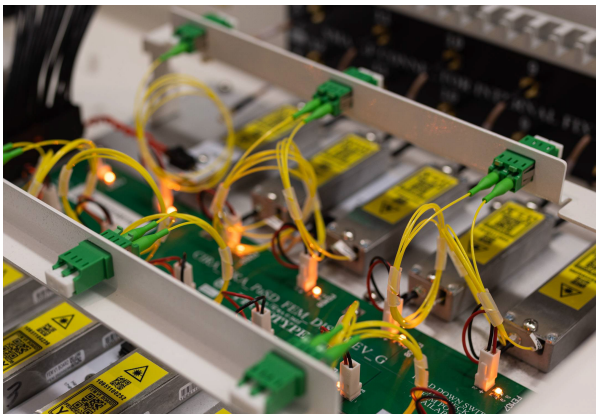
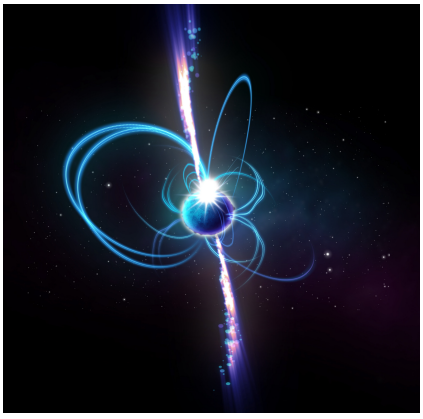


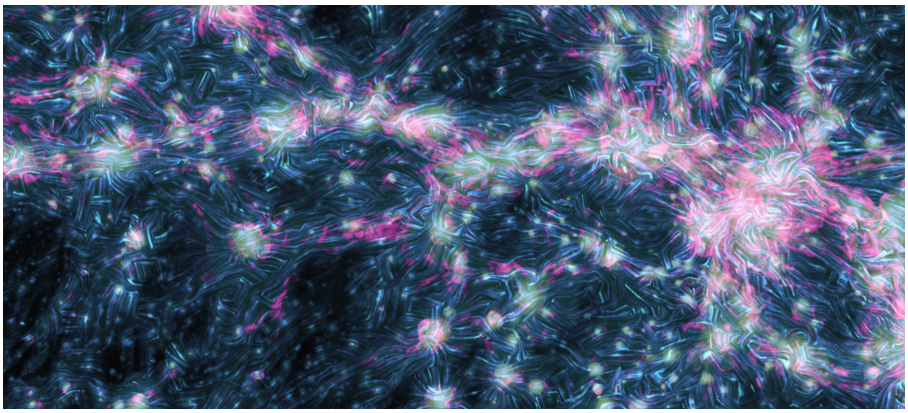
ICRAR

International Centre for Radio Astronomy Research

ICRAR III Five Year Report

2019-2024





Front cover illustration

All images credit: ICRAR unless otherwise noted.

1. Outreach team member Tim Young observes the sun with a student from Wyndham District High School.
2. Close-up of a PaSD SMART Box prototype, developed at ICRAR, which will provide power and data connections to the SKA-Low telescope now under construction in the Mid-West.
3. The staff and students of ICRAR assembled for the March 2024 all-hands meeting, farewelling interim Executive Director Lister Staveley-Smith.
4. The 2022 Exmouth total solar eclipse, a recent highlight of the astronomical calendar for WA and the world, attracted excited commentary and outreach efforts from ICRAR researchers.
5. An artist's depiction of a long-period radio transient, ICRAR's largest media story to date, discovered by Natasha Hurley-Walker, Honours student Tyrone O'Doherty, and their team.
6. The ICRAR executive team, as at the end of ICRAR III
7. A TeraNet ground station developed using SKA spin-off technology, awarded a Demonstrator Grant by the Australian Space Agency. Credit: D. Obreschkow.
8. ICRAR staff members discuss the Murchison Widefield Array radio telescope with members of the public at the Astrofest astronomy festival, now in its 15th year.
9. Magnetic fields in the Cosmic Web, the largest structures in the universe, as modeled by ICRAR's Tessa Vernstrom. Credit: F. Vazza, D. Wittor and J. West

Acknowledgement of Country

Kaya! Wandjoo!

Hello! Welcome!

We acknowledge that Aboriginal and Torres Strait Islander people are Australia's first astronomers. We acknowledge their long-standing systems of knowledge on which we continue to build, and we acknowledge the Traditional Custodians of the unceded lands on which we are meeting today.

We are on Wajuk Noongar boodja, Wajuk Noongar country, and we pay our respects to their Elders past and present, and extend that respect to all First Peoples.

We acknowledge the Wajarri-Yamaji people who are traditional custodians of the land on which the MRO is sited.

INTERNATIONAL CENTRE FOR RADIO ASTRONOMY RESEARCH (ICRAR)

Final Report 2019-24

To comply with the 2019-24 Financial Assistance Agreement (FAA) Clause 13.2 and Schedule Item 4.2.

NB: When completing any of the sub-sections of this Final Report, please note that if any of the requested information has already been provided in a previous sub-section of the report, it does not need to be repeated in the sub-section being completed. However, please make reference to the relevant previous sub-section for this information.

Table of Contents

SECTION A: HIGHLIGHTS

A.1 ICRAR III HIGHLIGHTS

Please outline ICRAR's highlights as they relate to the Project Objectives and Outcomes. The highlights should:

- Be provided as bullet points of two to five sentences each;
- Be suitable for release into the public domain;
- Be written in plain English so that they are easily understood by a lay audience;
- Include the significance, such as the potential or achieved benefits for Western Australia;
- Include the benefits for industry and other end-users;

1. Growth and Impact Highlights

- **ICRAR's Excellence**: ICRAR continued to excel in research, training, and capacity-building in Western Australia (WA) over the five-year reporting period. On average, 140 staff were employed. ICRAR also contributed to job creation in WA by sustaining core employment and expanding opportunities through translational activities, winning competitive grants, and hosting national and international collaborators.
- **Postgraduate Program Development**: The postgraduate program grew stronger, overcoming the challenges posed by the COVID-19 pandemic. Each year, an average of 89 postgraduate students enrolled at ICRAR, with 36% being international and 64% national. This diverse cohort reflects the global interest in radio astronomy and the high-impact research conducted at ICRAR. During this period, 97 students graduated, 61% with a Doctor of Philosophy (PhD), contributing a critical talent pipeline for the WA economy and beyond.

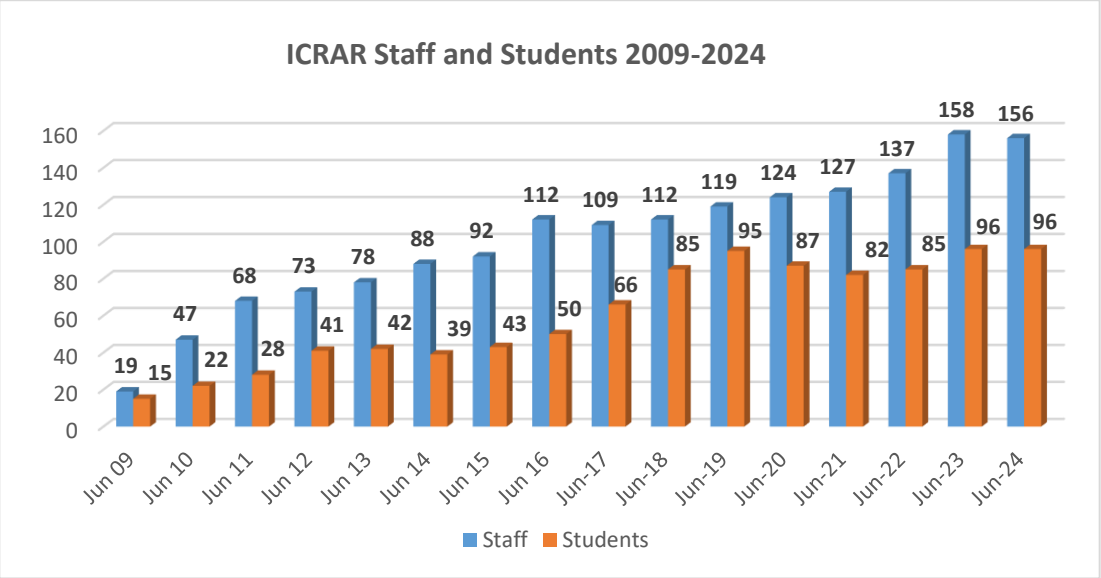


Figure 1: ICRAR staff and student 2009 – 2024 numbers.

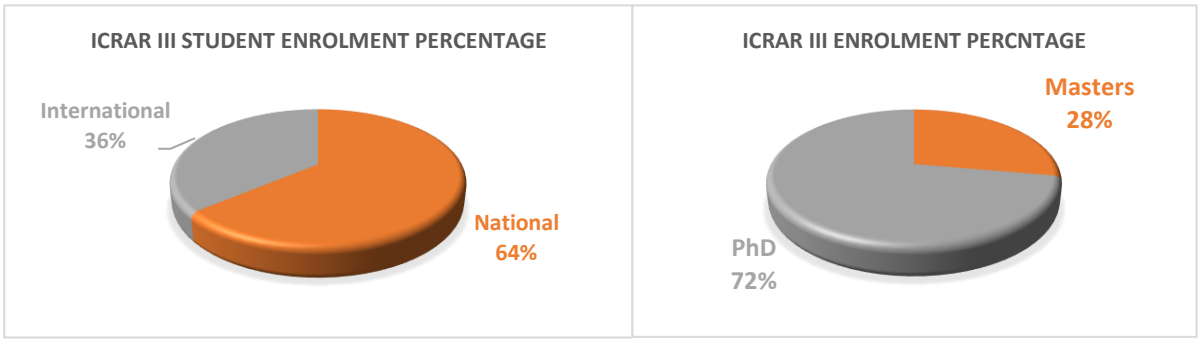


Figure 2: ICRAR III student enrolments.

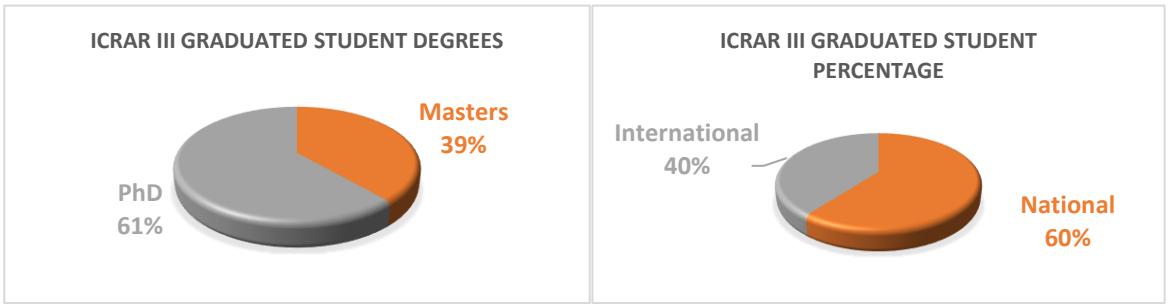


Figure 3: ICRAR III graduated students.

- **Global Scientific Contributions**: Over the five-year period, ICRAR made significant contributions to global scientific literature, underscoring ICRAR's research influence. Key international collaborations included the United States of America (USA), Germany, Italy, United Kingdom (UK), France, and the Netherlands (details in Appendix A). Since 2009, these works garnered 135,124 citations.

