Simulating radio observations with KARABO

Alexandre Referiger, André Csillaghy, Alex Pascal, Devin Chricton, Filip Schmeka, Jennifer Studer, Lukas Gehrig, Luis Fernando Machado Poletti Valle, Marta Spinelli, Michele Bianco, Rohit Sharma, Simon Felix, Pascale Berner, Vincenzo Timmel
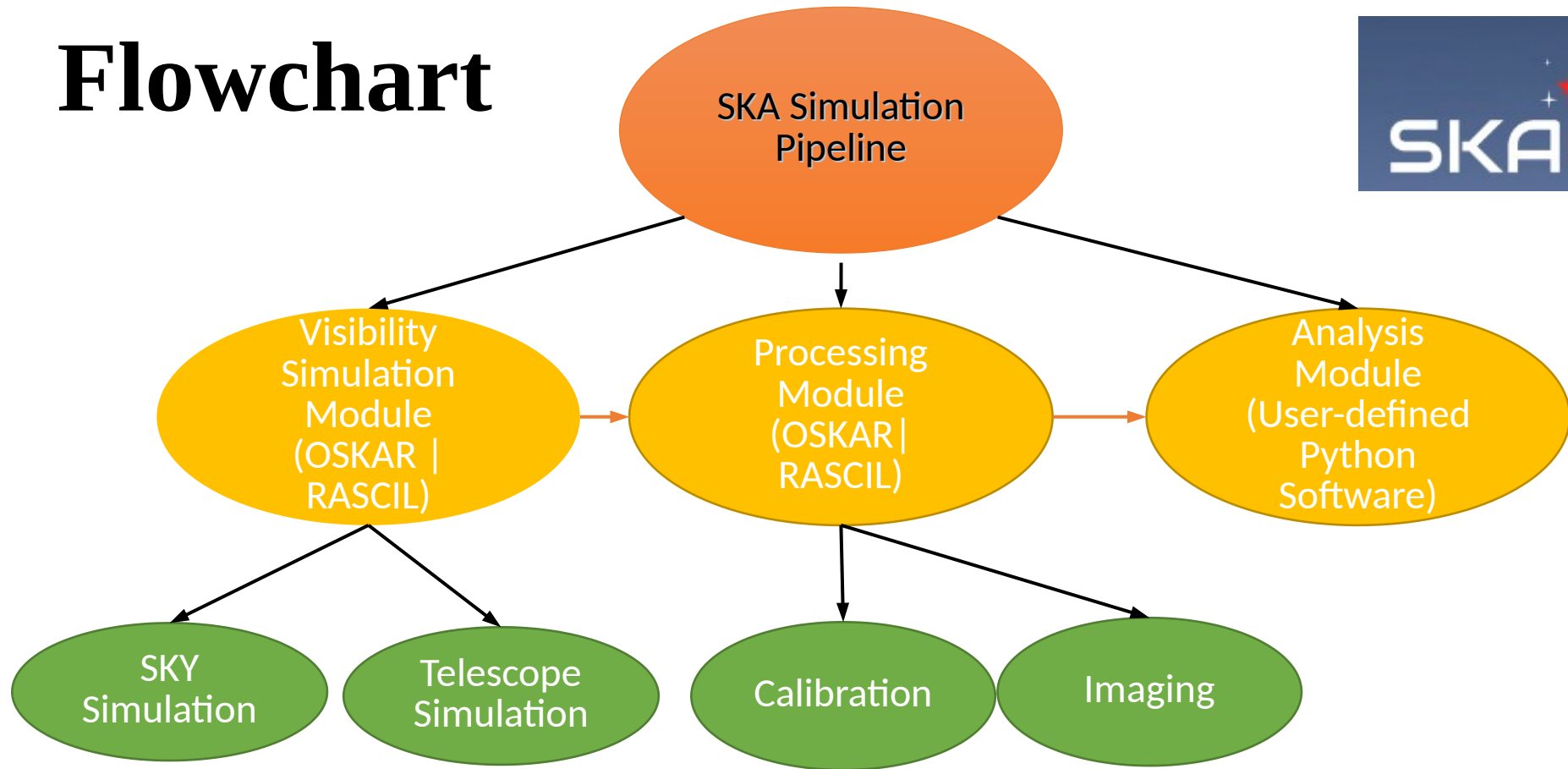
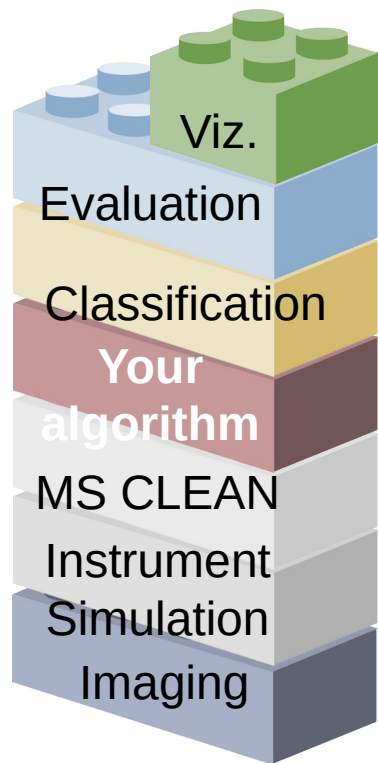**- Presented by: Rohit Sharma, FHNW, Windisch**

6th September 2023
SKA Days Meeting, University of Zurich, Switzerland

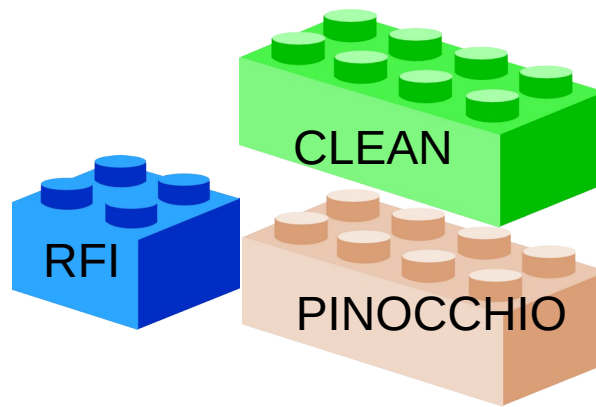# Flowchart

Introduction

Fast and easy ramp-up.

