The Square Kilometre Array

Dr. Chiara Ferrari
(SKA-France Director, Chair of European SKA Forum, OCA)
SKA at a glance

- A global collaboration to design, build and operate the next generation radio astronomy observatory
- A new Inter-Governmental Organisation for astronomy and fundamental physics with 50+ year lifetime

- It will consist of:
  - An array of ~200 dishes in ZA
  - An array of ~131000 antennas in AU
  - A global HQ in UK
  - Two data computing centres in ZA & AU + A worldwide network of SKA regional centres (SRC)

- SKA is now:
  - Q4/2020: IGO exists
  - Q2/2021: construction activity begins
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SKA Phase 1 (SKA1)

SKA1-LOW (AUS)
130,000 log periodic antennas

SKA1-MID (SA)
197 dishes (15m)

= 50 MHz 350 MHz 15 GHz
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“This is the culmination of many years of work by hundreds of people, whose talents and dedication are the driving force behind the SKA. That collective effort, guided with skill and efficiency by the safe hands of the SKA Office, has brought us to this point.”

Dr Catherine Cesarsky
Chair of the SKA Board of Directors
Development of the SKA project
### Baseline budget

The graph on the right shows the expenditure over the 10-year period, outlining construction capital cost, construction support, operations and business enabling functions, and the Observatory Development Programme cost.

Construction of SKA1 is estimated to cost €1.282 billion (June 2020). A further €0.704 billion (June 2020) will support the first 10 years of SKA Observatory operations.

### Baseline schedule

The formal end of construction will be signified by a successful Operations Readiness Review (ORR). This review will demonstrate the ability of the Observatory to execute a set of key observing modes, illustrated by end-to-end tests of representative Science Verification projects from proposal preparation to (public) data delivery. This process confirms compliance to Level 0 requirements and the ability to execute high-priority science cases.

However, handover of the commissioned and verified system for scheduled observing will be gradual. It is expected that specific modes will be released in sequence, starting with basic (and commonly used) modes, and allowing particularly difficult and more esoteric modes to be added over time.

### Key project milestones

<table>
<thead>
<tr>
<th>Event</th>
<th>SKA-Low</th>
<th>SKA-Mid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start of construction (T0)</td>
<td>1st July 2021</td>
<td>1st July 2021</td>
</tr>
<tr>
<td>Earliest start of major contracts (C0)</td>
<td>August 2021</td>
<td>August 2021</td>
</tr>
<tr>
<td>Array Assembly 0.5 finish (AA0.5)</td>
<td>February 2024</td>
<td>March 2024</td>
</tr>
<tr>
<td>SKA-Low = 6-station array</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SKA-Mid = 4 stations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Array Assembly 1 finish (AA1)</td>
<td>February 2025</td>
<td>February 2025</td>
</tr>
<tr>
<td>SKA-Low = 18-station array</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SKA-Mid = 8 stations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Array Assembly 2 finish (AA2)</td>
<td>February 2026</td>
<td>December 2025</td>
</tr>
<tr>
<td>SKA-Low = 64 stations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SKA-Mid = 64 stations, baselines mostly &lt;20km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Array Assembly 3 finish (AA3)</td>
<td>January 2027</td>
<td>September 2026</td>
</tr>
<tr>
<td>SKA-Low = 256-station array, including long baselines</td>
<td>November 2027</td>
<td></td>
</tr>
<tr>
<td>SKA-Mid = 128-station array, including long baselines</td>
<td>December 2027</td>
<td></td>
</tr>
<tr>
<td>Array Assembly 4 finish (AA4)</td>
<td>November 2027</td>
<td>June 2027</td>
</tr>
<tr>
<td>SKA-Low = full Low array</td>
<td>January 2028</td>
<td>December 2027</td>
</tr>
<tr>
<td>SKA-Mid = full Mid array, including MeerKAT dishes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operational Readiness Review (ORR)</td>
<td>January 2028</td>
<td>December 2027</td>
</tr>
<tr>
<td>End of construction</td>
<td>July 2029</td>
<td>July 2029</td>
</tr>
</tbody>
</table>
Development of the SKA project

