The Australian SKA Pathfinder: A 'next generation' Radio Telescope

DOUGLAS C.-J. BOCK
CSIRO ASTRONOMY AND SPACE SCIENCE

Fig. 1: ASKAP antennas, each 12 m in diameter, at the Murchison Radio-astronomy Observatory. Credit: Australian SKA Office.

ABSTRACT

The Australian SKA Pathfinder is a new 36-element radio interferometer designed to be a fast survey telescope. Its key technology, phased-array receivers designed by CSIRO, has shown proven advantages in bandwidth, field of view and adaptability. ASKAP is located at a superbly 'radio quiet' site in Western Australia, one of the sites that will house the international Square Kilometre Array.

INTRODUCTION

The Australian Square Kilometre Array Pathfinder (ASKAP) is a radio telescope, a 36-dish interferometer, built and operated by Australia's largest national research organisation, CSIRO (the Commonwealth Scientific and Industrial Research Organisation). CSIRO also operates radio telescopes at three sites in eastern Australia and has a history in radio astronomy stretching back to the 1940s. Until 2008, the land on which ASKAP sits was a pastoral station (cattle ranch) in remote Western Australia, 300 km from the nearest town, Geraldton. It is now the Murchison Radio-astronomy Observatory, one the world's premier locations for radio astronomy because of its superb 'radio quietness' (low levels of radio interference).

A FAST SURVEY TELESCOPE

As its name suggests, ASKAP was designed to address fundamental science and technology goals for the coming Square Kilometre Array (SKA), the world's largest radio telescope project. The low-frequency telescopes of the SKA (those covering 50–350 MHz) will be housed at the MRO, the mid-frequency ones (350 MHz–14 GHz) in South Africa's Karoo region. ASKAP's science goals

Fig. 2: Top: CSIRO engineer Mark Bowen with a traditional feedhorn. Bottom: a CSIRO phased-array feed being installed on an ASKAP antenna. Credits: CSIRO

directly address the SKA's science priorities, and the lessons from building its real-time calibration pipeline will be directly applicable to the SKA, which will also process data in real time.

But ASKAP is more than an SKA testbed. It is specifically designed to be a fast, mid-frequency survey telescope, and its high dynamic range and wide field of view will make it a leading telescope in its own right for many years. The key to ASKAP's success as a survey telescope lies in its radio receivers, phased-array feeds designed and built by CSIRO.

PHASED-ARRAY FEEDS

Traditionally, radio telescope feeds have been large, metallic, horn-like structures. They are designed to efficiently collect radio energy reflected by the antenna surface, but are sensitive to one direction only and cannot fully sample the sky at any instant. In recent years, therefore, several radio astronomy groups have been experimenting with phased-array feeds (PAFs) and related aperture-array technologies, which can efficiently gather off-axis signals to observe in multiple directions simultaneously.

A phased-array feed typically consists of simple receptors, closely packed in the focal plane of the antenna. The voltages from these receptors are combined to form beams on the sky. When done digitally, this is computationally intensive. However, the advantage is that the direction of the beams is not fixed by the hardware but is controlled by varying the weighting of different elements of the PAF. This means that the beams can be tailored to meet the specific needs of a project. PAFs have two other major advantages, one being a large instantaneous field of view: in the case of the ASKAP PAFs, 30 square degrees. Third, PAFs can achieve extremely wide bandwidths. The commissioning observations shown in Fig. 5, made with a 6-dish array, have a bandwidth of 300 MHz.

These are leading performance figures for an astronomical PAF. For comparison, the *Apertif* PAFs being installed on the Westerbork Synthesis Radio Telescope in The Netherlands will give that telescope an instantaneous field of view of eight square degrees and a bandwidth of 300 MHz. The PAF being developed by the US National Radio Astronomy Observatory is still very much an experimental instrument, with a bandwidth of just 50 MHz, although it is designed to be cryogenically cooled for maximum sensitivity.

