



Phased Array Feeds

A new technology for wide-field radio astronomy

Aidan Hotan | ASKAP Project Scientist

29th September 2017

CSIRO ASTRONOMY AND SPACE SCIENCE
www.csiro.au



Outline

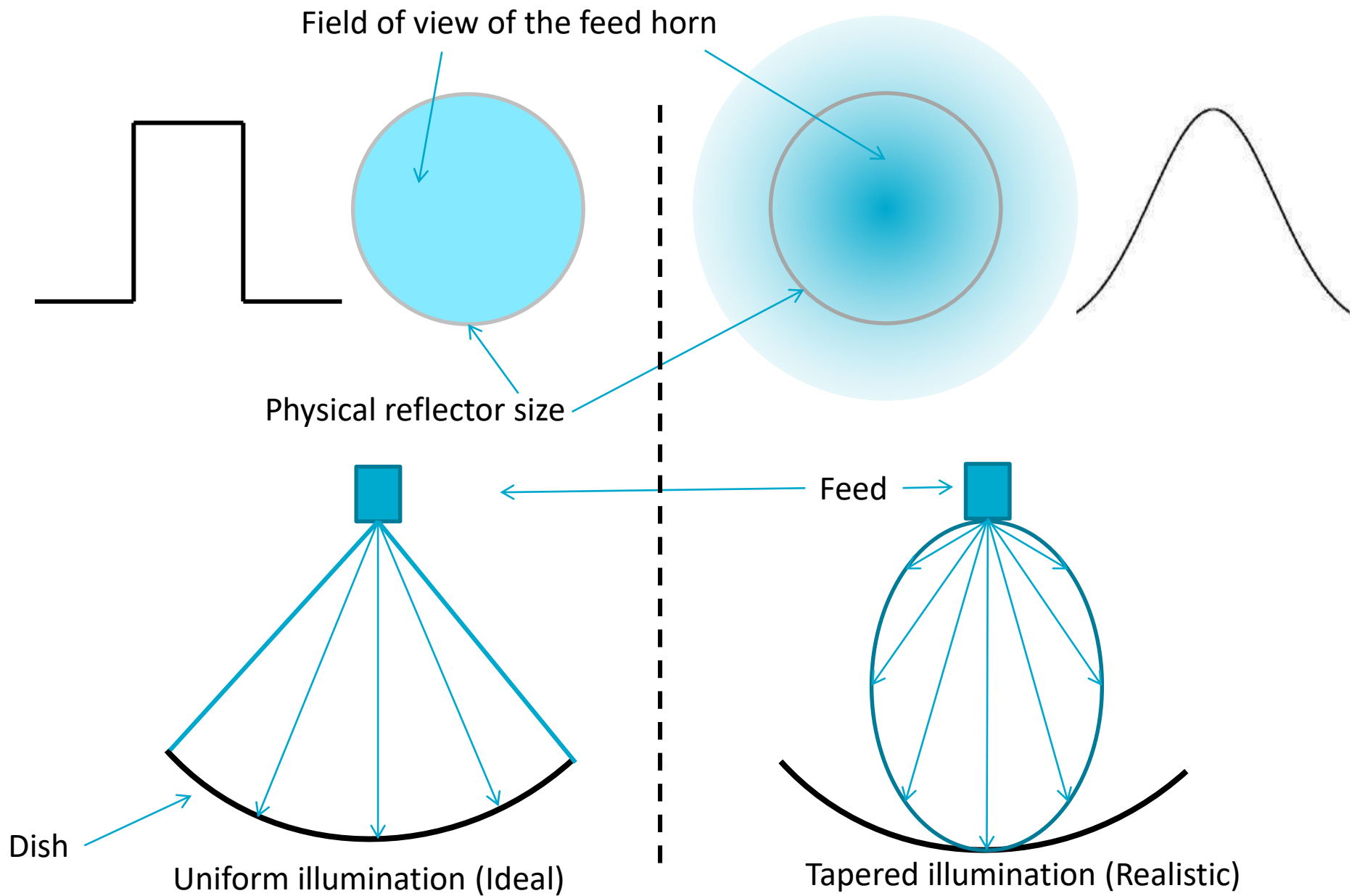
- Review of radio astronomy concepts
 - Single antenna beam pattern (diffraction limit)
 - Dish antenna feeds, illumination and primary beam shape
- Short history of phased arrays in radio astronomy
- The use of phased arrays as dish antenna feeds
- Forming electronic beams on ASKAP
 - Beam-forming in theory and practice
 - Optimising beams for science

Single dish antennas - the diffraction limit

- The spatial resolution that can be achieved by an imaging system is governed by the size of the light-gathering aperture
 - This limit is rarely approached at optical wavelengths, but in radio astronomy it is typically what defines the “primary beam” of a telescope
- The Airy pattern associated with diffraction due to a circular aperture is also the sensitivity profile (beam) of a uniformly-illuminated parabolic reflector
- There is an inverse relationship between aperture size and the diameter of the diffraction pattern
 - Large antennas have lots of gain but also a small field of view

Radio telescope receivers

- Radio telescopes usually have a single feed horn at their focus
 - This lets the telescope receive signals incident along the optical axis
- A feed horn is itself an antenna
 - It is designed to efficiently couple free-space radiation into a waveguide
 - It will impose its own response pattern on the telescope (illumination)
- Feed horns are typically less sensitive to radiation coming from the edges of the dish, compared to the centre
 - Uniform illumination requires an infinitely sharp cut-off, which is unphysical
 - In practice we must balance efficiency against spill-over and side-lobe levels

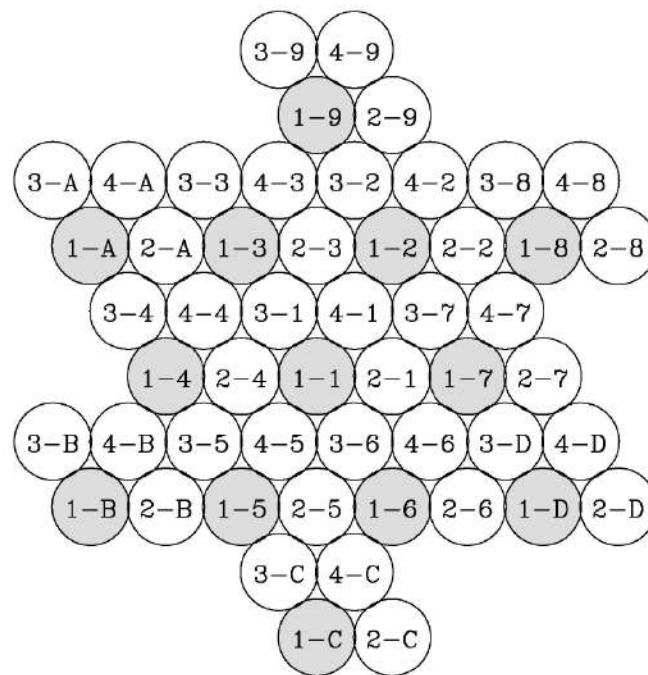


Gaussian primary beam approximation

- We often approximate the illumination pattern as a 2D Gaussian
 - Neglecting aperture blockage, reflections from support struts, etc.
- The (voltage) beam of a radio telescope is the 2D Fourier transform of its illumination pattern
- The Fourier transform of a Gaussian is another Gaussian, so tapered illumination acts to suppress side-lobes
 - It is common to assume a Gaussian shape for primary beam correction when making images. **Keep this in mind as a starting point!**
- See <http://www.cv.nrao.edu/course/ast534/2DApertures.html> for a discussion of the theory behind all this

Multi-beam feeds on dish antennas

- Survey speed (how quickly we can image a given area of sky to a given sensitivity level) can be improved using multiple primary beams simultaneously



