Australia's National Science Agency

Australia Telescope National Facility

Annual Report 2019–20


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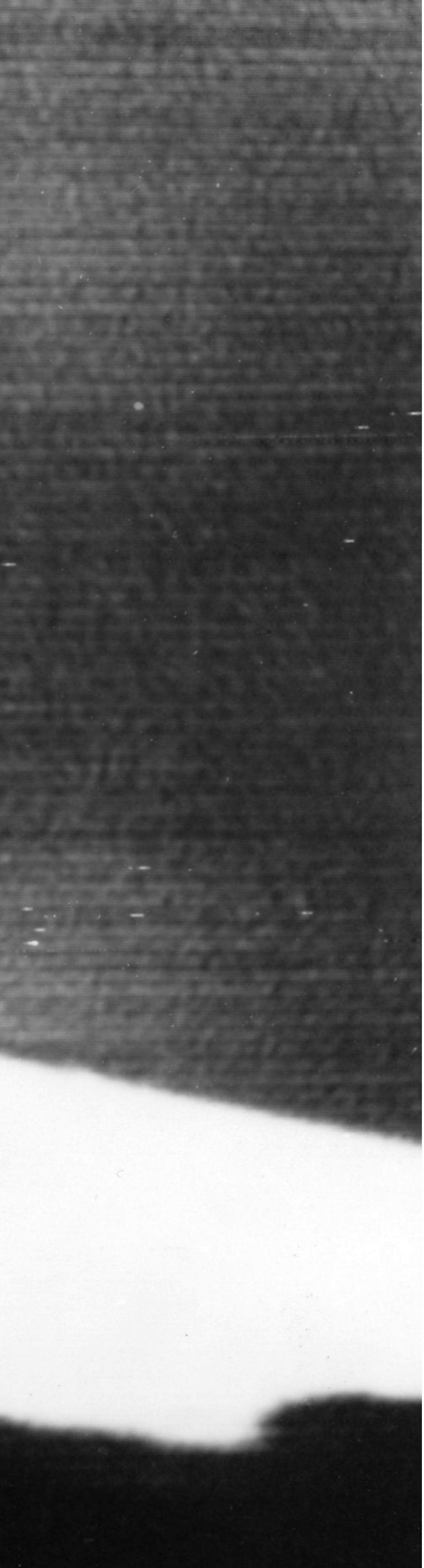

Contents

CSIRO Australia Telescope National Facility

Annual Report 2019–20

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This is the report of the CSIRO Australia Telescope National Facility for the period 1 July 2019 to 30 June 2020 and is approved by its Steering Committee.

Editor: Nic Svenson

Science highlights: Helen Sim

Cover: The Parkes radio telescope with the Moon and the surface of the Moon. Images: Alex Cherney and NASA.

Inside cover: Buzz Aldrin steps onto the lunar surface, as received by the Parkes radio telescope. Image: NASA.

Chair's report

Prof David Skellern, Chair, ATNF Steering Committee. Photo: John Sarkissian.

The Australia Telescope National Facility Steering Committee (ATSC) met twice this year. By our May 2020 meeting, COVID-19 constraints were in full force and we met virtually, not in Perth as had been planned.

While we didn't get to see the remarkable Australian Square Kilometre Array Pathfinder (ASKAP), we were impressed mightily by the results coming from it. The images from the Rapid ASKAP Continuum Survey (RACS) are beautiful, while the latest news from the fast radio burst (FRB) team is truly extraordinary (see Science highlights) and the critically important ASKAP pilot survey program has provided more than just hints of how impressive full-scale surveys will be. A fully functioning ASKAP and transition to the era of the Square Kilometre Array (SKA) are clearly, and rightly, the ATNF's top priorities.

We were this year presented with a science case for the Australia Telescope Compact Array (ATCA). The ATNF, and facilities around the world, are being asked to keep aging instruments operational longer than expected. That is, until the SKA is online. We found the case for ATCA operation until this time to be compelling, a position mirrored by the Australian Academy of Science National Committee for Astronomy's mid-term review of its Decadal Plan for Australian Astronomy. The ATNF's partners in the university sector clearly feel the same way and were this year successful in securing Australian Research Council funding for an urgent and essential upgrade of ATCA's digital system that should see it through until at least 2025.

The mid-term review and the ATSC also both made recommendations highlighting the importance of instrumentation development. We hold that the ATNF's radio astronomy engineering and computing group is of long-term value to CSIRO. Its work sustains and advances the nation's science in astronomy, and it demonstrably adds value to other telescopes around the world. But it also adds value to Australia's growing space sector (where ATNF know-how is being applied) and it could be better utilised in support of advanced manufacturing, computing, big data, and telecommunications, the latter notably in software defined radio engineering. Ensuring an appropriately skilled workforce is vital to Australia's future industries. While the ATNF is playing its part in ensuring that Australia's future engineering, computing and data analytics professionals acquire high level occupational skills, we believe there is untapped potential here.

After a year of rigorous market analysis and thorough consultation with industry, the ATSC was this year presented with a plan that would see technology developed for ASKAP applied to the looming bottleneck in satellite communications. Development of the plan was led by commercialisation specialist, Dr Ilana Feain, whose position we recommended be created, so it is tremendously satisfying to see a solid commercial opportunity that leverages ATNF technology laid out in detail. We wish Dr Feain every success in her efforts to get the plan funded. Apart from solving a pressing problem for the satellite communication industry and end users, the realisation of this opportunity would provide a clear demonstration of return on investment in ASKAP and potentially provide the global astronomy community with cost effective commercial solutions for radio interference mitigation.

Another commercial activity endorsed this year is that of a small team undertaking a feasibility study of potential near horizon business models that leverage the telescopes and other infrastructure of the ATNF. While opportunistic commercial use has occurred in the past, the team is taking a more structured approach to the sale of telescope time, scoping in areas such as future Lunar missions, deep space missions, space situational awareness (including asteroid tracking), education and tourism.

We continue our strong endorsement of the ATNF's plans to increase gender diversity, particularly in the engineering disciplines. The appointment this year of the first Macquarie University, CSIRO Astronomy and Space Science Women in Engineering Scholarship holder is a welcome step.

On the operational front, the ATSC appoints the ATNF Users' Committee (ATUC) and the Time Assignment Committee (TAC). We are grateful for the connection to the community provided by ATUC and of the diligence of the TAC.

The ATSC is an advisory committee to the CSIRO Board. As such, we commend this Annual Report to the Board and to the astronomy community.

Director's report

Dr Douglas Bock, Director, ATNF. Photo: Wheeler Studios.

This year our newest telescope, ASKAP, achieved a major milestone by completing a program of pilot surveys with the full 36-antenna array. Each of the survey teams received around 100 hours of observing time to test and optimise their survey strategies. The strong engagement of the wider ASKAP community throughout the pilot surveys was particularly important.

The scientific highlight of the year was again ASKAP fast radio burst (FRB) detections. These flashes of high intensity radio waves have now been used to discover the missing 'ordinary' matter of the Universe. Sadly, celebrations were cut short with the death of one of the principal investigators: Jean-Pierre Macquart.

The Square Kilometre Array (SKA) project made a major advance by passing its Critical Design Reviews. We continued to prepare for construction and commenced work as the Site Entity, delivering Australia's obligations under the SKA Convention (treaty). South Africa became the first SKA host nation to ratify the treaty: it was also examined by Australia's parliamentary Joint Standing Committee on Treaties, which supported ratification in Australia. The planned partnership between CSIRO and the SKA Observatory to operate SKA in Australia is reflected in a memorandum of understanding negotiated during the year.

2019 marked the 50th anniversary of the Apollo 11 Moon landing and we include here a feature on the role our Parkes radio telescope, and Australia's space tracking facilities, played in the legendary broadcast. The anniversary was the occasion for a massive communications campaign, which captured 55.5 million views in Australia through mainstream media alone. We hope it will lead to a new wave of Australians taking up careers in science, technology, engineering and maths.

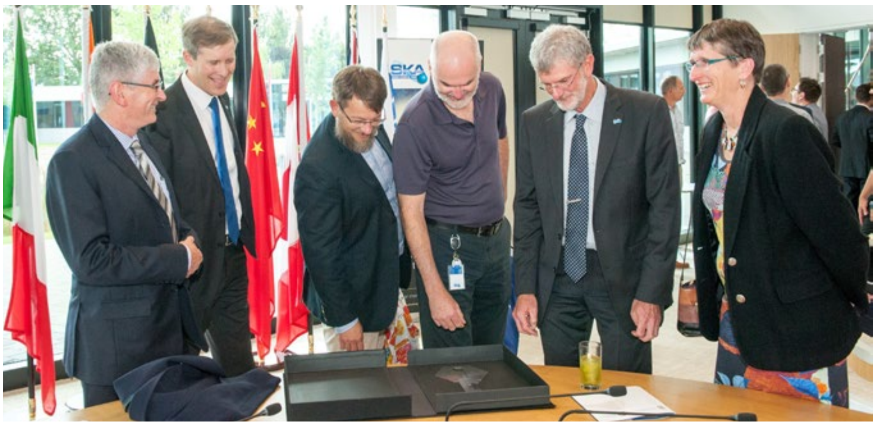
Our innovative low frequency ultra-wideband receiver has been operating on Parkes for a year and is now requested by almost all users. Parkes continued to support the Breakthrough Listen program searching for 'technosignatures' (evidence of technology) beyond our Solar System and to follow up pulsar discoveries made by China's Five-hundred metre Aperture Spherical Telescope (where our 19-beam receiver has been in operation for some two years). The next major receiver development for Parkes is a cryogenically cooled, next-generation, phased array feed receiver, supported by our university partners and the Australian Research Council (ARC).

Also with the support of the ARC and university partners, we commenced a project to replace the Australia Telescope Compact Array's aging digital signal processing 'back end' with cutting-edge digital technology developed in our Technologies for Radio Astronomy program. Along with increased bandwidth and greater observing flexibility, this technology will allow active mitigation of radio frequency interference, which is an important area of research as interference continues to increase.

Alongside growth in Australia's space industry, we started to explore new applications for our technologies. These include using our high-speed digital processing expertise on small satellites, our antennas for space situational awareness and our cutting-edge receivers for space communications.

This year has been a challenging one. The summer was one of the hottest on record and catastrophic bushfires raged in the eastern states. While our telescopes were largely unscathed, some staff lost property, and many spent their holidays volunteering with emergency services or community groups supporting them and the affected communities. Then came the COVID-19 pandemic. We took special precautions around our operations staff and telescope sites. As a consequence, and because the virus did not spread in regional Australia, we were able to maintain operations. The stresses of these strange times have been felt by all of us and I particularly wish to thank the staff of the ATNF for their tolerance, perseverance and for the support that they have provided one another.

My thanks to the ATSC, ATUC, TAC, and my management team, for their advice and guidance over the year.



Douglas Bock (second from left) with fellow Australians at the opening of the SKA Headquarters in Manchester. The ceremonial key is made from the original dish surface of the nearby Lovell Telescope. Image: SKAO.

Management team

ATNF Director and Director CSIRO Astronomy and Space Science

Douglas Bock

Deputy Director

Sarah Pearce

ATNF Chief Scientist

Elaine Sadler

Program Director, SKA

Antony Schinckel

Program Director, Technologies for Radio Astronomy

Tasso Tzioumis

Program Director, ATNF Science

Phil Edwards

Program Director, ATNF Operations

John Reynolds

Chief Operating Officer

Kate Callaghan

About us

The Australian Square Kilometre Array Pathfinder.

We operate world-class radio astronomy facilities for users from across Australia and around the world. We are global leaders in technology and research, exploiting the world's premier radio quiet site. We attract and retain the best staff.

The Australia Telescope National Facility (ATNF) is operated by Australia's national science agency, CSIRO (the Commonwealth Scientific and Industrial Research Organisation).

The ATNF comprises the:

- Parkes radio telescope
- Australia Telescope Compact Array (ATCA)
- Australian Square Kilometre Array Pathfinder (ASKAP)
- combination of instruments forming the Long Baseline Array (LBA)
- associated research and development program[1].

The ATNF is the major part of CSIRO Astronomy and Space Science (CASS), a Business Unit within CSIRO.

CASS also includes:

- NASA's Canberra Deep Space Communication Complex (CDSCC) at Tidbinbilla. We also manage Australian astronomers' access to CDSCC antennas.
- The European Space Agency (ESA) tracking station at New Norcia north of Perth.
- The CSIRO Centre for Earth Observation, which includes managing Australian researchers' access to the NovaSAR Earth observation satellite.
- CSIRO's Space Technology Future Science Platform.

Our major sites.

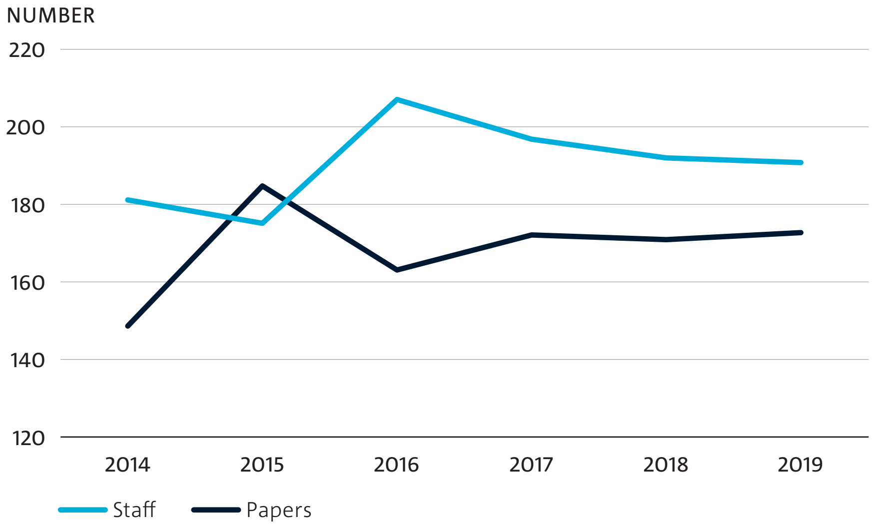


Figure 1: Total publications by staff over time.

ASKAP
Collecting area 36 x 12 m
Frequency range 0.7-1.8 GHz
Bandwidth 288 MHz
Field of view 30 deg^2

ATCA
Collecting area 6 x 22 m
Frequency range 1-105 GHz
Bandwidth 4 GHz
Configurable antenna location

Parkes Radio Telescope
Diameter 64 m
Frequency range 0.7-26 GHz
Bandwidths up to 1 GHz

1 Our 22-m Mopra telescope near Coonabarabran is not offered as part of the ATNF.

The Canberra Deep Space Communication Complex, operated by CSIRO Astronomy and Space Science. Image: CDSCC.

Mission

To develop and operate world-class National Facilities in radio astronomy.

- Operate the ATNF as a financially viable and user-focused research facility for the benefit of the Australian and international communities.
- Play a key role in the international Square Kilometre Array (SKA) project, covering in-country operations, science leadership and technology development.
- Deliver world-class science through exploitation of our southern location and technological advantages.
- Develop, apply and commercialise our innovative technologies and big data processing techniques.
- Foster a diverse and creative workforce.

Operations

The ATNF affords astronomers all over the world the opportunity to use its telescopes free of charge. Access is based on the scientific merit of the proposed observing project. Australian astronomers have access to many overseas facilities on the same principle.

Telescope access can also be purchased outside the merit allocation framework. We have such agreements with, for example, the Breakthrough Prize Foundation and the National Astronomical Observatories of China.

Twice a year a call for observing proposals is made to the international astronomical community. In recent years about 100 observing proposals have been received each semester, representing over 500 astronomers. The largest number of proposers are affiliated with Australian institutions. Beyond Australia, the countries with the largest numbers of proposers are the USA, UK, Germany and Italy.

In 2019, 132 papers using data from ATNF telescopes were published in refereed journals. Overall, our staff published 173 refereed papers, including those using data from other facilities (Fig. 1).

Governance

The Director of CASS is also the ATNF Director and is ultimately responsible to the Minister for Industry, Science and Technology via the CSIRO Executive and the CSIRO Board.

The CSIRO Board appoints the ATNF Steering Committee (ATSC) which provides high-level advice to the Director, and CSIRO, on the ongoing delivery of radio astronomy capabilities for the nation.

The ATSC appoints the ATNF Users Committee (ATUC), which represents the interests of astronomers who use ATNF telescopes, and the Time Assignment Committee (TAC), which reviews observing proposals. Committee membership is at Appendix D.

Staff and funding

The ATNF received $35.7m in funding from CSIRO: $1.8m for capital expenditure and $33.9m for operations (including overheads but not depreciation of assets). This is supplemented with $16.6m from external sources, such as sale of receivers and telescope time and funding for our SKA work (Fig. 2). Also included is $1.5m for ASKAP operations from the National Collaborative Research Infrastructure Strategy, administered by Astronomy Australia Limited. A financial summary appears in **Appendix A**.

As at 30 June 2020, CSIRO employed 191 people on activities related to radio astronomy around Australia (Fig. 3). The list of staff is at **Appendix B**.

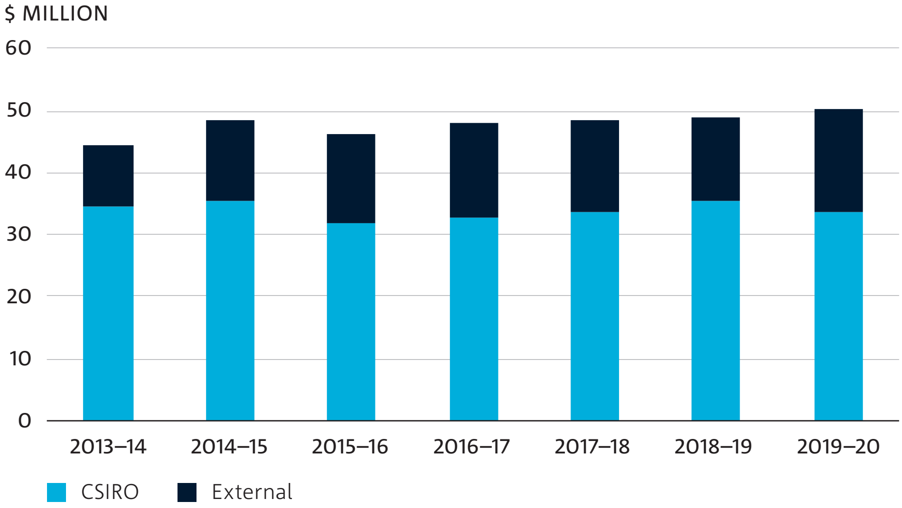


Figure 2: Funding by source over time.

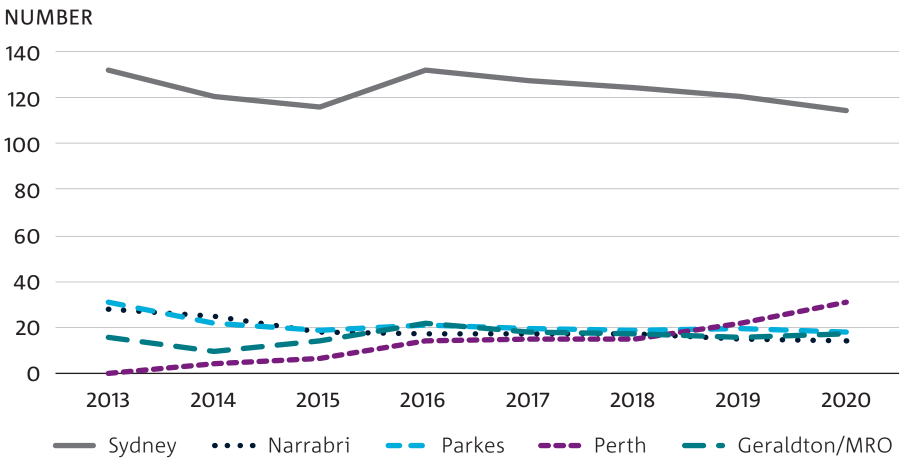


Figure 3: ATNF staff by site over time.

Traditional owners

We acknowledge the Traditional Owners of the land of all our sites and pay our respects to their Elders past, present and future:

- Marsfield, Sydney, Wallamuttagil people of the Gurringai nation
- Paul Wild Observatory, Narrabri, Gomeroi
- Parkes Observatory, Wiradjuri
- Mopra, Coonabarabran, Gamilaroi
- CDSCC, Ngunnawal and Ngambri
- Kensington, Perth, Whadjuk people of the Noongar nation
- Geraldton, Nhanhangardi, Amangu, Wilunyu and Naaguja
- Murchison Radio-astronomy Observatory and Boolardy Station, Wajarri Yamatji

This year CSIRO had plaques acknowledging the traditional owners installed in a prominent position at all our sites.

WA Senators Slade Brockman and Matt O'Sullivan visit the MRO. Image: Jesse Wotton.

Performance indicators

The Australia Telescope Compact Array.

Telescope usage

Over the two observing semesters covered by this Report 213 observing proposals were received: 113 for the April to September 2019 semester and 100 for October 2019 to March 2020.

The oversubscription rate (the factor by which proposals exceed available telescope time) was 1.2 for the Parkes radio telescope and 1.7 for ATCA (after excluding allocations for ATCA Legacy Projects) and 1.4 for the Long Baseline Array (LBA).

In this reporting period, observing proposals were received from 762 individual researchers from 34 countries. ATNF staff led 17% of these proposals, 27% were led by staff of other Australian institutions and 57% by overseas researchers.

On both ATCA and Parkes, up to 10% of time is made available as Director's Time. This is time that is initially not allocated in the published version of the schedule, but which can be made available later for approved observing projects. In this reporting period, Director's Time has been used for triggered NAPA (Non A Priori Assignable) and Target of Opportunity proposals, makeup time where proposals have lost time for various reasons, extensions of existing projects, and small pilot studies or test observations.

The key performance goals for ATCA and Parkes are:

- at least 70% of telescope time be successfully used for observing
- no more than 5% of scheduled observing time lost due to equipment failure.

ASKAP is now operating with all 36 antennas and the first surveys are complete. These Pilot Surveys were undertaken for each ASKAP Survey Science Project and were designed to incrementally test more aspects of telescope functionality and robustness and build towards commencement of full-scale survey programs.

Massive dust storms swept the central west of New South Wales in January 2020. Wind gusts peaked at 84 kilometres per hour on the dish edge. Image: Parkes Observatory webcam.

As ASKAP commenced astronomy operations, the ATSC agreed that the fraction of time successfully used for observing be 30% in 2019/20, rising 10% per year to be 70% in 2023/24. The fraction of scheduled observing time lost due to equipment failure is to be no more than 5% across all years.

In this reporting period, time successfully used for observing at Parkes rose to 79%, while ATCA fell to 75% (Fig. 4). ATCA scheduled observing time lost through equipment failure was stable, but Parkes saw a slight increase to 3%. Idle time at ATCA rose slightly while Parkes, once again, bore the brunt of bad weather. ASKAP exceeded its first performance targets, achieving 35% of time used for successful observing and only losing 2.6% of scheduled observing time due to equipment failure.

In addition, the ATNF handles proposals requesting service observations with the 70-m and 34-m antennas of the CDSCC, which are available under the Host Country agreement. In this reporting period, 113 hours were used for observing under this agreement: 95 hours were as part of the LBA. CDSCC antennas are increasingly used in partnership with ATCA (and sometimes Parkes) to track near-Earth objects. Being a communications station, CDSCC antennas transmit as well as receive. A signal is beamed at a passing asteroid and the reflection is detected by an ATNF telescope. This enables physical properties of the asteroid to be inferred and for details of its orbit to be refined.

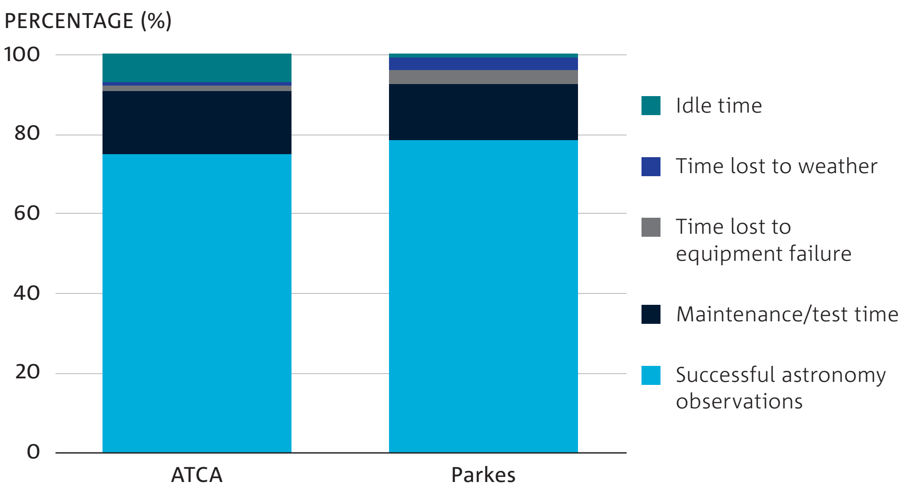


Figure 4: Use of ATCA and Parkes in this reporting period.

