ExCALIBUR 10

LEARNED EXASCALE COMPUTATIONAL IMAGING (LEXCI): UPDATE

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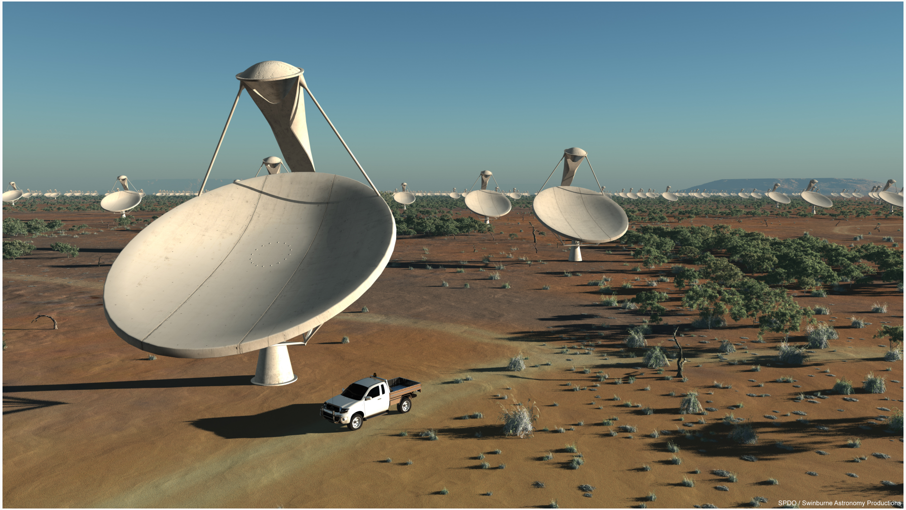
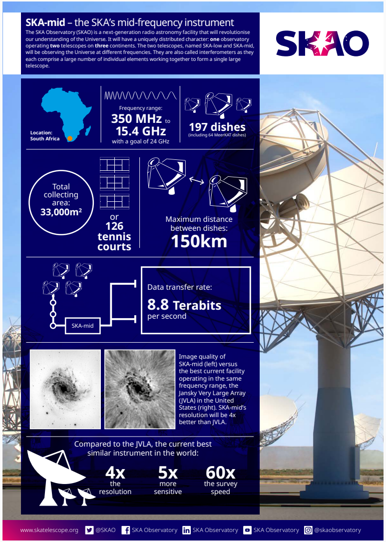
Engineer's House, 11-12 October 2023

Met Office
UK Research and Innovation
UK Atomic Energy Authority

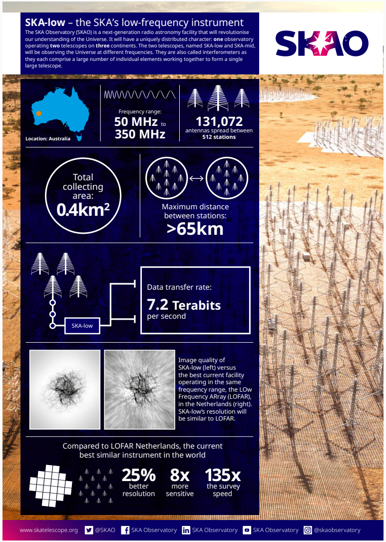
Canonical application: Square Kilometre Array (SKA)



