low science commissioning



AAVS2

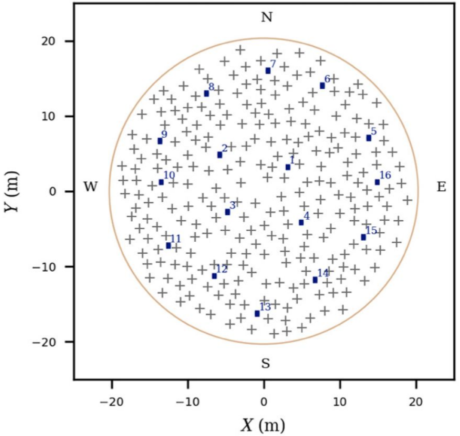


Operational at MRO since Dec. 2019

→ Frequency coverage: 50-350 MHz

→ FoV ~ 90°

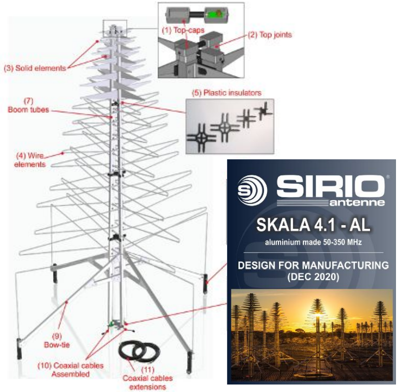
→ Angular resolution: ~9° - 1.3° (50 -- 350 MHz)



close-packed

pseudo-random

38m diameter



256 **SKALA4.1al**

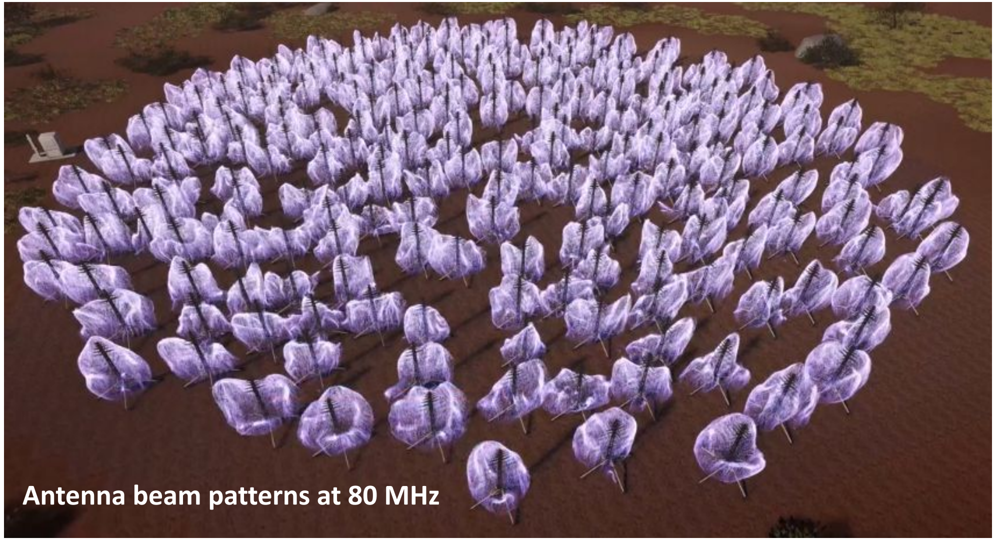
log periodic - 2 pol.