Build **custom** pipelines
with our building blocks.

Add your own blocks.

Flexible Building Blocks which can be
connected, used stand-alone or replaced

- SKA data simulator

- Karabo is a Square
  Kilometer Array Digital
  Twin Pipeline, which is
  written in Python and set up
  in an interactive Jupyter
  Notebook environment.

- Two specific radio telescope
  packages are used:

- OSKAR: Responsible for
  the simulation of the sky and
  the telescope

- RASCIL: Responsible for
  imaging

Technical Features of Karabo

- System noise

- Primary Beam

- Skymodels from Catalog e.g. GLEAM, MIGHTEE

- Ionospheric Screens

- Parallelisation by Channels / Long observation module

- Integration of Pinnochio (Dark Matter halo Simulation)

- Multiple telescopes (> 25) configuration

- Future: RASCIL & OSKAR synchronous workflows

System Noise → Karabo
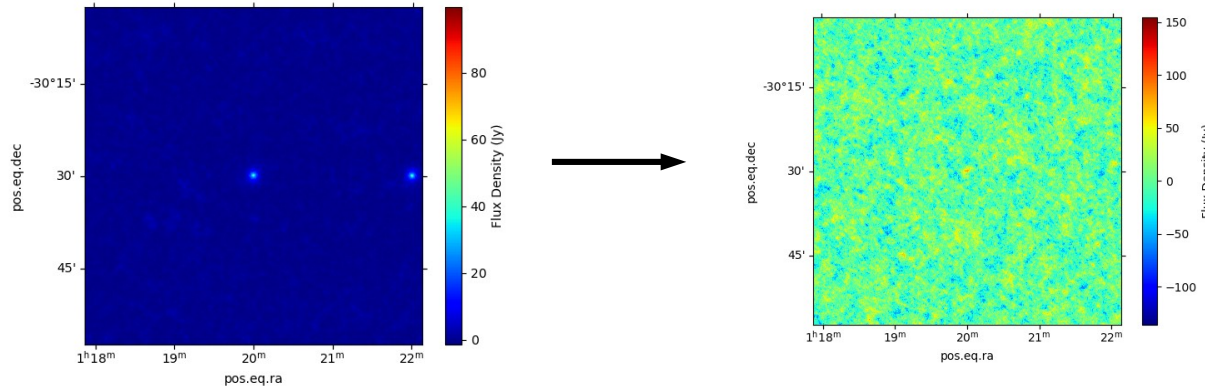
- Averaged baseline-based RMS noise

- Input RMS noise = 8000 Jy

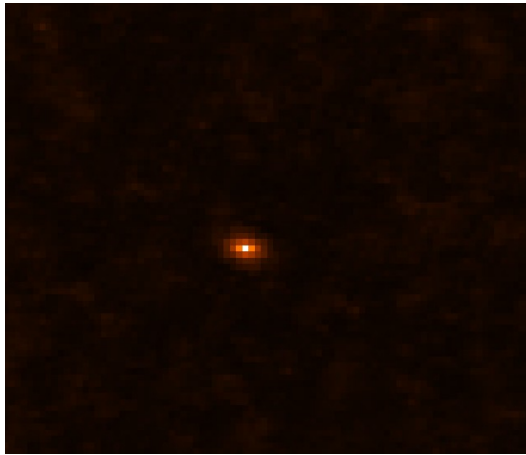- For Meerkat nd ~ 2016

- Image RMS ~ 50

Baseline RMS

$$\sigma_{p,q} = k_{\mathrm{B}} \sqrt{\dfrac{2\, T_p T_q}{A_p A_q\, \eta_p \eta_q\, \Delta\nu\, \tau_{\mathrm{acc}}}}$$

$$\sigma_{p,q} = \sqrt{\dfrac{S_p S_q}{2\, \Delta\nu\, \tau_{\mathrm{acc}}}}$$
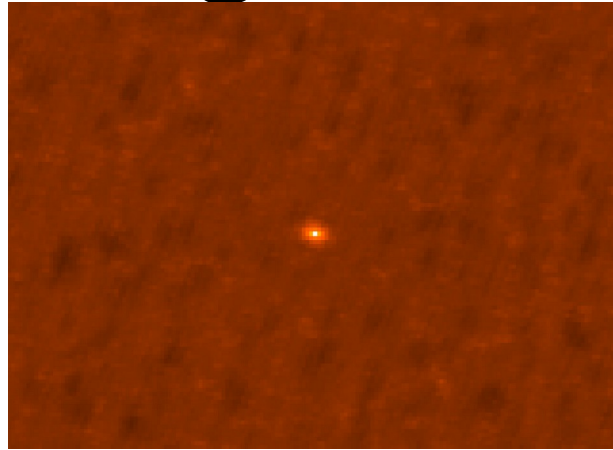
Image RMS

$$\sigma_{\mathrm{im}} = \dfrac{\sigma_{p,q}}{\sqrt{\dfrac{n_a(n_a-1)}{2}\dfrac{\tau_0}{\tau_{\mathrm{acc}}}}} = \dfrac{\sigma_{p,q}}{\sqrt{n_d}}$$
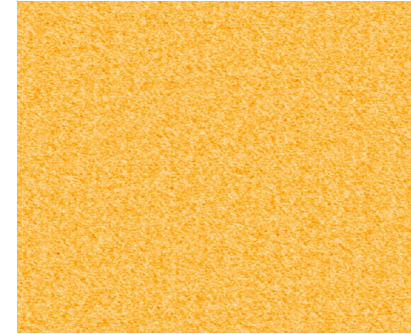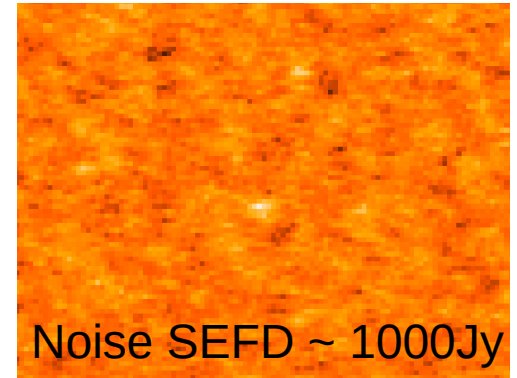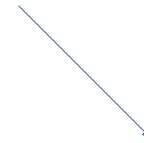
Impact of primary beam on Images