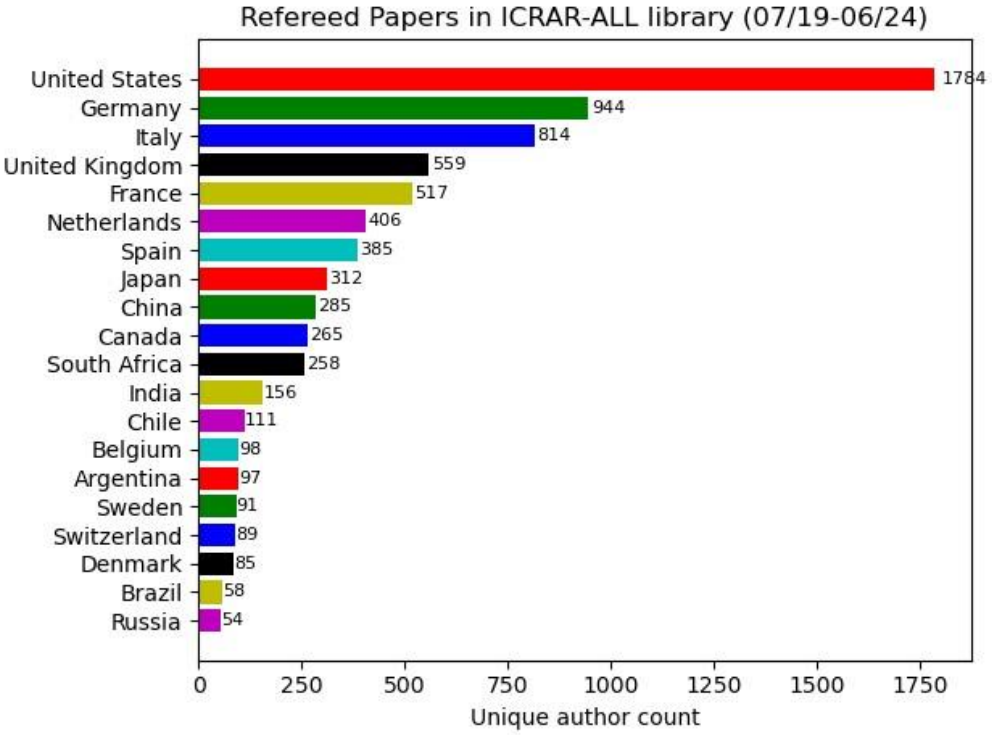


Figure 4: Refereed papers in ICRAR-ALL library (07/19 – 06/24) by country.

- **STEM Contributions**: ICRAR supported WA's Science, Technology, Engineering, and Maths (STEM) agenda, delivering 155 university coursework units to 5,045 students. The disciplines spanned physics, astronomy, data science, computing, mathematics, and statistics.
- **Student Development and Internships**: ICRAR's summer studentships offered undergraduate/ course work students valuable research experience, attracting interns from across Australia and New Zealand, with 21% from outside WA. Furthermore, Year 10 and Year 11 students participated in work experience programs, gaining exposure to astronomy, engineering, and data science. These programs were impacted by COVID-19 between 2019/20 and 2021/22.
- **Grant Success**: ICRAR leveraged State and Joint Venture (JV) funding to secure $57.8 million in additional grants and contracts during ICRAR III, achieving 145% of its key performance indicators (KPI) of $40 million over the five-year period. Eighty-four percent of these grants came from outside WA, bolstering the state's economy. From 2009 to 30 June 2024, ICRAR secured a total of $145.4 million in grants.

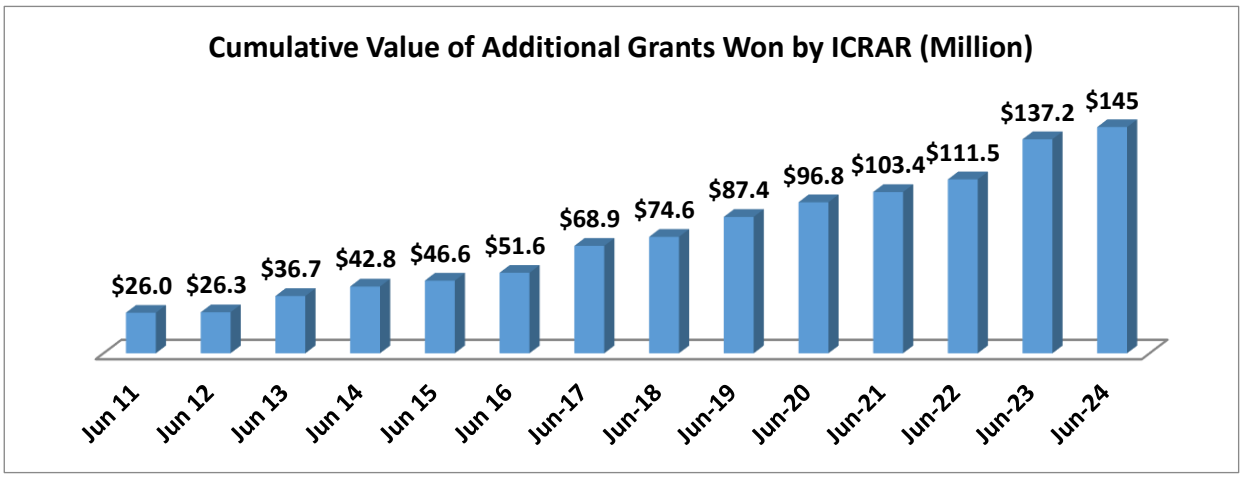


Figure 5: Cumulative value of additional grants won by ICRAR.

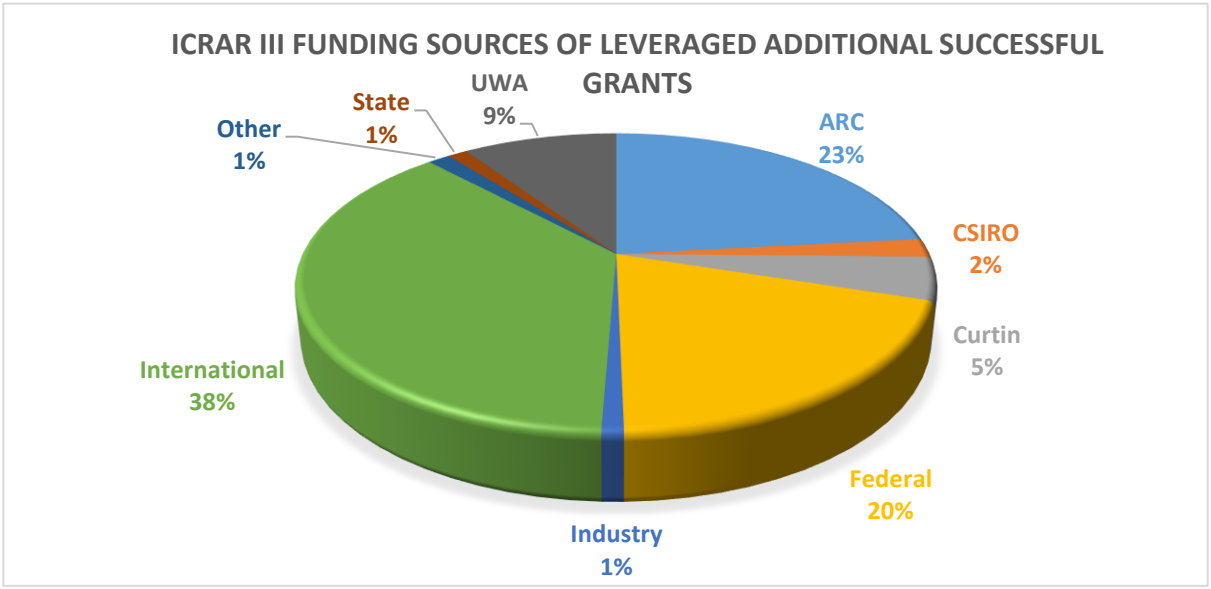


Figure 6: Funding sources of leveraged additional successful grants.

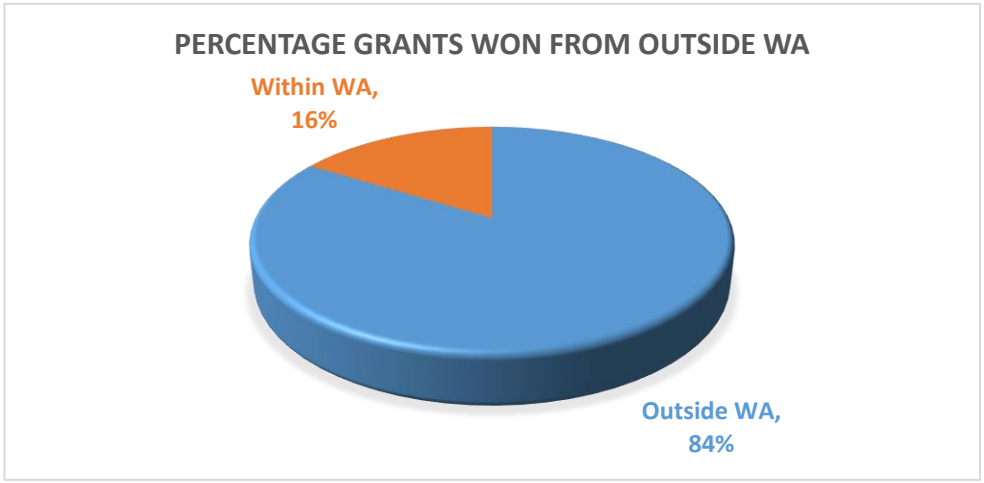


Figure 7: Percentage grants won from outside WA.

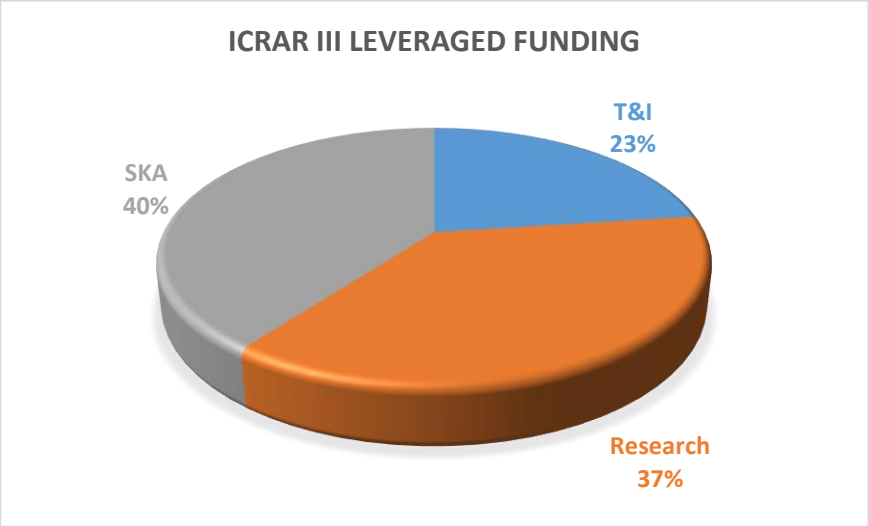


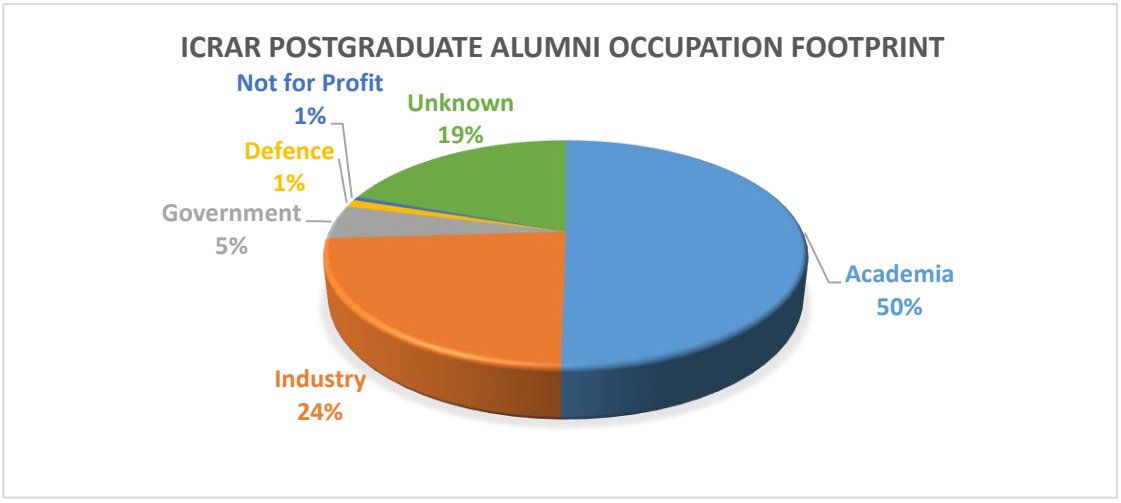
Figure 8: ICRAR III Leveraged Funding as a Percentage

