Australia's National
Science Agency

The Australia Telescope National Facility from now to 2035

August 2024

1 Overview

This document describes our 10-year vision for CSIRO's Australia Telescope National Facility (ATNF) and is provided as an input to preparing the Australian Astronomy Decadal Plan for the period 2026 to 2035. The principles included here have been developed in consultation with ATNF staff, the ATNF Steering Committee and the user community as described in the final section.

Once operational, the two SKA telescopes – SKA-Mid and SKA-Low – will undoubtedly dominate the radio astronomy landscape in their specific research areas. Smaller, more agile instruments will complement the SKA telescopes and will remain essential for long-term monitoring, probing high angular resolutions, flexibly responding to new areas of research and exploiting changing technology to develop future instrumentation.

Enhancements to our facilities will be driven by the evolving science cases made possible by the next generation of telescopes, not only from the SKA telescopes and others operating across the electromagnetic spectrum but also from gravitational wave observatories and neutrino detectors. Such upgrades will maintain the ATNF for the wide-ranging science carried out by the global astronomy community. We aim to maximise Australia's investment in joining and co-hosting the SKA project in part by using the ATNF facilities explicitly to support, extend and complement the SKA telescopes.

This document has two primary goals:

- to be CSIRO's stand-alone submission to the National Committee for Astronomy describing CSIRO's vision for the role of the ATNF in the era of science conducted with the SKA telescopes, and
- to respond to Decadal Plan Working Group 2.2 National and University Facilities on the capabilities of the ATNF over the coming decade.

Our current facilities, capabilities and planned upgrades are described in Section 2 and summarised in the Appendix. Our vision for the ATNF in the SKA era is presented in Sections 3 and 4.

2 CSIRO's Australia Telescope National Facility

CSIRO operates several radio astronomy observatories and data archives that are collectively known as the Australia Telescope National Facility (ATNF). We are comprised of specialists who work across operations, research and technology. Our technology development program is the cornerstone of the ATNF and is an internationally recognised source of innovative radio astronomy instrumentation, which can lead to industrial spinoffs.

Modern radio astronomy has become dependent on robust firmware, sophisticated embedded computing infrastructure, large-scale data archives, real-time processing algorithms and specific expertise. The ATNF boasts a comprehensive range of expertise, spanning from the intricacies of front-end receivers to deploying machine learning algorithms for analysing the vast data volumes contained within our archives to evolving observatory operations to be increasingly autonomous.

The ATNF includes:

- Our technology, science, operations and software groups which drive new research, technologies and operate our instruments and sites,
- the ASKAP radio telescope with its wide field of view in a legislated radio quiet zone,
- the Australia Telescope Compact Array (ATCA) with its wide frequency coverage, quick response times and flexible configurations,
- Murriyang, our Parkes radio telescope, which is the only large single dish radio telescope dedicated to science observations in the southern hemisphere,
- the Long Baseline Array (LBA) providing VLBI baselines across Australia,
- the Mopra antenna, which is used for single-dish observations, particularly at millimetre wavelengths and as part of the ATNF during LBA sessions, and
- astronomical data archives that currently provide 10PB of data, as well as various catalogues, databases and software packages used for obtaining and processing data from our facilities.

For two semesters per year, the ATNF accepts Principal Investigator-driven proposals from the national and international community. ASKAP also carries out long-term science programs driven by large science teams.

The ATNF activities are detailed in our annual reports. We acknowledge support for our operations from the National Collaborative Research Infrastructure Strategy (NCRIS) as well as the sale of telescope time for astronomy or for space-related activities and the sale of our technology to other observatories.

Figure 1: Wajarri artist Margaret Whitehurst's artwork, *RACS*, was commissioned to celebrate ASKAP's first all-sky survey. ASKAP operates on the traditional lands of the Wajarri Yamaji at Inyarrimanha Ilgari Bundara, our Murchison Radio-astronomy Observatory. As part of broader initiatives within CSIRO, there is a commitment to invest in Aboriginal and Torres Strait Islander cultural knowledge in relation to science, and the greater participation of Aboriginal and Torres Strait Islander peoples in Australia's research and innovation landscape. This commitment will continue across the ATNF through employment opportunities, naming of instruments and infrastructure, and many other initiatives.

