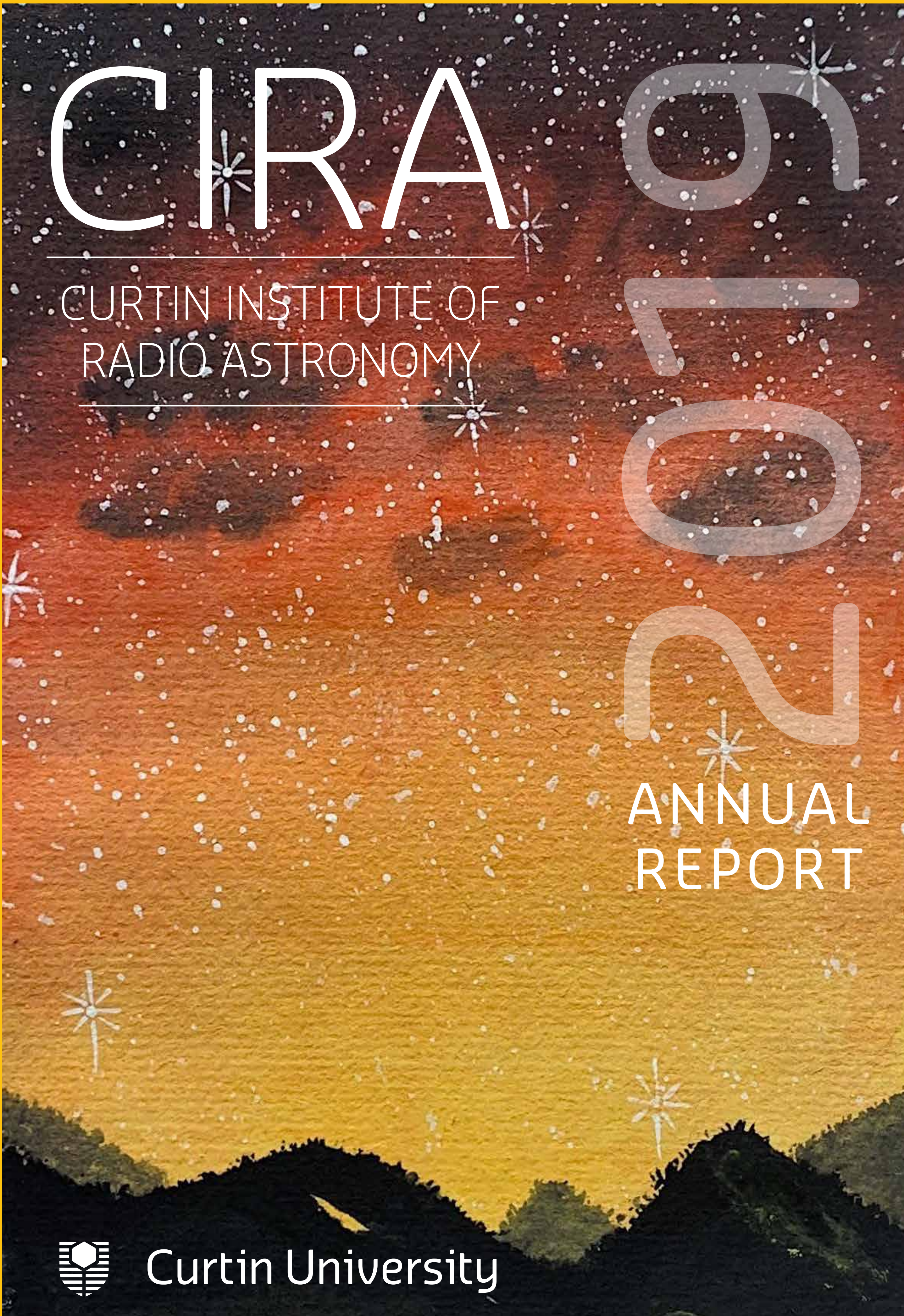

CIRA

CURTIN INSTITUTE OF RADIO ASTRONOMY

2019

ANNUAL REPORT

Curtin University

Curtin University

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This annual report covers the calendar year 2019

Editors:
Mia Walker
Chamila Thrum

Images on the front and back highlight CIRA activities in 2019

Front cover:

Watercolour painting by CIRA PhD student Dilpreet Kaur

Back cover:

AAVS2 (left) and EDA2 (right), prototype arrays in the Bridging Phase of the Square Kilometre Array (SKA), completed in 2019. Credit: ICRAR/Curtin.

Jean-Pierre (JP) Macquart

20 August 1974 - 9 June 2020

The CIRA Annual Report this year is dedicated to the memory of Associate Professor Jean-Pierre (JP) Macquart. JP was a much loved member of CIRA, being one of the first staff members of the institute appointed in 2009, and of the Australian and international astronomy communities. We will remember his enthusiasm, excitement, and passion for science, his breakthrough research (featured in this report), and his delight in teaching students. We will greatly miss his presence at CIRA and we extend our deepest condolences to his wife Sherine and their two children.

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Annual Report 2019
Curtin Institute of Radio Astronomy

CIRA GOVERNANCE

Institutes at Curtin University conventionally have Boards to advise the University and Directors on policy and directions. CIRA and its programs are very closely aligned with the International Centre for Radio Astronomy Research (ICRAR), an equal Joint Venture between Curtin University and The University of Western Australia. ICRAR has a fully-constituted Board, including representation from Curtin University. To minimise duplication in reporting, CIRA's programs are formally monitored and assessed via the ICRAR Executive and Board.

EXECUTIVE SUMMARY

Steven Tingay

Director's Report

It is a pleasure, once again, to present the Curtin Institute of Radio Astronomy Annual Report to colleagues and stakeholders, summarising and celebrating CIRA's collective success in 2019 and pointing the way toward CIRA's future activities.

As usual, we have a very high volume of material to report and, as always, restricting ourselves to the highlights is a challenge. Across Science, Engineering, and MWA Operations, in all areas we have achieved excellent outcomes in terms of publications, external grant income, and the visibility of our staff and students in national and international fora and the media.

I'm immensely proud and appreciative of all our staff and students who have made a positive contribution at CIRA. In particular, I greatly appreciate the support of the CIRA Executive, Mr Tom Booler, and Profs Davidson, Johnston-Hollitt, and Miller-Jones in assisting me with CIRA's strategic activities and in managing the different lines of CIRA business.

The last year saw the commencement of the third phase of funding for the ICRAR Joint Venture with UWA, supported by the JV partners and the State Government. ICRAR is CIRA's biggest activity and ICRARIII will run until mid-2024. During this period we expect SKA construction to commence, following the formation of the SKA Observatory as an Intergovernmental Organisation (IGO), as soon as 2021. CIRA has played a leading role in pre-construction activities for the SKA and we are well placed to participate in SKA construction, commissioning, early operations, and early science in coming years.

I expect that many of CIRA's areas of science and engineering will feature heavily in the early phases of the SKA, for example Epoch of Reionisation experiments, probes of physics using Fast Radio Bursts, all manner of accretion physics, large-scale surveys, and our antenna and electronics technical developments. Our expertise in designing, building, commissioning, and operating low frequency radio telescopes, based on our experience with the MWA over many years, will remain at the fore.

So, the next few years will be very exciting and, I hope, a very productive period for CIRA and its staff and students.

As always, there will be challenges on the road ahead and we have been adept at navigating what have been mostly financial, technical, and political challenges (the normal business of managing and executing cutting edge international research at scale). However, as of writing this text in early 2020, the world is facing a new challenge, the COVID-19 virus. Across Australia in all sectors, the current situation is changing the way society and the economy operates. This is certainly true in the university sector. Thus far, Curtin University has responded to this challenge very well, with staff, students, and our core business at the heart of the response. At CIRA, we have also positively adapted, with the support of staff and students.

The next couple of years will likely bring some additional uncertainty and change. However, the fundamentals at CIRA are very solid and I see no reason we cannot positively navigate the evolving situation. It is clear already that there a number of lessons to learn from the COVID-19 experience and we intend to put these lessons to good use.

James Miller-Jones

Director's Report

Strengthened by a number of new staff and students, the past year saw CIRA's science team enjoy their most productive year since the institute was founded in 2007, with 123 peer-reviewed publications, including four that appeared in the prestigious journals Nature and Science. The impact of this work extended to the popular press, with several successful media releases that were picked up in over 60 countries, with a cumulative potential reach of several billion people.

2019 also saw excellent returns from CIRA's strong engagement with the ARC's national competitive grants program, with CIRA staff leading two successful Discovery grants, and Dr Natasha Hurley-Walker winning a Future Fellowship. CIRA's long-term focus on the overlap between radio astronomy and engineering also came to the fore, with Dr Clancy James leading a successful LIEF grant to install a particle detector array at the MWA site, enabling new studies of cosmic rays. CIRA staff were also key participants in two additional LIEF bids to upgrade CSIRO's Parkes radio telescope with a cryogenic phased array feed, and CSIRO's Australia Telescope Compact Array with a new GPU-based correlator. These three projects will enable many new and exciting results from three of Australia's major radio telescope facilities, which between them underpin a wide range of CIRA science.

From a more organisational perspective, the mid-year transition to the third phase of ICRAR saw the science team adopt a more coherent structure, refocusing our efforts on four main areas of strength. While three of these were the natural evolution of existing projects, the establishment of a new science theme of Pulsars and Fast Transients brings additional visibility to the high-impact work being done in this area. Beyond this slight refocusing of our primary research activities, the transition also provided a renewed emphasis on our undergraduate teaching activities, as well as stimulating engagement with industry, in conjunction with the new Translation and Impact program led by Tom Booler. I have been delighted to see staff at all levels engaging with these activities, which I am confident will flourish over the coming years. An early highlight in this domain is the MWA space situational awareness work, which is already initiating new projects with a range of stakeholders. I would like to thank the entire science team for their professionalism and commitment in adjusting to the new structure and expectations, and to the administrative and executive teams who have played key roles in ensuring a smooth and seamless transition to ICRAR 3.

CIRA's long-standing commitment to undergraduate teaching continued through 2019, and it was very pleasing to see staff engaging with other areas of the School, supervising students from beyond our traditional association with the Physics & Astronomy and Electrical Engineering disciplines. Growing such interdisciplinary links fosters collaboration with other areas, leading to new opportunities and research projects, and we look forward to growing this potential over the coming years.

The opportunity to get involved in radio astronomy and the SKA has long been highlighted in our undergraduate teaching and outreach work, and it was very good to see a large cohort of Curtin undergraduates go on to win PhD scholarships in the University's most recent RTP round. This is testament to both their hard work, and the dedication of all the lecturers and undergraduate project supervisors who continue to inspire our students. The past year also saw six PhD completions from the science group, with our new graduates winning postdoctoral positions both in Australia and overseas, or moving on to apply their valuable skills in other areas. We wish them, and all our other departing staff, all the best for the future.

With a number of new staff and students, a well-focused science program, and long-term support through ARC grants, the ICRAR joint venture and the ASTRO-3D ARC Centre of Excellence, the next few years should prove to be a very exciting time for CIRA. I am very much looking forward to all the science to come.

ENGINEERING

David Davidson

Director's Report

2019 continued the trajectory started in 2018, with a very strong focus on SKA-LOW, closing off ICRAR 2 and transitioning to ICRAR 3 mid-year.

The CIRA engineering group continued its tradition of high-impact work, from highly theoretical to extremely practical. With much of the planning for the transition to ICRAR III in place in good time, the actual transition was largely seamless for the engineering team.

The year was dominated by SKA Bridging work, which covers the period between pre-construction, which was driven primarily by the consortia, and construction, which will be largely driven by the SKAO. In collaboration with INAF, a very challenging program was outlined in late 2018 to deploy a complete 256-element SKA-LOW station on the MRO, using the new SKALA4.1 antenna developed by INAF from the SKA reference design. This was specifically designed to mitigate the risk associated with station-level calibration identified in the lead-up to the December 2018 Critical Design Review.

By May 2019, the Aperture Array Verification System 1.5 (one-and-a-half), consisting of 48 SKALA4.1 antennas deployed in three clusters of 16 was on site, and commissioning work commenced almost immediately. By year-end, the full 256 element array (now called AAVS2) was in place, and data was being captured and processed. At the same time, carefully verified and cross-checked computational simulations of the electromagnetic performance of the entire antenna array were undertaken at CIRA and INAF. Simulating, building and commissioning a full 256 element station within a year was an extremely ambitious stretch goal, and it reflects great credit on our staff here and our colleagues from INAF that this was accomplished within this period. More details of this project are provided in some of the articles in this report.

On the engineering front, the research program continued to produce quality publications rooted in CIRA's instrumentation programs and the field in general. We contributed extensively to SKA-TEL-SKO-0001088, "Report on the Station Calibration Task", submitted as part of the SKA System Critical Design Review in December 2019. A number of papers based on our SKA-LOW work were presented at leading antenna engineering conferences during the year. These included the European Conference on Antennas and Propagation (Krakow, April 2019); the International Symposium on Antennas and Propagation (Atlanta, July 2019) ; the International Conference on Electromagnetics in Advanced Applications (Grenada, September 2019); and the International Conference on Antenna Measurements and Applications (Bali, October 2019). At the Atlanta and Grenada conferences, I jointly organized special sessions on radio astronomy instrumentation with international colleagues.

Regarding personnel, a new appointment was made in the Engineering group; Dr Maria Kovaleva joined us from Macquarie University. She is an expert in antenna design and analysis, and also worked in industry. Dr Gregory Hellbourg accepted a position at Caltech and left us in December.

Additionally, we continued our traditional teaching within electrical and electronic engineering, being responsible for three undergraduate courses.

With the SKA treaty (which sets up the necessary intergovernmental organization) now in the process of being ratified, 2020 promises to be equally busy as we gear up for the first stages of SKA construction, now scheduled for early 2021.

Tom Booler

Director's Report

2019 was a period of significant change. The transition from ICRAR 2 to ICRAR 3 on 1 July was the culmination of an enormous amount of preparation and planning, and marked an evolution in the programmatic focus of CIRA.

Since its inception CIRA has been focussed on contributing to and preparing for the SKA. The SKA is a complex, multi-disciplinary, multi-generational project and this is reflected in every aspect of CIRA's make-up and program. Everything from the composition of the group through to the nature of the activities we are engaged in, reflects CIRA's raison d'être of ensuring that Curtin, Western Australia and Australia have impact in and benefit from the SKA.

Being an organisation with an identifiable and unambiguous focus has been a significant factor in CIRA's record of successful engagement with all classes of stakeholder. CIRA has leveraged a relatively high level of general awareness of astronomy (across most stakeholder demographics), and 'brand recognition' for specific activities like the MWA and SKA, into long term and mutually beneficial relationships with stakeholders in the Government, Industry, Community and Research sectors. The strong relationships we have forged with key stakeholders reinforces and contributes to expansion of our profile and reputation. This, in-turn, helps us to establish new fronts of engagement and seed new relationships.

This cycle of investment in relationships requires a continuity of engagement—in terms of personnel and focus—over a considerable period of time in order to yield maximum benefit. Many of CIRA's key Government, Industry, Community and Research sector relationships have been formed in the overarching context of the SKA Project, and have been developing for nearly a decade. This long-form engagement strategy has seen us profit immeasurably in profile, reputation and influence; while providing our partners and collaborators with access and insight into the domain-specific requirements and considerations of the international projects that we are engaged in.

CIRA's continuing success and growing profile have resulted in rapid and consistent growth in the scope—including number, nature and quality—of opportunities it has to create impact. The 'ICRAR 3' program includes, for the first time, resources dedicated to fostering, facilitating and generating impact from opportunities that are not traditional 'core business'. This new focus will be delivered through the 'Translation and Impact' (T+I) program.

The objectives of the ICRAR-Curtin T+I program are to set the conditions for CIRA personnel to participate in T+I initiatives; to identify, nurture and transition T+I opportunities into stable delivery models; and to support delivery of T+I outcomes, through the provision of project support services.

The T+I program is organised into three activity streams:

Administration: this stream provides the business support functions required to enable the efficient operations of CIRA. Its mission is to support the delivery focussed personnel and activities across the Science, Engineering and T+I programs at CIRA.

Engagement: this stream translates the expertise and experience of CIRA personnel into impacts in domains other than radio-astronomy. Its primary mission is to identify and match opportunities to CIRA's capabilities and capacity. The dedicated resources in this stream will be utilised to enable and coordinate the engagement of CIRA personnel in engagement initiatives.

SKA: this stream is focussed specifically on coordination of CIRA's ongoing engagement with and support of the SKA Project. It consists of dedicated project management resources to coordinate our contributions across a range of SKA-related activities. Its mission is to ensure that CIRA's participation in SKA is high-quality and high-impact, and that it promotes meaningful engagement with and opportunities for West Australian and Australian stakeholders.

Having focussed on 'change' as a key reportable for the year, it would be remiss of me not to acknowledge the Herculean contribution made by Tina Salisbury to the nuts and bolts of planning and implementing that change. I'm confident I speak on behalf of all CIRA Directors in saying that Tina's tireless commitment to wrapping our flights fancy in reality, and the necessary process and procedure, has been a key ingredient in CIRA's ongoing success.

Melanie Johnston-Hollitt

Director's Report

MWA

2019 was yet another successful year for the MWA with a number of positive milestones to celebrate.

I negotiated the first increase in operational funding since operations commenced in 2013, and furthermore we were granted the first multi-year operations contract with Astronomy Australia Limited. This funding represents a 13% increase on the Australian component of MWA operations and allows the MWA node of the All-Sky Virtual Observatory (ASVO) to move from a prototype to a fully supported component of the telescope. On the collaboration front, and in another first, we achieved a fully executed MWA Collaboration Agreement between the lead organisations in each of the 6 countries involved in the MWA: Australia, Canada, China, Japan, New Zealand and the United States. This agreement forms the basis of the Phase II MWA operations which will continue to mid-2021, and provides the framework for planning for Phase III, which was defined the be an operational and upgrade phase running from mid-2021 to mid-2026. As part of considerations of this next phase of the MWA, the MWA operations team worked in conjunction with members of CIRA's engineering group to complete the design of a new MWA correlator which will be the first significant upgrade to be undertaken in Phase III. Dubbed 'MWAX', the new correlator will replace the IBM iDataplex which has been deployed in the field since 2012. MWAX is designed to have more flexible configurations and to support the ingest of all 256 antenna tiles of the telescope array, making it the starting point on the road to a full '256T' MWA.

On the operations side further improvements were made to the MWA website, the new MWA wiki, and the MWA ASVO, as well as the installation of a new triggering system designed by CIRA science staff in conjunction with MWA operations team members. The triggering system is an excellent example of the symbiotic relationship between the science team at CIRA and MWA operations, and will benefit all MWA users. A paper describing the system was published by Hancock et al. (2019). CIRA science and engineering staff also worked with the MWA team to successfully deploy a new instrument at the Murchison Radio Observatory under the MWA External Instruments Policy. The Central Redundant Array Mega-tile (CRAM) project is designed to improve the characterisation of both the MWA Phase II hexagon tile beam patterns, and the foreground emission for Epoch of Reionisation (EoR) science.

In terms of personnel, Ms Rike McLernon commenced as Administrative Officer in late 2019 taking the MWA operations team to a total of six people. 2019 also saw the MWA team travel to India and Shanghai to present at the ARDRA and SKA international meetings. Both events had a strong component of 'lessons learnt' from the MWA for the design, construction, and operation of future instruments, and it is a testament to the work done by the operations team to be invited to share their work internationally.

A number of significant papers appeared in 2019 including the MWA Phase II science paper by Beardsley et al. and the EoR limit papers by Li et al. and Barry et al., which set the two lowest limits year for detection of the EoR of all EoR experiments. Although these particular publications were led by other members of the collaboration, CIRA continues to play a large role in the scientific exploitation of the MWA, leading 36% of all MWA papers published in 2019, and co-authoring 80%. As I noted last year, this symbiotic relationship between MWA operations and the scientific and engineering efforts at CIRA highlight the important role CIRA plays in both supporting the telescope and that the MWA plays in the overall output of the institute.

We achieved a lot in 2019 for the MWA across the operations, management, governance and scientific exploitation of the array. Much of the work that was done puts the MWA is a fantastic position to complete the rest of Phase II and to start the detailed planning and implementation of Phase III. As always I am indebted to the MWA Operations and Management teams for making the MWA a success, and I look forward to seeing what 2020 brings.

Diversity, Inclusion, Equity

The CIRA Development Committee (DevCom)

Christene Lynch

The CIRA Development Committee (DevCom) started 2019 with the introduction of many new members and the creation of a new role within DevCom, the Pleiades Representative. The creation of this role was motivated in recognition of the immense amount of work the 2018 committee put into the successful application to the Inclusion, Diversity, and Equity in Astronomy Chapter of the Astronomical Society of Australia for CIRA's recent Silver Pleiades award (pictured). This role is responsible for thinking strategically about the initiatives developed and implemented by DevCom and how they best prepare CIRA for future Pleiades applications.

Early in 2019, DevCom had several discussions about CIRA's environmental impact, which led to the creation of the CIRA Sustainability Committee. The goal of this committee is to develop and promote a sustainable workplace for all CIRA staff, students and visitors. Members will work to monitor and reduce the impact of CIRA on the environment. The Sustainability Committee reports directly to DevCom and gives monthly updates of their activities at the DevCom meetings. Early initiatives have included investigating what support Curtin can provide for staff and student cyclists at CIRA, and a presentation on how to dispose of waste and recycling properly.

Motivated by the excellent presentations on career development by previous DevCom chair, Richard Plotkin, and Visiting Women's Fellow Anna Frebel, DevCom began developing a webpage to help CIRA staff during their annual career conversation. This page is a living document, and DevCom will update it with helpful career planning resources and change it as guidelines from the University change.

"The CIRA Development Committee (DevCom) provides advice to the CIRA Directors, and aims to foster an environment where all staff can flourish irrespective of role, age, gender, sexual orientation, disability, race, religion, etc. It recognises that a way to promote diversity and representation, at all levels, is through development and support of existing, and future, staff and students. It draws on University and other resources to provide initiatives to develop CIRA's talent and to improve the overall working environment. The committee is also a portal to provide advice for academic and nonacademic staff on career development, progression and recognition."

DevCom Mission Statement

To help develop more effective communication within CIRA, Devcom organised a communications workshop run by GenderMatters. Participants came to understand how differences in personality types can impact communication and how to overcome these differences for more effective communication and teamwork. The workshop was well-received by those who took part, and DevCom plans to host similar workshops in the future.

CIRA's responses in the Ngalang Waangi -- Our Voice 2019 survey, motivated DevCom to look into mental health first aid training. While several CIRA staff already had mental health first aid training, DevCom decided that having as broad a group as possible receiving this training would be desirable. Thus Devcom organised for additional volunteers to receive this training through the University.

DevCom ended the year by hosting an International Potluck Lunch, which celebrated the diversity of cultures found within CIRA. Over 20 volunteers brought a dish, drink, or snack that represented them, their family, or their culture. Many more participated by enjoying the lunch, which included a broad range of items hailing from all over the world, and had lively discussions about the various items on offer.

The 2019 Development Committee consisted of Paul Hancock (Chair), Andrew Williams (Deputy Chair), Christene Lynch (Scribe), Pikky Atri (SAGE Liasion), Randall Wayth (Pleiades Representative), Daniel Ung, Clancy James, Dilpreet Kaur (Student Representative), Alex Williamson (Student Representative), and Nipanjana Patra.

HIGHLIGHTS

Above: The Milky Way Galaxy rises over the Australian Square Kilometre Array Pathfinder. ASKAP consists of 36 antennas, each with a field of view of 30 square degrees, distributed with separations up to ~6km. Credit: CSIRO/Alex Cherney

SCIENCE

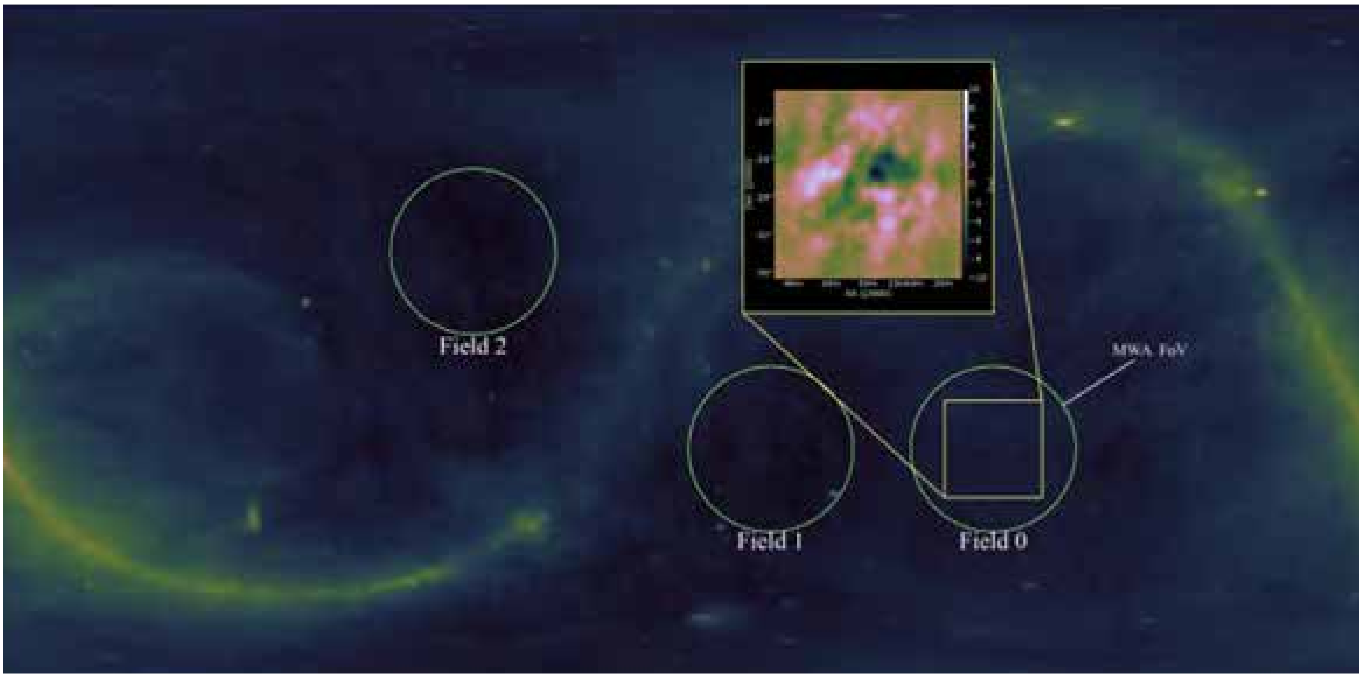
Left: Mengyao Xue receiving the 2019 Ken and Julie Michael prize for ICRAR-Curtin, which recognises the outstanding achievements of ICRAR graduate students at both nodes. Mengyao has made important steps in the study of pulsars with the MWA, conducting the first low-frequency MWA pulsar census using the high time-resolution VCS mode of the instrument, and characterising the polarisation performance of the telescope in tied array mode. Her work (which has resulted in two lead author publications and two more co-authored papers) has provided new insights into pulsar emission properties and the Galactic pulsar population, and will feed into future plans for low-frequency pulsar studies with the SKA. Credit: ICRAR-Curtin. Sam McSweeney (image, below) also won this award in 2018.

Below: ExxonMobil 2019 Student Scientist of the Year finalist Sam McSweeney (right) with family. Sam's research yields important insights on the physical mechanism responsible for producing radio emission pulses from super-dense neutron stars that cannot be studied in Earth-based experiments. Aside from tackling one of the outstanding problems in astrophysics, known as the 'radio pulsar emission mechanism', this work has broader implications for developing high powered telescopes used in gravitational-wave science. His work was also recognised with a Letter of Commendation from the Curtin Chancellor for an exceptionally high quality PhD thesis. Credit: MCB Photographics and Cathy Fogliani

Searching for evidence of the first stars across cosmic time and space

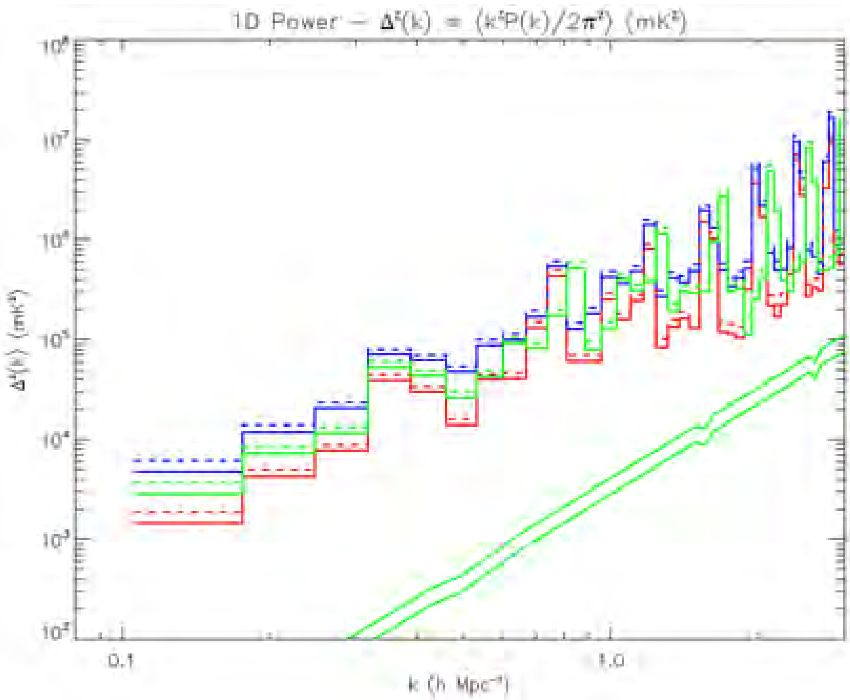
Cathryn Trott and the MWA EoR team

Figure 1, below: Location of the three MWA EoR experiment observing fields used in this work, placed away from the bright contamination of the Milky Way's Galactic Plane. Credit: D. Jacobs, ASU, 2016



SCIENCE

Figure 2, right: Measured power as a function of spatial scale: this power spectrum is the output data product of the experiment, and encodes the size and distribution of ionised and non-ionised regions of the Universe. Credit: Trott et al, 2020



The first billion years of the Universe's history witnessed a large number of remarkable cosmic events that shape the sky we observe today.