Key Science Challenges

Data Challenges

Science Commissioning

Early Science, Shared Risk, PI Proposals

KSP Workshops, KSP Proposals

Major Science Meetings

- 2012
- 2016
- 2019
- 2020
- 2021
- 2013
- 2018
- 2019
- 2020
- 2021
- 2022
- 2029

IAP Seminar - 04/12/20
A Golden Age for Radio Astronomy

Some of the SKA Pathfinders

- NenuFAR
  - France
  - 10-85 MHz
- LOFAR
  - Europe
  - 30-80 MHz + 110-240 MHz
- CHIME
  - Canada
  - 400-800 MHz
- APERTIF
  - The Netherlands
  - 1 - 1.750 GHz
- JVLA
  - US
  - 1 - 50 GHz

SKA Precursors

- MWA
  - Australia
  - 80 - 300 MHz
- ASKAP
  - Australia
  - 700 - 1800 MHz
- HERA
  - South Africa
  - 50 - 250 MHz
- MeerKAT
  - South Africa
  - 0.580 – 14 GHz

SKA

- SKA1-LOW
  - Australia
  - 50 MHz - 350 MHz
- SKA1-MID
  - South Africa
  - 350 MHz – 15.4 GHz
Diffuse emission and filaments at different scales

Heywood et al., Nature, 2019

Govoni et al. 2019, Science

The galaxy clusters pair A0399 - A0401


Optics: OSS and Per 350/1351 (slitless) – Red; X-rays: XMM-Newton – Yellow; y parameters: PIANCE satellite – Blue, radio 140 MHz (LOFAR).

Image credits: M. Morganti - INAF.
Radio continuum surveys

Mauch et al., AJ, 2020

Table 1. Summary of RACS parameters with those of other comparable surveys. The tabulated data allow comparison with RACS; for detailed information consult the reference papers mentioned in Section 1.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Frequency (MHz)</th>
<th>Bandwidth (MHz)</th>
<th>Resolution (arcsec)</th>
<th>Sky coverage (deg$^2$)</th>
<th>Sensitivity (mJy beam$^{-1}$)</th>
<th>Polarization</th>
<th>$N_{\text{sources}}$ ($\times 10^6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLSSr</td>
<td>73.8</td>
<td>3.12</td>
<td>75</td>
<td>30 793</td>
<td>100</td>
<td>/</td>
<td>0.93</td>
</tr>
<tr>
<td>GLEAM</td>
<td>87, 118, 154, 185, 215</td>
<td>30.72</td>
<td>120</td>
<td>27 691</td>
<td>6–10</td>
<td>I, Q, U, V</td>
<td>0.33</td>
</tr>
<tr>
<td>TGSS</td>
<td>150</td>
<td>16.7</td>
<td>25</td>
<td>36 900</td>
<td>2–5</td>
<td>/</td>
<td>0.62</td>
</tr>
<tr>
<td>RACS$^a$</td>
<td>887.5</td>
<td>288</td>
<td>15</td>
<td>36 656</td>
<td>~0.25</td>
<td>I, Q, U, V</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>1 295.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 655.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RACS$^b$</td>
<td>887.5</td>
<td>288</td>
<td>15–25</td>
<td>34 240</td>
<td>0.2–0.4</td>
<td>/</td>
<td>2.8</td>
</tr>
<tr>
<td>SUMSS</td>
<td>843</td>
<td>3</td>
<td>45</td>
<td>10 300</td>
<td>1.5</td>
<td>RC</td>
<td>0.2</td>
</tr>
<tr>
<td>+MGPS-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NVSS</td>
<td>1 346, 1 435</td>
<td>42</td>
<td>45</td>
<td>33 800</td>
<td>0.45</td>
<td>I, Q, U</td>
<td>2</td>
</tr>
<tr>
<td>VLASS</td>
<td>3 000</td>
<td>2 000</td>
<td>2.5</td>
<td>33 885</td>
<td>0.07</td>
<td>I, Q, U</td>
<td>5.3</td>
</tr>
</tbody>
</table>

