



To synchronise the array, high quality local oscillator signals will be sent from a central master timebase, an ultra pure 16 MHz carrier.

Connecting antennas to the central site digital signal processing (beamformer and correlator) will require terabit per second data (Tbps) pipelines over distances of up to 8 km. The total output data rate per antenna will be approximately 2 Tbps and the total input rate to the digital beamformers will be a continuous 72 Tbps. Commercial off-the-shelf 1 Ge ethernet will be networked to each antenna and around site for system monitoring and control.

A long-haul (400 km) DWDM data transmission system with three intermediate repeater huts will transport visibility data from the remote array site (the MRO) to the MRO Support Facility in Geraldton and beyond. High data rate paths will also be required back (bi-directional) to the ASKAP site from other remote antenna installations around the continent as a demonstration for the SKA. Initial ASKAP requirements are for a 1 Gbps link expandable to several hundred gigabits per second using 10 Gbps DWDM. The fibre choice (dispersion shifted G655) will enable expansion to 40 Gbps and 100 Gbps per wavelength for future SKA requirements.

Future options

Other applicable technologies are also being considered for ASKAP and the SKA. An RF over-fibre-optic system, which will minimise self generated radio-frequency interference at the PAF, could be developed to get signals from the PAF, perhaps as far as the central site.

RF-over-fibre offers low signal loss at microwave frequencies. The challenge for ASKAP engineers is to develop very low cost, single mode DFB or VCSEL based multimode multiple parallel optical connector RF-over fibre solutions to ensure good dynamic range (typically 100 dB/Hz^{2/3}) and acceptable amplitude and phase stability over calibration timescales.

The Parkes Testbed Facility and antenna integration model

To trial and further develop ASKAP systems a single, 12-m diameter antenna has been commissioned at Parkes Observatory. This antenna is a fully operational, astronomically capable dish, termed the Parkes Testbed Facility (PTF). The function of the PTF is to provide a dedicated platform for field tests of novel CSIRO-developed PAFs at

Parkes where the radio frequency interference environment is significantly better than at CSIRO's site in Sydney, and the Parkes 64-m dish provides a platform for deeper, more sensitive testing of the PAF in tandem with the PTF.

Note: The PTF is not a prototype ASKAP antenna. The tendering process for ASKAP antennas is now closed, with the contract having been awarded to CETCS4.

Due to the challenge of integrating a whole new system at the remote ASKAP observatory, CSIRO commissioned Wild Sets, a film set company, to build a model dubbed 'SAPKAP' (so named because it is made of wood). SAPKAP, a full-scale model of the ASKAP pedestal, mount and hub, has enabled the ASKAP team to learn how to set up a working ASKAP antenna before heading out to remote Western Australia.



ASKAP's prototype phased array feed on the Parkes Testbed Facility. Credit: David McClenaghan, CSIRO.

For further information

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What is ASKAP?

The Australian Square Kilometre Array Pathfinder (ASKAP) is a next-generation radio telescope of great complexity and technological ambition. It will be a world-leading instrument in its own right, and a key demonstrator of new technologies for the Square Kilometre Array (SKA) radio telescope.

ASKAP is being led by CSIRO in collaboration with leading scientists and engineers in The Netherlands, Canada and the USA, as well as colleagues from a number of Australian universities.

ASKAP is being built at the Murchison Radio-astronomy Observatory (MRO) in the Mid West region of Western Australia; the MRO is also Australia and New Zealand's candidate location for the central part of the SKA. The region is extremely sparsely populated and superbly 'radio quiet'. It also offers excellent sky coverage, ionospheric stability and benign tropospheric conditions. Once completed, ASKAP will operate as part of CSIRO's Australia Telescope National Facility for use by national and international scientists.

