Phased Array Feeds & Primary Beams

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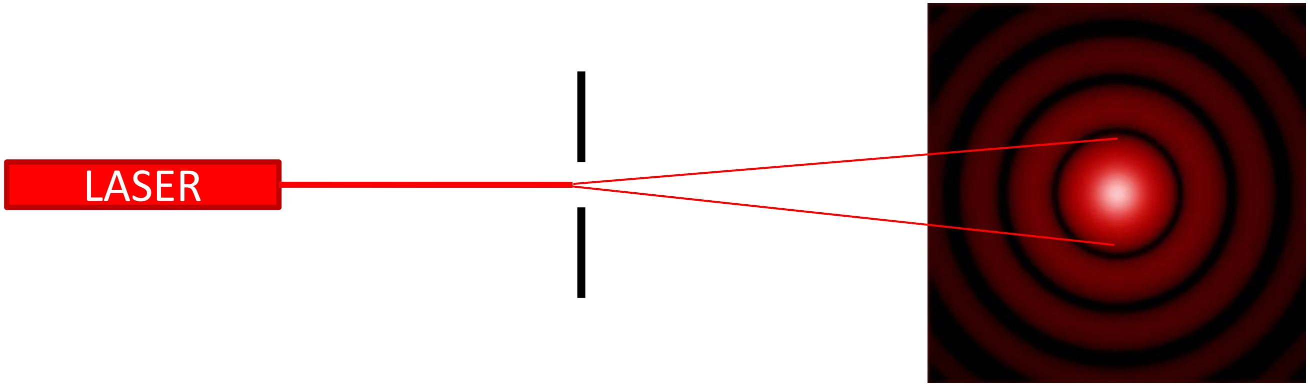
Outline

- Review of parabolic (dish) antennas.
  - Focal plane response to a distant point source (diffraction limit).
  - Traditional feeds, reflector illumination and primary beam shape.
- Short history of phased arrays in radio astronomy.
- The use of phased arrays as dish antenna feeds.

- The mechanics of beamforming.
  - How beamforming works (from several perspectives).
  - Optimising for maximum sensitivity.
  - Advantages of adaptive beamforming.

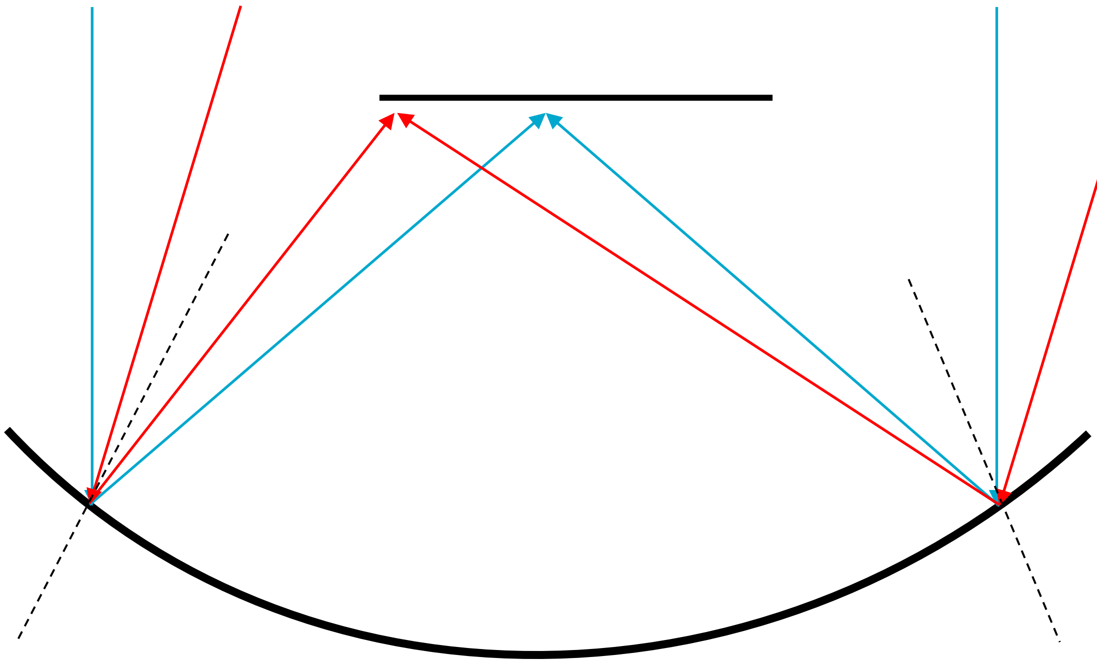
The Diffraction Limit (Review)

- In any optical imaging system, the best spatial resolution that can be achieved is related to the size of the light-gathering aperture.
  - This limit is rarely approached in practice at optical wavelengths, but in radio astronomy it is typically what defines the "primary beam" of a telescope.
- The "Airy Disk" commonly associated with circular aperture diffraction in optics is also the response of a uniformly illuminated parabolic reflector (same maths, different wavelength).



Radio Telescopes Have a Focal Plane

- Just like an optical telescope, a parabolic radio dish will focus off-axis rays to an off-axis point in the focal plane.
  - Off-axis directions suffer from coma distortion, but this is small within a reasonable area around the optical axis.



