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SKAO, SKA Precursors/pathfinders and ESO Facilities

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In The Messenger 192 a short report was published on the ESO–SKAO workshop Coordinated Surveys of the Southern Sky, which was held at ESO in Garching in early 2023. An important goal of this workshop was to publish a collection of articles that describe in some detail what existing synergetic science would be possible with well-planned coordinated surveys using ESO and SKAO facilities. The other four articles in this edition of The Messenger, covering respectively the Galaxy, galaxy formation and evolution, cosmology, and the epoch of reionisation and cosmic dawn, present such synergies and promising ways forward, and serve as references for ESO–SKAO coordinated surveys. By way of introduction, this article describes the SKAO and SKA precursor/pathfinder facilities and also briefly highlights the current and future ESO instrumentation that will be of particular importance for such coordinated surveys of the southern sky.

The Square Kilometre Array Observatory

The Square Kilometre Array Observatory (SKAO), currently under construction, will comprise two instruments: SKA-Low, consisting of stations each of 256 log-periodic antennas to observe in the 50–350 MHz frequency range (Labate et al., 2022), and SKA-Mid, consisting of dishes to observe in five frequency bands in the 350 MHz – 15.4 GHz range (Swart, Dewdney & Cremonini, 2022).

The SKA-Low site is located at Inyarrimanha Ilgari Bundara, CSIRO's Murchison Radio-astronomy Observatory in Western Australia, on the lands of the Wajarri Yamaji, who are the Traditional Owners and native title holders of the observatory site. The SKA-Mid site is located in South Africa's semi-desert Karoo region.

The '*baseline*' design for SKA (see Table 1), also referred to in the literature as SKA Phase 1, consists of 512 SKA-Low stations and 197 SKA-Mid dishes (64 of which will be integrated from the currently operating MeerKAT telescope). Only SKA-Mid Band 1 (0.35–1.05 GHz), Band 2 (0.95–1.76 GHz) and Band 5 (4.6–15.4 GHz) receivers will be initially deployed, with the others to be added at a later date.

The SKAO is scheduled to begin science operations after the end of construction, towards the end of the decade. While SKAO is committed to delivering the design baseline, funding to meet this goal has not been fully secured yet. With the funding currently secured, SKAO is working towards delivering an intermediate stage called AA*, which will consist of 144 Mid dishes (including the 64 MeerKAT dishes) and 307 Low stations. As more funding becomes available, the gap between AA* and the design baseline will be bridged while maintaining a continuously working and expanding facility. More information on the different array assemblies can be found on SKAO's website[2].

The science programme for the SKAO will be determined through competitive calls for proposals from the scientific community. It is foreseen that the majority of the telescope time will go towards Key Science Projects (KSPs), large observational programmes, running for several years, to explore new frontiers in, for example, galaxy evolution and cosmology, cosmic magnetism, the laws of gravity, time-domain astrophysics, extraterrestrial life and the unknown (see the SKA Science Book[3] for a comprehensive description of the SKA science cases). The science community behind the SKA is organised in science working groups[4] (SWGs).

Nominal Frequency (GHz)	0.11	0.3	0.77	1.4	6.7	12.5
Frequency range (GHz)	0.05–0.35	0.05–0.35	0.35–1.05	0.95–1.76	4.6–8.5	8.3–15.4
Telescope	Low	Low	Mid	Mid	Mid	Mid
Maximum baseline length (km)	73.4	159.6				
FoV at nominal frequency (arcmin)[a]	277	101	102	57	12	6
Max bandwidth (MHz)	300	300	700	810	3900	2 × 2500
Continuum channel width (kHz)	5.4	5.4	13.4	13.4	13.4	13.4
Finest zoom channel width (Hz)	14.1	14.1	210	210	210	210
Width of a single tuneable spectral window at narrowest zoom channel width (MHz)	0.024	0.024	3.1	3.1	3.1	3.1
Continuum RMS (μJy/beam)[b]	9	8.2	2.6	1.4	1	1.2
Line RMS (μJy/beam)[c]	407	410	140	78	56	69

Table 1. Anticipated performance of the SKA baseline design. The sensitivities listed here are indicative values. Accurate sensitivity values for different observational setups can be estimated using the SKA sensitivity calculators[1].

Of the science cases that are being developed, several either rely on or would benefit from synergy with instruments operating at different wavelengths. Some examples include Target of Opportunity, where an observation is triggered by an external event, such as a detection by another facility, and Coordinated Projects, where observations are carried out on multiple facilities.

Several currently operational SKA precursors and pathfinder facilities[5] are producing state-of-the-art radio science. Below we describe in particular the facilities that were mentioned at the workshop and in the articles in this issue of The Messenger.