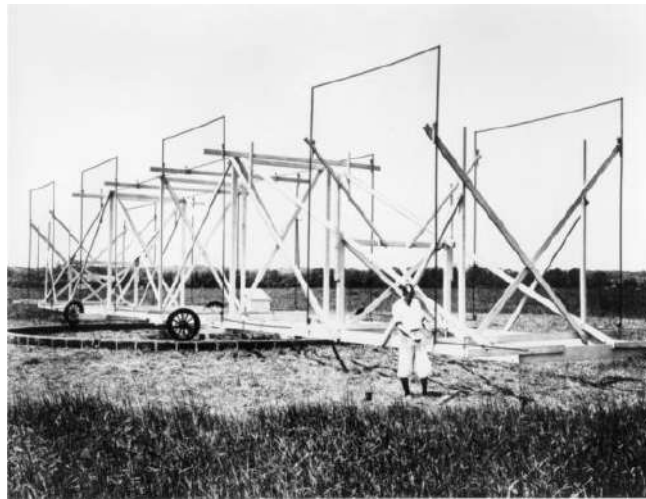
Best of both worlds: multi-beam arrays

- The next logical step – imaging with an array of multi-beam antennas. Good spatial resolution and increased field of view!
 - Correlate signals from the same beams on different antennas (or more, if signal processing power allows!)
 - Mosaic these simultaneous beams using standard techniques, or jointly deconvolve all the visibilities (Naomi's talk yesterday)
- Physical multi-feed systems are cumbersome and expensive
 - Building multi-beam feeds for small antennas required new technology
- One solution is the Phased Array Feed (PAF)
 - Also known as a Focal Plane Array (FPA)

Quick history lesson - phased arrays

- Reflecting antennas give good directional gain, but this can also be achieved by combining signals from several dipoles
 - This is not quite the same as interferometry, phased arrays work **additively**, not **multiplicatively**
- Phased arrays were used at the very beginning of radio astronomy
 - Jansky's famous "merry go round" is an example of a Bruce antenna (a class of dipole array) and was used to discover radio emission from the Milky Way

Jansky's antenna at Bell Labs in 1932, operating at 20.5 MHz

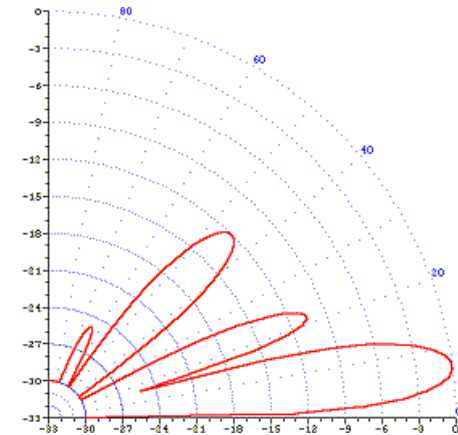
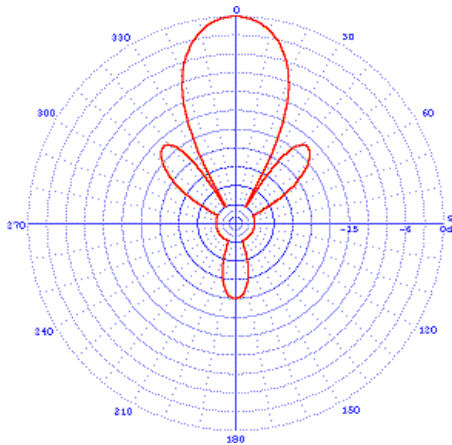
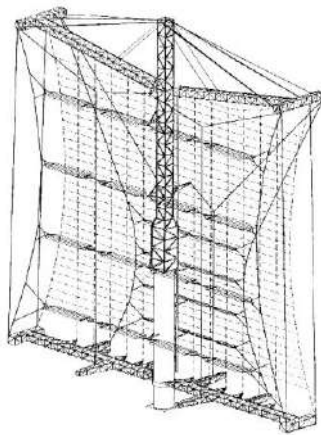


As mentioned by Aaron yesterday!

Phased arrays in communications

- Bruce antennas (and [Curtain arrays](#) in general) are typically hard-wired and fed from a single input, with mechanical steering

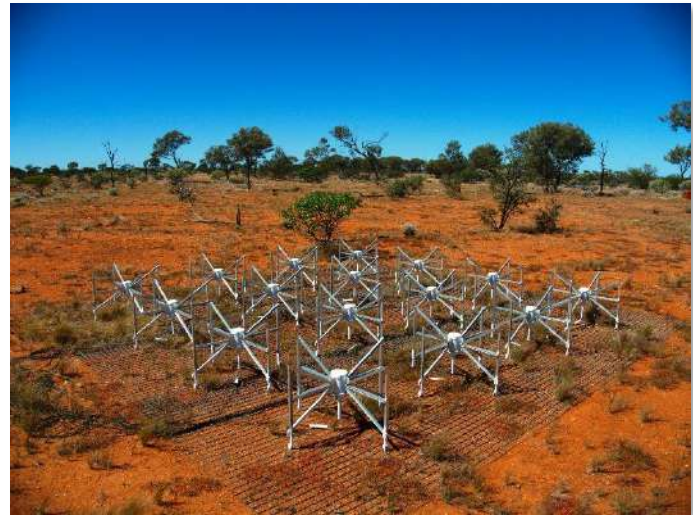
Images from Broadcast Belgium
www.broadcast.be



- More flexible phased arrays have **independently-fed elements** that can be added with **different phases**
 - This allows the antenna primary beam to be steered electronically (by changing the relative phases between elements)

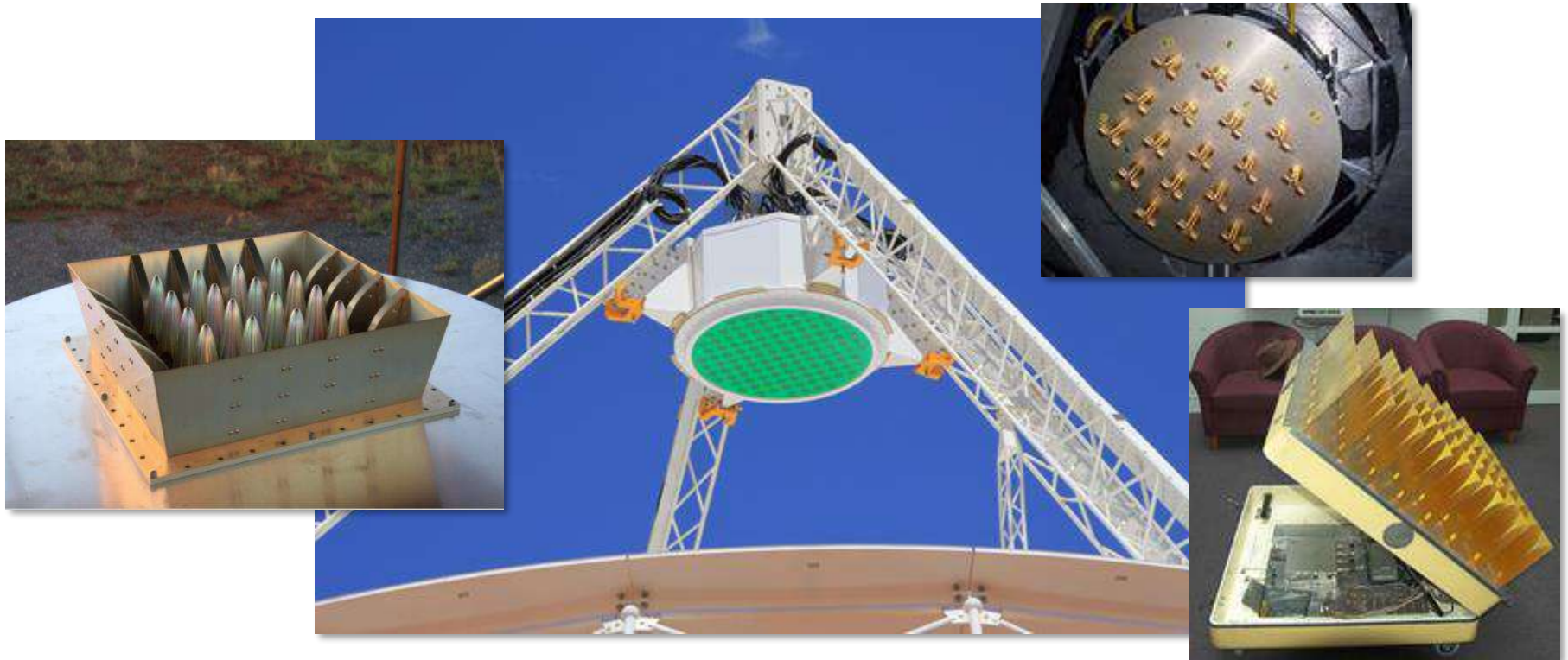
Aperture arrays in radio astronomy

- In modern jargon, a phased array that receives radiation directly from the sky is known as an aperture array
 - Because the elements themselves form the aperture of the telescope
- LOFAR in the Netherlands and the MWA in Western Australia are both aperture array telescopes
 - Aperture arrays will also form the low-frequency part of the SKA