Fig. 3: Field of view. An ASKAP image of the Apus field, made in April 2016. This radio-continuum image was created using 36 beams and represents the full ASKAP field of view of 30 square degrees. (The Moon is shown for comparison.) The image has an rms of about 300 microJansky per beam and contains more than 1300 sources, most of which are distant galaxies emitting strongly at radio wavelengths. Credit: ASKAP team (unpublished image)

Third axis of rotation

Radio astronomy antennas have traditionally had only two axes of rotation (e.g. to move the telescope in altitude and azimuthal angle). This results in the feed being rotated with respect to the sky as the telescope tracks an object over time. When using a PAF, such rotation requires the PAF's beams on the sky to be electronically steered: that is, continually updated. ASKAP therefore incorporates an unusual feature: a third axis of rotation that allows the PAF to be kept fixed with respect to the field being observed. Using this 'roll' axis significantly suppresses imaging artefacts while minimising computing complexity.

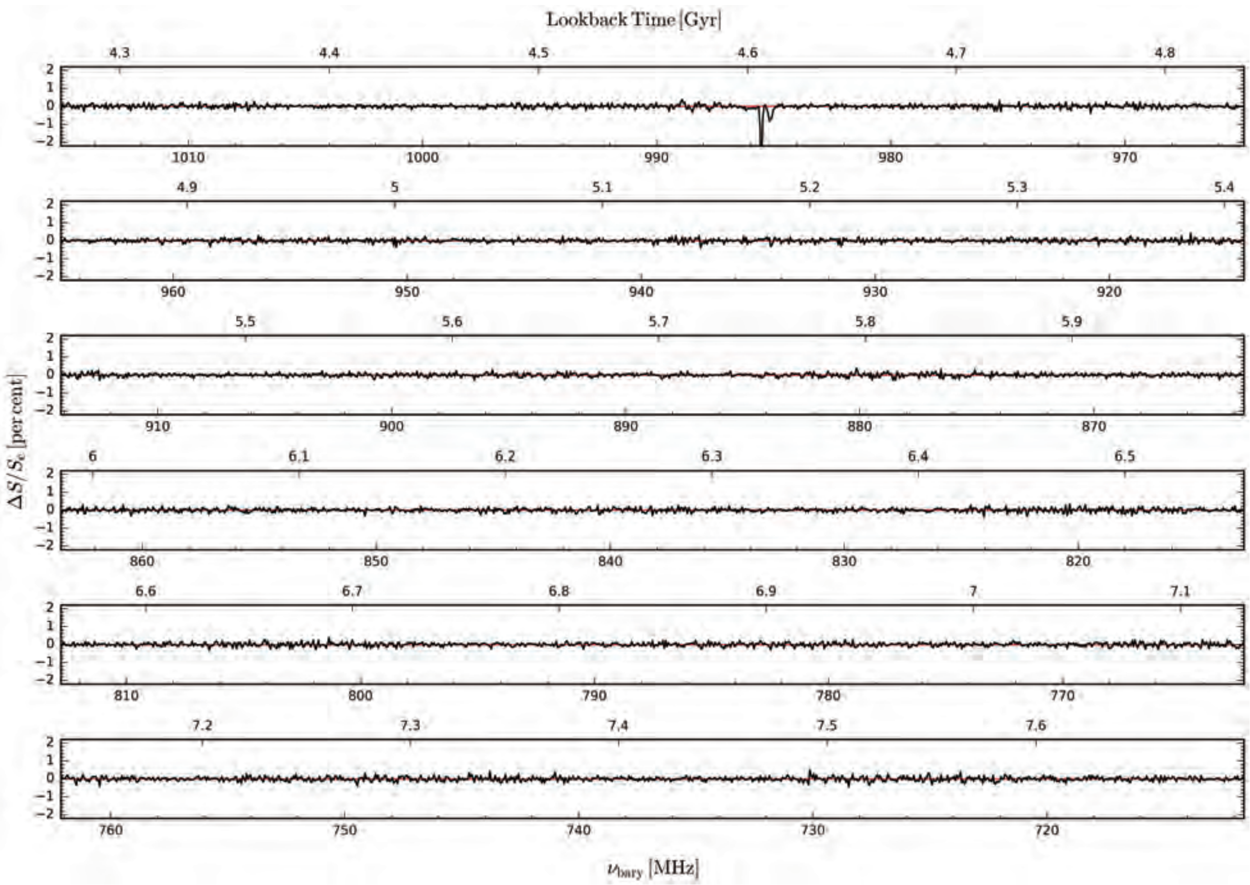

Fig. 4: Wide bandwidth. One of ASKAP's major initial projects is a survey for neutral hydrogen (HI) in absorption. This commissioning observation [2], made with six ASKAP antennas, shows the radio spectrum over 711.5–1015.5 MHz towards a young 'radio galaxy' (a galaxy emitting strongly at radio wavelengths) called PKS B1740–517. A single absorption line is visible in the spectrum at 985.5 MHz, equal to a redshift of z = 0.4413. The freedom of the remainder of the spectrum from human-generated signals demonstrates the extreme radio quietness of the Murchison Radio-astronomy Observatory.

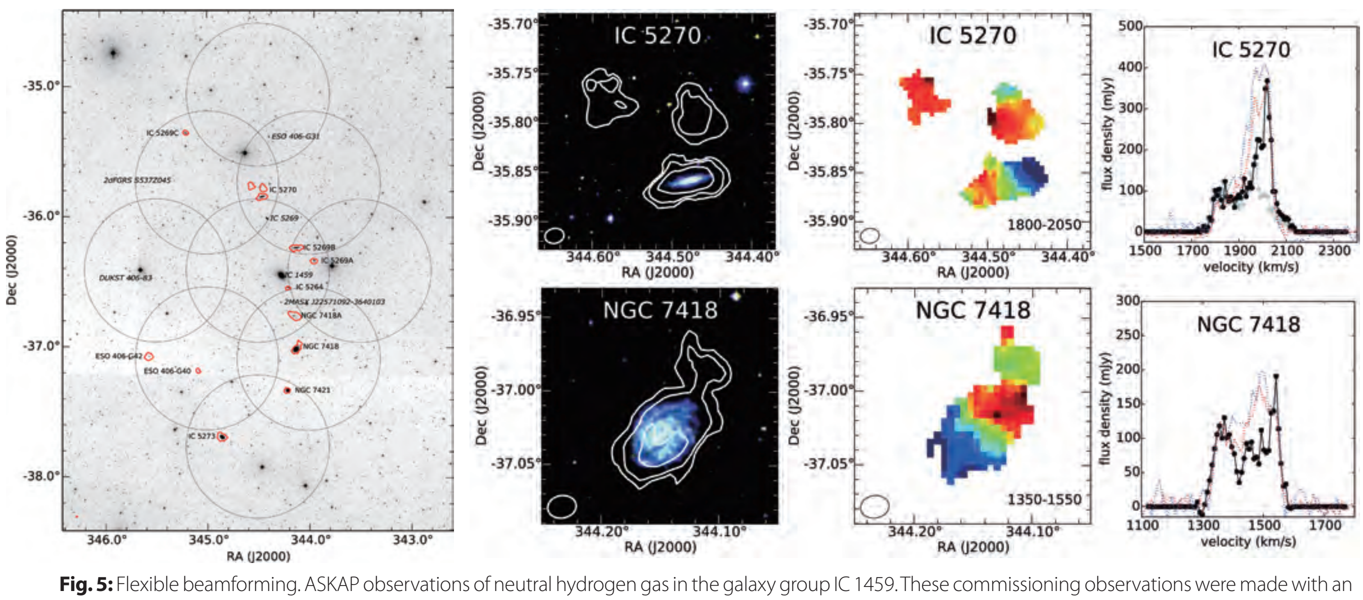

Fig. 5: Flexible beamforming. ASKAP observations of neutral hydrogen gas in the galaxy group IC 1459. These commissioning observations were made with an array of six antennas, fitted with an early design of the CSIRO PAFs. Nine beams (grey circles, left) were arranged to cover the field efficiently; neutral-hydrogen spectra and velocity fields (right) were recorded for a number of individual galaxies [1].