- **SKA Contributions**: ICRAR played a crucial role in the construction of the Square Kilometre Array (SKA), securing contracts as the sole source provider for the Software Development and SKA-Mid Phase Synchronisation System. These contracts, involved designing, manufacturing, installing, and commissioning the SKA-Mid Telescope's reference frequency distribution system. Another contract focused on developing a prototype SKA-Low Power and Signal Distribution (PaSD) system. More than 50 ICRAR researchers contributed to SKA committees facilitating the project's planning and construction (see Appendix A for details).
- **Collaborations with CSIRO and Pawsey**: ICRAR collaborated extensively with Commonwealth Scientific and Industrial Research Organisation (CSIRO), Pawsey Supercomputing Research Centre, (Pawsey) and other organisations through joint appointments, training activities, and involvement in SKA construction and survey projects, including the Australian SKA Pathfinder (ASKAP) full survey, which began in late 2022. Additionally, ICRAR played a leading and critical role in the establishment of the $63 million Australian SKA Regional Centre (AusSRC) alongside CSIRO, Pawsey, Curtin University (Curtin), and UWA.
- **International Engagement**: ICRAR welcomed collaborators from 35 countries during the five-year reporting period. Seminars were delivered by visiting collaborators, though visitor numbers were significantly impacted by the COVID-19 pandemic (see Section C.1 for more details). Notable visits included a delegation from the Chinese Ministry of Science and Technology, led by Minister Mr. Hejun Yin and Chinese Ambassador Mr. Xiao Qian, for a roundtable on science and technology cooperation. The Minister visited ICRAR despite very limited time available to him in WA.

Figure 9: Australia-China Science and Technology Cooperation Round Table Meeting 18 June 2024 (Credit: UWA).

Figure 10: ICRAR visitors.

- **Global Alumni Network**: ICRAR-trained researchers, including research staff and postgraduate students, serve as global ambassadors for WA.



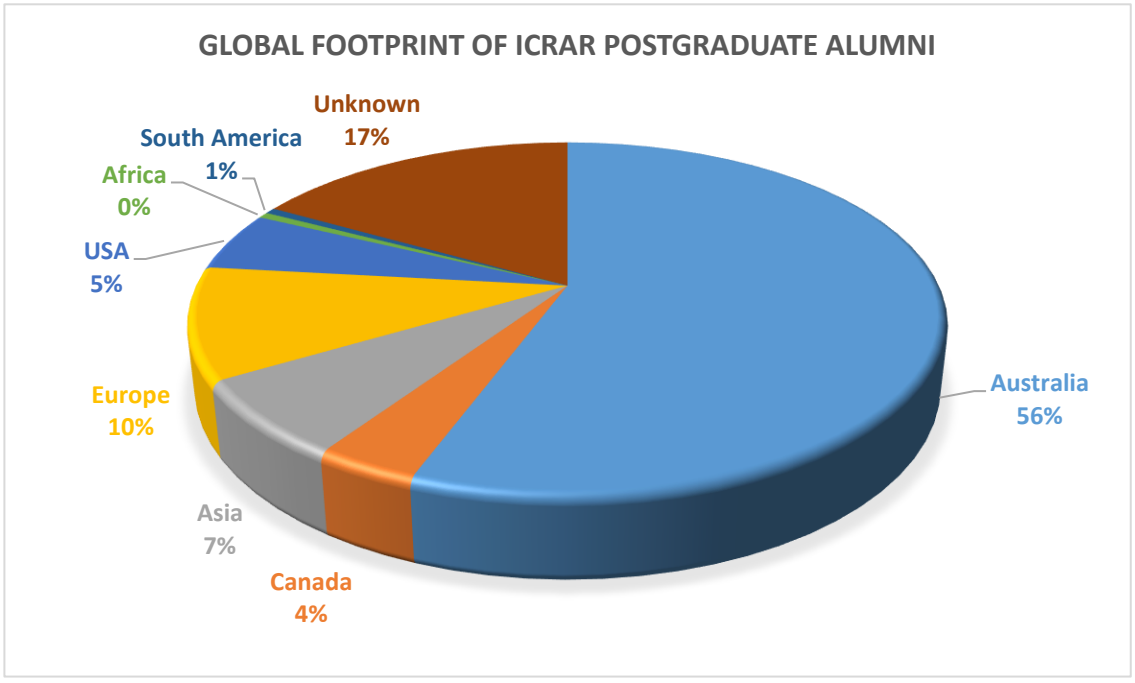


Figure 11: ICRAR postgraduate alumni statistics.

2. Highlights of Research Excellence, Translation, and Impact (T&I)

- **Recognition and Esteem for WA**: ICRAR's contributions have enhanced WA's prestige in the global scientific community. Numerous national and international awards recognised the work of ICRAR staff, showcasing the far-reaching impact of their research beyond astronomy. These accolades demonstrate that ICRAR's research is among the best being performed both within Australia and internationally. The full list of awards and recognitions is provided in Appendix G.
- **Strategic Translation of Research**: During this reporting period, ICRAR focused on translating its research excellence, particularly its expertise developed for the SKA, into various domains, such as space, data science, defence, marine, agriculture, and citizen science (for example see section 2b).

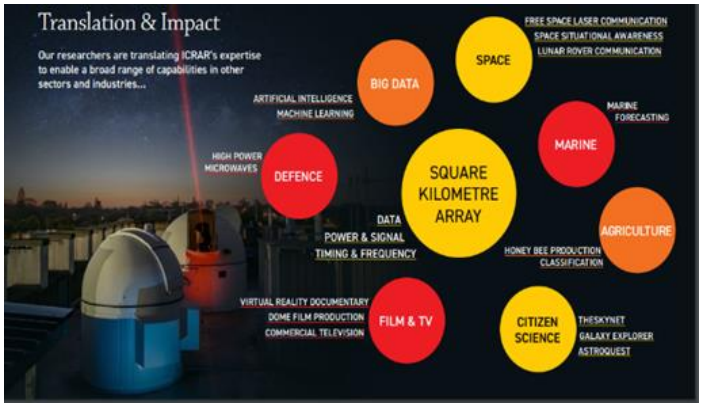


Figure 12: T&I of ICRAR's expertise to a broad range of capabilities in other sectors and industries (Credit: ICRAR).

2a. *Research Excellence Highlights*

- **Discovery of a new class of slowly pulsating source in data from WA's Murchison Widefield Array (MWA) telescope**: The transient group within ICRAR's science program opened a new field of research when an Honours student discovered a new class of slowly pulsating source in data from WA's MWA radio telescope. These mysterious objects challenge our understanding of how rotating stellar remnants produce pulsed signals and are now being found in data from leading radio telescopes all over the world, including WA's ASKAP. The first discovery, led from the ICRAR science team, led to the most successful media release in ICRAR's 15-year history, promoting ICRAR's scientific excellence to a huge global audience.
- **High-impact pulsar science with WA's MWA and other leading global facilities:** Over the past 5 years the pulsar team within the ICRAR science program have pursued high-impact pulsar science, both with WA's MWA radio telescope, and with other leading global facilities. They have developed the MWA's capability to detect and study pulsars, allowing the world's radio astronomers to use the telescope to undertake preparatory science for one of the SKA's leading scientific goals. They have surveyed the entire southern sky in search of new pulsars and made some of the first scientific contributions with SKA-low stations. Their contributions to the Australian and USA pulsar timing array teams led to the ICRAR science team's most impactful and highly cited publications of the past five years, reporting the first evidence of very low frequency gravitational waves from orbiting supermassive black holes scattered throughout the Universe.
- **Improving the data quality obtained from the James Webb Space Telescope (JWST**): ICRAR researchers have played a leading role in improving the data quality obtained from JWST. Our team developed several bespoke tools that are now central to the work of various international teams using JWST data. This has positioned ICRAR at the forefront of JWST's scientific exploitation, enabling the team to lead or contribute to multiple studies shedding new light on galaxy evolution across cosmic time, including several publications in prestigious journals such as *Nature* and *Nature Astronomy*.

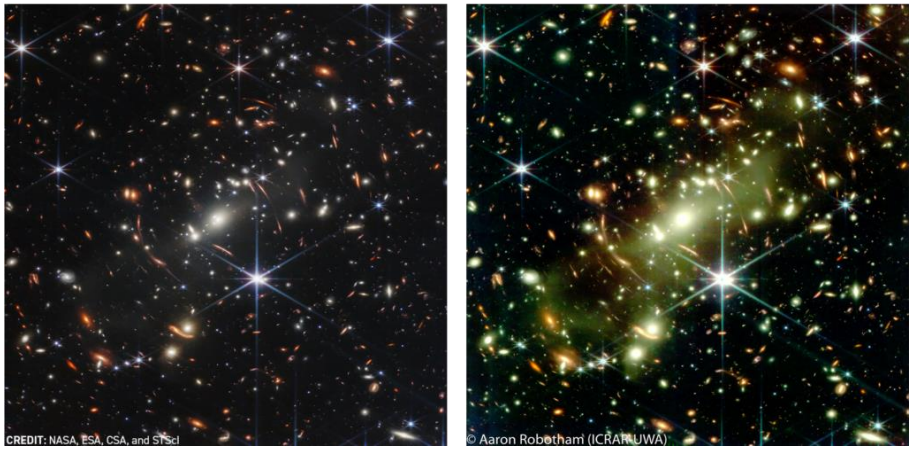


Figure 13: The image created by the ICRAR team (right) allowed our researchers to extract more features from JWST data. (Credit: Professor Aaron Robotham, ICRAR).