1.6m x 2.1; 10kg

reference design for SKA-Low

Van Es + 2020 , *Macario+ 2022* , *Perini+ 2022*, *Bolli + 2020*

AAVS2 antenna and station beam patterns



credits: ICRAR
(animation 1)

Mutual coupling effects → **Embedded Element Patterns (EEPs)** more pronounced at low frequencies

SKA-Low sensitivity and polarization performance addressed by EM modelling (e.g. *Bolli, Davidson + 2022*)

credits: ICRAR (animation 2)

Observing with AAVS2 as a transit interferometer

- Period: 4/2020 - 2/2021 (quiet Sun)
- zenith pointed snapshots
- every 5', across 22-24 h → ~**300** snapshots/obs.
- 6 coarse channels of ~ 1 MHz
- two consecutive integrations of 0.14 s, separated by 0.14 s (for *difference imaging*)

ν_c (MHz)	Start time, UT (yyyy/mm/dd, hh:mm:ss)
54.7	2021/02/19, 03 : 03 : 01
70.3	2020/04/17, 08 : 59 : 25
110.2	2020/04/21, 10 : 19 : 31
159.4	2020/04/07, 16 : 26 : 58
229.8	2020/04/19, 03 : 52 : 11
320.3	2020/04/22, 11 : 09 : 11

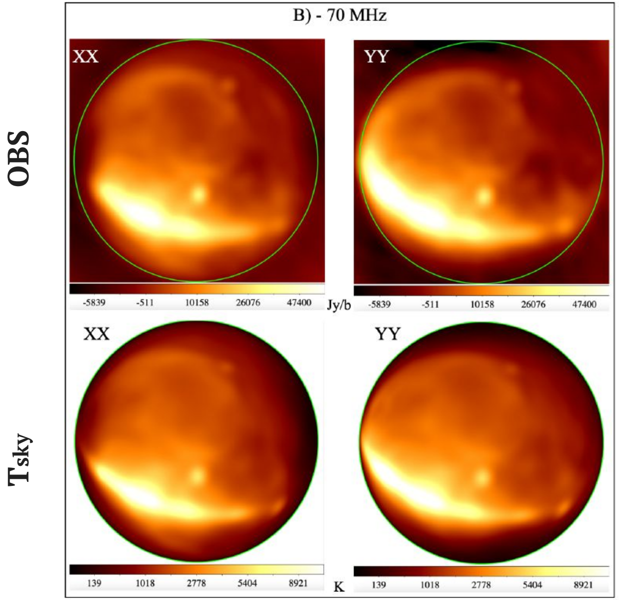
- Simple **Sun-based calibration**: use only **Sun** (at transit), assuming average EEPs
- all-sky XX, YY and Stokes images *mainly* aimed at verifying:

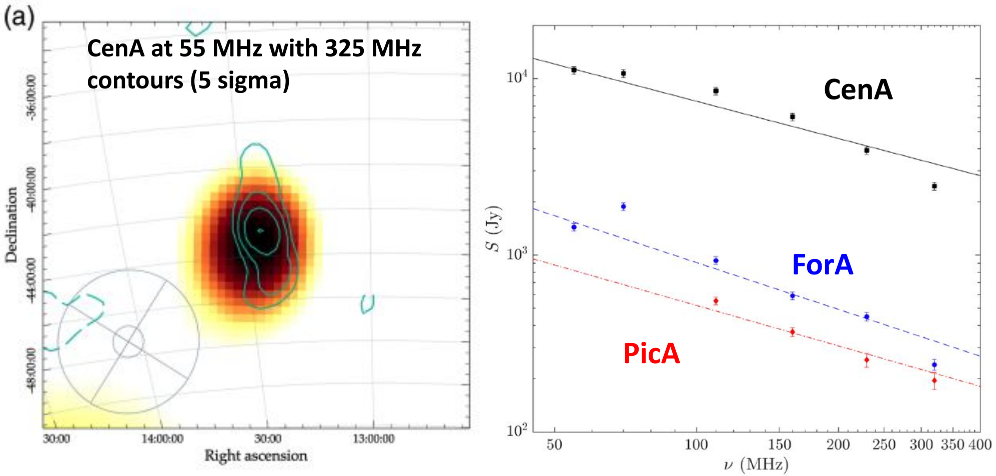
→ Sensitivity performance
Macario+ 2022

→ Polarization performance
Macario+ 2023 (submitted to PASA)

Calibration and imaging (Macario+ 2022, JATIS)