Within a few hundred thousand years of the Big Bang, the Universe had cooled sufficiently for light photons, protons and electrons to freeze-out from their primordial soup, and travel independently in space. This released the photons we now observe as the Cosmic Microwave Background, and otherwise allowed the protons and electrons to recombine together as hydrogen atoms. These Cosmic Dark Ages contained no stars or galaxies, but their seeds were present in the form of dark matter potential wells, ready to accumulate the cooling baryons in their centres and start fusion processes. These first generations of stars are expected to formed within 200 million years of the Big Bang, and their existence started to transform the otherwise cold and unobservable hydrogen gas through local heating close to stars, and photodissociation. This period is termed the Epoch of Reionisation (EoR), and marks the period when these first generations of stars produced enough ionising photons to transform the cold and neutral Universe to a warm and ionised Universe.

Low-frequency radio telescopes, such as the Murchison Widefield Array (MWA) in the Western Australian desert, are hunting for the signal from this primordial hydrogen. By tracing the gas over space and time, we can learn about the very first stars in the Cosmos: how massive were they? How long did they live? How were they clustered, and what did they produce when they died? In this work, the MWA EoR team analysed and published the largest set of EoR data for any experiment internationally, producing the most stringent constraints on the amplitude and structure of the signal spanning 350 million years of history and almost 3000 square degrees of the sky. Figure 1 shows the observing fields for the project.

This 12 billion year-old signal is exceptionally weak, and therefore we observe the same patches of sky for several hundred hours to reach the required noise level. The MWA EoR project generates huge amounts of observational data. Accumulated over the past five years of scientific observation, the MWA archive, housed at the Pawsey Supercomputing Centre, contains 2.7 terabytes of raw data. These data are produced from almost 3000 hours on-sky on the three key observational sky fields for the project.

The data challenges of the project, both in sheer size of the datasets, and in the sophisticated data analysis steps, require software pipelines that can efficiently and effectively treat the data. This requires high-performance computing infrastructure, to manage the data transfer, computing memory requirements and data storage challenges.

For this project, Pawsey resources were used for data storage and calibration processing, including generation of data quality metrics that are used for choosing the cleanest data to proceed to the next stage of processing. From an initial set of 800 hours of raw observed data, 450 hours were identified to be of sufficient quality for advancement. These data were then transferred to DownUnder GeoSolutions (DuG) in West Perth, for the final stage of data processing.

The combined expertise and infrastructure of the Pawsey, DuG, and science team collaboration, underpinned by high-quality data from the MWA, led to the analysis and publication of the largest set of data from any EoR project globally. This allowed the first ever census of the full MWA EoR database, spanning five years of observations, three regions of the southern sky, and 350 million years of the early Universe's history, starting only 500 millions after the Big Bang. Figure 2 shows an example power spectrum produced from the data; this quantifies the amplitude of fluctuations in the temperature of the hydrogen gas as a function of spatial scale, thereby encoding the size and distribution of ionised and non-ionised regions of the Universe.

Combined with the sheer data volume studied, this work has allowed the EoR team to explore the effect of different observational designs, and identify the best fields and observing frequencies for this experiment. These studies were then used to choose the best sets to publish as the final scientific measurements. These results measure the amount of power in the sky on different spatial scales, and are used to explore the evolution and growth of the first stars and galaxies in the Universe. The breadth and depth of the measurements can be used as observational evidence in modelling the early Universe, including constraints on the temperature of gas at early times, and the amount of light radiated from the first generations of stars. This is ongoing analysis, which will link the MWA observations with real astrophysics from the very earliest periods of the Universe's history.

Towards observing Cosmic Dawn with a radio interferometer

Benjamin McKinley

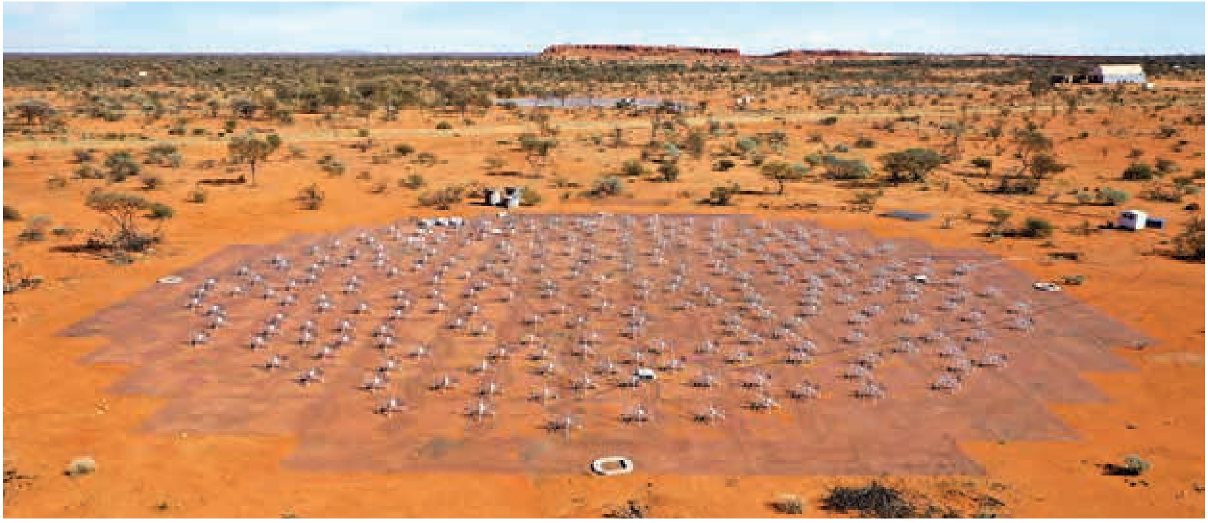
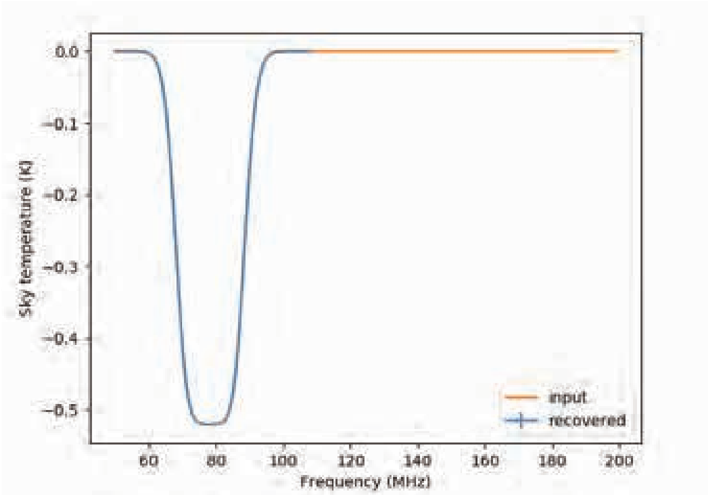


Figure 1, above: Aerial view of the second Engineering Development Array, EDA-2. Credit: ICRAR-Curtin, 2019



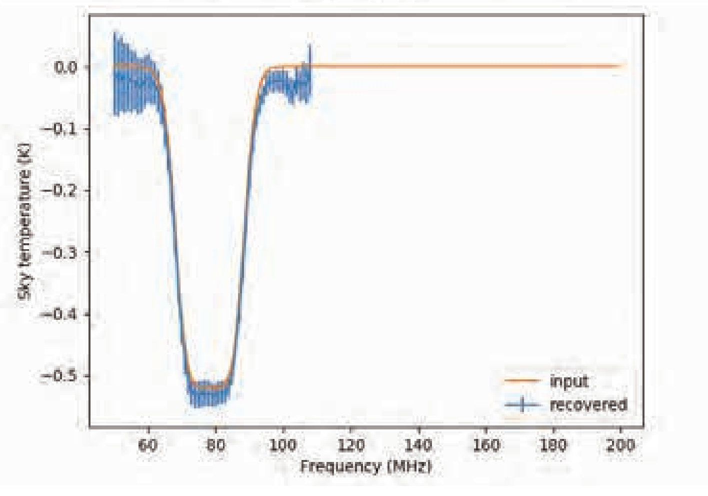


Figure 2a, right, top.

Figure 2b, right, bottom.

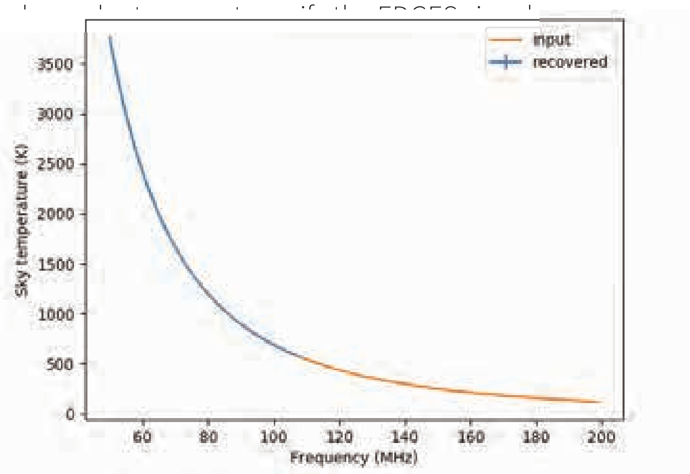
Credit: McKinley, 2019

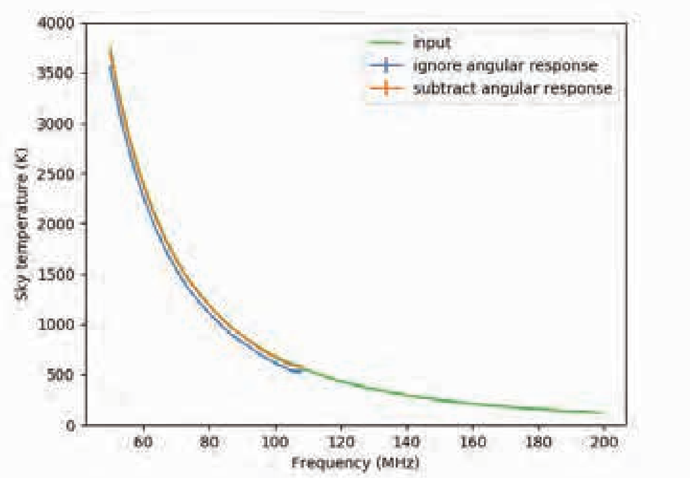
SCIENCE

The redshifted 21-cm signal from neutral hydrogen is the most promising opportunity to directly observe the Universe's first billion years of evolution.

The faint signal should be detectable at low radio frequencies (50 - 300 MHz), however, it is obscured by bright foregrounds sources and requires extreme precision in instrumental calibration. The EDGES experiment (Bowman et. al., 2018) has made the first claimed detection of the sky-averaged or 'global' 21-cm signal. Many experiments are now attempting to verify their unexpected results. Most of these global-signal experiments make use of a single dipole or monopole antenna and such systems can be prone to systematic effects that could cause a false detection.

An alternative approach is to use a radio interferometer, which consists of two or more interconnected antennas. In general, radio interferometers measure angular fluctuations in sky brightness and are largely insensitive to the global average. However, interferometers with very short baselines (less than a wavelength) do have a significant global-signal response. While interferometers are not immune to effects that may corrupt measurements of the redshifted 21-cm signal, the systematics involved are quite different from single-dipole experiments and they therefore offer an i





In 2019 I commenced a project that aims to use an interferometric array of closely-spaced antennas to detect the global signal from neutral hydrogen in the early Universe. The goal is to verify the EDGES result and extend the measurement to later times when the reionisation of the Universe is predicted to have occurred. The project has been broken up into several phases; 1. Realistic simulations to verify that the detection is possible with an interferometric array; 2. Verification of the simulation results using the Engineering Development Array - 2 (EDA-2, shown in Fig. 1); 3. Design of a system capable of making the required measurements; 4. Deployment and commissioning of a prototype array at the Murchison Radio-astronomy Observatory; 5. Observations with the prototype array and planning for a final system.

The work completed in 2019 was mainly focused on the first phase, simulations. A number of approaches to the problem were considered, including experimenting with different array layouts and even using a single baseline that physically rotates and changes length. The method that was found to produce the most desirable results involves calculating the expected response of the EDA-2 to a uniform sky and fitting it to the measured data (from simulations including noise and a realistic sky model). We solve for a scaling factor between the two quantities at each frequency, which is gives us an estimate of the global-signal response.

Results from the simulations show that the technique works for a noiseless sky with just a global 21-cm signal (1a) and for the same signal with noise in a 4-min EDA-2 observation (1b). Fig 2a shows that the EDA-2 can measure a global foreground signal (shown here is the all-sky average of the Global Sky Model (GSM) from de Oliveira-Costa et. al. 2008 with noise). Finally in 2b we show that we can extract the global foreground signal for a simulation that includes a realistic GSM sky with angular variations, using angular-structure subtraction in visibility space. Phase 2 is now underway, with early EDA-2 data showing promising results.

Figure 3a, left, top.

Figure 3b, left, bottom.

Credit: McKinley, 2019

An ancient double degenerate merger in the Milky Way halo

Adela Kawka

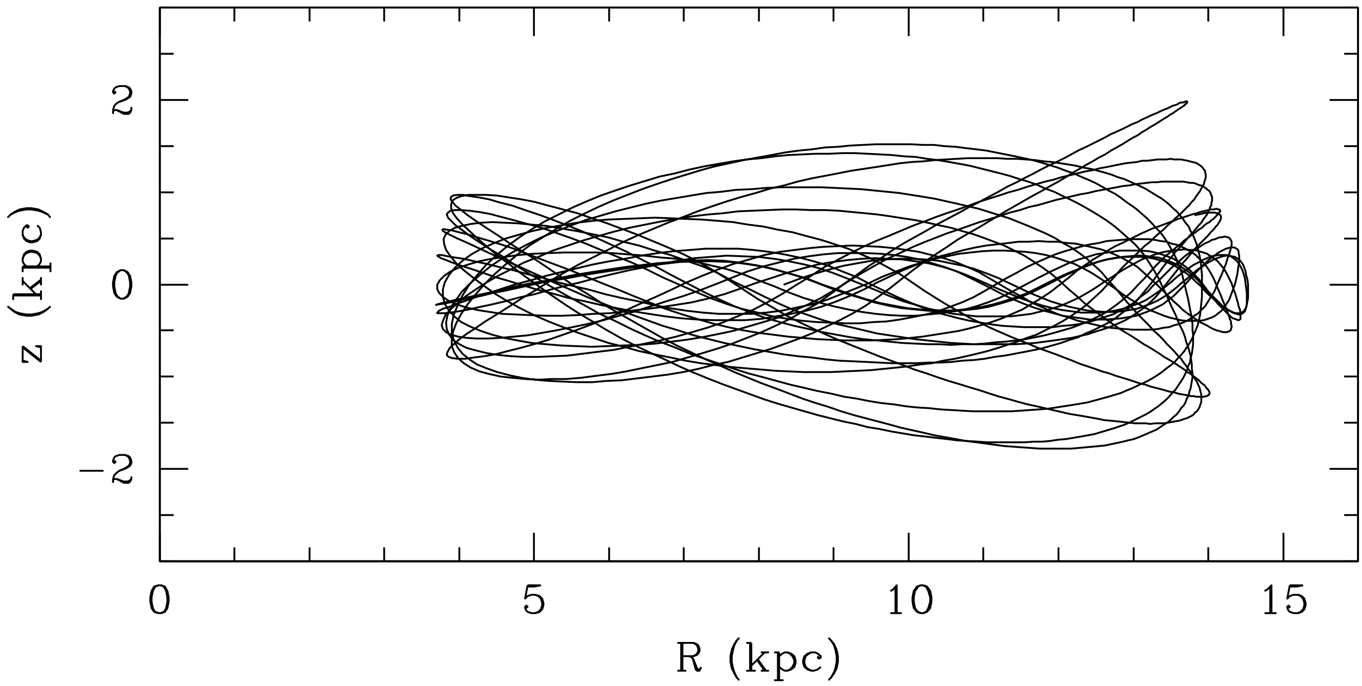


Figure 1, above: Orbits of LP 93-21 in the meridional plane; Galactic height (z) versus radial distance R. Credit: Kawka, 2020

White dwarfs are compact stars that are no longer burning any fuel and they are the final stage in the life of most stars.

Their simple structure and predictable cooling rates make them ideal chronometers in conducting Galactic archaeology and measuring the age of the Galaxy. Like many types of stars, white dwarfs are found in binary systems. White dwarfs are often paired with another white dwarf but also with members of many other classes of evolved or unevolved stars such as main-sequence stars, red giants, or even neutron stars. However, the incidence of binarity in the white dwarf population is only about half of the incidence of binarity in stars on the main-sequence. This suggests that a significant fraction of the white dwarf population is the result of stellar mergers.

The expected properties of white dwarfs that formed in stellar mergers are, primarily, a larger mass than average, but also a fast rotation, a peculiar atmospheric composition, or a magnetic field generated by the merger process. One peculiar class of objects displays most of these properties and are known as the hot DQ white dwarfs. Since their discovery in 2007 (Dufour et al. 2007, Nature, 450, 522) only a handful of these objects are known. Their main attribute is an atmosphere dominated by carbon rather than the more common hydrogen and helium rich atmospheres. These hot DQs also have effective temperatures ranging from 18000 to 24000 K. Since 2007, hot DQs were found to be fast rotators and most of them have a magnetic field.

Although their mass remained unknown until Gaia measured their parallaxes and theoretical mass-radius relations showed that hot DQs are unusually more massive, all of them exceeding 0.8 solar masses. A question remains concerning the fate of these objects. We should be able to observe cooler, older versions of these stars.

LP 93-21 is a DQ white dwarf that is cooler than hot DQs with an effective temperature of about 9500 K. It was first identified as a high proper motion white dwarf in the Luyten Palomar survey. A parallax was measured as part of the U.S. Naval Observatory parallax programme however the uncertainty was too large to place useful constraints on the mass of LP 93-21. The parallax measurement from the second data release of Gaia revealed LP 93-21 to be massive with a mass of 1.1 solar masses.

We have conducted an analysis of the stellar properties and the Galactic motion of LP 93-21 (Kawka et al. 2020, MNRAS, 491, L40) showing that LP 93-21 formed from the merger of two stars. Assuming single star evolution, the high mass of LP 93-21 would imply a progenitor of about 6 solar masses that would have evolved into a white dwarf in less than 100 million years. Combined with a cooling age of about 2.3 billion years, LP 93-21 would have formed in the Galactic disk and would be confined to the thin disk. However, using the astrometric measurements from Gaia, we showed that LP 93-21 is on a retrograde Galactic orbit meaning that it is a halo object and therefore very old. The only possible explanation for this age paradox is that LP 93-21 is the end product of binary star evolution that ended when the two stellar components merged. The most likely progenitors of LP 93-21 are two carbon-oxygen core white dwarfs that formed many billions of years ago from two low mass stars (about 2 solar masses) which then slowly approached each other by the release of gravitational radiation until they merged to form a more massive white dwarf some 2.3 billion years ago. The merger scenario also offers a natural explanation for the carbon-rich atmosphere and high mass of this object. Future studies should aim at a search for photometric variability which should reveal a short rotational period and the presence of a magnetic field.

The retrograde orbit of LP 93-21 could be explained by two variations of a common scenario. The first is that the progenitor system of LP 93-21 formed in a satellite galaxy that was accreted by the Milky Way in ancient times. The second scenario is that LP 93-21 was born in the Milky Way but was later driven into a retrograde orbit due to the accretion of a satellite galaxy more than 7 billion years ago. Again, both scenarios indicate that LP 93-21 is much older than implied from single star evolution.

Real-time imaging of jets from a rapidly-accreting black hole

James Miller-Jones

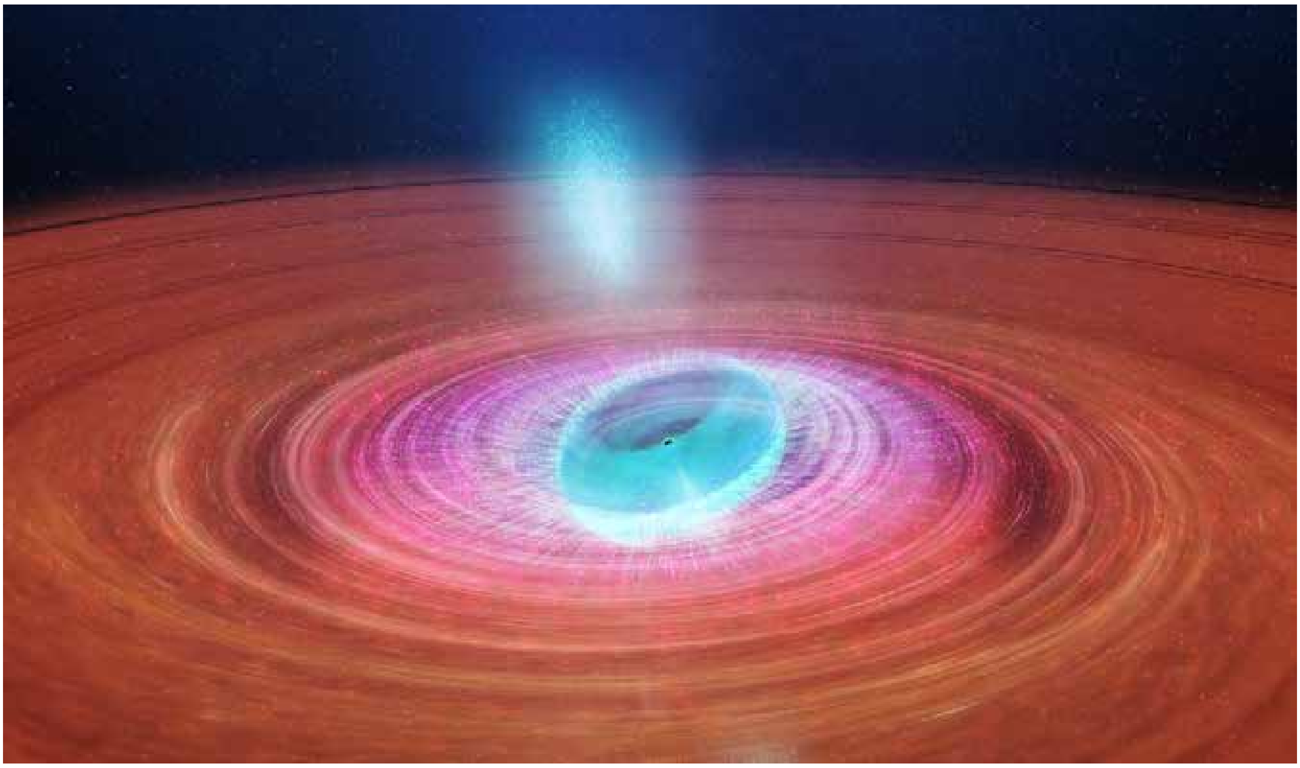


Figure 1, above: Artist's impression of the accretion disk around the black hole X-ray binary V404 Cygni, showing the puffed-up inner disk at the centre that is precessing around the black hole, and the launching of jet ejecta that are redirected perpendicular to the disk. Credit: ICRAR

SCIENCE

The recent imaging of a black hole photon ring by the Event Horizon Telescope collaboration has shown the power of high angular resolution imaging in probing accreting black holes.

But while this huge step has opened up a critical new window on black holes, it is just one (albeit very important) piece of this physical puzzle. With a mass in excess of six billion solar masses, the black hole that was imaged in the centre of the galaxy M87 evolves on very long timescales; light itself would take 36 hours to cross the event horizon. To probe the dynamics of how mass falls into and is ejected from the vicinity of a black hole, we need to look at lower-mass systems, which evolve on much faster timescales.

X-ray binaries containing star-sized black holes have long been used to probe the physics of accretion inflow and jet outflow, and the connection between these two universal phenomena. While direct imaging of such systems cannot reach the same angular resolution (in terms of Schwarzschild radii) as is possible for nearby supermassive black holes, the lower black hole masses (by factors of several million) allow us to observe these systems evolving in real time. Furthermore, X-ray binaries are often very well characterised, as optical observations during low-activity periods can determine key physical parameters such as orbital periods and inclinations, and the masses of the components.

The black hole X-ray binary V404 Cygni was first identified following a bright outburst in 1989. It comprises a 9 solar-mass black hole in a 6.5-day orbit with a 0.7 solar-mass subgiant companion. With an extremely accurate distance from radio parallax observations, it is an ideal laboratory to probe the physics of accretion and jet ejection. In mid-2015, after 26 years of quiescence, this system entered a new outburst phase, in which it reached the theoretical maximum accretion luminosity for a black hole of its mass. Our JACPOT XRB team (the Jet Acceleration and Collimation Probe of Transient X-ray Binaries) took this opportunity to trigger a long-standing program on the National Science Foundation's Very Long Baseline Array, to provide high-angular resolution radio imaging of the evolving jets over the course of this outburst.

Low-resolution radio monitoring from the Karl G. Jansky Very Large Array and the Arcminute Microkelvin Imager - Large Array had already shown that the radio jets were both bright and extremely variable. The rapid brightness variations meant that we could not use standard radio astronomy techniques to combine all our high angular resolution radio data into a single image. Instead, we were forced to break up our observations into short, 70-second long chunks. This enabled us to make a movie of the radio jets evolving over a four-hour period - the first example of real-time imaging of black hole jets. Our movie showed the ejection of ten different jet components over the course of the observations. Remarkably, we found the jet direction to vary over time, swinging by about 30 degrees in less than 3 hours – and possibly as short as minutes; we only sampled the jet direction at the time of ejection of each component. In other systems where the jet direction has been seen to change rapidly, the position angle changes occurred on timescales much longer than the binary orbital period. However, the rapid changes that we saw in V404 Cygni required a different explanation.

Thanks to earlier studies detailing the X-ray properties of the outburst, we knew that the intense radiation from close to the black hole had caused the inner few thousand kilometres of the accretion disk to become puffed up into a toroidal configuration. When the disk is misaligned with the black hole spin, general relativity tells us that particles out of the equatorial plane will precess due to the frame dragging effect of the black hole spin. Under the right circumstances, the inner regions of the disk can precess as a single solid body. In such a situation, theoretical simulations have shown that the precessing disk can redirect the jets launched from the innermost regions, close to the black hole. This scenario was fully consistent with our observations, providing evidence of a direct link between the dynamics of the accretion flow and the behaviour of the jets. Such Lense-Thirring precession should occur around any rapidly-feeding black hole whose spin axis is misaligned with the angular momentum of the gas reservoir from which it is accreting. It could therefore be prevalent in rapidly-feeding supermassive black holes and tidal disruption events.

This work provides a taste of what can be achieved with high resolution imaging. The strong evidence for spin-orbit misalignment in other X-ray binaries suggests that similar physics could be seen in other rapidly-accreting systems, and the deployment of new imaging algorithms could improve the power of this technique going forwards.