ASKAP specifications

ASKAP will be a wide field-of-view, survey telescope with:

- ▶ 36 antennas, each 12 metres in diameter, that will give a total collecting area of approximately 4,000 m²
- ▶ system temperature of less than 50 K
- ▶ frequency range 0.7 to 1.8 GHz
- ▶ 300 MHz instantaneous bandwidth with high-resolution and continuum modes
- ▶ a field-of-view of approximately 30 square degrees
- ▶ maximum resolution of 8 arcseconds.

ASKAP is pioneering the use of phased array feeds (PAFs) in dish antennas for radio astronomy. Each PAF will consist of 188 individual elements (receivers) as the focal plane detectors. A dedicated digital 'beamformer' for each antenna will manipulate and interpret the raw astronomical signals from the PAFs; the data from the whole array will then be cross-correlated to provide the calibrated astronomical data. The beamformer and correlator systems are complex, special-purpose computing systems built from field programmable gate arrays.

Artist's impression of a complete ASKAP at the Murchison Radio-astronomy Observatory (MRO). Credit: Swinburne Astronomy Productions, design data provided by CSIRO.



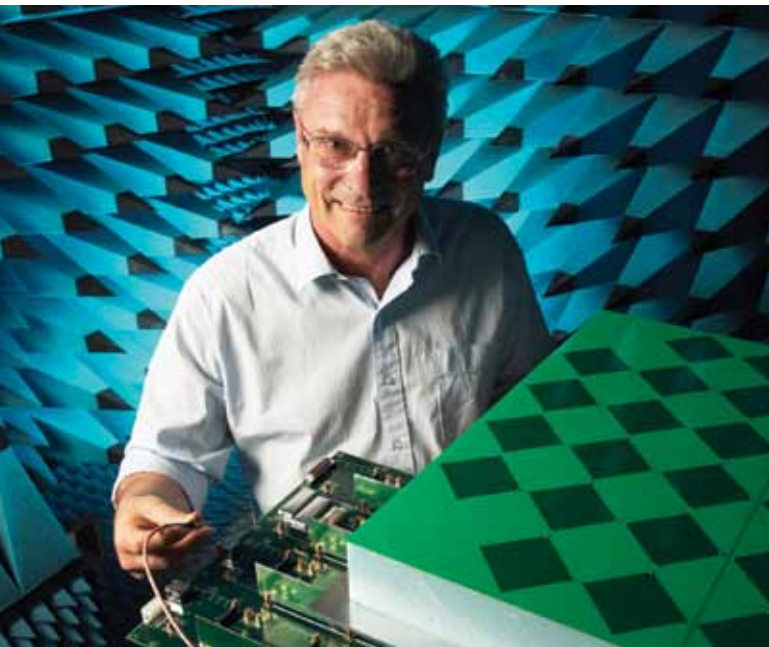
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CSIRO Digital Systems Engineer John O'Sullivan with a revolutionary detector-receiver array being developed for the ASKAP telescope. This is a prototype of a receiver system that will ultimately enable a three-fold increase in the area of sky mapped. Credit: Chris Walsh, Patrick Jones Photo Studio.

Technical challenges

There are many technical challenges to be overcome in designing and building ASKAP, including:

- ▶ design, modelling and testing of sensitive phased array feeds suitable for radio astronomy
- ▶ low-noise receivers (low-cost, large-N), and the development of efficient 'receiver on chip' solutions
- ▶ development of algorithms and processing techniques for very high dynamic range imaging over wide fields of view
- ▶ design and build techniques for 12-m diameter radio astronomy antennas at low unit cost and with minimal on-site commissioning and maintenance
- ▶ efficient development of the observatory site including 'green' energy supply options and an effective radio-quiet zone covering the SKA frequency range
- ▶ computing (including data storage) and data transport from the remote observatory site to the processing centre
- ▶ design and build of 36 188-input digital beamformers.

Phased array feeds (PAFs)

The development of PAFs suitable for radio astronomy is one of the central challenges for ASKAP.