SPECIAL SECTION ON THE SKA OBSERVATORY
5 January 2022
Characterization of the SKA1-Low prototype station Aperture Array Verification System 2



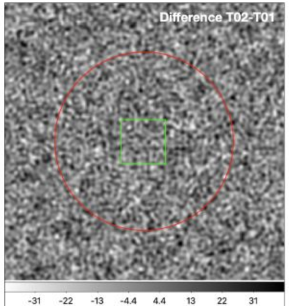


1. Sun based calibration efficient (>70 MHz)
Good agreement with brightness Tsky maps (extrapolated from GSM), at all frequencies

2. Flux scales are consistent
A-team sources integrated spectra agree with expected power-laws from literature

Sensitivity (Macario+ 2022)

Difference images - noise - SEFD - A/T

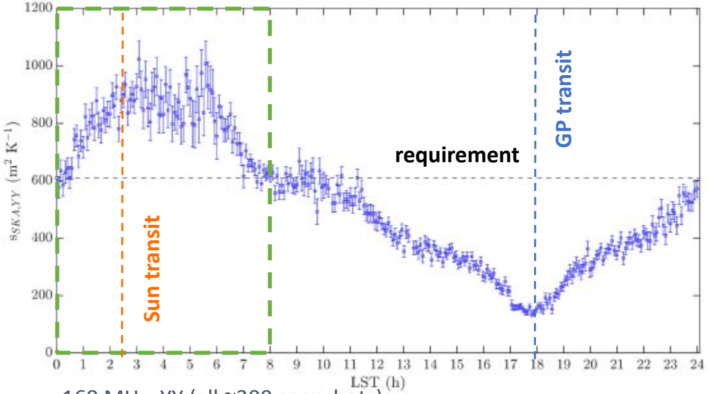


$$SEFD_{s,p} \simeq \frac{\sigma_p}{\sqrt{2}} \eta \sqrt{t_i B} \frac{N}{256} \quad \text{Jy}$$

$$s_{s,p} \equiv \frac{A_{eff}}{T_{sys}} = 10^{26} \frac{2k}{SEFD_{s,p}} \quad \text{m}^2\text{K}^{-1}$$

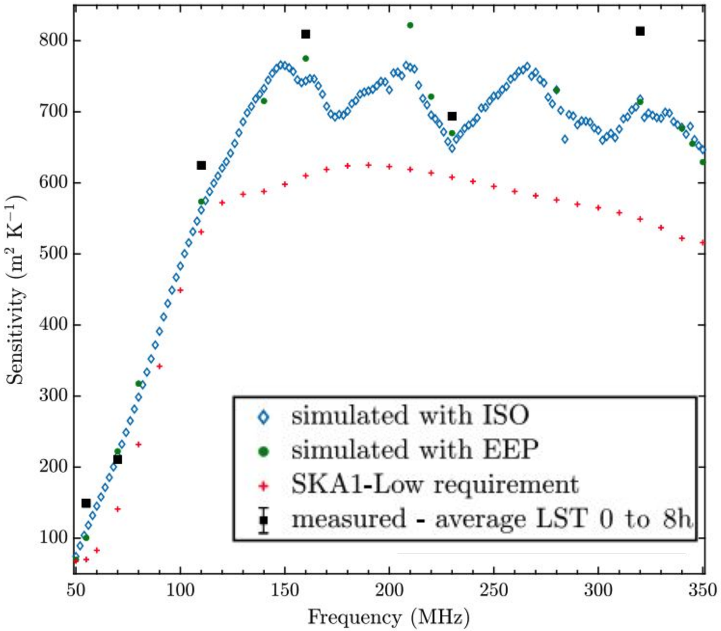
x 512

SKA-Low A/T per polarization



160 MHz, YY (all ~300 snapshots)

6 frequencies



3. First ever observational validation of SKA-Low sensitivity across its bandwidth

- good agreement with simulation (≲13%)
- meet SKA-Low req. at all frequencies (up to ~2.3 higher)