- **Challenging current understanding of galaxy formation and evolution:** The discoveries made by our team during the ICRAR III period have significantly challenged our current understanding of galaxy formation and evolution. To address these challenges, our Cosmological Theory group has improved existing theoretical models by leveraging new suites of cosmological hydrodynamical simulations and developing innovative semi-analytical models. Key achievements include advancing our understanding of gas removal processes in galaxies (recognised nationally with an award from the Astronomical Society of Australia (ASA)) and explaining the origin of massive quiescent galaxies at early cosmic epochs, as discovered by JWST.
- **Scientific exploitation of the ASKAP Telescope:** The ICRAR science team achieved significant milestones in the scientific exploitation of ASKAP. Both the Widefield ASKAP L-band Legacy All-sky Blind SurveY (WALLABY) and the Deep Investigation of Neutral Gas Origins (DINGO) successfully completed their pilot phases and early science publications and began full survey operations toward the end of ICRAR III. The team has already published over 40 papers. Most notably, the WALLABY team released its first data set to the scientific community, providing atomic hydrogen maps for hundreds of galaxies obtained with the ASKAP telescope, covering 180 square degrees of the sky—the equivalent area of over 700 full moons.

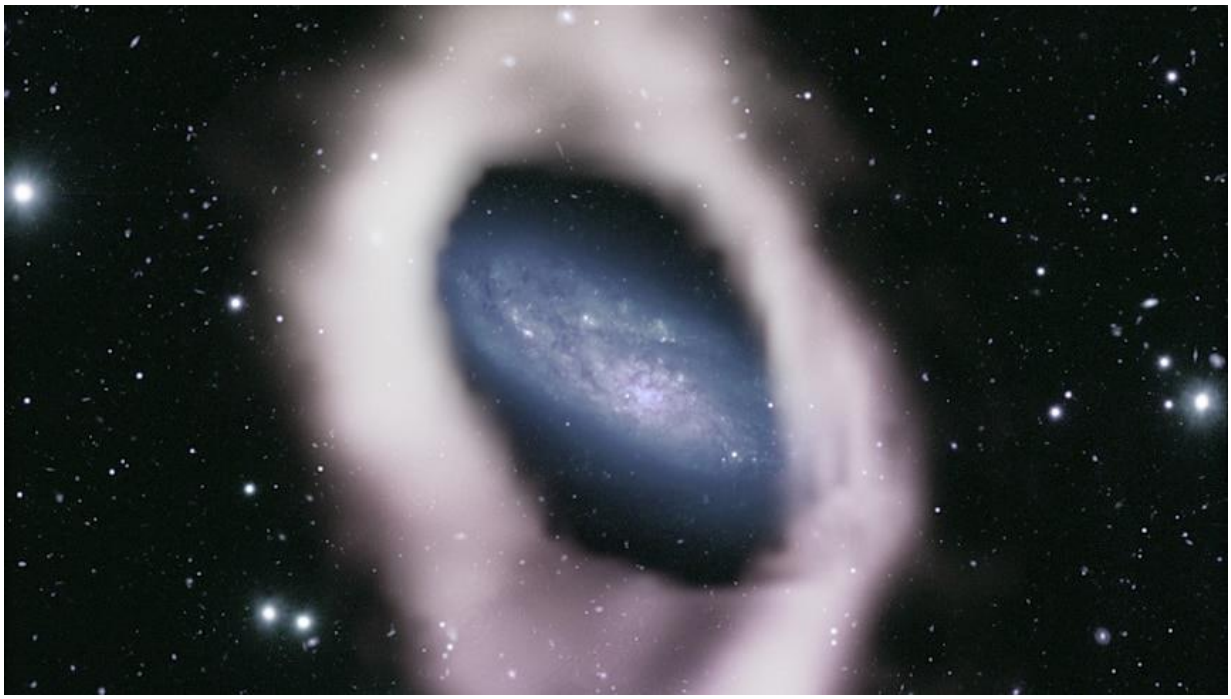


Figure 14: A colourised radio telescope image of the central disk of NGC 4632 surrounded by a thick band of hydrogen gas (white) (Credit: Jayanne English (U. Manitoba), Nathan Deg (Queen's University) & WALLABY Survey. CSIRO/ASKAP radio telescope, National Observatory of Japan (NAOJ)/Subaru Telescope).

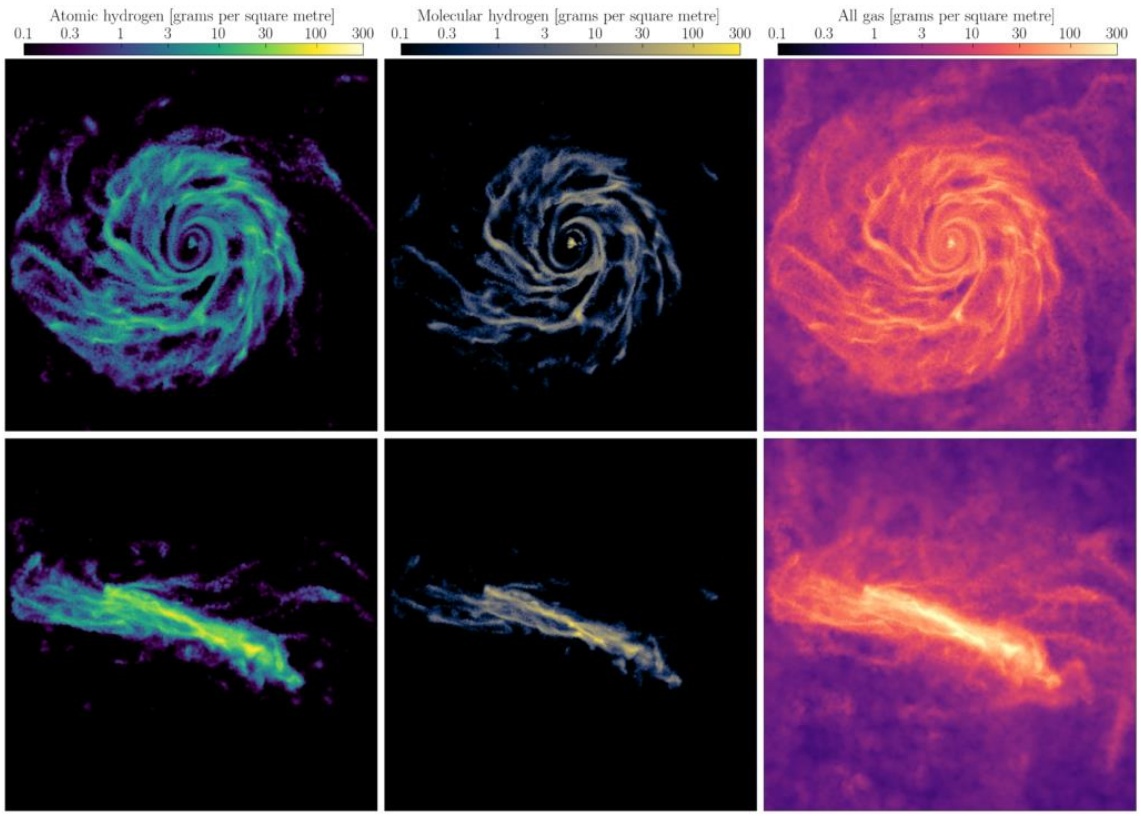


Figure 15: A massive, simulated galaxy showing its first signs of gas stripping (Credit: Adam Stevens, ICRAR).

- **Co-leadership of the flagship Commensal Real-time ASKAP Fast Transients (CRAFT) project on WA's ASKAP:** The ICRAR science team's co-leadership of the flagship CRAFT project on WA's ASKAP radio telescope has led to key scientific advances in the exciting and rapidly evolving field of Fast Radio Bursts (FRB). This work allowed the ICRAR science team to detect the "missing matter" in the Universe, showing that half of the normal matter in the Universe was in the vast spaces between galaxies, and thereby solving a decades-old scientific problem. The potential of this work for new and impactful science led to the award of an Australian Research Council (ARC) Discovery Project, bringing funding into WA, and allowing the team to use these exceptionally energetic cosmic events to understand the evolution of the Universe. The international excellence of the work was recognised by the award of the prestigious Newcomb-Cleveland Prize to the CRAFT team by the American Association for the Advancement of Science (AAAS).
- **Searching for signs of the first stars and galaxies to form in the Universe:** The Epoch of Reionisation team within the ICRAR science program have been searching for signs of the first stars and galaxies to form in the Universe. While this is an extremely challenging experiment, the team members have placed some of the deepest limits to date on the strength of this very faint signal. To process the enormous volumes of data required for this project, they have collaborated closely with both Pawsey and local industry partner DUG Technology (DUG), demonstrating the value of industry collaborations in radio astronomy. The quality of the team's work has been recognised by the award of both a highly sought-after Forrest Fellowship, as well as a prestigious Nancy Millis Medal from the Australian Academy of Science (AAS).

2b. Translation Highlights

Over the five years, ICRAR undertook numerous T&I activities, with multiple projects at ICRAR. These projects demonstrate how radio astronomers' skills are transferable and can contribute to diversifying the WA economy. The T&I team organised various activities and events to highlight the potential career pathways that can stem from radio astronomy into other sectors. A few highlights are presented below.

- **MWA:** The ICRAR led MWA telescope celebrated 10 years of operations in July 2023. International MWA collaborators past and present, gathered in Perth for a conference including visits to Pawsey, the Perth Observatory, and the Perth office of the Square Kilometre Array Observatory (SKAO) organisation. The conference celebrated MWA's scientific achievements, as well as the enduring relationships forged with businesses and stakeholders in the Mid-West region of WA. A highlight of the conference was a presentation from the Manager of Yamaji Art, who described their 14-year relationship with ICRAR's radio astronomers as being "in the true spirit of reconciliation".

Figure 16: Yamaji Art is the longest running Aboriginal art centre in the Midwest, and to mark the 10-year anniversary of MWA Operations, Yamaji artists showcased decorating a 3D 'beam pattern' of an MWA antenna tile. (Credit: Curtin).

- **PaSD:** The ICRAR Engineering Team designed the PaSD system for the Antenna Stations that will make up the SKA-Low Telescope, in WA. The design team, working with West Australian companies and suppliers, met specifications for the emission of radio frequency interference that were so demanding they couldn't be tested in Australia. This unprecedented technical achievement will help to ensure SKA-Low is sensitive to the extremely faint signals required to undertake groundbreaking science. Having successfully demonstrated the PaSD system on a prototype Station, the SKA awarded a contract to manufacture the system at scale to West Australian company AVI.

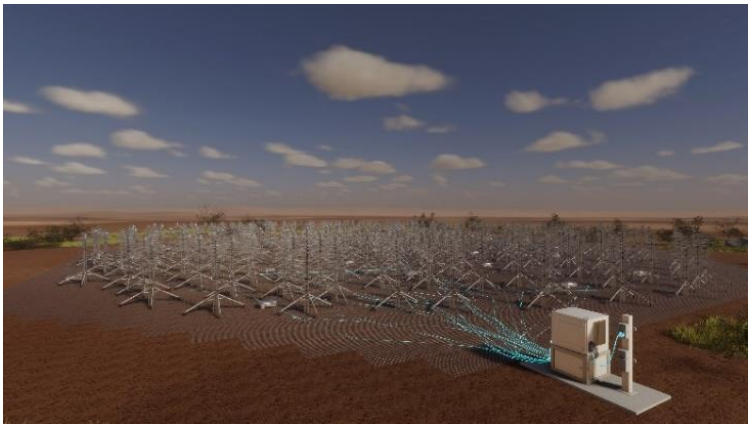


Figure 17: Artist's impression of an SKA-Low Station, featuring ICRAR designed PaSD system (white boxes within and adjacent to the antenna station) (Credit: Scott Bell).