The PAFs will be receive-only phased arrays used with parabolic reflector dishes to provide an instantaneous wide field-of-view. The aim is to produce the wide field-of-view

capacity using multiple simultaneous electronic beams of more than an octave bandwidth, without substantial degradation in antenna gain/efficiency, noise temperature, sidelobes or stability compared to the best single-horn feed with cryogenic cooling in current use for radio astronomy.

ASKAP engineers, led by John O'Sullivan, have modelled and prototyped a 'chequerboard' PAF solution, which will use low noise amplifiers (LNAs) specifically designed for the array, while collaborators in The Netherlands, Canada and the USA are investigating alternative PAF architectures (eg wideband Vivaldi-type PAFs) that also show great promise.

Specific challenges for the realisation of the PAF are:

- ▶ obtaining the extended bandwidth required for radio astronomy whilst retaining performance and controlling array resonant behaviour
- ▶ investigation of new array options with better performance potential in, for instance, bandwidth and the ability to feed reflectors of short focal ratio (eg <0.5) without loss in gain
- ▶ design of a suitable low-noise amplifier to work in conjunction with the chequerboard array, with a total system temperature of around 50 K
- ▶ extending the PAF modelling tools to handle large arrays (188 elements) at high levels of accuracy. This includes electromagnetic modelling of the reflector, array, LNAs and associated coupling structures and beamforming behaviour
- ▶ refining the range and antenna measurement methodology for phased arrays to verify performance
- ▶ determining a cost-effective signal transport method that can handle a total instantaneous signal bandwidth of ~30 GHz per polarisation (ie total 60 GHz) from the array
- ▶ calibration and monitoring of individual signal paths to allow maintenance of beam accuracy during observations.

Attaining the performance of the LNAs both for ASKAP and the SKA is a critical issue. Moreover, for the SKA tens of thousands of these components will be required so cost is the driving issue. There are already hints that 90 micron and 130 micron CMOS technologies could attain the required LNA performance. The LNA would be followed by a receiver on a chip, with separate analog-to-digital and digital vertical cavity surface-emitting laser optical outputs. This receiver system could be integrated into the PAF package, perhaps even on SKA Phase 1 timescales.

Digital beamformers

The signals received by the 188 phased array receivers on each ASKAP antenna will be digitised for real-time beamforming, frequency channelisation and correlation. The cost-effective solution for ASKAP is to build these systems using field programmable gate arrays (FPGAs).

Each antenna will require a digital beamformer to process the dual-polarisation baseband signals, each of 300 MHz bandwidth and digitised at 768 MHz and 8 bits so that the data rate per receiver is 6.14 gigabits per second (Gbps). These inputs will be processed by the first-stage polyphase filterbank. This will reduce the fractional bandwidth of each channel to less than 1%. Thus, across each band the beamforming weights can be approximated by a single complex number. The coarse filterbank data is oversampled so that the fine filterbank preceding the beamformer avoids attenuation and interchannel crosstalk at the edges of the coarse filterbank channels.

The beamformer will be designed to accept digitised data or coarse filterbank data. The beamformer will then generate about 30 dual polarisation beams, via a simple 'weight and sum' process with the data channelised to the resolution suitable for spectroscopic analysis (5 kHz).

The beam data are then transported to the correlator. The correlator calculates full Stokes parameters for all beams, channels and baselines. In the correlator, coarse frequency resolution will be obtained by channel averaging with the expectation that building a system with a single internal frequency resolution will save considerable time in programming and configuring the correlator. The output from the correlator goes to the main ASKAP computer for real-time imaging and data storage.