The Host Galaxies of Fast Radio Bursts

Jean-Pierre Macquart and the CRAFT collaboration

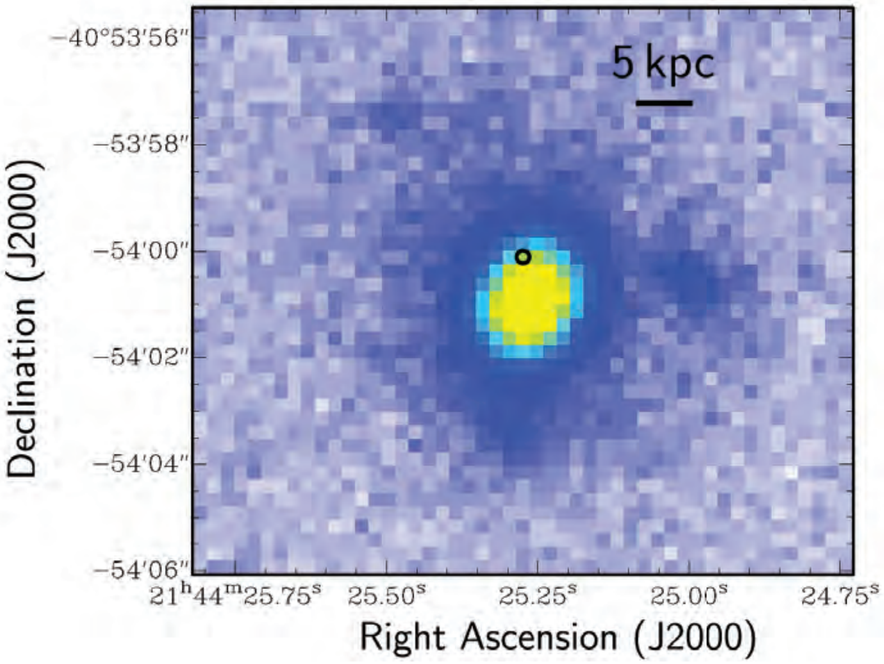


Figure 1, left: The position of FRB 180924 as localised by ASKAP (black circle) overlaid on an optical image of its host galaxy obtained with the European Southern Observatory's Very Large Telescope (VLT). Credit: Macquart, 2019

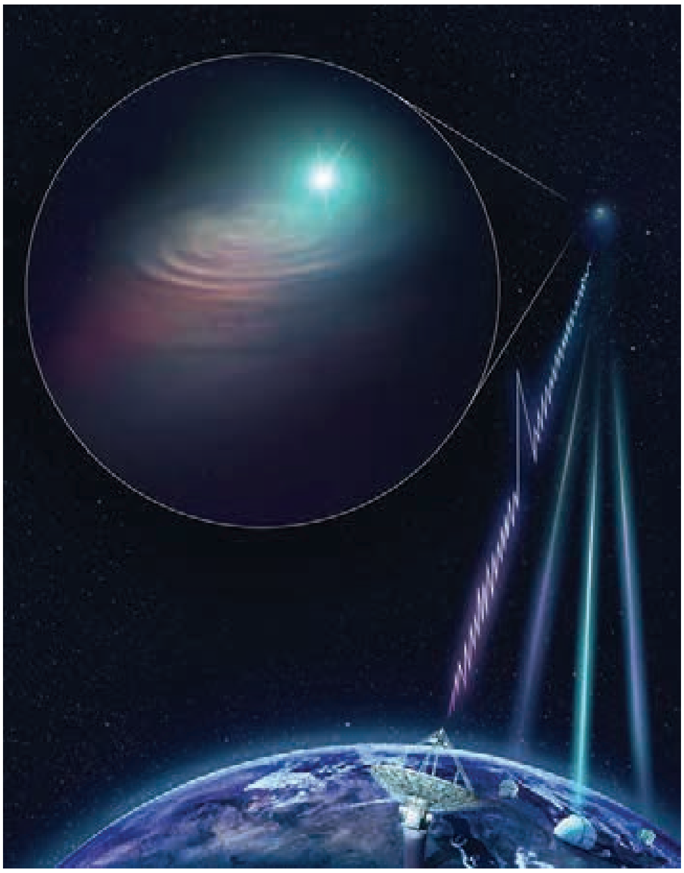


Figure 2, right: Determining the properties of FRB host environments is a multi-wavelength effort, requiring coordination between radio and optical observatories. While ASKAP provides the precise position of each FRB, we have used optical observatories including the 10m Keck telescopes, the VLT and Gemini telescopes to measure the redshifts of each burst and to determine the physical properties (e.g. star formation rate and hydrogen gas column) of the region in which the burst occurred. Credit: CSIRO/Dr Andrew Howells

Fast radio bursts (FRBs) are mysterious flashes of electromagnetic radiation so intense that their millisecond-timescale emission is visible across the Cosmos.

Every day, over three thousand of these events occur across the sky, each releasing more energy than our Sun would in 80 years. Since the first reported discovery, with the Parkes radio telescope in 2007, teams of astronomers across the world have been striving to gather clues about the emission properties to understand how such incredible bursts can be produced.

The biggest and most fundamental part of the puzzle involves measuring where these bursts are produced. But localisation is an exceptionally hard feat: to uniquely identify which galaxy a burst originated in requires us to measure the burst position to better than an arcsecond (1/3600th of a degree). Even better accuracy is required to measure where in the host galaxy the burst originated: was it in the galaxy centre, on a spiral arm, or did it occur outside the stellar disk? Up until recently the only telescopes with wide enough fields of view to be able to capture the emission from FRBs also had poor resolving power. The Parkes radio telescope, for instance, is readily able to detect FRBs, but cannot determine the position of the burst to better than about a tenth of a degree.

Enter the Australian Square Kilometre Array Pathfinder, or ASKAP, located on the radio quiet Murchison Radio Observatory (see image on Highlights page). Its 30 square degree field of view imparts a supreme advantage by being able to net FRBs easily. And its 36 antennas, distributed out to separations of 6km across the desert floor gives it just the right resolving power to measure to sub-arcsecond accuracy. Its custom-designed firmware built into the telescope electronics allows it to localise every single detected FRB to such an accuracy that we can unambiguously determine which galaxy it came from, where in the galaxy it came from, exactly how far away the burst was, and even investigate whether there was anything unusual about the burst location that could have produced such an energetic event. ASKAP has now begun localising a collection of FRBs, and has begun amassing information on where these bursts are produced.

The very first detection revealed a burst that emanated from a galaxy at a redshift of 0.34, meaning that the light from burst had travelled for 3.8 billion years before reaching us here on Earth! This astounding result was published in Science (Bannister et al. 2019), and even made the front cover of the journal. Moreover, the accuracy of the localisation was far better than we had dared expect: the brightness of the burst was so high we had enough to signal to measure the position to 0.2", and determine that the burst occurred on the outskirts of the galaxy, some 12000-15000 light years (3-4 kiloparsecs) from the centre of the galaxy.

The second localised burst, whose properties were published in another Science article (Prochaska, Macquart et al. 2019), was even more remarkable. Through a one in one hundred statistical fluke, the radiation from this burst actually grazed the halo of another large galaxy 900 million years into its 4.9 billion year passage to the Earth. This provided an astounding opportunity to understand the outer reaches of galaxies, their gaseous halos. This is important because the halo of gas can actually extend out 10 times further than the stars in a galaxy, and can contain a substantial amount of the matter that's in a galaxy. But it's very difficult to see the gas directly with a telescope. We expected the signal from the fast radio burst to be distorted by the galaxy: if you go out on a hot summer's day, you see the air shimmering and the trees in the background look distorted because of the temperature and density fluctuations in the air. In a similar way, that the signal from the fast radio burst was expected to be completely distorted after passing through the hot atmosphere of the galaxy.

Instead of the stormy galactic weather we were expecting, the pulse we observed travelled through a calm sea of unperturbed gas. It wasn't distorted at all! The finding suggests that galaxy halos are much more serene than previously thought, with gas that is less turbulent, less dense and less magnetised than expected. Understanding the nature of these galaxy halos is important because they can help us understand why material is ejected from galaxies, causing them to stop growing. The halo gas provides a fossil record of these ejection processes.

So our detection of this FRB not only told us about the environments in host galaxies that generate FRBs themselves, it also told us how matter is ejected from galaxy and how magnetic fields are transported from them. This work revealed something entirely new about galactic halos. We can only wonder what the next ten FRBs localised with ASKAP will tell us!

PKS 2250-351: A Giant Radio Galaxy in Abell 3936

Nicholas Seymour

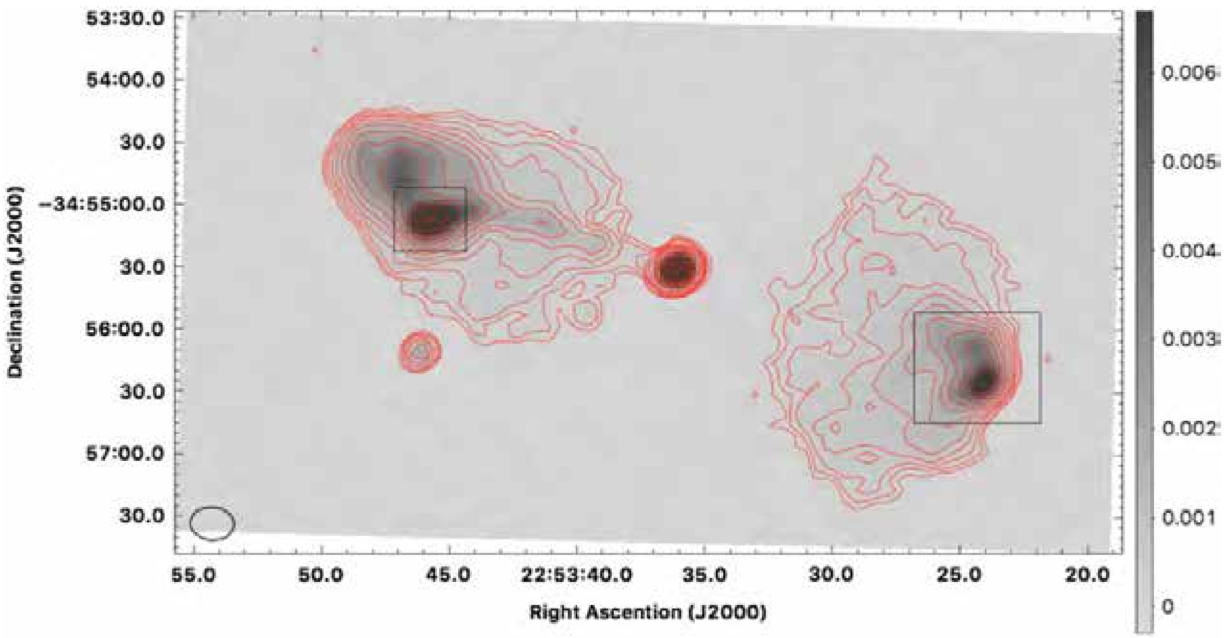


Figure 1, above: Greyscale image of PKS 2250-351 from our 888 MHz ASKAP continuum data. The local RMS is ~64 μJy/beam and the restoring beam is indicated in the lower left. The greyscale is a linear stretch in Jy/beam as indicated by the colour bar. The red contours start at 4 sigma and increase by factors of √2. The core is clearly identified as well as hotspots positioned on top of diffuse emission from the lobes. Within the eastern lobe, the jet is observed with several knots. The total angular size is 5.66 arcmin (~1.2 Mpc) with equal lobe lengths. However, the width of each lobe is markedly different with the western lobe being 1.4 times wider than the eastern lobe. Credit: Seymour, 2019

SCIENCE

Giant radio galaxies (GRG) are a unique class of radio galaxies with lobes which not only extend beyond their host galaxy, but are greater than one megaparsec in projected size (>3.3 million light years).

Like regular radio galaxies they are powered by black holes with masses a million to billion times greater the Sun. In Seymour et al. (2020) we conducted a detailed study of a GRG known as PKS 2250-351 which lies in the GAMA 23 survey field. Hence, we can take advantage of the superb multi-wavelength data available in this field in particular the broad-band radio data from the MWA/GLEAM, ASKAP/EMU and ATCA/GLASS surveys.

Abell 3936 is an amorphous cluster with no clear centre. Its non-detection in X-rays suggests it is an unrelaxed, although likely massive (~1014 million solar masses), cluster. Within this dynamical environment lies PKS 2250-351 with a projected extent of ~1.2 Mpc. Figure 1 presents the radio morphology of PKS 2250-351 from the ASKAP/EMU early science observations. The lobes of the radio galaxy lie in an approximately east-west orientation and both have a spectral index of α = -1 (Sν ~ να) slightly steeper than typical radio galaxies. The radio core is bright and identifies the host galaxy, spectroscopically confirmed to lie in Abell 3936 at z=0.2115. The lobes are of equal length, but the eastern lobe is about 30% narrower and 30% more luminous.

It is likely that the asymmetry of the lobes is caused by an increase in the density of the hot intracluster medium (ICM) towards the densest concentration of galaxies (see Figure 2), reducing the eastern lobe's ability to expand perpendicular to the jet. The prominence of the jet in the eastern lobe could partly be explained by the increasingly dense ICM into which it is drilling. The knots and kinks seen in the jet could be due to hydrodynamical instabilities. Future X-ray observations will provide additional clues on these issues, potentially providing evidence of the interaction of the radio lobes with the ICM.

The host galaxy of PKS 2250-351 is a massive elliptical galaxy with negligible star formation. However, it has prominent mid-infrared emission for an elliptical which is likely due to hot dust heated by accretion onto the central super-massive black hole. We estimate a bolometric luminosity of the active galactic nucleus (AGN) of 1.4x10e11 solar luminosities, consistent with that estimated from the [OIII]λ5007 optical emission line. Assuming this galaxy lies on the local 'M-σ relation' (which relates the mass of the central black hole to that of the host galaxy/bulge) we estimate that the accretion rate is roughly 1% of its maximum 'Eddington' value. This accretion rate value is at the approximate transition between the inefficient 'advection-dominated' mode to the efficient 'thin-disc' mode of the accretion disc around the black hole.

We estimate the radio jet powers in two ways: one from the lobes (a time-averaged measure) and one from the hot spots (an instantaneous measure). The lobe-derived jet power is an order of magnitude greater than the hot spot-derived jet power. We suggest that this inconsistency is caused by a change the accretion mode. The advection-dominated mode can produce a radio jet which is approximately ten times more powerful (for the same black hole mass and accretion rate) than the thin disc mode. Hence, if the accretion disk has just changed (or is changing) from the advection-dominated to thin disk mode then this could explain the decrease implied by the difference in jet power estimates.

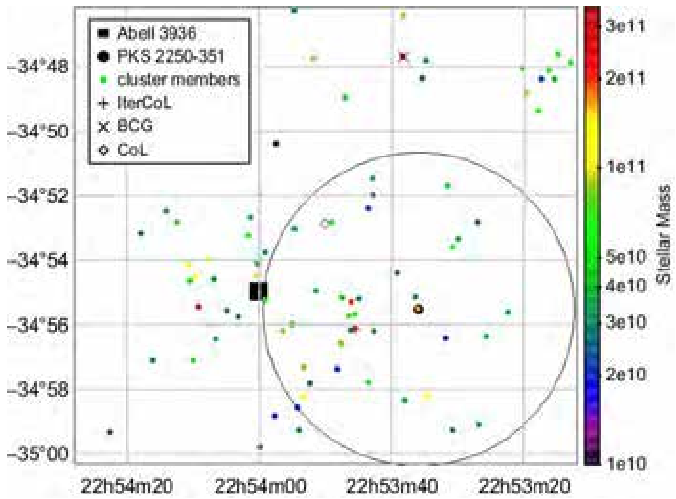


Figure 2, above: Sky distribution of spectroscopically confirmed GAMA sources lying at 0.207 ≤ z ≤ 0.2180 (i.e. Δ(cz) ≤ 1,500 km s−1). PKS 2250-351 is indicated by a larger black dot surrounded by a 1 Mpc radius circle. The large black square is the Abell cluster position and the '+', 'X', and diamond indicate three different estimates of the cluster centre from the GAMA group catalogue. The colour code of the galaxies indicates their stellar masses. The radio galaxy lies to the west of our most confident estimate of the cluster centre, the Iterative Centre of Light (IterCoL). Credit: Seymour, 2019

Strong low-frequency radio flaring from Cygnus X-3 observed with LOFAR

Jess Broderick and Jaiverdhan Chauhan

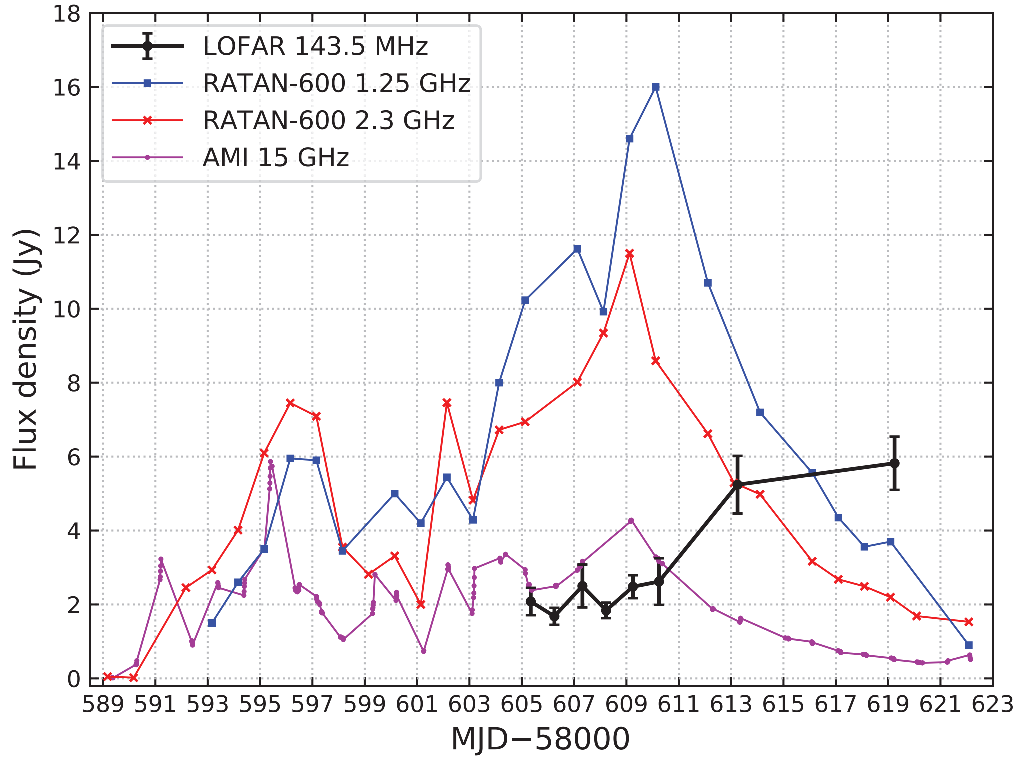
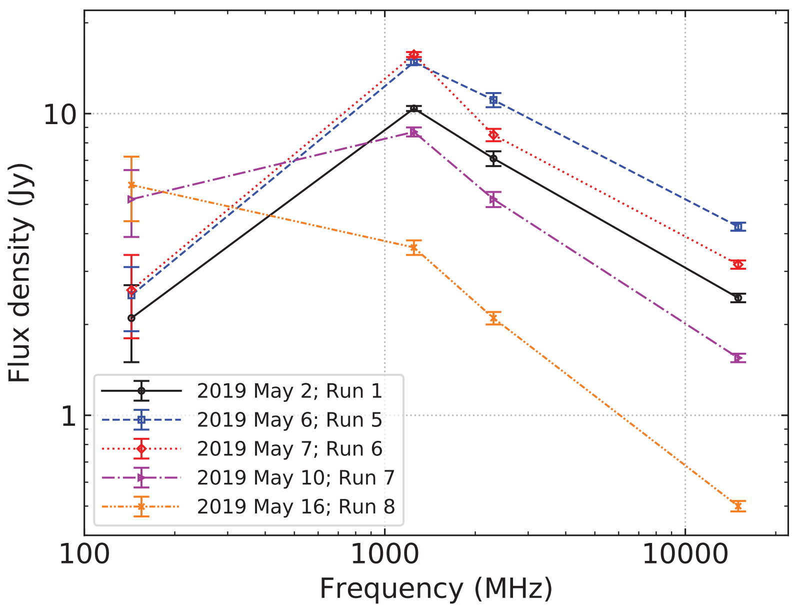


Figure 2, left: Multi-frequency light curves for Cygnus X-3 during the 2019 April–May flare. In addition to data from LOFAR in the Netherlands, there are light curves from the RATAN-600 telescope in Russia, and the AMI Large Array in the United Kingdom. Note how the LOFAR light curve is very different to the higher-frequency light curves. The x-axis is expressed in terms of the Modified Julian Date; 589 = April 16, and 623 = May 20. For the purpose of clarity, error bars are only shown for the LOFAR data points. Credit: Broderick, 2020

SCIENCE

Figure 3, right: Broadband radio spectra for Cygnus X-3 at various points during our observing campaign. The data points are from the same facilities described in the Fig. 2 caption. The shape of the spectrum clearly changed as the flaring event progressed. Credit: Broderick, 2020



X-ray binaries (XRBs) are ideal astrophysical laboratories for studying the connection between accretion and jet production.

Cygnus X-3 is a Galactic XRB that was discovered in 1967. This is a special system comprising a primary compact object (it remains unclear whether this is a stellar-mass black hole or a neutron star), in orbit with a Wolf–Rayet star. Every few years, giant radio flares are observed from Cygnus X-3, produced by relativistic jets. Despite these outbursts being studied for half a century, there are not many corresponding low-frequency (< 300 MHz) radio data sets. The Low-Frequency Array (LOFAR), a pan-European radio telescope with its core located in the north-east of the Netherlands, is an ideal facility to rectify this issue.

A major outburst from Cygnus X-3 was detected on 2019 April 17. Bright flaring was to continue for over a month. On May 2, we triggered an approved LOFAR programme to obtain 143.5-MHz observations of this extended flaring activity. Eight observations in total were carried out from May 2–16. Cygnus X-3 was sufficiently bright such that it was easily detected in our LOFAR data (Fig. 1). However, the image quality was significantly affected by the extremely bright radio galaxy Cygnus A, which was within the LOFAR field of view of our observations. This meant that extra care was required to calibrate the data.

In addition to the 143.5-MHz LOFAR observations, we examined contemporaneous monitoring data from both the RATAN-600 telescope and the AMI Large Array, at frequencies of 1.25, 2.3 and 15 GHz. Bright radio flaring can be seen in the light curves at all frequencies, but the shape of the LOFAR light curve is clearly different to the GHz-frequency data (Fig. 2). The initial 143.5-MHz flux density level, about 2 Jy, was two orders of magnitudes brighter than its usual value. The flux density then increased by nearly a factor of three by the end of our observing campaign; this is one of the brightest flux densities measured thus far for Cygnus X-3 at low frequencies. Unfortunately, we did not have additional observing time to see if the LOFAR light curve continued to rise.

The most likely interpretation for the LOFAR light curve is that we observed the delayed, low-frequency equivalent of the brightest flare detected at GHz frequencies. As the synchrotron-emitting plasmons from the outburst expanded, they became progressively less opaque to emission at lower and lower frequencies. Therefore, at the same time as the LOFAR flux density increased, the flux densities at higher frequencies were already beginning to decay, having previously evolved on shorter time-scales.

Some of the properties of the outburst are still not well understood, however. There is a suggestion that the LOFAR peak flux density was brighter than expected. Additionally, our data did not allow us to easily differentiate between several candidate absorption mechanisms to explain why the spectrum initially turned over at low frequencies (Fig. 3). What is likely complicating the picture is that the flaring continued for over a month. Discrete flares corresponding to distinct episodes of particle acceleration, with well-defined peaks at GHz frequencies, become less peaked and 'washed out' in the LOFAR band, which means that there is a strong likelihood that multiple flares became blended together in the LOFAR light curve, making the interpretation significantly more complicated. Additional analysis and modelling is needed as part of future work.

The international team that carried out this work included CIRA astronomers Jess Broderick and Jaiverdhan Chauhan. This project was initially reported as an Astronomers' Telegram (no. 12764; Broderick et al. 2019). Our study has now also been submitted as a research article to Monthly Notices of the Royal Astronomical Society (Broderick et al. 2020). Further LOFAR observations are planned for the next giant outburst from Cygnus X-3.

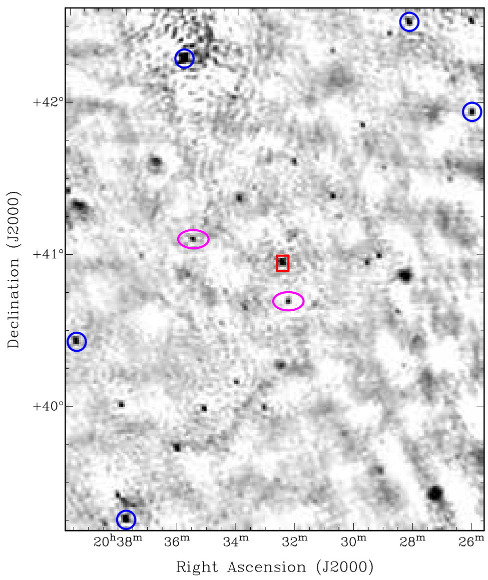


Figure 1, above: Inner part of a LOFAR image centred on Cygnus X-3 (marked with the red square). Five field sources (marked with blue circles) were used to calibrate the flux density scale, and two sources near Cygnus X-3 (marked with magenta ellipses) were then used to verify the accuracy of the calibration. Credit: Broderick, 2020

Ramping up pulsar science and capabilities for the MWA

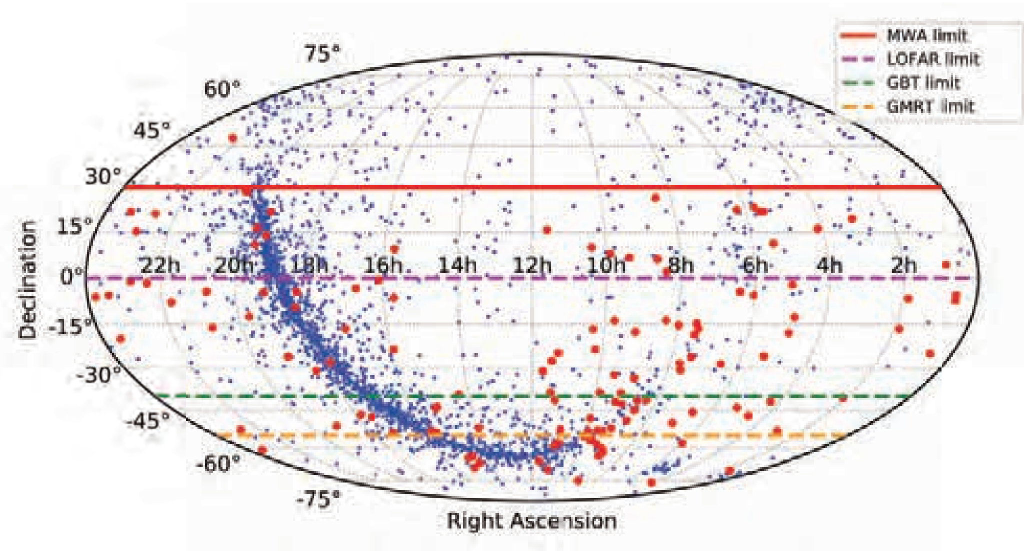
Ramesh Bhat

With the successful PhD completions by the first cohort of students and the development of a series of new capabilities to further the pulsar science program at the MWA, the Curtin pulsar science activity marks its first significant milestone.

2019 has been a significant year for pulsar science at Curtin – an activity that began a few years ago when the MWA was equipped with just the most basic capability – the ability to record raw voltages from the tiles and perform an incoherent addition of detected powers. Despite ~5% of the full-array sensitivity achieved back then, the scientific promise was evident with the publication of the first pulsar science result on the low-frequency detection of the millisecond pulsar PSR J0437-4715, enabling its scintillation and profile evolution to be studied for the first time at uncommonly observed frequencies (Bhat et al. 2014). MWA pulsar science has come a long way since then, in terms of developing both new capabilities via software instrumentation around the voltage-capture system, and executing a wide range of science projects – all thanks to the sustained enthusiasm from a small but close-knit group of students determined to pursue their research whilst supporting, and even leading, related technical/software developments, despite the many challenges posed by the non-traditional pulsar capability provided by the MWA.

The research theme for these PhD completions (Meyers, McSweeney and Xue) was conceived around the early science capabilities of the MWA – i.e. exploring the pulsar emission mechanism, probing the interstellar medium via pulsars, or a combination of both. The concerted effort in this direction has led to a significant research output, with a total of eight refereed publications from the PhD theses alone, four of which were published in 2019 (McSweeney et al. 2019a, 2019b, Meyers et al. 2019, Xue et al. 2019). Their research also upheld Curtin's high standards, bringing accolades for Sam McSweeney and Mengyao Xue in the form of the Ken and Julie Michael Prize (in 2018 and 2019 respectively), for the most outstanding piece of research in radio astronomy science within ICRAR. McSweeney's PhD thesis also received a Letter of Commendation from the Chancellor. All students have now moved to their new jobs at different institutions: Bradley Meyers commenced a post-doctoral research position at the University of British Columbia to work on pulsar science with the Canadian CHIME telescope; Mengyao Xue commenced as a FAST fellow at the National Astronomical Observatories of China to pursue pulsar science using the 500-metre aperture FAST telescope; and CIRA welcomed Samuel McSweeney as a new research staff within the pulsar team. In his new role, Sam McSweeney will support and strengthen many of the activities and initiatives under the pulsars and fast transients theme within ICRAR3's SC4 program.