10 Jy source

With Primary Beam

With Primary Beam and
Noise SEFD ~ 5000 Jy

Noise SEFD ~ 1000Jy

Use Cases

- Simulated Dark matter halo & Intensity Mapping

- Mock HI MIGHTEE Catalogue

- Source Detection

- Ionospheric Studies

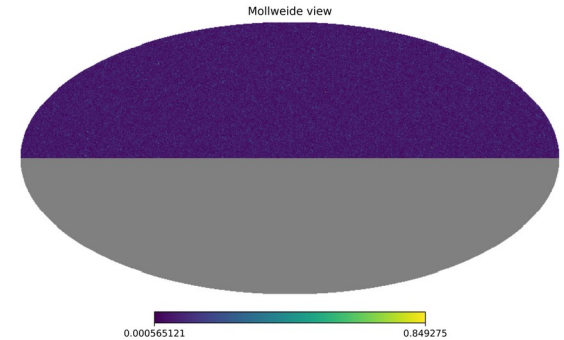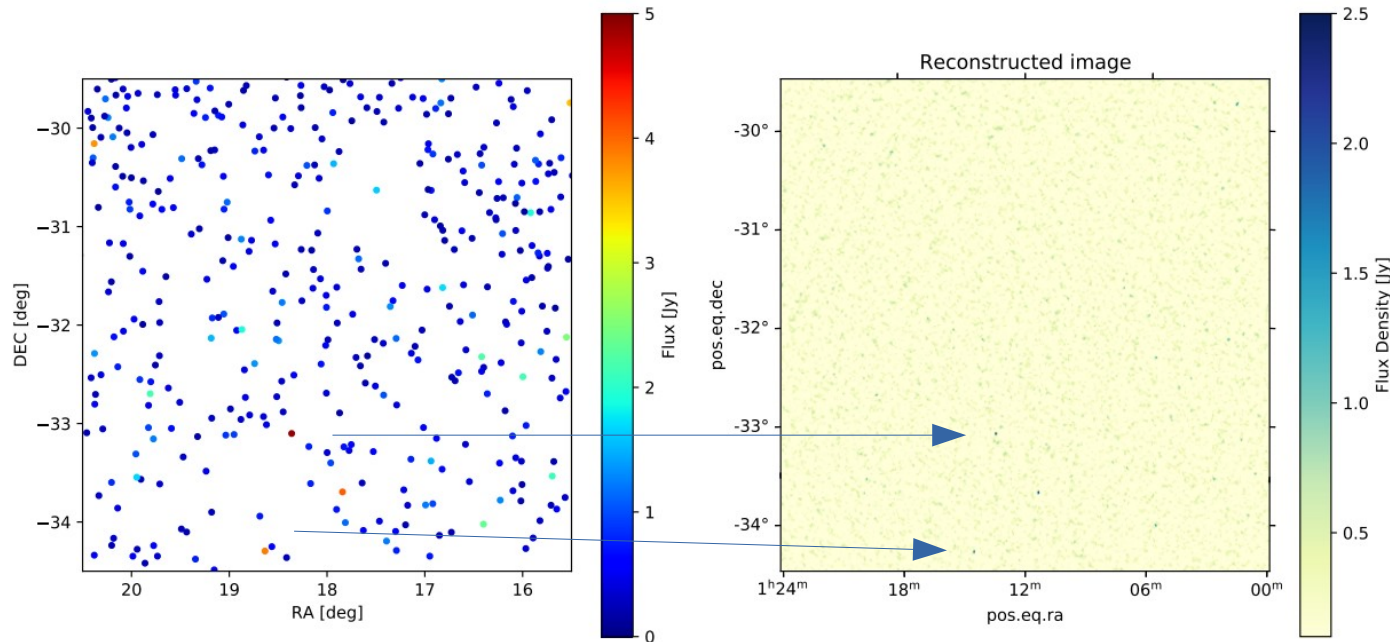- EoR / SKA Data Challenge – 3

- Solar Physics

Simulated Dark Matter Halo Skymodels and Intensity Mapping

- Dark matter halo – Pinnochio Simulation

- Halo to HI mass distribution -

- Catalog of simulated HI sources

$$M_{\mathrm{HI}}(M) = \alpha f_{\mathrm{H,c}} M \left(\frac{M}{10^{11} h^{-1} M_\odot} \right)^\beta \exp \left[- \left(\frac{v_{c,0}}{v_c(M)} \right)^3 \right]$$

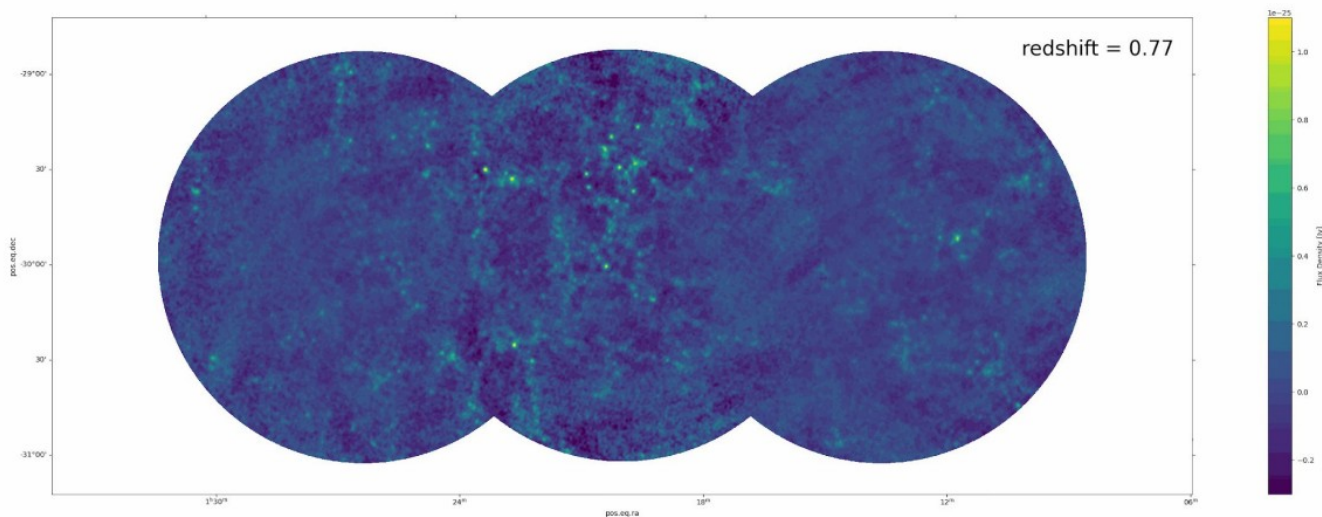Padmanabhan, Refregier & Amara (2017)