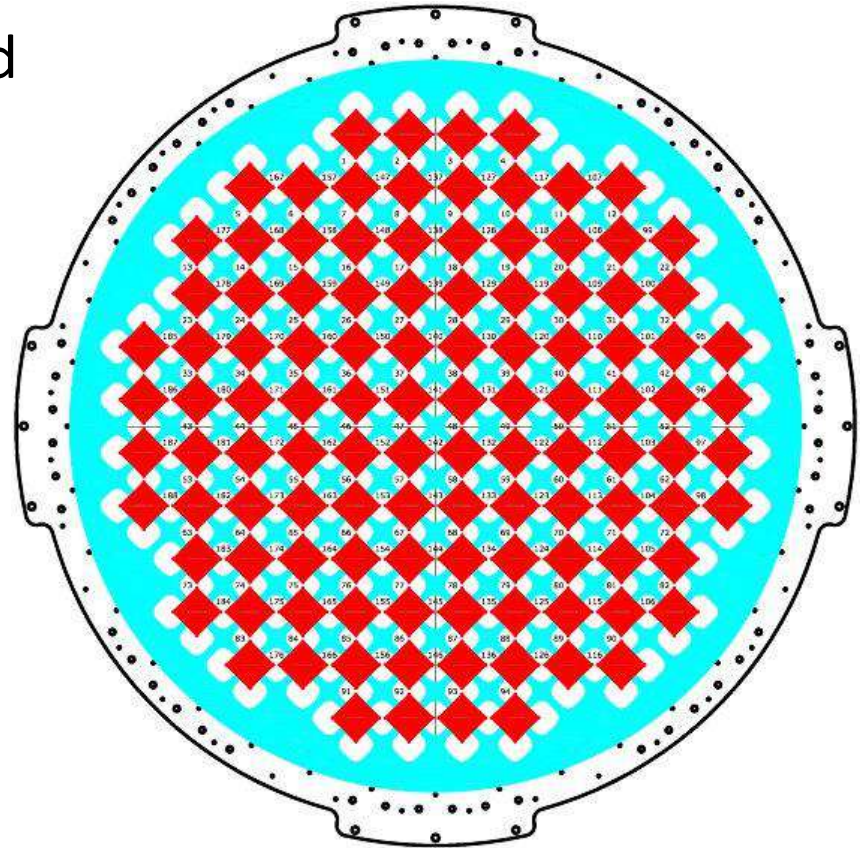
Phased array feeds in radio astronomy

- Phased arrays can also be used at the focal plane of a parabolic antenna, in place of a traditional feed horn
 - Ideally, we need to Nyquist sample the E-M field in the focal plane

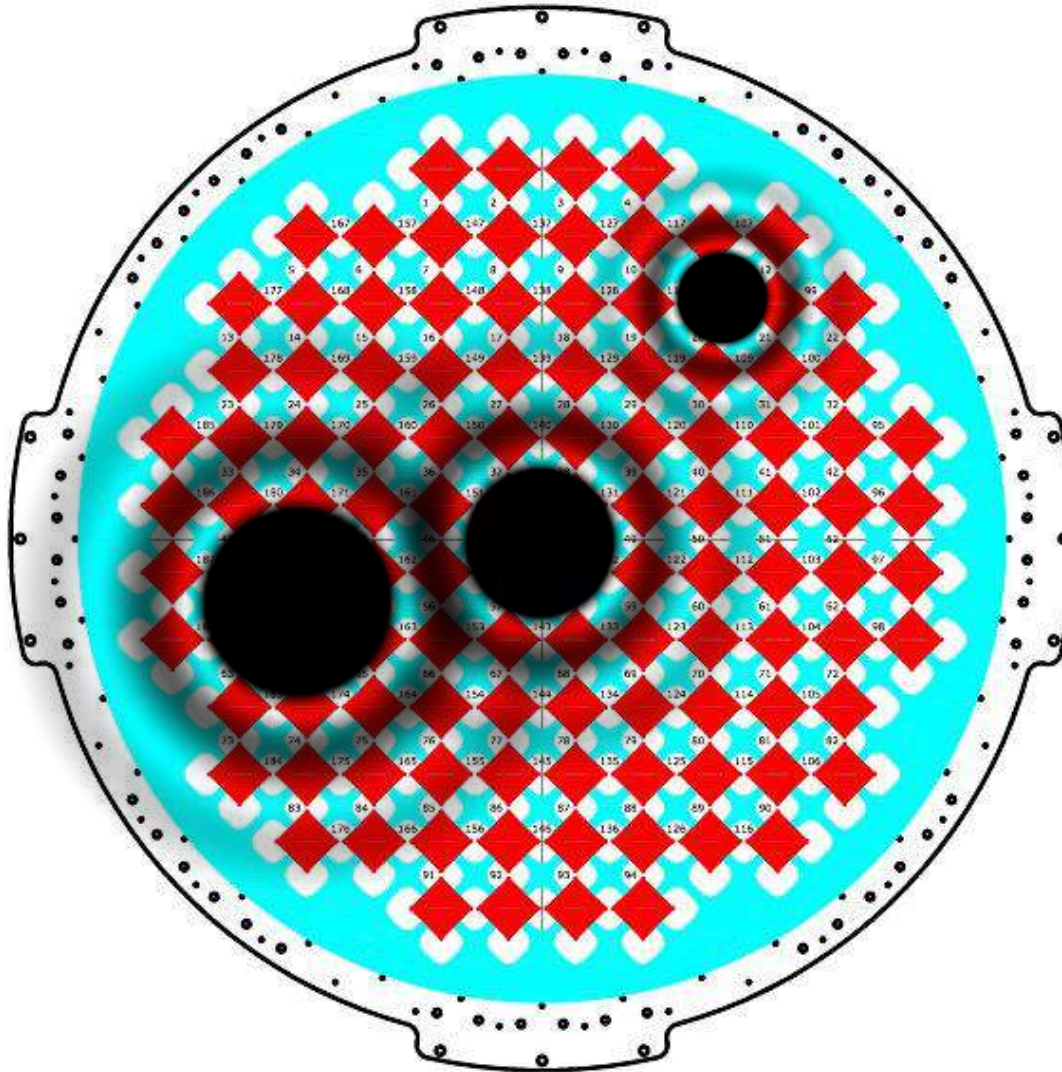


ASKAP's chequerboard PAF

- 2D (dual polarisation) array of “bow tie” dipoles on a square grid
 - Elements are spaced by 90 mm
- Broad frequency coverage, from 700 MHz to 1800 MHz
- Complete sampling of the wavefront in the focal plane
- 188 individual amplifiers, each with their own complex gain



What does a PAF see?