- **Aperture Array Verification System (AAVS) version:** ICRAR has built and operated successive generations of SKA-Low prototype stations at the Inyarimannah Ilgari Bundarah, CSIRO's Murchison Radio Astronomy Observatory, since 2011. In ICRAR III, the AAVS3 was deployed by the SKA with ICRAR's support. Experience gleaned through building and operating the AAVS family of prototypes has directly driven significant evolution of the SKA-Low Station design and allowed engineers and astronomers to attack some of the key technical challenges to be overcome if SKA-Low is to realise its full potential.
- **SKA-Low Station simulation and modelling:** The scale and electromagnetic complexity of SKA-Low Stations pushes the tools and techniques of computational electromagnetics to their limits. Commercial simulation tools and solvers are not up to the task. During ICRAR III, the Electromagnetic Modelling and Simulation Team at ICRAR developed world leading techniques to address this unprecedented challenge. The models and simulation tools developed by the team are used by SKA to understand how the various Antenna Station layouts and configurations they have designed will perform.

Figure 18: Artist's impression of SKA-Low Station beam pattern. (Credit: Scott Bell).

- **Directed Energy:** Leveraging the underlying skill sets and interests of its team of Radio Astronomy Engineers, ICRAR undertook a multi-year program of work to investigate the effects of directed energy on electronics. The work was funded by the Defence Science and Technology Group (DSTG) and aimed to understand how electronics suffer and fail when subjected to high-power microwave energy. This work will help engineers and product designers to design systems that are more resilient against electromagnetic disruption. The team developed novel approaches and methods of enquiry that can reduce the cost of undertaking this type of research, which has garnered international attention. This project enabled 3 industry funded Higher Degree Research (HDR) students.
- **Space Domain Awareness:** A Western Australian Defence Science Centre (DSC) Collaborative Research Grant (CRG) helped the Engineering Team at ICRAR demonstrate that technology and techniques developed for radio astronomy could be effectively applied to Space Domain Awareness (SDA). The team developed a portable SDA system that successfully demonstrated the tracking of aircraft around Perth, and satellites in earth orbit. The success of the project—which included development of domestic supply chains for all the necessary hardware— was leveraged into a larger demonstration system in collaboration with Australian defence company, Nova Systems. A 16-element fixed array was deployed at Nova Systems' Peterborough Space Precinct in regional South Australia. This system is being used to demonstrate the utility of radio astronomy approaches in SDA, for civil and defence applications.

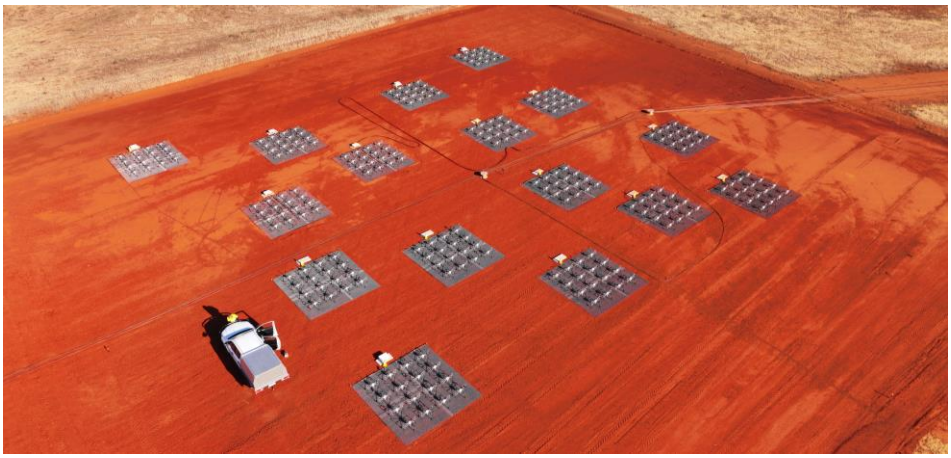


Figure 19: Top: Mobile SDA system deployed at the Australian Automation and Robotics Precinct (AARP). Bottom: The SDA demonstration system deployed at Peterborough Space Precinct in collaboration with Nova Systems.

- **Collaboration with DUG:** ICRAR continued its collaboration with WA-based, global service provider, DUG, to support the radio astronomy data processing, demonstrating the benefits of optimising radio astronomy processing pipelines to leverage modern high performance computing (HPC) capabilities, while also allowing DUG to further diversify its operations outside of its traditional oil and gas contexts. ICRAR hosts two DUG sponsored PhD students, one of whom is conducting award winning research resulting in the detection of unintended out-of-band emissions from Starlink satellites.
- **SKA Project Science Data Processor Design and Architecture:** In 2021, following many years of involvement in the pre-construction of the SKA Science Data Processor design and architecture, the ICRAR Data Intensive Astronomy (DIA) team was awarded a framework contract by the SKAO. The team provides domain expertise and software engineering services to implement significant parts of the data management and processing software for the telescopes. As part of the pre-construction work, the team has also developed a sophisticated science workflow development and execution software package, which had been used to demonstrate the ability to execute a radio astronomy workflow at SKA scale on the biggest supercomputers in the world. This work was nominated for the Gordon Bell prize in 2020.

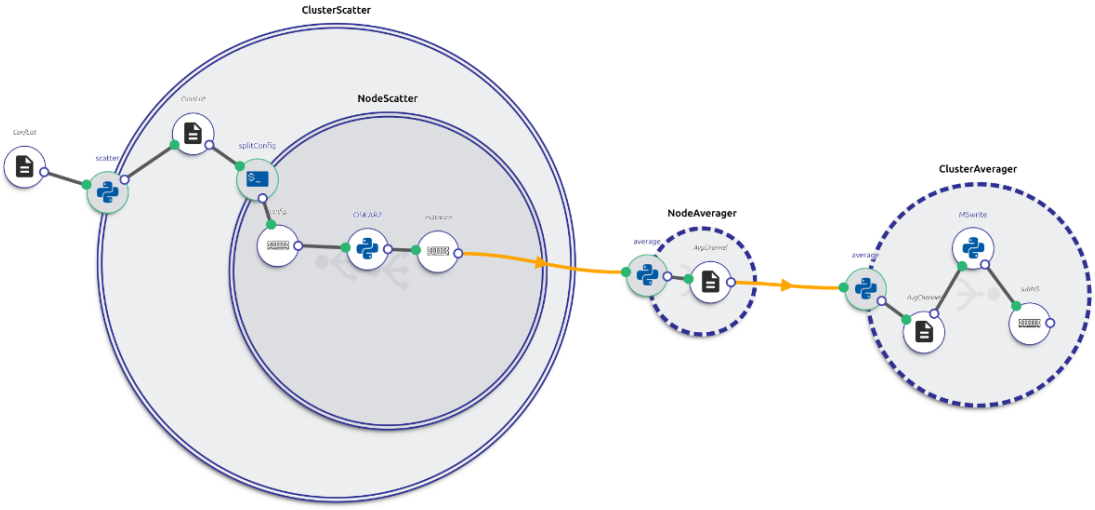


Figure 20: The conceptual representation of the workflow executed on the Summit supercomputer. The full representation contains more than 75,000 individual tasks.

- **SKA Regional Centre:** The DIA team had been continuingly active in promoting the idea and the need of having a SKA Regional Centre (SRC) in Australia. Some preparatory activities included international meetings and workshops, industry briefing and community workshops, and initial prototyping of SRC functionality. To support this, ICRAR's DIA team successfully applied for federal grants and secured a significant contribution from CSIRO to conduct a design study. All this work provided the technical basis for the successful submission of a proposal for $63M to the federal

government to fund the AusSRC. Starting from 2023, the AusSRC is a separate, independent JV organisation and fully funded for 10 years.

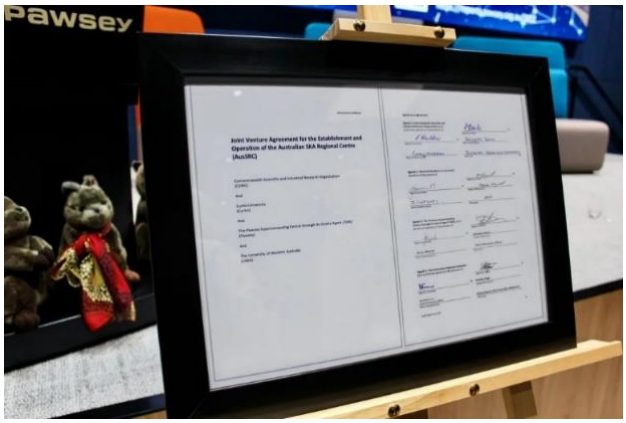


Figure 21: The signature page of the AusSRC joint venture established in 2023.

- **Survey Science Support for the SKA high priority science objectives:** The DIA team supported globally diverse Survey-Science projects spanning the Compute Intensive interests of DIA and the core science drivers of ICRAR. Deep multi-epoch spectral line surveys are fundamental to the SKA high priority science objectives, primarily for the HI signal from the distant and the near Universe. These combine multiple days of observations, potentially taken over many years, to reach unprecedented sensitivities. However, the SKA observatory cannot store the immense datasets it will generate every day for more than a few days. Thus, teams are forced to store an intermediate data product, and these are extremely sensitive to systematic errors that will build up and prevent the required sensitivity being reached. The DIA team is developing several innovative solutions to address these issues, using the Very Large Array (VLA) Radio Telescope, survey COSMOS HI Large Extragalactic Survey (CHILES), and the ASKAP DINGO deep spectral line survey. In the latter case the team have defined a new data product for the SKAO, which allows the original raw data to be stored and manipulated. This allows any systematic errors to be identified and removed in the observational frame – where it is both clearest and most localised in extent.

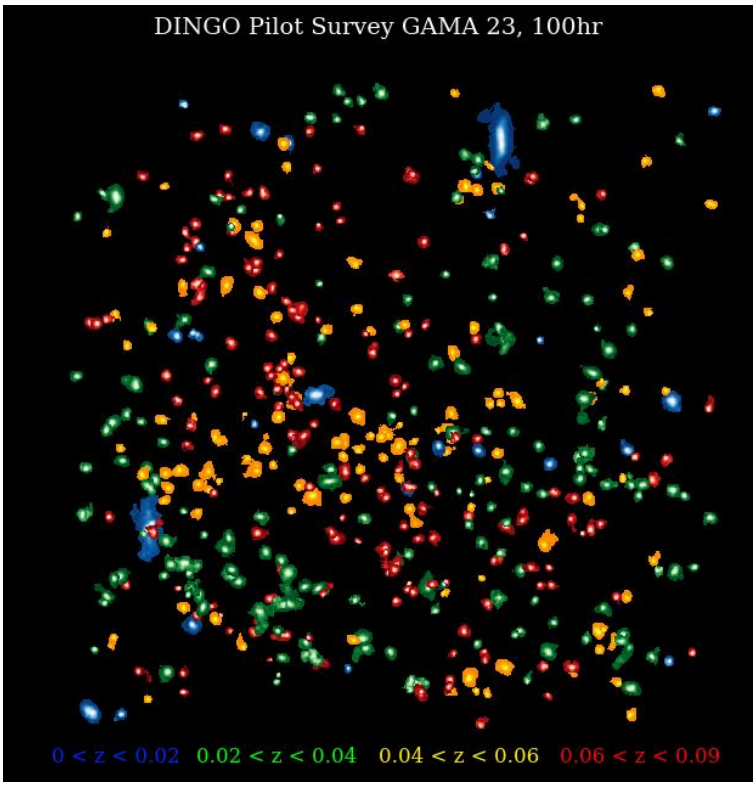


Figure 22: Images of the 500 individual moment-0 sources detected in the G23 field in the deep pilot observations of DINGO. The individual galaxies are zoomed by a factor of four for the visualisation and colour-coded by redshift. This brings out the large-scale structure of the streams. (Credit: J. Rhee, DINGO project scientist).