Time allocation

From 1 April 2019 to 31 March 2020, 91 proposals were allocated time on ATCA or the Parkes radio telescope (counting each proposal only once each even though a number were submitted in both semesters): 43 proposals were given time on ATCA and 48 on Parkes. This number has again decreased for ATCA most likely due to some large projects in recent years, such as the four on-going Legacy Projects (which take up ~35% of available observing time). To some extent, members of the Legacy Teams are tied up in those big projects, so are not submitting smaller proposals. However, we are now starting to see more ASKAP follow-up proposals for time on ATCA. In this period, 14 proposals were allocated time on the LBA and 2 on CDSCC antennas. Successful proposals are listed in **Appendix G**.

Time allocated to observing teams using ATCA and Parkes (broken down in different ways) is shown in Figures 5-8 (where each year captures the observing semesters that end in that year, except for 2017 which captures October 2016 to March 2018). The trend over the last six years has been for a greater proportion of ATCA time to go to investigators from Australian universities, at the expense of overseas investigators, and for there to be a slight increase in the proportion of Parkes time going to CSIRO investigators, at the expense of `other Australian' researchers. LBA experiments involved 17 unique principal investigators (PIs), 6 of whom were affiliated with an Australian institution. Australian collaborators were involved in 10 of the 12 experiments that were led by international PIs.

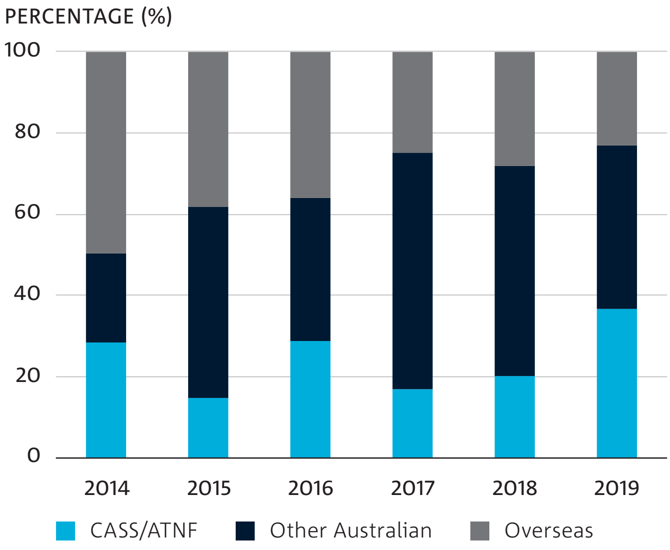


Figure 5: ATCA time allocation by PI.

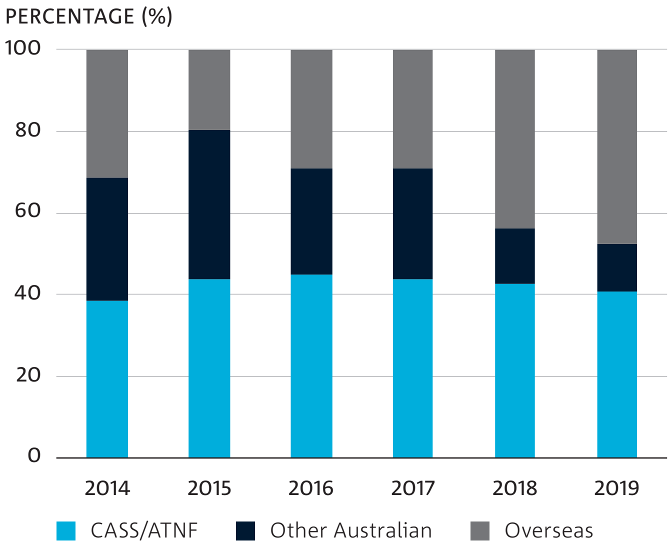


Figure 6: Parkes time allocation by PI.

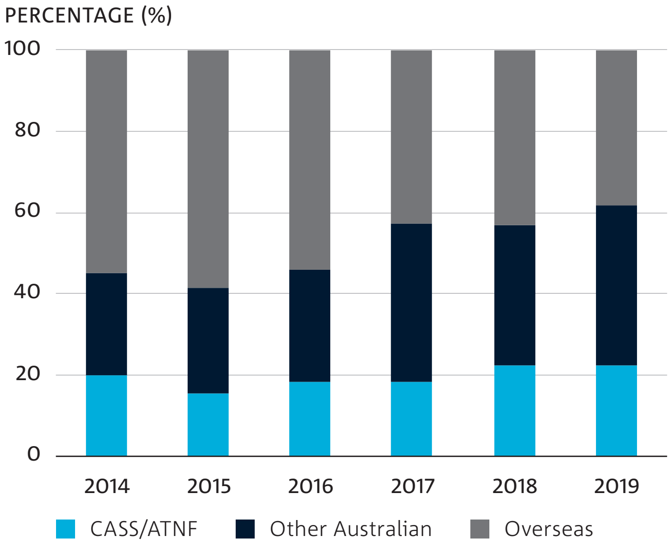


Figure 7: ATCA time allocation by all investigators. Time allocated to each proposal has been divided evenly between all authors on the proposal.

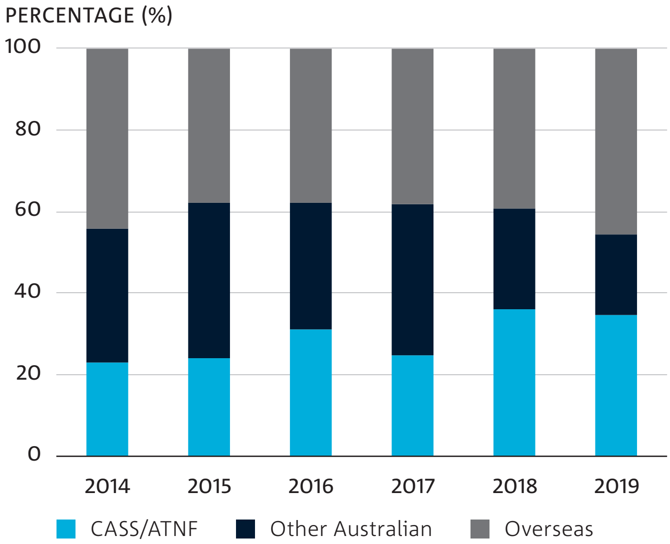


Figure 8: Parkes time allocation by all investigators. Time allocated to each proposal has been divided evenly between all authors on the proposal.

Publications

In 2019, 132 papers using data from ATNF telescopes were published in refereed journals. Of these, 65% included a CSIRO author or authors.

In 2019 there were 173 refereed publications by ATNF staff, including scientific papers with data from other facilities. In total, 219 refereed journal papers and 18 conference papers – both those using National Facility data and other papers by our staff – were published during the year. They are listed in **Appendix H**.

As anticipated, ASKAP publications have risen significantly in the last year with the results of Early Science and the first Pilot Survey observations now flowing through. ATCA publications have dropped a little, which was expected given the significant fraction of time devoted to the Legacy Projects in recent years.

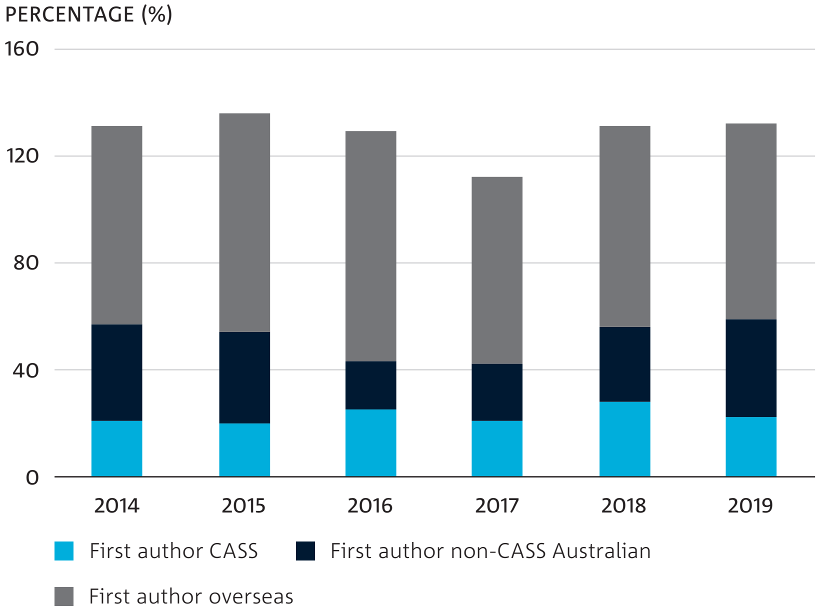


Figure 9: Publications that use data from ATNF telescopes by calendar year.

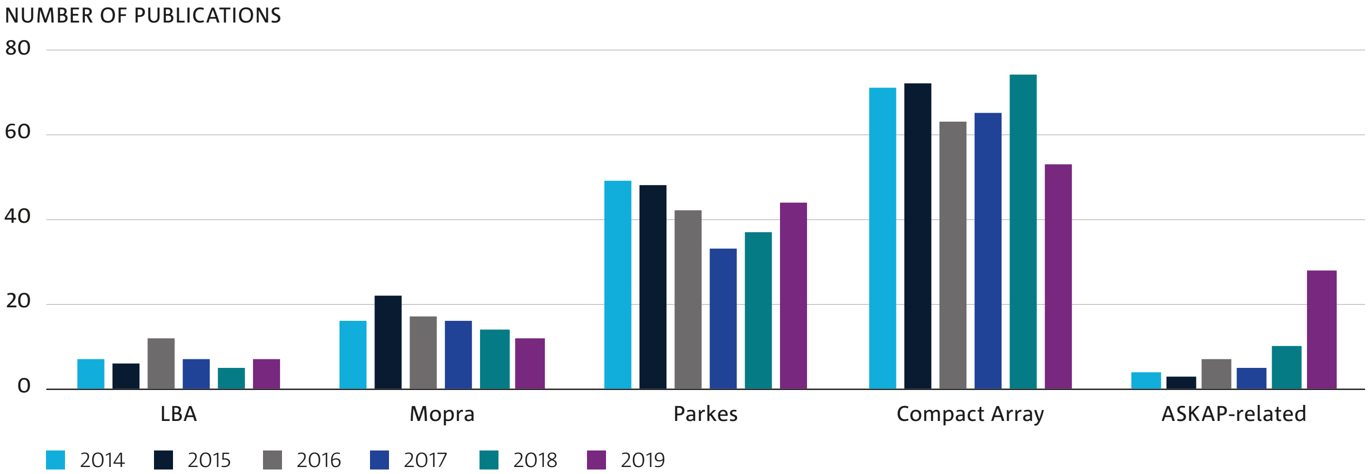


Figure 10: Publications in refereed journals that include data from ATNF telescopes grouped by telescope. A few papers with data from more than one instrument are counted more than once.

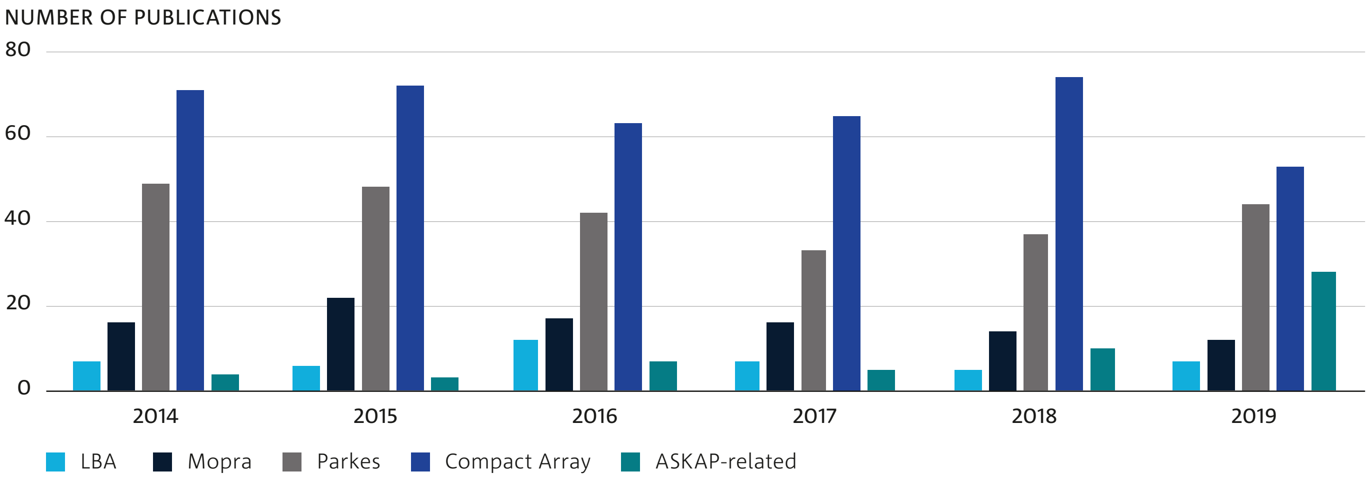
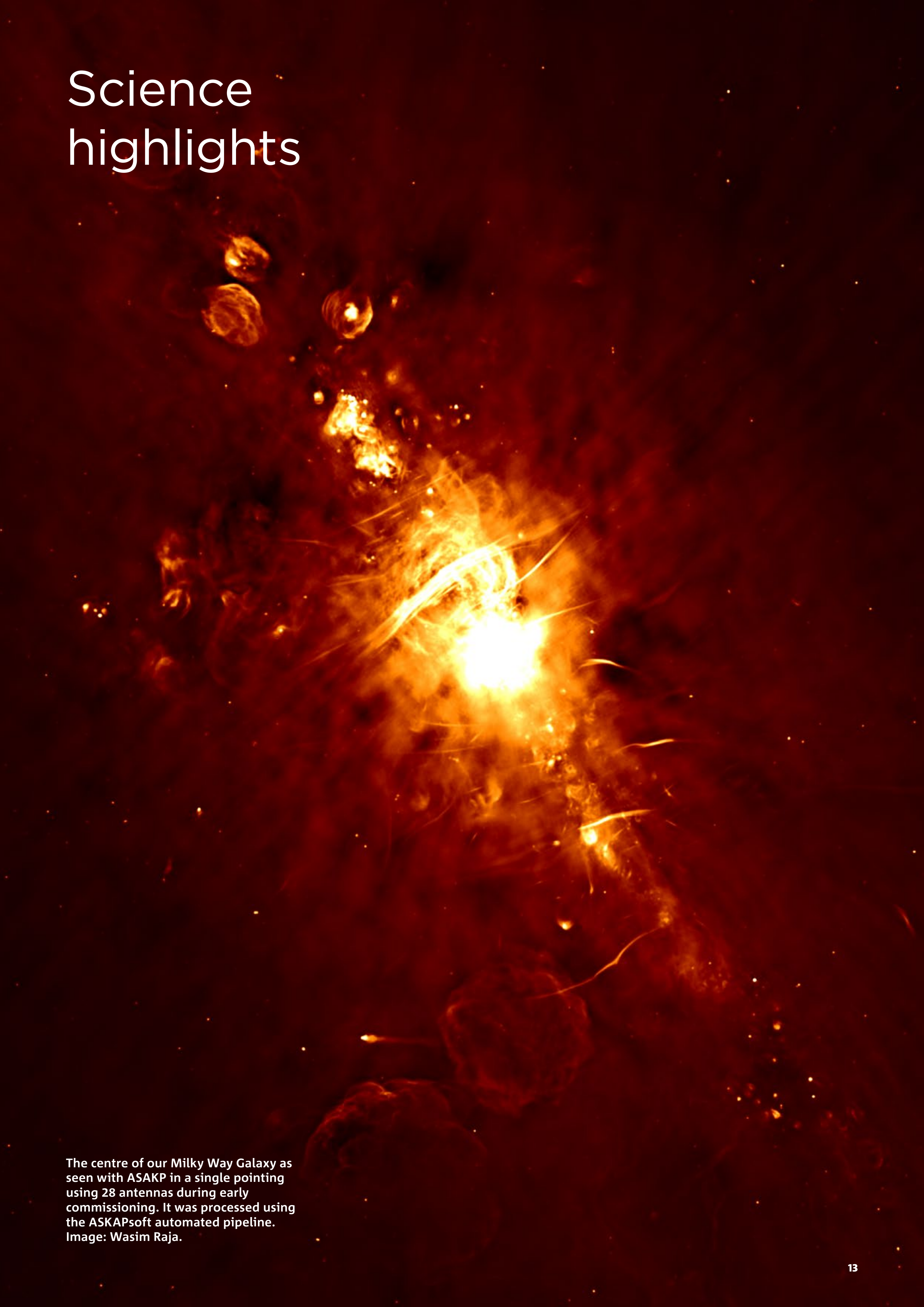


Figure 11: Publications in refereed journals that include data from ATNF telescopes grouped by year. A few papers with data from more than one instrument are counted more than once.

Science highlights



The centre of our Milky Way Galaxy as seen with ASAKP in a single pointing using 28 antennas during early commissioning. It was processed using the ASKAPsoft automated pipeline. Image: Wasim Raja.

ATCA helps capture details of mysterious ‘cow’

Anna Ho
California Institute of Technology

ATCA and other telescopes have observed the first nearby example of a new class of cosmic object: fast blue optical transients, which first appeared in optical surveys.

In the last decade astronomers started doing surveys that visited each target patch of sky once a night. This revealed transient sources previously missed, including highly luminous ones that rose and fell in just a few days.

These rapid transients appeared in star-forming galaxies, which hinted that they might be unusual supernovae (exploding stars). But most examples were too far away ($z > 0.1$) to observe in detail. And most were found in recorded data well after they had faded, so they were not followed up with other observations.

In 2018 the ATLAS telescope in Hawaii spotted a source brightening rapidly at optical wavelengths. Officially named AT2018cow (and quickly dubbed ‘the cow’), it was clearly something unusual: it reached peak brightness three to six times faster than ordinary supernovae and it became 10-100 times brighter. Its spectrum was not typical of a supernova. And no gamma-rays were seen, suggesting it was not a gamma-ray burst either.

AT2018cow lay in the galaxy CGCG 137-068, 196 million light-years (60 Mpc) away – close enough to study in detail. Soon at least two dozen major telescopes were trained on it.

Most transient sources are hard to detect at millimetre (short radio) wavelengths, being either too dim or fading within a day. But AT2018cow was still bright days after its discovery. Anna Ho (Caltech) and her collaborators were able to observe it at wavelengths from radio to submillimetre, using ATCA (at 5-34 GHz), the Smithsonian Millimeter Array (215-351 GHz) and the Atacama Large Millimeter/submillimeter Array (336-671 GHz). Their observations spanned 76 days.

AT2018cow proved to be a remarkable radio source. Peaking at nearly 10^{41} ergs, it was far stronger at radio wavelengths than even the most radio-luminous supernovae.

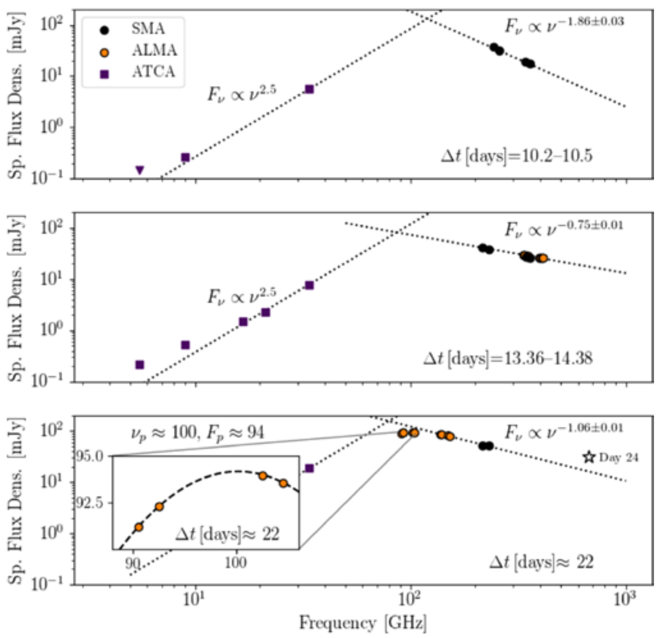
Their wide range of observing frequencies let Ho and her collaborators gauge the source’s spectral energy distribution (SED): how the signal strength varies with frequency. The distribution’s shape implied that the millimetre/submillimetre emission was coming from a shell of dense gas impacted by a shock wave from an explosion.

Because the observations stretched over several weeks, the researchers could look at how the SED changed with time and measure or estimate its peak on different dates. The emission peaked at relatively high frequencies, implying that the initial explosion was very energetic and had taken place inside dense gas.

From their own observations, and those of others, Ho and her collaborators pieced together a picture of what had unfolded in AT2018cow. Fast-moving ejecta from an explosion sped out into a dense shell of gas, giving rise to the radio emission. Slower ejecta, heated by a central source, expanded and emitted ultraviolet, optical and infrared radiation. And within the dense radio-emitting shell, a black hole or magnetar drove the generation of X-rays.

So, what was AT2018cow? The most likely options are a supernova, or a star being ripped apart by a black hole (a tidal disruption event). The millimetre and radio observations point to the presence of high-density gas, which favours a supernova. AT2018cow stood out from other fast transients because of its strong millimetre and submillimetre emission; however, other supernovae might appear just as bright at millimetre wavelengths if observed early in their development, Ho and her collaborators suggest.

Ho, A.Y.Q.; Phinney, E.S.; Ravi, V.; et al. “AT2018cow: A Luminous Millimeter Transient.” ApJ, 871:73 (2019).



The spectrum of AT2018cow at three epochs (from Ho et al. 2019). The ATCA data at frequencies below 40 GHz are consistent with an optically thick, or self-absorbed, spectrum whereas at higher frequencies the spectrum becomes optically thin.

ASKAP finds the Universe's missing matter

Jean-Pierre Macquart
International Centre for Radio Astronomy Research, Curtin University

By pinpointing the origins of fast radio bursts (FRBs), ASKAP has fulfilled a 20-year quest to locate most of the 'ordinary' matter (that is, not dark matter) in the Universe.

Stars and planets, gas and dust, trees and people – all are made of particles called baryons, collectively known as baryonic matter. But the Universe is also home to the exotic dark matter and dark energy. And the dark stuff dominates. In the 1990s cosmologists calculated that baryonic matter makes up less than 5% of the Universe's mass.

Astronomers then set out to look for all the baryonic matter. Yet, after two decades, they'd found only half of what was expected. The problem? Less than a quarter of the Universe's baryons are in galaxies and galaxy clusters – places where they could be readily observed. The rest were thought to lurk, chiefly in the form of charged particles, in the space between galaxies.

Here they were hard to detect: all the existing techniques for finding them had limitations. What astronomers needed was a new, comprehensive tool. They got one, in the form of FRBs.

Discovered in Parkes data in 2007, FRBs are short, sharp spikes of radio energy. Most come from galaxies beyond ours, often at great distances. Bursts interact with all the charged particles they meet on their journey to Earth, which slows them down. The longer radio wavelengths in a burst are delayed most and arrive on Earth a little later than the shorter ones. This tell-tale sign is called frequency dispersion.

A burst can meet matter anywhere along on its path: in and around its galaxy of origin, in intergalactic space, and then in and around our Galaxy. All this matter will increase the burst's frequency dispersion, but only the matter in intergalactic space will contribute a distance-related component. The further an FRB travels – that is, the greater its redshift – the more frequency dispersion it shows.

ASKAP began hunting for fast radio bursts in 2017 as part of the CRAFT (Commensal Real-time ASKAP Fast Transients) survey, a project started by Jean-Pierre Macquart (ICRAR/Curtin University) and then jointly led by him, Keith Bannister (CSIRO), and Ryan Shannon (Swinburne University of Technology). In 2018 the CRAFT team used ASKAP to both detect a single FRB pulse and identify the galaxy it came from – the first time this had been done.

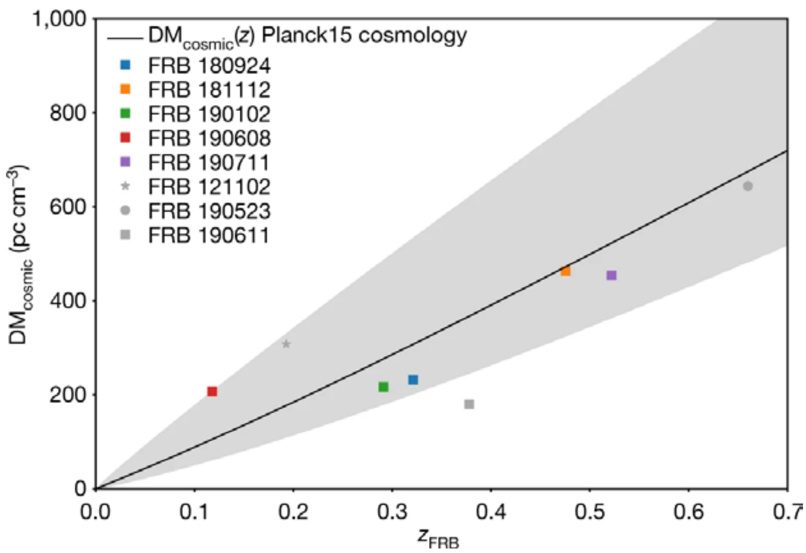
By July 2019 the team had a number of FRBs that had been traced to their host galaxies. Five were considered outstandingly good examples.