Polarization performance (Macario+ 2023, sub.): IXR

Intrinsic cross polarization ratio (**IXR**) → measures the *polarization purity* of the system

Instrum. pol. leakage

$$D = \frac{\sqrt{M_{10}^2 + M_{20}^2 + M_{30}^2}}{|M_{00}|}$$

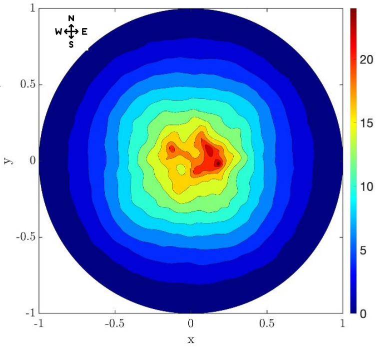
$$IXR_M(\theta,\varphi) = \frac{1}{D(\theta,\varphi)}$$

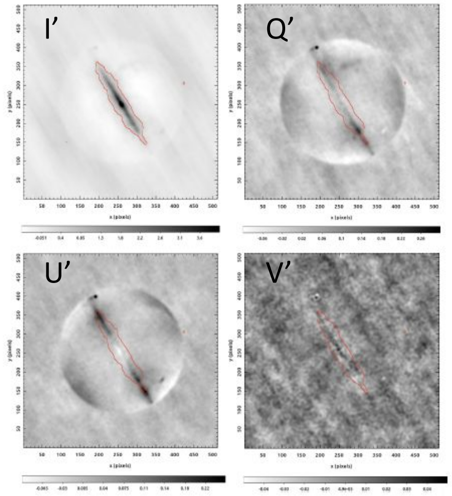
Mueller IXR *Carozzi & Woan, 2011*

Mueller matrix elements at each (θ,φ) computed from **EM simulations**

see e.g. *Bolli, Davidson +, 2022*

Simulated IXR map (160 MHz, dB)





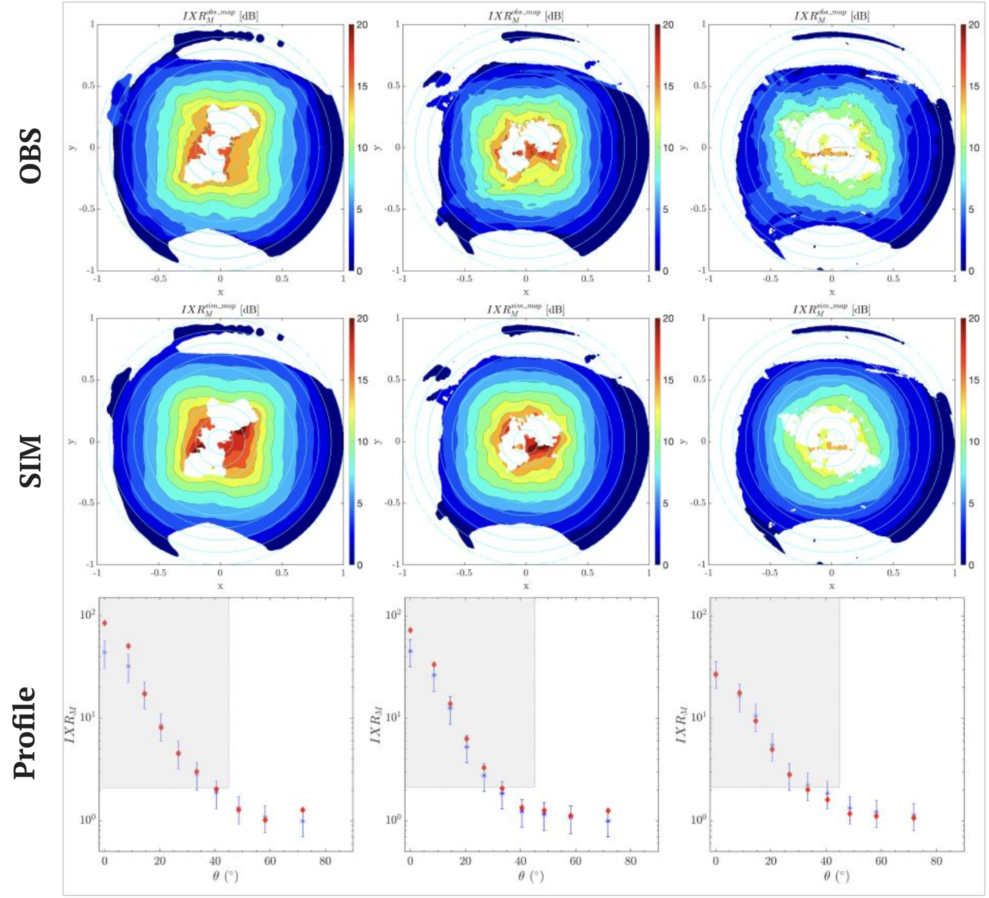
Assumption:
sky emission is *largely* ***unpolarised***