More in Pascal and Luis talks on Friday

Simulated Dark Matter Halo Skymodels and Intensity Mapping
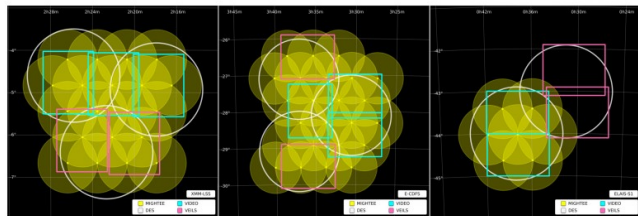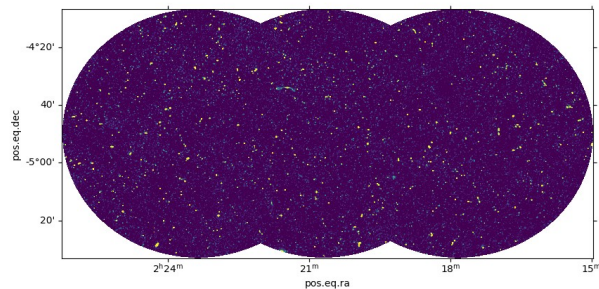
- Requires good primary beam characterization

- Large scale images using Mosaicing

More in Pascal and Luis talks on Friday

Mock-MIGHTEE Survey

MeerKAT International GHz Tiered
Extragalactic Exploration (MIGHTEE)

Figure 4: Current plausible pointing strategies for (left-to-right) XMM-LSS (20 pointings, 6.7 deg²), E-CDFS (24 pointings, 8.3 deg²) and ELAIS-S1 (7 pointings, 1.6 deg²). Not shown here is the fourth COSMOS field, which will consist of a single deep pointing. In practice the grid of E-CDFS pointings will be snapped to the LADUMA pointing centre, requiring only 23 additional pointings from MIGHTEE.

Frequency Band	Resolution (arcseconds)	Field of View (degrees)	RMS noise in one hour (microJy)
1.75 – 2.50 GHz	4	0.65	∼5
0.90 - 1.67 GHz	6	1.1	4.7
0.58 - 1.01 GHz	10	1.75	9.0

Total FoV	20 deg²	
Frequency Coverage	900-1670 MHz	
Total Bandwidth	770 MHz	
Nominal sensitivity	1 micro Jy	
Spatial - resolution	~ 6 arcsec	
Observation time per pointing	16 hour	2 micro Jy per beam
Spectral Line	26 kHz	90 micro Jy per beam
Total Channels	32,728	3.27 kHz (Narrowband Extended) 26 kHz (Wideband fine)
Coarse Chanels	4096	208 kHz

L-band: 18cm to 33 cm (910 MHz – 1670 MHz)

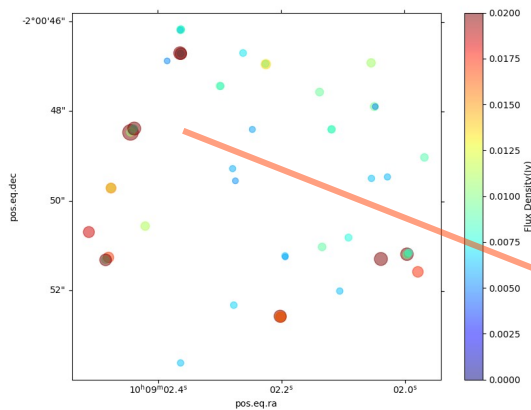S-band Low: 11 cm to 16 cm (1875 – 2727 MHz)

S-band high: 8 cm to 13 cm (2300 MHz - 3750 MHz)

S-band FoV = 4 deg2 in E-CDFS (Chandra Deep Field South) and 1.5 deg2 in COSMOS (Cosmic Evolution Survey)
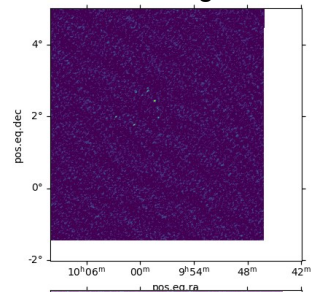
For 40 pointing and coarse bandwidth, we will have 40*4096 = 163k MS / Images
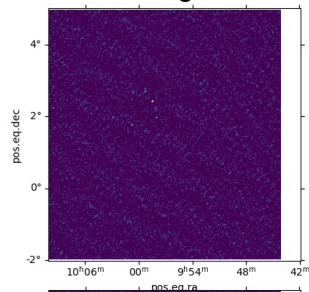
For fine bandwidth, we have 1.3 million MS / Images