SKA sites



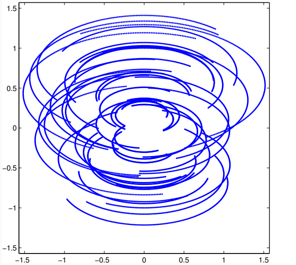
SKA-mid – the SKA's mid-frequency instrument
The SKA Observatory (SKAO) is a next-generation radio astronomy facility that will revolutionise our understanding of the Universe. It will have a uniquely distributed character: one observatory operating two telescopes on three continents. The two telescopes, named SKA-low and SKA-mid, will be observing the Universe at different frequencies. They are also called interferometers as they each comprise a large number of individual elements working together to form a single large telescope.
SKAO
Location: South Africa
Frequency range:
350 MHz to 15.4 GHz
with a goal of 24 GHz
197 dishes
(including 64 MeerKAT dishes)
Total collecting area: 33,000m²
or 126 tennis courts
Maximum distance between dishes:
150km
SKA-mid
Data transfer rate:
8.8 Terabits
per second
Image quality of SKA-mid (left) versus the best current facility operating in the same frequency range, the Jansky Very Large Array (JVLA) in the United States (right). SKA-mid's resolution will be 4x better than JVLA.
Compared to the JVLA, the current best similar instrument in the world:
4x the resolution
5x more sensitive
60x the survey speed
www.skatelescope.org @SKAO SKA Observatory SKA Observatory SKA Observatory @skaobservatory



SKA-low – the SKA's low-frequency instrument
The SKA Observatory (SKAO) is a next-generation radio astronomy facility that will revolutionise our understanding of the Universe. It will have a uniquely distributed character: one observatory operating two telescopes on three continents. The two telescopes, named SKA-low and SKA-mid, will be observing the Universe at different frequencies. They are also called interferometers as they each comprise a large number of individual elements working together to form a single large telescope.
SKAO
Location: Australia
Frequency range:
50 MHz to 350 MHz
131,072
antennas spread between 512 stations
Total collecting area:
0.4km²
Maximum distance between stations:
>65km
SKA-low
Data transfer rate:
7.2 Terabits
per second
Image quality of SKA-low (left) versus the best current facility operating in the same frequency range, the LOw Frequency ARray (LOFAR), in the Netherlands (right). SKA-low's resolution will be similar to LOFAR.
Compared to LOFAR Netherlands, the current best similar instrument in the world
25% better resolution
8x more sensitive
135x the survey speed
www.skatelescope.org @SKAO SKA Observatory SKA Observatory SKA Observatory @skaobservatory

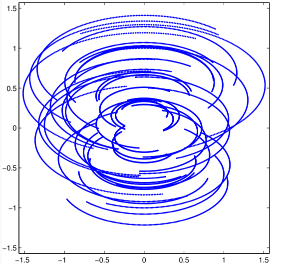
Radio interferometric telescopes acquire “Fourier” measurements

“Fourier” Measurements $\Rightarrow$



Radio interferometric telescopes acquire “Fourier” measurements

“Fourier” Measurements $\Rightarrow$



Interferometric imaging is an **exascale computational inverse imaging problem:**

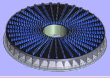
Recover an image from noisy and incomplete “Fourier” measurements.

LEXCI application domains more broadly

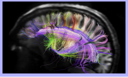
Learned Exascale Computational Imaging (LEXCI)

Radio Interferometry
e.g. MWA, SKA

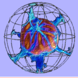
Optical Interferometry
e.g. SPIDER



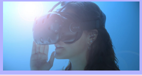
Medical Imaging
e.g. Diffusion MRI



Seismic Imaging
e.g. Mantle Plumes



Computer Graphics
e.g. Inverse Rendering



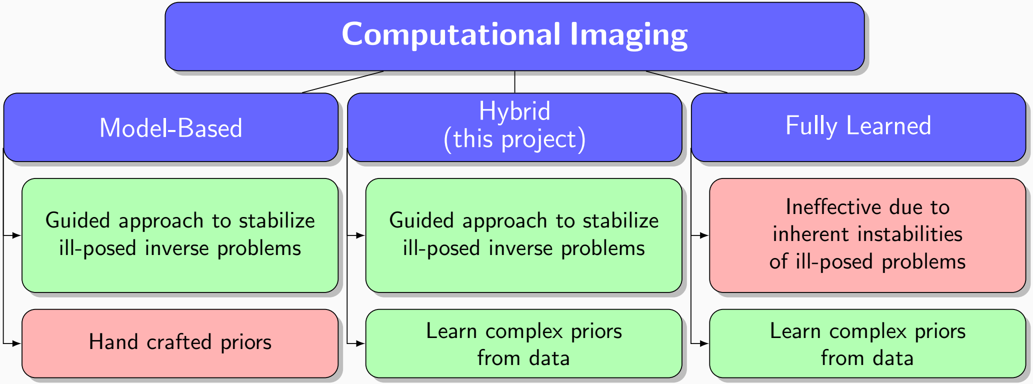
LEXCI project

Astronomical Imaging | **Planetary & Climate Science** | **Molecular Biology** | **Optical Photography** | **Geophysics**