Macquart led an analysis of these bursts and others that had been localised to within an arcsecond. He and collaborators took the bursts' measured frequency dispersion (abbreviated as DM) and subtracted estimates for the contributions associated with both our Galaxy and the host galaxies. This gave them the contribution from intergalactic baryons, DM_{cosmic}. Then for each burst they plotted DM_{cosmic} against the host galaxy's redshift, z_{FRB}.

The points matched the relation predicted by theory. Macquart and his collaborators had found the missing baryons. The DM_{cosmic}–z_{FRB} relation has now been named the Macquart relation. The Macquart relation has more to give. When they have many FRBs to work with, astronomers will be able to use it to constrain the density of baryons around both our Galaxy and the FRB host galaxies.

Jean-Pierre Macquart died unexpectedly on 9 June 2020, 11 days after this work was published in *Nature*. He was one of Australia's leading theoretical astrophysicists and his work on FRBs is a major part of his legacy.

Macquart, J.; Prochaska, J.X.; McQuinn, M; et al. "A census of baryons in the Universe from localized fast radio bursts." Nature 581, 391-395 (2020)



The DM_{cosmic}–redshift relation (Macquart relation) for localised FRBs. The solid line is the predicted relationship. The shaded region covers 90% of the DM_{cosmic} values allowed by a model of galactic halos (from Macquart et al. 2020).

Parkes proves a spinning white dwarf drags space-time

Vivek Venkatraman Krishnan
Max Planck Institute for Radio Astronomy

Eighteen years of observations with the Parkes radio telescope have established that a fast-spinning white dwarf star is dragging space-time in its vicinity around with it. It's the first time this effect has been seen in a binary pulsar system.

PSR J1141–6545 is a radio pulsar with a spin period of ~394 milliseconds. It orbits its companion star, a white dwarf, in just under five hours. The system is one of only two pulsar-white dwarf partnerships where the white dwarf is known to have formed before the pulsar. This implies that the system evolved in an unusual way, with the white dwarf being 'spun up' by material transferred from its companion star before that star exploded and created the pulsar.

PSR J1141–6545 was discovered with the Parkes telescope in 1999. An international team led by Swinburne University of Technology has spent two decades recording the times its pulses arrive on Earth, using both Parkes and, since 2015, the University of Sydney's UTMOST telescope. This pulsar timing has been used to measure the system's characteristics with exquisite accuracy.

In 2008 the researchers showed the pulsar's orbit is shrinking (Bhat et al. 2008). Now a member of this research group, Vivek Venkatraman Krishnan (MPIfR), has led work which demonstrates that the plane of the orbit is also tilting (known as precessing).

The changing tilt is being driven mainly by the spin of the white dwarf through two effects. One is a Newtonian (non-relativistic) effect, quadrupole spin-orbit coupling. The other is a prediction of the general theory of relativity: frame-dragging, in which a spinning body drags nearby space-time around with it.

Venkatraman Krishnan and his collaborators sought to establish the sizes of these two effects. They measured the rate at which the pulsar's orbital plane is tilting. But there were key unknowns: two angles in the geometry of the system and the white dwarf's spin period.

The researchers used Markov chain Monte Carlo computations to obtain likelihood distributions for both effects. For all allowed values of the two unknown angles, there was always a contribution from frame-dragging. Frame-dragging has been seen before – satellites have confirmed that the spinning Earth creates it – but this is the first time it has been shown to occur in a binary pulsar system.

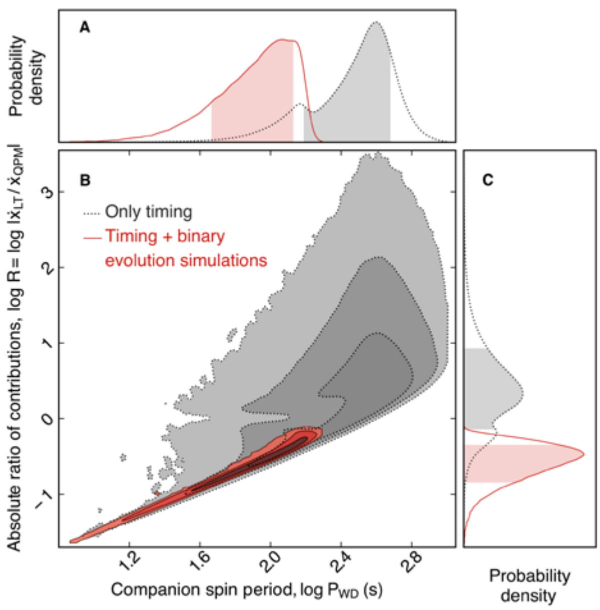
Using Bayesian statistics, the researchers also inferred that the white dwarf takes no more than 900 seconds (15 minutes) to spin around. This is extraordinarily fast and confirms that this star was indeed 'spun up' by mass transfer from its original companion.

With that evidence in hand, the researchers ran simulations of how the system had evolved. These let them constrain the white dwarf's spin period even further, to less than 200 seconds.

By measuring the relativistic effects in the PSR J1141–6545 system, Venkatraman Krishnan and his collaborators have determined the masses of both the white dwarf and the pulsar; measured the inclination of the pulsar's orbit and its rate of change; put a upper limit on the white dwarf's spin period; and confirmed the history of this remarkable system.

Bhat, N.D.R; Bailes, M.; and Verbiest, J.P.W. "Gravitational-radiation losses from the pulsar-white-dwarf binary PSR J1141-6545". Phys. Rev. D 77, 124017 (2008)

Venkatraman Krishnan, V.; Bailes, M.; van Straten, W.; et al. "Lense-Thirring frame-dragging induced by a fast-rotating white dwarf in a binary pulsar system", Science, vol. 367, issue 6477, pp. 577-580 (2020)



The rapid rotation of the white dwarf companion to PSR J1141–6545 induces relativistic (LT) and non-relativistic (QPM) spin-orbit interactions that cause the pulsar's orbit to precess ($\dot{X}$). Panel B shows the constraints on the white dwarf's spin period and the absolute ratio of the two contributions. The contours define 68%, 95% and 99% likelihood confidence intervals: the grey, dotted contours arise only from pulsar timing, while the red, solid ones also include constraints from binary evolution simulations. Panels A and C show the corresponding derived probability densities with their 68% confidence intervals shaded (adapted from Venkatraman Krishnan et al. 2020).

ATCA sees star-making potential of little galaxy

Katherine Jameson
Australian National University

A tiny galaxy that orbits ours has turned out to be surprisingly rich in cold atomic hydrogen, a phase gas goes through on its way to forming stars. For a galaxy to make stars, it must first cool and condense some of its reservoir of atomic hydrogen gas (HI) into clouds of molecular hydrogen (H_2). If these clouds collapse and compress the gas further, stars form.

In our galaxy, the Milky Way, the HI is cooled mostly by elements such as oxygen and carbon in the interstellar medium, the gas between the stars. But what happens in galaxies where the interstellar medium is very different? A test case, the Small Magellanic Cloud (SMC), orbits the Milky Way. The SMC is an irregular dwarf galaxy and its interstellar medium is far less rich in oxygen and carbon than the Milky Way's. To see how well the SMC cools HI, we need to determine what fraction of its gas is cold. The key tool for doing this is the characteristic radio emission of HI, a spectral line with a wavelength 21 cm.

HI both emits this radiation and absorbs it: hot gas tends to emit while cool gas tends to absorb. To trace cold HI in a galaxy, astronomers look for regions absorbing 21-cm emission from background radio sources (that is, galaxies behind the one being studied).

Katherine Jameson, an ANU postdoc at the time and now an ATNF Bolton Fellow, and her collaborators used ATCA to look for HI absorption across the SMC, detecting it against 37 of their 55 background sources. ATCA, with its high angular resolving power, is ideal for looking for the absorption signal because it's not sensitive to the large-scale emission from the warm HI.

The researchers then compared their absorption measurements with previous measurements of SMC HI emission that combined Parkes and ATCA data. The ratio of absorption to emission gives the average 'spin temperature' (which tracks the gas's average physical temperature) of the mixture of cold and warm gas along the line of sight.

Each feature in the absorption spectra represents an individual cold HI cloud. Taking them one by one, Jameson and her collaborators plotted absorption as a function of emission and used the resulting plots to estimate the clouds' temperatures. The average temperature was ~30 K (-243 C), about 10 degrees lower than that of cold clouds in the Milky Way.

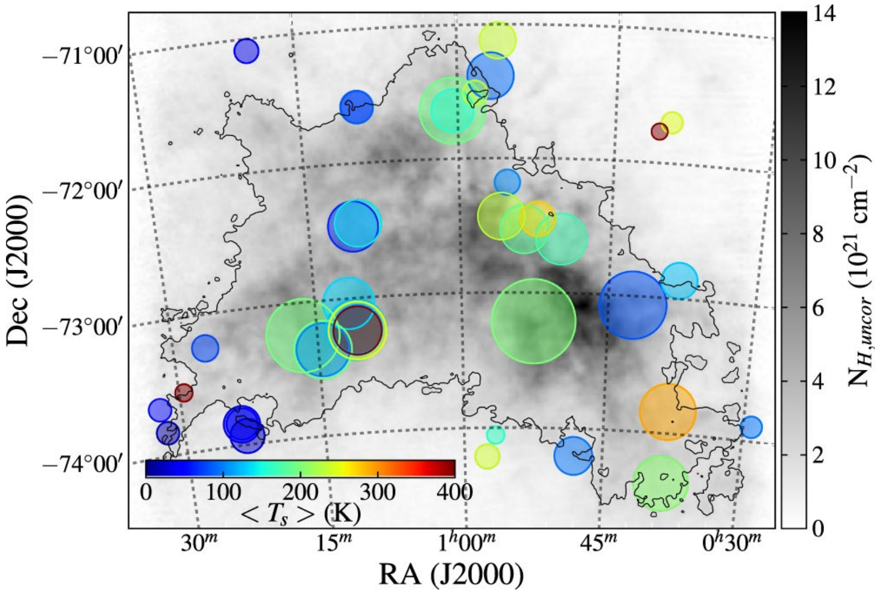
Strikingly, the temperatures of these clouds seem unrelated to their opacity, their location in the SMC, or the amount of HI along the line of sight. The cold clouds seem to be peppered randomly throughout the warm gas. The average spin temperature of the SMC gas was 150 K. From this the researchers calculated the fraction of cold HI in the SMC to be ~20%, which is similar to that of the Milky Way (~15-20%).

This work builds on an ATCA study of the SMC carried out in the 1990s (Dickey et al. 2000). Upgrades done since then have given ATCA greater sensitivity and velocity resolution. As a result, Jameson and her collaborators detected absorption in three times as many sources, including seven in which Dickey et al. had not seen absorption.

Despite its very different chemical composition, the SMC is as rich in cold HI clouds as the Milky Way. How the SMC has cooled this gas is still an open question.

Dickey, J.M.; Mebold, U.; Stanimirovic, S.; and Staveley-Smith, L. "Cold Atomic Gas in the Small Magellanic Cloud". ApJ, 536:756–772 (2000)

Jameson, K.E.; McClure-Griffiths, N.M; Liu, B.; et al. "An ATCA Survey of HI Absorption in the Magellanic Clouds. I. HI Gas Temperature Measurements in the Small Magellanic Cloud". ApJ Supplement Series, 244:7 (2019)



Spin temperatures measured with ATCA across the Small Magellanic Cloud. The greyscale background shows HI density. Coloured circles represent average spin temperature along the line of sight (colour scale, bottom left): these temperatures are generally low, suggesting a significant fraction of cold gas. The size of each circle shows the measurement's signal-to-noise ratio. (From Jameson et al. 2019)

LBA tracks a travelling trigger for masers

Ross Burns
National Astronomical Observatory of Japan

The Long Baseline Array (LBA) has seen an expanding ring of radio emission that may signal a young star 'feeding'. Stars grow in fits and starts. A protostar is born in a disk of gas and dust. Every so often the disk sheds clumps of gas that fall onto the infant object, fattening it up.

Astronomers have known for decades that some types of low-mass stars grow in this episodic way. But in the last few years they've realised high-mass stars must too. Now they're looking for signs of the process – known as variable accretion – at work.

Accretion is hard to spot directly but can be detected through its effect on bright radio sources called masers. These develop around a star in regions of gas where the temperature and density are just right and are powered by the star's radiation. Young high-mass stars are often signposted by a particular kind of maser, one created by methanol molecules and emitting radio waves at 6.7 GHz.

In 2006 the Parkes radio telescope found a source of this 6.7-GHz emission, G358.93-0.03, lying 22 000 light-years (6.75 kpc) away in our Galaxy. In 2019 NOAJ's Hitachi 32-m telescope north of Tokyo saw this source flaring: its 6.7-GHz emission jumping ninefold in less than two weeks.

Follow-up observations were made at several wavelengths. In the submillimetre, G358.93-0.03 was resolved into a cluster of several objects: the strongest, G358-MM1, was seen to brighten almost threefold. G358-MM1 looked to be a high-mass protostar undergoing accretion.

Ross Burns (NAOJ) and his collaborators used the LBA to study the 6.7 GHz maser emission around G358–MM1 at high resolution. They observed twice, 26 days apart. The first round of observations used Australian antennas (ATCA, Mopra and antennas at Ceduna and Hobart), plus others at Warkworth, New Zealand, and Hartebeesthoek, South Africa; the second round used the same line-up but with Parkes instead of Hartebeesthoek.

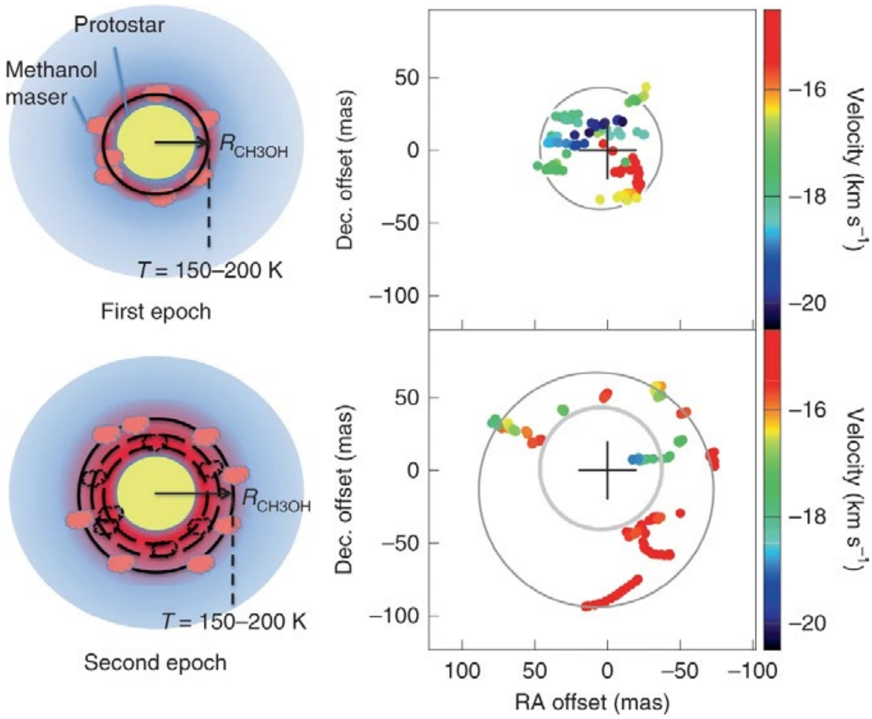
The maser emission lay roughly in a ring, centred on a core detected at millimetre wavelengths. This ring is probably the edge of a three-dimensional shell surrounding G358-MM1.

The ring swelled rapidly between the two observations, its radius growing from 40 milliarcseconds to 77 in 26 days – that is, between 1 and 2 milliarcseconds per day. Given the source's distance, this growth rate corresponds to 4-8% of the speed of light. But methanol clouds can't travel that fast. The researchers concluded they were seeing masers being kindled then quenched in an expanding shell, as conditions favourable for making them propagated out from G358-MM1. The travelling trigger for maser formation was probably a 'heatwave' – a higher level of far-infrared radiation that poured out of G358-MM1 after a clump of gas fell onto the young star.

Two other high-mass protostars, S255IR-NIRS3 and NGC6334I-MM1, have been seen to brighten rapidly, apparently as the result of accretion. But G358-MM1's outburst differed from those events: it rose and fell faster and didn't brighten at millimetre or near-infrared wavelengths.

High-resolution maser observations of similar events will help show how diverse accretion bursts can be in high-mass stars. And studying examples of episodic accretion in our Galaxy will help us understand it in the early universe, where, modelling suggests, it was ubiquitous.

Burns, R.A.; Sugiyama, K.; Hirota, T.; et al. "A heatwave of accretion energy traced by masers in the G358-MM1 high-mass maser protostar." Nature Astronomy, 4, 506-510 (2020).



Schematic illustration of the methanol masers observed in G358-MM1. (From Burns et al.)

Observatory reports

The Parkes radio telescope tracks the Moon in rehearsal for the Apollo 11 landing. Image: ATNF Image Archive.

Australia Telescope Compact Array

Australia's High Commissioner to South Africa, Ms Gita Kumath, visits in September. Image Phil Edwards.

Science highlights

- Following a rapid response trigger from a maser flare toward the system G 358.931-0.030, ATCA examined how several different species of maser emissions varied. Observations revealed three new torsionally-excited class II methanol maser transitions, which will enable significant improvements to models of this class of masers and illustrates the importance of rapid response (Breen et al. 2019 ApJ 876, L25).
- Long-term ATCA observations of the binary neutron-star merger GW 170817, famous as the first observed electromagnetic counterpart to a gravitational-wave detection, led to the conclusion that the collision produced a relativistic jet (Troja et al. 2019 MNRAS 489, 1919).
- ATCA was used to confirm the discovery of a new gamma-ray binary system 4FGL J1405.1-6119, which is likely to be an O-star and rapidly rotating neutron star pair. (Corbet et al. 2019 ApJ 884, 93).

GLASS, the GAMA Legacy ATCA Southern Survey, is now complete after 3051 hours observing. It began in October 2016. Of the three remaining Legacy Projects (which together are allocated roughly one-third of observing time), Imaging Galaxies Intergalactic and Nearby Environments (IMAGINE) will finish next.

Early in 2020, the Narrabri region welcomed the return of widespread rainfall, but the rain also revealed the sorry state of the weatherproof covers over the vertex rooms in each dish (these rooms sit directly under the dish surface and house the receivers). Covers were coming loose and were no longer watertight. With no spares, and the original material no longer available, the hunt was on to find a lightweight but strong material able to withstand harsh climatic conditions, bird droppings, bird strike, and yet be invisible to radio waves. After much bench testing and prototyping, the antennas now bear brand new Dyneema covers and sensors have been installed to detect if the covers come off.

An exceptional feature of ATCA is that five of its six antennas move along railway tracks. Once in the right position, the antenna is plugged into the nearest station post, which provides power and data connectivity. After 30 years the electrics were in need of attention and water ingress was noted in several stations. We have overhauled stations on the north-south track and are now working on the east-west track.

The buildings on site also got some attention this year. The control building switchboard was replaced and a second uninterruptible power supply installed, lessening the chance of power failure to the screened room (housing such important systems as the correlator and timing equipment). The visitors centre was closed in March in response to COVID-19, giving us the opportunity to renovate its interior.

Early in 2020 we and our university partners were awarded an Australian Research Council grant to replace the Compact Array Broadband Backend, the digital signal processing system that converts raw data from ATCA's antennas into information astronomers can use. CABB was one of the earliest broadband digital systems and a world-leader when it was built 15 years ago, but technology has moved on and we can no longer source spare parts. CSIRO will receive $530 000 as part of the overall $2.6m project led by Western Sydney University to develop a state-of-the-art system based on modern signal processing techniques and cutting-edge software (see **Technology development**). This will double the telescope's bandwidth, preparing ATCA for its next career: particularly in following up ASKAP detections.

Repairing station posts. Image: Tim Wilson.

Parkes radio telescope

Science highlights

- Publication of the 2.3 GHz (S-Band) all sky polarisation survey with Parkes, revealing magnetised structure across the southern sky, including prominent depolarisation towards the inner Galaxy (Carretti et al. 2019 MNRAS 489, 2330).
- Discovery of five millisecond pulsars in the Omega Centauri globular cluster through a combination of Parkes' ultra-wideband receiver and ATCA observations (Dai et al. 2020 ApJ 888:L18).
- 40 new pulsars from the High Time Resolution Universe Pulsar Survey (Cameron et al. 2020 MNRAS 493 1063).

2019 was, of course, the Apollo 11 50th Anniversary (see overleaf). This was further commemorated by the IEEE honouring Parkes with the first of its prestigious Milestones to be recognised in Australia.

We are in the midst of a program to update the receiver suite of our 64-m steerable dish. The low frequency ultra-wideband receiver (UWB-L), installed in 2018 (Hobbs et al. 2020 PASA 37, E012), is now enabling impactful science. Indeed, in the October 2019 semester, the astronomy community almost universally requested the UWB-L in its observing proposals.

The Breakthrough Listen project maintained its regular observing (~1700 hours across the year), completing its Galactic plane survey and targeted searches of nearby stars (e.g. Price et al. 2020 AJ 159, 86). This project has now largely transitioned to observing with the UWB-L and commenced a deep search of the Galactic centre.

Observing projects have this year transitioned to the new web-based control system, DHAGU (the Wiradjuri word for 'where to?'), designed for the UWB-L, and new UWB-L modes of operation have continued to expand: for example, simultaneously observing in high spectral- and high time-resolution modes. We ran three training sessions for UWB-L and DHAGU in March attracting ~50 participants. These were to be in person but transitioned to online in light of COVID-19.

With remote observing being the norm, Parkes continued observing through the months impacted by COVID-19. Our education and outreach program, PULSE@Parkes also continued, albeit online (see **People and community**). COVID-19 presented the opportunity of characterising the radio frequency interference (RFI) environment (because the visitors' centre was closed and there were fewer aircraft). Led by George Hobbs, the team characterised signals within the UWB-L band and how they varied with time and direction. These data are being folded into our work on active RFI mitigation (see **Technology development**).

While Parkes weathered COVID-19, the hot, dry summer that preceded the pandemic was a real challenge. Days over 38°C required observing only in directions where the breeze could cool the dish and Site Leader, Mal Smith, was driven to hose down the compressors to keep the telescope operational. But some days were simply too hot, and the telescope had to be stowed. The region was also hit by severe dust storms.

There were no large maintenance shutdowns this year, but the telescope jacks (which lift the moveable telescope structure much like a car jack) were extensively refurbished. This work is crucial to upcoming maintenance of the azimuth gearboxes and other systems.

The transformation of the Parkes receiver fleet continues with development of a cryogenically cooled next-generation phased array feed receiving funding from the Australian Research Council in early 2020. The full-size prototype is under construction (see **Technology development**).

The jacks (blue) that lift the movable part of the telescope structure were overhauled this year. Image: Brett Preisig.

Parkes is honoured with the first IEEE Milestone to be made in Australia, for achievement of reception of the Apollo 11 TV and telemetry signals. On 11 October 2019, IEEE President Elect, Prof Toshio Fukuda, and IEEE History Committee representative, Mr David Burger, unveiled the plaque. Image: John Sarkissian.

Parkes' giant leap

At 12.56 pm on Monday, 21 July 1969, 600 million people watched the first human step on the Moon through television signals received courtesy of Australian radio astronomy and space tracking facilities.

CSIRO's Parkes radio telescope is designed to track galaxies and pulsars and other astronomical objects across the sky and its large collecting area (the dish has a diameter of 64 m) gives it great sensitivity. These capabilities also make Parkes ideal for tracking spacecraft.