$^a$ RACS full survey capability.
$^b$ RACS first data release.
Circular radio objects

- **Similar features**
  - Strong circular symmetry with ~1 arcmin diameter
  - Steep spectral index ($\alpha \sim 1$)
  - Located at high galactic latitude & Two of them are very close together

- **Imaging artefacts?** No: detected by more than one telescope and with different software
- **SNR?** **Very unlikely:** very unlikely position, except if new class of high-latitude SNR
- **Planetary Nebulae?** No: very unlikely density at ORC galactic latitudes; too steep spectrum
- **Ring around Wolf-Rayet star?** No: too big; too steep spectrum
- **Face-on SF or ring galaxy?** No: no associated optical emission
- **Galactic wind termination shock?** Possible??? Size/energetics OK; never observed before
- **Bent-tail radio galaxies?** No: no host galaxy; no cluster/ICM
- **Lobe from radio galaxies?** No: no companions/central galaxy; too big (ORC4)
- **Cluster halos?** No: no clusters/too regular morphology
- **Einstein ring?** **Very unlikely:** too big/regular

Norris et al., PASA, 2020
Fast Radio Bursts (FRB)

- First FRB discovered in 2007 in Parkes data of 2001 (Lorimer et al. 2007)
- After a low detection rate (few dozens until 2017), hundreds of FRBs known today, repeaters or non-repeaters - Big impact from CHIME and ASKAP
- First repeater detected in 2012 at Arecibo, host galaxy identified in 2017 (Chatterjee et al. 2017) - low mass, low-metallicity dwarf galaxy at redshift $z = 0.193$ (Tendulkar et al. 2017)
- Non repeaters discovered later on in higher-$z$ more massive, less SF active galaxies (e.g. Bannister et al. 2019, Ravi et al. 2019): different physical origin?
- But: repeating FRBs seems to have a wide range of luminosities, and originate from diverse host galaxies and local environments
- In 2020, first likely FRB - repeating - associated to a galactic magnetar (CHIME/FRB Coll. 2020, Bochenek et al. 2020, Kirsten et al. 2020)
- Recent analysis of archival radio and X-ray data of another galactic source suggests that there exists a continuum of magnetar radio burst energies, sometimes looking like FRB (Israel et al. 2020)
FRBs: powerful cosmological tools

- FRB traversing the halo of a galaxy with surprisingly low density and weak magnetic field: new and transformative technique for exploring the nature of galaxy halos (Prochaska et al. 2019)

- Direct measurement of the baryon content of the Universe using the dispersion of a sample of localized fast radio bursts (FRBs): cosmic baryon density consistent with Cosmic Microwave Background and Big Bang Nucleosynthesis (Macquart et al. 2020)
Why building the SKA?
Why building the SKA?

Figure 1:
Top Panels: SKA1 reference surveys in comparison with existing surveys and/or surveys planned for the next future with SKA pathfinders and precursors. LOFAR, VLASS and SKA1 reference surveys are highlighted in blue, orange and red respectively. Different symbols refer to different survey coverage: all-sky (filled circles); wide tiers (filled triangles); deep tiers (asterisks); ultra deep tiers (starred symbols).

Left: Depth (5σ flux limit) vs. frequency. Band 1 and/or 2 SKA surveys are all shown at a reference frequency of 1.4 GHz. The red and blue dashed lines indicate a slope of $\sim n^{-1}$ for different 1.4 GHz flux normalizations.