2019 also marked the successful development and science demonstration of several new pulsar capabilities for the MWA, which will ensure its continued scientific exploitation for pulsar science. These include: (i) the ability for coherent combination of voltage signals from 128 tiles to attain maximal sensitivity (Ord et al. 2019), (ii) polarimetric capabilities within tied-array beam-forming (Xue et al. 2019), (iii) the ability to attain microsecond time resolution for high-quality studies of millisecond pulsars (Kaur et al. 2019), and (iv) leveraging the frequency complementarity with other major facilities (Parkes and GMRT) for co-observing campaigns to study pulsar emission mechanism



Figure, left: Pulsars in the radio-sky: all-sky distribution of known pulsars (blue circles); to date, 130 pulsars have been detected with the MWA (red circles). These include binary and millisecond pulsars, as well as intermittent and long-period ones, demonstrating the MWA's sensitivity to a wide variety of these exotic objects. The MWA can observe anywhere below the solid red line; the declination limits of other (northern) telescopes are shown as the dashed lines. . Credit: Swainston, 2020

(Meyers et al. 2019; McSweeney et al. 2019). With the addition of these and other related capabilities, such as the simultaneous sampling of multiple frequency sub-bands for pulsar science (Bhat et al. 2018) and the development of a voltage buffer mode for the detection of transient pulsars (Meyers et al. 2018), the MWA is fast emerging as a premier facility for low-frequency pulsar astronomy. Many of these capabilities are already in routine use and are beginning to enable new projects within MWA science.

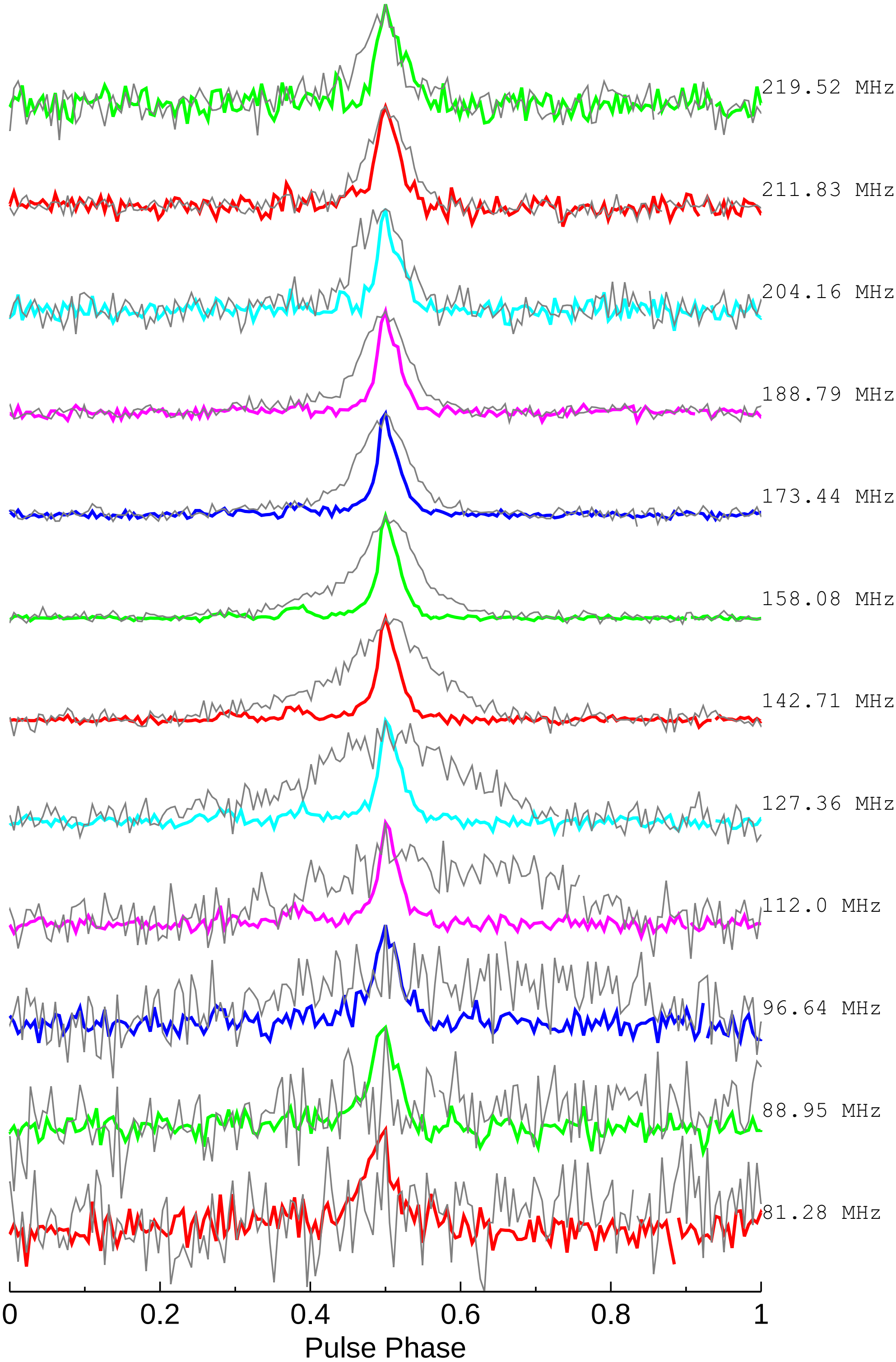
With the renewed momentum imparted through all this and the experience gained in the process, and, furthermore, motivated by the recent upgrade to MWA Phase 2, the Curtin pulsar team has now embarked on a major ambitious project that will exploit the MWA's pulsar science niche: the Southern-sky MWA Rapid Two-meter (SMART) survey, which commenced last year. It is an all-sky pulsar survey at the low frequencies of the MWA, aiming to exploit some unique strengths of the instrument, especially its large field of view and voltage-capture functionality. The project will accrue 3 PB of high time resolution voltage (VCS) data, and will require significant computational resources for data processing (~7 million service units). A multi-pixel beamformer has been developed by the Curtin PhD candidate Nicholas Swainston to support the project, and has been successfully benchmarked on Swinburne's OzSTAR supercomputer. The development of an end-to-end pipeline to process and detect a large sample of known pulsars has been an integral part of this effort: the processing of survey and archival data has led to the detection of 130 pulsars to date, more than doubling the number of pulsar detections from the early days (Xue et al. 2017), but with the important distinction that many of them are now made at vastly improved sensitivities and often in full polarimetry. An exciting highlight is the discovery of the first new pulsar with the MWA, follow-up studies of which are under way, and will be reported in an upcoming publication.

The opportunities presented for new science and skill development in software instrumentation continues to attract new students to pursue pulsar science at Curtin. Susmita Sett, a recent Masters graduate from the University of Manchester, is the newest addition to the group. Her research will take advantage of the interferometric and tied-array capabilities of the MWA for pulsar searching applications. The Curtin pulsar science program has also been an excellent training ground for undergraduate students, with a new cohort of four joining the group in the current semester. While some are engaged in high-sensitivity applications such as pulsar emission studies, some are keen to help with the development and integration of machine learning algorithms in support of the SMART survey effort.

By steadily pushing the MWA's pulsar capabilities into competitive space, and seeing that an all-sky pulsar survey program takes off the ground, the Curtin pulsar science program has come a long way and has now crossed a significant milestone. With upgrade plans moving forward for the MWA, particularly the development of a new correlator and beamformer to support a 256-tile MWA (Phase 3), the future appears brighter and more promising for pulsar science with the MWA, which has the potential to emerge as an excellent pulsar monitoring machine at low frequencies.

Millisecond pulsar PSR J2241-5236 at microsecond time resolution

Dilpreet Kaur and Ramesh Bhat



SCIENCE

Millisecond pulsars (MSPs), also known as recycled pulsars, are formed via accretion of matter and angular momentum from binary companions. They have pulse periods of the order of a few milliseconds, and their rotational stability is significantly superior compared to normal (younger) pulsars. As a result, their pulse arrival times can be measured, and also predicted, with high accuracies.

One of the high-profile applications of MSPs is in Pulsar Timing Array (PTA) experiments, which aim to detect nanohertz-frequency gravitational waves, produced by mergers of supermassive black hole binary systems as galaxies formed and evolved in the early history of the Universe. For PTAs to succeed, it is necessary to achieve high timing precisions (~100-200 nanoseconds) for a large sample of MSPs, over long-time spans (of the order of ~10-20 years). PTAs need to tackle a multitude of challenges before they can reach this ambitious goal, and this involves developing a thorough understanding of the emission and physical properties of pulsars that form PTAs, characteristics of the instruments used for observations, and the effects on pulsar signals as they pass through the ionised interstellar medium (ISM).

The magnitude of the ISM effects scale strongly with the inverse of radio observing frequency. Therefore, pulsar observations are typically carried out at relatively high radio frequencies (above ~1 GHz), where the propagation effects due to the ISM tend to be relatively smaller. On the other hand, observations at lower frequencies (< 300 MHz) can potentially allow a robust characterization of ISM effects, unlike those at higher frequencies where their impact on timing measurements are not easy to discern. The MWA offers the strategic advantages for undertaking low-frequency studies of southern MSPs, many of which are the prime targets for both current and future PTAs. It is the only low-frequency capable facility that shares common sky with both the Parkes and MeerKAT telescopes. The low frequencies of the MWA are particularly well suited for characterising the ISM along the sightlines of PTA pulsars.

Figure 1, far left: MWA detection of the millisecond pulsar PSR J2241-5236 across the 80 to 220 MHz frequency range. The pulsar is detected throughout the observed band; the coherently de-dispersed profiles (in colour) are overlaid with those using the 10-kHz VCS resolution (in grey), where the pulse profiles are significantly broadened and the pulsar was not detectable below 120 MHz. Credit: Kaur, 2019

MSP science at the low frequencies of the MWA require phase-coherent de-dispersion to be performed on data in order to alleviate substantial dispersive smearing when pulsar detections are made using traditional filterbank-type (i.e. channelized) data; for instance, even with the 100-µs/10-kHz resolutions of the MWA voltage capture system (VCS), it is almost impossible to resolve fine temporal structures in the pulse profiles of short period MSPs (Figure 1). Thanks to our recent breakthrough in the MWA pulsar processing pipeline (McSweeney et al. 2020), we are now able to reconstruct the time series at a much higher time resolution of ~0.78 µs, which has enabled us to obtain high-fidelity detections of MSPs with the MWA.

MSP J2241−5236 provides an excellent test case to showcase this new capability. Its extremely narrow pulse profile (width ~150 µs) and a low dispersion measure (DM) of 11.41085 pc cm-3 makes it a highly promising target for PTAs. With the new beamformer capability to synthesise microsecond time resolution voltage data, it has become possible for us to perform phase-coherent de-dispersion on MWA VCS data. This has enabled pulsar detections down to frequencies of ~80 MHz, revealing the low frequency emission properties of this important pulsar for the first time. Our detections also reveal a dual-precursor feature in the pulse profile of this pulsar, which is less prominent, or almost undetectable, at higher frequencies (see Figure 2). With these developments, we are currently reaching micro-second level timing precision for this pulsar.

In combination with the MWA's large frequency lever arm (80-220 MHz), this has allowed us to obtain highly precise DM measurements – almost an order of magnitude better than those currently achievable at timing (PTA) frequencies (~1-2 GHz). Our observations also reveal temporal DM variations of the order of 0.00066 pc cm-3 for this pulsar. Such minute variations in DM can still be important in the context of PTA efforts, as any residual uncorrected DM variations can potentially impact the achievable timing precision in PTAs.

Since PSR J2241−5236 is in a 3.5-hour, almost circular orbit with a low-mass (~ 0.01 Solar Mass) white dwarf, there is a possibility that small-amplitude DM variations can be caused by the companion winds. In order to explore this in detail, new observations have been made with the MWA to span across the full orbit, the data from which are currently being analysed. (Continued...)

Figure 3, above: Watercolour painting of binary system PSR J2241-5236, with pulsar radio signals being received by MWA antennas. Credit: Kaur, 2020

These early science results open up some interesting questions; e.g. how important are low-frequency DM measurements in aiding PTA efforts? How much DM contributions can be produced by companion winds? How the profile evolution can impact pulsar timing? Many of these are important topics of investigation in the context of pulsar timing arrays; however, there have been limited observational investigations to date, especially at the low frequencies where high-precision DM measurements are now obtainable using low-frequency facilities like the MWA.

In order to gain further insights, and also to explore recently theorised chromaticity (frequency dependence) in pulsar DM – as a consequence of multi-path propagation effects (Cordes et al. 2016) – we have undertaken an ambitious, multi-telescope observing campaign involving contemporaneous and/or simultaneous use of the MWA, GMRT and Parkes telescopes. The combination of these telescopes provides an unprecedented frequency coverage from ~100 MHz to 4 GHz, which is very useful for the investigation of pulsar dispersion and profile evolution. Besides gaining useful insights into ISM effects and their impact on PTAs, this may also inform optimal observing strategies for PTAs in the SKA era.

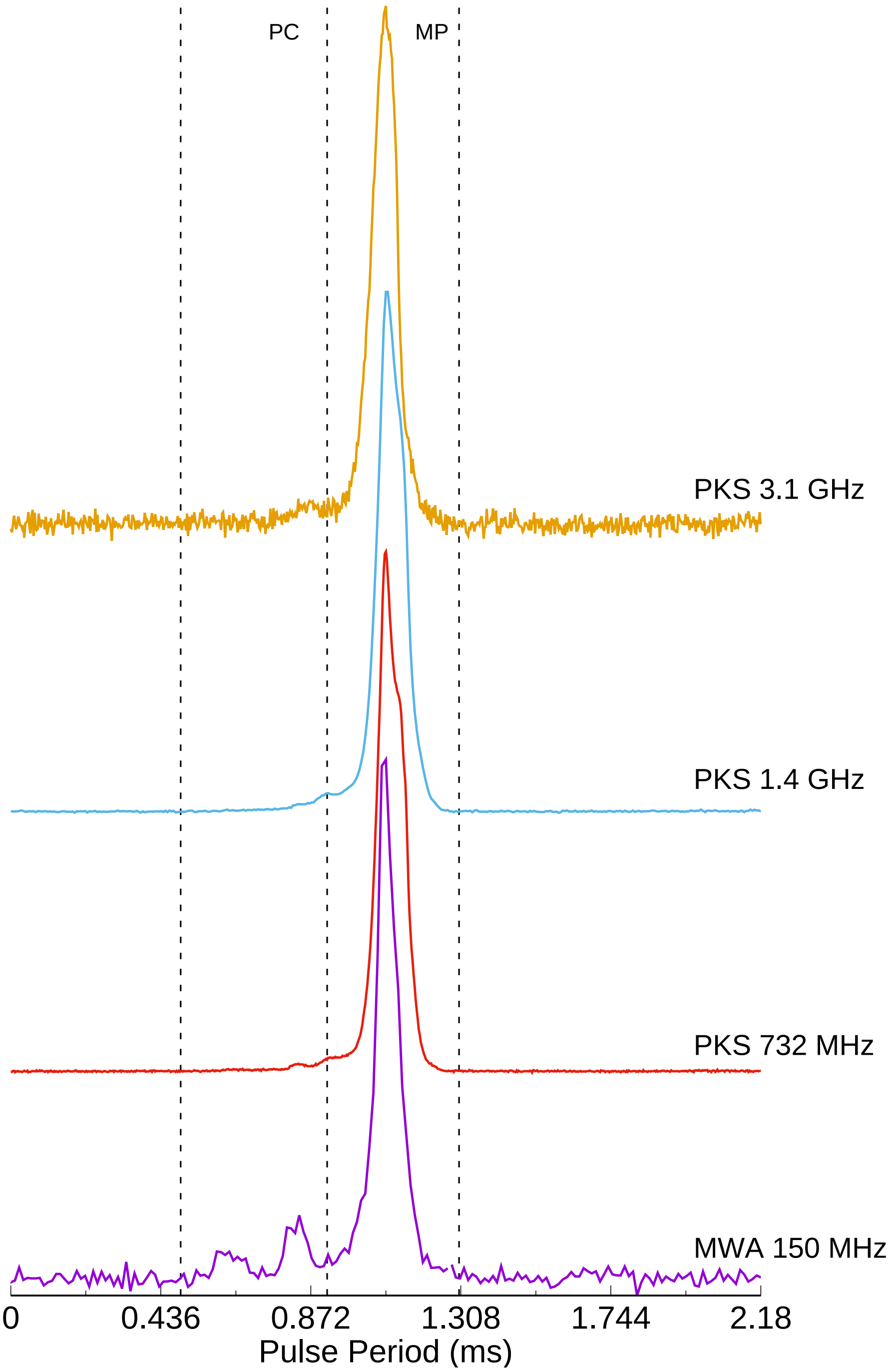


Figure 2, right: Integrated pulse profiles of PSR J2241−5236 at frequencies from 150 MHz to 3.1 GHz. The MWA detection has revealed two precursor components that are less prominent at high frequencies of the Parkes telescope. Credit: Kaur, 2019

Counting beamlets in PSR B0031-07's emission beam

Sam McSweeney

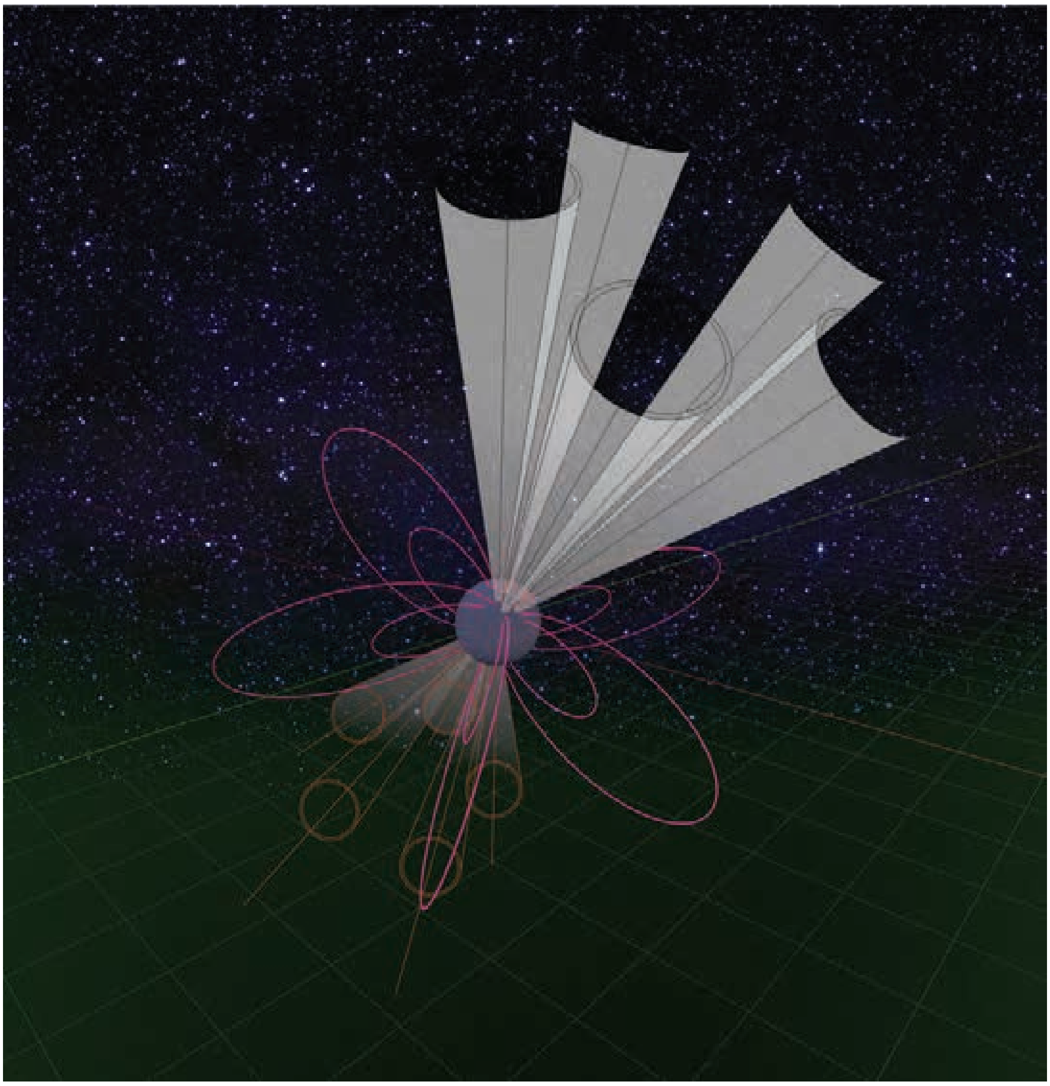


Figure 1, above: A toy model of a pulsar emission beam consisting of five beamlets arranged in a carousel around the pulsar's magnetic axis. Credit: McSweeney

SCIENCE

The holy grail of pulsar research is a comprehensive theory of the emission mechanism that can explain the wide variety of morphologies and behaviours exhibited across the approximately 2800 radio pulsars known to date.

Such variety is a double-edged sword, increasing the number of parameters required by any candidate theory, whilst simultaneously providing a rich reservoir of vital clues. Because pulsars are rapidly rotating neutron stars whose emission beams are highly collimated, geometric effects are an important consideration in all emission theories. Therefore, it has proven invaluable to develop methods for determining the geometry of a pulsar system by making as few assumptions about the underlying emission mechanism as possible. Individual pulsars can only begin to reveal their secrets once the beam shape and emission geometry are well-understood.

One pulsar that stands out and is worthy of in-depth studies is PSR B0031-07. The pulsar spins approximately once every second and is located over 3000 light-years away. Its emission exhibits many interesting phenomena, each of which is remarkable, but seeing many of them in a single object is rare. Two of these phenomena, called "subpulse drifting" and "mode switching", are thought to be inextricably linked to the emission beam shape, thereby offering a unique opportunity to study this pulsar's geometry. By studying this pulsar's emission in detail, McSweeney et al. (2019) were able to ascertain a solution for its emission beam shape, which can be used to constrain theories of pulsar radio emission mechanism.

B0031-07 exhibits the (putatively common "subpulse drifting" phenomenon, where individual subpulses – discrete bursts of emission, typically much narrower than the average pulse shape – appear to march steadily in time from one rotation to the next. Subpulse drifting has long been cited as evidence that the emission beam consists of a "carousel" of subbeams – also called "beamlets" – centred on, and slowly rotating around, the pulsar's magnetic axis (cf. the seminal paper by Ruderman & Sutherland, 1975). In this model, the "drifting" pattern emerges as the carousel presents a different configuration to the observer each time the emission beam swings past the observer's line of sight. The rotation speed of the carousel is purely a function of the ultra-strong magnetic and electric fields present near the pulsar's surface. Because the magnetic and electric fields are so strong (~10^12 G and 10^12 V), it would require a lot of energy to significantly change them – ergo, the carousel rotation is, to first order, expected to be constant.

At first glance, a constant carousel rotation rate implies a constant subpulse drift rate. However, this is apparently at odds with what we actually observe! Besides subpulse drifting, B0031-07 also exhibits "mode switching," in which the subpulse drift rate occasionally changes suddenly and dramatically, with each "mode" lasting for only about a minute or two! At first blush, this may seem like a death knell for the carousel model – but, not necessarily! It could be that the apparent changes in subpulse drift rate are an illusion caused by the fact that the carousel is sampled for only a small fraction of the rotation period – the so-called "aliasing" problem. If instead of the rotation speed changing, the carousel changes the number of beamlets, then the apparent drift rate will change as long as the carousel speed is fast enough that a different set of beamlets comes into view with each successive rotation. Requiring the carousel to rotate this quickly also helps to bring the rotation speed more in line with the back-of-the-envelope calculations that were originally performed by Ruderman & Sutherland (1975)!

Working out the precise combination of number of beamlets, carousel speed, degree of aliasing, and viewing geometry that yields the correct drift rate in multiple modes, is far from trivial; yet McSweeney et al. (2019) have been able to successfully arrive at a self-consistent solution in which the three modes observed in B0031-07 can be attributed to carousels consisting of 13, 14, and 15 beamlets, respectively. This elevates B0031-07 into a very small group of pulsars whose emission beam shape is known with some confidence – adding greatly to its potential for constraining theories of pulsar emission mechanism.

This analysis is also the culmination of a long-term study of B0031-07 carried out over the course of McSweeney's PhD, whose research made extensive use of the low frequency capabilities of the Murchison Widefield Array (MWA) in Western Australia (McSweeney et al. 2017a), as well as high-time resolution data obtained from coordinated observing campaign involving both the MWA and the Giant Metrewave Radio Telescope (GMRT) in India. Although the pulsar already revealed some of its secrets, this rich data set still has more stories to tell.

Catching frame-dragging in action

Ramesh Bhat

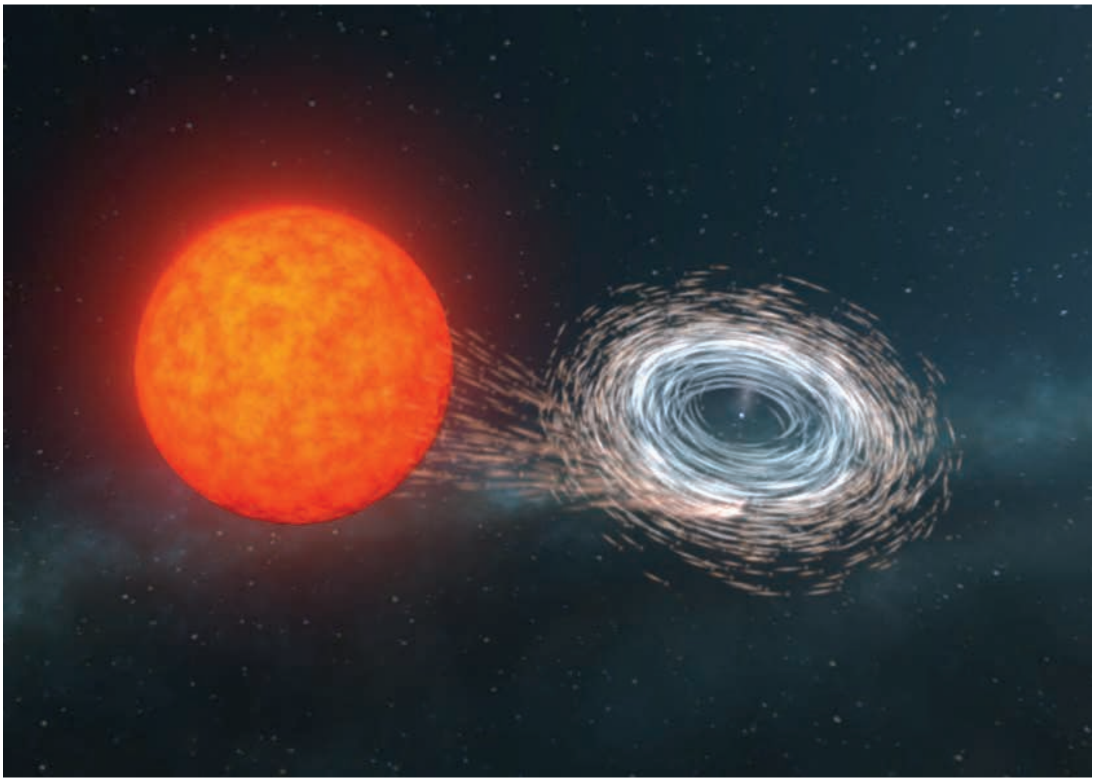


Figure 1, above: Artist's impression of a white dwarf being spun-up by the transfer of matter from its companion. Material at the surface of the swollen star falls towards the white dwarf and forms a disk of material travelling so quickly that it causes the star to spin rapidly. Credit: ARC Centre of Excellence for Gravitational Wave Discovery

SCIENCE

20 years of patient monitoring and perseverance in mapping the orbit of an exotic binary pulsar system has led to the confirmation of frame-dragging – a prediction of Einstein's General Theory of Relativity that manifests as a gradual change in the orientation of the plane of the pulsar orbit.

In the year 2000, a binary pulsar system was discovered using the Parkes radio telescope. The system consists of a stellar pair in which a neutron star (i.e. pulsar) is spinning at a rate of 150 times per minute and is orbiting around a white dwarf companion star as massive as our Sun. The pulsar, which goes by the name PSR J1141-6545, only takes about five hours to orbit its companion, and the extent of the entire system is small enough to fit well inside the diameter of the Sun. Unlike most other pulsars in similarly compact binaries, this pulsar turned out to be much younger, with an estimated age of ~1.4 million years old.