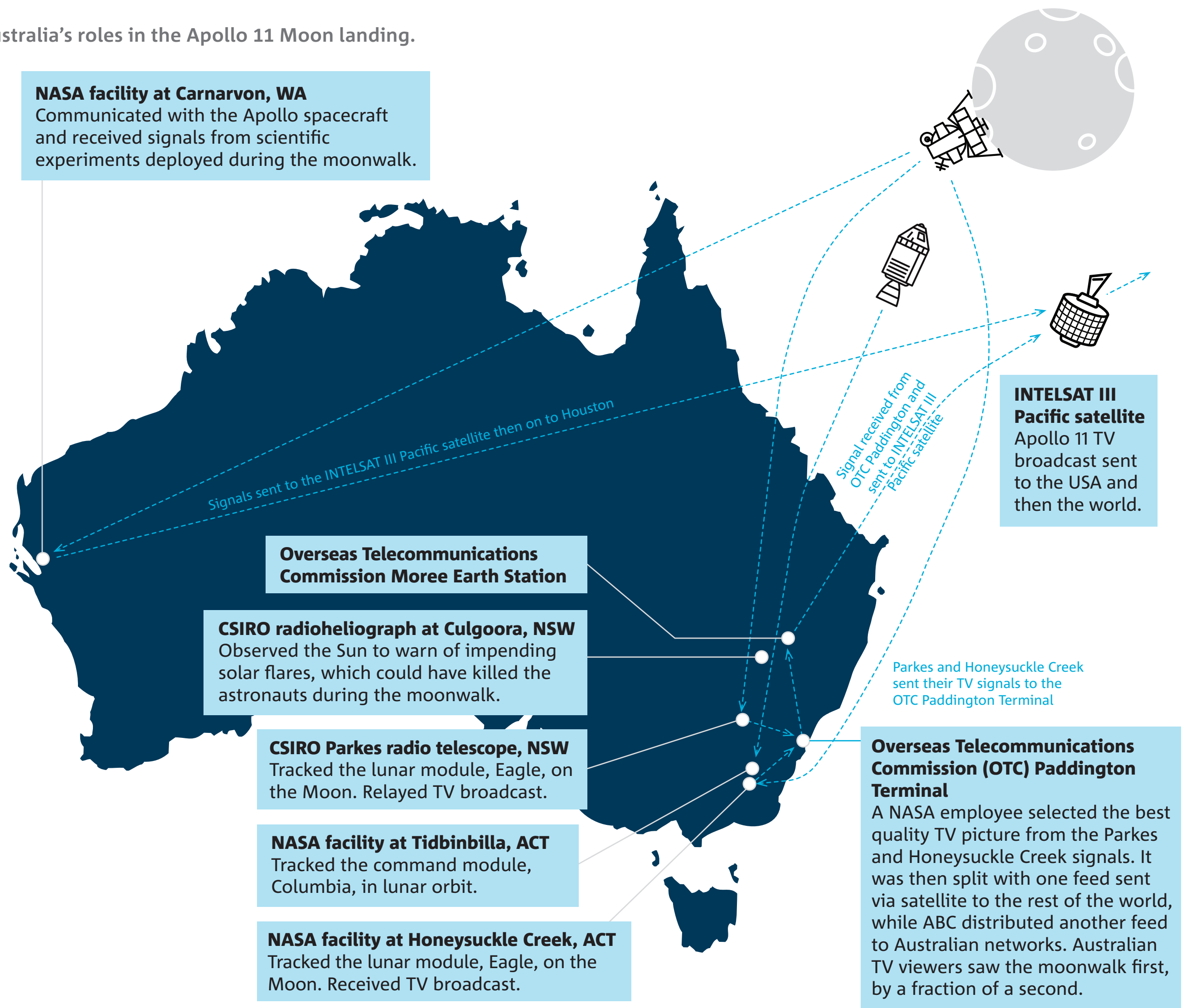
In late 1968, NASA requested the involvement of Parkes in the upcoming Apollo 11 mission to receive the faint signals from the lunar module while it was on the surface of the Moon.

In the original mission plan, the astronauts would land during the coverage period of NASA's Goldstone tracking station in California, USA, at 6.17 am (AEST) with the moonwalk occurring soon after landing. The moon would not rise at Parkes until 1.02 pm (AEST), so Parkes would be a backup in case of a delayed moonwalk. NASA's tracking station at Honeysuckle Creek, near Canberra, Australia, would track the command module and co-ordinate the other Australian stations, during the moonwalk (see graphic).

Australia's Postmaster General's department established microwave links and voice communication channels for Parkes. NASA provided data recorders, equipment to convert incoming signals from the Moon into a television picture and the receiving equipment. CSIRO designed and built the feed horns for the Parkes receivers to NASA specifications (see box).

Some two months before launch NASA changed the plan: the astronauts were now required to rest for ten hours after landing. This meant the Moon would have set for Goldstone before the moonwalk began, but it would be high overhead at Parkes. Consequently, Parkes' role was upgraded from backup to prime receiving station for the historic moonwalk.

Australia's roles in the Apollo 11 Moon landing.





L to R: Neil 'Fox' Mason and Dennis Gill at the control desk. Fox drove the dish throughout the moonwalk but was not allowed to leave his post so did not see the famous event until the TV replay that evening. Image: ATNF Image Archive. The team watches the moonwalk on the small monitor in the Parkes control room. Image: ATNF Image Archive. Astronaut Michael Collins took this photo from the command module orbiting the Moon the day before the landing. Australia is in the top left of the globe and the storm gathering over the eastern seaboard is clearly visible. Image: NASA.

The television signals were to be sent from Parkes via the microwave links, to the Overseas Telecommunications Commission (OTC) terminal in Sydney. From there the television signal would be split: one split would go to the Australian Broadcasting Commission studios for Australian television networks, the other went to the OTC Earth Station at Moree for satellite transmission to NASA Mission Control in Houston, Texas, for international broadcast.

In the weeks leading up to the launch, the team at Parkes installed and tested all of the receiving equipment, the microwave relays, and the tracking procedures. They even practised hand-cranking the dish to follow the spacecraft in case of a power failure.

Tranquillity base…

Right on schedule (6.17 am AEST) on 21 July, astronauts Neil Armstrong and Edwin (Buzz) Aldrin landed the lunar module, Eagle, on the surface of the Moon at the Sea of Tranquillity with Goldstone tracking.

The schedule required the astronauts to rest before attempting the moonwalk, but Armstrong opted to head out straight away – who could have slept at a moment like that! Fortunately for the Australian team, it took the astronauts some time to don their spacesuits and depressurise the lunar module, so the Moon was on the verge of rising over Parkes as they opened the hatch.

Down on Earth, the massive Parkes dish was tipped right over – almost touching the ground – to receive the signals as soon as the Moon rose high enough above the horizon. But a storm had been brewing all morning and chose that moment to hit, buffeting the dish with wind gusts of 110 km per hour. The telescope tower shook, the structure of the dish groaned, and the wind alarms sounded, but the team held its collective nerve – a scene made famous in the iconic Australian movie, *The Dish*. The wind abated a little and, just as Buzz Aldrin switched on the TV camera mounted on the side of the lunar module, Parkes picked up the signal using its less sensitive off-axis feed.

The Moon had not yet set at Goldstone, so it too was able to pick up the TV signal. The smaller 26-m antenna at Honeysuckle Creek could tip lower to the horizon than Parkes and was also able to take the signal. For the first few minutes NASA alternated between the TV signals being received at Goldstone and Honeysuckle, searching for the best TV picture to broadcast. Eight minutes in, the Moon finally rose into the field of view of Parkes' main receiver. The signal was so much stronger that NASA switched to Parkes – this can be seen on the footage as a marked brightening and improvement in contrast as Armstrong walks on the Moon. NASA stayed with Parkes for the remainder of the 2.5-hour broadcast. The weather at Parkes did not improve (there was even a hailstorm) so the telescope was operating well outside its safety limits.

While the visuals alternated between Goldstone, Honeysuckle Creek, and Parkes (and it was Honeysuckle that caught Armstrong's step onto the Moon), the audio signal, with those famous words '…one giant leap…', came through Goldstone.

Stalwart support

Based on the success of the Apollo 11 mission, Parkes was contracted to support all subsequent Apollo manned lunar landing missions. We again stand ready, this time to support NASA's Artemis mission, named after the twin sister of Apollo, which aims to land the first woman, and the next man, on the Moon.

John Sarkissian OAM

Operations Scientist, Parkes Radio Observatory

Feed horn

Two identical receivers were installed for the Apollo 11 mission: one at the focus of the telescope (on-axis), the other offset a small distance (off-axis). The receivers were commercial units, but CSIRO's Bruce Thomas designed the feed horns, which funnel the signals to the receiver electronics. The horn for the on-axis receiver was a one wavelength, two hybrid-mode corrugated horn – the first of its kind. The horn for the off-axis receiver had a smooth circular cross-section with a flared tapered aperture and a corrugation surrounding the aperture. The corrugations increased the sensitivity and bandwidth of the receivers and was one reason Parkes performed so well.

The corrugated feed horns of the Lunar receivers visible on the underside of Parkes' focus cabin. Image: ATNF Image Archive.

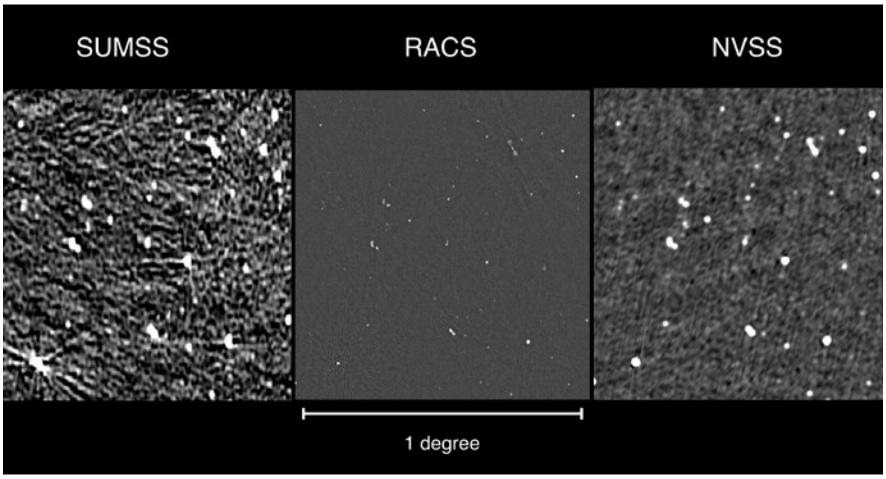
Australian Square Kilometre Array Pathfinder

Science highlights

- The growing number of fast radio bursts localised with ASKAP has seen them used as cosmological probes (see **Science highlights**), including to investigate the properties of galaxies they pass through (Prochaska et al.2019 Science 366, 231).
- ASKAP is now a crucial follow-up instrument to detections from the Laser Interferometer Gravitational-wave Observatory (LIGO). Repeated observations were made of the field surrounding LIGO event S190814bv and one candidate radio counterpart was found, but further observations ruled out any association with the gravitational wave event (Dobie et al. 2019 ApJL 887:L13).
- ASKAP's polarisation capabilities were used to detect periodic transient emission from active dwarf star UV Ceti (Zic et al. 2019 MNRAS 488, 559), confirming that auroral activity can occur in M-dwarf stars.
- A new pulsar (PSR J1431-6328) was serendipitously discovered in ASKAP data (Kaplan et al. 2019 ApJ 884:96). Detected as a highly polarised, steep-spectrum continuum source during test observations, follow-up with Parkes found pulses of 2.77 milliseconds. This rapid spin rate makes the pulsar difficult to detect in traditional pulsar searches and indicates ASKAP's potential in this field.

ASKAP, our newest telescope of 36 12-m dishes, concluded its first pilot surveys on 14 May 2020 after 304 days. Observing of ~100 hours was done for each of EMU, WALLABY, POSSUM, DINGO, CRAFT, VAST, GASKAP, FLASH and LIGO. The goal was to verify that ASKAP can meet the science data quality requirements of each team. Translating these requirements into observing modes was a joint effort between the observatory and the teams, with iteration over the survey strategies, telescope configuration and processing parameters. The Pawsey Supercomputing Centre provided additional data storage, which proved instrumental in completing the pilot surveys. Data processing is proceeding well (see **Data archives**) and roughly a dozen papers are in preparation.

The ASKAP community has rallied around the pilot surveys as a source of scientific discovery and an example of the telescope's workflow – full-scale science quality data flowed through to the archive for the first time. Communication with our diverse and distributed community remains key to achieving mutual goals. Channels such as the monthly science forum and newsletter complement events organised by the survey science teams. Weekly workshops bring together groups with similar interests and large-scale workshops are held to plan major activities, such as the second phase of pilot surveys. Project scientists nominated by each survey science team take an active role in all these events, providing a common point of contact with observatory staff.



A typical RACS image (middle, σ = 235 μJy) compared to the previous best surveys: Sydney University Molonglo Sky Survey (SUMSS, left. σ = 1.5mJy) and the NRAO VLA Sky Survey (NVSS, right. σ = 530 μJy). Each box is one degree wide. RACS clearly has superior sensitivity and resolution, meeting our goal of making it the new benchmark in radio continuum surveys around 1 GHz. Image: Dave McConnell.

ASKAP observing during a pilot survey. Image: Brett Hiscock.

We are now planning a second phase of pilot surveys that will merge several observing strategies, allowing them to run concurrently and improve the overall efficiency of survey operations.

Processing of ASKAP's first all-sky survey, the Rapid ASKAP Continuum Survey (RACS), is proceeding well. Our staff and collaborators from the University of Sydney performed extensive cross-checks to verify data quality. This led to improved understanding of ASKAP's phased array feed primary beams, which will now be incorporated into the image processing software. When the data are released, they will provide the world's best sensitivity and resolution all-sky catalogue at centimetre wavelengths (~1 GHz).

Engineering development continues alongside telescope operations with establishment of a routine test, release and test again process that dedicates time each week to rolling out software and firmware updates. This will ensure that the efficiency of the telescope continues to improve, while minimising disruption to science observations. ASKAP's image processing software and associated pipeline scripts continue to be tuned as we, and the survey science teams, gain experience with full-scale pilot survey data.

The CSIRO ASKAP Science Data Archive (CSADA) is now receiving regular deposits of data, providing the first opportunity to test quality reporting, cut-out services and other features (see **Data archives**). ASKAP is unique among ATNF telescopes in that CASDA is the primary point of interaction for external astronomers as all observations are run by our staff – this is the model that will be used by the SKA.

Murchison Radio-astronomy Observatory

The Murchison Radio-astronomy Observatory (MRO) in Western Australia is 300 km from the coastal town of Geraldton on a former pastoral property, Boolardy Station. CSIRO acknowledges the Wajarri Yamatji as the traditional owners of the observatory site.

The Murchison region has a low population density so there is less radio frequency interference (RFI) that can drown out or mimic the weak signals radio telescopes are trying to detect. This radio quiet environment is protected by a series of concentric zones; within 70 km of the centre of the MRO, radio astronomy is the primary user of spectrum. CSIRO also has strict standards to keep interference made on site to a minimum and an RFI monitoring system is in place (see **Radio environment**).

The MRO is powered by a hybrid power station with a 1.85 MW solar component. It is designed to run for a large part of the day without recourse to diesel.

The MRO also hosts the:

- Murchison Widefield Array (MWA), a low-frequency instrument of 4096 dipole antennas operated by Curtin University on behalf of an international consortium of some 21 organisations, including CSIRO.
- Experiment to Detect the Global Epoch-of-Reionisation Signature (EDGES), a radio spectrometer operated by Arizona State University and the Massachusetts Institute of Technology's Haystack Observatory.
- SKA test arrays, the Aperture Array Verification System, which tests prototype SKA1-Low antennas, and the Early Development Array, which uses MWA antennas in the configuration of an SKA1-Low station. Both are operated by an international consortium, led by Curtin University.

Long Baseline Array

Science highlights

- The radio afterglow from gravitational wave event GW170817 (a binary neutron star merger) may have been produced by a narrow relativistic jet or an isotropic outflow. A global telescope array, including elements of the LBA, was used to constrain the apparent source size, indicating that GW170817 produced a structured relativistic jet. (Ghirlanda et al. 2019 Science 363, 968).
- Final results from the LBA Calibrator Survey: a catalogue of accurate positions and correlated flux densities for 1100 compact extragalactic radio sources. This work increased by six times the number of compact radio sources south of declination -40° with positions known to milliarcsecond accuracy. (Petrov et al. 2019 MNRAS 485, 88).
- Measurement of the proper motion of two black hole X-ray binaries which, combined with other data, showed that three quarters of such systems receive potential kick velocities in excess of 70 km per second on formation (Atri et al. 2019 MNRAS 489, 3116).

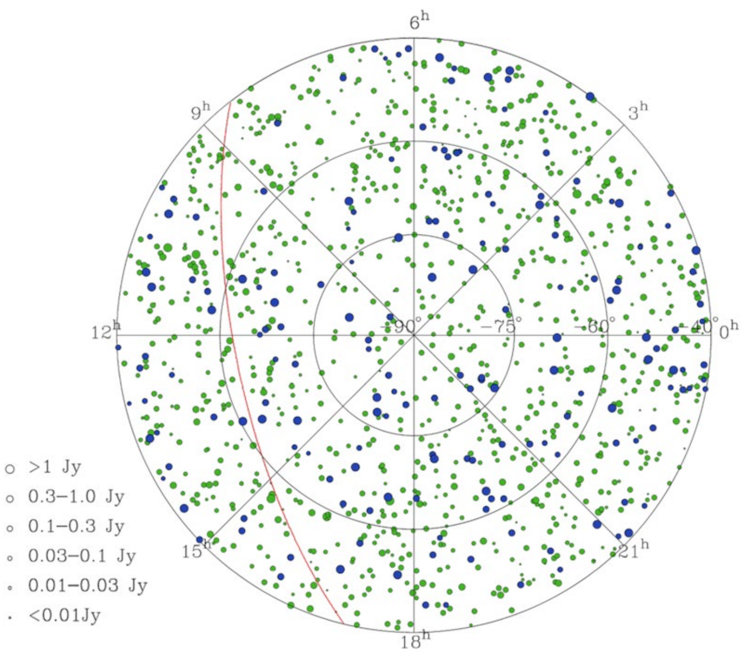
The Long Baseline Array (LBA) is a network of telescopes across Australia and the southern hemisphere used together for simultaneous observations, a technique called very long baseline interferometry (VLBI). There were 20 LBA experiments in the two observing semesters covered by this Report, totalling 425 hours observing.

The bulk of LBA observations occurred during four dedicated VLBI sessions, however an increasing number of experiments happen outside these sessions, such as target of opportunity and non a-priori assignable observations (of which there were five), and joint observations with other international VLBI arrays which have specific timing requirements. One experiment in this period, for example, was a joint observation with the European VLBI Network to improve sky coverage along the jet axis of a giant radio galaxy.

LBA experiments (other than global ones) were correlated by CSIRO staff using the Distributed FX (DiFX) software correlator running on the Magnus supercomputer at the Pawsey Supercomputing Centre in Perth. A total of 23 user projects were correlated representing ~297 hours of observations. This system has been running reasonably smoothly, with a median time of 111 days between observation and release of data. The processing time is dominated by the time taken to transfer data (median 93 days), largely due to a problem with the disk array in Hobart which took some time to repair. A total of 258 000 hours of CPU time was used on Magnus. All correlator output was uploaded to the Australia Telescope Online Archive once verified (see **Data archives**).

Antennas used at least once in the LBA in 2019/20 and where data was correlated at the Pawsey Supercomputing Centre.

- Parkes radio telescope
- ATCA
- Mopra
- CDSCC, three 34-m and 70-m
- University of Tasmanaia, 20-m and 12-m in Hobart and the 32-m in Ceduna, plus their AuScope 12-m in Yarragadee and Katherine
- South African Radio Astronomy Observatory, 26-m in Hartebeesthoek
- Auckland University of Technology, 12-m and 30-m in Warkworth
- Shangai Astronomical Observatory, 65-m Tianma
- Yunnan Astronomical Observatory, 40-m dish in Kunming
- National Institute of Information and Communications Technology, 34-m in Kashima
- National Astronomical Observatory of Japan 32-m Hitachi and Yamaguchi



Results of the LBA Calibrator Survey of compact radio sources in the Southern hemisphere at 8.3 GHz. Blue dots are sources known before the survey. Image: Petrov et al. 2019 MNRAS 485, 1.

Data archives

Science highlights

- Discovery of 21 confirmed and 2 candidate supernova remnants (SNRs) from a multiwavelength study of the Small Magellanic Cloud (SMC) using ATCA archival data (Maggi et al. 2019 A&A 631, 127). SMC SNRs were found to be larger and less elongated than counterparts in the neighbouring Large Magellanic Cloud (LMC), suggesting that the LMC has a denser interstellar medium.
- A multifrequency study of the mode-switching phenomena of PSR J0614+222. Using Parkes archival data at 686, 1369 and 3100 MHz, and data at other frequencies from the literature, the pulse width, brightness and phase offset of PSR J0614+222 were studied as a function of frequency. The mode occurring earlier in the pulse phase (Mode A) has a flatter spectrum than the second mode (Mode B), and the two modes show a different dependence of pulse width with frequency (Zhang et al. 2020 ApJ 890, 31).

Our data archives include the Australia Telescope Online Archive (ATOA), the Parkes Pulsar Archive – the primary component of CSIRO's Data Access Portal (DAP) – and the CSIRO ASKAP Science Data Archive (CASDA). At least 7 papers used ATOA archival data this year and another 5 used the Parkes Pulsar Archive.

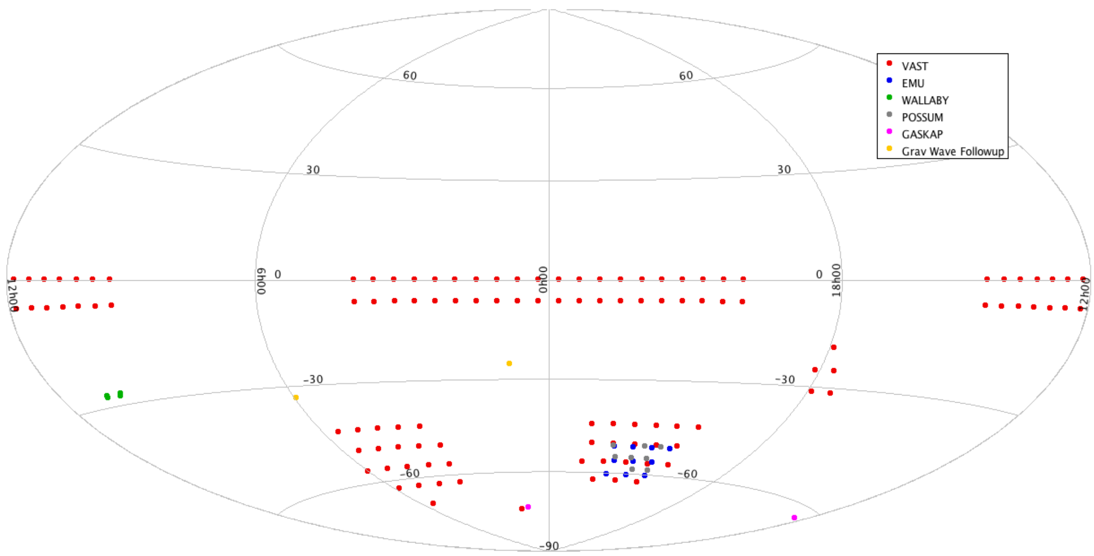
The ATOA this year expanded in scope to store files produced by the Parkes radio telescope's ultra-wideband receiver in its new Single Dish Hierarchical Data Format (SDHDF). The ATOA dataset is now ~308 TB and growing at ~60 TB/year – half of that growth being SDHDF data. In 2019/20, more than 4 TB of ATOA files were downloaded per month.

The DAP is the primary access point for Parkes pulsar data. The DAP contains 2.5 PB, over 90% of which is pulsar data, and the DAP is growing at ~700 TB annually. Over 1.5 PB are now publicly available. During this reporting period, ~70 pulsar collections (each up to 1.5 TB) were accessed per month, one quarter of which were downloaded to high performance computing facilities run by the two main pulsar groups in Australia, at Swinburne University of Technology and CSIRO.

Developments to the pulsar DAP include revamped web pages and improved search functionality (https://data.csiro.au/), enhancements to the data verification and ingest pipelines and improved access to data by high-performance computing users.

Much of the data from ASKAP's first pilot surveys are already processed and deposited into CASDA. This includes all of EMU and VAST, the first field from WALLABY and some data from POSSUM and GASKAP (see image). CASDA now contains ~192 TB of data and handles more than 7000 queries per month.

Developments include a new CASDA webpage (casda.csiro.au), which now hosts data validation reports and highlights primary images and data cubes in search results. We have implemented a common authentication between CASDA and the Australian Astronomical Observatory's Data Central. We have integrated catalog and image/cube upload for user-uploaded value-added data (Level 7) and developed a CASDA module for the Astroquery package of Astropy (an ecosystem of interoperable astronomy software packages). This allows astronomers to search for and download ASKAP data as part of their Python workflows.



Sky coverage of ASKAP pilot survey data in CASDA in equatorial coordinates as of late June 2020. Dots mark the centre of each ~30 deg^2 pointing. Image: Minh Huynh.