Mueller matrix elements at each (θ,φ) measured from **observations** *(Stokes all-sky images)*

$$L(\theta,\phi) = \frac{|M_{00}(\theta,\phi)|}{\sqrt{M_{10}^2(\theta,\phi) + M_{20}^2(\theta,\phi) + M_{30}^2(\theta,\phi)}} = \frac{|I'(\theta,\phi)|}{\sqrt{Q'^2(\theta,\phi) + U'^2(\theta,\phi) + V'^2(\theta,\phi)}} = IXR_M(\theta,\phi).$$

Novel IXR mapping algorithm:
– uses the Galactic Plane I, Q, U, V emission (> 5 sigma) as IXR *tracer*
– compute and reconstruct all-sky **observed IXR maps** comparable with simulated maps

Polarization performance (Macario+ 2023, sub.): results



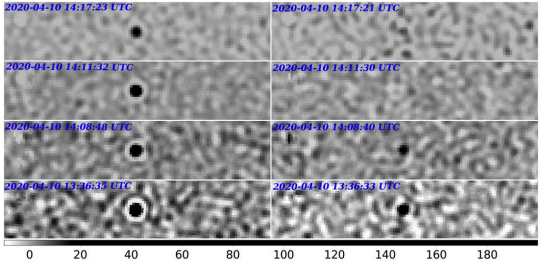
3. First observational verification of SKA-Low station IXR (polarization performance)

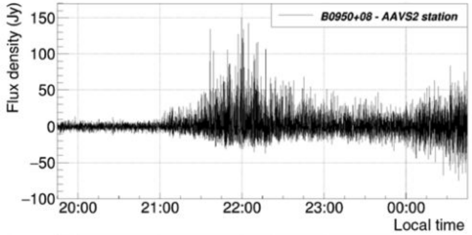
- very good morphological agreement between observed and simulated IXR maps
- good consistency of IXR values in radial profiles
- SKA-Low IXR requirement* satisfied

*at least 12 dB over the whole observing band within the HPBW up to observing angles of 45°

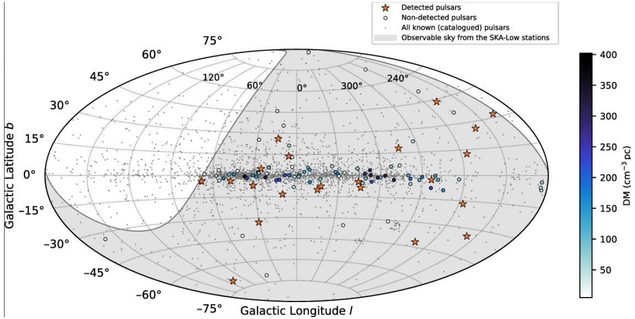
Highlights of scientific results with AAVS2