CSIRO's ASKAP radio telescope

The Australian SKA Pathfinder (ASKAP) radio telescope is owned and operated by CSIRO, Australia's national science agency. It is located at Inyarrimanha Ilgari Bundara, the CSIRO's Murchison Radio-astronomy Observatory in Western Australia, on the lands of the Wajarri Yamaji, who are the Traditional Owners and native title holders of the observatory site. The array comprises 36 dish antennas, 12 metres in diameter, and operates across the frequency range of 700 MHz to 1.8 GHz with a contiguous bandwidth of up to 288 MHz. Spectral-line observations can span this entire bandwidth with a channel size of 18.5 kHz, or in zoom modes for finer resolution (up to 0.58 kHz) with a tradeoff in bandwidth. A more detailed description of the technical design and capabilities of ASKAP is given by Hotan et al. (2021).

A defining characteristic of ASKAP is its phased-array feed technology, which forms 36 beams on the sky to give an instantaneous field of view of 6 × 6 degrees in the lowest frequency band. This wide-field capability makes ASKAP particularly adept at swiftly mapping large areas of the sky. ASKAP observations are autonomously scheduled and processed using a specialised data reduction pipeline written in ASKAPsoft. After processing, science-ready data products are uploaded to CSIRO's Astronomy Science Data Archives[6] (CASDA) where, after a short validation period, they are publicly available.

Reflecting ASKAP's unique surveying capability, the majority of the available observing time is dedicated to a set of nine Survey Science Projects (SSPs) which are being conducted over a five-year period. Under the guest science scheme, about 10% of the observing time is open to all astronomers. These large surveys[7] cover a wide range of science topics, including studies of neutral hydrogen from the Milky Way out to a redshift of one (GASKAP, WALLABY, DINGO, FLASH) mapping the continuum and polarisation properties of galaxies (EMU, POSSUM) and studying radio transients (VAST) and fast radio bursts (CRAFT). This is in addition to observatory-led projects such as the Rapid ASKAP Continuum Survey (Hale et al., 2021; Duchesne et al., 2021) which provides a rich legacy dataset of radio continuum sources across the entire southern hemisphere.

The Low Frequency Array

The Low Frequency Array (LOFAR; van Haarlem et al., 2013) is an innovative low-frequency radio telescope, composed of antenna 'stations' across Europe. Each LOFAR station contains both Low Band Antennas (LBA), operating between about 10 and 90 MHz, and High Band Antennas (HBA), operating between 110 and 240 MHz. LOFAR stations have no moving parts: the signals from the antennas are combined at station level using advanced beam-forming technologies to enable the station to steer and track across the sky, resulting in a highly flexible system.

LOFAR has a dense core in the north of the Netherlands, with 24 antenna stations within a 2-kilometre radius; this is complemented by a further 14 'remote' Dutch stations with baselines out to around 100 kilometres and an increasing number of international stations (14, as of early 2024) with baselines out to 2000 kilometres. At 150 MHz, the international stations allow the angular resolution to improve from 6 arcseconds using only the Dutch stations to 0.3 arcseconds with the full international array.

With a sensitivity more than 100 times better than any previous telescope at these low frequencies, (sub-)arcsecond angular resolution, an enormous field of view, and an agile system, LOFAR supports an extremely broad and diverse science case, from cosmology to Solar System studies. Major projects include its unique low-frequency surveys, such as the LOFAR Two-Metre Sky Survey (LoTSS; Shimwell et al., 2022), the LoTSS Deep Fields (Best et al., 2023), the LOFAR LBA Sky Survey (LoLSS; de Gasperin et al., 2023) and the LOFAR Tied-Array All Sky Survey (LOTASS; Sanidas et al., 2019).

While LOFAR's northern location (and poorer sensitivity at equatorial declinations) restricts potential overlap with ESO facilities, there has been considerable effort to combine LOFAR data with multi-wavelength northern hemisphere surveys (for example, Williams et al., 2019; Hardcastle et al., 2023), and future projects build further upon this (for example, WEAVE-LOFAR; Smith et al., 2016). The vast array of science that this work has enabled clearly showcases the opportunities for synergies between future SKA and ESO surveys, as well as developing many of the required tools and techniques.

MeerKAT

Located in the semi-desert region in the Northern Cape, South Africa, the MeerKAT radio telescope consists of 64 offset-Gregorian dishes 13.5 metres in diameter. Table 2 gives the basic telescope specifications and Table 3 gives the available correlator channelisation modes. Further information can be found on the MeerKAT knowledge base[8].