Radio environment

Radio telescopes study the Universe using receivers so sensitive they could detect a mobile phone on the far side of the Solar System, so small portions of the radio spectrum are set aside for radio astronomy to avoid interference from other users of the spectrum, such as the telecommunications sector.

Our staff work hard to retain as much spectrum as possible for radio astronomy and play pivotal roles in the regulatory bodies that manage use of the radio spectrum. At the international level it is the Radio Sector of the International Telecommunication Union (ITU-R) whose activities culminate every four years in the World Radio Conference (WRC). The most recent WRC was held in November 2019 and consensus was sought between radio spectrum users on frequency use, allocations, and protections, resulting in variations to the treaty-level document, the Radio Regulations. Competition for radio spectrum is fierce, with commercial entities often at odds with the research community.

The Australian Communications and Media Authority (ACMA) is the national regulator and in 2006 we worked together to establish Radio Notification Zones around several radio telescopes, including ATCA and Parkes. Under these measures CSIRO must be notified of applications for radio licences within frequency and distance limits specific to each site.

For the MRO, we worked with ACMA to establish the Australian Radio Quiet Zone WA (ARQZWA): a series of concentric rings centred on the MRO with different levels of protection as the distance from the telescopes increases. Within 70 km of the centre of the MRO, for example, radio astronomy is the primary user of the spectrum, while the outer ring (protecting low frequencies) extends 260 km from the observatory. Applicants for radio licences within the various rings of the ARQZWA are directed by ACMA to work with us to develop a workable, compliant solution – and we have found one each time we have been formally asked.

The RFI tower at the MRO monitors mobile phone signals and other interference occurring within and far outside the ARQZWA.

Radio astronomers routinely observe outside the allocated bands as signals from space span the entire electromagnetic spectrum and so modern telescope receivers have increasingly wide bandwidths. But the increasing number of communications applications is making observing more difficult because of the radio frequency interference (RFI) they cause. This is a particular issue for instruments studying the early Universe, which 'look back' billions of years, because signals that would have fallen in a protected radio astronomy band have been shifted by the expansion of the Universe to frequencies below 200 MHz – most of which are allocated to communication services. This is where the ARQZWA comes into play: the 2018 detection made by EDGES of the first stars forming could not have been made at any other observatory and bodes well for the SKA's low frequency telescope.

We are also taking a more hands-on approach to managing RFI by monitoring the radio environment at our observatories. This gives us visibility of long-term trends and allows us to detect all users of the spectrum. This guides development of mitigation techniques to overcome interference that cannot be addressed through regulatory action alone (see **Technology development**). In the case of active mitigation, interference is automatically filtered out – which risks accidentally removing real signals that look like interference. FRBs, for instance, might have never been found if short duration signals had been filtered out – as might be done to remove digital TV transmissions, for example.

Square Kilometre Array

Dr Maria Grazia Labate, SKA-Low Telescope Engineer at the MRO. Image: ICRAR/Curtin University.

Square Kilometre Array

SKA in Australia

CSIRO's Murchison Radio-astronomy Observatory (MRO) will be home to the low frequency telescope of the Square Kilometre Array (SKA) project: SKA1-Low. It will comprise up to 132 000 dipole antennas grouped into 512 stations along spiral arms running the length and breadth of Boolardy Station, as well as a large central processing facility, a power station and an accommodation facility.

Staff with key roles in the SKA include:

- Douglas Bock, Australia's Science Director on the SKA Board.
- Sarah Pearce, member of the Council Preparatory Task Force overseeing transition of the SKA Organisation (a UK company) into an intergovernmental organisation.
- Phil Edwards, Chair of Australia's SKA Science Advisory Committee.
- Antony Schinckel, seconded to the SKA Organisation as its Head of SKA Construction Planning in Australia.
- Rebecca Wheadon, our newly appointed MRO Site Entity lead.

Site entity

This year we commenced work as the MRO Site Entity, delivering on Australia's obligations under the SKA Treaty on behalf of the Australian Government. Together with colleagues of the Australian SKA Office in the Department of Industry, Science, Energy and Resources, we worked on activities necessary to allow SKA1-Low to be built and operated here.

The most important of these is the Indigenous Land Use Agreement (ILUA) with the Wajarri Yamatji traditional owners. The MRO already has an ILUA, but, as SKA1-Low will go beyond the boundaries of the current MRO to span virtually all Boolardy Station, a new ILUA is required. Antony Schinckel is CSIRO's negotiator of this new ILUA. Major items are agreed, and technical legal drafting is largely complete, but the planned community meetings, where hundreds of traditional owners gather to approve the agreement that has been struck by their representatives, could not be held because of the pandemic.

The terms of the new lease with the Western Australian State Government were also agreed this year. Land beyond the current MRO is deemed to be for pastoral use, not radio astronomy, so a new lease is required to transition the rest of Boolardy Station to radio astronomy. However, granting of the lease is contingent on registration of the ILUA and both are contingent on the SKA Council voting to build SKA1-Low in Australia.

A crucial component of our MRO Site Entity work is surveying the land for artefacts or sites of significance to the traditional owners. Over 70% of the land to be occupied by SKA infrastructure has now been surveyed. This work has revealed sensitivities over a portion of Boolardy Station and several options for how to avoid the area without compromising science outcomes were proposed and evaluated.

As part of host country operations planning, SKA South Africa's Karoo Site Manager, Dawie Fourie, and systems engineer Clifford Gumede, toured the MRO with Kevin Ferguson, Head of ATNF Observatory Operations in the west. Image: Shaun Amy.

Heritage surveying on Boolardy Station. Image: Kerry Ardern.

Auxiliary facilities

Essential to operation of the SKA in Australia, but not included in the SKA's construction project, are several facilities that have seen much development over the past year.

Engineering Operations Centre. Initial concept designs have been developed and funding is being sought for this facility that is similar in purpose to our current Murchison Support Facility in Geraldton, but will be almost three times the size.

Boolardy Accommodation Facility. Concept designs have been developed and funding is being sought for a permanent accommodation facility of some 80 beds for staff and visitors of all the telescopes at the MRO.

Australian SKA Regional Centre. The first staff for the AusSRC were appointed this year and projects commenced taking the most complex computing challenges from ASKAP and the MWA and working with the science teams on the best way to solve them. The SKA project includes ingest of data from the telescopes and initial data reduction (in Australia's case, at CSIRO's Pawsey Supercomputing Centre in Perth), but does not provide for astronomers' access to the data. The AusSRC, a consortium of CSIRO, ICRAR and Astronomy Australia Limited, will provide the crucial link between telescope data and the astronomy community.

International sphere

South Africa became the first SKA host country to ratify the SKA Convention on 2 June 2020. The Convention is the first formal step in transitioning the SKA Organisation into an intergovernmental body, the SKA Observatory. For this treaty-level document to come into force, it must be ratified by the three host nations, plus two members.

Together with colleagues in DISER, we have this year worked with the SKA Organisation on the terms of the Hosting Agreement: a legal instrument between Australia and the SKA Observatory, essential to allow the operation of SKA1-Low here.

Dame Jocelyn Bell Burnell, co-discoverer of the first radio pulsars, gives the keynote lecture at the opening of the new SKA Headquarters in Manchester, UK. Image: SKAO.

Operations partnership

A partnership model will be used for operation of the SKA telescopes in Australia and South Africa, to best draw on the expertise of the host countries but ensure functional control remains with the SKA Observatory. Principles for this partnership were developed this year and described in a memorandum of understanding (MoU) negotiated between CSIRO and the SKA Organisation. The MoU sets out a model that will see staff from the SKA Observatory and CSIRO working as a team in support of SKA construction, commissioning and operations, and sets out high level principles around governance, employment and health and safety. With more than 100 people to be working in Australia under the partnership, this will see a substantial growth in radio astronomy staff in Perth and Geraldton.

Construction

A key role for the SKA Council Preparatory Task Force is allocating construction roles for member nations. Detailed national and international negotiations this year saw Australia confirm its priorities for SKA construction and win the allocation of these. CSIRO will take a leading part in Australian site infrastructure, assembly integration and verification of SKA1-Low, and construction of its correlator and beamformer. We will also partner in developing software for the SKA and in managing manufacture and deployment of the antenna stations on site at the MRO.

Design development

After six years' designing the components of the SKA telescopes, the entire system design passed review by an independent panel in December 2019. There was, however, more work required to get the design documentation to the point where contracts for construction could be put out to tender: a phase known as Bridging.

Correlator and beamformer

The correlator/beamformer system for SKA1-Low, named Perentie after an Australian lizard, has at its heart our Gemini high performance signal processing boards which will handle some 1.5 Pb per second from the telescope.

Together with partners ASTRON, in the Netherlands, and Auckland University of Technology, in New Zealand, we achieved a major milestone in April when the first Gemini boards came off the production line. ASTRON equipped Gemini's high bandwidth memory-enabled boards with an optimised liquid cooled monolithic heatsink, to dissipate the considerable amount of heat generated by the electronics, and a backplane which supports synchronisation of all the boards.

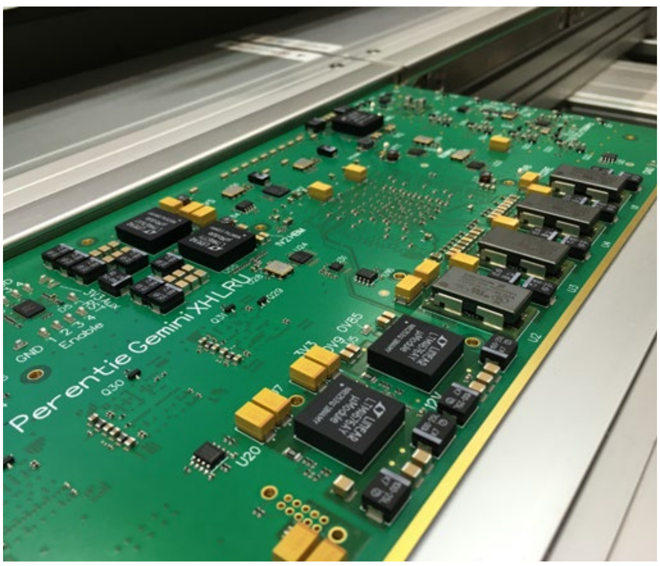
We made significant advances in firmware and software for the Perentie system and its interface with other parts of the telescope. We are also developing integrated models and emulators for testing interfaces and overall system performance throughout SKA construction.

Our laboratory in Sydney, formerly used to test ASKAP digital systems, has been transformed into a Prototype System Integration facility for SKA1-Low. As for ASKAP, this facility mimics the computing set-up in the central processing facility at the MRO and is where relevant SKA1-Low systems will be brought together and tested before deployment to the MRO. We installed the first tile processing module, built for the prototype low frequency aperture array, and the first pulsar timing beam server and have interfaced them with Perentie.

Assembly integration and verification

We worked closely with the SKA Organisation to develop the concept for and then plan a critical early SKA1-Low deliverable: Array Assembly 0.5. AA0.5 will comprise six stations of 256 antennas each (plus supporting systems) and will be capable of producing images, although its primary purpose is to de-risk the system design and major procurements.

We have this year produced the technical specifications for the Integration Test Facility and developed the model for how it will be used in testing sub-systems of SKA1-Low before they are deployed to the MRO. This facility will be part of the Engineering Operations Centre in Geraldton.



A Gemini board has 1000 parts, the biggest challenge being the 50 mm square FPGA with its 2892 connections. Image: ASTRON.

Science data processor

Our work this year focused on further development of our software prototype for the SKA's Science Data Processor (SDP). Based on ASKAP's YANDAsoft, and named yanda after the Wajarri Yamatji word for image, the SDP will process data from the correlator (received at rates of around 5 Tb per second) and produce up to 300 PB per year, per telescope of images and other science-ready data products. These data products will then be distributed to SKA Regional Centres for access by the astronomy community. We also continued development of the monitoring, control and calibration system software prototype for SKA-Low.

Site infrastructure

This year was spent implementing design changes arising from the system critical design review, impact assessment of subsequent engineering change proposals and implementation of those that were approved. Work on changes to the layout of the telescope prompted by these activities is on hold pending completion of the heritage surveys, which have been delayed by the impacts of COVID-19. We also undertook a thorough cost review and contributed to an options analysis for reducing costs. Our work on power for SKA-Low, while still in its early days, has grown in scope to include defining technical requirements.

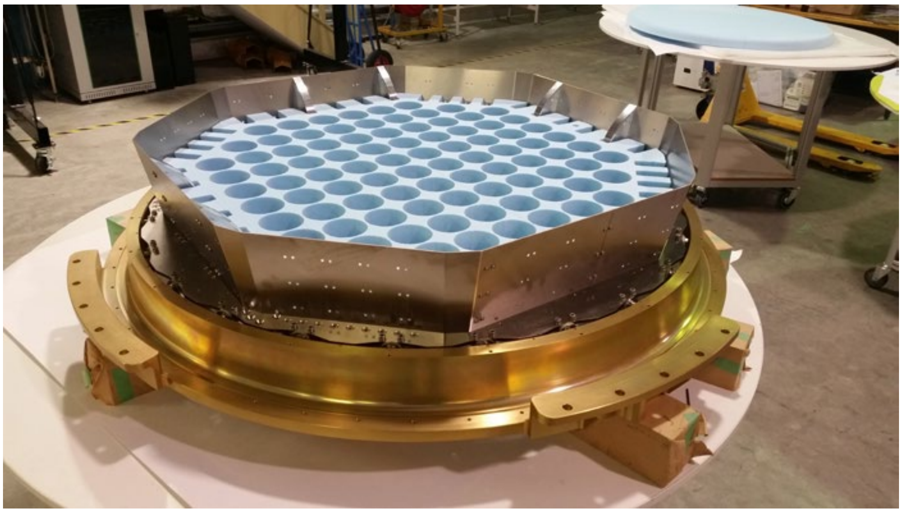
Technology development

The distinctive rocket-shaped receiver elements integral to the design of the cryogenically cooled phased array feed. Image: Shaun Amy.

Technology development

Parkes CryoPAF

Design and construction of a cryogenically cooled phased array feed (CryoPAF) receiver for the Parkes radio telescope (which promises an up to 30-fold increase in survey speed compared with the multibeam receiver) has gained momentum following a $1.15m Australian Research Council (ARC) grant, supporting the broader $3m project.



The CryoPAF structural thermal model. The grid of circular pockets in the foam will accommodate the rocket elements. Image: Nick Carter.

The design of the CryoPAF is modular, comprising 26 eight-channel low noise amplifier (LNA) modules in the cooled part of the receiver (the cryostat) and corresponding 'warm' electronic modules outside to provide additional amplification, filtering and digitisation using state-of-the-art Radio Frequency System on a Chip (RFSoC) devices. Commercially available programmable network switches and Field Programmable Gate Array (FPGA) processing boards are being investigated for the CryoPAF beamformer, which will feed a cluster of Graphics Processing Unit (GPU) servers for correlation and scientific data processing.

The full-size cryostat passed leak testing with a vacuum load equivalent to 10 T. The first cooldown achieved temperatures of 28 K across the ground plane, exceeding the design target of <35 K. The cryostat will contain 88 distinctive 'rocket' elements forming 196 active channels. The rocket elements have been manufactured and are being silver plated to improve their emissivity and minimise the thermal load.

Prototype LNAs have been fabricated in a European foundry for Microwave Monolithic Integrated Circuits (MMICs) and cryogenically tested in our Sydney laboratory. A number of improvements were identified and incorporated into the design. An alternative LNA design based on discrete transistors is also being investigated as a means of mitigating the schedule risk associated with fabrication of the MMIC LNAs. A scheme to allow the injection of noise calibration signals directly at the LNA input is being prototyped in preparation for integration into a prototype eight-channel LNA module.

A mechanical prototype of the integrated warm electronics module incorporating the radio frequency (RF) signal chain (which conditions the signals before digitisation) and the RFSoC-based digitiser is complete. The prototype module is being used to verify the mechanical attributes, thermal performance and radio frequency interference (RFI) shielding effectiveness of the design. A prototype of the RF electronics, providing amplification and band selection, has been evaluated. Assembly and testing of the prototype digitiser was delayed due to supply chain issues; although firmware to control the digitiser and provide the first stage filterbank, located in the RFSoC device, is complete. Work on the firmware for the beamformer has also commenced.

ATCA digital upgrade

System level design and detailed planning for the upgrade of ATCA's digital system is underway, with news of $530 000 in ARC funding, supporting a broader $2.6m project: the Broadband Integrated-GPU Correlator for the Australia Telescope (BIGCAT). This project will replace the aging Compact Array Broadband Backend (CABB) signal processing electronics and double the processed bandwidth from 4 GHz to 8 GHz (which will also require replacement of the RF signal chain and the timing distribution system).

BIGCAT replaces the existing CABB Analog to Digital Converters (ADCs) with state-of-the-art RFSoC technology, also being developed as part of the CryoPAF project. The old correlator will be replaced by one based on GPUs. This will greatly increase the flexibility of ATCA, enabling implementation of innovative signal processing techniques and active RFI mitigation.

Radio Frequency System on a Chip

We have continued to investigate RFSoC technology as a potential next-generation digitisation and digital signal processing platform relevant to a range of radio astronomy applications. The RFSoC devices incorporate multiple high-speed ADCs, an Arm® microprocessor and programmable logic in a single package, enabling much greater integration of the signal processing chain. This technology has been developed for the software defined radio market and has the potential to be a common platform for future systems.

Work is divided into two streams (Jimble and Bluering) targeting different applications.

Jimble uses an 8-channel device running at 4 giga samples per second (GSps) that simultaneously digitise 8 channels, each 2 GHz wide. The on-board programmable logic and Arm® processor enable incorporation of the first stage filterbank, ethernet interfaces and the control and monitor functionality within the RFSoC chip. A prototype Jimble board has been built and detailed performance evaluation is underway. Jimble targets applications such as the CryoPAF, BIGCAT and future ultra-wideband systems.

Bluering is based around a 16-channel, 2GSps device and includes 16 customisable daughterboards, which contain the input RF signal conditioning electronics. The first prototype signal processing board completed initial testing of key components. Two of the 16 customisable RF modules have been produced and their RF performance is undergoing comprehensive testing. Bluering is also liquid cooled and shielded, to ensure operation in remote and RFI-challenged environments. Bluering targets array-based astronomy instruments, such as low frequency aperture arrays.

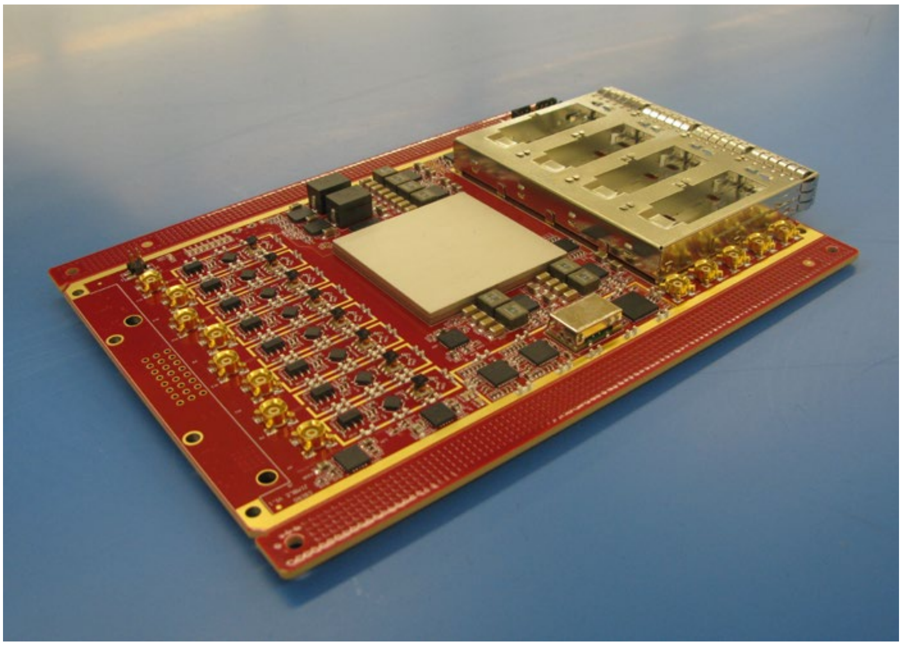
Jimble and Bluering use a common time and frequency distribution system, currently under development. The timing system allows synchronisation of multiple boards, necessary for array-based applications. The firmware and software required for control and monitor of the RFSoC device, ethernet communication and support other functions is well advanced and is available to support detailed performance evaluation.

RFI mitigation

In partnership with institutions in Australia and internationally, we have been investigating RFI mitigation algorithms and their implementation, particularly regarding PAFs, the low frequency ultra-wideband receiver and in pulsar science.

We took advantage of the pandemic shutdown and quantified the radio environment at the Parkes radio telescope. This provides a baseline for exploring mitigation strategies and for ensuring that the CryoPAF will work in Parkes' RFI environment. We have also deployed a frequency interpolation technique on ASKAP to stop PAF beams being corrupted by RFI that occurs during measurements taken to calculate the beamformer weights.

We are also working on new time/frequency domain RFI mitigation algorithms and prototyping their implementation on the latest RFSoC devices, targeting both single pixel receivers and PAF systems.



A prototype Jimble board using cutting edge RFSoC technology. Image: Puzzle Precision.

The FAST radio telescope in the mountains of Guizhou province. Image: NAOC.

FAST impact

When the National Astronomical Observatories of China (NAOC) was considering options for design and manufacture of the flagship receiver for its Five hundred metre Aperture Spherical Telescope (FAST), at the time under construction in the mountains of Guizhou province, they came to us because of our track record in building similar receivers: for our 64-m Parkes telescope (13 beams) and for the 305-m Arecibo telescope in Puerto Rico (7 beams). For FAST we built a 19-beam wideband receiver: the largest and most complex we've ever made.

A recent independent analysis[2] of this four-year project revealed a total impact value of $19.4m associated with: contract revenue for follow-up observations with the Parkes radio telescope, scientific discovery (counted in publications and citations), soft diplomacy, formation of human capital (through students, for example) and increased scientific and research exports.

FAST is the largest single reflector telescope in the world. It has double the sensitivity, 5-10 times the survey speed and has up to three times the sky coverage of the next largest radio telescope (Arecibo). Most of FAST's science goals rely on surveys, and our multibeam receiver multiplies the speed, or equivalently the depth, of these surveys by 19 times. FAST expects to discover ~10 000 new galaxies and ~4000 pulsars and has purchased around 2000 hours observing time on the Parkes radio telescope to confirm its potential pulsar sightings.

The receiver was installed in 2018 so it is still early days for scientific output however, working with our Chinese colleagues, Parkes confirmed 24% of the new pulsars observed by FAST from 2017-2019, including the first pulsar discovered by FAST – found during commissioning. The collaboration has also led to six papers jointly authored by NAOC and CSIRO staff.

The research benefits of more precise observations include:

- a reduction in the amount of individual resources necessary to participate in research, with more time available for data analysis as opposed to observing
- improved ability of astronomers to distinguish common events from anomalies and hence build out a more comprehensive image of our skies
- higher probability of successful discoveries.

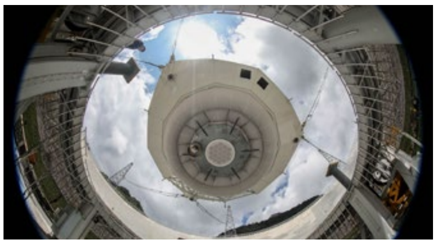
We have hosted five international PhD students analysing FAST data and/or making follow-up observations with Parkes. Overall, an estimated 50 students are involved in FAST projects across 133 Principal Investigator programs from 21 institutions. The skills gained by these students through designing software to store, use and analyse data from FAST and/or Parkes, is just one example of the human capital being generated by this collaboration.

Astronomy plays an important role in the broader Australia-China bilateral relationship as it provides apolitical avenues for engagement and shows how Australia and China can be global partners. This project is one part of a radio astronomy relationship between the two countries that spans some 40 years. Our FAST collaboration is aligned to the Foreign Policy White Paper and the Global Innovation Strategy, both part of the Australian Government's National Innovation and Science Agenda.

We developed highly specialised components and techniques for the 19-beam receiver. For example, the key component of the receiver's low noise performance, the LNAs, were designed and built in-house and are among the world's best. We have since applied the LNA bias circuits, LNAs, and the advanced FPGA-based monitor and control system, to the ultra-wideband receiver, currently installed on Parkes and attracting international interest, leading to potential increased scientific and research exports.

FAST will produce an estimated 18.8 PB of data per annum, requiring a throughput data rate capability of 150 TB per day. The ATNF is no stranger to handling big data and we were contracted by NAOC to advise on the requirements for archiving of pulsar and spectral line data from FAST, specifically because of our experience with the Parkes Pulsar Archive and CASDA (see Data archives).

Our international reputation for outstanding radio astronomy receivers is built on our unique combination of engineering capability (cryogenics, electronic, electro-magnetic, digital and software), telescope operations experience and astronomy expertise. We understand every aspect of how a receiver should work and that's what sets us apart.