Use on single dishes

ASKAP is an interferometer, but the PAF is also now showing its worth for single dishes. CSIRO has supplied Germany's Max Planck Institute for Radio Astronomy (MPIfR) a version of the ASKAP PAF for use on the 100-m Effelsberg telescope near Bonn, Germany. This was installed on the telescope in April this year and is now being used to hunt for fast radio bursts (FRBs), the enigmatic millisecond bursts discovered in 2007 in archival data recorded by CSIRO's 64-m Parkes telescope. Before being shipped to Germany, the instrument was installed on Parkes for six months of commissioning observations.

Fig. 6: Installation of the MPIfR phased-array feed on the Parkes telescope: the view from inside the telescope's focus cabin. Credit: Xinping Deng (MPIfR)

A paper summarising the commissioning observations on Parkes [3] has now been accepted for publication. It shows that the PAF allows radio-frequency interference to be markedly reduced, using a spatial filtering technique based on projecting out the signature of an interferer [4].

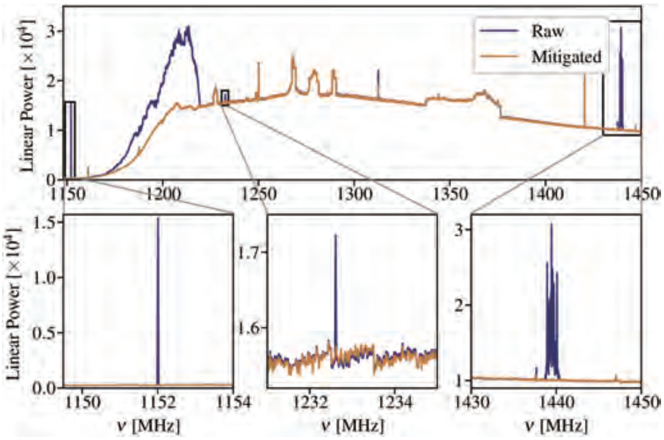

Fig. 7: Mitigating radio-frequency interference with the MPIfR phased-array feed on Parkes: a sample spectrum before (blue) and after (red) applying a real-time projection algorithm for RFI mitigation [3].

Crucially, the PAF also eliminates 90 per cent of the 'baseband ripple', standing waves in the signal caused by reflections from parts of the telescope's structure and which can limit calibration. This significant reduction is a result of the PAF covering more of the focal plane than other receivers: greater collecting area means less energy is available for multipath reflections. It may be possible to suppress the standing wave even further, using more advanced beamforming techniques. The measured system temperature divided by aperture efficiency (T_{sys}/η) of this PAF on Parkes in the 1.2–1.4 GHz band was ~60 K, but we are now developing a cryogenically cooled version for long-term use on Parkes that could achieve a T_{sys}/η of 25 K or less.

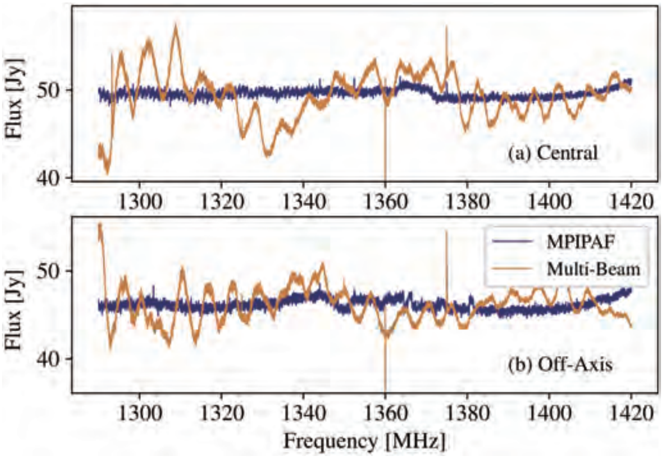

Fig. 8: Sample spectra of the radio source PKS 1934–638 (prior to bandpass correction) from the most commonly used receiver on Parkes, the multibeam receiver (brown), and the MPIfR phased-array feed (blue) [3].