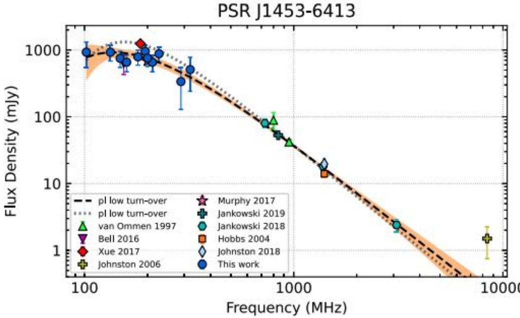
- Southern Hemisphere real-time all-sky imager and transient monitoring *(Sokolowski et al. 21)*





- 22 pulsars detections and spectral analysis *(Lee + 22)*



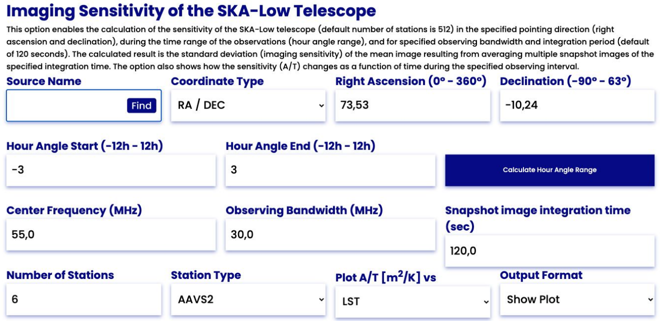


SKA-Low sensitivity online calculator (Sokolowski+22)

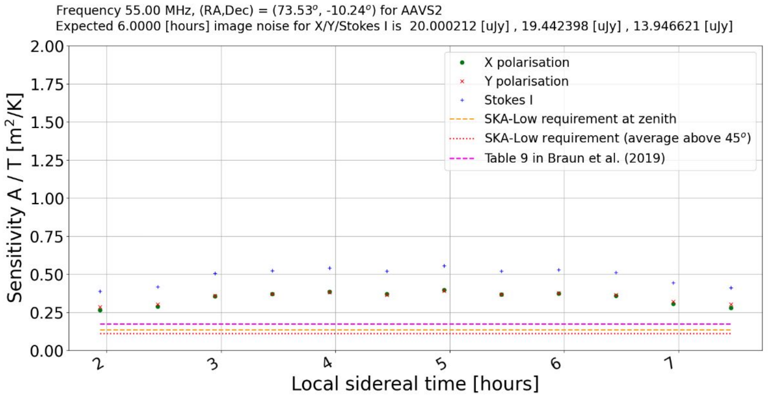
http://skalowsensitivitybackup-env.eba-daehsrjt.ap-southeast-2.elasticbeanstalk.com/

Database of pre-computed sensitivity values
(10 MHz steps in 50-350 MHz, 1/2 hour LST intervals, and 5 degree pointing direction resolution)

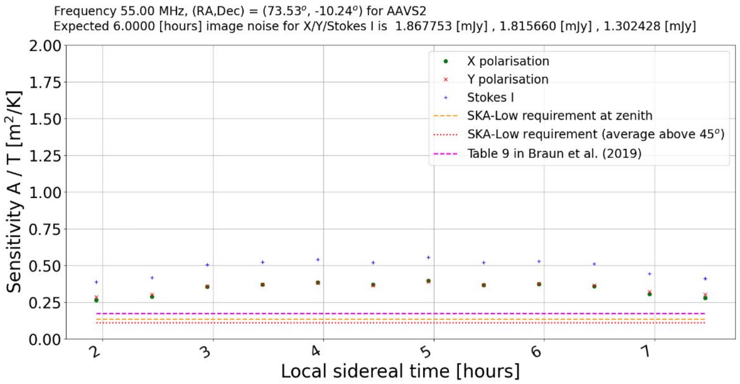
1. Station A/T vs frequency (at specified RA/DEC or Az/El)
2. Station A/T vs LST (at specified RA/DEC or Az/El)
3. Station all-sky sensitivity maps
4. **Telescope Imaging sensitivity (for your "favourite" source)**
   (choice on: n of stations, bw, int time, frequency and tracking time)