The focus cabin of FAST, with the 19-beam receiver on board, is hoisted into position. Image: Xinhua.

4 Centre for International Economics (April 2020). Costs and benefits calculated from an Australian perspective.

People and community

An astronaut actor entertains the crowd at Parkes' Apollo 11 anniversary weekend.

Staff

There are currently 191 people working on radio astronomy in CSIRO: that is, in the ATNF and our SKA activities (**Appendix B**). There were 2 joint appointments and 1 secondment. We exceeded CSIRO's target of 3% indigenous employment with 8 staff identifying as indigenous. The gender breakdown of CASS staff is at **Appendix C**.

CSIRO's Science in Australia Gender Equity (SAGE) program undertook a benchmarking exercise which assessed the gender breakdown of CASS staff weighted against the gender diversity in matched disciplines and organisations and set targets based on this benchmark plus 10%. This found that: the percentage of CASS' female research staff exceeded the target, but the percentage of female technical staff fell below the target. Improving our gender balance relies on there being qualified women: we have established an undergraduate scholarship program for women in engineering with Macquarie University in Sydney and have appointed our first scholar. Further work on this front, as well as the technical trades, will be considered by CASS' Diversity and Inclusion Committee.

Diversity and inclusion

Our commitment to ensuring a safe, respectful, inclusive and diverse environment for staff and visitors continued this year as we welcomed new Diversity Champion, Kevin Ferguson, following Jane Kaczmarek's departure to take up a new job in Canada. Jane's stepping down provided the opportunity for a review of the position and of the Diversity and Inclusion (D&I) Committee. The review also considered the results of the Culture Survey conducted in June 2019.

Overall the survey results were positive: the majority of respondents had good relationships with colleagues, felt valued at work, believe people are treated respectfully and fairly and that culture and diversity is supported by their colleagues. Younger staff, staff with caring responsibilities and those identifying as LGBTQI+, while reporting better relationships with colleagues, also reported experiencing more discomfort with how they felt their lives were perceived.

As a result of these bodies of work, the Diversity Champion's role was clarified, terms of reference agreed for the Committee and a process commenced to refresh its membership. The Diversity Champion is to be the link between CASS and wider CSIRO activities, including the SAGE initiative. They lead the D&I Committee and now attend all meetings of the CASS Executive. The D&I Committee is formed of volunteers passionate about creating a culture of inclusivity and respect throughout CASS.

The Committee will provide a forum for staff, students and visitors and facilitate the exchange of information and ideas and assist in developing a common understanding of issues facing CASS. It will also identify areas in which we have scope to improve diversity and inclusion, understand potential barriers to that happening and recommend and support the implementation of targeted actions to help remove these barriers.

The expression of interest process for new Committee members closed on 1 July 2020. The first task for the refreshed Committee will be to develop and implement an annual D&I Action Plan. Meanwhile, ongoing activities such as a buddy system for new staff and mentoring of staff at any career stage continued.

Awards

Our award winners include:

- Karren Lee-Waddell – CSIRO John Philip Award for Promotion of Excellence in Young Scientists.
- Robin Wark – CSIRO Lifetime Achievement Award.
- Sarah Pearce – New South Wales (NSW) Telstra Business Woman of the Year.
- Sarah Pearce – selected into Science and Technology Australia's Superstars of STEM program.
- Charlotte Sobey – selected into the science communication program, Fresh Science.
- Jane Kaczmarek and Karen Lee-Waddell – among five young leaders selected to represent CSIRO at the prestigious Science and Technology in Society Forum in Kyoto from 4-7 October.
- Douglas Bock – elected a Fellow of the Australian Academy of Technology and Engineering
- Rob Hollow – made Life Member of the Science Teachers' Association of NSW.

Education and Outreach Officer, Rob Hollow, is made a life member of the Science Teachers Association of NSW. Image: STANSW.

Indigenous engagement

Recognising that it is important to not just attract, but to retain and to develop, Indigenous staff, we have developed an Indigenous Talent Management Plan to grow the options available. One of our co-supervised students, Karlie Noon, became the first Indigenous student to obtain a Masters of Astronomy and Astrophysics (Advanced) from the Australian National University. CSIRO also co-hosted the virtual ceremony for the 2019 Aboriginal and Torres Strait Islander STEM Student Achievement Award, which was made to year 12 student Alana Dooley in Perth. We look forward to supporting Alana as she pursues her dream of studying astrophysics.

We continued our significant engagement with the Wajarri Yamatji, traditional owners of the MRO, principally through the Indigenous Land Use Agreement in areas such as:

- educational support, such as mentoring and visits to the MRO
- contracting, employment and training opportunities
- acknowledgement of traditional owners in science publications using data from the MRO
- an Indigenous heritage induction for all who work on or visit the MRO.

Robin Wark wins the CSIRO Medal for Lifetime Achievement and Karen Lee-Waddell wins the John Philip Young Scientist of the Year award.

Sarah Pearce: NSW Telstra Business Woman of the Year and Superstar of STEM.

Charlotte Sobey takes the pub test at Fresh Science. Image: Ross Swanborough.

Health, safety and environment

ATNF staff again reported no medical treatment injuries, that is, no injuries that required medical treatment beyond first aid, and one lost time injury (LTI), that is, where one or more day was lost from work after an injury. The LTI was due to a musculoskeletal injury incurred doing a routine task.

Health, safety and environment incidents over time.

PERIOD	E INCIDENTS	H&S INCIDENTS	LTI	MTI
Jan–Dec 2014	1	14	1	0
Jan–Dec 2015	2	4	3	2
Jan–Dec 2016	0	12	0	2
Jan 2017 – Jun 2018	1	23	1	0
Jul 2018 – Jun 2019	0	8	1	0
Jul 2019 – Jun 2020	0	8	1	0

E = environmental, H&S = health and safety, LTI = lost time injury, MTI = medical treatment injury

Education

Postgraduate students

This reporting period saw ATNF staff co-supervise 33 PhD students and 1 Masters student (Fig. 12). While the number of students remains stable, they were drawn from a larger range of institutions (Fig. 13). Our staff also co-supervised two honours students for the industrial placement component of their degrees. In this reporting period, 7 students were awarded PhDs and three earned their Masters. Student affiliations and thesis titles are listed in **Appendix E** and **Appendix F**.

Undergraduate vacation scholars

The 2019-20 Undergraduate Vacation Scholarship program had 14 students: 10 in Sydney, 3 in Perth and one at the CDSCC. Several of this year's projects involved examining new ASKAP data, while others focused on space, satellites and communications, along with the usual mix of astrophysics and engineering. All the students visited ATCA in January and got the opportunity to gain observing experience with a major facility. The program concluded with the annual Student Symposium in February where each student presented their research.

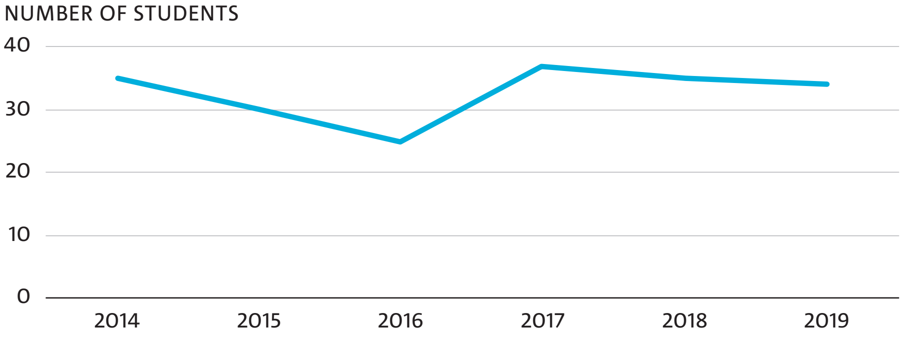


Figure 12: Postgraduate students co-supervised by ATNF staff over time.

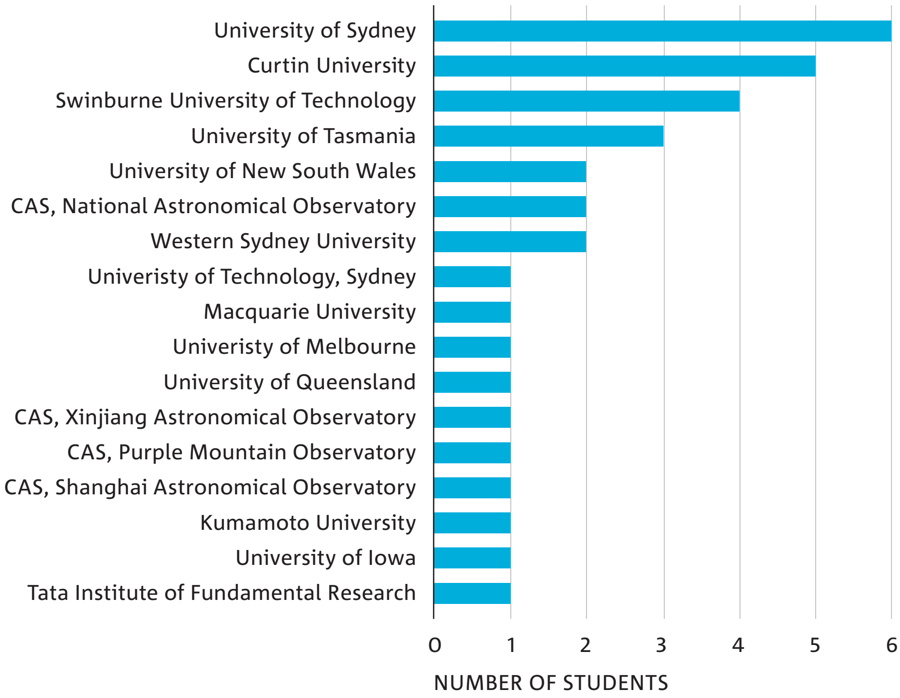


Figure 13: Affiliation of co-supervised postgraduate students.

Summer vacation scholars on an ATCA dish. Image: Jamie Stevens.

Radio school

The annual Radio Astronomy School was held at ATCA from 30 September to 4 October 2019. Aimed at postgraduate students, the school involved a mix of lectures and hands-on workshops presented by astronomers and engineers from Australia and overseas. While single-dish telescopes were part of the curriculum, the emphasis this year was on interferometry and managing very large data sets, which followed on from last year's school at ASKAP. The 35 students and 24 lecturers and visiting staff were joined on the last day by 25 undergraduate students from the University of Sydney's Talented Student Program in Physics.

School visits

Several staff were active in the STEM Professionals in Schools program, working with partner schools over the year. National Science Week in August saw several staff head to Geraldton to give talks and run hands-on activities at Geraldton Primary School, Champion Bay Senior High School, Meekatharra School of the Air, Central Regional institute for Technical and Further Education and the Geraldton Museum.

Students and staff from Pia Wadjarri Remote Community School made their annual visit to the MRO in October. This was followed by astronomy activities back at school the next day.

Education specialist, Rob Hollow, ran specialist workshops for science teachers at science teacher conferences in Adelaide, Darwin and Melbourne.

PULSE@Parkes

Our educational program, PULSE@Parkes, designed to give school students the opportunity to observe with the Parkes radio telescope, this year saw more than 160 students and 25 teachers from 19 schools take part. As part of the Apollo 11 open days at Parkes in July 2019, about 500 people participated and the program also ran at Perth Astrofest in February 2020.

We held a special session at the Robotic Telescopes, Student Research and Education conference in Melbourne in December, which gave international participants the chance to observe and learn more about the program.

We again held a session in collaboration with the Pawsey Supercomputing Centre for students from four Perth schools visiting the facility. After this, COVID-19 restrictions saw us develop ways of delivering PULSE@Parkes remotely, supported by CSIRO Education and Outreach. This approach has proved so successful, we intend offering the program remotely even after restrictions ease. It has also opened the program to schools in regional areas, interstate and overseas. We ran a remote session for 35 Year 9 girls across northern Queensland who are in CSIRO's Young Indigenous Women's STEM Academy and we were part of CSIRO's trial of a Virtual Work Experience Program, which saw five students from three states work together over a week observing with Parkes and analysing their data. We also ran a remote session for school students in a radio astronomy summer school at the Sardinia Radio Telescope in Italy. Here we reconnected with Marta Burgay of the Italian National Institute for Astrophysics who had been involved in early PULSE@Parkes sessions in 2008.

Jane Kaczmarek and students from the Pia Wadjarri Remote Community School on their annual excursion to the MRO – here with ASKAP digital equipment in the control building. Image: Rob Hollow.

Chenoa Tremblay at a school in Perth.

Outreach and media

Our approach in recent years of working with our partners to promote joint research outcomes continued this year to great effect. For example, we worked with the International Centre for Radio Astronomy Research to promote the *Science* paper describing the missing matter of the Universe discovery that started with ASKAP finding and localising FRBs. We provided images, broadcast-quality footage and other content as well as comprehensive background material for journalists and supported the university's press release via our social media channels.

To celebrate the centenary of the International Astronomical Union, we joined with partners around the nation to create Australia's video contribution highlighting astronomical discoveries made 'down under'. One of our principal international partners is, of course, the SKA Organisation. We provided staff for interview and supplied other content for its annual promotion of Women in Engineering Day and regularly contribute stories to its magazine *Contact*.

Perth Astrofest in February was again a success with thousands of people attending for science shows, talks and exhibits, such as ours for CASS and the SKA. CSIRO is a sponsor of Perth Astrofest and were proud to see it named joint winner of the Chevron Science Engagement Initiative of the Year in the Premier's Science Awards. Sydney Astrofest didn't go ahead due to COVID-19.

For the Moon to the Murchison event, part of National Science Week in August, we worked with our partners to deliver six science outreach events in Geraldton, reaching 600 people with the wonder of astronomy and space science, and the role CSIRO is playing in the region.

For the past couple of years we have been actively managing the ATNF Twitter account (@CSIRO_ATNF) which now has around 3700 followers and that number is climbing steadily. We are finding social media, Twitter in particular, to be a to highly successful mechanism for amplifying the reach of our stories.

Another important aspect of our outreach work is our visitors' centres at the Parkes radio telescope and ATCA. Numbers were down on last year's results due to closure of both facilities in March due to COVID-19 (see table). Parkes would have had a record-breaking year were it not for the virus: 13 248 people came through the visitors centre on the Apollo anniversary weekend.

Number of visitors to ATCA and the Parkes Radio Telescope.

	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20
Parkes	68 427	95 212	83 851	105 085	112 224	100 013
ATCA	10 971	11 511	10 965	12 081	10 363	7434

Apollo 11 anniversary celebration

CSIRO's campaign to mark the 50th anniversary of the Apollo 11 Moon landing and Australia's role in supporting the historic mission was one of the largest integrated marketing and communications campaigns we have ever undertaken. We started three months before the anniversary, staggering events to maximise coverage and avoid news fatigue. The lynchpin of the campaign was its website (www.csiro.au/apollo11) featuring historical information, a national event calendar and

CSIRO's Dave Williams speaks at the opening of the Apollo 11 exhibition at the Powerhouse Museum in Sydney. Image: Gabby Russell.

Open days at the Parkes radio telescope attracted 19 500 visitors. Image: Stephen Holland.

CSIRO staff and volunteers were easy to spot guiding some 2226 people on the telescope and around the site. Image: Chris Khoury.

CSIRO's Moon landing footage is donated to the National Film and Sound Archive. From left: Dave Williams (CSIRO), Badri Younes (NASA) The Hon Karen Andrews MP, The Hon Paul Fletcher MP, Jan Müller (NFSA).

resources for students, teachers and media. The site's 147 pages were viewed over 34 000 times.

We were principal sponsor of an Apollo 11 exhibition at the Powerhouse Museum in Sydney, which included artefacts such as the feed horn from Parkes that captured the signals from the Moon. The year-long exhibition attracted 181 935 visitors in its first six months.

For CSIRO's Discovery Centre in Canberra we developed a virtual reality experience, Earthlight: Lunar Hub, taking visitors on an immersive tour through a fictional Moon base before a walk on the lunar surface. We also supported exhibitions at Questacon, the National Museum of Australia and Geoscience Australia.

We worked with leading metropolitan and regional media groups on exclusive Apollo 11 content, a commemorative poster and lift-outs. In total, more than 3300 news stories were produced across Australian TV, radio, print and websites, reaching an audience of 55.5 million. Our posts on social media were viewed over 4.1 million times by more than 2.7 million people.

We joined with the Australian Space Agency to create a brief about Australia's involvement for the Department of Foreign Affairs and Trade. Australia's embassies and consulates around the world used social media and local events to promote Australia's role and our ongoing excellence in STEM.

We also donated the only copy of the restored television footage of the Apollo 11 Moon landing to reside outside the United States, which had been presented to CSIRO, to the National Film and Sound Archive.

The anniversary weekend

Open days at the Parkes radio telescope on 20 and 21 July attracted 19 500 visitors (almost double the population of Parkes) including the US Ambassador to Australia, a former astronaut, Australia's Deputy Prime Minister and the Minister for Industry, Science and Technology. With The Dish as backdrop, we rebroadcast the Moon landing 'as it happened', and more than a thousand people gathered 'on location' on the (very cold) Saturday night to watch the iconic Australian movie *The Dish*.

All free to air television networks covered the open days, with eight programs doing at least 46 live crosses to the telescope. ABC Local Radio broadcast several programs live from the event. Overall, media coverage around the weekend reached at least 7.8 million Australians

The open days had a positive impact for the local community as well. The Parkes' Visitor Information Centre had a 300% increase in custom and accommodation was booked out in towns across the central west region.

Over the weekend, 110 staff and their families volunteered their time to make the weekend a success.

That's a wrap

The campaign resulted in overwhelmingly positive feedback for CSIRO, raised awareness of Australia's contribution to the Apollo 11 mission, CSIRO and our partners. Its success shows the pride Australians have in the nation's technological achievements and their fascination with what our future in space holds.

Astronomy community

The ATNF User Committee (ATUC) represents astronomers who use ATNF instruments. ATUC meets twice a year and is a forum for users to raise problems with operation of the facility and to discuss and recommend priorities for its future development. The April 2020 meeting was, for the first time, held entirely online. ATUC's reports, and the ATNF Director's replies, are available on the web.

Meetings, workshops, conferences and colloquia

With the advent of COVID-19, many meetings in 2020 were postponed or cancelled. The scientific meetings we did host, or in which we had significant participation, include:

AusSRC Community Workshop. Our staff co-organised this event, held at Mt Stromlo near Canberra on 8 November, to further develop the vision for a global network of SKA Regional Centres, focussing on data processing for ASKAP and MWA surveys.

Australia-ESO Joint Conference. CSIRO sponsored the 2nd such conference, which was held in Perth, 17-21 February, and looked at coordination of next-generation galaxy evolution surveys. Elaine Sadler chaired the first day and she and other staff gave talks.

Bolton Symposium. This forum, to promote collaboration between early career researchers and those with more seniority, was held in Perth on 10 March.

IAU Astronomy for Equity, Diversity and Inclusion. We were gold sponsors of the inaugural IAU symposium (S358) on this important topic, which was held in Tokyo, Japan 12-15 November. Jimi Green chaired the session on inclusion, diversity, equity, and empathy in communicating astronomy.

ICRARcon. A number of staff were invited to this biennial internal workshop of Curtin University and the University of Western Australia, held 24-26 September at Margaret River in Western Australia.

International VLBI Technology. We hosted the 8th workshop in this annual series at our Sydney site, 18-20 November.

New Zealand SKA Forum. This event brought together the Science for SKA and Computing for SKA Colloquia in Auckland, New Zealand from 12-15 February. CSIRO staff gave talks including experience with ASKAP's ingest pipeline and the digital signal processing system for SKA1-Low.

OzSKA. The annual Australian SKA meeting was held at Mt Stromlo Observatory, near Canberra, 6-7 November. Opened by SKA Director General, Phil Diamond, the two-day program featured many talks from CSIRO staff.

PAF Workshop. This annual workshop was hosted by the Max Planck Institute for Radio Astronomy in Bonn, Germany, 16-18 September. CSIRO staff spoke on topics including using PAFs in noisy radio environments and development of the CryoPAF.

RFI 2019. The 5th in this series of workshops focussed on coexisting with RFI and was held in Toulouse, France, 23-26 September. Balthasar Indermühle was the Technical Program Chair, Carol Wilson was on the Scientific Organising Committee and these and other staff chaired sessions and/or presented talks.

SAFe6. The 6th SKA Scaled Agile Framework (SAFe) Program Increment planning meeting was hosted by CSIRO and ICRAR and sponsored by DISER and held 24-28 February in Perth. This quarterly event in the SKA calendar gathered together engineers and researchers involved in designing and developing software and firmware prototypes for the SKA and included a visit to the MRO.

Senior digital engineer, Grant Hampson, speaks at the SKA Engineering conference in Shanghai. Image: SKAO.

SKA Engineering. The final SKA engineering meeting was held in Shanghai, China, 25-28 November. It focused on system design, operations plans and, for the first time, presented the full design of both SKA telescopes.

SKA VLBI. Two staff were on the scientific organising committee and several spoke at this workshop in Manchester, UK, 14-17 October, which introduced VLBI capabilities of the SKA and discussed potential SKA-VLBI observing programmes.

SPARCS. Several staff spoke at the 9th SKA Pathfinder Radio Continuum Survey meeting 'Pathfinders get to work' in Lisbon, Portugal, 6-10 May.

World Radiocommunication Conference. This major event of the International Telecommunications Union was held in Sharm el-Sheikh, Egypt, 28 October to 5 November. Balthasar Indermühle and Tasso Tzioumis were among Australia's negotiators and Carol Wilson chaired the working group forming the agenda for the next WRC.

Appendices

Parkes Elvis Festival contestants DeanZ and Shania Sarsfield. Image: John Sarkissian.

A: Financial summary

The table below summarises revenue and expenditure applied to CSIRO's radio astronomy activities ($'000s).

The notable factors affecting the financial results for this year include an increase to external funding, primarily due to SKA site entity funding, and a decrease in CSIRO indirect appropriation, due to a revaluation of the useful life of assets and changes in depreciation. Travel spend was reduced both due to a budget realignment and COVID-19. ATNF funding supported 169 FTE in FY 19/20, an increase of three on the previous year.

OPERATING	YEAR TO 30 JUNE 2015	YEAR TO 30 JUNE 2016	YEAR TO 30 JUNE 2017	YEAR TO 30 JUNE 2018	YEAR TO 30 JUNE 2019	YEAR TO 30 JUNE 2020
Revenue						
External	13 209	14 377	15 418	14 889	13 806	16 648
CSIRO direct appropriation	18 454	18 282	19 532	20 632	20 612	20 550
CSIRO indirect appropriation[1]	22 019	23 812	25 099	25 637	25 261	18 754
Total revenue	53 682	56 471	60 049	61 158	59 679	55 952
Expenditure						
Salaries	19 545	21 179	22 784	20 959	22 289	24 096
Travel	1 429	1 981	1 866	1 713	1 879	1 269
Other operating	9334	8837	11 708	13 250	10 562	11 977
Overheads[2]	14 506	13 711	13 492	13 316	14 947	13 394
Depreciation & amortisation	7 513	10 101	11 607	12 321	10 314	5360
Total expenses	52 327	55 809	61 457	61 559	59 991	56 096
Operating result	1 355	662	-1 408	-401	-312	-144

1. CSIRO indirect appropriation is funding for: overheads, depreciation and amortisation.
2. Overheads include support services such as human resources, health and safety, finance and property services.

The table below shows CSIRO capital investment, including from the Science and Industry Endowment Fund.

CAPITAL INVESTMENT	YEAR TO 30 JUNE 2015	YEAR TO 30 JUNE 2016	YEAR TO 30 JUNE 2017	YEAR TO 30 JUNE 2018	YEAR TO 30 JUNE 2019	YEAR TO 30 JUNE 2020
ATNF	855	1 310	547	2 360	1 445	1 823
ASKAP	15 179	9 728	3 121	1 235		

B: Staff list

People contributing to radio astronomy: ATNF and the SKA as at 30 June 2020. Includes casual staff, joint appointments, honorary fellows and those employed under contractor or labour-hire arrangements, but not students. Note: many people working on SKA projects are based in another Program, such as Technologies.