Example Simulation of MIGHTEE Survey
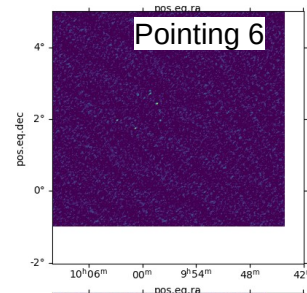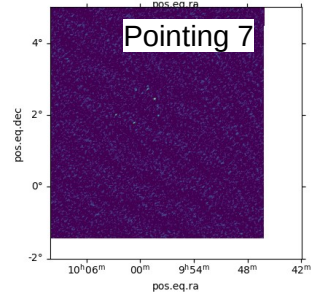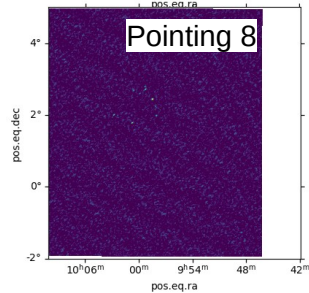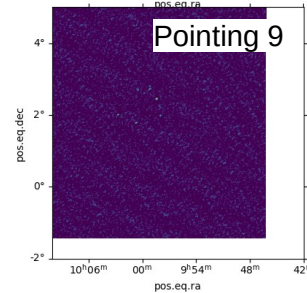
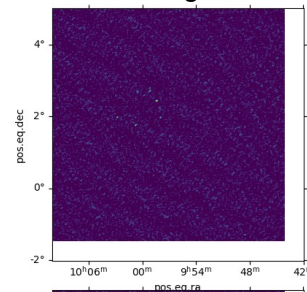# Mock Data Execution time
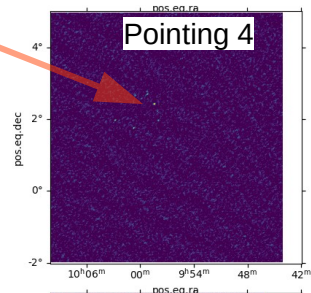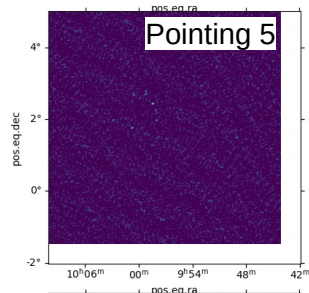
| #	Run	Time until vis run (s) from the start	Time until vis file written (s)	Time until image file written (s)
0	Snapshot Run – 1 channel	20.5	20.6	24.8
1	Snapshot Run – 1 Channel with thermal noise	24.2	24.2	30.3
2	Snapshot Run – 10 Channel with thermal noise	22.4	22.4	46.55
3	Snapshot Run – 30 Channel with thermal noise	30.2	30.2	148.2
4	Snapshot Run – 60 Channel with thermal noise	40.3	40.3	247.2
5	Snapshot Run – 80 Channel with thermal noise	42.2	42.2	373.6
6	Snapshot Run – 100 Channel with thermal noise	44.4	44.4	537.7
7	10 h (1 timestamp) + 1 channel + thermal noise	23.8	23.8	28.8
8	10 h (1 timestamp) + 30 channel + thermal noise	26.7	26.7	148.3
9	10 h (30 timestamp) + 30 channel + thermal noise	111.5	111.6	247.2
10	10 h (100 timestamp) + 30 channel + thermal noise	331	331	469
11	1 channel + 1 timestamp + 13 sources	20.9	20.9	24.2
12	1 channel + 1 timestamp + 1122 sources	25.7	25.7	28.74
13	1 channel + 1 timestamp + 9896 sources	26.8	26.8	30.1
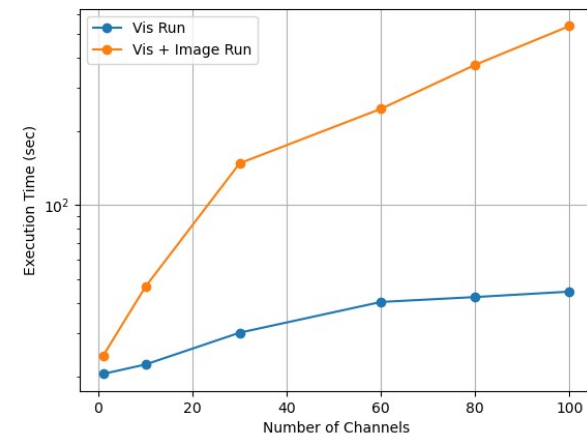
+ For 30,000 channels and 1 channel, the estimated time ~ 161310 sec ~ 2 days
+ For 40 pointing, 80 days with single core!
+ With 80 cores, estimated time ~ 1 days for 1 timestamp
+ For 16h observation with 10 min time-intergation each, we get total 96 timestamps. We get total 96 days with 80 cores. With 1000 cores, we can reduce it to ~ 8 days.
+ For 30 min time-integration, we can reduce execution time by factor 3, i.e. 2-3 days.
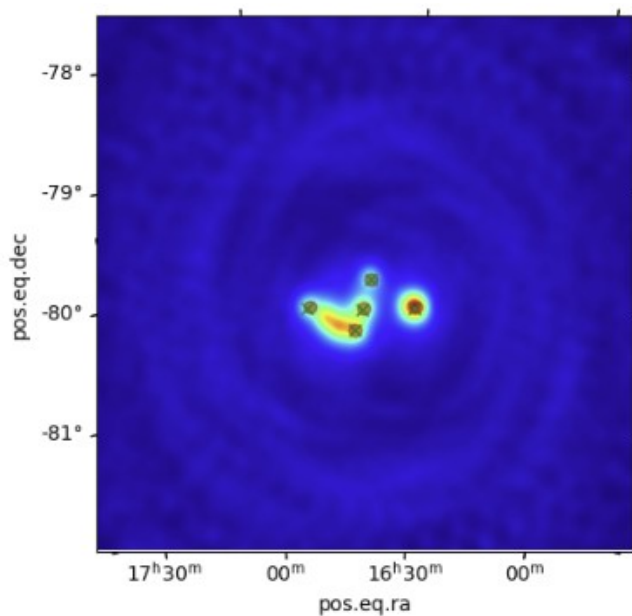
Source Detection Evaluation and Comparisons
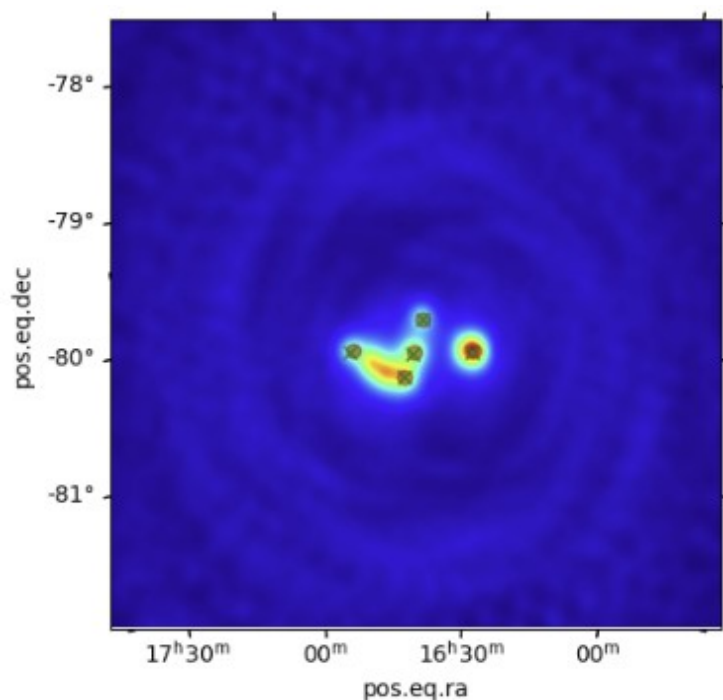
- ***source_detection.ipynb*** shows how to use *detect_sources_in_image*