My favourite source SKA-Low (512 stations)



My favourite source AA0.5 (6 stations)



Warnings: Only the thermal noise (no confusion, no ionospheric effects), uv-coverage, calibration and imaging choices not included

AAVS3 commissioning: the INAF observing team involvement

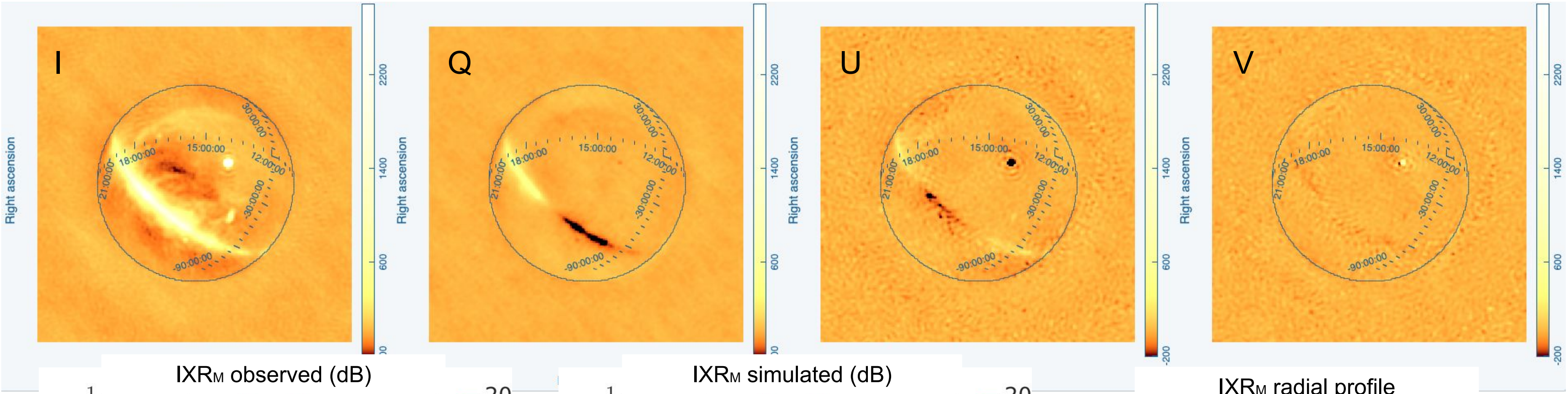
Array calibration, Imaging, sensitivity, IXR

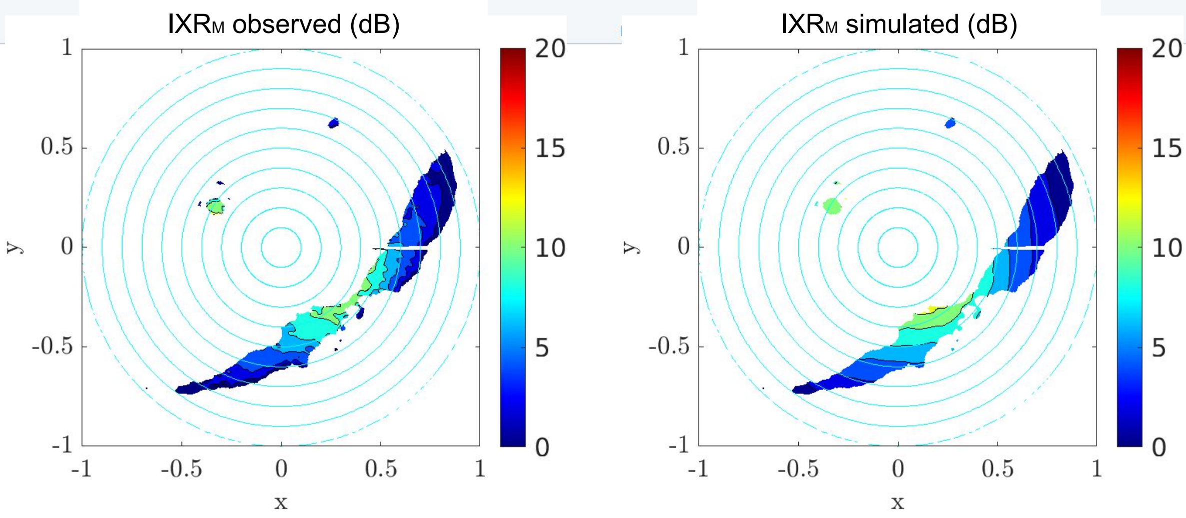
Commissioning plan: **Dec 2023- March 2024**