SYDNEY (NSW)		
Ahmed	Azeem	SKA
Allen	Graham	SKA
Amy	Shaun	Operations
Ardern	Kerry	SKA
Bannister	Keith	Technologies
Baquiran	Mia	Technologies
Barker	Steve	Technologies
Bekiaris	Georgios	Science
Bengston	Keith	Technologies
Beresford	Ron	Technologies
Bhandari	Shivani	Science
Bhandari	Yukti	Operations
Biswas	Raj	Technologies
Bock	Douglas	Management
Bolin	Andrew	Technologies
Bourne	Michael	Technologies
Bowen	Mark	Technologies
Brothers	Michael	Technologies
Bunton	John	Technologies
Callaghan	Kate	Management
Cameron	Andrew	Science
Carter	Nick	Technologies
Castillo	Santiago	Technologies
Chapman	Jessica	Science
Chekkala	Raji	Technologies
Chen	Yuqing	Technologies
Cheng	Wan	Technologies
Chippendale	Aaron	Technologies
Chow	Kate	SKA
Chung	Yoon	Technologies
Cooper	Adam	Technologies
Cooper	Paul	Technologies
Craig	Daniel	Operations
Dai	Shi	Science
D'Costa	Howard	SKA
Death	Michael	Technologies
Deng	Xinping	Technologies
Doherty	Paul	Technologies
Drazenovic	Vicki	Operations
Dunning	Alex	Technologies
Edwards	Leanne	Operations
Edwards	Phil	Science
Ekers	Ron	Science
Feain	Ilana	Technologies
Fedeli	Jordan	Technologies
George	Daniel	Technologies
Gough	Russell	Technologies
Gray	Amanda	Science
Hampson	Grant	Technologies
Hartmann	Carmel	SKA
Hayman	Douglas	Technologies
Hobbs	George	Science
Hollow	Robert	Science
Howard	Eric	Operations
Humphrey	David	Technologies
Huynh	Minh	Technologies
Indermuehle	Balthasar	Science
Ingold	Brett	Technologies
Jeganathan	Kanapathippillai	Technologies
Johnston	Simon	Science
Kesteven	Michael	Technologies
Koribalski	Baerbel	Science
Kosmynin	Arkadi	Operations
Lee-Waddell	Karen	Science
Lenc	Emil	Science
Lennon	Brett	Operations
Lim	Boon	Technologies
Luo	Rui	Science
Mackay	Simon	Technologies
Macleod	Adam	SKA
Madden	Cathy	Management

SYDNEY (NSW) (CONTINUED)		
Mahony	Elizabeth	Science
Manchester	Dick	Science
Marquarding	Malte	Operations
McConnell	David	Science
McIntyre	Vincent	Operations
Mitchell	Daniel	Operations
Moss	Vanessa	Science
Norris	Ray	Science
Nosrati	Hamed	Technologies
Ord	Stephen	Operations
Pearce	Sarah	Management
Perry	Grant	Technologies
Petranovic	Aeva	Operations
Phillips	Chris	Science
Pilawa	Mike	Technologies
Pope	Nathan	Operations
Raja	Wasim	Operations
Reilly	Les	Technologies
Reynolds	John	Operations
Rispler	Adrian	SKA
Roberts	Paul	Technologies
Roush	Peter	Technologies
Sadler	Elaine	Science
Schinckel	Antony	SKA
Severs	Sean	Technologies
Shaw	Robert	Technologies
Smart	Ken	Technologies
Smith	Stephanie	Technologies
Storey	Michelle	SKA
Svenson	Nic	Management
Tearall	Liz	Management
Tesoriero	Julie	Technologies
Toomey	Lawrence	Science
Troup	Euan	Operations
Tuthill	John	Technologies
Tzioumis	Tasso	Technologies
Voronkov	Max	Operations
Whiting	Matthew	Science
Wiedemann	Markus	Technologies
Wieringa	Mark	Operations
Wilson	Carol	Technologies
Wu	Xinyu	Operations

NARRABRI (NSW)		
Cole	James	Operations
Forbes	Kylee	Operations
George	Mike	Operations
Hill	Mike	Operations
Kelly	Pam	Operations
Lee	Kun	Operations
Mirtschin	Peter	Operations
Rex	Jordan	Operations
Stevens	Jamie	Operations
Sunderland	Graeme	Operations
Trindall	Jane	Operations
Wilson	Chris	Operations
Wilson	John	Operations
Wilson	Tim	Operations

PARKES (NSW)		
Abbey	Alex	Operations
Clark	David	Operations
Hoyle	Simon	Operations

Kaletsch	Robert	Operations
Lees	Tom	Operations
Lensson	Erik	Operations
Mader	Stacy	Operations
Milgate	Lynette	Operations
Palmer	Kyasha	Operations
Preisig	Brett	Operations
Reeves	Ken	Operations
Ruckley	Tim	Operations
Sarkissian	John	Operations
Sarkissian	Annie	Operations
Sharwood	Warren	Operations
Smith	Mal	Operations
Trim	Tricia	Operations
Unger	Karin	Operations
PERTH (WA)		
Austin	Matt	Operations
Bastholm	Eric	Operations
Bignall	Hayley	Science
Broderick	Jess	Science
Chhetri	Rajan	Science
Cloake	Beth	Operations
Elagali	Ahmed	Science
Ferguson	Kevin	Operations
Galvin	Tim	Science
Green	Jimi	Science
Guzman	Juan	Operations
Hale	Catherine	Science
Haskins	Craig	Operations
Heald	George	Science
Hotan	Aidan	Science
Huynh	Minh	Science
Jameson	Katie	Science
Reynolds	Cormac	Science
Roja	Maria	Science
Sobey	Charlotte	Science
Taylor	Zoe	Operations
Thomson	Alec	Science
Tremblay	Chenoa	Science
Vernstrom	Tessa	Science
Wheadon	Rebecca	SKA
Wong	Ivy	Science
Yu	Yun	Science
Zhang	Xiang	Science
GERALDTON & MRO (WA)		
Boddington	Leonie	Operations
Cox	Tom	Operations
Danischewsky	Shaina	Operations
Desmond	Rochelle	Operations
Hannah	James	Operations
Harding	Alex	Operations
Hathway	Steve	Operations
Hiscock	Brett	Operations
McConigley	Ryan	Operations
McCormack	Bernadette	Operations
Merry	Clarence	Operations
Morris	John	Operations
Pena	Will	Operations
Puls	Lou	Operations
Reay	Michael	Operations
Rowan	Haydn	Operations
Warhurst	Kurt	Operations

C: Demographic data

These figures show people contributing to radio astronomy: ATNF and the SKA. Includes casual staff, joint appointments and, from 2020, those employed under contractor or labour hire arrangements. Does not include honourary fellows or students.

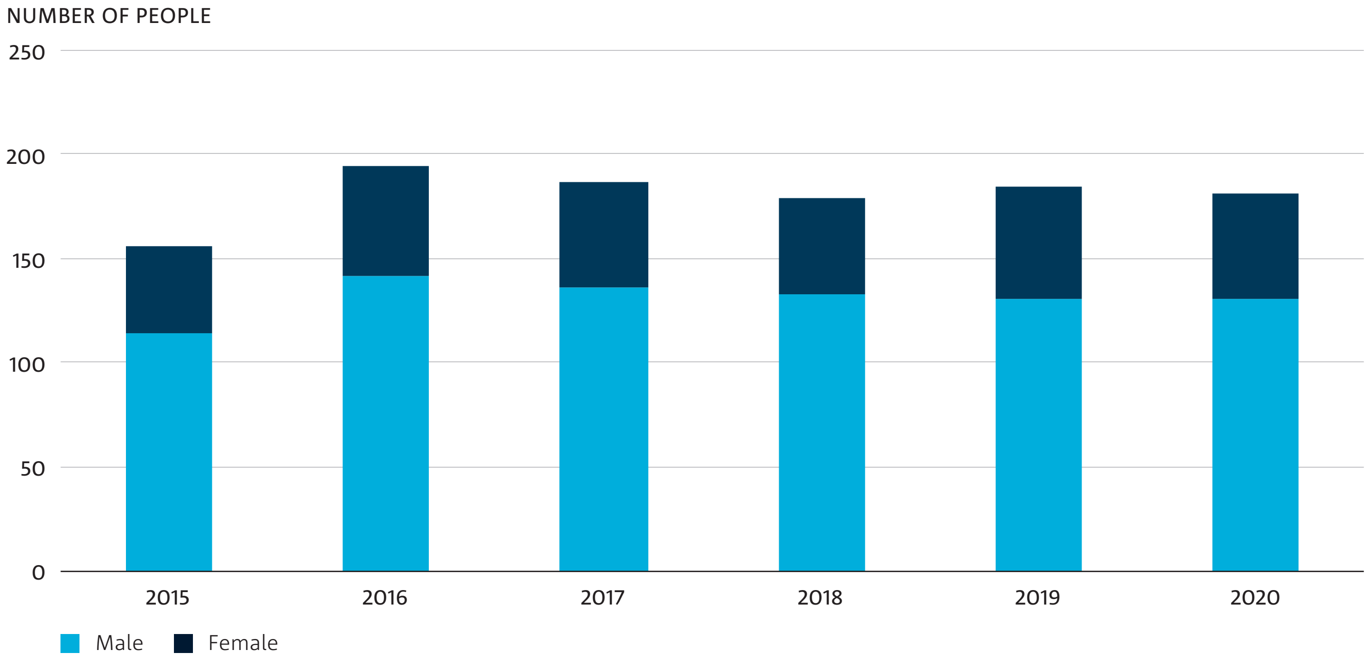


Figure 14: Gender breakdown over time.

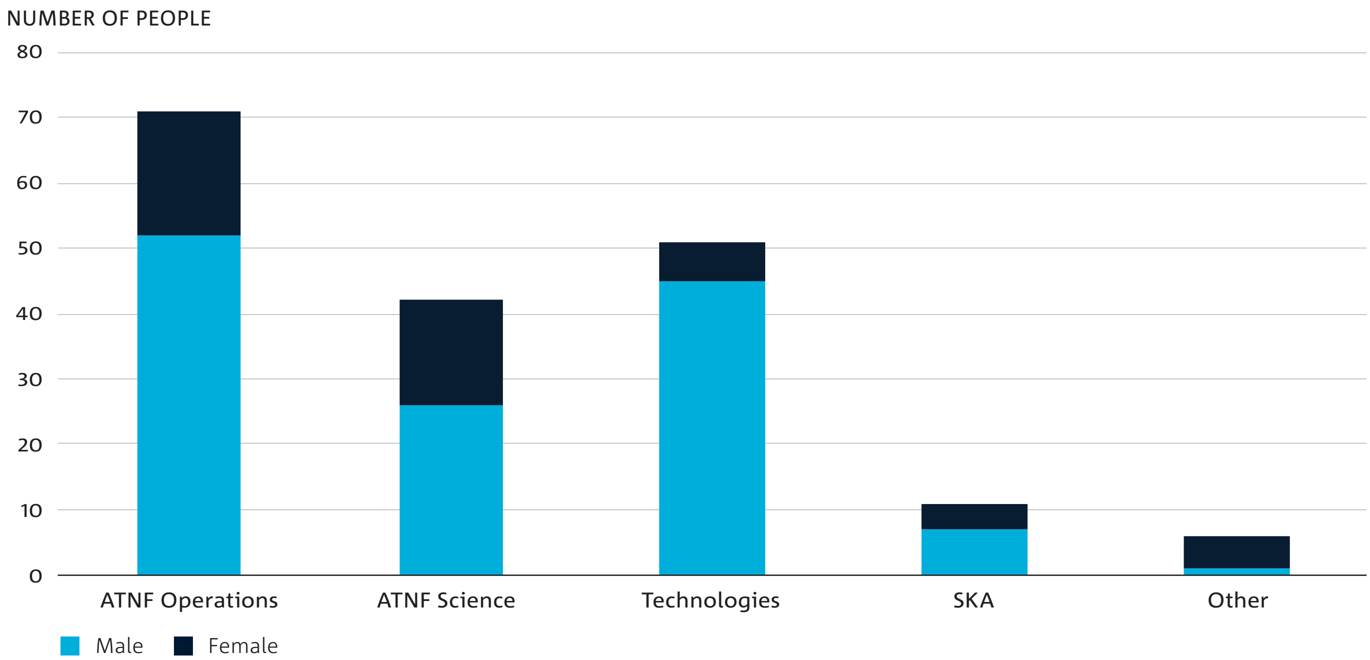


Figure 15: Gender breakdown across Programs as at 30 June 2020. Note: many staff working on SKA projects are based in other Programs, such as Technologies.

D: Committee membership

Years in brackets indicate when a member stood down.

ATNF Steering Committee

Chair

Dr David Skellern AO, RoZetta Institute

Australian astronomy community

Prof Matthew Bailes, Swinburne University of Technology (2019)

A/Prof Cathryn Trott, Curtin University (2019)

Prof David Davidson, Curtin University

Prof Sarah Brough, University of NSW

Prof Naomi McClure-Griffiths, Australian National University

Prof Tara Murphy, University of Sydney

International astronomy community

Prof John Carlstrom, University of Chicago (2019)

Prof Scott Ransom, National Radio Astronomy Observatory, USA

Prof Michael Wise, Netherlands Institute of Space Research

Prof Xiang-Ping Wu, National Astronomical Observatories of China

Australian stakeholder communities

Ms Catherine Livingstone AO

Dr David Skellern AO, RoZetta Institute

Ex-officio

Mr Brendan Dalton, Chief Information Officer, CSIRO

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Dr Hayley Bignall, Executive Officer (2019)

Dr Jimi Green, Executive Officer

Amanda Gray, Administration

E: Postgraduate students

Postgraduate students co-supervised by ATNF staff as of 30 June 2020 (PhD, unless marked otherwise).

NAME	UNIVERSITY	PROJECT TITLE
Wayne Arcus	Curtin University	Fast radio bursts as cosmic probes
Aman Chokshi	University of Melbourne	Low frequency beam simulations
Daniele d'Antonio	University of Technology Sydney	Radio afterglow of gravitational waves
Cherie Day	Swinburne University of Technology	Pinpointing the origin of fast radio bursts
Dougal Dobie	University of Sydney	Radio transient detection using the Australian Square Kilometre Array Pathfinder
Yi Feng	Chinese Academy of Science (CAS) National Astronomical Observatory	Jitter noise and gravitational waves
Sarah Hegarty	Swinburne University of Technology	Accelerating and enhancing knowledge discovery for the petascale astronomy era
Lucas Hyland	University of Tasmania	Structure of the Milky Way
Dilpreet Kaur	Curtin University	Probing the interstellar medium towards timing array pulsars with the MWA
James Leung	University of Sydney	An ASKAP search for gamma ray burst afterglows
John Lopez	University of New South Wales	Molecular clouds in the Milky Way: peering into the galactic centre and unravelling the origins of Planck cold clumps
Marcus Lower	Swinburne University of Technology	Application of astrophysical inference to next generational pulsar timing datasets
Peter MacGregor (MRes)	Western Sydney University	An Investigation of the diffuse radio emission in the galaxy cluster Abell S1136
Perica Manojlovic	Western Sydney University	Origin of the diffuse emission of galaxy clusters in the SPT field
Noor Md Said	University of Tasmania	Intraday variability of active galaxies
Shannon Melrose	University of New South Wales	Characterising the star formation properties of the interstellar medium
Chikaedu Ogbodo	Macquarie University	MAGMO: mapping the galactic magnetic field with masers
Dylan Pare	University of Iowa	Radio polarimetric observations of non-thermal filaments in the Galactic Centre: probing the magnetic field structure
Aditya Parthasarathy Madapusi	Swinburne University of Technology	High precision pulsar timing in the SKA era
Steve Prabu	Curtin University	Space debris detection using the Murchison Widefield Array
Harry Qiu	University of Sydney	Exploring the dynamic radio sky with ASKAP
Tristan Reynolds	University of Western Australia	The effect of the environment on the neutral hydrogen content of Galaxies
Jonathan Rogers	University of Tasmania	Unravelling the physics of galaxies and active galactic nuclei in the Square Kilometre Array era
Gary Segal	University of Queensland	Machine learning algorithms for detecting the interesting and the unexpected
Renzhi Su	CAS, Shanghai Astronomical Observatory	Tracing fuelling and feedback in powerful radio galaxies with 21-cm HI absorption
Abhimanyu Susobhanan	Tata Institute of Fundamental Research	Search for gravitational waves from eccentric super-massive black hole binaries in the Parkes pulsar timing array data sets
Jishnu Thekkeppattu	Curtin University	Towards detection of the redshifted 21-cm signal from cosmic dawn and epoch of reionisation

NAME	UNIVERSITY	PROJECT TITLE
Shuangqiang Wang	CAS, Xinjiang Astronomical Observatory.	Radio observations of the two intermittent pulsars: J1841-0500 and J1832+0029
Yuanming Wang	University of Sydney	Searching for extreme transients with ASKAP
Ziteng Wang	University of Sydney	Radio follow-up of gravitational wave events
Naoyuki Yonemaru	Kumamoto University	Simulation of gravitational wave signals from cosmic strings and the effects of the interstellar medium
Chao Zhang	CAS, National Astronomical Observatory.	Pulsar search with interpretable machine learning
Songbo Zhang	CAS, Purple Mountain Observatory	Searching for radio bursts in archival Parkes data
Andrew Zic	University of Sydney	Characterising the low frequency radio emission of dwarf stars and planets

F: PhD theses

Theses awarded to co-supervised postgraduate students (PhD, unless marked otherwise).

NAME	UNIVERSITY	MONTH AWARDED	THESIS TITLE
Ahmed Elagali	University of Western Australia	March 2020	Studies of interacting galaxies and the environmental effects on their evolution
Hiroki Kumamoto	Kumamoto University	March 2020	The observational studies of pulsars for detecting gravitational waves by radio telescopes
Ali Lalbakhsh	Macquarie University	March 2020	All-dielectric near-field transforming structures to dielectric-less metasurfaces for high-gain antenna systems
Kieran Luken (MSc)	Western Sydney University	September 2019	An investigation of machine learning algorithms for the estimation of galaxy redshift
Lachlan Marnoch (MSc)	Macquarie University	April 2020	The host galaxies and possible progenitors of fast radio bursts
Tommy Marshman (MSc)	Macquarie University	June 2020	Finding pulsars in a new SETI survey with a GPU based pipeline
Tiege McCarthy	University of Tasmania	June 2020	Class I methanol masers toward external galaxies
Bradley Meyers	Curtin University	September 2019	Investigating the links between radio pulsar populations that display intermittent emission phenomena at low frequencies
Karlie Noon (MSc)	Australian National University	November 2019	Distances and motions of high velocity clouds
Stuart Weston	Auckland University of Technology	October 2019	Astronomical catalogue cross identification for data mining and statistical analysis of the infrared and faint radio sky
Lei Zhang	National Astronomical Observatory, CAS	May 2020	Pulsar observation and study with FAST and Parkes radio telescope

G: Observing programs

Proposals allocated time on ATNF telescopes over the April 2019 – September 2019 and October 2019 – March 2020 semesters. A small number of target of opportunity observations are not listed.

ATCA

OBSERVERS	PROGRAM	Nº
Stevens, Edwards, Wieringa, Moss	ATCA Calibrators	C007
Lundqvist, Perez Torres, Ryder, Bjornsson, Fransson, Filipovic, Kundu	Probing type Ia supernova progenitors with ATCA	C1303
Ryder, Kundu, Filipovic, Anderson, Stockdale, Renaud, Kotak	NAPA observations of core-collapse supernovae	C1473
Edwards, Stevens, Ojha, Kadler, Wilms	ATCA monitoring of Fermi gamma-ray sources	C1730
Luken, Filipovic, Wong, Maxted, Alsaberi, de Horta, Brose	Evolution study of the youngest Galactic SNR G1.9+0.3	C1952
Possenti, Wieringa, Esposito, Israel, Rea, Burgay	Continuum radio emission from magnetars in outburst	C2456
Atri, Miller-Jones, Jonker, Maccarone, Nelemans, Sivakoff, Tzioumis	Constraining black hole formation with LBA astrometry	C2538
Russell, Miller-Jones, Sivakoff, Altamirano, Soria, Krimm, Tetarenko	Jet-disc coupling in black hole X-ray binary outbursts	C2601
Massardi, Lopez-Caniego, de Zotti, Bonato, Galluzzi	The ultimate definition of blazar candidates in the H-ATLAS fields	C2673
Coti Zelati, Russell, Papitto, de Martino	Deep radio observations of the transitional pulsar candidate CXOU J110926.4-650224	C3007
Russell, Altamirano, Ceccobello, Markoff, Miller-Jones, Russell, Sivakoff, Soria, Tetarenko	The evolving jet properties of transient black hole X-ray binaries	C3057
Huynh, Seymour, Shabala, Davies, Robotham, Sadler, Wong, Meyer, Prandoni, Riseley, Murphy, Smolcic, Butler, Turner, Drouart, Gurkanuygun, Swan, Rogers, Galvin, Kapinska, Delhaize, Chow, O'Brien, Hopkins, Norris, White, Marvil, Collier, Franzen	GAMA Legacy ATCA Southern Survey (GLASS): A legacy 4 cm survey of the GAMA G23 field	C3132
Breen, Walsh, Rowell, Ellingsen, Cunningham, Jones, Burton, Contreras, Schneider, Voronkov, Ott, De wilt, Green, Barnes, Longmore, Indermuehle, Fuller, Avison, Smith, Bronfman, Novak, Toth, Jordan, Hyland, McCarthy, Phillips, Federrath, Jackson, Fissel, Kainulainen, Dawson	Dense gas across the Milky Way – The 'full-strength' MALT45	C3145
van Velzen, Miller-Jones, Anderson, Shappee, Jonker, Arcavi, Holoien, Gezari	Radio emission from stellar tidal disruption flares	C3148
Jackson, Barnes, Rathborne, Longmore, Contreras, Sanhueza, Hogge, Stephens, Whitaker, Walker, Smith, Krumholz, Kruijssen, Walsh, Caselli, Cunningham, Ott, Allingham, Killerby-Smith, Breen, Jordan	A comprehensive ATCA census of high-mass cores	C3152
Popping, de Blok, Gannon, Heald, Koribalski, Lee-Waddell, Lopez-Sanchez, Spitler, Madrid, Moss, Meyer, Obreschkow, Pisano, Power, Rhee, Staveley-Smith, Wang, Westmeier, Wolf, Kaczmarek, Sardone, Vinsen, Elagali, Wong, Kleiner	Imaging galaxies intergalactic and nearby environment	C3157
Dannerbauer, Emonts, Huynh, Smail, Jin, Thomson, Altieri, Allison, Aretxaga, Brandt, Chapman, Casey, de Breuck, Drouart, Hodge, Indermuehle, Kimball, Kodama, Koyama, Lagos, Lehnert, Miley, Narayanan, Norris, Rottgering, Schinnerer, Seymour, Swinbank, Valtchanov, Julie Wardlow, Simpson	COALAS: CO ATCA Legacy Archive of Star-forming galaxies	C3181
Anderson, Bell, Hancock, Lynch, Miller-Jones, Bahramian, Bannister, Kaplan, Murphy, Ryder, Macquart, Plotkin	ATCA rapid-response triggering on X-ray and gamma-ray superflares from the smallest stars	C3200
Anderson, Bell, Hancock, Miller-Jones, Bahramian, Rowlinson, Aksulu, Bannister, van der Horst, Macquart, Ryder, Plotkin, Wijers	ATCA rapid-response triggering on Swift detected short gamma-ray bursts: Exploring the link with gravitational wave events	C3204
Shannon, Bannister, Macquart, Bhandari, Mahony, Deller, Dodson, Flynn, James, Oslowski, Prochaska, Sadler, Tejos, Day	Radio continuum emission from ASKAP-localised fast radio bursts	C3211