Forming beams with a phased array feed

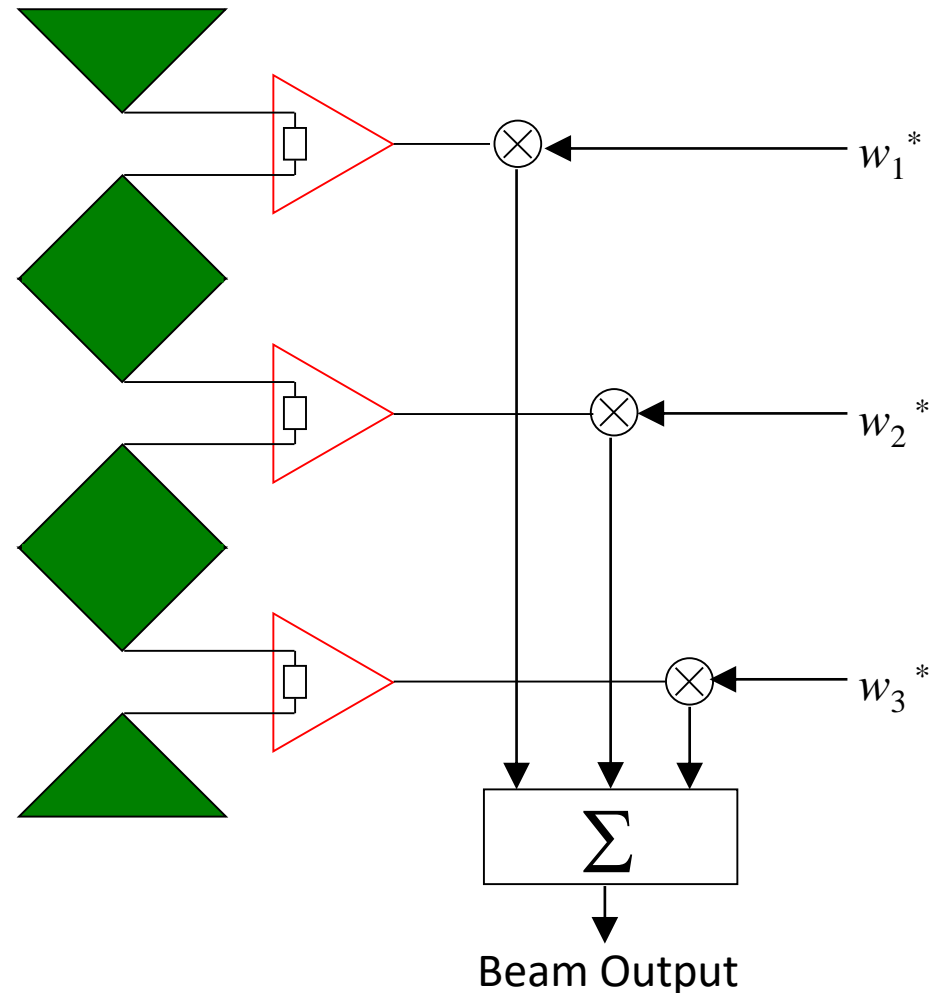
- Beams can be formed using physical methods – delays between elements introduced by lengths of cable
 - This tends to be simple and cost effective, but difficult to change
 - MWA uses this approach
- Beams can also be formed digitally using signal processors
 - This is highly flexible (weights can be updated at any time to form arbitrary beams) but also computationally expensive
 - ASKAP uses this approach
- Either way, we must include a **beam-former** in the signal path

Beam-formers and bandwidth

- Just like correlation, beam-forming is best done over a relatively narrow bandwidth (the Airy pattern is a function of frequency)
 - Need **frequency-dependent weights** to maintain efficiency across the band
- For ASKAP, we independently form beams on 1 MHz channels
- If we had infinite computing power, no beam-former would be necessary. We could compute interferometer visibilities across all combinations of PAF elements from all antennas
 - This would be ideal for optimising UV coverage, RFI rejection, etc.

Forming beams – a hardware perspective

- Amplifiers are connected to the inside corners of each dipole antenna
 - A single conductive patch contributes to several elements
- The signal from each element is digitally sampled
- Samples from each port are multiplied by their own complex weight
- Weighted voltages are summed to a single number
 - This is done for each time sample, frequency channel and beam

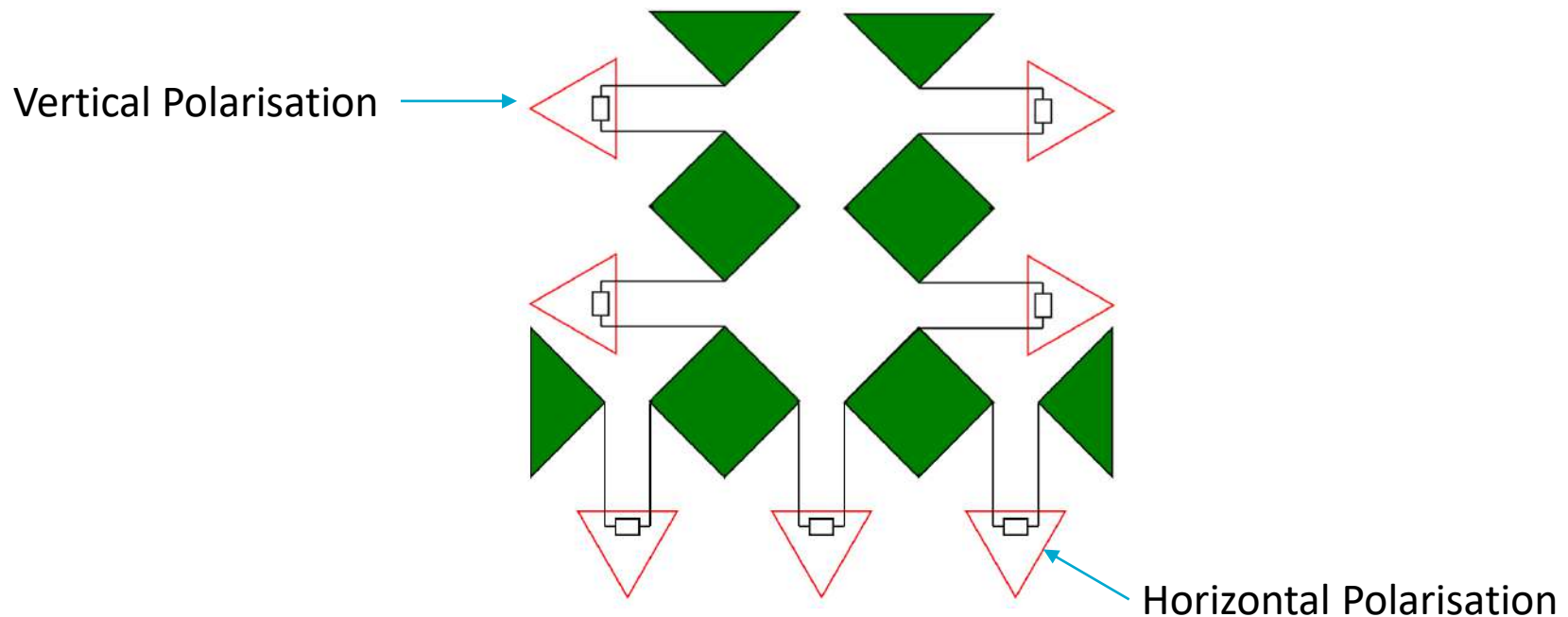


Forming multiple simultaneous beams

- Because we have ample photons at radio wavelengths, we can make many copies of the signal from each array element
 - Ron explained this on Monday
- Each set of copies can be combined using its own set of weights
- We can steer several beams in different directions simultaneously
 - The field of view is now limited by Coma distortion off-axis, an intrinsic property of any parabolic reflector
- PAF beams can be closely packed on the sky
 - Once beams start to overlap, we reach a point of diminishing returns