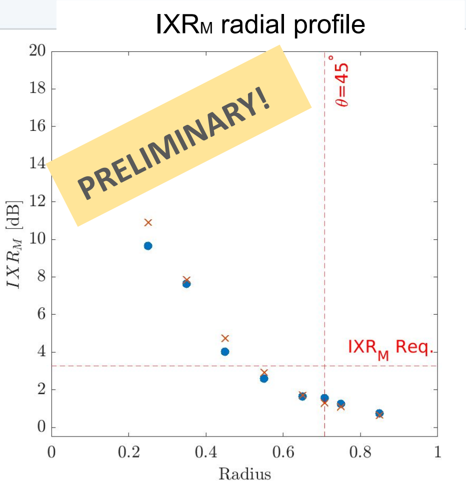
Test	Objective and key results	Station layout
Calibration using sky model (Sun + Galaxy + point sources) + EEPs	Calibration solves for antenna gains vs frequency Make comparisons between the AAVS2 (pseudo random) and AAVS3 (Vogel)	AAVS2 and AAVS3 (simultaneous tests)
Flux Calibration	Establish calibration procedures	AAVS3 (simultaneous tests with AAVS2 is preferable)
Gain and bandpass calibration with Sun	Establish calibration procedures with CASA or MIRIAD.	AAVS2 and AAVS3 (simultaneous tests)

Test	Objective and key results	Station layout
All Sky imaging for 24h	all-sky images using CASA or MIRIAD	AAVS2 and AAVS3 (simultaneous tests)
System sensitivity	Station SEFD verification with the GSM and EEPs Imaging sensitivity for 3C444 (TBC) and A/T vs. time	AAVS3
IXR measurements	Establish IXR analysis procedures	AAVS3

AAVS3 first light: 15’ correlated data (27/10/23) - 160 MHz - Polarization images (Sun based calibration)







Summary and future work

Main results so far:

- SKA-Low **sensitivity** and **polarization** performance *addressed by EM simulations*
- SKA-Low **sensitivity** *validated through AAVS2 observations*,
- SKA-Low *sensitivity calculator* online
- AAVS2 **polarization** response *initially verified through IXR* observed maps

Next: keep exploiting and growing the **INAF team expertise** towards the *next phases* of SKA-Low construction

- AAVS2/AAVS3: *commissioning plan tasks* (cal. & imaging, sensitivity, IXR)
- AA0.5 first observations upcoming (under construction, expected 2024)

→ ***getting ready for SKA-low science commissioning!***

SKA Phase1 construction Proposal

Key project milestone	Identifier	LOW Telescope
Start of construction	T0	1st July 2021
Earliest start of major contracts	C0	August 2021
Array Assembly 0.5 finish	AA0.5	February 2024
Array Assembly 1 finish	AA1	February 2025
Array Assembly 2 finish	AA2	February 2026
Array Assembly 3 finish	AA3	January 2027
Array Assembly 4 finish	AA4	November 2027
Operations Readiness Review	ORR	January 2028
End of Construction		July 2029

- 6-station array
  - Basic array element calibration demonstrated
  - Observation calibration demonstrated
  - Imaging validated by comparison with results from MWA
  - Data reduction expected to be offline

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