Number of antennas	64 (offset Gregorian)
Dish diameter (nominal)	13.5 m
Minimum baseline	29 m
Maximum baseline	7 700 m
Frequency range (UHF)	580–1015 MHz (544–1088 MHz digitised)
Frequency range (L)	900–1670 MHz (856–1712 MHz digitised)
Frequency ranges (S)	S0: 1750–2625 MHz S1: 1968–2843 MHz S2: 2187–3062 MHz S3: 2406–3281 MHz S4: 2625–3500 MHz

Table 2. MeerKAT basic telescope specifications.

Mode	Channels	L-band channel width	UHF-band channel width	S-band channel width
Wideband coarse	4096 (4k)	208.984 kHz	132.812 kHz	213.623 kHz
Wideband fine	32768 (32k)	26.123 kHz	16.602 kHz	26.703 kHz
Narrowband extended (107 MHz bandwidth)[d]	32768 (32k)	3.3 kHz	–	
Narrowband extended (54 MHz bandwidth)[d]	32768 (32k)	1.633 kHz	–	

Table 3. Available correlator channelisation modes.

MeerKAT's wide field of view and sensitivity make it an excellent survey instrument, but it is also excellent for deep follow-up observations.

Many datasets are no longer proprietary and visibilities are available through the archive interface[9]. In addition, the SARAO Science Verification Legacy Surveys (among other data products of interest) are available as fully calibrated Stokes I image cubes from the SARAO data repository[10]. This includes the 1.28-GHz Galactic Centre Mosaic (Heywood et al., 2022), the 1.3-GHz Survey of the Small Magellanic Cloud (Cotton et al., 2024) and the 1.3-GHz Galactic Plane Survey (Goedhart et al., 2024). These datasets open up a large discovery space for multi-wavelength astronomy.

The Murchison Widefield Array

The Murchison Widefield Array[11] (MWA; Tingay et al., 2013; Wayth et al., 2018) is an SKA-Low precursor. The telescope is located at CSIRO's Murchison Radio-astronomy Observatory in Western Australia, on the lands of the Wajarri Yamaji, who are the Traditional Owners and native title holders of the observatory site. An international project, the MWA collaboration comprises 28 partner institutions from Australia, Japan, China, Canada, the United States and Switzerland.

The telescope consists of 256 'tiles', each with 4 × 4 dual-polarisation dipole antennas. The effective width of each tile is about 4 metres. Currently, the telescope operates in two configurations of 128 tiles each. The compact configuration includes two 36-tile hexagonal sub-arrays and is particularly suitable for epoch of reionisation observations thanks to its surface brightness sensitivity and calibratability. The extended configuration, comprising the remaining 128 tiles, has a maximum baseline of approximately 5.3 kilometres.

With its combination of very wide bandwidth (70–300 MHz; instantaneous bandwidth 30.72 MHz), huge field of view (for example, approximately 600 square degrees at 150 MHz), excellent *u*, *v* coverage, high time and frequency resolutions (for example, as good as 250 ms or 200 Hz when correlating), and agile, advanced beamforming capabilities, the MWA is a very powerful low-frequency facility for conducting arcminute-resolution studies of the sky below a declination of about +30 degrees.

In full science operation since 2013, the MWA has facilitated transformational low-frequency science across five key themes: the epoch of reionisation, Galactic science, time-domain, space weather, and pulsars and fast transients (see, for example, Beardsley et al., 2019 for an overview of results). An example of a major survey project well-matched with potential ESO synergies, and that has achieved significant impact in the literature, is the 70–230 MHz GaLactic and Extragalactic All-sky MWA survey (GLEAM; for example, Wayth et al., 2015; Hurley-Walker et al., 2017): over 300 000 extragalactic radio sources were catalogued with broadband low-frequency spectral information.

The MWA long-term archive is hosted at the Pawsey Supercomputing Research Centre[12] and has over 45 PB of data at the time of writing. Data can be downloaded using the MWA node of the All-Sky Virtual Observatory[13].

'Phase III' of MWA science operations has recently commenced, during which it will be possible to conduct imaging and high-time-resolution beamforming with all 256 tiles, allowing improved sensitivity and *u*, *v* coverage. Such functionality will be enabled by a new, next-generation, flexible correlator (MWAX; Morrison et al., 2023), as well as a new receiver suite that is expected to be in place during 2025. MWA operations have also significantly influenced the designs of the SKA-Low prototypes (for example, Wayth et al., 2017; Benthem et al., 2021; Wayth et al., 2022; Macario et al., 2022), as well as the design of SKA-Low itself.