The pulsar's spin and age indicate that the pulsar has not (yet) been "recycled", a process by which a pulsar robs matter and angular momentum from its companion, converting the "ordinary" pulsar into a much faster spinning "millisecond pulsar". However, despite the seemingly ordinary type of the pulsar itself, the excitement started with the first tentative confirmation (Bailes et al. 2003) that the system is behaving as per Einstein's general theory of relativity – specifically, the rate at which the orbit was shrinking was found to be in agreement with general relativity. A few years later it was also shown (Hotan et al. 2005) that the emission signature of the pulsar (i.e. the pulse profile as we see using a telescope) was changing steadily with time, as a result of general relativistic precession effects, causing a gradual change in the orientation of the pulsar's radio emission beam relative to the observer's line of sight. More rigorous (and unambiguous) confirmation that the system is working as per the prescription of the general theory of relativity came some years later, when the shrinkage of the orbit was shown to agree with the prediction from General Relativity within a few percent (Bhat et al. 2008). At the time, this placed some of the most stringent constraints on competing alternative theories of gravity (e.g. scalar-tensor theories that invoke an additional scalar coupling with matter). The system was slated to enable more stringent tests of the theories of gravity in the years to come. (Continued...)

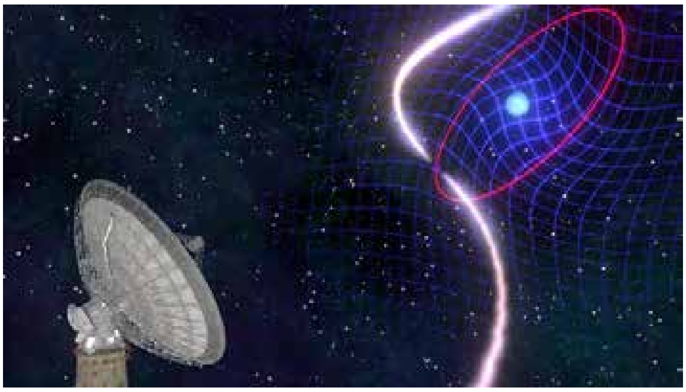


Figure 2a, above: An artist's depiction of frame-dragging: two spinning stars twisting space and time

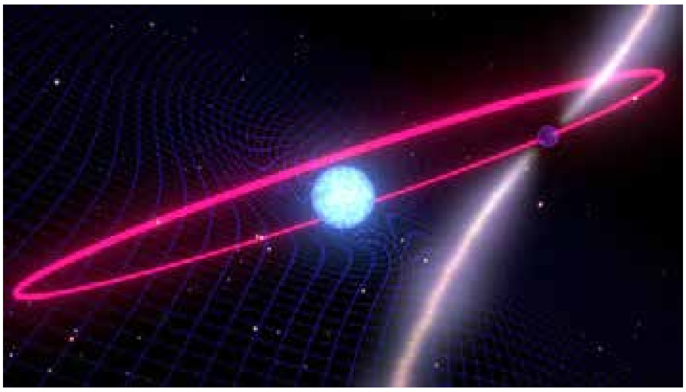


Figure 2b, above: The binary system of a white dwarf star (centre) and its companion pulsar (neutron star) make an excellent natural gravitational laboratory

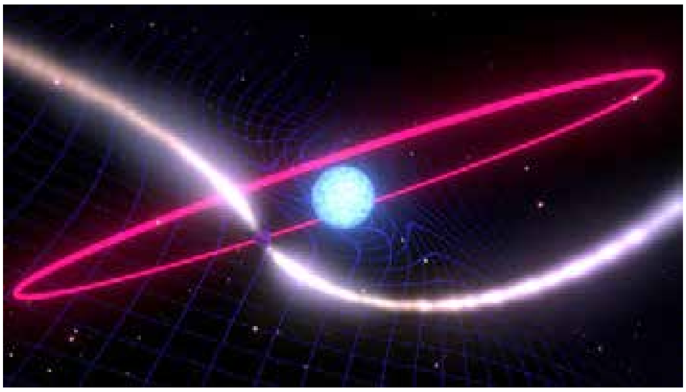


Figure 2c, above: The binary system PSR J1141-6545 was discovered by the CSIRO's Parkes radio telescope. The pulsar orbits its white dwarf companion every 4.8 hours

Figure 2d, above: The white dwarf's rapid rotation drags the space-time around it, causing the entire orbit to tumble in space. Credit: Mark Myers, ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav)

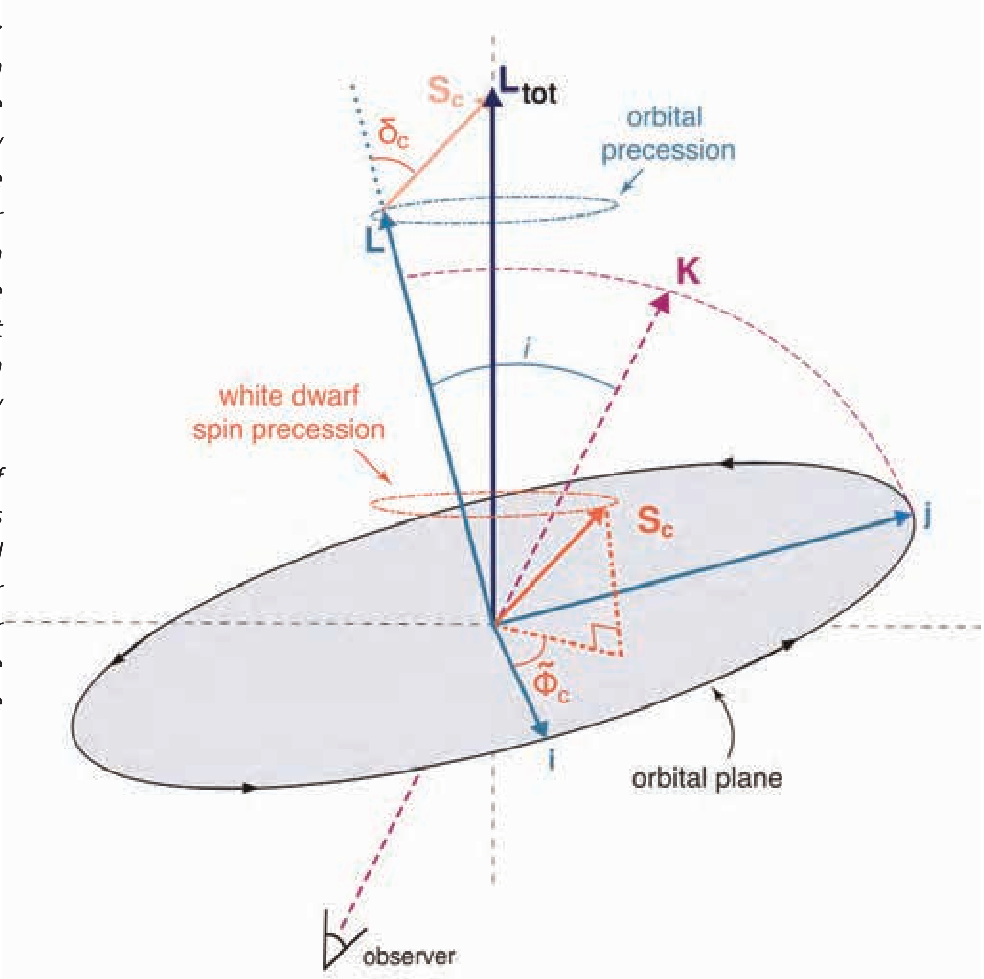


Figure 3, right: A diagram illustrating the orbital geometry of the white dwarf-pulsar binary system J1141-6545. The plane of the orbit is inclined from the sky plane by about 70 degrees. The spin axes of both the stars precess around the total angular momentum vector (shown by the black vertical line pointing upward).

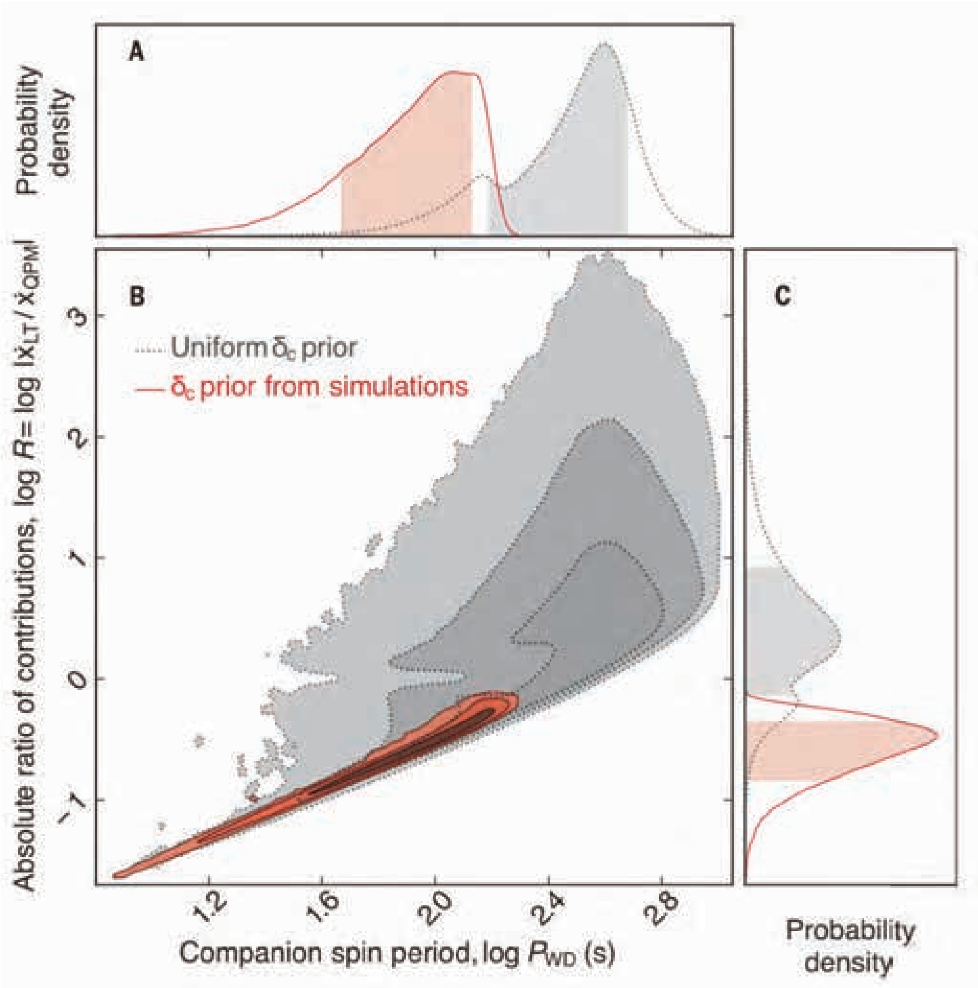


Figure 4, right: A graphical summary of the dominant contributions to orbital precession from the rotation of the white dwarf. The ratio of the contributions from the general relativistic Lense-Thirring precession and the Newtonian mass-quadrupole moment is plotted against the rotation period of the white dwarf. The detection of frame-dragging and modelling of stellar evolution constrain the rotation period to less than 200 seconds.

But, alas, much of the excitement was dampened in the following years as the pulsar underwent a massive "glitch" in 2007 – an abrupt spin-up followed by a long, gradual recovery – thought to be caused by complex physics at work in the interiors of these ultra-dense objects. The long recovery time (~years), along with the complexity seen in the form of a time-varying emission signature, essentially meant that the longer-term prospects of using this system for furthering gravitational theories were looking unlikely. This is because stringent tests of gravitational theories require both rotational stability and stability of the pulsar's profile in order to make careful and reliable measurements of pulse arrival times -- precisely the ingredients that are lacking when glitches occur..

However, PSR J1141-6545 had more surprises in store. In 2019, Australian astronomers became determined to unravel the intricacies of the system, and teamed up with some expert researchers from Germany. A Swinburne PhD student (Venkataraman Krishnan) was given the task of untangling the various competing relativistic effects. The result from this analysis was astonishing – unless an allowance was made for a gradual change in the orientation of the plane of the pulsar's orbit, general relativity made no sense! It was evident that we had discovered compelling confirmation of "frame-dragging" in this astronomical system, one of whose effects is to make the pulsar's orbit tilt over time.

The significance of this discovery lies in the fact that frame-dragging is one of the less-tested predictions of Einstein's theory of relativity. Frame-dragging describes how a spinning body drags the very fabric of space-time in its vicinity around with it. This was first realised in 1918 by two Austrian mathematicians, Josef Lense and Hans Thirring, only a couple of years after Albert Einstein formulated General Relativity. In everyday life, the effect is miniscule and almost undetectable, and its first verification had to wait until the early part of this century when NASA's $750 million Gravity Probe B satellite measured the very subtle effect caused by the rotation of the Earth through the detection of tiny angular displacements in gyroscopes on-board. However, when the object in question is a fast rotating white dwarf, the effect can be 100 million times stronger!

This experiment was only possible because the white dwarf happens to be spinning as fast as it is – once every few minutes -- much faster than most similar objects that we currently know of. This kind of system (i.e. consisting of a "normally spinning" neutron star and a "fast-rotating" white dwarf) is rare, by virtue of the truly exotic evolutionary path it must have taken to end up in such a configuration. How can such a system form? Normally, when pairs of stars are born, the more massive (primary) star ends its life first, oftentimes creating a white dwarf star. Before the second star (secondary) dies, it transfers matter to its white dwarf companion. A disk then forms as this material falls toward the white dwarf, and over the course of tens of thousands of years, this process spins up the white dwarf until it rotates once every few minutes. This fascinating theoretical conjecture has been convincingly demonstrated through in-depth modeling and simulations.

The combination of both the discovery of such a rare system and the subsequent meticulous study of its behaviour throughout the following twenty years finally paid off in the form of a stunning verification of Einstein's theory of General Relativity: the observation of frame-dragging in an astronomical system that is smaller than the size of our Sun but located several hundred quadrillion kilometers away. It has also confirmed the existence of fast-rotating white dwarfs in the Universe. This stands as yet another testimony to Einstein's theory of gravity, which continues to shine even after a century after its formulation!

CIRA and KM3NeT: the first year

Clancy James

Figure 1, left: A KM3NeT detection unit prior to deployment. Below: the unit on the sea floor, awaiting an acoustic signal to unravel. Credit: KM3NeT Collaboration

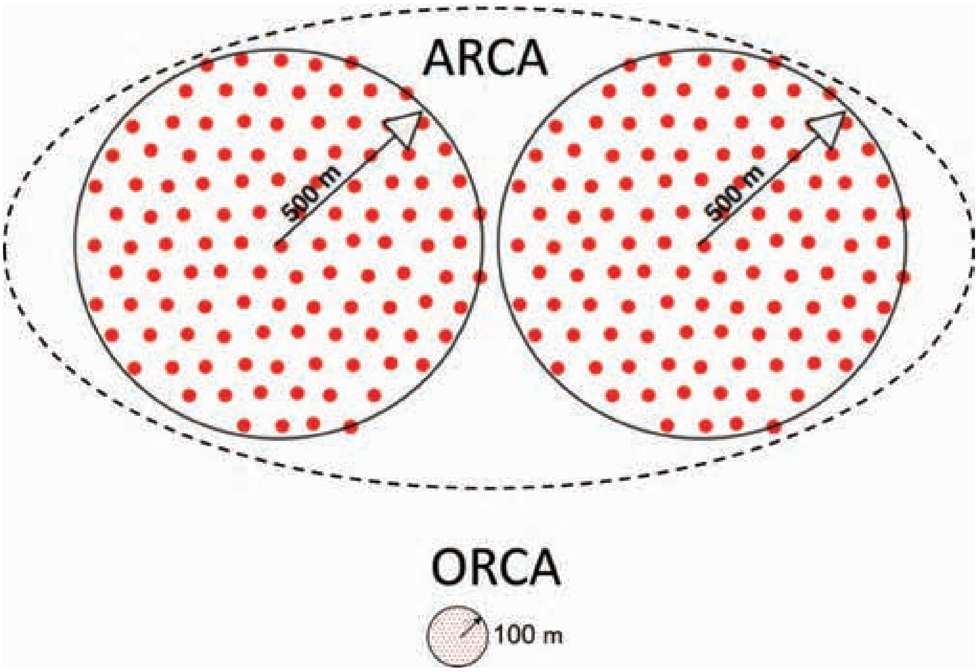


Figure 2, above: Diagram showing the eventual layouts of the ARCA and ORCA detectors, which together make up KM3NeT. In this diagram, each red dot represents on "detection unit", consisting of a line of 18 digital optical modules, each containing 31 photon detectors (PMTs: photomultiplier tubes). Combined, ARCA and ORCA will consist of approximately 345 units, i.e. 192,510 PMTs. Credit: KM3NeT Collaboration

KM3NeT is an underwater neutrino telescope currently under construction at two sites in the Mediterranean Sea. It detects neutrinos by looking for the light generated by high-energy particles produced when neutrinos interact in the water surrounding the detector. Most high-energy particles arriving from above the detector however are produced by cosmic rays hitting the atmosphere, and down-going neutrinos are difficult to identify. However, only neutrinos – which almost never interact with matter – can make it through the Earth to produce particles coming from beneath the detector. This means that neutrino telescopes primarily look downwards, through the Earth. KM3NeT's location on the other side of the world therefore means that it studies the same sky as Australian telescopes.

When KM3NeT is complete, it will consist of two detectors, ARCA and ORCA, shown in Figure 2. ARCA ('Astroparticle Research with Cosmics in the Abyss') is designed to detect high-energy (Tev-PeV) neutrinos produced in energetic astrophysical processes. ORCA ('Oscillation Research with Cosmics in the Abyss') aims to study the properties of neutrinos themselves, using GeV neutrinos produced when cosmic rays interact in the Earth's atmosphere. These detectors are deployed on the bottom of the sea floor, which is dark enough that the rare photons produced in neutrino interactions can be identified.

Curtin University joined the KM3NeT collaboration in late 2018, although signing of the Memorandum of Understanding by all 57 institutes over 18 countries was only completed in February 2020. KM3NeT has specifically been designed to have a high angular resolution, and to study sites of high-energy particle acceleration such as supernova remnants and the Galactic centre, as well as extragalactic objects such as blazars. Australia's unique location therefore makes it an ideal place to perform astronomical follow-up observations of neutrinos detected by KM3NeT.

This last year has seen several major milestones for KM3NeT. Firstly, KM3NeT's Phase 2.0 funding milestone was passed, meaning it is on track to be fully funded (at 125 M€). Secondly, construction of Phase 1.0 ORCA was completed on 27th January 2020, with the deployment of six detection units (5% of the final detector).

KM3NeT/ORCA has already identified its first neutrinos, and measured how the rate of downgoing cosmic-ray muons decreases with depth. One of the neutrinos identified by KM3NeT/ORCA is illustrated in Figure 3.

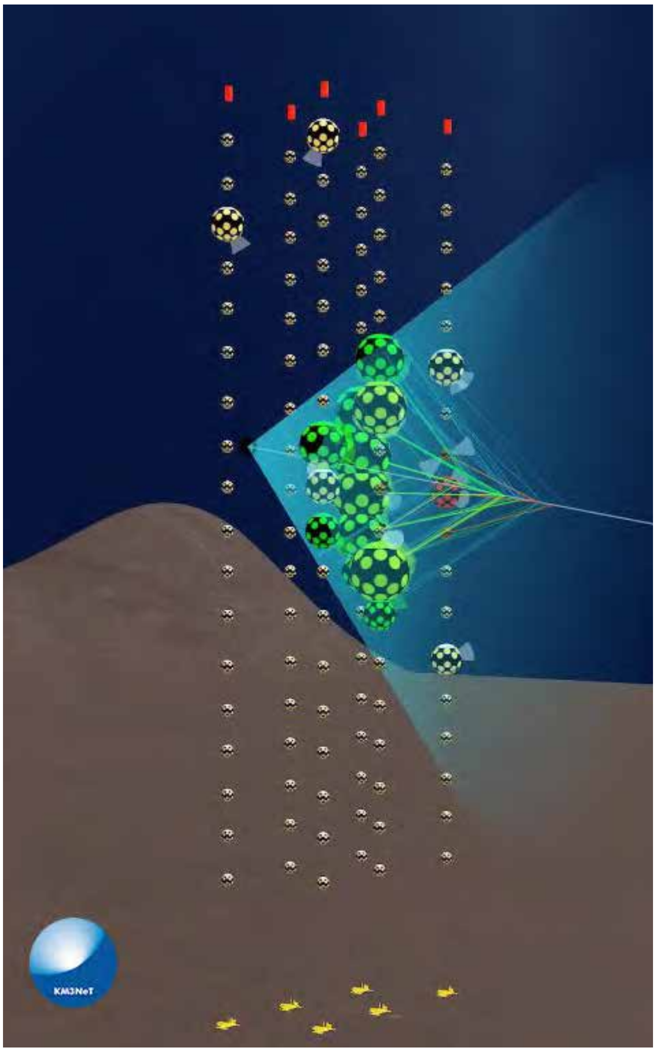
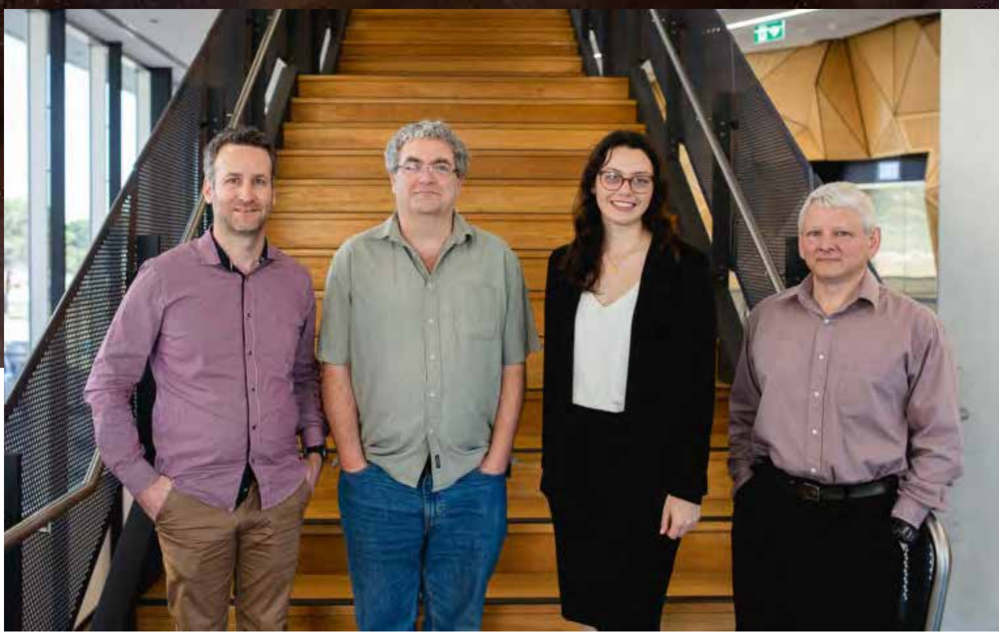


Figure 3, right: A display of a neutrino event detected by KM3NeT/ORCA. The enlarged optical modules are those where photons have been detected. The blue shading, and the lines, are the reconstructed shock front of Cherenkov photons. The incoming line shows the reconstructed direction of a muon produced by an upgoing neutrino interacting in the vicinity of the detector. Credit: KM3NeT Collaboration

HIGHLIGHTS

Below: The majority of the MWA Operations team had the privilege of speaking on at the Australia-India Research & Development in Radio Astronomy (ARDRA) meeting in Lonavala, India. Credit: ARDRA



Above: Part of the MWA Operations team, who were nominated for the 2019 VC Excellence Award in Collaboration. From left to right: Greg Sleap, Andrew Williams, Mia Walker and David Emrich. Credit: Curtin

MWA & OPERATIONS

Above: Attendees of the SKA Shanghai meeting, 'Concluding our Past, Realising our Future'; a prelude to the SKA System Critical Design Review. Presentations by CIRA staff included a keynote science talk, operations 'lessons learned', and a MWA commissioning talk. Credit: SKA

Building a bridge between prototypes and the full SKA Low Frequency Array

Randall Wayth, on behalf of an international
team based at CIRA and INAF

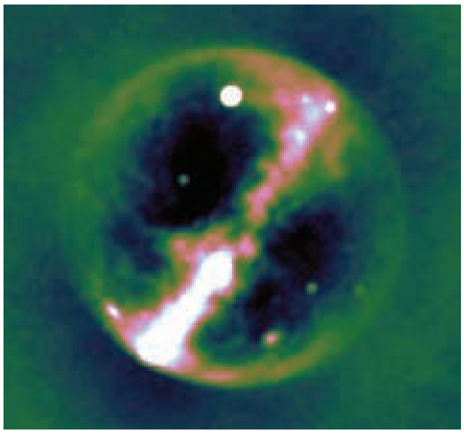


Figure 1, above: The first all-sky image captured with the EDA2 from 24 July 2019. The image is from approximately 1 second of data captured at 160 MHz using ~1 MHz of bandwidth. The Galactic plane including familiar objects such as the Crab pulsar supernova remnant and the Gum Nebula, Rosette nebula are visible as well as the Large Magellanic Clouds. The bright round spot top of centre is the Sun. Credit: Wayth, Sokolowski, 2019

Major progress on the road to the future Square Kilometre Array Low Frequency Array (SKA-LOW) was made in 2019 with the deployment of two new prototype arrays at the Murchison Radio-Astronomy Observatory (MRO), as part of the SKA Bridging Phase project. The Engineering Development Array 2 (EDA2) is one of those systems and is a second generation SKA-Low prototype. The EDA2 builds on the technology and expertise from previous prototypes (the AAVS1 and EDA1) and incorporates changes to improve the deployability and complexity of the signal transport systems.

Like its predecessor (the EDA1, see CIRA annual report 2015) EDA2 is comprised of 256 MWA dipole antennas that are pseudo-randomly spread over a 35 metre diameter area. Each 256-antenna array is a "station" in SKA terminology. Each dual-polarisation antenna receives radio signals between 50 and 350 MHz and amplifies the signal before transmitting it on a short length of coaxial cable to an in-field aggregation point (the SMART boxes, described below). Inside the SMART boxes, the signal is converted to optical and is transmitted via optical fibre back to the MRO control building approximately 5 km away. As in previous prototype systems, the optical signals are converted back to electrical signals, amplified, filtered and digitised in the custom-built Tile Processing Modules (TPMs), housed in the MRO control building.

The EDA2 system is thus a fully flexible system where signals from each individual dipole antenna are digitised before being combined to form an array. This design principle - combining the signals from many smaller antennas to work as a single large antenna - is called an "aperture array". The aperture array concept has been around for decades, however it is usually confined to systems with relatively narrow bandwidth. What is unusual about the SKA concept is both the large bandwidth (approximately 300 MHz is used) and the sheer number of antennas: the full SKA1-Low will contain over 131,000 individual antennas.

The Aperture Array Verification System 2 (AAVS2) is the second prototype system deployed in 2019. The overall architecture of AAVS2 is identical to the EDA2, the key difference being the use of the SKA baseline design "SKALA4.1-AL" antennas, which were developed by INAF with industry partners. A key driver for deployment of two prototypes with different antennas was to address the cost/performance/complexity trade-off that exists around the choice of antenna for SKA-Low, and to address unresolved issues about the calibration performance of AAVS1. Data were taken using astronomical sources as well as from specially equipped drones to address questions of how well the detailed performance of each antenna type was understood.

The combined efforts of the CIRA-based team and our international collaborators - primarily based at INAF and the SKA Office - generated detailed models and

Figure 2, above: Aerial view of the completed EDA2 station. Credit: ICRAR, 2019

comparison data for the models to assess how well the station antenna performance was understood. The output of the data analysis effort culminated in the SKA Low Station Calibration Report, which addressed all of the concerns previously raised about the calibratability of the SKA-LOW stations. This report contributed a large part to the resulting successful System Critical Design Review for SKA-LOW, which closed out the formal design phase of the System Engineering process for SKA-LOW. With this final milestone passed, SKA-Low is able to move into the construction phase.

The EDA2 and AAVS2 prototype systems will continue operation into 2020 to perform more detailed system verification tasks and operate for dedicated niche science programs, where these arrays are especially suitable for wide bandwidth and/or all-sky problems.