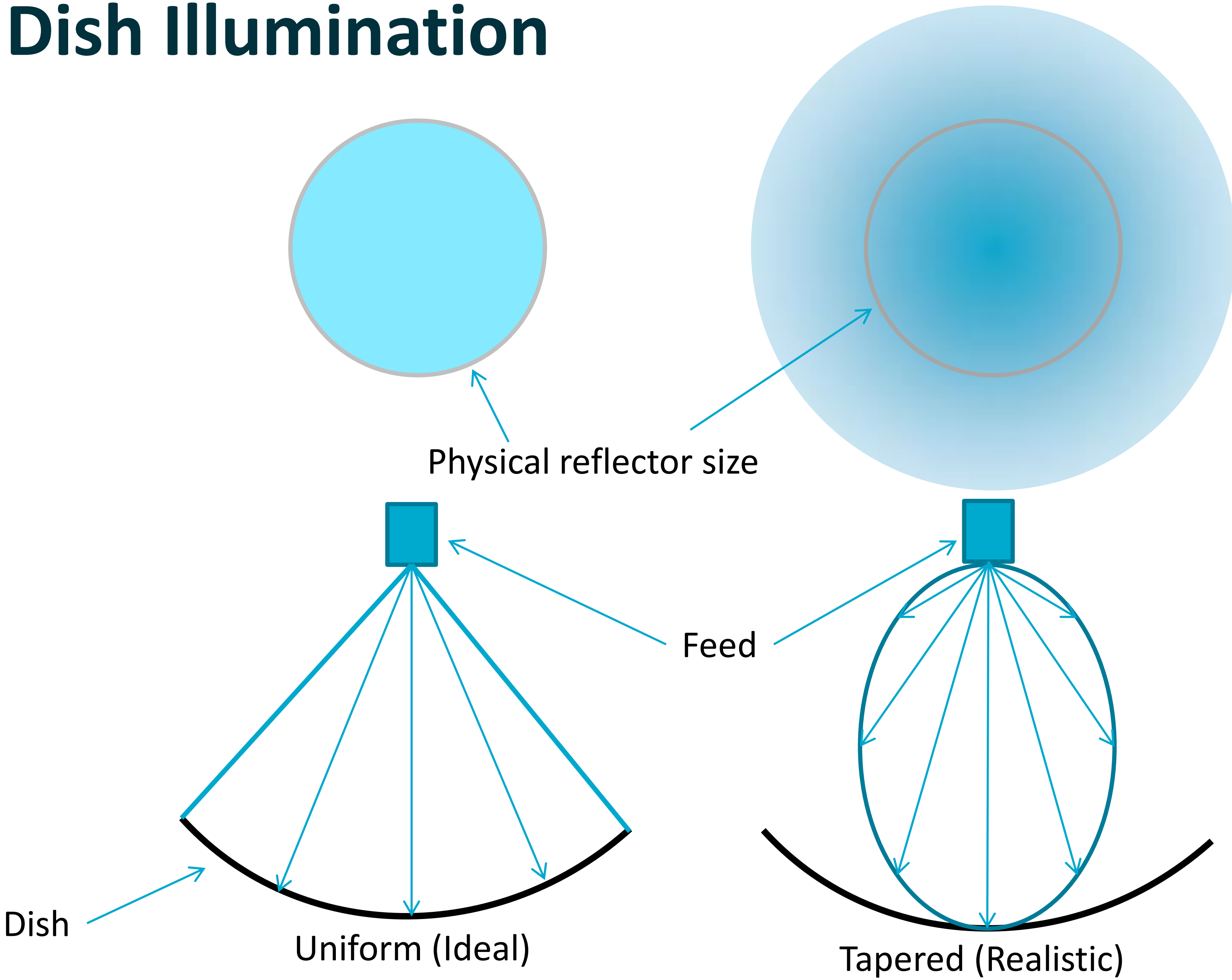
Radio Astronomy Feeds (Review)

- Traditional radio telescopes have a single feed horn at the focus.
  - This limits the telescope to receive signals incident along the optical axis.
  - Off-axis sources appear in parts of the focal plane where there is no feed and are therefore lost.

- A physical 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 middle.
  - There is some loss of efficiency, but this is balanced by reduced spill-over and decreased side-lobes.

Dish Illumination



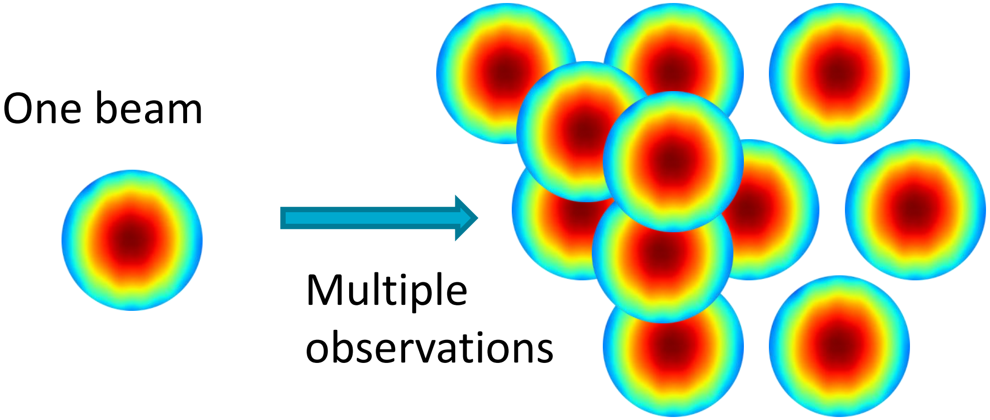
Gaussian Primary Beams (Review)

- We often approximate the illumination pattern as a 2D Gaussian.
  - Neglecting aperture blockage, reflections from support struts, etc.
- It turns out that the point source response of a radio telescope is the 2D FT of its illumination pattern.
- Since the FT of a Gaussian is another Gaussian, tapered illumination also acts to suppress side-lobes (though in reality they are still present at some level).
  - It is common to assume a Gaussian shape for primary beam correction when calculating source fluxes in an image.

- See http://www.cv.nrao.edu/course/astr534/2DApertures.html for a discussion of the theory behind all this.

Single Dish Imaging

- A single dish has one pixel. It can only record the total power captured within its primary beam at any given time.
- To make an image, the single beam must be pointed in different directions and the readings plotted on a sky grid.
- If the primary beam shape is known, it is possible to make a mosaic over a given field with near-uniform sensitivity, by putting the centre of one point on the half power radius of the previous.



Imaging with Several Antennas (Review)

- Correlating the signals from several single-dish antennas allows you to make an image within the primary beam.
  - Resolution now limited by the longest distance between any two antennas.
- Spatial information is sparsely sampled. With few telescopes, image quality is poor. Can be improved using more antennas, Earth rotation synthesis or multi-frequency synthesis.
- Array antennas are usually smaller than single dish antennas, making the primary beam larger.
- Imaging of areas larger than the primary beam still requires multiple observations and mosaicking.