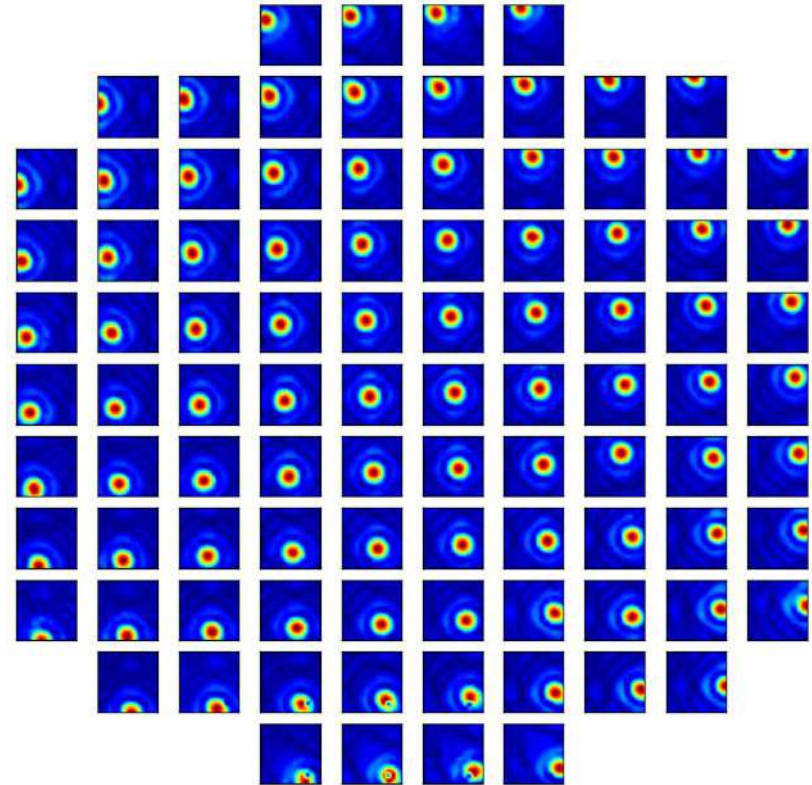
Polarisation of PAF elements

- ASKAP PAF elements are linearly polarised. Half of the 188 elements are aligned in X, the other half in Y
- Beams can be formed using any combination of elements, including opposite polarisations



Forming beams – a conceptual perspective

- Each PAF element has its own view of the sky (beam) via the reflector
- We can design a set of beams that suit our needs by combining the beams of the elements
 - Any formed beam is a **linear combination** of single port beams
- If we can model the desired beam properties, we can obtain weights by fitting for the closest match



Holography of 94 PAF elements from one polarisation. Image by Sarah Hegarty

Practical considerations when forming beams

- PAFs typically use an “adaptive” beam-forming approach
 - Beams are formed in response to measured parameters
- Much of what defines a beam is the path length between elements
- However, each amplifier has its own complex gain
 - In particular, the phase of each amplifier is randomly distributed
- This means that beam weights are **unique to an individual PAF**
- Each element emits thermal radiation that is received by its neighbours
 - Adjacent elements do not receive completely independent signals
- Beam-forming algorithms have been extensively researched, but usually with other applications in mind.
 - Astronomers are busy catching up!

Maximum sensitivity beam-forming

- In general, the output of a beam-former can be expressed as:

$$y_k[i] = \mathbf{w}_k^T \mathbf{x}[i]$$

Beam k output at time i

Weight vector for beam k

PAF element outputs at time i

- [Applebaum \(1976\)](#) derived a simple expression for the weights that determine the maximum sensitivity beam:

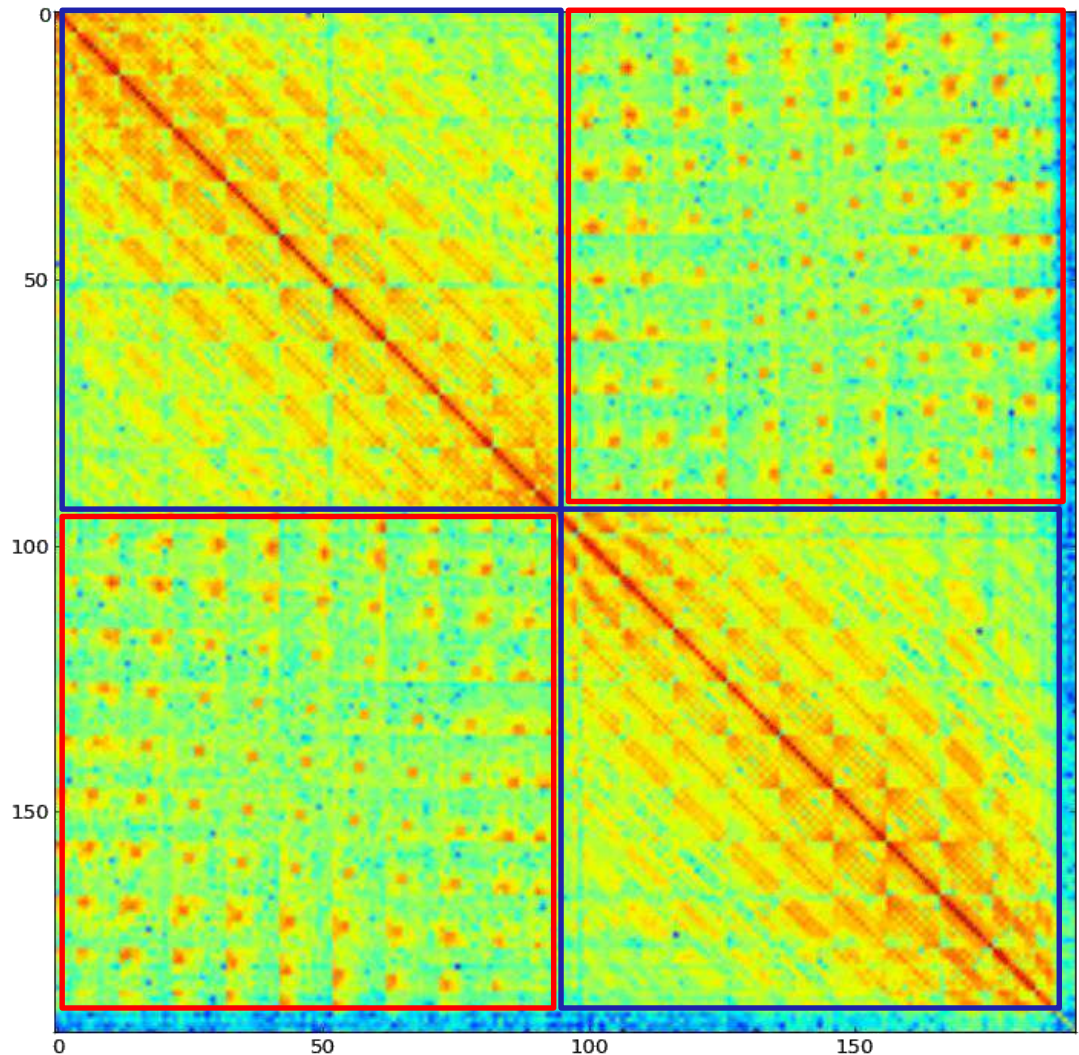
$$\mathbf{w}_k = \hat{\mathbf{R}}_n^{-1} \hat{\mathbf{v}}_k$$

Noise covariance matrix

Steering vector (response of PAF elements to a point source in the direction of beam k)

PAF element correlations – the ACM

- The beam-former must also compute the Array Covariance Matrix
 - This is expensive, only done for a subset of time
- Can always see correlation between nearby ports (even of different polarisations)
- ACM structure is mostly due to PAF's physical geometry



Maximum sensitivity beamforming

- In general, the output of a beamformer can be expressed as:

$$y_k[i] = \mathbf{w}_k^T \mathbf{x}[i]$$

Beam k output at time i

Weight vector for beam k

PAF element outputs at time i

- [Applebaum \(1976\)](#) derived a simple expression for the weights that define the maximum sensitivity beam:

$$\mathbf{w}_k = \hat{\mathbf{R}}_n^{-1} \hat{\mathbf{v}}_k$$

Noise covariance matrix
(ACM with no strong sources in the field)

Steering vector (response of PAF elements to a point source in the direction of interest for beam k)