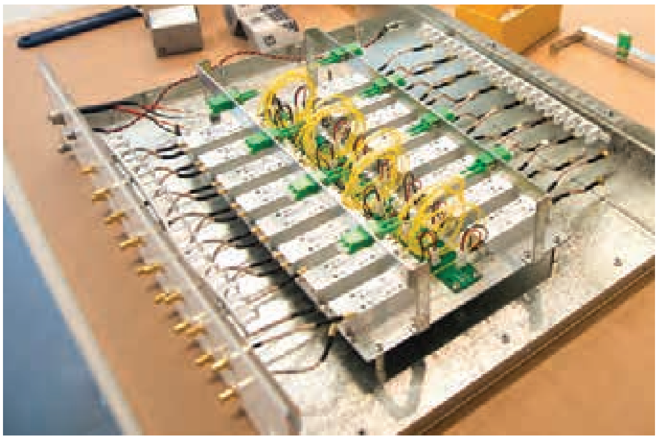


Figure 3, above: Inside a SMART box. 16 boxes are deployed on each of the EDA2 and AAVS2 stations. Credit: ICRAR, 2019

A SMARTer approach to signal and power distribution

A key improvement in the design of the EDA2 and AAVS2 was the introduction of "Small Modular Aggregation & RFoF Trunk" (SMART) boxes to provide in-field signal aggregation and power distribution for antennas. The design was motivated in part by the unwieldy collection of large custom-built cables used for AAVS1, which proved to be highly impractical. Also providing motivation was the use of MWA beamformers in the EDA1, which provided the proof-of-principle that in-field boxes could be situated inside a station to reduce cabling complexity without affecting the performance of the array. Designed by a CIRA/INAF collaboration, the SMART boxes accept standard coaxial cables over short runs (7 to 10 metres) from each antenna and provide power to the antennas over the same coaxial cable. Inside the box, the "Front End Modules" (FEMs) are the key components converting electrical signals to optical. Optical fibres are fed through a metal tube to prevent electromagnetic radiation leakage from the enclosure, then routed to nearby Field Node Distribution Hubs (FNDHs), which have large-scale power and signal transport connections. Power is supplied to the SMART box via filters and a power supply unit in the SMART box provides power for the FEMs and antennas. The combination of SMART boxes and FNDHs provide a practical, scalable power and signal transport solution for a large-scale SKA-Low system.

Site Operations in Review

Andrew McPhail

Figure 1, above: Discussing the game plan for the day with the CIRA operations team, Geraldton contractors, and INAF engineers. Credit: ICRAR, 2019

Figure 2, above: EDA2 Dipole antennas being installed on the mesh ground plane. In the middle of the photo is shown the equipment used to accurately survey each dipole location. Credit: Curtin, 2019

Figure 3, above: A MWA receiver (white box) secured to the new lifting frame on an all-terrain telehandler, to be installed at a new location. Credit: Curtin, 2019

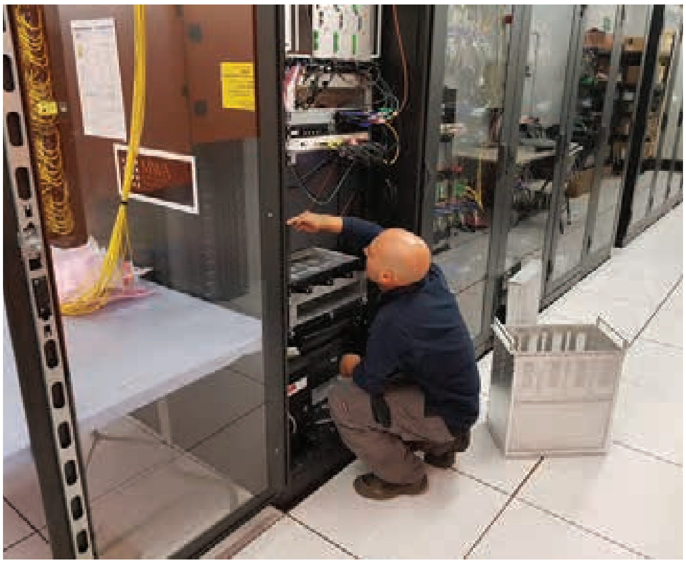


Figure 4, above: Andrea Mattana from INAF installing equipment in the MRO Control building. Credit: Curtin, 2019

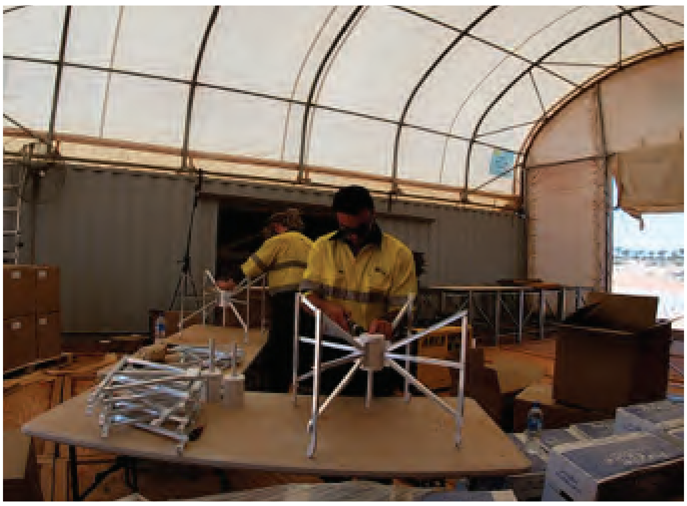


Figure 5, above: Geraldton contractors building MWA dipole antennas for EDA2. Credit: Curtin, 2019

Working in the Murchison always provides its own set of challenges and rewards, and this year was no exception. Parallel to the growth of the SKA footprint on the Observatory, the MWA telescope continued to go from strength to strength with the support of the operations team.

The MWA needs to be manually reconfigured between its extended and compact configurations, usually twice a year, and in 2019 this occurred in January and August. A reconfiguration of the array was normally a 2-3 week activity. It involves moving 8 receivers (the size of a large fridge) to new locations, disconnecting and hibernating 128 antenna tiles whilst reconnecting and establishing communications with 128 different antenna tiles. The task is not easy and requires constant attention and care to some items of equipment for which there is no replacement.

In late 2018, the operations staff began to explore different options to reduce costs, risks and effort associated with reconfiguring the MWA, whilst increasing observation time available on the telescope. We identified that time savings could be achieved by changing the manner in which receivers are moved and the sequence of events. A Geraldton-based metal fabrication company was used to create a specific receiver lifting frame to securely and safely lift, transport and place the receivers between locations. These improvements reduced the turnaround time between array configurations to one week. A second week on site allows the team to conduct maintenance concurrent to observations.

The focus then turned to increasing the efficiency of labour time on site. The aim was to reduce the amount of people required for a site activity to a total of six in the first week and four in the second. Although financial resources are a significant factor in planning of all site trips, the most important consideration is safety for all involved.

The 8 person CIRA Ops team is very small and are required to support a range of tasks from onsite maintenance, remote monitor and control right through to data management and dissemination for all telescopes on site. Due to the lack of numbers, formal redundancy - backup persons – is not possible. Therefore, all team members have developed significant knowledge and skills about the job specific tasks of other members of the team to such a degree that in moments such as this, important...

Figure 6, above: Aerial view of the dome shelter on site, where the antennas for SKA Low stations were constructed. Credit: ICRAR, 2019

Figure 7, left: GCo Electrical contractors connecting cables between EDA2 antennas and SMART boxes. Credit: ICRAR, 2019

Figure 8, right: Balance contractor testing the electrical connections on a SMART box. Credit: ICRAR, 2019

...operations goals can continue to be achieved. In this case, one CIRA staff supported on the ground by our local Geraldton based contractors and remotely supported by the balance of the Ops team at CIRA were still able to achieve the reconfiguration and parallel SKA tasks within the two week window.

The Ops team are also exploring different technical and software options to remotely reconfigure the MWA from CIRA. This will require investment in new equipment but the extra capability will be significant. The aim is to have all 256 tiles connected to the receivers at any one time. This will permit some form of mode switching between groups of 128 tiles to permit on-demand reconfiguration between compact and extended observations which in turn may present increased opportunity to respond to time sensitive, event triggered observations.

CIRA Ops personnel also supported the efforts of A/ Prof Randall Wayth and Gurashish Singh to achieve the commissioning of the Central Redundant Array Mega-tile (CRAM). CRAM consists of 64 dipoles in an 8 x8 configuration and is located in the centre of one of the hexagon arrays that form part of MWA. A single antenna was installed on a tall pole to detect and characterise radio interfence, for Bach Nguyen's PhD student project.

installation and commissioning of two SKA arrays – EDA2 and AAVS2 required significant effort by the CIRA Operations team, which is covered in other articles in this report.

The entire process was a learning experience for all involved. Processes and procedures used to install one component were improved and refined when the same component was installed on the next array. In some cases, the refinement and improvement was a case of taking two steps back, choosing a new direction and developing a complete new procedure.

With the expansion in the number of arrays on site and the planned installation of further power hungry equipment, the capacity of onsite power supply was improved in July-August 2019 with the installation of a new 100kVA High Voltage Transformer (HVTX).

There were countless hours of maintenance and fault finding that occurred through the year, and some incredible logistical challenges, but it's worth it to work in one of the most harshly beautifulplaces in Australia.

FAQ

Q: How can I get on site?

A: CSIRO offered two public open days on site in 2018, and given its success, were looking to host a similar event again in 2020- so keep an eye out on their CSIROnews Facebook page. Alternatively, you could get a job in the operations team – but you may have to wait till one of us dies first.

Q: Are the flies really that bad?

A: Yes. But between the months of May-July they are obscured by swarms of biting midgies that can crawl up sleeves and through fly nets.

Q: How hot does it get?

A: This year I recorded a temp of 49.9°C whilst walking out to a solar panel tile. On that day alone I drank six litres of water before 10am and I made the mistake of picking up a spanner left lying in the sun with an un-gloved hand. I would like to say I have not made that mistake twice but I am not that smart.

Q: Is it very quiet?

A: No. The flies are too noisy, and Dave tells too many puns.

Figure 9, above: The 'dipole on a pole' deployed at site to detect radio interference from Geraldton. Credit: Curtin, 2019

Dealing with Obsolescence in MWA hardware

David Emrich

MWA & OPERATIONS

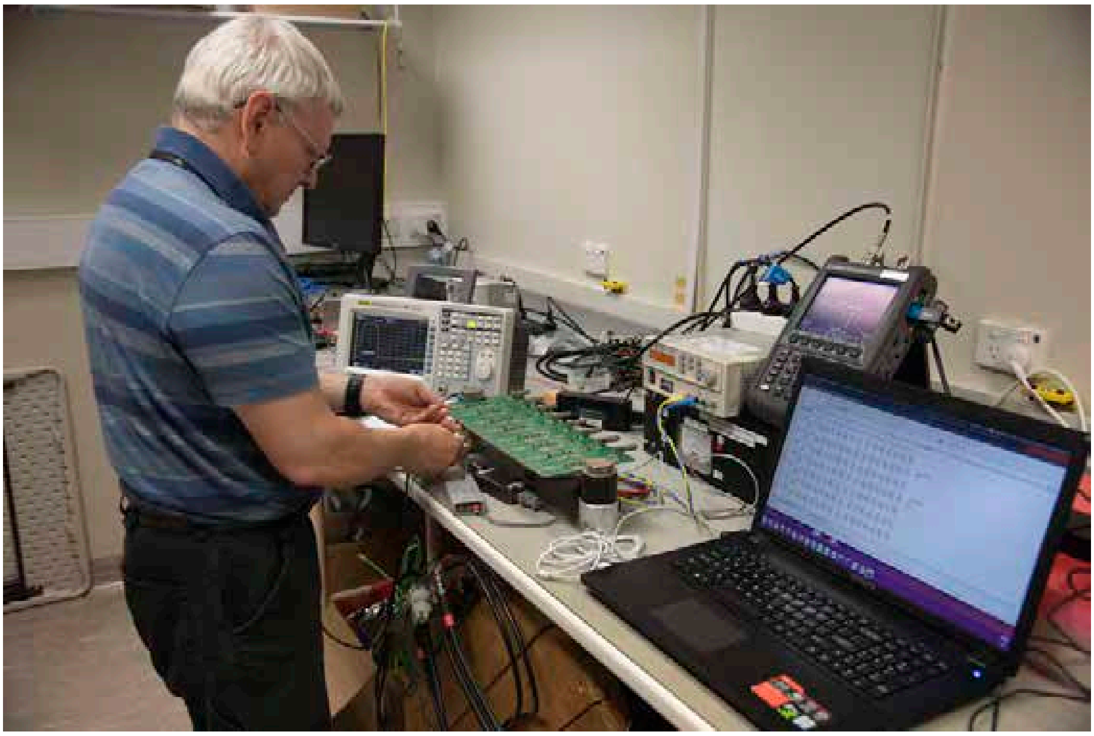


Figure 1, above: MWA Hardware Manager David Emrich testing ASC modules in the CIRA lab after obsolete chip replacement. Credit: Curtin

Figure 2, left: Mia Walker removing an ASC module from inside a reciever on site. Credit: Curtin

The MWA telescope is built from a mix of off-the-shelf and custom hardware, with most of the custom electronics being in the front-end of the system, on site. As time passes it can become difficult to obtain spare parts to repair custom components, which is necessary when sub-systems fail either with age, or through events such as lightning strikes.

In particular, nearly every amplifier chip from the antennas to the digitizer inputs is now obsolete, and much work has been done over the past two years to source and test replacement parts that are still in production.

In the case of the Low-Noise Amplifier (LNA) boards that are installed in the collecting antennas, we identified a replacement chip that is very nearly identical in performance to the original chip. A small number of LNA boards has been fitted with this new chip and laboratory test results have indicated a simple chip replacement is satisfactory without further rework.

However, for the case of the amplifier chips in the beam-formers (BF) and Analog Signal Conditioning modules (ASC), no direct drop-in replacement chips were offered by the manufacturer and there were little to no global stocks of the end-of-life parts. The suggested replacement chips operated substantially the same at mobile and Wi-Fi frequencies, but performance below 350MHz (in the MWA band) was inadequate and required supporting components to be altered to compensate.

This meant a somewhat extended process of collaboration with manufacturers Field Application Engineers and laboratory modifications and testing to find near-match suitable replacements, and design and test circuit modifications to make them operate stably in our system, without materially affecting the operation of the telescope.

The two design goals that drove this upgrade/ modification process were: avoiding a re-draft of the circuit board layouts by selecting chips that had the same physical footprint as those being replaced, and making sure that each sub-system (LNA, BF, ASC) operated as near as identical with the new parts.

By re-using existing circuit boards we saved a huge financial burden which would have been associated with the purchase of 512 new BF delay-line boards and 32 new ASC boards. And by ensuring that each sub-system operates effectively identically to the original design, there is no issue with ‘mixing and matching’ original sub-systems with modified/upgraded systems in the field. This in turn has allowed us to conduct a phased upgrade program, which keeps the telescope operational as much as possible.

While there were physically identical replacement chips for all the amplifiers in the beam-former, their electrical power and RF performance were different enough to require the replacement of several biasing resistors and the development of a small daughter-board to modify the gain of the final amplifier stage to bring the total beam-former performance / gain up to the original level. This is a large operation due to the high parts count (~90 parts) per board and the large number (~600) of boards. Therefore the tasks of removing the obsolete parts and associated resistors and populating the new parts and daughterboards is being outsourced to local electronics company Convergence Engineering support. Testing and re-integration of the upgraded boards is being done at CIRA.

For the ASC modules, the selection of components required to stabilise the new chips in the circuit boards was more complicated. This was due to the high-gain (~60dB) and small circuit-board area, as well as matching impedance requirements for the new chips. Due to the much smaller number of chips and boards the entire ASC upgrade program is being conducted at CIRA.

While every effort was made to select new chips with relatively long lifetimes, MWA remains at the mercy of a semiconductor market that is driven by changes in the mobile communications industry which may lead to future obsolescence and / or incompatibility issues that require re-investigation of this work.

As at the end of calendar year 2019, approximately half the operational fleet of 32 ASC modules have been replaced with upgraded units, and the first few hand-modified beam-formers have been tested in the field.

We expect to finalise the ASC replacement during 2020, as well as deliver many more upgraded beam-formers to the field, however given the large number of beamformers this process will likely extend into 2021.

Taking MWA Services to the Cloud

Greg Sleap

MWA & OPERATIONS

Figure 1, above: An example of the racks of equipment at Amazon Web Services (AWS). Credit: Amazon

The MWA, as a cutting edge low frequency radio telescope led by Curtin University, is producing enormous amounts of data and distributing it around the world. As a result, the MWA Operations team are always looking to utilise the latest technologies and techniques to meet the needs of the scientific community.

At the start of 2019, the MWA Operations team maintained several physical servers that provide mission critical services that support the operation of the telescope. These servers, as well as key components of the MWA's publicly accessible data portal (the MWA ASVO) were running on several older physical servers, located at the Pawsey Supercomputing Centre (Pawsey). The MWA Operations team also provides the MWA collaboration with member-only tools, such as membership management, mailing lists and a wiki, as well as a federated identity management system which were all also running on ageing physical servers at the Curtin Institute of Radio Astronomy (CIRA).

Traditionally, telescopes, like the MWA, provision these types of services on physical servers at or near the instrument. For the MWA, these services were located in both Pawsey and CIRA, and both locations had limited opportunities for expansion as MWA's needs grew. In the modern age of distributed teams, high-data volumes and ever increasing compute requirements, this approach limits the speed at which science can occur.

In early 2019, the MWA Operations team was already beginning to work more closely with Curtin University's information technology department, now known as Digital & Technology Solutions (DTS). DTS had been gradually developing expertise in cloud computing technologies, particularly with Amazon Web Services (AWS). AWS offers a multitude of different solutions including provisioning of virtual machines (via it's Elastic Cloud Compute service - aka EC2). After some design and planning meetings with the DTS Cloud team, the team embarked on a joint project to not only migrate MWA servers at Pawsey and CIRA to virtual machine EC2 instances in AWS, but to set up a robust, expandable platform to enable future innovation and expansion.

There are many benefits associated with expanding into the cloud: firstly MWA could expand its server delivery capabilities to deliver cutting edge science without limit. Working in the cloud, new servers and services can be provisioned in minutes, allowing us to be agile in responding to new opportunities. Secondly, it would improve reliability by replacing our ageing physical machines with virtual machines. Virtual machines run on AWS hardware spread across their three Australian data centres. If AWS has a hardware failure or needs to replace their hardware, our EC2 instances will be migrated to other AWS hardware automatically and without interruption to our services. Thirdly, AWS operates their services in a high density hypervisor system, running many EC2 instances per physical server. This results in significantly lower power consumption and carbon emissions compared to MWA running our own physical servers. Importantly, the total cost of ownership would also be significantly less than maintaining our physical servers and their associated support, power and housing costs.

Working with the DTS Cloud, Systems, and Information Security teams, the MWA Operations team migrated over all of these services to AWS throughout 2019. In addition, we took advantage of the ease in which AWS instances can be created and also set up a second group of instances for development and testing purposes, something we previously were only able to do in a limited way when working with physical servers. Another key benefit of this project was that DTS would now assume responsibility for backups, operating system software patching and cybersecurity for these EC2 instances- further reducing the support burden for the relatively small MWA Operations team, and allowing us to focus on future innovations and opportunities.

Transitioning to cloud computing for non-data intensive aspects of MWA operations has benefited the MWA enormously- reducing overheads, risks and costs, but most importantly allowing us to innovate and expand our capabilities without limit. In the future, the MWA Operations team intends on investigating offloading other physical server processes running at Pawsey into the cloud, which are more compute and data-intensive, taking ful advantage of scalable, low cost computing resources the cloud provides. With MWA utilising cloud computing and the opportunities it brings, the sky's the limit!

HIGHLIGHTS

Below: The AAVS2 station, completed in 2019, with 256 'Christmas-tree' antennas. Credit: ICRAR

Above: SKA engineer Maria Grazia (left) and CIRA's David Minchin (right) examining results at the site of AAVS2. Credit: ICRAR

ENGINEERING

Left: CIRA Engineer and Associate Lecturer Maria Kovaleva in front of an MWA antenna tile at the MRO. Credit: ICRAR

SKA's expanding footprint on site

David Minchin

Figure 1, above: The AAVS2 station, with SKALA4.1 antennas. Credit: ICRAR, 2019

ENGINEERING

Figure 2, above: Avoiding the flies as we put the cover on a temporary cable housing box. Credit: ICRAR, 2019

Figure 3, above: Phase 0 consisted of only 3 antennas; an MWA dipole, an INAF SKALA4.0 and SKALA4.1 . Credit: Curtin, 2019

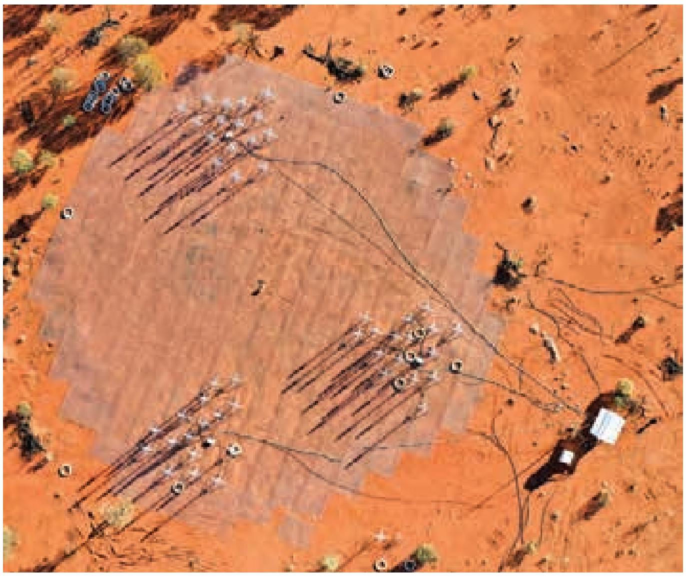


Figure 4, above: Phase 1 from above, showing 48 antennas deployed and connected to SMART boxes, and the FNDH to the right. Credit: ICRAR, 2019

Figure 5, above: Phase 2 from above, showing the complete AAVS2 array with 256 antennas deployed and connected to SMART boxes, and the FNDH to the right. Credit: ICRAR, 2019

2019 was a big year for Square Kilometre Array (SKA) related activities on the Murchison Radio Observatory (MRO). At the beginning of the year, on site there was a single field node, AAVS1, and the beginnings of Bridging Array Phase-0, which consisted of only three antennas. Other than that, there wasn't much besides a few survey pegs in the ground marking out the location of two future field nodes, AAVS2 and EDA2. Twelve months later this had evolved into two complete Phase-2 field nodes with 512 antennas fully commissioned and operational.

To help achieve this, February saw CIRA appoint two new staff members in support of the SKA related work, Projects Manager Mr Raunaq Bhushan and, Mr David Minchin, Senior Technical Officer in the Operations Team. That's me.

By mid-March all necessary surveying was completed to mark out Phase-1, the two new field nodes which would eventually evolve into Phase-2. This included the exact locations of 512 antennas, 32 SMART Boxes, and two Field Node Distribution Hubs (FNDH's). Also, the 40 metre diameter Earth mesh ground planes were laid in place for each.

Over the next three months the field nodes were partially built, culminating with 48 operational antennas on each. During this time several groups of engineers joined us from the Istituto Nazionale di Astrofisica (INAF) in Italy, to help with the construction and installation work. The teams built 18 SMART Boxes in Perth. Then, on site there was the positioning of two FNDH's with their Power Supply Units (PSU's), followed by construction of the antennas and, fibre optic cables were installed into the SMART Boxes. All this, along with 192 coax cables, optic fibre and, the DC power cables were all deployed onto the two ground planes. Other work required in the Correlator building included an interim server upgrade, Tile Processing Module (TPM) reallocation and, fibre optic cable patching. Phase-1 was complete.

The UAV Campaign was conducted in the beginning of June. A team of four engineers from three institutions in Italy (Institute of Electronics, Computer and Telecommunication Engineering (IEIIT), University of Malta (UM), and INAF) joined the CIRA Operations team for a week on site, and flew some 31 UAV sorties over AAVS1 and the two new field nodes. (Continued...)

Figure 6, left: David Emrich helping to put the FNDH together. Credit: Curtin, 2019

Figure 7, left: Commissioning the amplifiers on top of the SKALA4.1 antennas. Credit: ICRAR, 2019

Figure 8, left: Fabio Paonessa from IEIIT, tuning a UAV before flight. Credit: Curtin, 2019

Figure 9, left: Mitchell & Brown testing a fibre splice. Credit: Curtin, 2019

The UAV's were fitted with differential GPS, telemetry and, an RF synthesizer and matched antenna system. Enough data was gathered to start characterising the phased array antenna systems and to publish at least one paper. On our way home from this trip one of the vehicles broke down in the middle of nowhere. Luckily it was in the cooler months because it was an excellent lesson on how isolated we are out there and how entirely dependent we are on having reliable equipment, good communications and, good emergency procedures in place.

In July, the Field Processing Facility (FPF) was delivered to site. This is a pilot project designed to test the merits of mini correlators distributed across the further reaches of the SKA. The FPF is essentially a shielded, fully equipped and air-conditioned sea container protected by a modular roof structure. It is designed to be located close to the remote arrays and able to support the data processing function prior to data transfer to a data centre. This housed the Central Field Node Distribution Hub (CFNDH), allowing us to patch the field nodes to either the Correlator or to the FPF for digitisation and processing of the "sky signals". Local Geraldton company Mitchell & Brown cut and re-spliced one of the 576 core fibre optic cables to the Correlator building as part of this project.

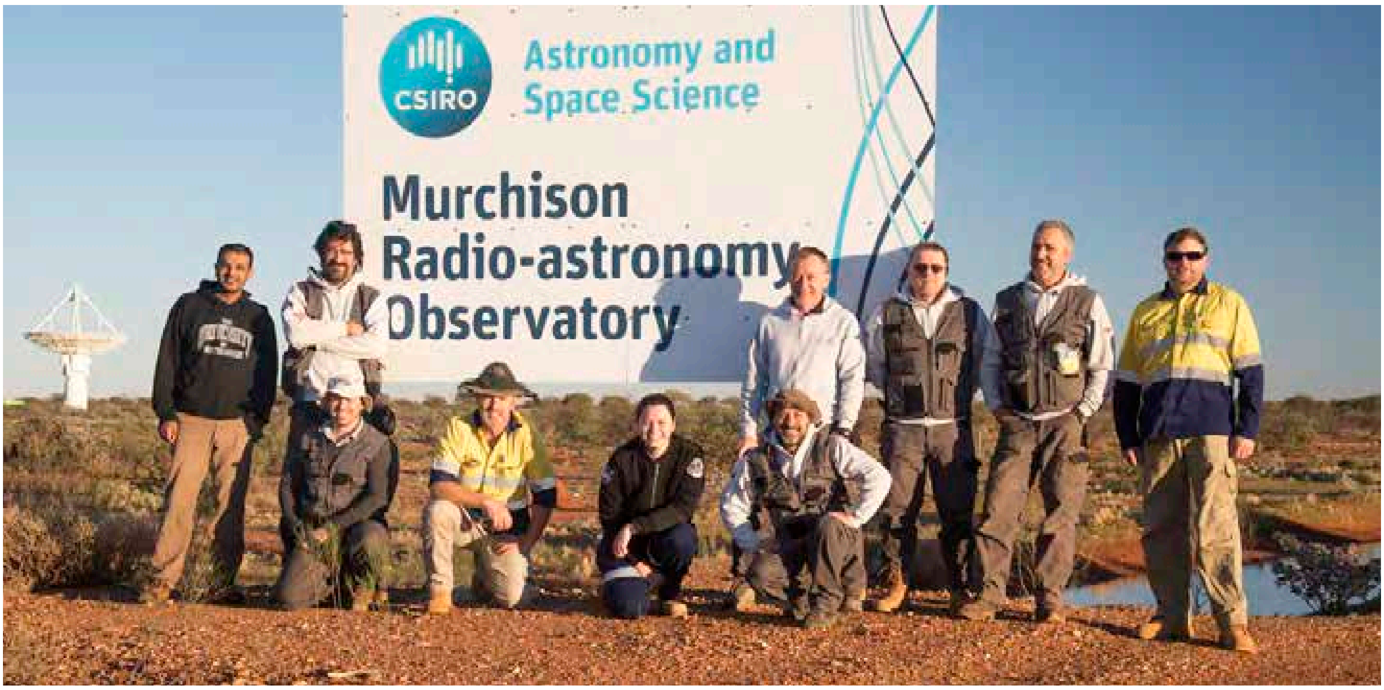
Phase-2. More visiting engineers from INAF, another batch of 18 SMART Boxes and 414 more antennas were built and deployed on the field nodes, along with 828 coax cables and, 50 power and optic fibre cables. Fibre Optic Break Out Tray's (FOBOT's) were installed in the FNDH's. The equipment racks in the Correlator needed more upgrades and reconfiguring.

AAVS1 was decommissioned, freeing up the TPM's for Phase-2. A new 40GB switch, a three kilowatt power supply and two new servers were installed, and all the fibres from the field were rerouted to the reassigned TPM's. Local company Gco provided all the electrical work and a lot of labour to help get this stage finished. EDA2 came on line in August, and AAVS2 was completed in November, with final commissioning in February 2020.

The entire process was a learning experience for all involved. Processes and procedures used to install one component were improved and refined when the same component was installed on the next array. In some cases, the refinement and improvement was a case of taking two steps back, choosing a new direction and developing a complete new procedure.