Existing Multibeam Feeds

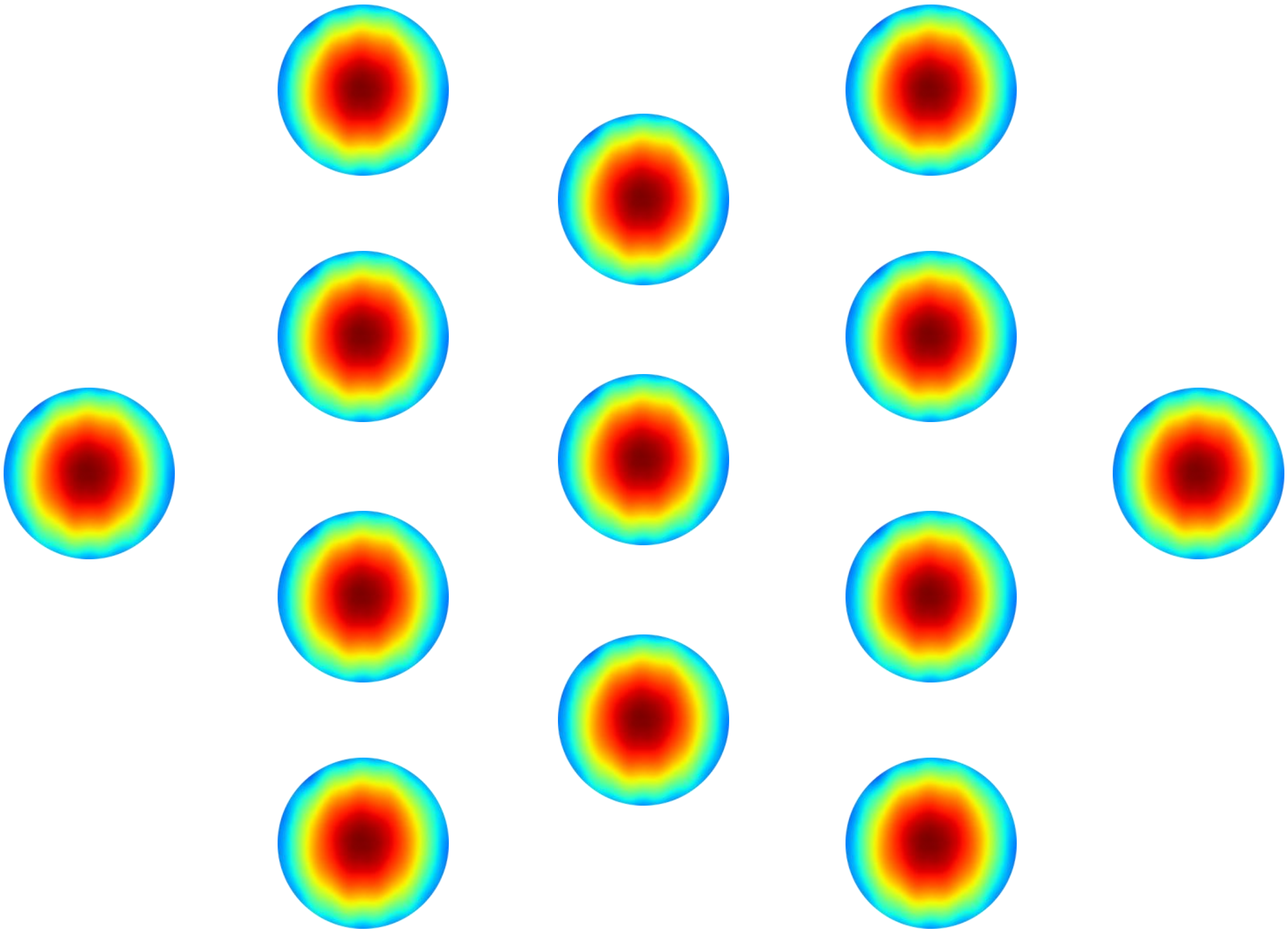
- Survey speed (how quickly we can image a given area of sky to a given sensitivity level) can be improved with multiple primary beams looking in different directions.


13-beam system for 21cm installed on the Parkes antenna in 1997 (still in operation).

Recall John’s talk – trade-off between gain and beam width. Having multiple beams avoids this limit, you can map an area of sky 13 times faster with 13 beams.

Beams are not “side-by-side”, as feeds are too big for that. Survey observations must interlace.

Parkes 21cm Multibeam Pattern

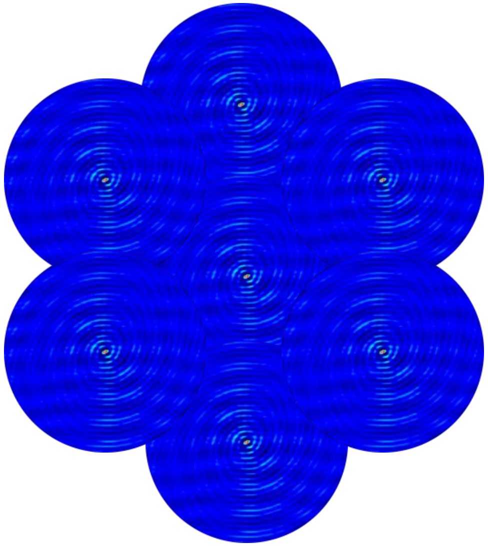


Best of Both Worlds: Multibeam Arrays

- The next logical step – imaging with an array of multibeam antennas. Good resolution and increased field of view!

Correlate corresponding beams from each antenna.

Same as having several arrays pointing at different places simultaneously.



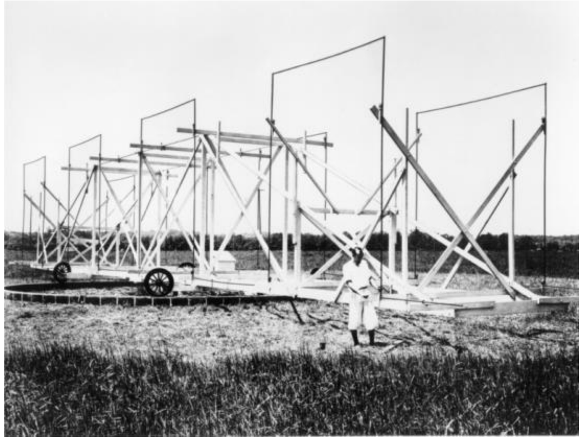
- Multibeam feed horns are too cumbersome and expensive (especially for smaller antennas). Need a more flexible alternative:

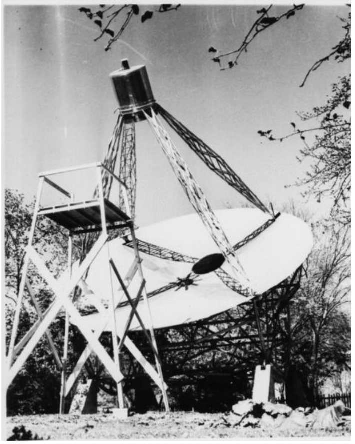
<u>Phased Array Feeds!</u>

Quick History Lesson - Phased Array Antennas

- Reflecting antennas give good directional gain, but this can also be achieved by combining signals from several simpler antennas.
  - This is not quite the same as interferometry, phased arrays work additively, not multiplicatively.
- Phased arrays are as old as radio astronomy.
  - Jansky's famous "merry go round" is an example of a Bruce antenna; an array of dipoles adding in phase. It pre-dates Reber's dish by several years.