Right: Depth (5σ flux limit) vs. angular resolution. The black and brown lines represent approximate estimates of the confusion limit at 120 MHz and 1 GHz respectively (see Appendix for more details).

Bottom panel: SKA1 reference surveys in comparison with existing or planned surveys. Only surveys with observing frequencies in the range 1-3 GHz are shown. Area coverage vs depth (5σ flux limit); for 3 GHz VLA surveys the flux limit has been rescaled to 1.4 GHz.

Prandoni & Seymour 2015
SKA observing modes

- Imaging
  - Continuum imaging: images of areas of the sky over a broad bandwidth
  - Spectral line/Zoom window imaging: higher spectral resolution images (hundreds of Hz)
- Pulsar Transient/Search: periodic/non-periodic pulses over a range of possible dispersion measure values (buffer for transients)
- Pulsar Timing: Converts tied-array voltage beams into folded integrated pulse profiles of pulsars to accurately measure the time-of-arrival (ToA)
- Flow-through: Record raw tied-array beam data for offline analysis
- Dynamic Spectrum: generic, high time-resolution, dynamic spectrum (time-versus-frequency distribution of intensity) that may be used for a broad range of scientific applications
- Very-Long Baseline Interferometry: tied-array beams to participate in VLBI observations, with other radio astronomy observatories located around the globe
Exploring the cosmos with the SKA

Braun et al. 2015
Exploring the cosmos with the SKA

- Cosmic dawn & Epoch of Reionisation
- Cosmology
- Galaxy evolution
- Cosmic magnetism
- Fundamental physics
- Transient sky
- Cradle of life
- Solar, Heliospheric and Ionospheric Physics

Braun et al. 2015
Galaxy evolution

Accretion of cold gas from the environment

Galaxy interactions

Environmental effects on gas content

Zafar et al. 2013

Osterloo et al. 2017

Duc & Renaud 2014

Kenney et al. 2004
Galaxy evolution

Accretion of cold gas from the environment

Duc & Renaud 2014

Galaxy interactions

Environmental effects on gas content

Murphy et al. 2015

Osterloo et al. 2017

Kenney et al. 2004

Zafar et al. 2013

Murphy+ 15

Murphy et al. 2015

Duc & Renaud 2014

Kenney et al. 2004

Zafar et al. 2013

Murphy+ 15

Murphy et al. 2015

Duc & Renaud 2014

Kenney et al. 2004
Galaxy evolution

Fernández et al. 2013

50h avec le JVLA
Galaxy evolution

With the JVLA on a 0.25 deg$^2$ field

<table>
<thead>
<tr>
<th>Survey</th>
<th>$\Omega$ deg$^2$</th>
<th>Frequency MHz</th>
<th>Resolution$^2$</th>
<th>$N$</th>
<th>&lt;z&gt; (z$_{lim}$)</th>
<th>$N_{HI}$ 10$^{20}$ cm$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galaxy/MS</td>
<td>400</td>
<td>1418-1422</td>
<td>5&quot;</td>
<td>4,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extragalactic</td>
<td>1000</td>
<td>200-350$^3$</td>
<td>10&quot;</td>
<td>5,000</td>
<td>1(3)</td>
<td></td>
</tr>
<tr>
<td>(absorption)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galaxy/MS</td>
<td>600</td>
<td>1418-1422</td>
<td>10$^{-1}$'</td>
<td>34,000</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>Medium wide</td>
<td>400</td>
<td>950-1420</td>
<td>10&quot;</td>
<td>34,000</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>Medium deep</td>
<td>20</td>
<td>950-1420</td>
<td>5&quot;</td>
<td>25,000</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Deep</td>
<td>1</td>
<td>600-1050</td>
<td>2&quot;</td>
<td>2,600</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Targeted</td>
<td>-</td>
<td>1400-1420</td>
<td>3&quot;-1'</td>
<td>50</td>
<td>0.002</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Staveley-Smith & Oosterloo 2015
Epoch of Reionisation and Cosmic Dawn

\[ \delta T_B \propto 28 \text{mK} \left(1 + \delta\right) x_{HI} \left(\frac{T_S - T_{CMB}}{T_S}\right) \left(1 + \frac{1}{H \frac{dv}{dr}}\right)^{-1} \]

\[ \frac{n_e}{n_0} \propto \exp \left(-\frac{h \nu_{21}}{k_B T_s}\right) \]