Current ATNF capabilities

Technology development

The world-leading ATNF instrumentation group works closely with our science and operations teams to develop and deliver innovative technologies for radio astronomy and industry. Recent ground-breaking instruments include novel wide-field receivers, such as the phased array feeds for Murriyang and ASKAP, as well as receiver and digital signal processing systems with unparalleled bandwidths, such those that power ATCA and Murriyang. Continued support for this technology development capability is essential to drive future innovation, both for our own unique national facility telescopes as well as for any prospective upgrades to the SKA project.

Murriyang, our Parkes radio telescope

Murriyang, on Wiradjuri Country, is used for high cadence monitoring campaigns of large numbers of sources such as pulsars, studying atomic hydrogen, and carrying out continuum and polarisation surveys. Being the primary single-dish telescope in the southern hemisphere, it provides zero-spacing data for interferometric data sets for surveys of diffuse radio sources and Galactic hydrogen. Murriyang remains an integral component of the Long Baseline Array (LBA).

The GPU-based backend instrument is highly flexible allowing commensal observations of spectral line, continuum and high-time resolution data sets. Murriyang will be expanded with a suite of wide-bandwidth receivers operating from 700 MHz to 27 GHz along with a survey capability stemming from a new cryogenically cooled phased array feed receiver (CryoPAF).

With new survey capability from the wide field of view available with the CryoPAF, Murriyang will survey large sky areas with both high time resolution and high spectral resolution.

Australia Telescope Compact Array (ATCA)

ATCA, on Gomeroi Country, responds extremely quickly to automatic triggers of astronomical events, has wide frequency coverage, and flexible array configurations. The backend system is currently being upgraded with a more flexible system (known as BIGCAT) that will increase the available bandwidth up to 8 GHz and allow for the formation of sub-arrays. ATCA is a key element of the LBA and international very long baseline interferometry (VLBI) networks.

The astronomical community is increasingly using ATCA for time-sensitive observations, capitalising on its extensive frequency range to complement

discoveries from high-energy space telescopes and gravitational wave detectors. ATCA also serves as a practical training ground for emerging radio astronomers, providing invaluable hands-on experience.

Looking ahead, some of ATCA’s mid frequency capabilities will be superseded by the SKA-Mid telescope and we are actively seeking ways to transition ATCA to new roles in order to ensure its financial future. Opportunities currently under consideration include expanding its contributions to spacecraft tracking and space situational awareness.

ASKAP radio telescope

With its wide field-of-view, spatial and spectral resolution, frequency coverage, direct links to high performance computing infrastructure, remote autonomous operations model and situation on a legislated radio-quiet site, ASKAP, on Wajarri Yamaji Country, is an ideal survey instrument.

Already it has made completely unexpected discoveries from giant odd radio circles to ultra-long-period transient sources, found millions of galaxies and has significantly increased the number of fast radio bursts localised to their host galaxies. With its unique three-axis rotation, ASKAP has exceptional polarisation capabilities, which are being exploited in studies of cosmic magnetism.

ASKAP commenced the full surveys for which it was designed in late 2022, and these are expected to take around five years to complete.

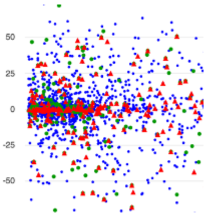
Current plans for ASKAP upgrades include improving high-performance computing reliability and data flow. Later upgrades to ASKAP would include increasing its sensitivity with the next generation of phased array feed receivers.

Long Baseline Array (LBA)

The LBA is the only VLBI network in the southern hemisphere and will be enhanced by the upgrades to the component elements described in the telescope sections above.

The LBA currently operates in the mid and high radio frequency bands generally scheduled during a few weeks each year. The primary goal of the LBA is to provide the highest possible angular resolution for imaging and for astrometry.