Jansky's antenna, Bell Labs, 1932, 20.5 MHz



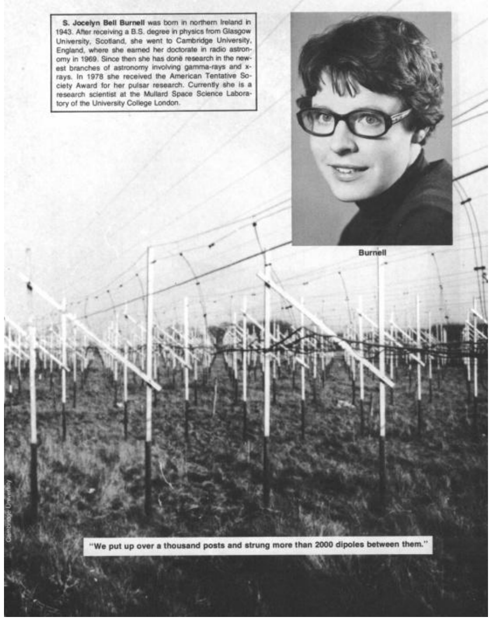


Reber's backyard dish, 1937 0.1 – 3.3 GHz

Phased Arrays in Radio Astronomy

- Bruce antennas (and Curtain arrays in general) are typically hard-wired and fed from a single input, with mechanical steering (if any).
- More flexible phased arrays have independently-fed elements that can be added with different delays.
  - This allows the antenna primary beam to be steered electronically (by changing the delays) rather than moving the structure itself.

Ryle & Hewish's Cambridge Interferometer was a 2D array of phased dipoles, operating in the 1950's and 60's. It produced the well-known 3C catalogue of radio sources. Jocelyn Bell serendipitously discovered the first pulsar while analysing this survey data!



Understanding Phased Arrays

- Any telescope captures a plane wave incident on an aperture of some size.
- Mirror-based telescopes focus the plane wave in free space using the geometry of the reflecting surface to provide gain.
- Phased arrays record the plane wave in several locations and “focus” or align the signals using lengths of cable or digital buffers. Signals added in phase constructively interfere.

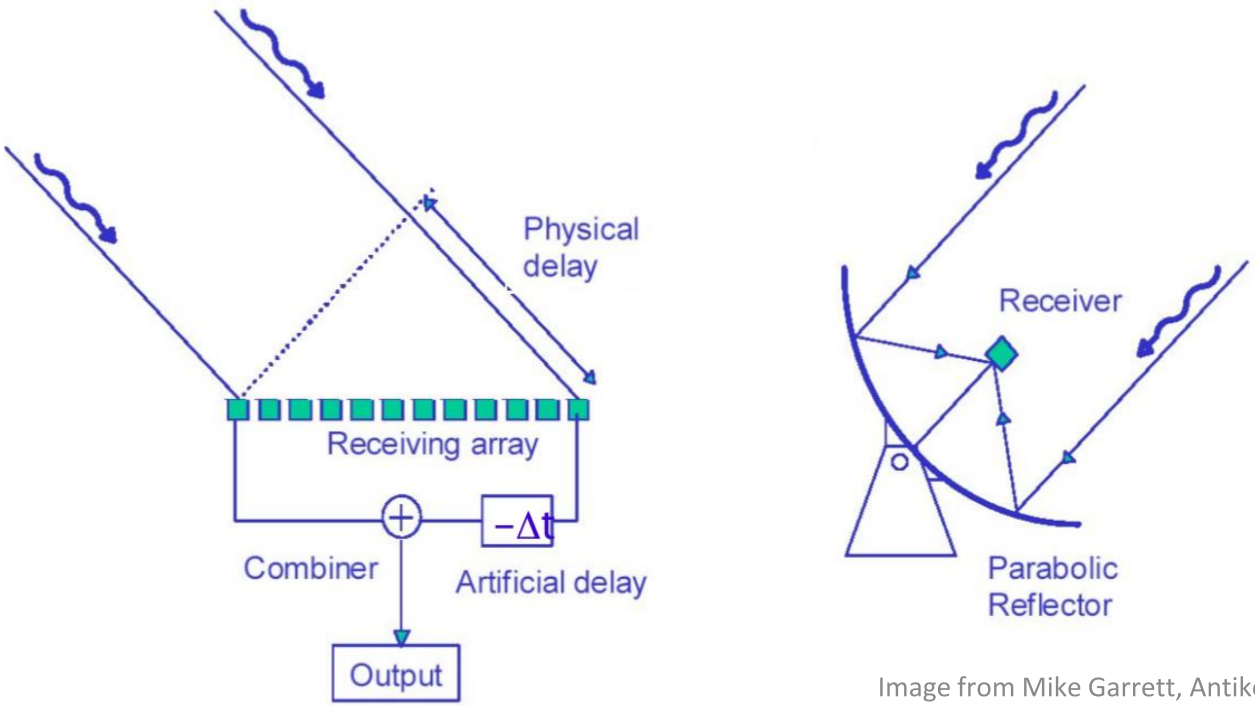
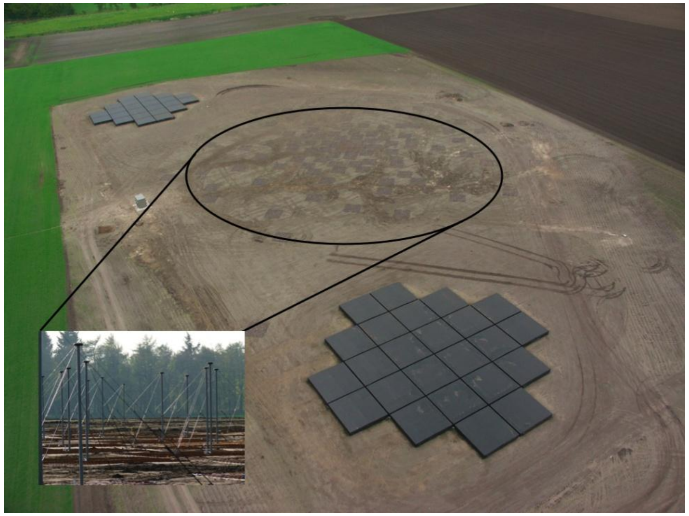
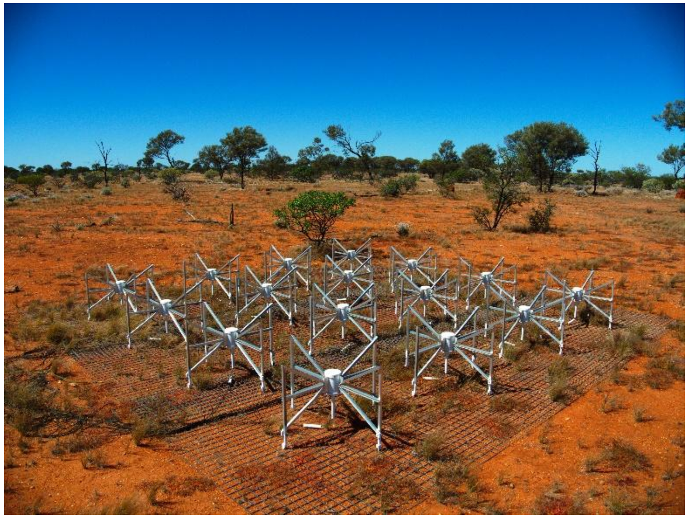