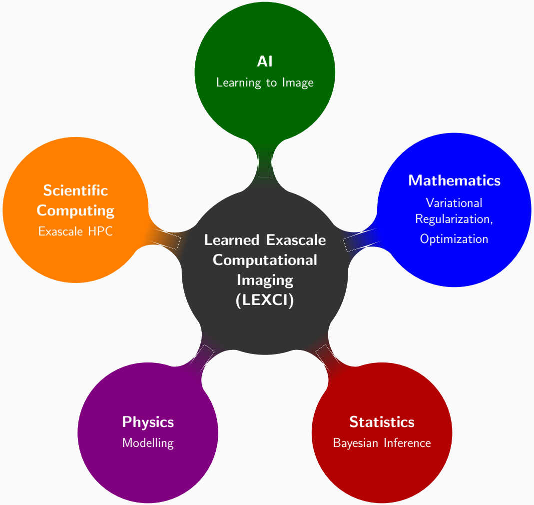
Acoustics | **Computer Vision** | **Many Others...**

Extended application areas

LEXCI hybrid approach



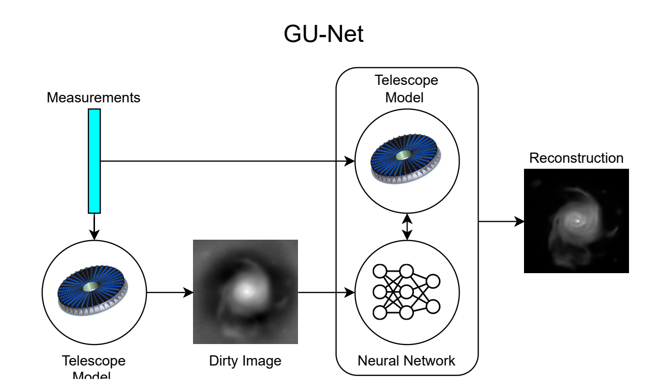
Cross-cutting research areas



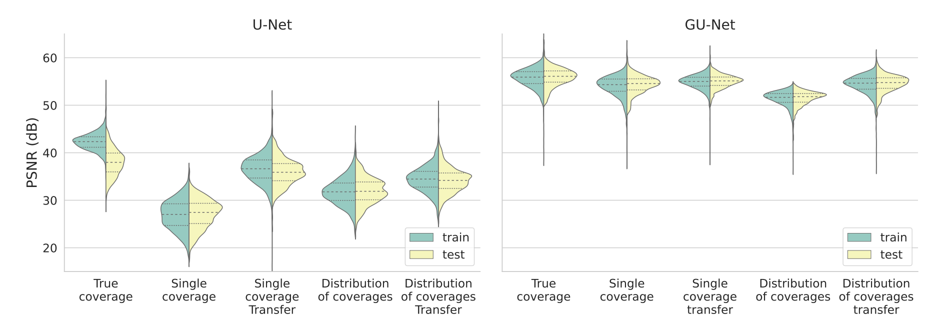
Integrate physical model of telescope

Integrate (differentiable) physical model of instrument into an architecture; plus multi-resolution instrument model. (Mars *et al.* 2023, Mars *et al.* in prep.)

Transfer learning to handle measurement operator variability (telescope configuration).



Distribution of radio interferometric reconstruction quality



Reconstruction quality (PSNR ↑) for different training strategies.

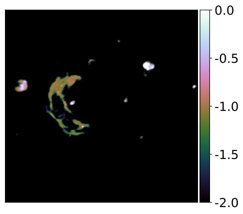
- ▷ Superior reconstruction quality.
- ▷ Imaging time speed-up of 50-600× relative to classical approaches.
- ▷ Support for varying measurement operators for the first time.