Incremental upgrades in bandwidths will become available from 2025. This will progressively allow bandwidth increases up to a factor of eight. Phased-array feeds operating across the same band at both ASKAP and Murriyang will enable a new capability of a single VLBI baseline over the overlapping bands between the ASKAP and Murriyang receivers.



Data processing and archives

Data processing pipelines and archives are now an integral part of the ATNF:

- Our high-time-resolution datasets from Murriyang are archived in the CSIRO Data Access Portal.
- Data from ASKAP are processed automatically using online pipelines and science-ready data products are then made available in the CSIRO ASKAP Science Data Archive (CASDA).
- Spectral line and continuum observations from Murriyang as well as data from ATCA are archived in the Australia Telescope Online Archive (ATOA). These are currently being migrated into CASDA.

These data archives are increasing at approximately 4PB/year, and this growth rate will double in a few years. Our continued upgrade path relates to improved pipeline data processing methods and towards cloud-based processing and access methods.

3 The role of the ATNF in the SKA era

The ATNF already supports and complements the current generation of radio telescopes such as the highly sensitive Five-hundred-meter Aperture Spherical Telescope (FAST), the Atacama Large Millimeter/submillimeter Array (ALMA) at high radio frequencies, and the Giant Metrewave Radio Telescope (GMRT) and the Murchison Widefield Array (MWA), which observe at low frequencies. We also operate alongside the current generation of optical, high-energy, gravitational wave and other multi-messenger observatories.

The incoming generation of radio telescopes will include the SKA telescopes themselves, large single telescopes such as the Qitai radio telescope and the optical Vera Rubin Observatory. Various large-scale radio instruments are proposed and likely to become operational during the period of the decadal plan, including the ngVLA and the DSA-2000, both in the northern hemisphere and both with capabilities that overlap with our instruments. As described in the remainder of this section the ATNF has a variety of roles to play alongside these observatories.

Extending the capabilities of the SKA telescopes

The ATNF has been involved with the SKA project from its initial planning. ATNF staff have provided intellectual contributions to its design and to delivering instrumentation and local infrastructure in Australia. The ATNF's locations, telescopes and engineering expertise are in an excellent position to support and extend the science goals of the SKA telescopes over the next decade.

Improving the resolution of SKA-Low

SKA-Low is designed for baselines up to 74 km. With our observatory sites on the eastern side of Australia we could extend these baselines to over 3000 km. This would enable the resolution of SKA-Low to match that of the James Webb Space Telescope (JWST). Our Low-frequency Australian Megametre-Baseline Demonstrator Array (LAMBDA) is being developed for this purpose. A fully operational LAMBDA would provide a major addition to the SKA-Low capabilities, allowing many of the SKA VLBI science cases to be achieved, including the study of distant galaxies from the early Universe at sub-Galactic scales as well as the detection and imaging of the non-thermal radio emission from extra-solar planets, which requires sub-arcsecond resolution. As a pathway towards this longer-term goal, we are currently developing an early prototype and increasing our staff expertise in low-frequency VLBI.

Complementing SKA-Low with precision radiometers

Our development of precision radiometers, such as the Global Imprints from Nascent Atoms to Now (GINAN) system, advances our strength in developing high performance antennas and receivers operating in and around the SKA-Low observing frequencies. Such radiometers will provide the absolute calibration of the radio sky required for setting the flux density scale needed for SKA-Low measurements. Additionally, such systems enable niche, high-risk, high-gain science measurements of the global cosmological 21-cm signal that are complementary to the Epoch of Reionisation science to be carried out with SKA-Low.

Complementing the SKA telescopes with our current facilities

Our current ATNF facilities, ATCA and Murriyang, will provide larger instantaneous bandwidths than available with the SKA telescopes, long-term monitoring with high cadence observations and smaller-scale PI-driven science. Murriyang will also provide zero-spacing single-dish data sets, while ATCA will provide fast triggered follow-up observations. As foreshadowed by Fender et al. (2024) there is strong scientific benefit of such an array in the southern hemisphere.