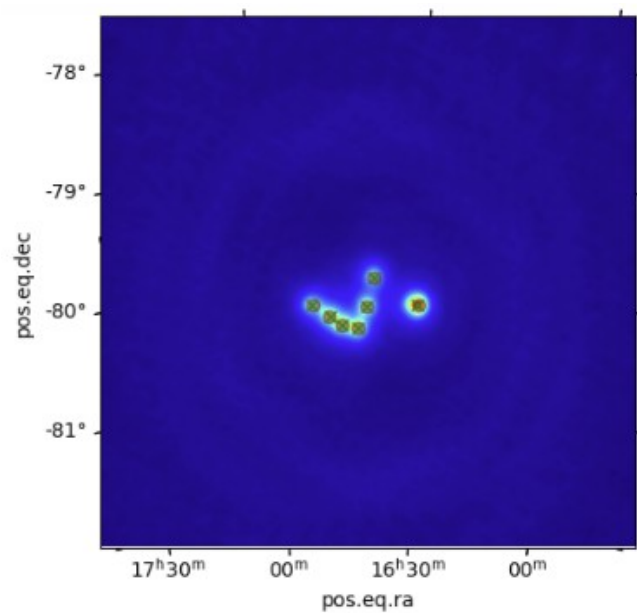- Handily callable functions such as *.plot()* allows fast comparisons between different algorithms.

# Source Detection Evaluation and Comparisons

Dirty Image

Clean Image

Ionosphere Effects

- Aratmospy: The ionospheric screen was 200 km by 200 km in size, and was modelled as two layers moving in different directions at different speeds to reduce the amount of repetition in the pattern over time: one layer moving at 150 km/h at 300 km altitude, and the other at 75 km/h at 310 km altitude.

- The resolution was 100 metres per pixel. At that altitude, the screen spanned a field of view of almost 40 degrees, so it also covered sources outside the primary beam.
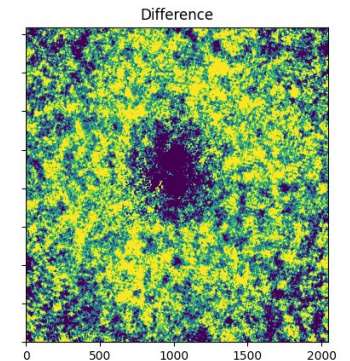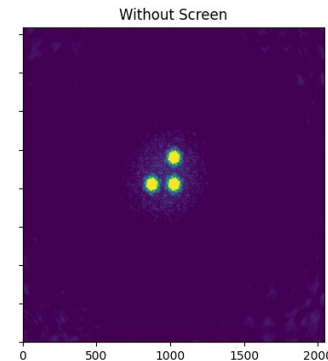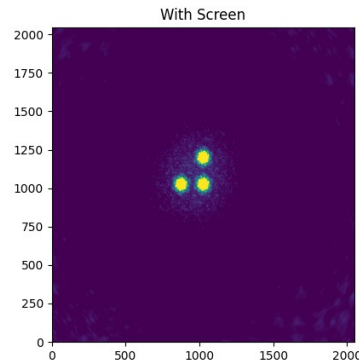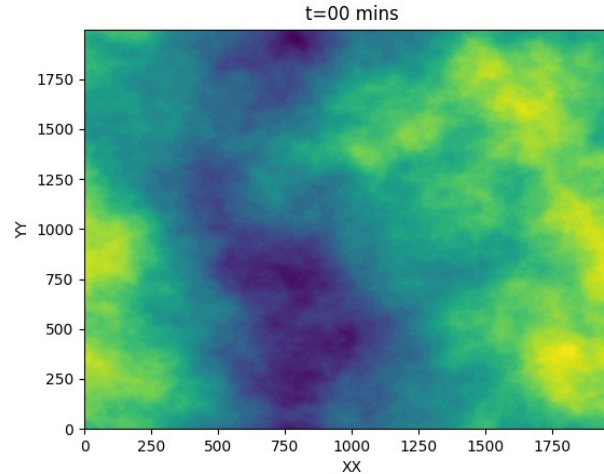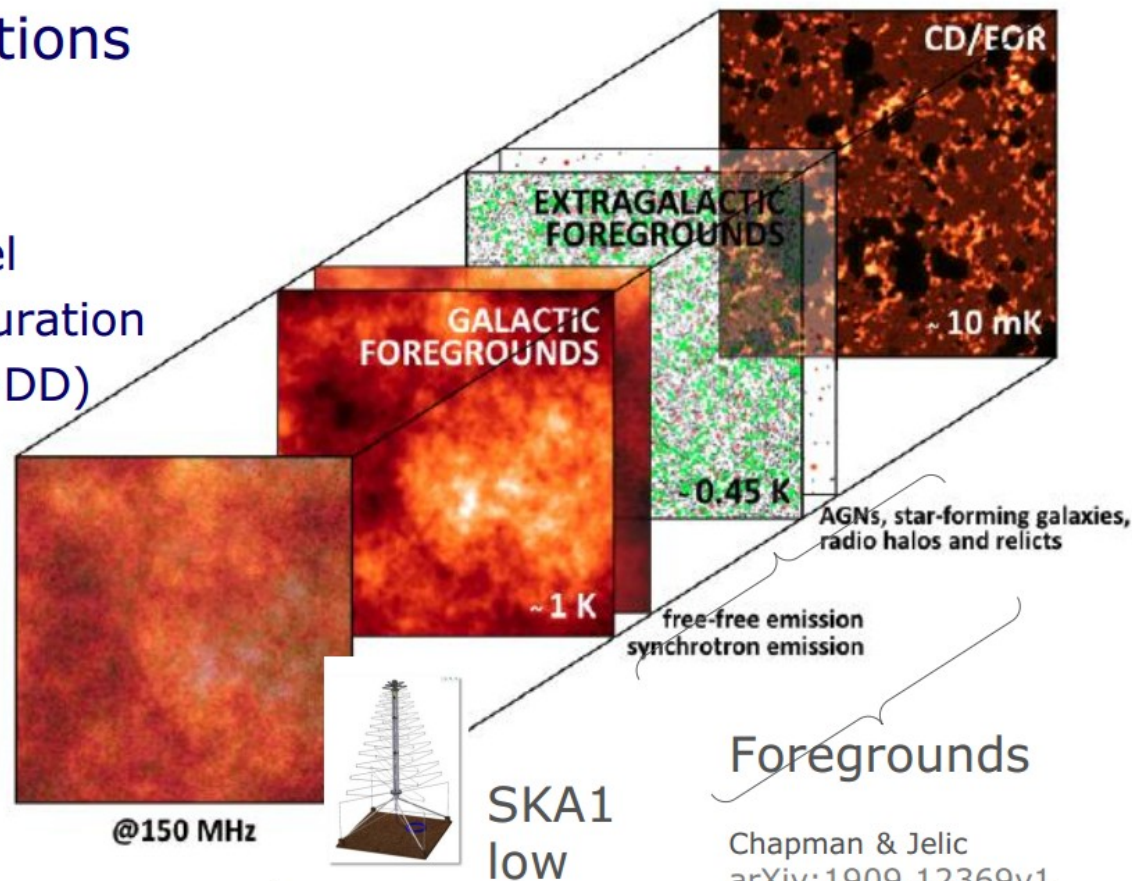
SKA Data Challenge - 3