- **Critical Software Support for Major Observatories Globally:** The DIA team is maintaining several operational critical software packages, one of which is the Next Generation Archive System (NGAS). This system is used by some of the biggest observatories in the world, including European Southern Observatory (ESO) and the Atacama Large Millemeter/Submillimeter Array (ALMA) and the ALMA Regional Centres. The original software has been developed already in 2000, but the DIA team keeps updating it to meet the demanding requirements of the upgraded telescopes. In 2020 ESO and ALMA conducted a review of NGAS and potential alternatives and decided to stay with NGAS, but upgrade it to the latest version maintained by DIA. This version had been enhanced to be able to deal with the data rates from the MWA. The actual roll-out of the software on all the storage computers of ESO, ALMA and the ALMA regional centres in all the sites around the world was only concluded in 2024, after very extensive additional testing, but is fully operational since. We are also maintaining two smaller projects, ijson and crc32c. The first is a very high-performance iterative parser of a popular format used throughout the computing world called Java Script Object Notation (JSON). This software receives almost 2.9 million downloads every week and is thus classified as a key Python ecosystem project. The other package still receives an impressive number of almost 250,000 downloads per week.
- **Critical Compute Lab Infrastructure:** The ICRAR Compute Lab has seen several upgrades and replacements of machines and storage. This is a fully serviced resource, which is used by many ICRAR scientists. One of the main highlights of the system is that it has a very high uptime and that it features almost 2PB of usable disk space as well as two graphics processing unit (GPU) machines, mostly used for machine learning (ML)/artificial intelligence (AI) development and a small Central Processing Unit (CPU) cluster. The Lab also features particularly good connectivity with Pawsey to support applications requiring data transfers between the two environments.

Figure 23: A few of the storage servers of the ICRAR Compute Lab.

- **Progress on SKA Prototypes**: Work on the SKA-Mid Frequency Distribution System is proceeding well. The first tranche of production hardware was shipped in August 2024, and mass-manufacturing production is now accelerating. Earlier in 2024, Dr. Tim Stevenson, Director of SKAO Quality Assurance, alongside SKAO engineers and Quality Assurance (QA) experts, visited ICRAR to inspect the progress on the production hardware. This visit highlighted the importance of collaboration in ensuring quality and precision in the development of these critical systems.

Figure 24: The SKAO QA team visited ICRAR to inspect SKA-Mid frequency distribution hardware.

- **Diversification of SKA Technology**: Over the last five years, the Astrophotonics Group has translated the SKA-Mid optical fibre-based technology to enable stable laser transmission through the atmosphere, thereby contributing towards ultra-precise optical timing, high-speed optical communications, and quantum technologies, for both terrestrial and space-based applications. This translation work has included collaborations with multiple national and international industry partners and Australian defence agencies.

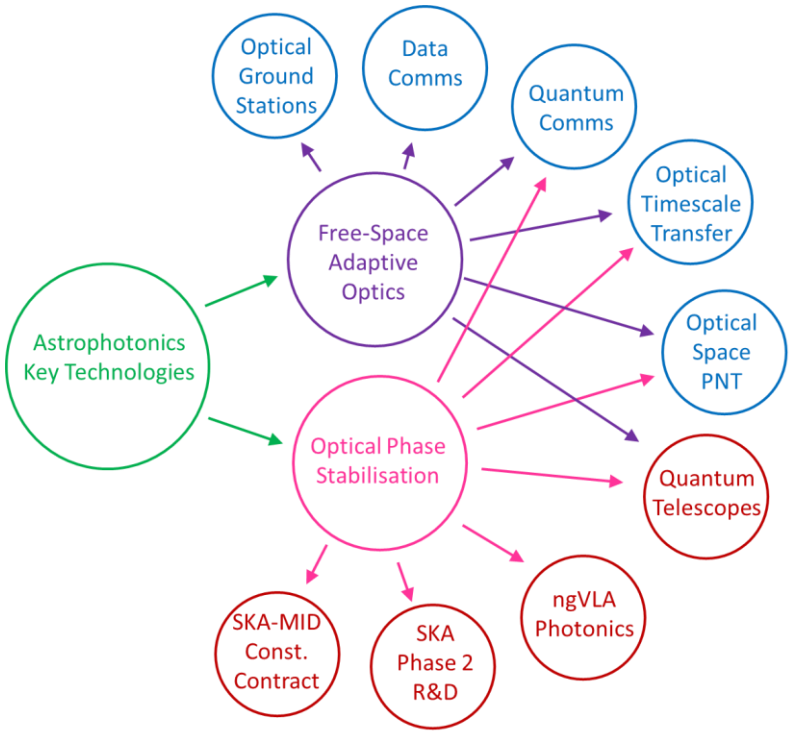


Figure 25: Astrophotonics key technologies.

Figure 26: Teranet mobile optical communications network.

- **SmartSat Cooperative Research Centre (CRC) Project:** In 2024, the Astrophotonics Group completed a four-year SmartSat Cooperative Research project on coherent free-space optical communications. Highlights from this project include publications reporting on the most stable atmospheric laser transmission and also the highest data rate transfer via a laser link to an aircraft. The project culminated with a free-space optical communications technology showcase at Exercise Talisman Sabre, and demonstration to defence industry leaders including the Director General for Navy Intelligence and Information Warfare. The demonstration conducted included laser links to moving land, air, and maritime targets.

Figure 27: The Exercise Talisman Sabre delegates visiting ICRAR.

Figure 28: Showcase of Astrophotonics free-space optical communications technology at Exercise Talisman Sabre.

- **TeraNet Project:** During ICRAR III, the Astrophotonics Group has been developing optical ground station infrastructure to enable laser communication between ground and space. This work included the installation of the first optical communications ground station in the southern hemisphere in 2021, and the extension towards a network of three optical ground stations as part of the $6.5M Australian Space Agency TeraNet project. This ground station network will be capable of supporting low-Earth orbit communications, lunar communications, and next-generation optical positioning and timing services. Recent highlight included validating the first two ground station in the network by capturing laser signals from the German Flying Laptop satellite, and successfully passing the project's Critical Design Review.
- **Swell Forecasting**: This ML project, started in 2021, improves wave swell forecasts using real-time data and 12-hour predictions to create 5-day forecasts for the Liquefied Natural Gas (LNG) terminal at Barrow Island. It analyses recent and predicted wave data to refine wave spectra, providing detailed wave height, period, and direction information. These accurate forecasts enhance ship loading efficiency and maritime safety.

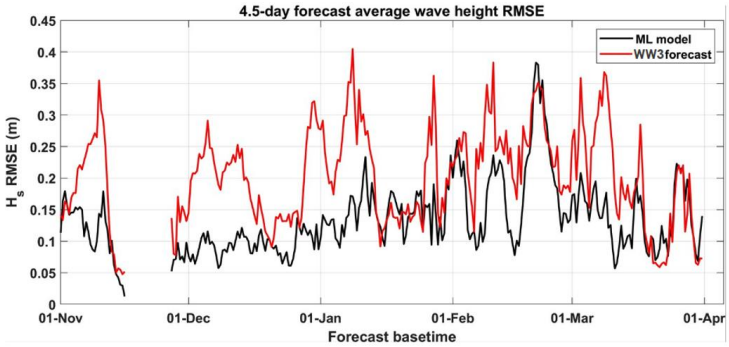


Figure 29: Comparison of Error between ML forecast and traditional forecast

- **Assistive Digital Technologies**: ICRAR initiated a new collaborative project with Algoma University in Canada, developing an assistive digital technologies website to support people with disabilities. The project directly benefits from the involvement of two DIA team members with first-hand experience with disabilities, furthering ICRAR's inclusive approach to technology development.

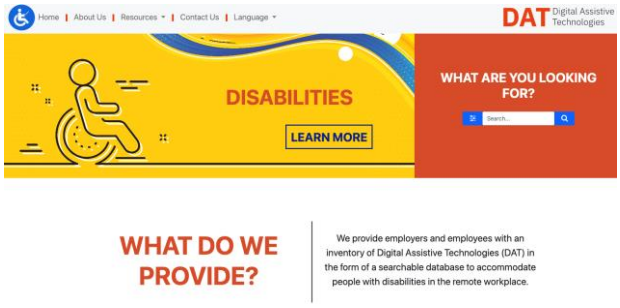


Figure 30: Digital Assistive Technologies (DAT) Front Page.

- **Wind Forecasting**: This ML project creates local wind forecasts for WA's Department of Primary Industries and Regional Development (DPIRD). It uses data from DPIRD weather stations and the European Centre for Medium-Range Weather forecasts (ECMWF) to generate 8-hour predictions for Southwest WA. These aid farmers and Department of Fire and Emergency Services (DFES) in agriculture and bushfire management. The project is expanding to include rain and solar luminosity forecasts, supporting solar farms and energy planning.

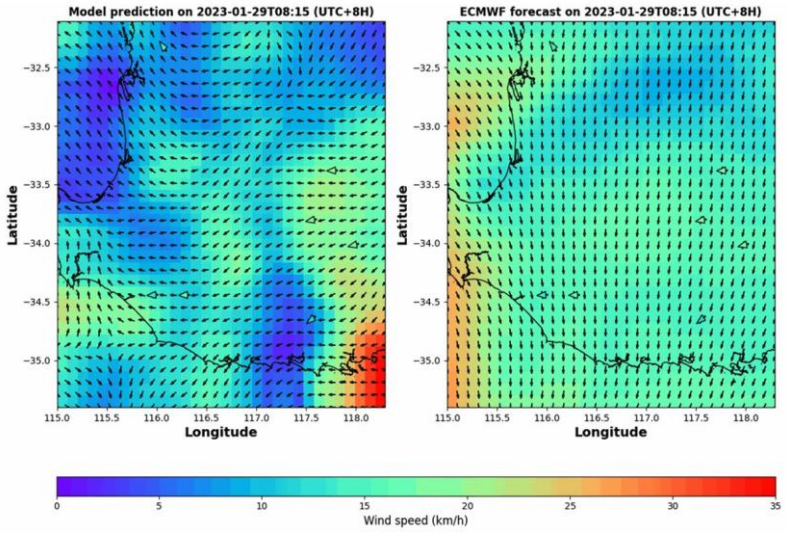


Figure 31: Comparison of ML (left) and traditional (right) wind forecasts.

- **Whale Monitoring Technology**: This project uses ML and Explainable Artificial Intelligence (XAI) to identify individual blue, pygmy blue, and southern right whales from photographs. The algorithms recognise unique physical features, with XAI making the identification process transparent. This enhances accuracy in whale identification, supporting conservation efforts through improved tracking and monitoring.