Image from Mike Garrett, Antikeythra to the SKA, 2012

Aperture Arrays

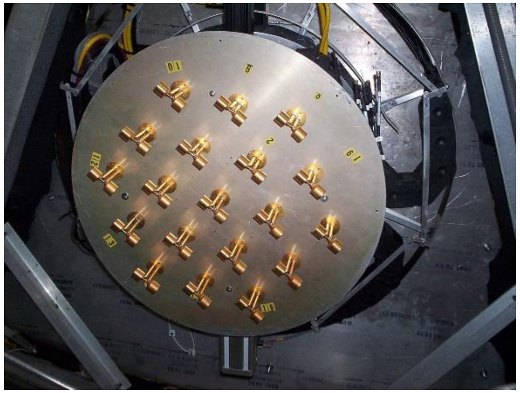
- In modern jargon, a phased array that receives radiation directly from the sky is known as an aperture array (because the elements themselves form the aperture of the telescope).
- LOFAR in the Netherlands and the MWA in Western Australia are both aperture array telescopes (Martin's talk).
- Aperture arrays will also form part of the SKA.

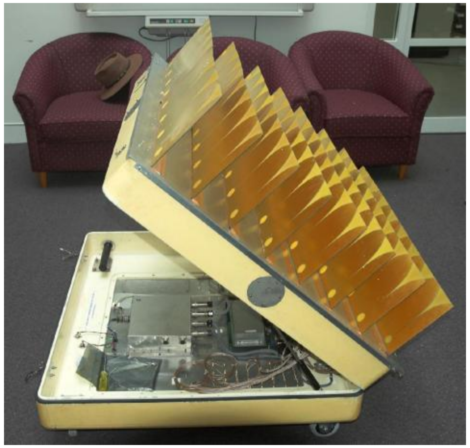




Phased Array Feeds

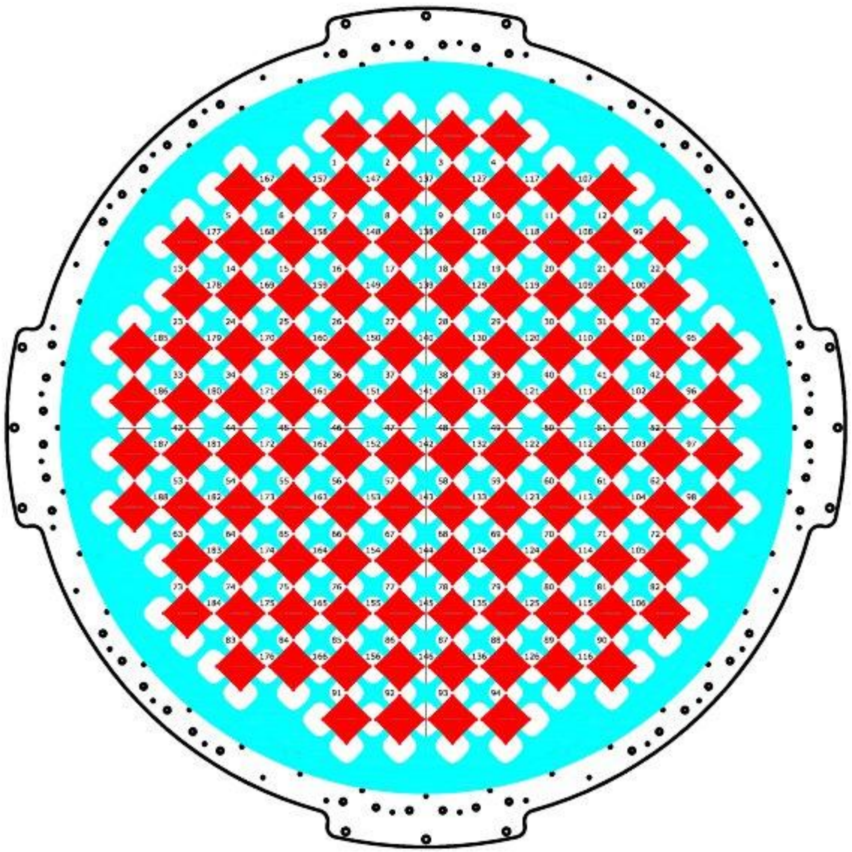
- Dense aperture arrays can be used at the focal plane of a parabolic antenna, in place of a traditional feed horn.