Synthetic Observations

- . Signal Cube
- . Foreground model
- . Telescope Configuration
- . Gain Errors (DI +DD)

Synthetic Data Cubes

@150 MHz

SKA1 low

Foregrounds

GALACTIC FOREGROUNDS ~1 K

EXTRAGALACTIC FOREGROUNDS ~0.45 K

CD/EOR ~10 mK

AGNs, star-forming galaxies, radio halos and relicts

free-free emission synchrotron emission
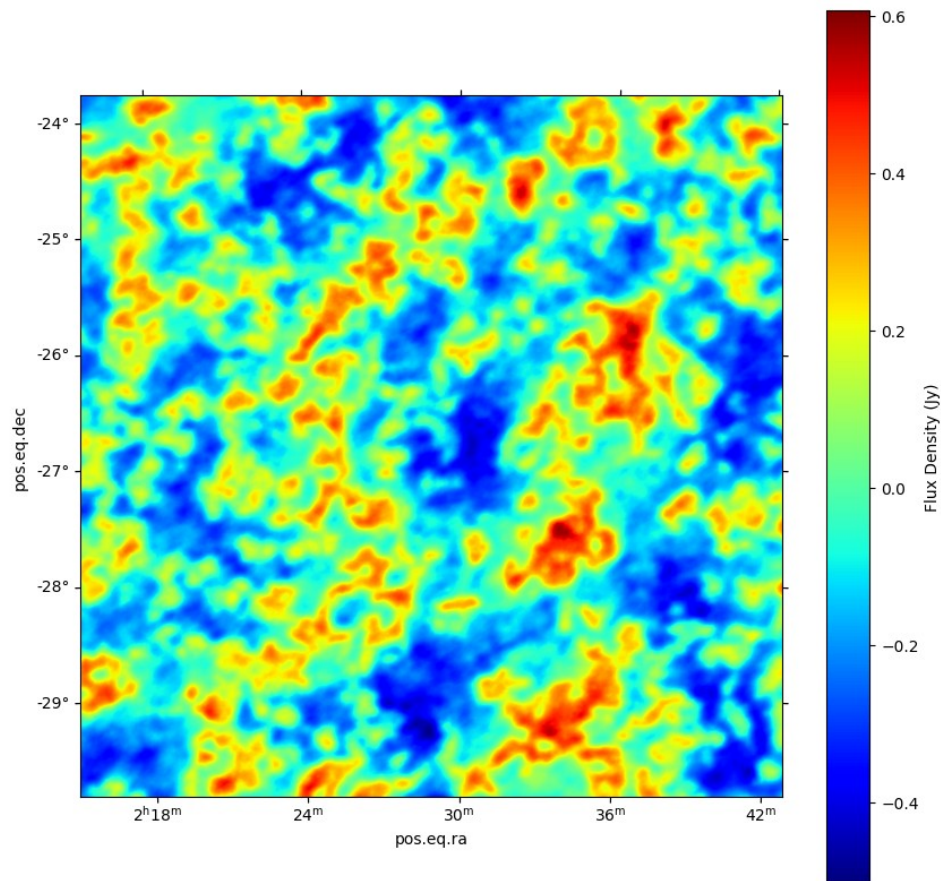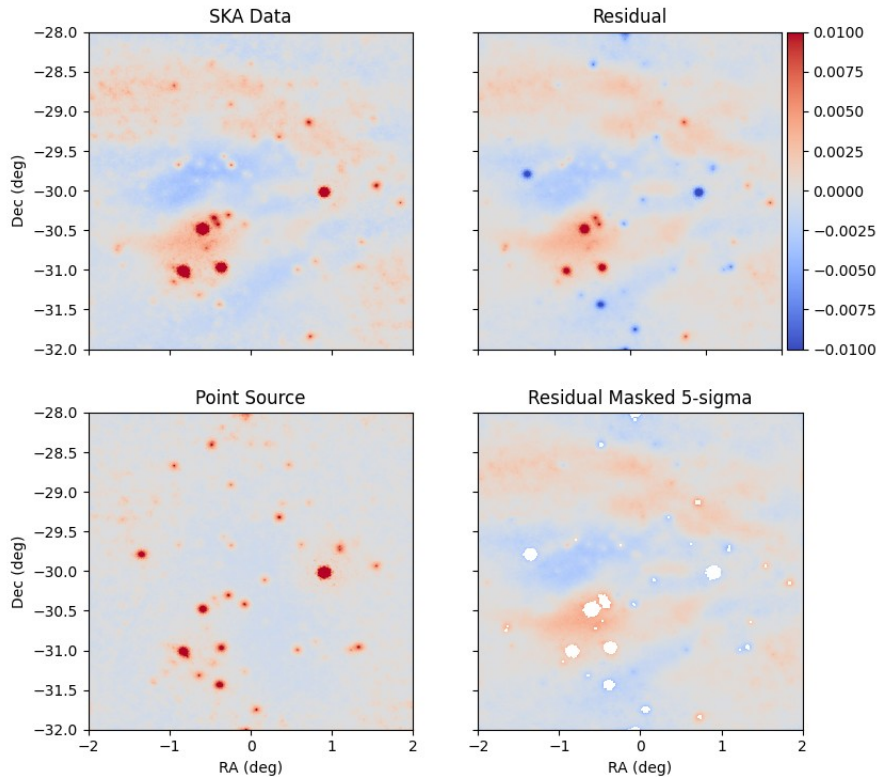
Chapman & Jelic arXiv:1909.12369v1