SCIENCE WITH ASKAP

PAFs have been built for all 36 antennas and installation will be complete by early 2018. The first five years of science with the full ASKAP array will be dominated by 10 major survey science projects, carried out by hundreds of researchers from around 20 countries. ASKAP's first phase of observations, 'Early Science', will employ 12 antennas, with up to 300 MHz of bandwidth and 36 beams.

Neutral hydrogen surveys

Early Science officially began in October 2016, with the first observations being made for a project called WALLABY (the Widefield ASKAP L-Band Legacy All-sky Blind surveY). This survey has been designed to study the properties, environments and large-scale distribution of gas-rich galaxies: it will cover 75 per cent of the sky (the entire sky south of declination +30 degrees) and is predicted to detect neutral hydrogen gas, HI, in more than 500,000 galaxies. The large extent and homogeneity of WALLABY will allow us to examine in detail galaxy formation and evolution, the role of galaxy mergers and interaction events, the HI mass function and its relation with galaxy density, the physical processes governing cool gas at low redshift, cosmological parameters relating to gas-rich galaxies, and the nature of the 'cosmic web' (intergalactic gas). WALLABY will lay the ground for key science to be carried out with the future Square Kilometre Array. By the end of 2016, four extragalactic WALLABY fields – the NGC 7232 group, the Fornax cluster, the Dorado group and a field centred on M83 – had been observed using 12 ASKAP antennas equipped with phased-array feeds. This observing generated over 400 hours of HI data, which tested not only the current capabilities of the array hardware, but also all aspects of the queued scheduling, data transfer and storage, data processing and analysis, and the eventual archiving and public release through the newly developed CSIRO ASKAP Science Data Archive (CASDA) system. WALLABY will be complemented by DINGO (Deep Investigation of Neutral Gas Origins), a survey similar to WALLABY but going deeper over a smaller area.

Radio-continuum survey

Studies of neutral hydrogen will make up a large part of ASKAP's work, but not all of it. ASKAP's major radio-continuum survey, EMU (Evolutionary Map of the Universe), is expected to increase the number of known cosmic radio sources about 30-fold, from around 2.5 million to 70 million. Key science goals for EMU are to trace the evolution of both star-forming galaxies and black holes, over significant periods of the Universe's history. EMU will cover almost as much area as NVSS (the NRAO VLA Sky Survey), the benchmark survey in this field, but will be 40 times more sensitive.

Polarisation survey

Another of the survey science projects will make use of the telescope's sensitivity to polarisation. This project is POSSUM (Polarisation Sky Survey of the Universe's Magnetism), a continuum polarisation survey of 75 per cent of the sky with a resolution of 10 arcseconds. The origin of cosmic magnetic fields is a fundamental, unsolved problem; magnetic fields are also key to understanding many other cosmic phenomena, such as the acceleration and propagation of cosmic rays. POSSUM will create a catalogue of Faraday rotation measures for around a million extragalactic radio sources that will allow the POSSUM team to determine the 3D geometry of the Milky Way's magnetic field; to test dynamo and other models for generating magnetic fields; and to carry out a comprehensive census of magnetic fields as a function of redshift in galaxies, in clusters and in the overall intergalactic medium.

Fast Radio Bursts

The survey-science project that has dominated ASKAP observing time this year is yet another type of project: a search for transient sources, CRAFT (the Commensal Real-time ASKAP Fast Transients survey). CRAFT observations to date have been focused on finding instances of a new cosmic phenomenon, fast radio bursts (FRBs) – bursts of radio waves lasting on the order of a millisecond that appear to come from the distant Universe. ASKAP detected its first FRB after less than four days of searching [5]. This rapidity implies that ASKAP will be extremely competitive in this exciting new field.

Gravitational-wave follow-up

The same wide field of view that helps ASKAP find FRBs also makes it well-suited for following up other transient signals, such as those from aLIGO (Advanced Laser Interferometer Gravitational-Wave Observatory). The direction of signals detected by aLIGO is poorly constrained, with on-sky error boxes ranging from ten to thousands of square degrees. ASKAP's wide field of view, plus its fast survey speed, can cover them quickly. In addition, ASKAP observes at 700 MHz to 1.8 GHz, and theoretical work [6] has suggested that 1.4 GHz is the most likely frequency at which to detect a radio flare from the merger of a compact binary system (two neutron stars or a neutron star and a black hole). ASKAP participates in the aLIGO/AdV [Advanced Virgo] Event Follow-up program and was among the instruments used for broadband follow up of the first aLIGO gravitational-wave transient, GW150914, in September 2015.