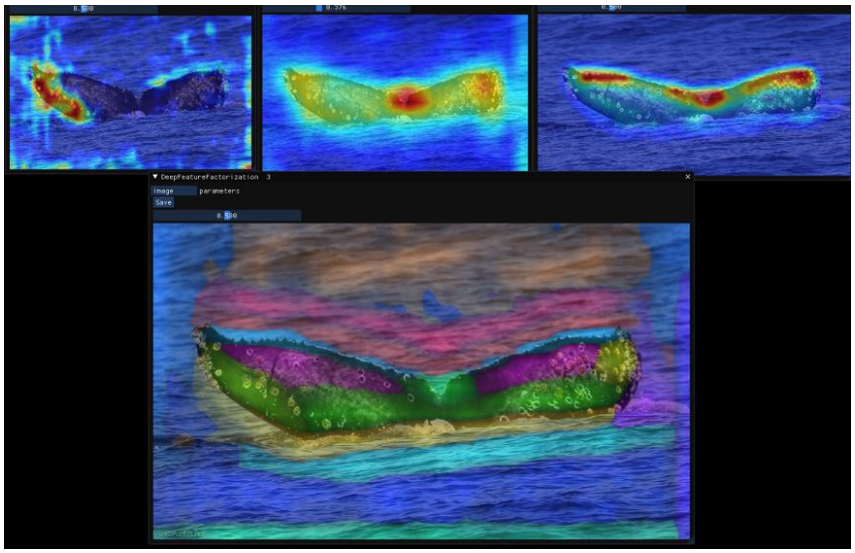


Figure 32: Tail segmentation used in whale identification.

- **Department of Agriculture, Fisheries and Forestry (DAFF)**: This project for the DAFF working with Y-Trace Pty Ltd uses blockchain and Interplanetary File System (IPFS) to track bee and bush food products from harvest to shelf. Producers can input data via voice, while QR codes on packaging allow verification of product origin and handling. This system enhances transparency and trust throughout the supply chain.
- **Australian Honeybees**: This project uses ML to analyse High-Performance Thin-Layer Chromatography (HPTLC) results from Queensland native bee honey samples. It clusters the data to identify patterns related to geographical or botanical origins. A 3D visualisation shows how samples from different sites group together, offering insights into honey diversity and distribution across Queensland. This aids quality control, traceability, and potential geographical indications for honey products.

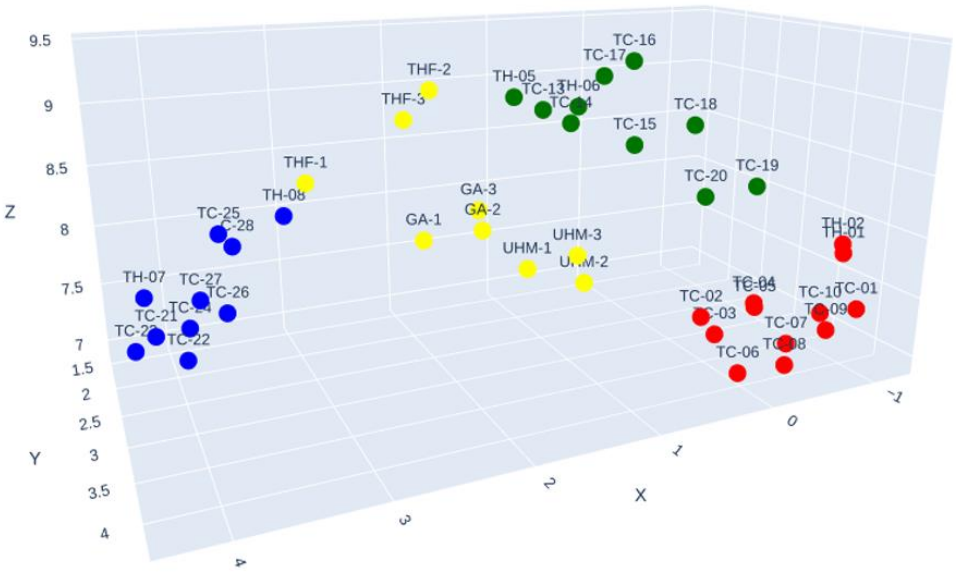


Figure 33: Native Australian Honey Clustering.

- **Jarrah/Marri/WA Honey Characterisation:** This project uses ML to analyse HPTLC results from WA honey samples, each labelled with an expected major component (e.g., Jarrah, Marri, Coastal Peppermint). The algorithms cluster samples based on chemical profiles, with a 3D visualisation showing how honey types group. The analysis reveals frequent mislabelling, as clustering patterns often differ from expected components, highlighting issues in honey authentication and labelling accuracy.

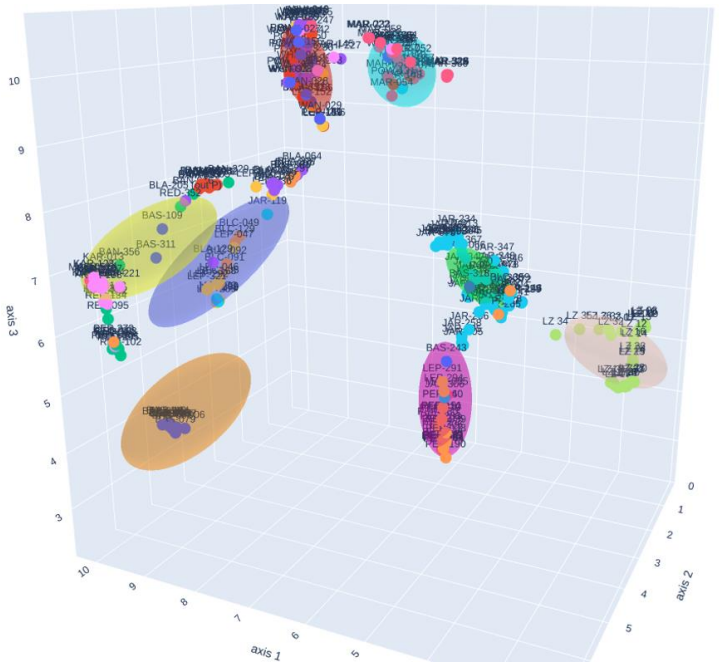


Figure 34: WA Honey Clustering.

- **Student Pathways and Transferable Skills:** With an eye on workforce development and the translation of skills from the radio astronomy domain into other industries the ICRAR T&I team has supported various initiatives to grow the skills of students in the pipeline. These include hosting the Indigenous Australian Engineering School (IAES) visits (and a follow-on intern placement from this program) and organising industry student events centred around transferable skills. Encouraging the uptake of HDR projects and out into industry ICRAR has also supported graduate internships and industry placed PhDs, leveraging connections with key collaborators such as DUG and Nova Systems.

Figure 35: Industry panel event highlighting the transferable skills of radio astronomy to students.

- **Training and Industry Success**: ICRAR's Science, Engineering, and DIA programs continued to mentor and produce high-quality graduates, many of whom received prestigious awards, such as the WA Premier's Science Awards (see Appendix A). Several graduates have secured industry-related roles in organisations like the Bureau of Meteorology, Horizon Power, and CSIRO's Future Science Platform, while others pursued postdoctoral research. This demonstrates the versatility and applicability of the skills acquired by ICRAR PhD students, further contributing to WA's diverse economy and talent pool.
- **Industry-Sponsored Postgraduates**: Across the Engineering, DIA, and Science teams, postgraduate students were engaged in industry-sponsored research, benefiting from close collaborations with sectors such as defence (see Section A.1, 2b), computing (see Section A.1, 2b), finance, and space. These students gained hands-on experience, equipping them with directly applicable skills for the workforce and underscoring the real-world impact of ICRAR's research.

3. Communication, Education and Outreach (CE&O) Highlights

ICRAR maintained its role as a leading voice in radio astronomy and an ambassador for WA's science and technology innovation through extensive public and stakeholder engagement. During the reporting period, ICRAR connected with 48,000 community members, 13,500 students and educators, released 48 media statements, and generated over 13,500 news articles globally, reaching nearly 31 million readers across an average of 98 countries. Since the launch of ICRAR, 156 media releases have been distributed, resulting in over 26,600 news articles, and reaching an estimated audience of over 59 million. The CE&O team travelled throughout WA, including to regional and Indigenous communities, delivering astronomy-themed events to support the State Government's STEM agenda. Collaborating with Scitech, Perth Observatory, WA Museum Boola Bardip, Astrotourism, Astronomy WA, and Deadly Science, ICRAR was instrumental in several key initiatives:

- **Astrofest**: As Australia's largest free astronomy event, Astrofest saw 16,500 attendees overall. In 2020, it won the Chevron Science Engagement Initiative of the Year at the Premier's Science Awards for its inspiring use of space and the night sky to engage West Australians. The 2023 event drew its largest crowd yet, with 5,500 visitors. The success of the Perth event spurred the creation of regional Astrofest events in Mt Magnet and Pingelly, with ICRAR playing a significant role in their development.
- **Star Dreaming**: Led by Professor Steven Tingay, ICRAR supported the production of Star Dreaming, a 360° full-dome film that explores Indigenous night sky stories and the SKA. Premiering at the CineOz Film Festival and WA Maritime Museum in 2022, the film garnered international acclaim, winning awards such as the Best Educational Film at Dome Fest West and the Janus Award at the Full-dome Festival.
- **Beyond the Milky Way Virtual Reality (VR) Documentary**: Launched in December 2021, this immersive VR documentary, narrated by Professor Brian Cox, showcased the Wajarri Yamaji community and the SKA-Low site. Watch more on *Beyond the Milky Way*.
- **Projects from Department of Industry, Science and Resources (DISR) Grant**: These funds were used to create a Wajarri Yamaji Planisphere, developed in collaboration with CSIRO, SKAO, and local elders. The planisphere was launched at stargazing events in the Murchison region in 2022. Other DISR-funded projects included multimedia assets and an SKA Augmented Reality Brochure, which was showcased at the International Astronomical Union (IAU) General Assembly Conference in South Africa in 2024.

Figure 36: Wajarri Yamaji Planisphere (left) and SKA Augmented Reality Brochure (right).

- **Stargirls+ STEM Camp**: Launched in 2022, this camp initially engaged high school students from Perth's metropolitan area. By 2024, with additional support from SKAO, the program expanded to include regional students from the Mid-West, including a participant from Dongara who received an SKAO scholarship. The camp was further extended to Kununurra, where male students were also invited to apply due to the region's limited educational opportunities.
- **SPICE-Physics-ICRAR Remote Internet Telescope (SPIRIT) Program**: ICRAR's SPIRIT initiative enables students to access professional astronomical tools and collect real-time data through robotic telescopes. Over five years, the program engaged 1,575 students from 40 schools. Participants controlled SPIRIT telescopes to capture astronomical images and complete research projects. Their work is showcased in the Astrophotography SPIRIT Student Competition at Astrofest. The SPIRIT observatory owes its success to Colin Eldridge, who donated land for the telescopes' construction and maintenance.
- **Regional Activities**: Committed to reaching regional communities, ICRAR conducted tours to at least one region each year, visiting areas such as the Pilbara, Gascoyne, East Kimberley, West Kimberley, Mid-West, Wheatbelt, Great Southern, and Goldfields. These tours offered hands-on STEM education to students and educators, enriching the STEM outreach in remote WA.
- **Top Media Releases of ICRAR III**:
  - FY2019-2020: Astronomers detect biggest explosion in the history of the Universe
    - 1297 articles in 57 countries with an estimated audience of 2.25 million
  - FY2020-2021: First black hole ever detected is more massive than we thought
    - 443 articles in 52 countries with an estimated audience of 2.4 million.
  - FY2021-2022: Mysterious objects unlike anything astronomers have seen before
    - 3,089 articles in 104 countries with an estimated audience of 13 million.
  - FY2022-2023: To the Moon and Back: Australia-first communications network paves the way for high-speed data in space.
    - 111 articles in 6 countries with an estimated audience of 2.7 million.
  - FY2023-2024: Hiding in plain sight, astronomers find a new type of stellar object
    - 641 articles in 43 countries with an estimated audience of 2.5 million.