Courtoisie: NAOJ
Epoch of Reionisation and Cosmic Dawn

Adapted: Pritchard & Loeb
Epoch of Reionisation and Cosmic Dawn

Courtesy: B. Semelin

Koopmans+ 15
Cosmic magnetism

Total intensity and polarisation of synchrotron radiation

Faraday Rotation

Faraday Tomography

Credit: Marijke Haerkorn
Using Rotation Measures to Reveal the Mysteries of the Magnetised Universe

Melanie Johnston-Hollitt

Johnston-Hollitt et al. (2004) ~ 1000 extragalactic RMs
Oppermann et al. (2012) ~ 40,000 extragalactic RMs
SKA 1 ~ 7 – 14 million extragalactic RMs

Figure 3: Top projection: The RM sky in Galactic coordinates as interpolated from ~ 1000 extragalactic RMs over a decade ago (Johnston-Hollitt 2003; Johnston-Hollitt et al. 2004). Middle projection: The RM Sky as determined from more sophisticated signal processing methods for ~ 40,000 extragalactic RMs (Oppermann et al. 2012, 2015). Note that the large-scale features of the field are largely unchanged between the top and middle panel, but the small scale information regarding the magnetic field of the Milky Way is greatly improved with a higher density of RMs. The bottom panel denotes that an all sky RM survey on SKA phase 1 with a sensitivity of 4 \( \mu \)Jy/beam at 2” resolution should provide 7-14 million extragalactic RMs with which to probe the RM sky. Red colour scales denote positive RMs and magnetic fields coming out of the plane of the sky, whilst blue colours denote negative RMs and fields going into the plane of the sky.

For further information see the following chapters in the 2015 SKA Science Case: Bonafede et al. (2015); Cassano et al. (2015); Gaensler et al. (2015); Giovannini et al. (2015); Govoni et al. (2015); Johnston-Hollitt et al. (2015a); Macquart et al. (2015); Taylor et al. (2015); Vacca et al. (2015); Vazza et al. (2015).

2.2 Magnetic Field of the Milky Way

Mapping the magnetic field of the Milky Way has been steadily improving over the last decade. The use of extragalactic background sources, embedded pulsars and observations of the diffuse synchrotron emission in polarisation surveys (Reich et al. 2004; Haverkorn et al. 2006; Stutz et al. 2014) have all played important roles in examining the large-scale magnetic field of our Galaxy (Stil et al. 2011; Oppermann et al. 2012). Such work continues to reveal surprising and previously unknown features such as giant magnetised outflows (Carretti et al. 2013), and has permitted mapping of the magnetic field in a range of discrete Galactic objects (McClure-Griffiths et al. 2010; 7

Density of background sources ~300x higher!
Cosmic magnetism

Figure 2: Schematic of a nearby galaxy cluster showing X-ray emission in purple, an extended radio source in pink, and unresolved radio sources in white if unpolarised and gold if polarised. Different path lengths to polarised sources are marked including unresolved background radio galaxies (dashed lines), unresolved embedded sources (dot-dashed lines) and extended embedded sources such as large tailed radio galaxies, the lobes of which are polarised and can be used as screen to examine the cluster magnetic field (solid lines). The wealth of sources located at different locations within the ICM will allow the first Faraday tomography of the magnetic field in galaxy clusters.