Obtaining a steering vector

- Can be done using **single-dish** ACM observations

- Recording ACMs while observing a strong source yields: $\hat{\mathbf{R}}_{s+n}$
- The required steering vector is the Eigenvector of the difference corresponding to the dominant eigenvalue λ (see [Landon et al. 2010](#)):

$$[\hat{\mathbf{R}}_{s+n} - \hat{\mathbf{R}}_n] \mathbf{v} = \lambda \mathbf{v}$$

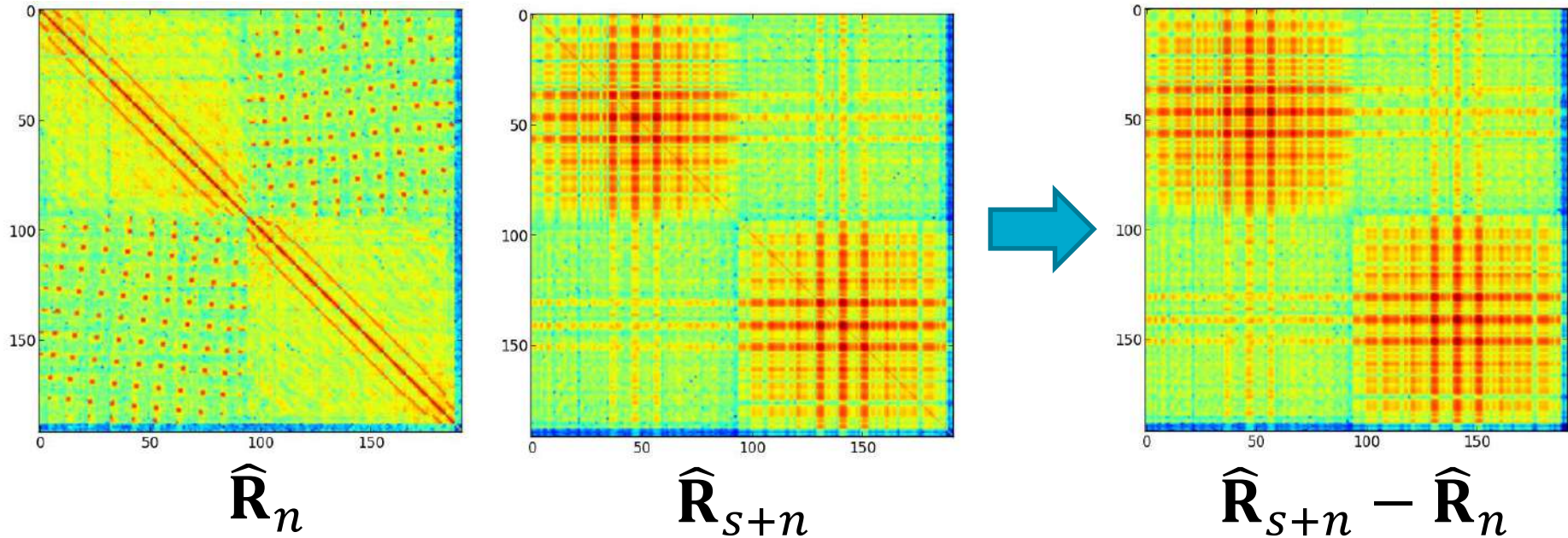
- If you have an interferometer, you can also measure the steering vector directly by pointing a reference antenna at a strong source
- There may be other interesting ways to find this information!

Signal

Noise

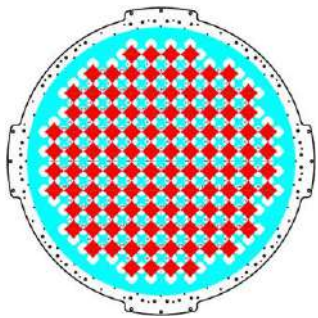
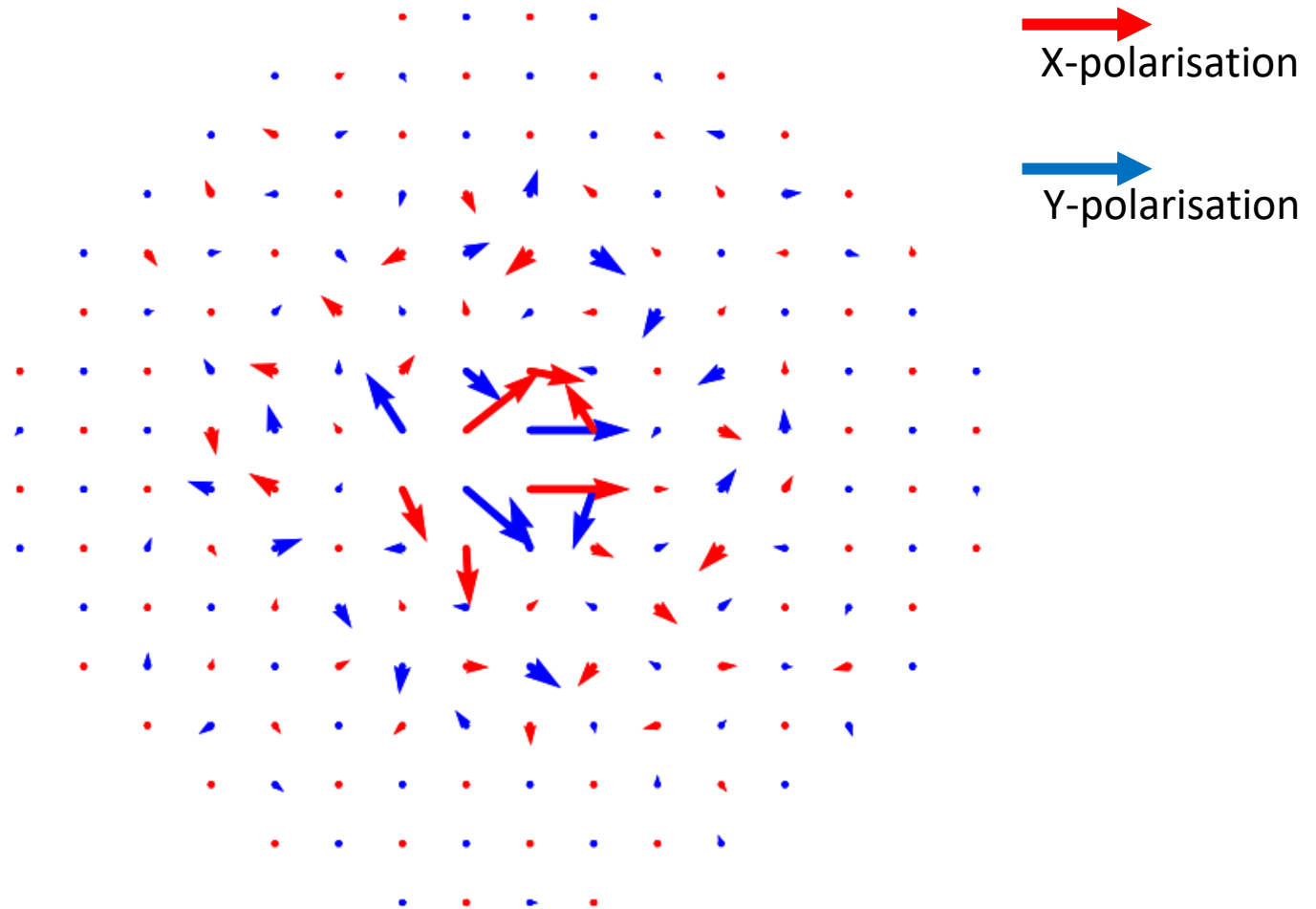
$\hat{\mathbf{R}}_{s+n}$