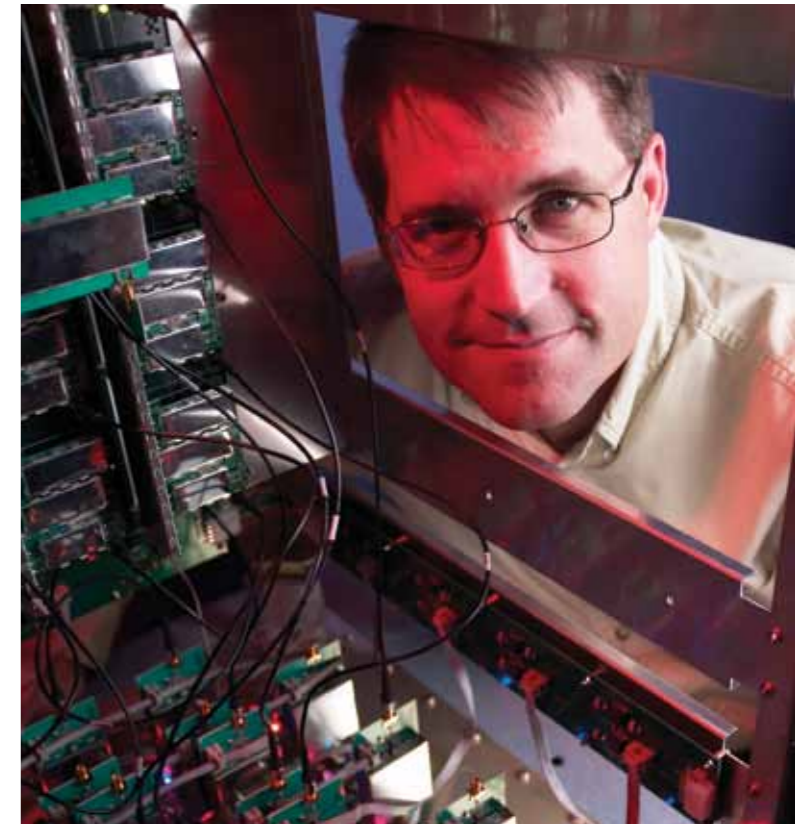
For ASKAP, the processing requirement in the beamformer and correlator systems amounts to about 1 peta (10^{15}) arithmetic operations per second, which exceeds the capabilities of even the fastest computer currently operating in the world.

Computing

Areas of technical challenge in ASKAP computing are:

- ▶ affordable data storage, since the yearly raw data rate will be about 40 petabytes (PB). The current plan is to only keep processed data (about 4 PB per year) but it would be preferable to keep all the data if affordable. This would require near-line access at about \$100 – \$500 per PB
- ▶ the processing load for the post-correlator computing systems is estimated at about 100 teraflops. ASKAP is investigating low cost (both capital and operational) solutions (FPGA, Cell, GPU, and multi-core solutions) to achieve this. At the moment there is no preferred solution and we expect to continue investigation until close to tendering in 2011.

ASKAP will have a unified computing system that is responsible for observing, processing and archiving observations. A loosely coupled architecture has been selected for the overall computing system. This will be implemented using the Internet communication engine (ICE) messaging framework, augmented by Python interfaces at the control level.



ASKAP Project Director Dave DeBoer with a prototype receiver for the Parkes Testbed Facility's phased array feed. Credit: Chris Walsh, Patrick Jones Photo Studio.

ASKAP will have a supercomputer-level machine operating in (soft) real time to process the data. The core reduction code will be written in C++. For the coordination of the necessary distributed processing we expect to use a mixture of ICE and the standard message passing interface.

ASKAP's telescope monitor and control system will be built using the open source Experimental Physics and Industrial Control System (EPICS). This system is mature, very capable, and widely used. In addition, the flavour of hardware interfaces built using EPICS is more familiar to engineers than alternative object-oriented frameworks.

Signal transport

The transport of astronomical data signals from the PAF to the analog-to-digital converter systems and on to the digital beamformer is a key challenge for ASKAP and for the SKA in the future. The hundreds of feed elements required in the PAF necessitate a large number of connections through rotating cable wraps at all three antenna axes. This contributes to tractor size and antenna weight. For the ASKAP Boolardy Engineering Test Array, the initial six-antenna array, the proposal is to use 40-m lengths of low loss expanded polyethylene dielectric coaxial cable with gain equalisation.