EoR - Simulations

- Karabo provide support to the vis simulations for SKADC-3 and imaging

- Parallisation by Channels

- Parallisation in Skymodels

See Michele's talk

SKADC3: Point Source Subtraction

- SKA Dataset with all artifacts

- GLEAM Catalog point source simulation with same observational parameters

- Visibilities are refined by subtraction – vector subtraction

- The residuals scales with the flux densities of the sources

- Images are refined to remove extreme residuals in the subtracted images
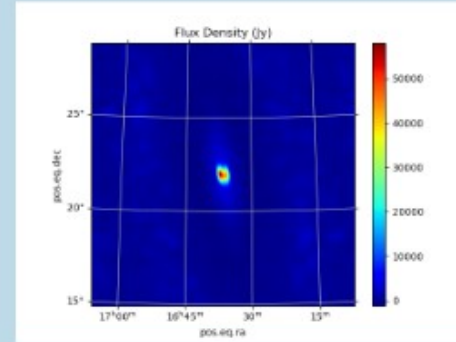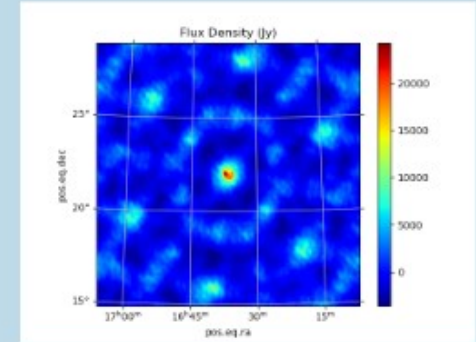
Solar Observations
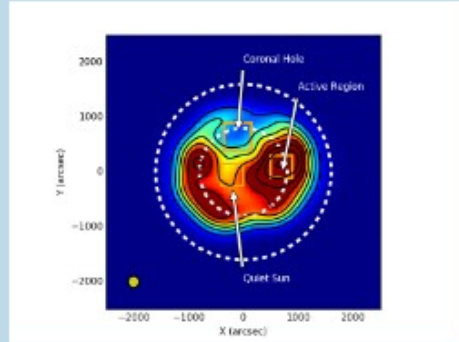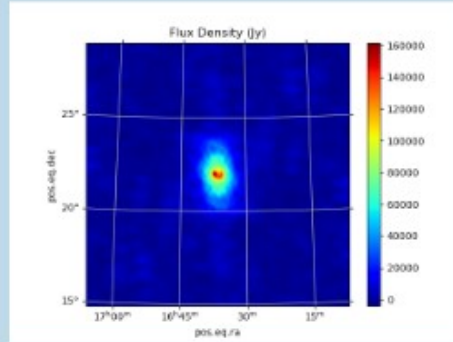
| Sun's Model | MWA | SKA-low | LOFAR |

- Quiet Sun - Extended and bright
- Radio burst – Compact and brighter
- Skymodel – Free-free emission maps
- Benchmarking with MWA Quiet Sun maps

Radio Interferometer Specifications

Instrument	$\nu(GHz)$	$\Delta\nu$ kHZ)	$\Delta t(s)$	SEFD (mSFU)
SKA-Low	0.05-0.35	15	0.001	0.5
LOFAR	0.03-0.24	100	0.01	30
MWA	0.08-0.30	10	0.5	5
SKA-mid	0.35-15.3	5	0.001	0.2
MeerKat	0.58-3.5	1.6	8	36
VLA	0.39-45	1000	0.05	42
ngVLA	5-100	200	< 0.001	23

Summary

- Karabo is a versatile tool and user-friendly
- Many use cases have been integrated
- Parallelised via channels
- Workflows are fast and efficient for CSCS deployments
- Many more features will come like wsclean integration, RFI modules, optimally handle extended sources etc.
- Future: RASCIL-based workflows and comparison with OSKAR
- Future: Integrate skymodels from Smoothed Particle Hydrodynamics (SPH) simulation

http://github.com/i4ds/Karabo-Pipeline

Code & Tech Doc.

https://swiss-ska.fhnw.ch/index.php/s/bJWAfTYyoJg3AGx

Files & Documentation

https://swissska.slack.com/

Chat in #digital-twin

| Report Issues | Request Features | Get Support | Contribute |