ESO facilities

The purpose of this section is to briefly highlight the current and planned instrumentation on ESO facilities that is of direct relevance to coordinated ESO–SKAO surveys. In particular we highlight four instruments/facilities that were mentioned frequently at the workshop, and which feature most prominently in the four science-focused articles in this Messenger issue. As these instruments are all introduced in much more detail in dedicated articles in previous Messenger editions, we describe them in much less detail than the SKA facilities.

Among the ESO instruments most referred to in the context of ESO–SKAO coordinated surveys, the 4-metre Multi-Object Spectroscopic Telescope (4MOST; de Jong et al., 2019) is one of the most conspicuous. 4MOST is a wide-field spectroscopic survey facility that is under development for the Visible and Infrared Survey Telescope for Astronomy (VISTA) and which will be able to simultaneously obtain spectra of around 2400 objects distributed over a field of view of 4.2 square degrees (see The Messenger 175 and 190 for descriptions of the planned surveys with this facility).

A future facility that is very frequently mentioned in this context is the new Multi-Object Optical and Near-infrared Spectrograph (MOONS; Cirasuolo et al., 2020) currently under construction for the Very Large Telescope (VLT), which will provide exquisite spectroscopic capabilities across the 0.65–1.8 µm wavelength range. Using ~1000 fibres across a field 25 arcminutes in diameter, it offers a spectroscopic resolving power between $R \sim 4000$ and $R \sim 18\,000$.

As for ESO's Extremely Large Telescope[14] (ELT) instruments, MOSAIC (Hammer et al., 2021) is particularly important. This multi-object spectrograph will use the widest possible field of view provided by the ELT, and will operate in the visible and near-infrared, covering 0.47–1.80 µm with R between 5000 and 20 000, over a field of view of 40 square arcminutes.

Another important facility for possible SKA synergies is the Atacama Large Millimeter/submillimeter Array[14] (ALMA), which, despite its limited field of view, provides a unique view of gas and dust across the Universe, fitting quite naturally alongside deep radio observations. ALMA currently provides continuum and spectral-line capabilities for wavelengths from 0.32 mm to 8.5 mm, and angular resolutions from 0.0048 arcseconds to 8.5 arcseconds on the array of 50 12-metre dishes. ALMA's field of view ranges from ~ 2.5 arcminutes at the lowest frequencies to 0.1 arcminutes in the highest frequency band. The Wideband Sensitivity Upgrade (WSU), which is currently in the planning phase, will improve ALMA's imaging speed by up to a factor of six, and increase the spectral grasp for high-spectral-resolution observations by one to two orders of magnitude.

Although these four instruments and facilities stand out as being crucially important for future synergetic surveys, it should be noted that many other VLT and ELT instruments are referred to as well in the context of ESO–SKAO joint observations. ESO's widefield multi-band imaging capabilities, as well as its optical/NIR spectroscopic and integral-field instruments, will all play a key role in maximising the science impact of coordinated surveys.

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Links

[1] SKA sensitivity calculators: https://www.skao.int/en/science-users/ska-tools/493/ska-sensitivity-calculators
[2] SKA array assemblies: https://www.skao.int/en/science-users/ska-tools/494/ska-staged-delivery-array-assemblies-and-subarrays
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[9] SARAO archive (requires login): https://apps.sarao.ac.za/katpaws/archive-search
[10] SARAO data repository: https://commons.datacite.org/doi.org?query=client.uid%3Awhno.ljncxe&resource-type=dataset
[11] MWA telescope: https://www.mwatelescope.org/
[12] Pawsey Supercomputing Research Centre: https://pawsey.org.au/
[13] MWA virtual observatory: https://asvo.mwatelescope.org/
[14] ESO's ELT: https://elt.eso.org
[15] ALMA: https://almascience.eso.org/

Notes

[a] Field of view is estimated using the relation FoV [deg] ~ 66 × (λ/D) where λ is the wavelength in metres and D is the diameter in metres. For SKA-Low, the station diameter is set to 39 m. For SKA-Mid, the dish diameter is set to 15 m.
[b] Naturally-weighted continuum sensitivity at Nominal Frequency for 1 hr assuming fractional bandwidth of 0.3.
[c] Naturally-weighted line sensitivity at Nominal Frequency for 1 hr, assuming fractional bandwidth per channel of 0.0001.
[d] The 'zoom' or narrowband modes run in parallel with the wideband coarse (4k) mode, i.e. you will receive two datasets, enabling continuum as well as spectral-line science.

SKAO

The 'big lift' of the main reflector onto the pedestal of the first SKA-Mid production dish on site in South Africa. The lift took place on 4 July 2024, and was carried out by a team from the SKAO, South African Radio Astronomy Observatory (SARAO) and China's CETC54.