SKA-Mid will lack the high resolution required to meet many of its scientific goals. This will come from the SKA telescopes acting as a sensitive element within existing VLBI arrays, or through the follow-up of SKA-led discoveries with independent VLBI arrays. The LBA has already demonstrated effective VLBI networks with the Hartebeesthoek telescope in South Africa and hence will continue to provide the southern hemisphere VLBI network in the SKA era.

Situated alongside SKA-Low, ASKAP will have a direct role in commensal observations. An exciting new science area for SKA-Low is the study of space weather, which has both societal applications and astrophysical interest. Through the study of interplanetary scintillation, SKA-Low will probe the magnetic field of coronal mass ejections at relatively large solar radii. Commensally, ASKAP will probe the same events, but at much closer radii. Together they will allow us to probe how space weather events evolve across interplanetary space.

Supporting the community through computing and algorithm development

We continue to take an active role in exploring, implementing and testing new algorithms relevant for next-generation radio astronomy facilities, including high dynamic range wide-field, spectral and polarimetric imaging, transient detection, efficient dedispersion and anomaly detection methods. The primary drivers are increasing the parameter space that we probe with our telescopes, maximising the probability of identifying signals of interest, while minimising the friction between observations and analysis. We also collaborate with international partners on distributing and exchanging expertise in efficient observatory operations.

Computing, algorithms and data centres are therefore fundamental to our goals. Computing technology evolves fast and the ATNF will maintain a research focus in this area to ensure that our solutions remain compatible with current and future, even speculative, advances. High-performance computing (HPC) and machine learning algorithms will continue to be an important focus, but quantum computing technology is advancing quickly. The dominant technology choice is yet to emerge and the potential applications to radio astronomy still need to be explored.

The SKA regional centres (SRCs) will provide access to the SKA telescopes' data products as well as providing platforms for advanced scientific analysis. The ATNF is a major participant in these data centres and the Australian SKA Regional Centre (AusSRC) is already enhancing its functionality through the processing of ASKAP survey data.

Mitigating the risks of radio frequency interference

Radio frequency interference (RFI) is currently a limiting factor for our ATNF telescopes in many of their primary observing bands. At the ATNF we are developing and implementing mitigation methods through software, hardware or legislative means. This work is essential for continued ground-based radio astronomy. We continue to be at the forefront of research into mitigation strategies and across all aspects of spectrum management for Australian astronomy. Such work will be invaluable across the coming decade, with our infrastructure ideal for assessing methods.

A pathway towards new capabilities for Australian astronomers in the SKA-era

Upgraded phased array feeds for ASKAP

Our technology and instrumentation development program is world-leading in the development of phased array receivers that have led to wide field-of-view survey instruments. Next-generation phased array feeds (PAFs) installed on the ASKAP antennas would revitalise the telescope in the SKA science era. In particular, we are planning a factor of two improvement in the current system temperature of the ASKAP PAFs. ASKAP will then be comparable to SKA-Mid for wide-area surveys, but with significantly more available observing time, at a tiny fraction of the cost and without the computational overheads required to process the data streams (and hence enable surveys with high-time or high-frequency resolution over wide sky areas). An upgraded ASKAP would be complementary to SKA-Mid, which is better suited for deep, pointed observations. We are currently developing a prototype next-generation PAF which will be installed on an ASKAP antenna as a demonstrator. This prototype will demonstrate the performance of the system and test the feasibility of a major upgrade of all the antennas. We will work with the wider astronomy community to develop the science case for a fully upgraded ASKAP, for which new funding would be needed.

Figure 2: Phased array technology is driving much of our technology development. This picture is of the cryogenically cooled phased array feed receiver (CryoPAF) for Murriyang being worked on by Santiago Castillo, our Senior Research Technician; we are also developing new systems for ASKAP and leveraging our expertise in phased-array technology for both commercial and astronomical applications.