OBSERVERS	PROGRAM	Nº
Bannister, Bignall, Stevens, Walker, Reynolds, Tuntsov, Md Said	TAILS: Testing the Association of Intra-hour variability with Local Stars	C3214
Plotkin, Miller-Jones, Gallo, Jonker, Russell, Homan, Tomsick, Kaaret	The disk/jet connection for hard state black holes	C3219
Heald, Alexander, Anderson, Basu, Brown, Callingham, Carretti, Crawford, Farnes, Filipovic, Gaensler, Galvin, Harvey-Smith, Johnston-Hollitt, Kaczmarek, Landecker, Leahy, Lenc, Mao, McClure-Griffiths, Miyashita, O'Sullivan, Pasetto, Purcell, Riseley, Rudnick, Schnitzeler, Sobey, Sun, Thomson, Zhang	The QUOCKA Survey	C3244
Dobie, Murphy, Kaplan, Lenc, Brown, Stewart, Bannister	Long term radio follow-up of GW170817	C3251
Kuznetsov, Doyle, Metodieva, Nakariakov, Li, Banerjee, Kupriyanova	Searching for superflares on nearby active solar-like stars	C3260
Pineda, Lynch, Moss, Zic, Lenc	Uncovering the population of radio ultracool dwarfs	C3261
Callingham, Pope, Tuthill, Marcote	Sampling the orbit of the newly discovered and brightest non-thermal radio-emitting colliding wind binary	C3267
Bojicic, Filipovic, Crawford, Galvin, Wong	High frequency observations of ASKAP detected SMC PNe	C3275
Dobie, Murphy, Kaplan, Stewart, Bell, Lenc, Bannister, Hotokezaka, Brown, Qiu, Zic	Radio follow-up of LIGO gravitational wave events	C3278
Chomiuk, Ryder, Sokolovsky, Filipovic, Alsaberi, Manojlovic, Aydi, Linford	E-nova project monitoring of Nova Muscae 2018 and Nova Carinae 2018	C3279
Plotkin, Miller-Jones, Bahramian, Reynolds, Gandhi	An ATCA-Gaia search for the weakest black hole Jets	C3280
Schulze, Bauer, de Ugarte Postigo, Hunt, Jonker, Klose, Malesani, Michalowski, Nicastro, Palazzi, Pellizzoni, Possenti, Tanvir, van der Horst, Wieringa, Brocato, Kann, Lamb, Lekshmi, Lyman, Misra, Pian, Kim, Stanway	The properties of compact-object mergers detected by LIGO and VIRGO	C3281
Moin, Ilyasi	Circinus X-1 high time resolution survey	C3284
Tothill, Stark, Chapman, Aravena, Marrone, Spilker, Vieira	SPT0348-62: Molecular content of a high-redshift massive protocluster	C3287
Lee-Waddell, Mahony, Koribalski, Bhandari	HI mapping of ESO 601-G036 and its neighbouring stellar plume	C3288
Laskar, Alexander, Berger, Bhandari, Chornock, Coppejans, Drout, van Eerten, Fong, Guidorzi, Margutti, Mundell, Schady	GRB physics with ATCA: Direct implications for the explosions and progenitors	C3289
Ghaavam, Filipovic, Tothill, Kaczmarek, Maxted, Bozzetto, Maggi, Alsaberi, Gurovich	ATCA radio continuum study of the LMC supernova remnant N 49: `bullet ejecta' or `bow-shock bullet ejecta' or `bow-shock' PWN	C3292
Alsaberi, Filipovic, Maitra, Maggi, Gurovich, Bozzetto, Sano, Ghaavam	New bow-shocked pulsar wind nebula in Small Magellanic Cloud	C3293
Brown, Parkash, Dzudzar, Murugeshan, Kilborn, Cluver	HI galaxies with little or no star formation	C3294
Filipovic, Alsaberi, Maitra, Oliveira, Ghaavam, Galvin, Grieve, Bozzetto, Maggi, For, Crawford, O'Brien, Norris, Sano, Sasaki, Staveley-Smith, Joseph, Wong, Tothill, Haberl, Rowell, van Loon, Bojicic, Gurovich, Gaensler, Chu, Yew, Pennock, Urosevic	A 5.5 GHz ATCA large survey of the Small Magellanic Cloud (SMC)	C3295
Vardoulaki, Filipovic, Norris, Britzen, Rudnick, Alsaberi	Revealing the putative binary nature of an X-shaped radio source behind the Small Magellanic Cloud	C3296
Dempsey, McClure-Griffiths, Buckland-Willis, Jameson	Follow-up observations of HI absorption near the SMC detected by ASKAP	C3297
van Den Eijnden, Degenaar, Russell, Miller-Jones, Wijnands, Sivakoff, Hernandez Santisteban, Rouco Escorial	Be/X-ray binary jets 1: jet monitoring at periastron passage	C3298

ATCA continued

OBSERVERS	PROGRAM	Nº
van Den Eijnden, Degenaar, Russell, Miller-Jones, Wijnands, Sivakoff, Hernandez Santisteban, Rouco Escorial	Be/X-ray binary jets 2: evolving jets during a giant outburst	C3299
Troja, Piro, Ricci, Wieringa, Cenko, Lien, Sakamoto	Electromagnetic counterparts to gravitational wave events	C3300
Bonato, Trombetti, Galluzzi, de Zotti, Massardi, Burigana, Negrello, Herranz	A systematic search for ultra-bright high-z strongly lensed galaxies in Planck catalogues	C3301
Benaglia, De Becker, Marcote, Blanco	Determining near-periastron properties of the hottest and most luminous colliding-wind binary with ATCA	C3302
Pineda, Villadsen, Moss	Searching for auroral star-planet interactions	C3303
Gusinskaia, Hessels, Russell, Miller-Jones, Deller, Jaodand	Mapping accretion states in transitional millisecond pulsars using (quasi-)simultaneous radio and X-ray observations	C3307
Lucas, Forbrich, Thompson, Dale, Krause, Minniti, Smith, Cross, Dekany, Ivanov, Kurtev, Saito, Catelan	Observation of a candidate protostellar collision	C3309
Wong, Elagali, Koss, Privon, Ricci, Smith, Trakhtenbrot	Pilot SHIBS: a pilot study for the Southern HI BASS survey	C3311
Horesh, Murphy, Dobie, Qiu	A study of an unexplored population of fast radio supernovae	C3312
Zhao, Dodson, Jung, Rioja, Stevens, de Vicente, Cho, Kino, Sohn, Hada, Johnson, Koyama, Nakamura, Krichbaum, Zensus, Savolainen, Lu, Giroletti, Gomez, Akiyama, Rygl, Hodgson, Fraga-Encinas, Moran, Algaba, Mizuno, Ros, Pötzl, Kim	Probing the vicinity of SMBHs with high-precision astrometry	C3313
Alexander, Leahy, Heald, Riseley, Callingham, Anderson	A polarised look at extended DRAGNs in Ophiuchus	C3315
Fenech, Prinja, Andrews, Clark, Oskinova, Rickard	Robust mass-loss measurements of massive stars: Constraining the clumping gradients in the outer winds	C3318
Horiuchi, Benner, Benson, Edwards, Stevens, Phillips, Stacy, Kruzins, Giorgini, Molyneux	Southern hemisphere radar observations of near-Earth asteroids (NEAs)	C3319
Wenger, Anderson, Armentrout, Balser, Bania, Dawson, Dickey, Jordan, McClure-Griffiths	Resolving the distance ambiguity for SHRDS HII regions	C3320
Orosz, Breen, Ellingsen, Voronkov, Burns, McCarthy, Hyland	ATCA follow-ups of maser flares	C3321
Laskar, Alexander, Berger, Bhandari, Blanchard, Chornock, Coppejans, Cowperthwaite, Duffell, Eftekhari, Fong, Gomez, Hajela, Hosseinzadeh, MacFadyen, Margutti, Metzger, Mundell, Nicholl, Paterson, Schady, Schroeder, Terreran, van Eerten, Villar, Williams, Xie	ATCA follow-up of NS mergers from LIGO/Virgo in O3	C3322
Bietenholz, Bartel, Bauer, Ellingsen, Dwarkadas, Horiuchi, Mtshweni, Tzioumis	The spectral energy distribution of SN 1996cr two decades after the explosion	C3323
Cala, Gomez, Miranda	Searching for SiO masers in extremely young planetary nebulae	C3324
Alexander, Wieringa, Berger, Blanchard, Chornock, Coppejans, Cowperthwaite, Eftekhari, Hosseinzadeh, Laskar, Margutti, Nicholl	Exploring mass ejection in SMBHs via radio observations of TDEs	C3325
Jones, Avison, Fuller, Breen, Voronkov, Green	Marking the end of evolution: The association of class II methanol masers with high-mass star formation	C3327
Kundu, Ryder	Investigating the progenitors of core-collapse supernova	C3328
Huynh, Seymour, Galvin	Probing the physics of high redshift AGN with water masers	C3331
Ross, Hurley-Walker, Callingham, Seymour	Unexpected low-frequency spectral variability of peaked-spectrum sources	C3333
Anderson, Miller-Jones, Rau, Wilms	ATCA follow-up of eROSITA-detected tidal disruption Events	C3334
Quici, Seymour	Constraining the broad-band radio SED between 0.1-9 GHz for dying radio galaxies	C3335

Parkes radio telescope

OBSERVERS	PROGRAM	Nº
Burgay, Kramer, Manchester, Stairs, Lorimer, Possenti, McLaughlin, Wex, Ferdman, Hu	Timing & geodetic precession in the double pulsar	P455
Hobbs, Coles, Manchester, Sarkissian, Wen, Zhang, Keith, Wang, Kerr, Dai, van Straten, Dempsey, Russell, Spiewak, Parthasarathy, Bailes, Bhat, Levin, Oslowski, Reardon, Shannon, Zhang, Zhu, Kaczmarek	A millisecond pulsar timing array	P456
Sobey, Johnston, Dai, Kerr, Weltevrede, Shannon, Manchester, Hobbs, Possenti, Kumamoto	Young pulsar timing: probing the physics of pulsars and neutron stars	P574
Hobbs, Hollow, Dai, Green, Kaczmarek, Zhang, Cameron	PULSE@Parkes (Pulsar Student Exploration online at Parkes)	P595
Hobbs, Manchester, Bailes, Reynolds, Johnston, Sarkissian, Dai, Green, Kaczmarek, van Straten, Jameson, Sobey, Mader, Oslowski, Shannon	Instrumental calibration for pulsar observing at Parkes	P737
Spiewak, Bailes, Barr, Burgay, Cameron, Camilo, Champion, Cromartie, Eatough, Ferdman, Freire, Jankowski, Johnston, Keith, Kerr, Kramer, Levin, Lorimer, Morello, Ng, Possenti, Ransom, Stappers, Ray, Stairs, van Straten, Wex	Timing of binary & millisecond pulsars discovered at Parkes	P789
Mader, Green, Dawson, Tremblay, Bracco	A search for methylidyne and hydroxyl in the Musca Dark Cloud	P798
Balakrishnan, Cameron, Champion, Kramer, Bailes, Johnston, Possenti, Stappers, Burgay, van Straten, Bhat, Petroff, Ng, Barr, Flynn, Jameson, Bhandari, Wongphecauxson	Initial follow-up of pulsar discoveries from the HTRU Galactic Plane survey	P860
Camilo, Lower, Scholz, Reynolds, Sarkissian, Johnston	Understanding the remarkable behaviour of radio magnetars	P885
Keane, Bailes, Barr, Bhandari, Bhat, Burgay, Caleb, Eatough, Farah, Flynn, Green, Jankowski, Jameson, Johnston, Kramer, Levin, Morello, Ng, Petroff, Possenti, Primak, Spiewak, Stappers, van Straten, Tiburzi, Venkatraman Krishnan	SUPERBx – The SUrvey for Pulsars & Extragalactic Radio Bursts Extension	P892
Hobbs, Coles, Keith, Manchester, Sarkissian, Kerr, Wen, Dempsey, You, Rosado, Lasky, Toomey, Zhang, Ravi, Wang, Russell, Spiewak, Bailes, Bhat, Burke, Oslowski, van Straten, Zhu, Dai, Reardon, Parthasarathy, Shannon	Where are the gravitational waves?	P895
Green, Robishaw, Mader, Tremblay, Dawson, Breen, Ogbodo	Dark magnetic fields	P935
Possenti, Ducci, Mereghetti, Burgay	Catching the first transitional pulsar in an early-type binary system	P945
Shannon, Oslowski, Bannister, Macquart, Bhandari, Deller, Dodson, Flynn, Kerr, James, Qiu, Farah, Phillips, Zhang, Kumar	Studying the southern repeating fast radio burst population with Parkes	P958
Mader, Green, Kaczmarek, Robishaw	Receiver characterisation	P960
Venkatraman Krishnan, Reardon, Bailes, van Straten, Keane, Oslowski, Bhat, Flynn	Orbital dynamics and the intra-binary medium of PSR J1141-6545	P971
Dawson, Bracco, Green, Joncas, Grenier, Hill, Lee, Mader, Wardle, Robishaw, Dame, Nguyen, Petzler, Miville-Deschenes, Krishnarao, Marchal	Simultaneous UWL observations of OH and CH in a pristine high-latitude cloud: benchmarking dark gas tracers	P974
Zhang, Hobbs, Li, Kaczmarek, Dai, Cameron	Characterising the broadband intermittency time scale, mode changing, periodicities and polarization variations of PSR J1926-0652	P985
Kumamoto, Dai, Takahashi, Hobbs, Sobey	Targeted search of steep spectrum sources with the ultra-wideband receiver	P986
Hollow, Hobbs, Green, Kaczmarek, Zhang, Dai, Toomey, Cameron, Oslowski, Sobey	Maximising the science and education output from PULSE@Parkes and OPTIMUS in the era of the wide-bandwidth receiver	P988
Li, Hobbs, Green, Krco, Stanimirovic, McClure-Griffiths, Dai, Cameron, Kaczmarek, Weisberg, Zhang	A follow-up study of stimulated emission toward PSR B1641-45	P990
Dai, Zhang, Johnston, Hobbs	A pulsar survey towards the Galactic Centre with the ultra-wideband low receiver	P991

Parkes radio telescope continued

OBSERVERS	PROGRAM	Nº
Han, Manchester, van Straten, Hobbs, Zhou	Magnetic field reversals in distant spiral arms	P996
Xie, Hobbs, Li, Wang, Zhang, Dai	Wideband receiver observations of bright pulsars: Flux density measurements	P1004
Cameron, Champion, Kramer, Bailes, Johnston, Possenti, Stappers, Balakrishnan	Mapping the orbits of two nulling, long spin-period pulsars	P1005
Zhang, Hobbs, Li, Dai, Toomey, Cameron, Zhu	The first ultra-high time resolution coherently de-dispersed search for new pulsars in globular clusters	P1006
Main, Antoniadis, Mahajan, Lin, Wucknitz	An ultra-wideband study of plasma lensing in eclipsing binaries	P1007
Tiburzi, Shaifullah, Verbiest, Janssen, Oslowski, Zucca, Moochickal Ambalappat, Fallows	Tracking the solar wind with pulsars	P1008
Tiburzi, Verbiest, Shaifullah, Zucca, Janssen, Oslowski, Fallows, Sarkissian, Donner, Moochickal Ambalappat	Tracking the solar wind with pulsars	P1008
Posselt, Dai, Manchester, Weltevrede, Pavlov	Probing for radio – X-ray correlations in the pulse profile of PSRB1055-52	P1010
Jankowski, Keane, Stappers	A wideband survey of pulsars with spectral features	P1011
Wang, Li, Lorimer, Cordes, Chatterjee, Pan, Zhu, Hobbs, Lynch, Wang, Cameron, Qian	Confirming a certain dispersion measures range of pulsar candidates	P1012
Meyers, Hobbs, Johnston, Dai, Wang, Shannon, Tremblay, Bhat	An ultra-wideband study of the intermittent pulsar J1107-5907	P1013
Liu, Krco, Li, Hobbs, Dawson, Stanimirovic	A search for small-scale structures in the ISM (few to hundreds of AU scales)	P1014
Li, Simard, Kirsten, Baker, Macquart, Main, Marthi, Pen	Testing models of interstellar scintillation with the Vela pulsar	P1015
Kaczmarek, Hobbs, Oslowski, Dai, Johnston	Instant GRRATificiation	P1016
Anderson, Kaczmarek, O'Sullivan, Carretti, Heald, Leahy, McClure-Griffiths, Sobey	The CenA lobes in ultra-high definition: Precision radio galaxy astrophysics with the Parkes UWL receiver and ASKAP	P1017
Zic, Lynch, Murphy, Price, Kaplan, Lenc, Croft	Wide-band radio monitoring of space weather on Proxima Centauri	P1018
van Jaarsveld, Stappers, Camilo, McBride	Searching for pulsations from a newly discovered pulsar bowshock nebula discovered with MeerKAT	P1019
Cameron, Champion, Kramer, Balakrishnan, Bailes, Johnston, Stappers, Possenti	Mapping the orbit of an enigmatic 1.5-yr eclipsing binary pulsar.	P1021
Zhang, Hobbs, Li, Dai, Toomey, Kaczmarek, Wang	The first well-calibrated, coherent de-dispersed search for pulsars in 47 Tucanae	P1022
Horiuchi, Benner, Benson, Edwards, Stevens, Phillips, Stacy, Kruzins, Giorgini, Molyneux	Southern hemisphere radar observations of near-Earth asteroids (NEAs)	P1024
Corongiu, Belfiore, Burgay, Clark, Nieder, de Luca, Mignani, Possenti, Ridolfi	Monitoring the radio pulsations and eclipses of the RB pulsar PSR J2039-5617.	P1025
Dai, Cameron, Kaplan, Hobbs, Lenc, Murphy	Follow-up of the ASKAP discovery of millisecond pulsar J1431-6328	P1027
Spitler, Wharton, Kramer, Johnston, Main, Eatough, Noutsos, Shao, Desvignes, Torne, Liu	Wideband characterization of Galactic center pulsars	P1028
Hobbs, Johnston, Li	Catching a pulse in the act of nulling	P1029
McSweeney, Bhat	The frequency-dependent phase shifts of subpulses due to relativistic effects	P1030
Primak, van Straten, Tiburzi, Parthasarathy	A pilot study to demonstrate novel radio pulsar emission analysis techniques	P1031
Venkatraman Krishnan, Freire, Kramer, Champion, Parthasarathy, Buchner, Lower	Mass measurements of southern binary pulsar systems	P1032
Venkatraman Krishnan, Freire	Estimating the Shapiro delay in the binary pulsar system PSR J1748-2021B	P1033

OBSERVERS	PROGRAM	Nº
Dai, Johnston, Kumamoto	Follow-up of the first millisecond pulsar discoveries in Omega Centauri and a new coherently de-dispersed survey	P1034
Li, Cameron, Hobbs, Zhang, Dai, Toomey, Dempsey, Zhu, Pan, Green, Kaczmarek, Wang, Wang, Miao, Yuan	FAST: category 1	PX500
Li, Cameron, Hobbs, Zhang, Dai, Toomey, Dempsey, Zhu, Pan, Green, Kaczmarek, Wang, Wang, Miao, Yuan	FAST: category 2	PX501
Siemion, Price, McMahon, Lebofsky, Isaacson, Gajjar, and the Berkeley SETI Institute	Breakthrough Listen	BL

LBA

OBSERVERS	PROGRAM	Nº
Kumar, Ellingsen, Reid, Brunthaler, Menten, Honma, Rioja, Dodson, Chibueze, Green, Krishnan, Sakai, Breen, Chen, Dawson, Fujisawa, Phillips, Sanna, Shen, Xu, Voronkov, Zheng, Goedhart, Zhang, Hyland, Orosz	Astrometric observation of methanol masers: determining Galactic structure and investigating high-mass star formation	V255
Atri, Miller-Jones, Jonker, Maccarone, Nelemans, Sivakoff, Tzioumis	Constraining black hole formation with LBA astrometry	V447
Burns, Rioja, Imai, Honma, Handa, Sakai, Ellingsen, Dodson, Orosz, Sugiyama, Krishnan	6.7 GHz maser parallax of a particularly interesting high-mass star forming region	V525
Orosz, Gomez, Tafoya, Imai, Suarez, Burns, Ellingsen, Hyland, Horiuchi	Astrometric measurements of the first water fountain planetary nebula	V544
Yang, Deller, Reynolds, Quick, Hobbs, Weston, Gurvits, Paragi, An, Hong, Chen, Xia, Yan, Guo, Ding, Li, Chen, Xu, Hao	Toward a sub-parsec accuracy for VLBI distance measurement of PSR J0437-4715	V558
Kirichenko, Shternin, Tanashkin, Shibanov, Voronkov, Zyuzin, Danilenko	Determining the distance to PSR B1727-47 by parallax measurements with VLBI	V560
Xu, Zhang	Distance and rotation of R Dor via VLBI maser astrometry	V576
Main, Baker, Deller, Kirsten, Reardon, Wucknitz	Imaging the scattering screens of PSR J0437-4715	V580
Burns, Breen, Orosz, Ellingsen, Sugiyama, Hirota, Kim, MacLeod, Brogan, Sobolev, Bayandina, Olech, van Den Heever	VLBI follow-ups of maser flares	V581
Riseley, Reynolds, Radcliffe	Resolving the core/jet system of the giant radio galaxy ESO 422-G028	V582
Titov, Shu, Zhang, Xu, He, Chen, Anderson, Phillips, Lunz, Heinkelmann, Lopez	VLBI observations of radio stars using large radio telescopes	V583
Golden, Reynolds	Resolving stellar magnetospheres using the LBA	V586
Ramakrishnan, Nagar, Bignall, Reynolds	EHT+ sample: parsec-scale structure of nearby AGNs	V587
Edwards, Stevens, Corbet, Marcote, Strader, Reynolds	A first epoch LBA observation of a new gamma-ray binary	V589
Marcote, Benaglia, De Becker, Blanco, Blanchard	Determining near-periastron properties of the hottest and most luminous colliding-wind binary with LBA	V191
Ojha, Kadler, Edwards, Ros, Wilms, Angioni, Beuchert, Dutka, Eberl, Fey, Hase, Horiuchi, Jauncey, Johnston, Katz, Klockner, Krauß, Kreter, Langejahn, Lindeholz, Lister, McEnery, Nesci, Phillips, Plotz, Pursimo, Quick, Reynolds, Rosch, Schulz, Taylor, Thompson, Tingay, Tosti, Tzioumis, Weber, Zensus	Physics of gamma-ray emitting AGN	V252
Bietenholz, Bartel, Bauer, Ellingsen, Dwarkadas, Horiuchi, Mtshweni, Tzioumis	Structure and size of SN 1996cr, the strongest optically-identified radio supernova	V253

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OBSERVERS	PROGRAM	Nº
Orosz, Gomez, Horiuchi, Imai	Monitoring of H_2O masers in all known water fountains	T215
Horiuchi, Benner, Benson, Edwards, Stevens, Phillips, Stacy, Kruzins, Giorgini, Molyneux	Southern hemisphere radar observations of near-Earth asteroids	C3319

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Legend

* Authors include ATNF staff
A ASKAP
C ATCA
M Mopra
O Other staff paper
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S SKA
T Tidbinbilla (CDSCC)
V VLBI

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Legend

* Authors include ATNF staff
A ASKAP
C ATCA
M Mopra
O Other staff paper
P Parkes
S SKA
T Tidbinbilla (CDSCC)
V VLBI

I: Abbreviations

This list does not include units of measure or chemical symbols.

ABBREVIATION	DESCRIPTION
ACMA	Australian Communications and Media Authority
ADC	Analog to digital converter
AO	Officer in the Order of Australia
ARC	Australian Research Council
ARQAWA	Australian Radio Quiet Zone (WA)
ASKAP	Australian SKA Pathfinder
ASTRON	Netherlands Institute for Radio Astronomy
ATCA	Australia Telescope Compact Array
ATNF	Australia Telescope National Facility
ATOA	Australia Telescope Online Archive
ATSC	ATNF Steering Committee
ATUC	ATNF User Committee
AusSRC	Australian SKA Regional Centre
BIGCAT	Broadband Integrated GPU-Correlator for the Australia Telescope
CABB	Compact Array Broadband Backend
CASDA	CSIRO ASKAP Science Data Archive
CAS	Chinese Academy of Sciences
CASS	CSIRO Astronomy and Space Science
CDSCC	Canberra Deep Space Communication Complex
CRAFT	Commensal Real-time ASKAP Fast Transients
CSIRO	Commonwealth Industrial and Scientific Research Organisation
DAP	Data Access Portal
DINGO	Deep Investigation of Neutral Gas Origins
DISER	Department of Industry, Science, Energy and Resources
EDGES	Experiment to Detect the Global Epoch of reionisation Signature
EMU	Evolutionary Map of the Universe
ESA	European Space Agency
ESO	European Southern Observatory
FAST	Five hundred meter Aperture Spherical Telescope (China)
FLASH	First Large Absorption Survey in HI
FPGA	Field Programmable Gate Array
FRB	Fast Radio Burst
FTE	Full Time Equivalent

ABBREVIATION	DESCRIPTION
GASKAP	Galactic ASKAP survey
GPU	Graphics Processing Unit
IAU	International Astronomical Union
ICRAR	International Centre for Radio Astronomy Research
IEEE	Institute of Electrical and Electronics Engineers
ILUA	Indigenous Land Use Agreement
LBA	Long Baseline Array
LIGO	Laser Interferometry Gravitational Wave Observatory
LNA	Low Noise Amplifier
MMIC	Mircowave Monolithic Integrated Circuit
MRO	Murchison Radio-astronomy Observatory
MWA	Murchison Widefield Array
NAOC	National Astronomical Observatories, Chinese Academy of Sciences
NAPA	Non A-Priori Assignable
NASA	National Aeronautics and Space Administration
NRAO	National Radio Astronomy Observatory (USA)
NSW	New South Wales
PAF	Phased Array Feed
PI	Principal Investigator
POSSUM	Polarisation Sky Survey of the Universe's Magnetism
RACS	Rapid ASKAP Continuum Survey
RFI	Radio Frequency Interference
RFSoC	Radio Frequency System on a Chip
SAGE	Science in Australia Gender Equity
SKA	Square Kilometre Array
SKAO	SKA Organisation
STEM	Science Technology Engineering and Mathematics
TAC	ATNF Time Assignment Committee
UWB	Ultra Wideband
VAST	Variables And Slow Transients
VLBI	Very Long Baseline Interferometry
WA	Western Australia
WALLABY	Widefield ASKAP L-band Legacy All-sky Blind survey

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