THE SQUARE KILOMETRE ARRAY

ASKAP observations to date highlight just how free the Murchison Radio-astronomy Observatory (MRO) is from radio-frequency interference. This bodes well for the Square Kilometre Array itself. The construction of the SKA's initial low-frequency array, SKA1-low, is due to start at the Murchison Radio-astronomy Observatory in 2020. This array of 120,000 log-periodic dipoles operating in the range 50–350 MHz is being optimised to image the Epoch of Reionisation (EOR), the period dur-

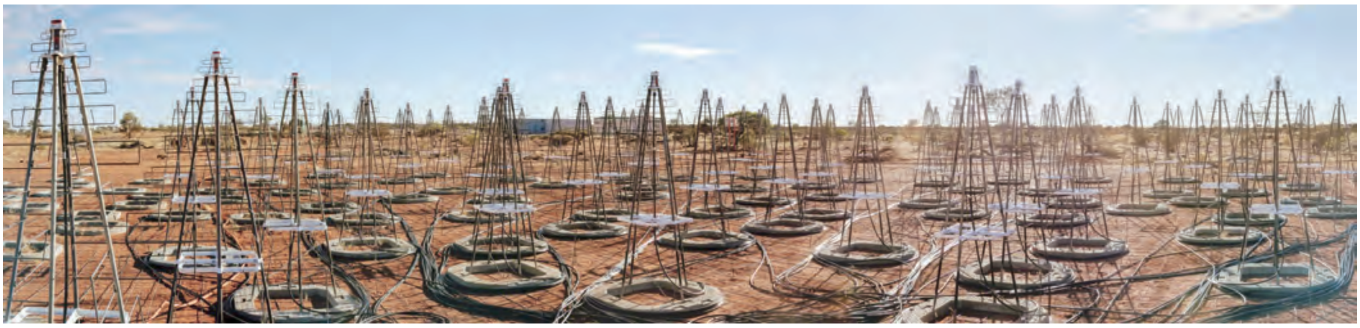

Fig. 9: An array of prototype SKA1-Low antennas at the MRO. Credit: ICRAR/Curtin University.

ing which the neutral Universe was ionised by the first luminous sources. This reionisation was complete within the first billion years of our Universe's life. SKA1-low will also be used to discover and time pulsars (rapidly rotating remnants of massive stars at the end of their lives), and to image magnetism.

The SKA is expected to produce of the order of 700 PB of processed data products each year. These data products will be delivered to users through a network of SKA Regional Centres that are currently being defined. These will provide opportunities for more countries in the Asia-Pacific region to be involved in the SKA. But more than that: with data rates so big they have outgrown the name 'big data', astronomy will be leading the world into the era of ultra-largescale data.

When fully operational, ASKAP's phased array feeds will produce every second what the Internet sees in a year – and this is around 1% of the SKA data rate. These data must therefore be processed locally before being transported to the Pawsey Centre in Perth for further analysis. This is giving us unique and exciting insights into how 'genuinely big' data processing platforms could be designed: combining embedded analytics in sensor systems and high performance computing or cloud processing platforms, leading to management techniques for open data and new data-driven discovery at scale – in science and in industry.

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Douglas Bock is the Director of CSIRO Astronomy and Space Science. After receiving a PhD from the University of Sydney in radio astronomy, he worked with the Berkeley–Illinois–Maryland Association Array and the Allen Telescope Array project at the University of California, Berkeley. He was Project Manager and then Assistant Director, Operations, for the Combined Array for Research in Millimeter-wave Astronomy (CARMA). He joined CSIRO in 2010. His professional interests are astronomical science, astronomical instrumentation, and building, managing and operating radio telescopes.