4. Diversity, Equity, and Inclusion Highlights

Figure 37: Attendees at the All-hands meeting of 20 March 2024.

- **Commitment to Diversity and Inclusion**: ICRAR remains dedicated to fostering diversity, equity, and inclusion (DEI) within its community. Both ICRAR's Development Committee (DevCom) at Curtin

and the DEI Committee at UWA worked to increase awareness and support staff and students throughout the year. Initiatives included celebrating multicultural festivals, showcasing their cultural significance, and sharing traditional foods. ICRAR also increased the visibility of gender and sexual orientation diversity, supporting activities aimed at improving the representation of minority groups across the lesbian, gay, bisexual, transgender, queer (or questioning), intersex, and asexual (or allies) (LGBTQIA+) spectrum. ICRAR's recognition and support of Indigenous Australian culture were further emphasised during National Aborigines and Islanders Day Observance Committee (NAIDOC) Week, with initiatives such as presentations on Indigenous astronomy, acknowledging First Nation peoples as the first astronomers in the region, and hosting a Reconciliation Week breakfast for staff and students.

- **Climate and Wellbeing Surveys**: ICRAR organised climate and wellbeing surveys to understand the challenges faced by staff and students. The survey results informed the development of an action plan to address these issues. ICRAR's ongoing commitment to diversity and inclusion in astronomical sciences and technology earned recognition from the ASA. In the reporting year, ICRAR received the Gold Pleiades Award, a recognition that had only been awarded to ICRAR across Australia and New Zealand in 2019, 2021, and again from 2023 to 2025.
- **Women in STEM**: ICRAR actively contributed to advancing the Women in STEM agenda in WA. The institute hosted a Visiting Fellowship for senior women astronomers, with staff leading university and faculty-level initiatives in this space. ICRAR's female staff members received prestigious awards, including Science and Technology Australia's Superstars of STEM Fellowships, and Forrest Fellowships (see Appendix E for more details).
- **Senior Women Visiting Fellowship Program**: As part of ICRAR's Visiting Fellowship Program, Dr. Prajval Shastri from the Tata Institute of Fundamental Research in India and Dr. Maria Labate from SKAO Headquarters visited ICRAR. They delivered talks on career pathways and work-life balance, and conducted discussions with staff and students on these topics. The program, previously impacted by COVID-19 restrictions, resumed in 2022 once those restrictions were lifted.

5. Difficulties Faced in ICRAR III

- **Impact of the COVID-19 Pandemic**: The COVID-19 pandemic had a lasting effect on ICRAR's core activities, as noted in board meetings, Finance and Audit Committee meetings, and previous annual reports. Travel restrictions remained in place for the first six months of 2022/23, affecting staff mobility. The cumulative impact of pandemic-related departures and hiring delays was felt throughout ICRAR III.
- **Challenges in Staffing and Retention**: ICRAR also faced significant challenges due to the rapid expansion of hiring by SKAO and CSIRO in WA, alongside an industry-wide shortage of skilled personnel. This, combined with ICRAR's limited ability to offer contracts beyond mid-2024, made it increasingly difficult to retain and recruit staff with the necessary expertise. These staffing issues may lead to under-expenditure in the next financial year if not urgently addressed. Applications for funding for 2024/25 and 2025/26 to 2029/30 were submitted to the Department of Jobs, Tourism, Science and Innovation (JTSI) on 15 December 2022 and 31 June 2023, respectively.

Supercomputing Delays and Communication Issues: ICRAR's work was further hindered by delays and communication issues with Pawsey. The primary supercomputer, Setonix, was not operational until mid-2022 and has remained unreliable since. As a result, the collection of ASKAP survey data and the processing of ASKAP and MWA data is well behind schedule due to the delays in commissioning and subsequent performance issues. This has particularly affected individuals with short-term horizons, such as staff on fixed-term contracts and PhD students on 3-to-4-year scholarships. For some, project delays jeopardised publication plans, and early-career researchers and PhD students reported a decline in their mental health due to these setbacks. These concerns were communicated to ICRAR's Board and Pawsey leadership. There has been recent active engagement and at the time of this report, some issues are resolving.

SECTION H.2: APPENDIX H - ACRONYMS AND ABBREVIATIONS

ACRONYM	DESCRIPTION
AAL	Astronomy Australia Limited
AAAS	American Association for the Advancement of Science
AARP	Australian Automation and Robotics Precinct
AAS	Australian Academy of Science
AAVS	Aperture Array Verification System
ACAMAR	Australia-China Consortium for Astrophysical Research
AFOSR	Air Force Office of Scientific Research
AI	Artificial Intelligence
ALMA	Atacama Large Millimeter/submillimeter Array
ANU	The Australian National University
AR	Augmented reality
ARC	Australian Research Council
ARDRA	Australia-India Research and Development in Radio Astronomy
AROSE	Australian Remote Operations for Space and Earth
ASA	The Astronomical Society of Australia Inc.
ASCA	Advanced Strategic Capabilities Accelerator
ASCC	Australian SKA Coordination Committee
ASKAP	Australian SKA Pathfinder
ASTRO 3D	ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions
ASTRON	Netherlands Institute for Radio Astronomy
ATCA	Australia Telescope Compact Array
AUD	Australian Dollar
AusSRC	Australian SKA Regional Centre
AWS	Amazon Web Services
BOM	Bureau of Meteorology
CE&O	Communication, Education and Outreach
CHILES	COSMOS HI Large Extragalactic Survey
CIRA	Curtin Institute of Radio Astronomy
CMOS	Complementary metal-oxide semiconductor
CoE	Centre of Excellence
COVID-19	World wide pandemic originating in 2019
CPU	Central Processing Unit
CRAFT	Commensal Realtime ASKAP Fast Transients
CRC	Cooperative Research Centre
CRG	Collaborative Research Grant
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Curtin	Curtin University
DAFF	Department of Agriculture, Fisheries and Forestry
DAS	Distributed Acoustic Sensing
DAT	Digital Assistive Technologies
DECRA	Discovery Early Career Researcher Award
DEI	Diversity, Equity and Inclusion
DevCom	Development Committee
DFAT	Department of Foreign Affairs and Trade
DFES	Department of Fire and Emergency Services
DIA	Data Intensive Astronomy
DIIS	Department of Industry, Innovation and Science (now DISR)
DINGO	Deep Investigation of Neutral Gas Origins
DISER	Department of Industry, Science, Energy and Resources (now DISR)
DISR	Department of Industry, Science and Resources (since 1 July 2022)
DPIRD	Department of Primary Industries and Regional Development
DSC	Defence Science Centre
DSTG	Defence Science and Technology Group
DUG	DUG Technology
ECMWF	European Centre for Medium-Range Weather Forecasts
ED	Executive Director
EFTSL	Equivalent full-time student load
ERA	Educational Radio Array
ESA	Electronically Steered Array

SECTION H.2: APPENDIX H - ACRONYMS AND ABBREVIATIONS

ACRONYM	DESCRIPTION
ESD	Electrostatic discharge
ESO	European Southern Observatory
F&A	Finance and Audit
FAA	Financial Assistance Agreement
FIDD	Foreign Interference Due Diligence
FRB	Fast Radio Bursts
FTE	Full-time equivalent
GDC	Gravity Discovery Centre
GLEAM	GaLactic and Extragalactic All-Sky MWA
GPU	Graphics processing unit
GU	Guangzhou University (China)
HDR	Higher Degree Research
HPC	High performance computing
HPM	High-Power Microwave
HPRF	High-Power Radio Frequency
HPTLC	High-Performance Thin-Layer Chromatography
IAES	Indigenous Australian Engineering School
IAU	International Astronomical Union
ICRAR	International Centre for Radio Astronomy Research
ICRAR-Curtin	ICRAR node at Curtin University
ICRAR-UWA	ICRAR node at The University of Western Australia
IF	Impact Factor
IGO	Intergovernmental Organization
IGS	Intelligent Ground Station
INAF	National Institute for Astrophysics (Italy)
IP	Intellectual Property
IPFS	Interplanetary File System
IT	Information Technology
ITF	Integrated Test Facility
JSON	Java Script Object Notation
JTSI	Department of Jobs, Tourism, Science and Innovation
JV	Joint Venture
JWST	James Webb Space Telescope
KIAA-PKU	Kavli Institute for Astronomy and Astrophysics (at Peking University)
KPI	Key Performance Indicator
KSP	Key Science Project
LGBTQIA+	Lesbian, gay, bisexual, transgender, queer (or questioning), intersex, and asexual (or allies)
LIEF	Linkage Infrastructure, Equipment and Facilities
LNG	Liquefied Natural Gas
LoI	Letter of Intent
MEM	Management Executive Meeting
ML	Machine Learning
MoU	Memorandum of Understanding
MRO	Murchison Radio-astronomy Observatory
MWA	Murchison Widefield Array
NAIDOC	National Aborigines and Islanders Day Observance Committee
NAOC	National Astronomical Observatories (Chinese Academy of Sciences)
NAOJ	National Observatory of Japan
NARIT	National Research Institute of Thailand
NASA	National Aeronautics and Space Administration
NCI	National Computational Infrastructure
NDA	Non-disclosure agreement
NEU	Northeastern University (China)
NGAS	Next Generation Archive System
NGC4632	Spiral Galaxy in the Virgo constellation
NGTF	Next Generation Technologies Fund
PaSD	Power and Signal Distribution
Pawsey	Pawsey Supercomputing Research Centre
PhD	Doctor of Philosophy
PSI	Poseidon Scientific Instruments
QA	Quality Assurance

SECTION H.2: APPENDIX H - ACRONYMS AND ABBREVIATIONS

ACRONYM	DESCRIPTION
R&D	Research and Development
RM	Receiver Modules
SaDT	Signal and Data Transport
SAT.FRQ-MID	SKA-MID Phase Synchronisation System
SDA	Space Domain Awareness
SDH&P	Science Data Handling and Processor
SDP	Science Data Processor
SDURI	Summer Down Under Research Internship (UWA)
SETI	Search For Extraterrestrial Intelligence
SHAO	Shanghai Astronomical Observatory
SIS	School of Indigenous Studies (UWA)
SKA	Square Kilometre Array
SKAO	Square Kilometre Array Organisation
SME	Small and Medium-sized Enterprise
SPIRIT	SPICE-Physics-ICRAR Remote Internet Telescope
SRC	SKA Regional Centre
SRR	System Requirements Review
STAWA	Science Teachers' Association of Western Australia
STEM	Science, Technology, Engineering, and Maths
SWG	Science Working Group
T&I	Translation and Impact
UK	United Kingdom
UNSW	The University of New South Wales
UQ	University of Queensland
USA	United States of America
UWA	University of Western Australia
VLA	Very Large Array
VR	Virtual Reality
WA	Western Australia
WALLABY	Widefield ASKAP L-band Legacy All-sky Blind SurveY
XAI	Explainable Artificial Intelligence
XAO	Xinjiang Astronomical Observatory