Single-dish beamforming on the Sun



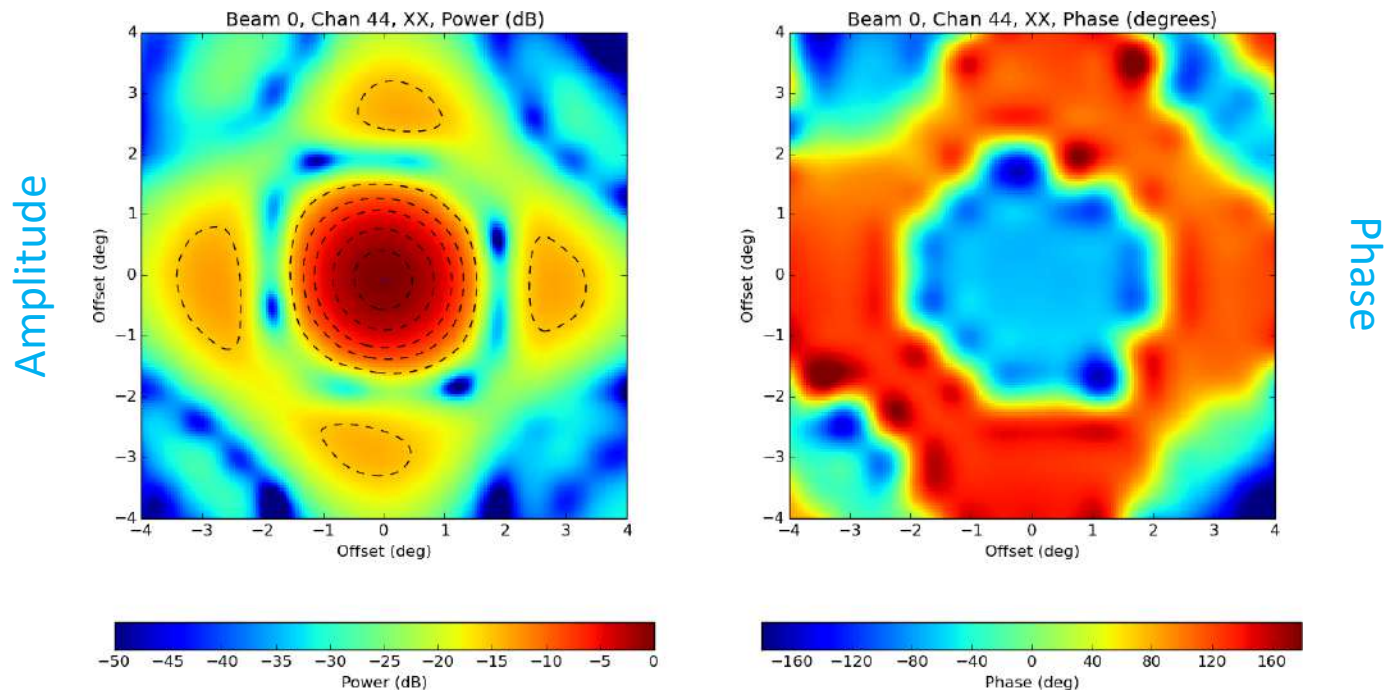
- Our steering vector is the dominant Eigenvector of the difference matrix
- The Sun dominates the noise in the above example. This gives the weights high significance. Weaker sources are less effective
- To make offset beams, point the antenna off-axis when measuring the steering vector. Need one observation for each beam

Maximum sensitivity beam weights



Shape of maximum sensitivity beams

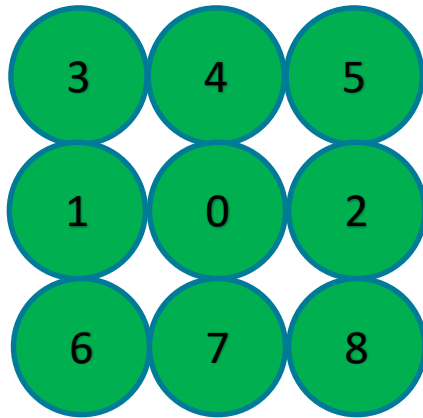
- Maximum sensitivity beam-forming does not constrain the shape of the beam, its symmetry, side-lobe levels, etc.
 - **Holography measurements** can be used to study the beam shape



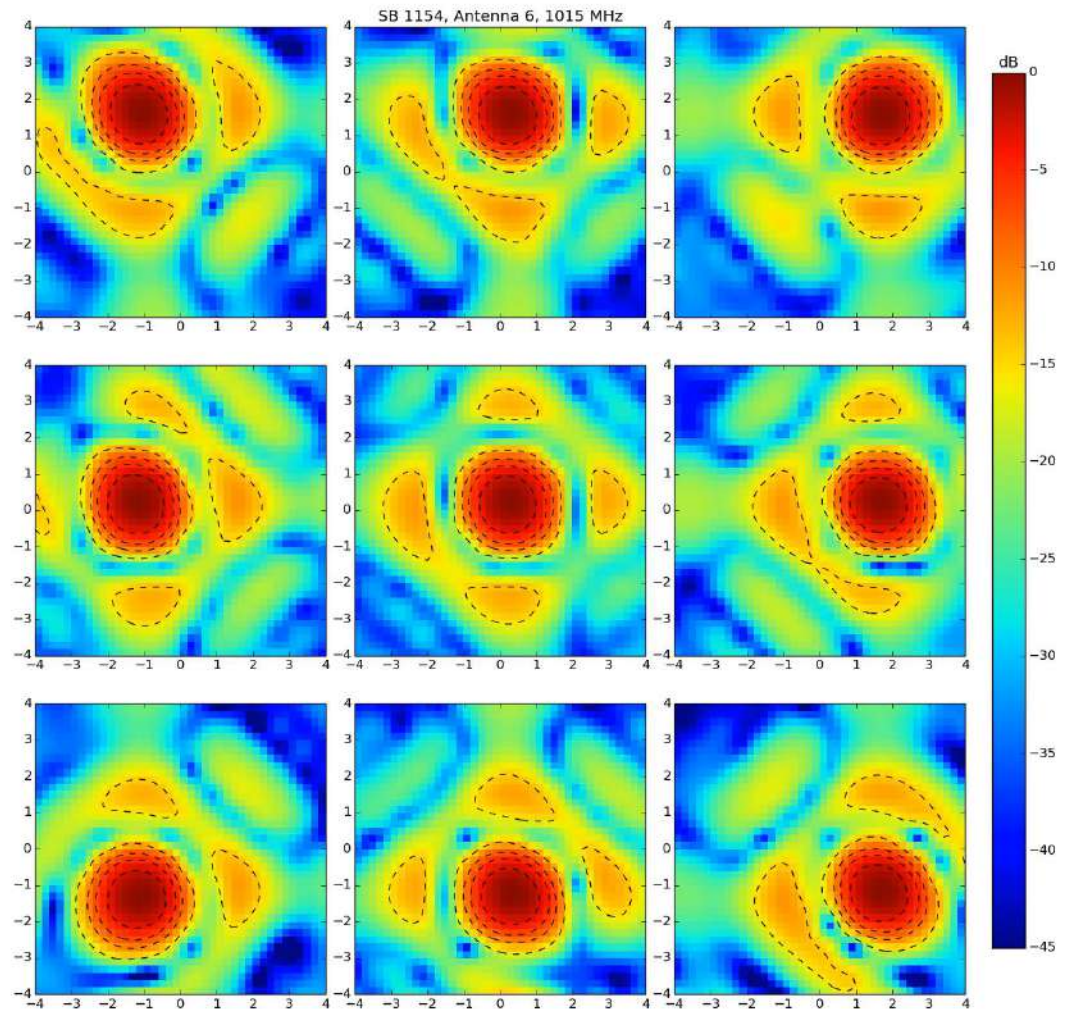
PAFs and antenna illumination

- Recall Alex's talk: a feed horn uses roughly 60% of the dish surface
 - The illumination pattern of a horn is fixed by its design, but the illumination pattern of a PAF is determined by beam weights
- The maximum sensitivity algorithm tends to favour increased efficiency for a PAF (~75%) at the cost of higher side-lobes
- The PAF and its supports present a significant aperture blockage
 - 4-fold symmetry can be seen in holography measurements as a result

Offset maximum sensitivity beam shapes



- Offset beams are elliptical, elongated radially
- Single polarisation beams are all slightly elliptical
- Shapes and locations can vary with antenna