An all-sky radio monitor

An obvious extension of our phased array technology is an aperture array with sufficient processing capacity to allow a significant section of the sky to be observed from a given site. Continuous monitoring, with sufficient sensitivity and frequency coverage, would complement all existing radio telescopes. Such an instrument would allow the detection of whole populations of transient sources as well as continuous monitoring of known sources from rise to set on a daily cadence. We are exploring the possibility of using LAMBDA (or similar) to form a low-frequency all-sky monitor, which will explore the transients at low frequencies. There is also a long-term goal where an aperture array with the sensitivity of Murriyang in the 0.5 to 1 GHz range and outriggers to > 10 km allows millions of fast radio bursts to be detected and localised. Such data sets would dominate cosmological studies out to high redshift, while being an ideal multi-messenger instrument. These will identify radio events linked to sources detected in any other waveband, and other multi-messenger all sky detectors, such as the gravitational wave instruments.

4 CSIRO's vision for the upcoming role of the ATNF

During the 2026-2035 Australian Astronomy Decadal Plan period, CSIRO's vision is to:

- continue to support a world-class technology and instrumentation development program (including software, hardware, the exploration of novel science that drives our instrumentation and cutting-edge experimentation) for future Australian and global radio astronomy,
- carry out an effective program of ASKAP surveys and explore telescope upgrade pathways,
- continue to operate Murriyang with a substantial program of external revenue to help fund its availability for science. The development of the UWB/M-H receiver will significantly increase its capabilities,
- transition ATCA to new roles as some of its core capabilities become substantially, but not entirely, supplanted by SKA-Mid,
- work with the community to define the SKA-era VLBI model, which will include continuing participation in mid-frequency VLBI and increasing our capability in low-frequency astronomy,
- include Aboriginal and Torres Strait Islander cultural knowledge in relation to science, and have greater participation of Aboriginal and Torres Strait Islander peoples in Australia's research and innovation landscape.

We will continue to maintain a 'ready to serve' stance regarding broad priorities of the Australian astronomy community, not just in radio astronomy, and will continue to engage in national discussion about how best to support government in forming a compelling case for Australian full membership in the European Southern Observatory (ESO) and third-generation gravitational wave detectors.

We acknowledge the Traditional Owners of the lands of all our sites and pay our respect to their Elders past and present:

The Astrophysics Lab, Marsfield, Wallumattagal People

Paul Wild Observatory, Narrabri, Gomeroi People

Parkes Observatory, Parkes, Wiradjuri People

Mopra Observatory, Coonabarabran, Gamilaroi People

ARRC, Kensington, Whadjuk People of the Noongar Nation

Murchison Support Facility, Geraldton, Nhanhangardi, Naaguja, Wilunyu and Amangu Peoples

Inyarrimanha Ilgari Bundara, our Murchison Radio-astronomy Observatory, Wajarri Yamaji People

Further reading

This document was initially based on the outcomes of a set of working groups in 2023 who considered the ATNF of the Future in the following documents:

- Future developments and opportunities in broad-EM and multi-messenger astronomy
- ATNF Science and Users
- Computing, algorithms and data centres
- Operating models and technology pathways for ATNF
- Working with and supporting the SKA

We also made use of the following publicly available documents:

- ATCA Future Science Plan 2020 [*14MB PDF*]
- Parkes Future Science Case 2020 [*37MB PDF*]
- ASKAP in the era of the SKA 2022 [*5MB PDF*]
- Tracking space weather events with ASKAP and Parkes 2022 [*2MB PDF*]
- Fender et al. (2024), https://arxiv.org/pdf/2402.04698

We acknowledge the ATNF of the Future discussions and working groups coordinated by George Heald and the ATNF User Committee meetings and science days. The first draft of this document was prepared by George Hobbs, Elizabeth Mahony, Mark Bowen and Eric Bastholm. We acknowledge significant contributions to this document from Rachel Rayner and Elaine Sadler.

Appendix: Summary of facility capabilities

Existing facilities of the ATNF, and those currently under development, are listed here with their current capabilities and improvements planned over the next four years. This table is designed to provide an overview of the current facility and the initial commitments which support our vision for the Decadal Plan.