With SKA1

Today

With SKA1

Coma-like cluster

\[ M_{\text{Cluster}} \sim 7 \times 10^{14} M_{\text{Sun}} \]

\[ M_{\text{Cluster}} \sim 10^{14} M_{\text{Sun}} \]

\[ M_{\text{Cluster}} \sim 10^{13} M_{\text{Sun}} \]
Pulsars

- Strongly self-gravitating compact bodies
- Very stable clocks

Test of gravitation theories

Astrophysics

- Emission physics
- Extreme magnetic fields
- Binary & stellar evolution
- Gravity
- Supernova explosions
- Superdense matter
The spectrum of gravitational wave astronomy

All three experiments measure changes in light travel times between objects due to GWs.

**Chapter 37 — Gravitational wave astronomy with the SKA — Janssen et al. (2015)**

A Pulsar Timing Array (PTA) is used as a cosmic gravitational wave (GW) detector. As described in the chapter by Janssen et al. (2015), Phase I essentially guarantees the direct detection of a GW signal. This may appear as a stochastic background from binary super-massive black holes in the process of early galaxy evolution, or it may be bright individual source(s) of this kind. Exotic phenomena like cosmic strings may also be expected to produce measurable GW signals, should they exist. The last ten years have seen a much better understanding of the source population, the detection procedures and the use of a PTA for fundamental physics (such as graviton properties, e.g. Lee et al. 2010) or single source localisation capabilities (e.g. Lee et al. 2011), all of which is described in the corresponding chapter.

**Chapter 38 — Understanding pulsar magnetospheres with the SKA — Karastergiou et al. (2015)**

Considerable progress has been made with our understanding of the pulsar emission mechanism in the last decade. However, the wide bandwidth and exceptional sensitivity of the SKA will revolutionise our understanding of radio emission from all types of radio emitting neutron stars. A perspective is provided on the latest developments and future prospects.

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**Figure 1:**

Pulsar-related discoveries as a function of time. The time of the first SKA Science Book is marked and some important (selected) discoveries since are marked. The right panel puts the current numbers into perspective with those expected for the SKA.
Synergies

Epoch of Reionisation
Star & Planet Formation
Galaxy evolution as a function of redshift and environment
The transient sky
Gravitational wave Science
Cosmology
The French SKA White Book

The richest synergy chapter ever published about SKA vs. other projects, including:

- instruments covering the whole electromagnetic spectrum
- gravitational wave detectors

178 co-authors from

- 40 research institutes
- 6 private companies
February 1st, 2018

Kick-off meeting of Maison SKA-France
Mai 17, 2018

MESRI publishes the French Large Research Infrastructure Roadmap
July 12, 2018

CNRS approved as new member of SKA0 by the SKA Board of Directors
November 15, 2019

Two new academic partners of Maison SKA-France
**SKA1-MID**
- 8.8 Tb/s
- Beam-forming

**SKA1-LOW**
- ~2 Pb/s

**Technology**
- 7.2 Tb/s
- Imaging & Science
- Pulsar search & Correlation

**Pulsar search & Correlation**
- 50 PFLOPS
- 2 x 5 Tb/s

**Imaging & Science**
- 250 PFLOPS
- 350 PB/telescope/yr (could be a lot, lot, lot more)
SKA contribution to a knowledge society

• SKA offers challenge and opportunities in terms of energy needs:
  o Reduction of the environmental impact associated with energy consumption of computing centre
  o Broader driver for the collaboration between Africa and Europe in the development of carbon-free energy system

• One of the “big science” Big Data projects driving the development of:
  o Open Science practices with much wider impact
  o Artificial Intelligence / Machine Learning-optimized exascale platforms
  o Networking and communication

• A lively collaboration between academia, society, research infrastructures and industry:
  o Acquired expertise in critical elements of the innovation sector (electricity supply, connectivity, IT, …)
  o Adaptability and capacity to produce novel solutions in emerging challenges
SKA contribution to a knowledge society

Open Science

Human capital development

Findable Accessible Interoperable Reusable