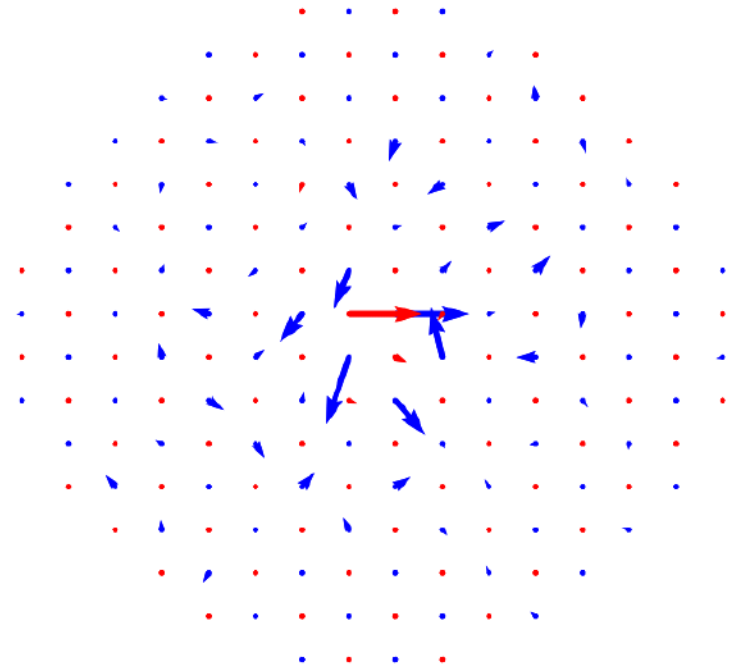
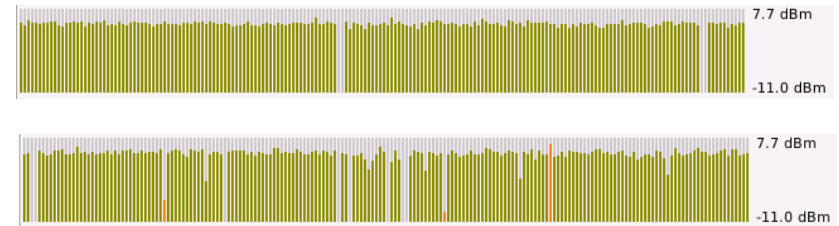
Tracking sources with offset beams

- With an Alt-Az mount the observed field rotates as we track
 - Offset beams will be non-stationary on the sky
 - Must either continuously update beam weights, or rotate antenna structure



Dealing with PAF element failures

- The complexity of a PAF gives it flexibility, but can be challenging
- With many elements, the chance of one or more not working properly at any time is high
- The maximum sensitivity algorithm can give “bad” ports an unreasonably high weight
- Automatic error detection and correction will be necessary

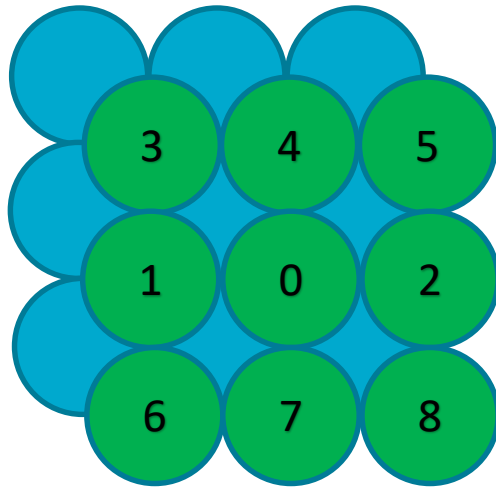


Other beam-forming methods

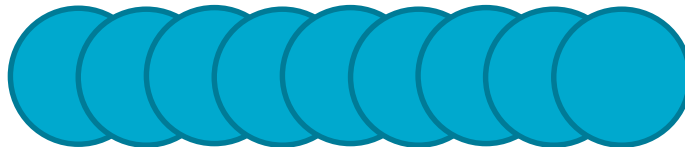
- Maximum sensitivity beam-forming uses the minimum number of observational constraints possible
 - An observation of a noise field and one compact source per beam
- Additional constraints can be used to optimise beams for parameters other than sensitivity
 - e.g. we could observe the reference source at several points around the desired half-power contour to optimise symmetry
 - Some sensitivity penalty will be incurred and beam-forming takes more time
- Ultimately, knowledge of the PAF element patterns can be used to design a near-arbitrary primary beam
 - This knowledge can come from electromagnetic models, observation, or both

Arranging beams on the sky

Square

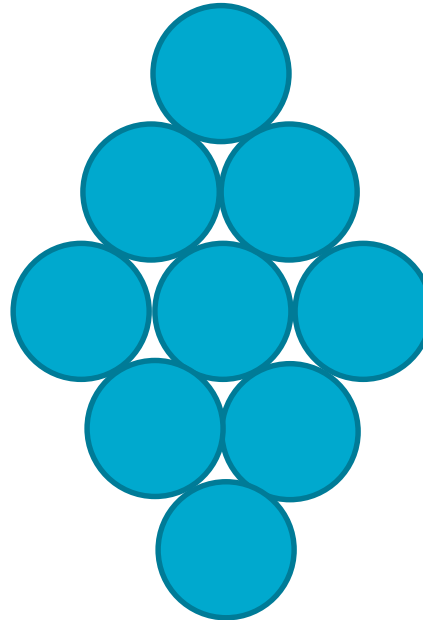


(with interleaving)

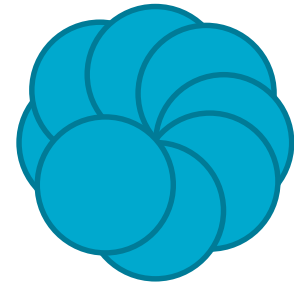


Line

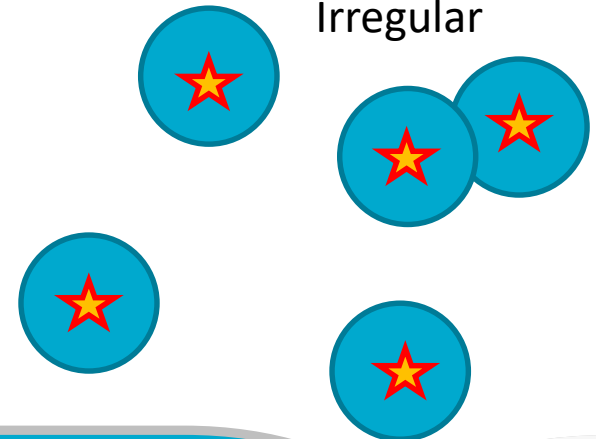
Diamond



Spirograph



Irregular



Designing footprints for astronomy

- While electronic beam-forming allows for great flexibility, there are some important limitations:
 - The total number of beams (and elements per beam) is limited by the signal processing power in the beam-former
 - Beams cannot be placed too close together as they would sample the same field and provide decreasing benefit (information theory, not design flaw!)
 - Large area surveys need footprints that tessellate and have Nyquist sampling
- Keep in mind that beam-forming is itself an approximation to the ideal case of a uniformly-sampled field of view
 - With Nyquist-spaced elements, we have enough information to combine beamforming and synthesis imaging into one mathematical whole

Summary

- As we have seen this week, interferometry makes use of limited spatial frequency information to reconstruct an image of the sky
- This process involves many assumptions, including:
 - The system and the sky are unchanging between calibration intervals
 - The primary beam and the synthesised beam shapes are well known
- PAFs increase the field of view of a radio telescope and grant some degree of control over its beams
 - Adaptive beam-forming vs fixed physical feeds and structures
 - We are still learning how to best use this technology
- More complex schemes may be possible in future:
 - Learn how to optimise beams for science goals – particularly polarimetry
 - Null out the signal from RFI sources as they move across the sky (Aaron's talk)

Thank you

CSIRO Astronomy and Space Science

Aidan Hotan

ASKAP Project Scientist

e aidan.hotan@csiro.au

w www.atnf.csiro.au

CSIRO ASTRONOMY AND SPACE SCIENCE

www.csiro.au