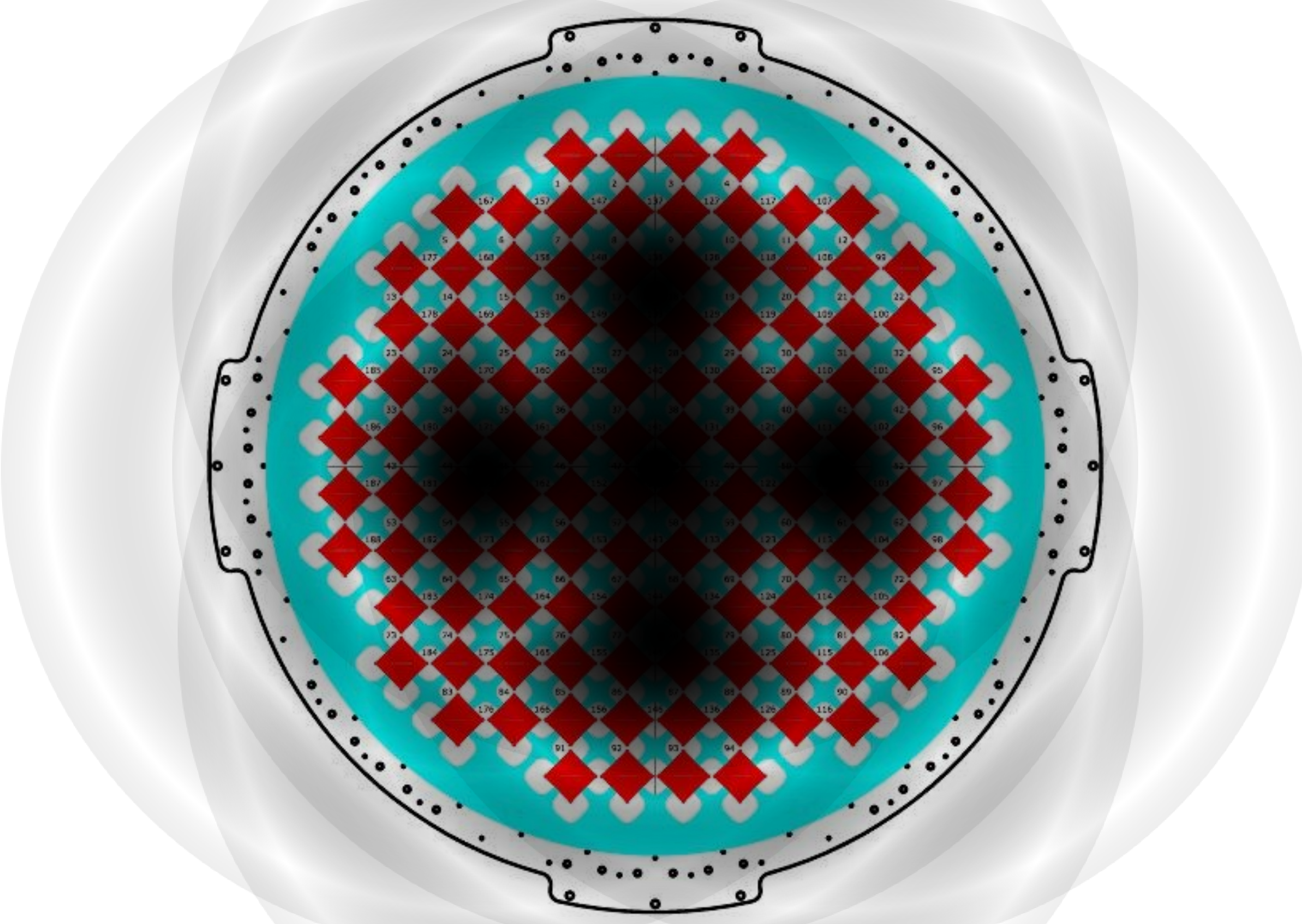


ASKAP Chequerboard PAF

- 2D (dual polarisation) array of “bow tie” dipoles on a grid.
- Broad frequency coverage, from 700 MHz to 1.8 GHz.
- Complete sampling of the wavefront in the focal plane.
  - The field of view can now be much larger than the primary beam of the telescope, as off-axis information is captured.



What does a PAF see?



Forming Beams with a Phased Array

- Beams can be formed by analog methods – delays between elements introduced by lengths of transmission line.
  - This tends to be simple and cost effective, but restrictive (MWA approach – Martin's talk).
- Beams can also be formed computationally. Sample the signal from each PAF element, then multiply by complex coefficients (weights) before adding the ports together numerically.
  - This is highly flexible (weights can be updated at any time to form arbitrary beams) but also computationally intensive.
  - ASKAP uses this approach.

- Must now include a beamformer in the telescope design.

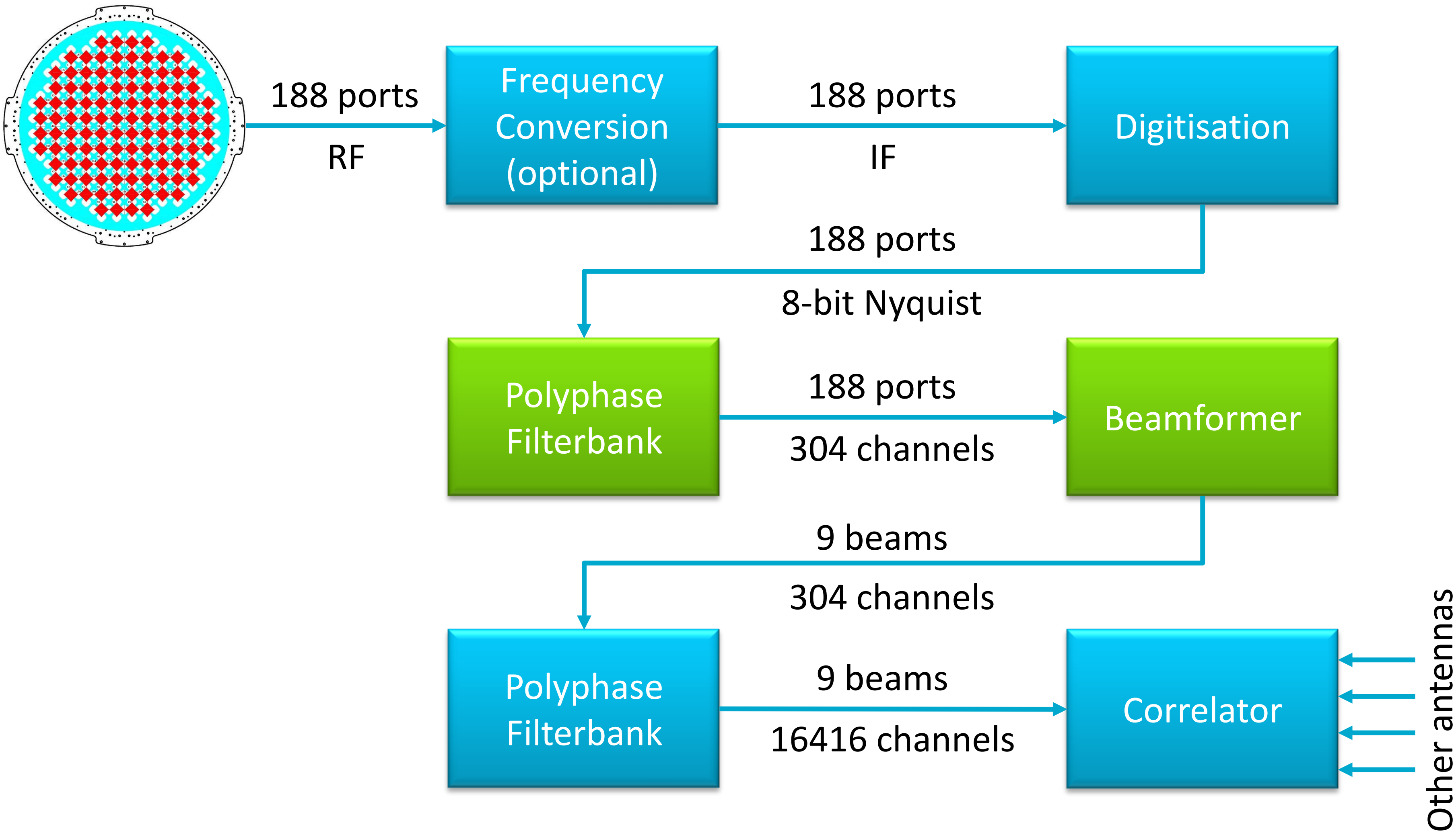
Beamformers and Bandwidth

- If we had infinite computing power, no beamformer would be necessary. We could compute visibilities across all PAF elements.

- Just like correlation, beamforming is best done over a relatively narrow bandwidth.
  - The size of the Airy pattern in the focal plane depends on the observing frequency. Low-frequency beams include strong contributions from more of the PAF ports than a high-frequency beam.
  - Need frequency-dependent weights to maintain efficiency across the band.