Scalable Bayesian UQ with learned data-driven priors

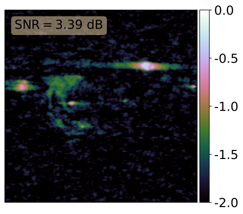
1. Statistical framework: Bayesian inference and MAP estimation.
2. Mathematical theory: probability concentration theorem for log-convex distributions.
3. Designed/constrained ML model: convex ML model with explicit potential.

$\rightsquigarrow$ **Scalable Bayesian uncertainty quantification (UQ)** with learned data-driven priors, which are highly expressive. (Liaudat *et al.* in prep.)

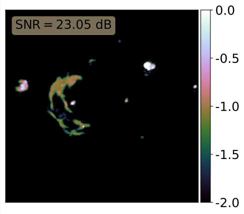
Reconstructed images



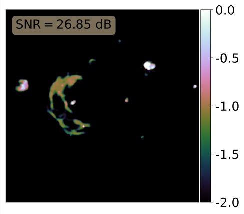
Ground truth



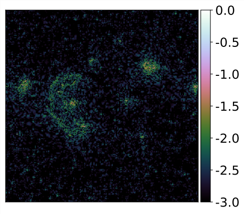
Dirty image
SNR=3.39 dB



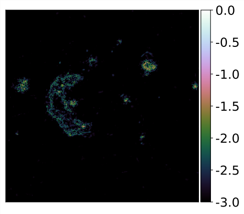
Reconstruction (classical)
SNR=23.05 dB



Reconstruction (learned)
SNR= 26.85 dB

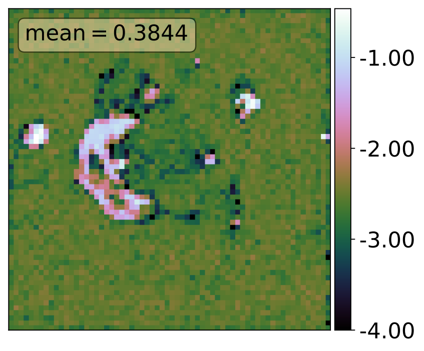


Error (classical)

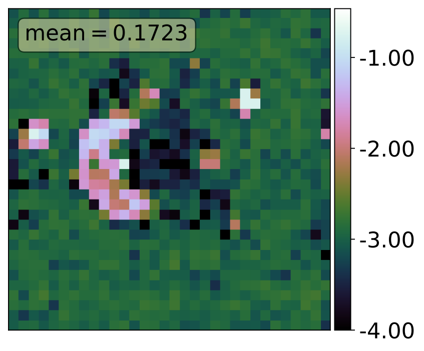


Error (learned)

Approximate pixel-level uncertainty quantification



LCI
(super-pixel size 4 × 4)



LCI
(super-pixel size 8 × 8)

Open-source codes (C++, MPI, OpenMP)

PURIFY code

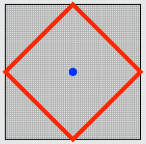
https://github.com/astro-informatics/purify

Next-generation radio interferometric imaging

PURIFY is a highly distributed and parallelized open-source C++ code for radio interferometric imaging, leveraging recent developments in the field of variational regularization and convex optimisation.

SOPT code

https://github.com/astro-informatics/sopt



Sparse OPTimisation

SOPT is a highly distributed and parallelized open-source C++ code for variational regularization and convex optimisation.

Computational strategy

- Hybrid deep learning (data-driven) & model-based approach
- Big data and big compute BUT moderate size models
- **Training and prototyping in** Python on current-generation hardware (TensorFlow, PyTorch)
- **Imaging (production) in** C++ on exascale hardware
  $\rightsquigarrow$ TensorFlow interoperability with C++ implemented and working well

Next steps

- **PyTorch** Interoperability with C++ (including gradients)
- Port uncertainty quantification to C++
- **Benchmark** on large data-sets
- **Unconference** in Spring 2024: *Applying LEXCI software to cross-cutting problems across domains*