	Facility	Description	Current capabilities	Planned upgrades
Existing	**ASKAP**	36 12-m antennas with a fixed array configuration. The dishes can rotate around the optical axis.	Phased array feeds providing 36 beams between 0.7 and 1.8 GHz. Embedded high performance computing and production of science-ready data products. Autonomous remote operations.	**2024+:** More stable high-performance-computing infrastructure. **2027+:** Improved sensitivity through new phased array feeds and potentially increased bandwidth.
	ATCA	Six 22-m antennas with flexible array configurations with a maximum baseline length of 6 km.	Frequency coverage: 1.1-3.1 GHz, 4-12 GHz, 16-25 GHz, 30-50 GHz, 83-105 GHz Two 2048 MHz bands, zoom-bands, pulsar-binning	**2025:** Backend upgrade to allow 8MHz bandwidth and flexible GPU-based astronomy modes. Infrastructure upgrade to ensure viability of continued ATCA operations.
	LBA	Long-baseline array consisting of the ATNF telescopes (Murriyang, ATCA and Mopra) as well as other national (Hobart, Ceduna, AuScope) and international telescopes.	Frequency coverage from 1.3 to 24 GHz Mopra/ATCA+international: 44 and 88 GHz VLBI	**2026+:** Bandwidth increase by up to a factor of 8. Potential ASKAP inclusion into the LBA. Potential ASKAP-Murriyang 700 MHz VLBI.
	Mopra	Single dish 22-m radio telescope, which is an integral part of the LBA, but not currently available for single dish, principal-investigator driven proposals.	Frequency coverage available in the following bands: 1.2–1.8, 2.2-2.8 GHz; 4.0–6.7 GHz and 8.0–9.2 GHz; 16–27 GHz; 30–50 GHz; and 76–117 GHz	Matching frequency coverage with ATCA, BIGCAT-style backend and realtime connection between Mopra and the BIGCAT correlator at ATCA.
	Murriyang	Single dish 64-mradio telescope at the Parkes Observatory	Wide-bandwidth single pixel receiver operating between 704 and 4032 MHz	**2024**: Cryo-PAF providing up to 72 beams between 700 MHz and 2 GHz

			8.1-8.5 GHz single pixel receiver Flexible GPU-based backend system providing commensal high-frequency and high-time resolution data streams and pulsar binning.	**2027:** wide-bandwidth, single pixel receivers operating between 4 and 27 GHz.
	Data archives and access	Either the raw data sets are directly archived (for Murriyang, ATCA and LBA), or after pipeline processing scripts have been applied for ASKAP.	CSIRO's Data Access Portal contains pulsar and fast radio burst data sets from Murriyang. The ATOA contains spectral line and continuum data from Murriyang as well as ATCA files. The CASDA archive stores ASKAP science-ready data products.	**2024:** The ATOA is currently being migrated to CASDA. **2025+** We expect more automated processing as data volumes are becoming prohibitive for storing all the raw data sets. Explore the use of cloud-based platforms for users to access and process data.
Moving towards	**LAMBDA**	Low-frequency VLBI capability to extend the SKA-Low in the ~150 to 350 MHz frequency band.	Test-bed systems currently being designed	Potential for three or more stations each with 256-elements across Australia with initial stations on our existing East-coast sites.
	Ginan	Low-frequency precision spectral radiometer	Ongoing development	Installation initially at Inyarrimanha Ilgari Bundara, our Murchison Radio-astronomy Observatory
	All-sky monitors	Aperture arrays providing very wide field-of-views and continuous monitoring.	Test-bed systems currently under consideration including a GREX antenna and our own instrumentation	Potential for a range of all-sky monitors from compact, insensitive systems to large collecting area facilities operating in the ~700 to 1000 MHz band and a potential all sky backend for the LAMBDA stations to operate at low frequencies.

As Australia's national science agency and innovation catalyst, CSIRO is solving the greatest challenges through innovative science and technology.

CSIRO. Unlocking a better future for everyone.

Contact us

1300 363 400
+61 3 9545 2176
csiro.au/contact
csiro.au

For further information

CSIRO Space and Astronomy
George Hobbs
+61 2 9372 4652
george.hobbs@csiro.au