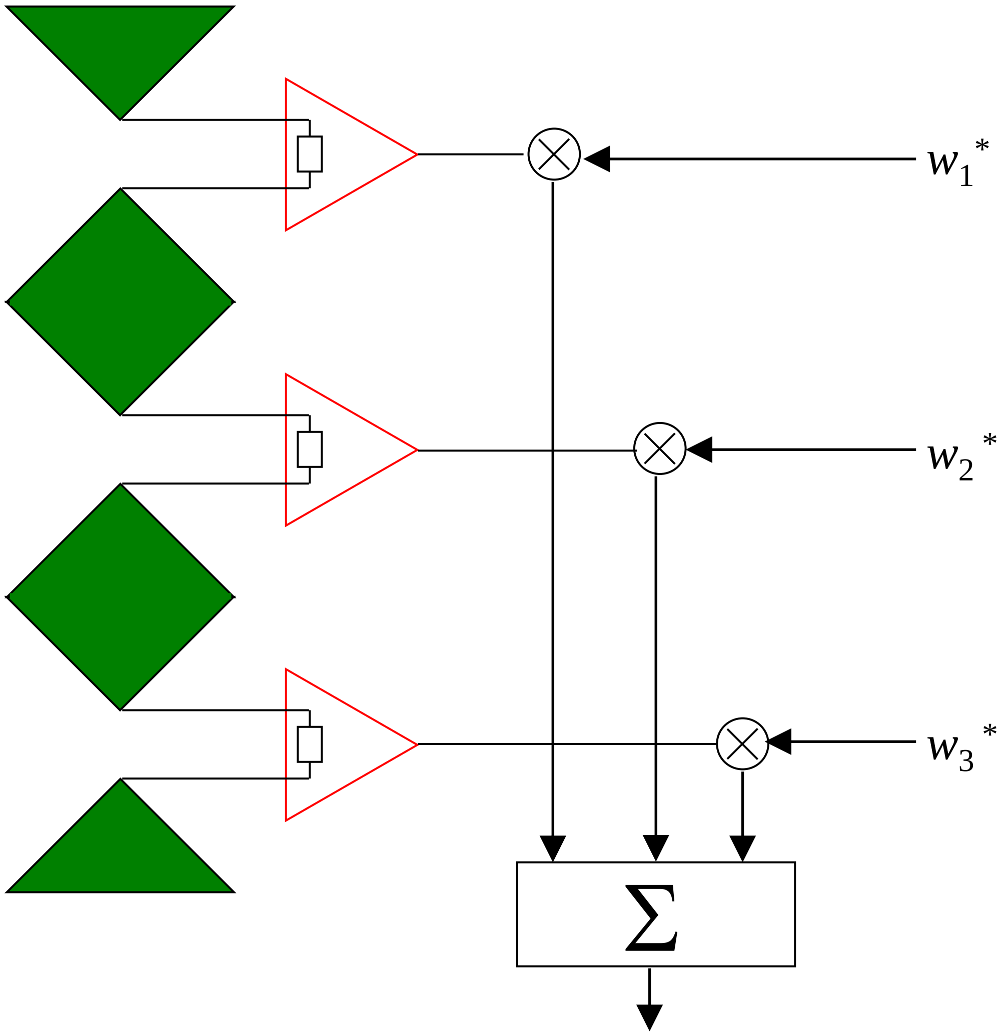
- For ASKAP, we independently form beams on 1 MHz channels.

Signal Path Including Beamformer



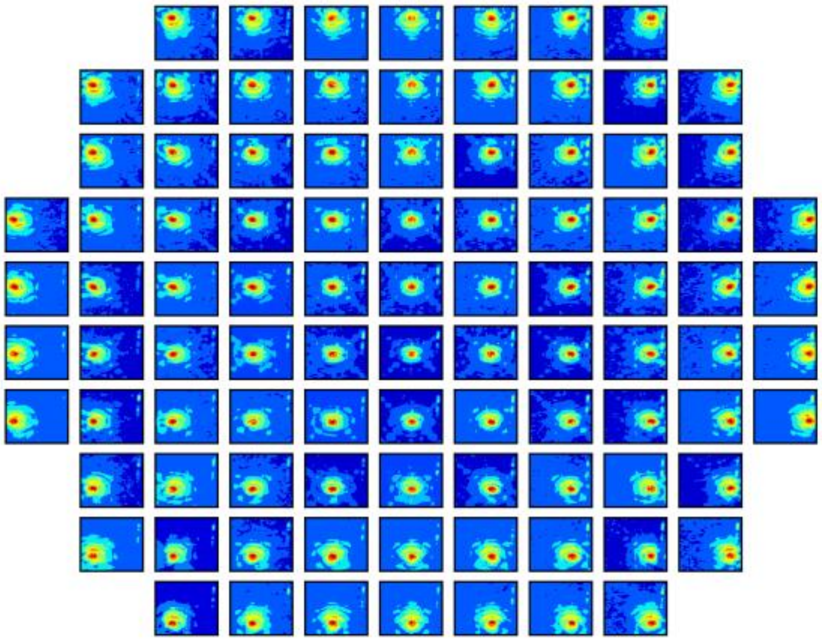
Forming Beams – Signal Processing Perspective

- Amplifiers are connected to the inside corners of each dipole antenna.
  - A single diamond patch contributes to several elements (ports).
- The signal from each element is digitally sampled.
- Samples from each port are multiplied by a corresponding complex weight.
- Weighted voltages are summed to a single number.
  - This is done for each frequency channel and beam.



Forming Beams – Sky Perspective

- Each ASKAP PAF has 188 elements.
- Each element has its own view of the sky (radiation pattern):
- We can design a set of beams that suit our needs by combining the signals from these elements.
- The resulting beam is a linear combination of all components.
- If we can define our desired beam properties, we can obtain weights by fitting for the closest match over all possible combinations.



Beamforming in Practice

- PAFs typically use an adaptive beamforming approach.
  - Beams are formed in response to measured parameters, rather than built in.
- Just like Phil's talk – phase is very important.
  - Most of what defines a beam is the geometric path length between elements.
- Each element has it own amplifier, with unique phase characteristics.
- Each element emits thermal radiation that is received by its neighbours.
- Adjacent elements do not receive completely independent sky signals.
  - So-called "embedded" element patterns are different to isolated elements (and also vary across the array due to its finite size).

- Weight calculation depends on theoretical models of the array, and / or parameters measured on the sky.
- The number of measurements required depends on the level of control you need over the beam properties, and accuracy of available models.