It was a busy twelve months, and there were a number of other SKA related projects that came and went throughout the year, just to make sure we didn't rest. There is no doubt that it was a massive multinational team effort, and I would like to thank everyone who helped to make my first year with CIRA so memorable.

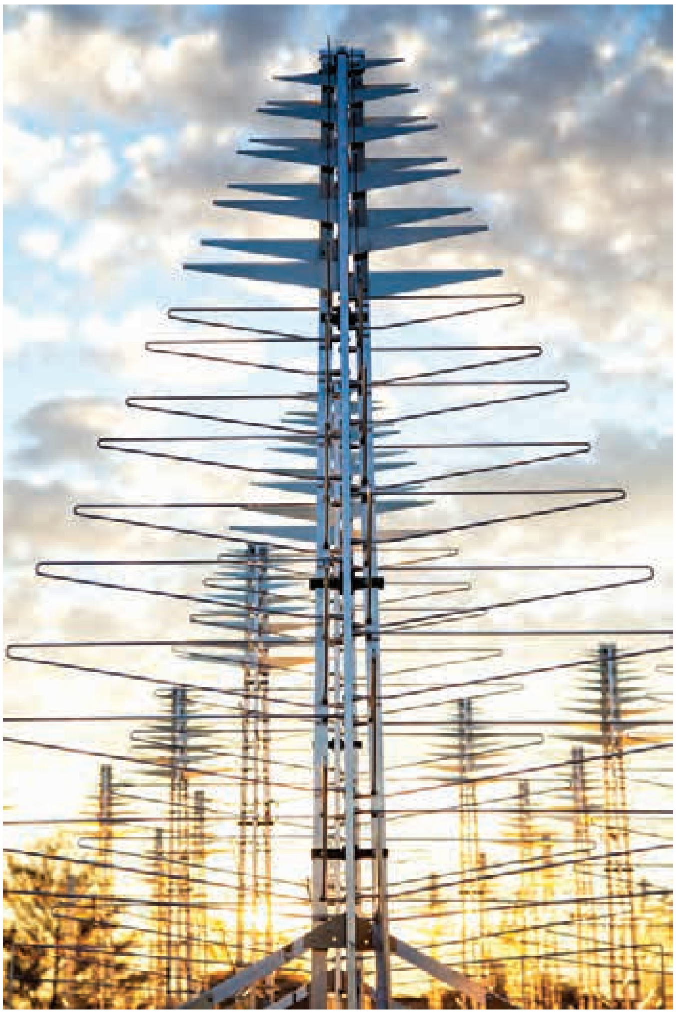
Figure 10, below: Some of the people that helped make the SKA Bridging Phase 2 a reality. Credit: INAF, 2019



Simulating the performance of antenna arrays

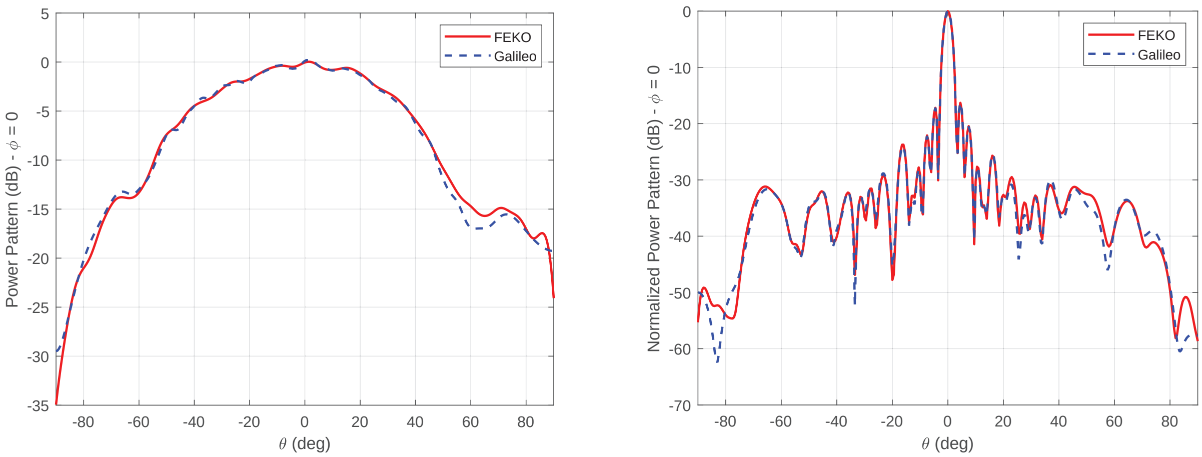
David Davidson, Tom Booler
and Daniel Ung

Figure 1, right: The SKALA4.1 antenna. Credit: ICRAR



ENGINEERING

Figure 2, below, left: An embedded element pattern. Vertical scale is logarithmic (decibels). Zenith (directly overhead) is in the middle of the horizontal scale. Below, right: A beamformed station pattern.



In collaboration with the Italian National Institute for Astrophysics (INAF), a very challenging program was outlined in late 2018 to deploy a complete 256-element SKA-LOW station on the MRO, using the new SKALA4.1 antenna developed by INAF from the SKA reference design. This was specifically designed to mitigate the risk associated with station-level calibration identified in the lead-up to the December 2018 Critical Design Review. By May 2019, the Aperture Array Verification System 1.5 (one-and-a-half), consisting of 48 SKALA4.1 antennas deployed in three clusters of 16 was on site, and commissioning work commenced almost immediately. By year-end, the full 256 element array (now called AAVS2) was in place, and data was being captured and processed.

The AAVS2 station is an array comprising 256 dual-polarized log-periodic SKALA4.1 antennas (see Fig 1), distributed on a wire-mesh ground. The maximum centre-centre distance between antennas is 38 m and the array layout is semi-random; some antenna positions have been fine-tuned to avoid mechanical interference and a reasonable walk-through to access every antenna. The demonstrator was deployed at the Murchison Radio-astronomy Observatory (MRO) site during the course of 2019; a picture of the completed array is shown in Figure 2. Two single-ended 50-ohm Low Noise Amplifiers are fully integrated in each antenna and are connected through coaxial cables (10-m long) to a box where the RF signals are pre-conditioned and converted for transmission via optical fibers to the central processing unit.

Computer simulation of the electromagnetic response of the entire station provides very powerful tools for accurate performance prediction. For modelling the highly-conducting SKALA4.1 antennas, the Method of Moments (MoM) is a very competitive method. CIRA and INAF have been using the commercial MoM simulation tools FEKO and Galileo to compute the antenna responses of the entire station. Due to the increased number of dipoles on each arm comprising the log-periodic structure compared to previous prototypes, the SKALA4.1 is appreciably more complex to model numerically than its predecessor in AAVS1, the SKALA2. Even after significant simplification of the MoM models from the original CAD files, the numerical models typically comprise well over a million degrees of freedom for the full 256 antenna station. Run-times per frequency point vary from days to weeks, depending on the convergence rates of the iterative solver used for the accelerated "fast" solution – the multilevel fast multipole method - even on powerful dedicated servers. FEKO simulations at Curtin have been carried out on a dedicated DEC PowerEdge 740 server.

The MoM computations produce "embedded delement patterns" (EEPs). These are the electric field beam patterns (often called "voltage patterns" in radio astronomy") for one array element operating, with all the others suitably terminated. The full array pattern is then obtained by a weighted sum of the EEPs, equivalent to beamforming. Comparative results for one EEP computed using FEKO and Galileo are shown in Figure 3. This antenna is located towards the eastern periphery of the station. Figure 4 shows a comparison of the zenith-pointing station beams in the plane of the dipoles (E-plane), beamformed from the computed EEPs. The patterns follow the expected behaviour.

With this work, we have been able to demonstrate excellent agreement between simulated patterns for an electromagnetically very large array. This has been possible by leveraging fast algorithms available in commercial codes, supporting parallel execution on powerful multi-core workstations, and by developing suitably simplified models of the individual array elements, viz. the SKALA4.1 antenna.

A drone campaign was undertaken following the initial roll-out of this array (the 48 element AAVS1.5). Results show an excellent agreement between simulations and measurements. However, the simulation and measurement of the embedded element patterns is not an end in itself; the key question still to be addressed is whether the significant variation in element patterns, caused by mutual coupling, will permit sufficiently accurate and rapid station-level calibration for SKA-LOW. The inter-element variability is especially pronounced at the lower end of the frequency band. Existing calibration scheme generally assume that all the EEPs are similar, and it is clear that this is not the case. Work on this continues.

Simulating, building and commissioning a full 256 element station within a year was an extremely ambitious stretch goal, and it reflects great credit on our staff here and our colleagues from INAF that this was accomplished within this period.

On-site shielding and radio emissions testing of a new Field Processing Facility

David Kenney

Figure 1, left: Field Processing Facility (FPF) at the MRO. Credit: Kenney, 2019

Figure 2, right: Shielding effectiveness testing of the FPF showing an antenna measurement pair, one located inside the shielded room while the other is located outside. Note the chamber double doors are opened for illustration only. Credit: Kenney, 2019

Figure 3, left: Radiated emissions testing of the FPF using high gain wideband antenna. Credit: Kenney, 2019

The Murchison Radio-Astronomy Observatory (MRO) is home to next-generation radio telescopes, and contains high-performance hardware. This equipment is a mix of custom and off-the-shelf sub-systems which typically generate large amounts of radiated radio emission. As a result, this equipment needs to be located in a shielded enclosure or building designed to contain these emissions.

Even though the MRO is located in a remote area of Western Australia and lies in a designated radio quite zone, on-site verification, particularly of the radiated emission, can prove to be quite a challenge.

The CSIRO Control Building at the MRO is designed to house the radio-astronomy back-end systems and provides over 160dB of radio frequency shielding. This shielding ensures that self-emission from the back-end hardware does not contaminate the astronomical signals.

With increasing demand for equipment to be located within the Control Building a shielding solution local to the Murchison Widefield Array (MWA) was procured. Manufactured by industry partner, Compliance Engineering, the Field Processing Facility (FPF), provides an RF shielded and temperature-controlled environment for expansion of precursor SKA instrumentation. Starting life as a 40-foot shipping, the FPF was designed to contain emissions from CISPR32 class A equipment (or better), typical of-the-shelf systems, to levels compliant with MRO requirements.

Like any other equipment deployed at the MRO, the FPF must also comply with radiated emissions requirements mandated for the MRO. Electrical systems, such as cooling and lighting, must be sufficiently shielded to ensure self-emission does not exceed permitted limits defined and controlled by CSIRO. While initial radiated emissions and shielding performance measurements were performed by Compliance Engineering at their facility in Keysborough, Victoria, extensive on-site verification testing was performed. Having travelled the thousands of kilometers from Victoria to the MRO by road, shielding performance and radiated emission verification was essential to verify compliance.

CSIRO have defined the "RFI Standards for Equipment to be deployed on the MRO". As the title suggests, this document sets limits on the equipment to be deployed at the MRO. The basis of assessment is the radiated emission section of Military Standard MIL-STD-461F. This section of the standard is referred to as RE102. The RE102 limits selected by CSIRO are the 'Navy Mobile and Army' (NM&A) limits. Depending on the distance to "other instruments", at the MRO, additional shielding is required. This effectively lowers the limits for the equipment being deployed. For instruments less than 1km apart, 80dB shielding is required. For instruments separated by more than 1km but less than 10km, 20dB shielding is required. Beyond 10km no additional shielding is required. As the FPF is located in the 1 to 10km range from other MRO instruments (ASKAP and EDGES), the target emissions threshold of 20dB below RE102 (Navy Mobile & Army) is used. Compliance with this limit is required for emission from the FPF and any equipment placed within the shielded room of the facility.

At the time of on-site testing, no astronomical instrumentation had been installed in the FPF. As such, verification of the shielding effectiveness of facility was required. Guided by IEEE Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures (299-2006) on-site verification of the FPF was performed.

Lead by EMC specialist, Dr Franz Schlagenhaufer and coordinated and supported by the CIRA engineering group, the shielding effectiveness and radiated emission of the Field Processing Facility was measured. Testing was coordinated with CSIRO and performed over several days during a period of limited site activity and limited telescope observation. To perform the on-site testing, equipment usually used in the Curtin University EMC chamber was optimised for the sensitive measurement with full system calibration and correction for absolute electric field measurement. Emission measurements were conducted in the frequency range 30 MHz to 5 GHz while shielding effectiveness tests covered the range of 100 MHz to 9 GHz.

Ambient RF emission from equipment such as satellite, broadcast and communication had to be differentiated from potential emission from the device under test.

Following extensive testing, data processing and reporting, the shielding of the Field Processing Facility meets the design specification (80 dB up to 1 GHz, 60 dB above 1 GHz) and it is suitable to house CISPR A compliant (or better) equipment located within the MWA. Radiated emissions testing deemed the FPF compliant with MRO RFI standards.

The Effect of Electrostatically Damaged Low-Noise Amplifiers on MWA Beam Patterns

Maria Kovaleva, Daniel Ung, Adrian Sutinjo, Budi Juswardy, David Davidson and Randall Wayth

Figure 1, left: Whirlwind ("willy-willy") at the MRO. Credit: Kovaleva, 2019

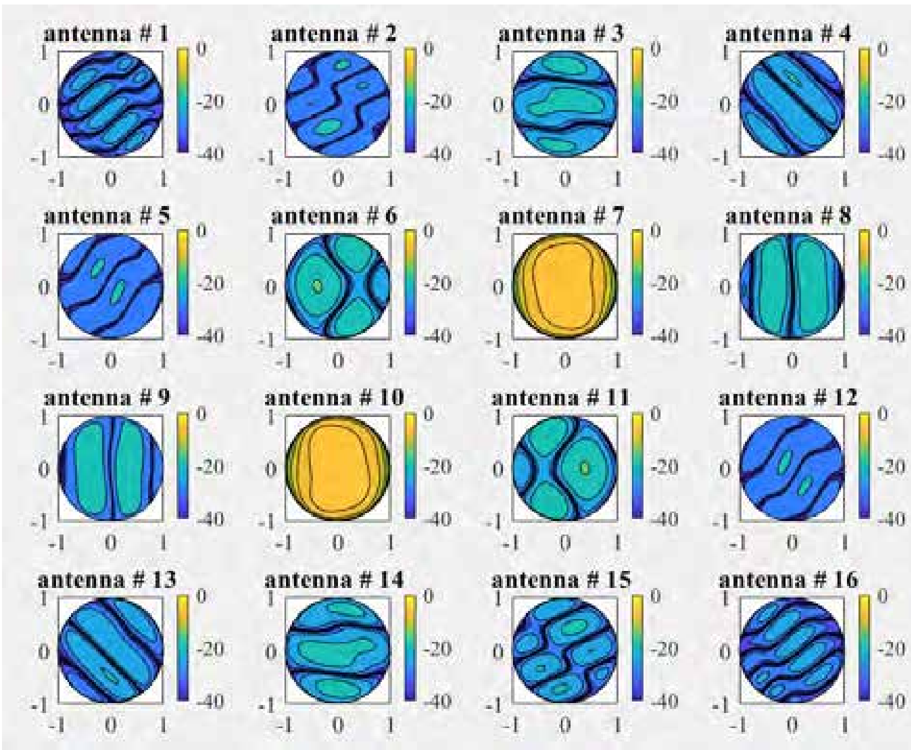


Figure 2, right: The difference (in dB) in E-fields between the initial and transformed embedded element patterns with the load Z(LNA)=28+j20 Ohm (at 160MHz) at antennas #7 and #10. Credit: Kovavela, 2019

Some natural phenomena occurring at the Western Australian site of the Square Kilometre Array (SKA), such as lightning or whirlwinds, can cause damage to electronic parts of radio telescopes. It is necessary to characterise the potential failure modes caused in low-noise amplifiers (LNAs), which in turn affect the antenna performance. We considered the Murchison Widefield Array (MWA) operating in the frequency range 80—300 MHz as an example for such a study.

In MWA, each tile consists of 16 bow-tie dual-polarised dipole antennas arranged as a 4-by-4 planar array with 1.1 m spacing and placed on a 5-by-5 m2 ground screen. Each antenna has an LNA in the centre, connecting two orthogonally polarised dipole arms. If a dipole is exposed to a lightning strike or whirlwind, sudden electric current flows through the sensitive electronics of the LNA and damages it. These are not uncommon events for the Murchison Radio-astronomy Observatory. When sand particles rub against each other in a whirlwind, a huge voltage potential is created that eventually discharges through such means as antennas and its electronics. To imitate the electrostatic damage (ESD) from lightning or whirlwinds, we set up EM Test Electrostatic Discharge Simulator located at Curtin Laboratory. We applied Severity Level 4 contactless (through air) ESD of 16.5 kV to an LNA test board, according to IEC 61000-4-2 test standard. This caused a transistor gate failure and brought LNA input impedance to a short circuit condition.

To analyse the effect of damaged LNAs on the MWA, we used measured impedance data of ESD-damaged LNAs in conjunction with network analysis methods for phased arrays. We developed a code that transforms initial electric fields of an MWA tile with working LNAs to new electric fields with damaged LNAs. This code allows us to calculate exact electric fields of antennas without the need to repeat time-consuming numerical simulations in FEKO. To demonstrate the accuracy of the method, we first applied it to a simple dipole antenna array. Then, we acquired embedded element patterns and array patterns of MWA with ESD-damaged LNAs. This is a powerful tool that generates antenna response for all potential failure modes within seconds and can be used in troubleshooting antenna arrays in general and MWA in particular.

In relation to MWA, we found that when two antenna elements in a tile are affected by damaged LNAs (for example, by willy-willy) that are in a short-circuit mode, the maximum difference in E-fields between the initial and affected embedded element patterns of neighbouring elements is -15 dB, which can affect observations. However, in MWA, the calibration occurs at a tile level, and thus, two damaged elements cause negligible effect on tile patterns for both zenith and off-centre pointing. This is a great result confirming robustness of MWA radio telescope. We intend to further use this technique on Engineering Development Arrays (EDAs) and the SKA-Low, where calibration is performed elementwise.

Figure 3, above: Laboratory electrostatic discharge test. Credit: Kovaleva, 2019

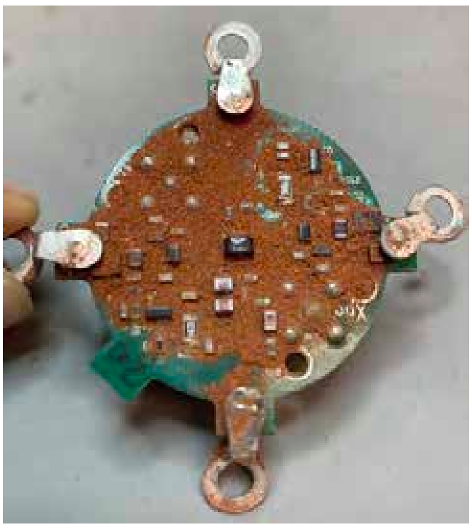


Figure 4, right: Dirty MWA low-noise amplifier (LNA) returned from the site. Credit: Kovaleva, 2019

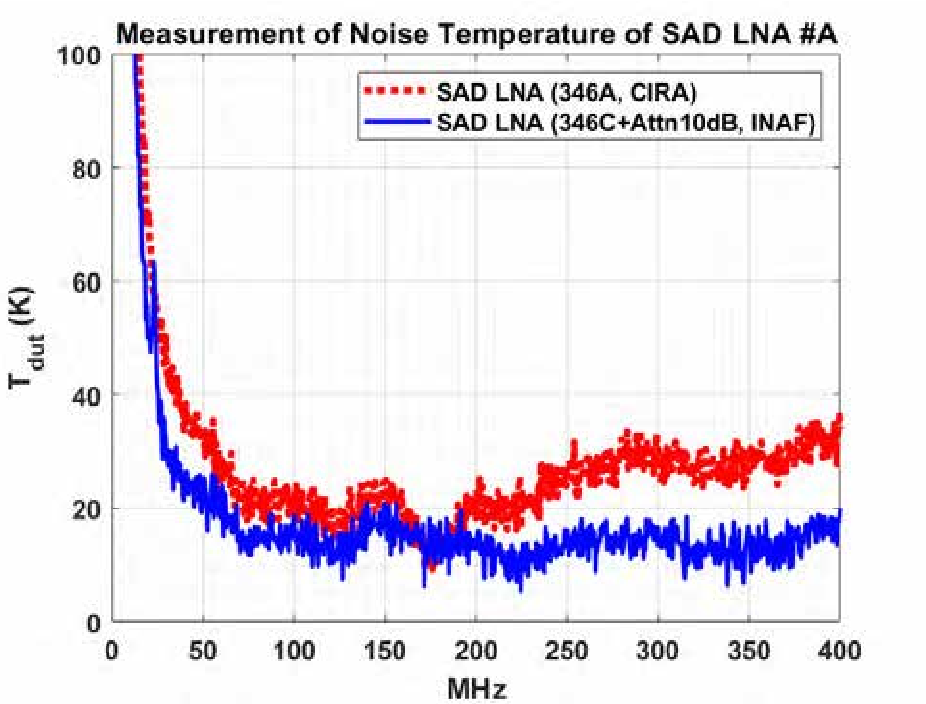
Automated Noise Parameter Extraction for the SKA-LOW

Budi Juswardy and Adrian Sutinjo

Figure 1, above: Noise parameter extraction setup in the CIRA lab. Credit: Juswardy, 2019

ENGINEERING

Figure 2, right: Measured noise temperature of Sardinia Array Demonstrator (SAD) low noise amplifier (LNA). Note that there is a difference of ~15K between measurements performed using an INAF calibrated noise source and a CIRA noise source. Credit: Juswardy, 2019



Engineers at the Curtin Institute of Radio Astronomy (CIRA) have extensive experience and expertise in low-noise measurement of devices used for low-frequency radio-astronomy receivers. In 2019 we developed and verified a method to extract the noise parameter of receiver devices operating around the low-frequency range of the Square Kilometer Array (SKA-LOW) radio telescope project, and are automating the measurement to enable rapid and accurate noise figure measurements of those devices. We conducted measurements of several low-noise amplifiers (LNAs) developed by our Italian collaborators at the Istituto Nazionale di Astrofisica (INAF), and performed noise source comparisons to establish a common baseline for noise figure measurements between the CIRA and INAF facilities.

We have been developing a measurement facility that enables us to characterise low-frequency LNAs in the SKA-LOW frequency band of 50 MHz to 350 MHz. The facility mainly consists of an RF shield chamber, Keysight N9030A Signal Analyser, Keysight ENA E5071C, CCMT-101 Focus Microwave Tuner, associated low-noise power supplies, noise sources (Keysight 346A and 346B), and a computer for controlling the instruments and processing the measured data.

In the second half of 2019, we performed verifications of the set-up used for noise parameter extraction [1, 2] and developed automated measurements. The tuner automation software offers guided step-by-step calibration and measurement procedures that enable relatively rapid and seamless noise parameter extraction of the device under test. This is achieved by interfacing the instruments and the tuner, automating the settings of the instruments, and recording the measurements files while following the ISO file naming convention for traceability and standardisation. With the automated script, we significantly reduce manual errors associated with instrumentation set-up and calibrations, manual naming of the measurement files, and reduce the time taken to perform the measurement from ~2-3 hours to approximately 90 minutes.

The automated script allowed us to repeatedly characterise the tuner, and the error associated with positioning tuner probes is reported in [2]. With our set-up and noise extraction method, the normalised relative error of the noise parameter extraction has been verified to be around 10-3 from the mean of the measurement. Even though the tuner is specified by the manufacturer to have the minimum operating frequency of 100 MHz, we managed to produce highly repeatable measurements down to 50 MHz.

We employed our noise parameter extraction set-up to characterise the Sardinia Array Demonstrator (SAD) LNAs as well as the SKA Log-periodic-dipole Antenna (SKALA) LNAs used in the SKA Bridging Activities. We managed to produce S-parameters for the SAD LNAs as well as SKALA 4.1AL LNAs, which can be utilised for SKA-low station simulations and noise characterisation. In addition, we performed noise parameter extraction measurements of those LNAs using calibrated noise sources available in our CIRA lab, as well as noise sources used at INAF in Medicina Radiotelescopes Lab, Italy, to understand the gaps in noise measurement results performed at both labs and to close these differences.

This effort led us to further improve the calibration of our noise source to reduce measurement uncertainty, as well as to enhance the automated script. We are currently developing concurrent verification to each key measurement step; this work is currently undertaken by a Curtin University Electrical Engineering fourth-year student. These activities serve as a training platform for students, as well as being actively pursued to enhance our noise measurement capabilities to support SKA-related activities and beyond.

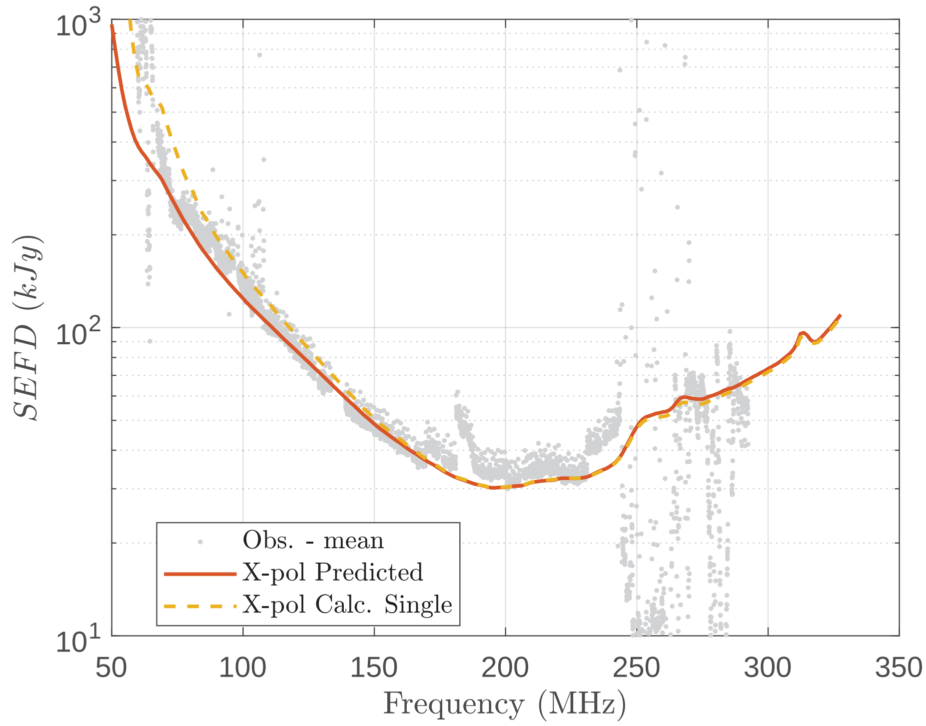
References:

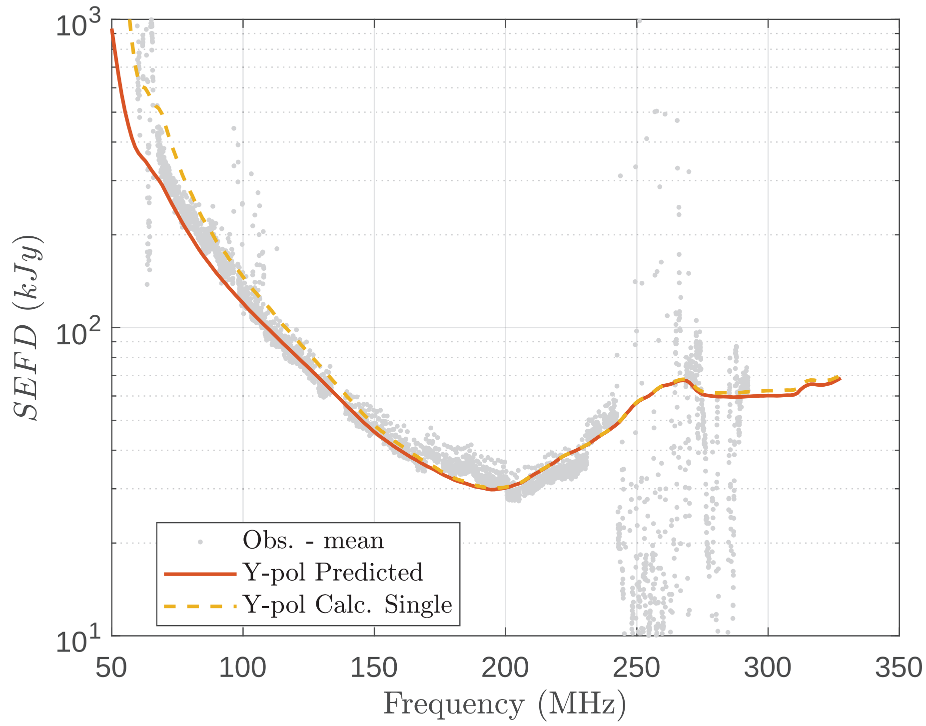
[1] A. Sutinjo, D. Ung, and B. Juswardy. 2018. "Cold-source noise measurement of a differential input single-ended output low-Noise amplifier connected to a low-frequency radio astronomy antenna." IEEE Transactions on Antennas and Propagation 66 (10): 5511-5520. DOI: 10.1109/TAP.2018.2854285, [Online].

[2] A. Sutinjo, L. Belostotski, B. Juswardy and D. Ung. 2020. "A Measure of Well-Spread Points in Noise Wave-Based Source Matrix for Wideband Noise Parameter Measurement: The SKA-Low Example," in IEEE Transactions on Microwave Theory and Techniques. DOI: 10.1109/TMTT.2020.2977287, [Online].

System Equivalent Flux Density of a MWA Tile

Daniel Ung, Marcin Sokolowski and Adrian Sutinjo





The System Equivalent Flux Density (SEFD) expressed in units of Jansky (Jy) is one of the figure of merit used to characterise a radio telescope. It represents the amount of flux needed to be produced by a source in a particular direction to match the noise power produced by the telescope (including other astronomical sources that are not of interest). The higher the SEFD, the poorer the performance as it indicates the telescope is either noisy or the beam is extremely broad.

To calculate the SEFD, we require knowledge of effective area, antenna temperature, radiation efficiency and receiver noise temperature. The dependence of each parameter are captured in Table 1.

For low-frequency phased array telescope such as the Murchison Widefield Array (MWA), the SEFD changes with respect to pointing angles unlike the dish-based telescope counterparts. This change occurs due to changing effective area, radiation efficiency and receiver noise temperature.

Over the course of 3 years, our engineering team has develop the necessary tools and knowledge to accurately calculate the SEFD for arbitrary pointing angles. For example, in 2016 an accurate simulation to obtain the far-field of the Murchison Widefield Array tile was completed. In 2018, our team developed a low-cost method of extracting the noise parameter of the MWA's LNA.

For the latest addition in 2019, our team has developed a tool to compute the receiver noise temperature which includes mutual coupling effects and as a by-product, a modified method of calculating radiation efficiency. Both of these works resulted in publication for 2 conferences, 1 IEEE APS transaction and 1 M.Phil thesis which received a commendation letter from the Chancellor of Curtin University.

As a verification step, we have compared our calculated SEFD with the observed SEFD of the MWA shown in Fig. 1 and 2.

Table 1, below: Knowledge of dependence required to calculate each parameter.

Parameter	Dependence
Effective area	Electric far-field
Antenna temperature	Electric far-field, Sky model (non-homogeneous)
Radiation efficiency	Electric far-field, S-parameter of array and attached low-noise amplifier (LNA)
Receiver noise temperature	S-parameter of array and attached LNA and noise parameters

Figure 1, far left, top: Comparison of calculated SEFD to the average SEFD of MWA tile (X-polarization) at a pointing angle of (phi=153.43 degrees, theta=15.37 degrees) obtained from astronomical observation. The observation was taken on the 7th December 2016 at 10:24:39 to 10:31:35 UTC. The observed source was 3C444 and on average the source was located at (phi=151.46 degrees, theta=18.3 degrees) during the entire observational period in which effective area was evaluated at. The observed data points displayed are from an average of ≈56 different MWA tiles. The dashed curve represents the SEFD of the MWA tile given that the receiver noise temperature was substituted with the results from the single isolated element. The missing data points around 137 MHz are due to strong interference from Orbcomm satellite and were removed before processing. At 242 - 270 MHz and 280 - 288 MHz the data shows signs of radio frequency interference (RFI). The RFI in the 242 - 272 MHz band is due to military satellite however, the source RFI interference in the 275 - 285 MHz band was not identified. Credit: Ung, 2019

Figure 2, far left, bottom: SEFD of MWA tile (Y-polarization) at a pointing angle of (phi=153.43 degrees, theta=15.37 degrees). The observational details are identical to the X-polarization. Credit: Ung, 2019

Protecting data cables from the extreme heat of the Murchison

Budi Juswardy

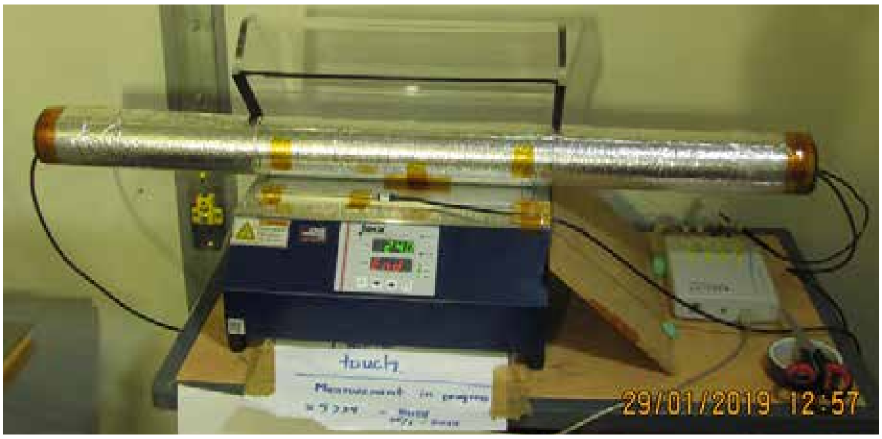


Figure 1, right: The set up for characterising temperature profile of insulation materials. Credit: Juswardy, 2019

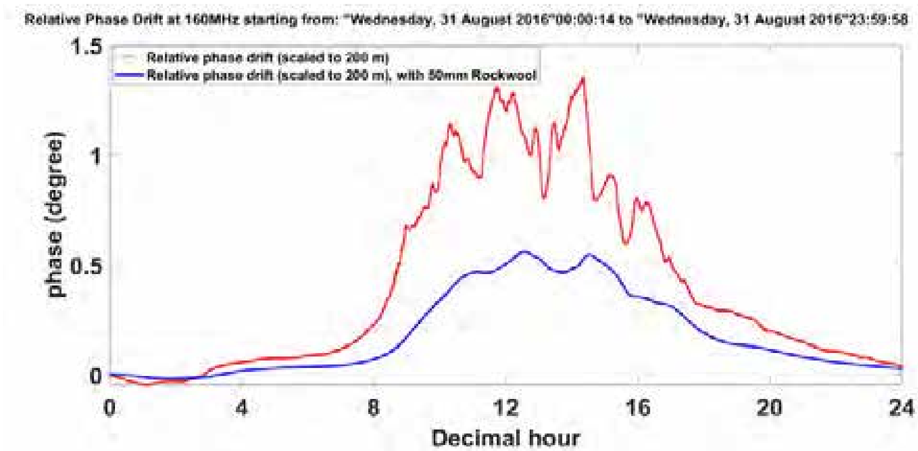


Figure 2, left: The estimated 24-hour relative phase drift of RF signal transmitted over 200 m fibre optic cable, with and without insulation. Credit: Juswardy, 2019

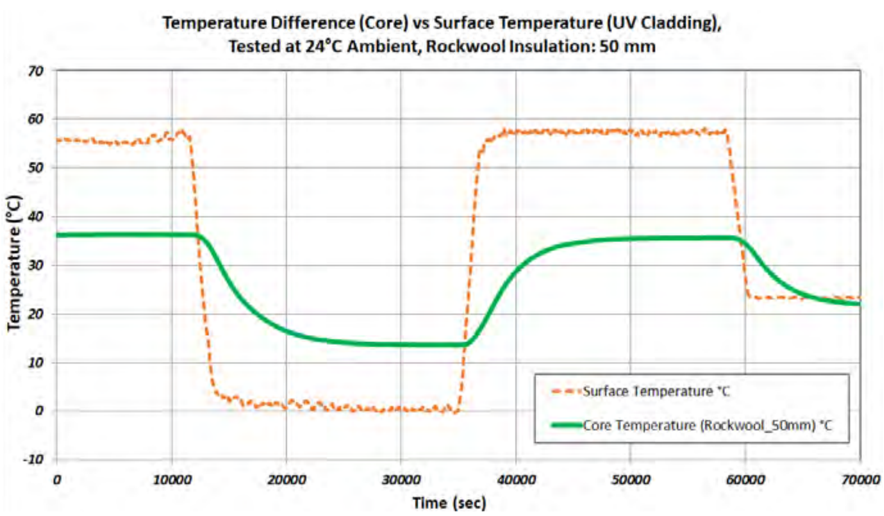


Figure 3, left: Thermal profiles on the surface and core of the insulation due to rapid temperature cycle. Credit: Juswardy, 2019

ENGINEERING

We present a summary on the selection process, modelling, characterisation and analysis of insulation solutions for surface-laid optical cable, in the context of SKA Bridging Array activities. The insulation is intended to provide thermal shielding to protect the cable from the elements (such as ambient temperature fluctuations, wind and solar irradiation) at the Murchison Radio-astronomy Observatory (MRO). We were able to estimate the phase stability of the radio-frequency (RF) signal transported across fibre cable, with and without insulation, to determine whether insulation is required for future cable installation.

RF-over-fibre (RFoF) optical links have been identified as an attractive solution for transporting analogue radio frequency (RF) signals in the low-frequency Square Kilometer-Array (SKA-LOW) project. By using RFoF, the RF signal is transmitted from the antenna directly into a central processing facility (CPF) a few kilometres away via fibre optic cable, replacing coaxial cables which have a limited transmission range. However, in a long-distance RF transmission over fibre cable, the effect of environmental temperature fluctuations on the phase stability of the RF signal propagating through the cable was found to be significant [1].

For the SKA Bridging Array activities, the plan was to build a few antenna stations, and process the signals relatively close to the field inside a shielded enclosure. The distance between a station and the shielded enclosure was envisaged to be around 200m. There were various discussions in the radio-astronomy community regarding the extent of thermal effects on the phase stability of the fibre cable, especially when assessing the calibration, radiation beam and visibility/imaging of the station array [2]. To ensure temperature effects on the fibre optic cable are “eliminated”, the ideal solution is to bury the fibre cable underground, and the steady soil temperature will ensure phase stability of the transmitted signal. However, as the transmission distance between the antennas and the (temporary) processing facility is relatively short in the SKA Bridging Array, it is not practical and economical to dig a trench at the MRO to bury the fibre optic cable. This motivated CIRA engineers to search for and evaluate several solutions that could provide us thermal stability comparable to underground burial, while still allow us to place and route the cable on the ground surface.

Measurements of numerous fibre optic cables at the MRO had been performed in the past, including buried and surface-laid cables currently used for the Murchison Widefield Array (MWA), Aperture Array Verification System (AAVS), and Engineering Demonstrator Array (EDA) projects. Based on these measured data, we developed criteria for selecting a suitable cable insulation. Several solutions were considered and characterised in the lab. It was found that 50 mm thick mineral wool piping insulation has a reduction factor of one third of the peak ambient temperature, as well as a delayed peak response of approximately 2-3 hours. This gives it a similar temperature damping and delay profile to burying the cable underground at a depth of ~1.7m.

We also developed a model to estimate the impact of varying the transmission length of the fiber cable on the phase stability of the transmitted RF signal, for burial and surface-laid cables with or without insulation. The methodology resulting from our investigation could potentially be adopted in selecting and assessing suitable insulation solutions for surface-laid coaxial cables as well as fibre cables, for a given phase stability requirement in other radio astronomy projects (such as MWA and EDA), should the need arise.

References:

[1] B. Juswardy, “Field Test Result at the MRO to Asssess Gain & Phase Variation of Fibre-optic Cable,” SKA, LFAA, SKA-TEL-LFAA-0400017, 2015.

[2] B. Juswardy, "Summary on the Assessment of Thermal Insulator for RFoF Optical LInk Cable." Curtin Institute of Radio Astronomy (CIRA) Internal report, Rev. 1, 17 June 2019.

Birth of a New Instrument: the Cyclic Imager

Ian Morrison and Greg Hellbourg

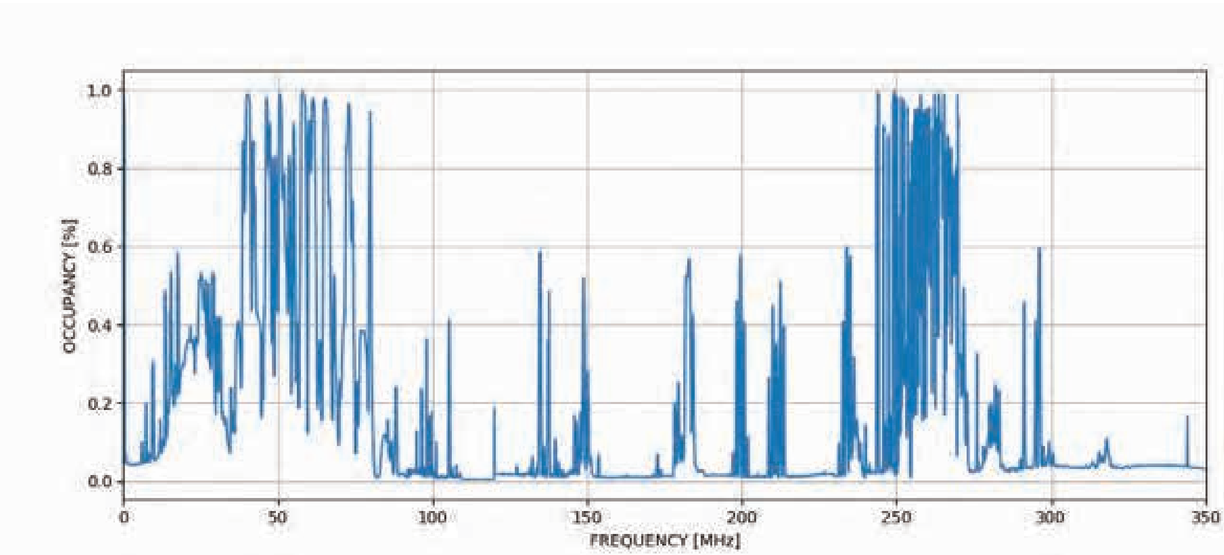


Figure 1, above: Spectrum occupancy as a function of frequency, showing typical RFI observed by the MWA radio telescope (as measured using the omnidirectional BIGHORN antenna). Credit: Morrison, 2019

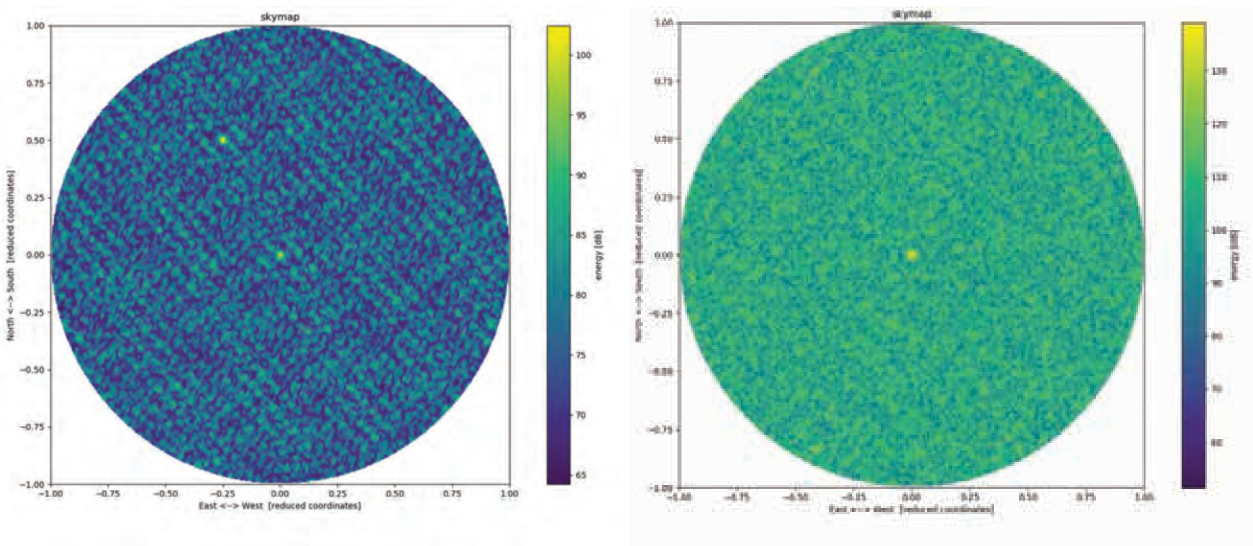


Figure 2, above: (Left) A conventional sky image containing an RFI source at the centre and a synthetically introduced natural source to the upper left. (Right) A cyclic image of the same area of the sky, containing only the RFI source. Credit: Morrison, 2019

Radio frequency interference (RFI) is a growing menace to radio astronomy, corrupting astronomical data and reducing the productivity of telescopes.

Even at a radio-quiet location like the Murchison Radio-astronomy Observatory (MRO) – the site of the CIRA-operated Murchison Widefield Array (MWA) – there is no avoiding RFI from distant radio/television broadcasts or satellites and aircraft passing overhead that transmit signals within the same frequency band at which the MWA is listening (80 to 300 MHz). The RFI problem for the MWA is compounded by its very large field-of-view, meaning there can be multiple sources of interference in view at any one time. The same issue will impact the forthcoming SKA-Low telescope that will also be located at the MRO. Being more sensitive, it will be even more affected by RFI.

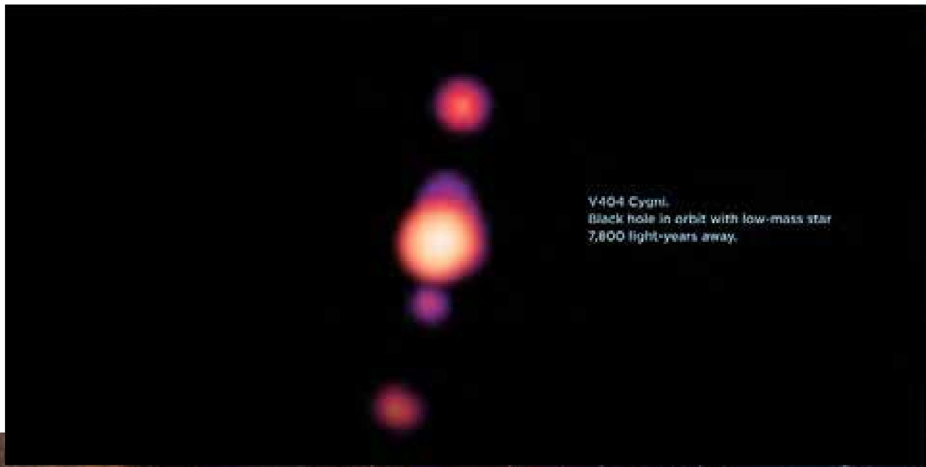
One way to mitigate the impact of RFI is to develop a forecasting model of when, where and at what frequencies different sources of RFI will appear and how they will move across the sky. With that model it becomes possible to optimise the scheduling of observations such that the impact of the RFI is minimised. The telescope can be tasked with observing a different part of the sky, and/or different frequencies, at times when the RFI is seen or predicted to be active. Exploiting directional information in such a strategy has not traditionally been done but offers huge potential benefits. The biggest obstacle to obtaining this directional information is the challenge of discriminating RFI from astronomical radio sources over a wide field-of-view.

Enter the "cyclic imager", a novel instrument conceived specifically for this purpose. In contrast to the conventional imaging process used with array telescopes, which maps the total incident power over all directions on the sky, the cyclic imager is sensitive only to human-generated RFI. It accomplishes this by exploiting fundamental differences in signal properties between natural sources and those of engineered RFI that will exhibit a statistical property known as cyclostationarity. Combining this selectivity within an imaging capability has never before been implemented, but CIRA engineers have developed a way to accomplish this. In fact two different methods have been conceived, which are being compared and contrasted to choose the most effective and readily implemented approach.

Following a successful proof-of-concept demonstration using simulated telescope data, at the end of 2019 the cyclic imaging concept was verified using real MWA telescope data from an observation corrupted by the downlink transmissions from the amateur radio ARISS system located on-board the International Space Station in low-Earth orbit. The figure below shows at left an image of part of the MWA's field-of-view that contains both a natural source and the ARISS RFI source at the centre. (The natural source is synthetic and was added to the raw telescope data in a calibrated way to assess the performance of the cyclic imaging algorithm.) At the right is the corresponding cyclic image (the world's first ever cyclic image!) of the same part of the sky, with only the RFI source now visible.

Going forward, we intend to develop a prototype instrument that can run in real-time alongside the other back-end processing functions of the MWA to provide constant all-sky RFI monitoring and localisation, the outputs of which can later be used to support optimised scheduling of telescope observations. Once operational and proven with the MWA, the capability will be demonstrated to other telescope operators with the goal of widespread adoption including Australia's forthcoming flagship telescope, SKA-Low.

HIGHLIGHTS



Right: Still from an animation produced for the discovery of rapidly swinging jets coming from V404 Cygni's black hole. Paper by Prof James Miller-Jones published in Nature. Credit: ICRAR

Above: An MWA tile on display at Astrofest 2019. Credit: ICRAR

TEACHING & OUTREACH

Above: Curtin and UWA staff, students and families at the Pullman Bunker Bay resort for astronomy conference ICRAR-Con 2019. Credit: ICRAR

CIRA's renowned researchers, sharing their passion for science

Mia Walker

Image, far right: Ink sketch of the participants at the ARDRA (Australia-India Research and Development in Radio Astronomy) conference. Many of the MWA and SKA staff at CIRA presented on engineering topics. Credit: Mia Walker, 2019

CIRA's staff and researchers are superstars in outreach and teaching, and their consistent effort and passion for science communication continued with great outcomes in 2019.

Events included talks on the explosive radio universe, SETI and pulsars at 'Pint of Science'; the networking events Science Café and the Innovator's Tea Party for high school students and professionals; the Anglo-American Discovery Open Forum - HIVE visit; setting up telescopes on the roof of Curtin's engineering building for Research Rumble; a live podcast recording of Ockham's Razor at the Harry Perkins Institute of Medical Research; more talks at Karrinyup Rotary Club, the Perth Observatory Volunteer Group, Astrotourism WA, and astronomy groups AGWA and ASWA; sending an Astronomer in Residence to Yulara, NT; and talking astronomy to children in the Starlight room at Perth Children's Hospital.

CIRA had another excellent year at Perth's annual astronomy festival, Astrofest, held at Curtin stadium. Staff and researchers helped at stalls, gave talks, showcased science and technology and volunteered with telescopes over the course of the night, which attracted over 5000 members of the public.

There was also a continued focus on speaking at schools (Como Primary School, Mount Beauty Secondary College, Perth College, Warwick Senior High School, Rossmoyne Senior High School, Methodist Ladies' College, Lathlain Primary School, Champion Bay Senior High School, Geraldton Primary School, Mercy College, Dalwallinu District High School) to encourage and inspire the younger generation to consider possible careers in astronomy or space sciences. Some of these talks were part of National Science Week, the Geraldton Goodness Festival and the Perth Science Festival, which also included events such as Women in STEM Breakfasts, presentations at Geraldton Museum and South Perth Library, and 'Meet the Scientists, Sign me Up!' brunch and interaction with deaf and hard of hearing children. CIRA PhD candidates also attended the UWA-ASPIRE regional camp to explain a PhD, reionisation and black holes to remote Year 11 students. The ASTRO-3D group celebrated the 50th anniversary of Apollo 11 mission with a Moon-based observing and activity night with the Millen Primary School Dad's group. CIRA researchers also discussed their science to high school students at the ConocoPhillips Science Experience and Quantum Words Perth.

CIRA also welcomed work experience students from local high schools for demonstrations and discussions of our science and engineering work over the course of a week. Curtin hosted students from the Indigenous Australian Engineering School (IAES), an annual event established by Engineering Aid Australia, and staff engaged them in astronomy activities at CIRA.

The CIRA executive team and MWA operations team featured often at international events, presenting talks

at conferences including the URSI Asia-Pacific Meeting, AARNet Workshop, NZ SKA Forum, SuperComputing Asia, 18th International Semantic Web Conference, Australia-India Research and Development in Radio Astronomy Meeting, OzSKA, and SKA Shanghai. Most of these research talks focussed on the MWA telescope as a SKA precursor instrument and the lessons that can be learned in the age of Big Data.

CIRA researchers are often involved in press releases associated with incredible science results, or called on for their expertise in all matters astronomy. In 2019 CIRA featured in interviews, podcast and articles with news groups including ABC (SW, Illawarra, Pilbara, online and Radio National), SBS, Canning Times, Triple J, 6PR, 2GB, 3AW, Curtin FM, New Scientist, RTR FM, BBC (Radio Five Live and The Inquiry), SpaceTime, MSN, Radio NZ, CCIWA. The topics ranged from women in STEM, the first photo of a black hole (the Event Horizon Telescope result), the V404 Cygni Nature paper, the first localised Fast Radio Burst, CIRA's silver Pleiades award for workplace diversity and equity, a near-miss asteroid, explosions in space and new supernova remnants detected with GLEAM-Gold.

Engineers and operations staff at CIRA also featured in promotional videos associated with the deployment of the SKA Bridging Phase arrays.

CIRA also contributes strongly in the delivery of Curtin undergraduate units in the Physics and Engineering streams at all levels, in addition to the supervision of undergraduate, Honours, Masters, and PhD projects. First year teaching covers the general units Physics and Introduction to Astronomy. Second year units taught by CIRA staff are: Physics of Stars and Galaxies, Statistical Mechanics and Thermodynamics, and Electromagnetism. Third/fourth year units include Relativistic Astrophysics and Cosmology, Exploring the Radio Universe, Nuclear and Particle Physics, Engineering Electromagnetics and Transmission Lines, Electronic Design, and Mobile Radio Communications, plus the honours unit Advanced Topics in Astrophysics.

As in previous years, CIRA ran a summer studentship program in 2019/20, aiming to engage with undergraduate students and expose them to the exciting research being done at CIRA. The students worked on a range of science projects, from white dwarfs to accretion onto supermassive black holes. SKA precursor and pathfinder instruments are often central to these projects, with students comparing diffuse cluster emission observed by both MWA and LOFAR, using particle detectors to trigger the MWA and detect cosmic rays, and looking for transient and variable active galactic nuclei using ASKAP surveys. These hands-on research experiences for undergraduates continue to provide stimulating learning experiences that often serve as gateways for Curtin undergraduates to enter Honours and eventually PhD programs within CIRA.

CIRA's STEM Superstar

Above: Dr Natasha Hurley-Walker and the 2019 -- 2020 Superstars at a social media training workshop at Google Headquarters in Sydney, May 2019. Credit: Science & Technology Australia

Left: Dr Natasha Hurley-Walker, Dr Kudzia Kanhutu, and Ms Narelle Underwood, three of the 2019 - 2020 Superstars of STEM, at Google Headquarters in Sydney, May 2019. Credit: Science & Technology Australia

In 2019, Dr Natasha Hurley-Walker became one of Australia's Superstars of STEM, a programme created by Science & Technology Australia (STA) to smash society's gender assumptions about scientists and increase the public visibility of women in STEM.

A cohort of 60 Australian female scientists and technologists aim to be role models for young women and girls, working toward equal representation in the media of women and men working in all fields in STEM. Dr Hurley-Walker attended six training workshops across Sydney, Melbourne, and Adelaide, advancing her communicaton skills and connecting her with a strong network of scientists across Australia. She was also a delegate at the Prime Minister's Prizes for Science, celebrating the scientists who have recently accomplished very high-impact research.

Working with participants over two years, the program strives to;

- Support 60 women employed in a range of roles in science, technology, engineering and mathematics to become highly visible public role models;
- Build the public profile of 60 women employed in STEM through training in public speaking, media and communicating with influence and through creating opportunities to practice their newly acquired skills;
- Empower participants to share their story and their work with general audiences by equipping them with advanced communications skills and an understanding of traditional media, social media and story-telling.
- Smash imposter syndrome and build confidence in a range of professional settings, participants will learn how to communicate with influence, in their workplaces, in the media and with leaders and politicians.
- Directly encourage young women and girls to study and stay in STEM, by program participants speaking with them in their schools and workplaces and by providing prominent public role models for them to aspire to.

2020 will see Dr Hurley-Walker engage with young women considering careers in STEM, showcasing the excellent science being performed across WA, and acting as a role model and guide to those who want to learn more.

Above: The 2019 -- 2020 Superstars of STEM cohort at our communication skills workshop in Melbourne, February 2019. Credit: Science & Technology Australia

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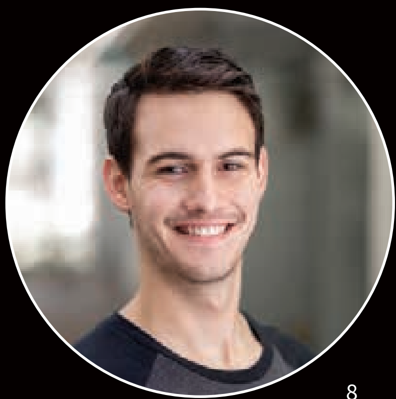
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