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:

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

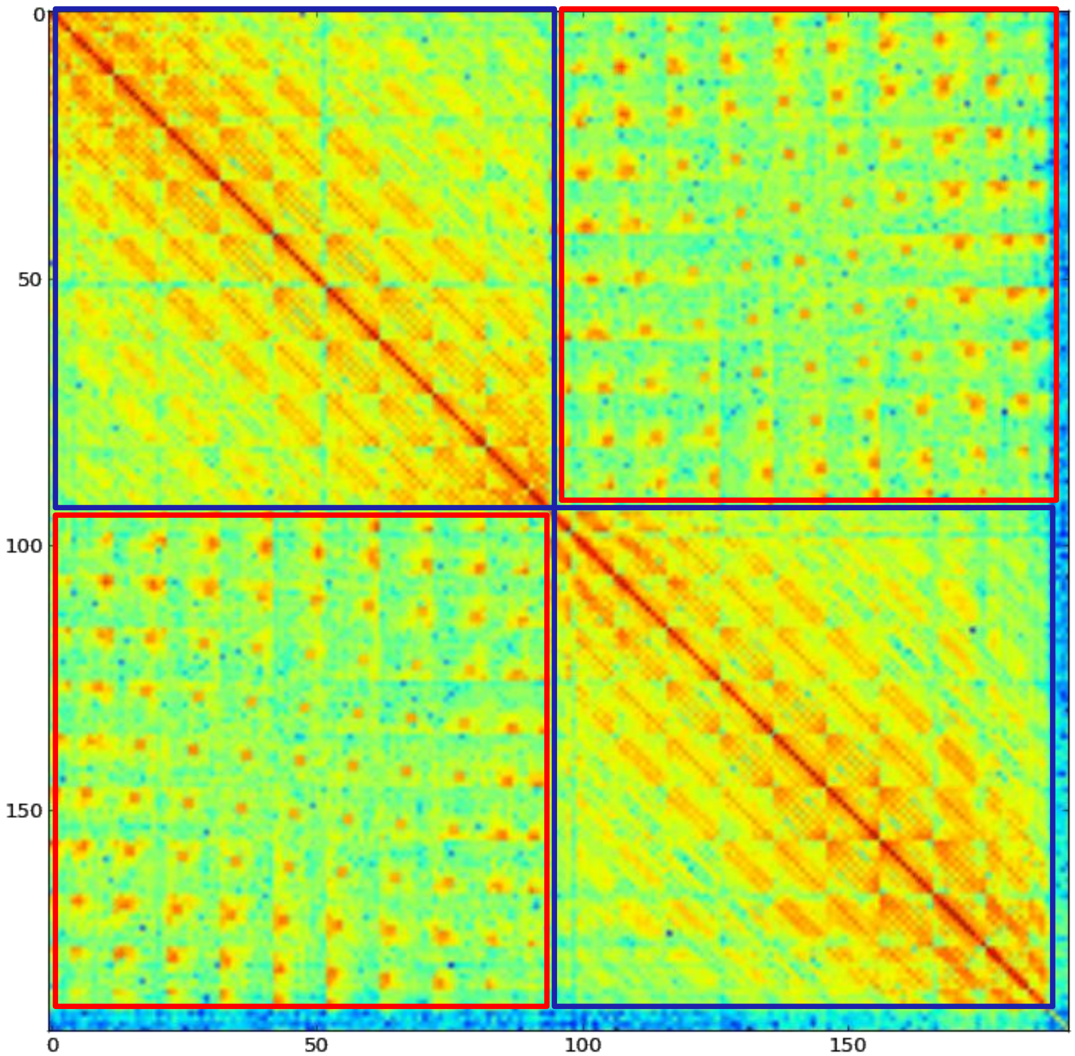
Noise covariance matrix

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

PAF Port Correlations – The ACM

- Receiving elements are closely packed.
  - Thermal emission from near neighbours and incoming radiation correlates strongly in neighbouring ports.
  - Visible structure mostly due to polarisation and port geometry.

- Computing the ACM is expensive – same as a 188-antenna array!



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Weight vector for beam k

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

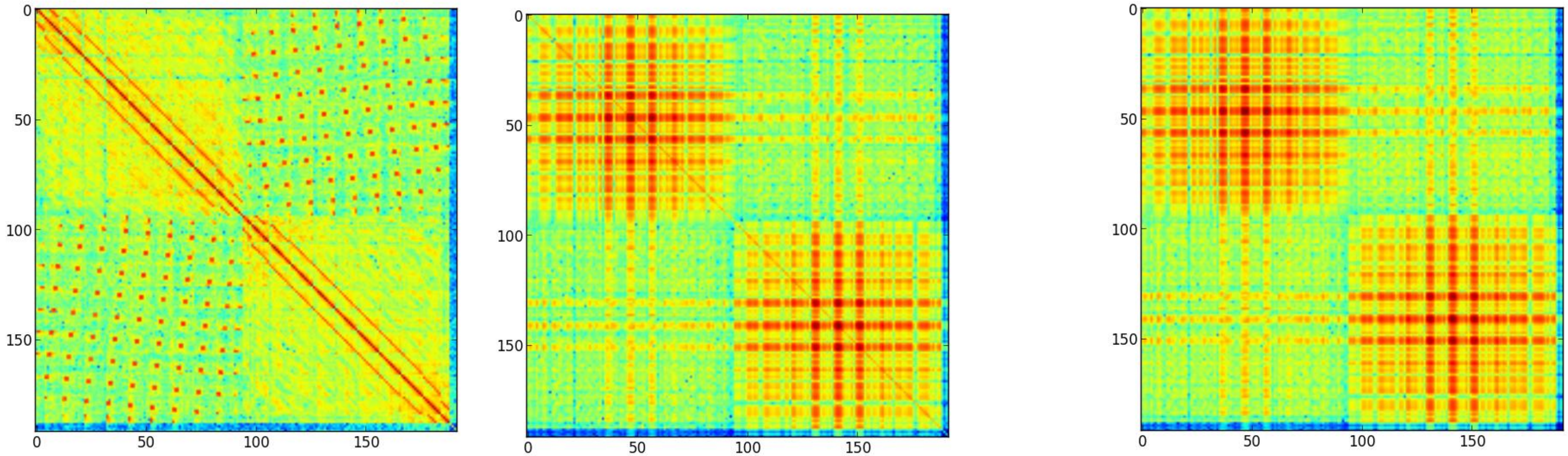
Obtaining a Steering Vector

- Can be done using single-dish ACM observations.
  - Pointing the antenna at a strong source yields: $\widehat{\mathbf{R}}_{s+n}$
  - The required steering vector is the Eigenvector of the difference corresponding to the dominant eigenvalue λ (see Landon et al. 2010):

$$\left[\widehat{\mathbf{R}}_{s+n} - \widehat{\mathbf{R}}_{n}\right]\mathbf{v} = \lambda\mathbf{v}$$

- If you have an interferometer, you can measure the steering vector directly by pointing a reference antenna at a strong source.
  - With ASKAP, we can do this using the normal correlator by loading single-port weights to the antenna under test.

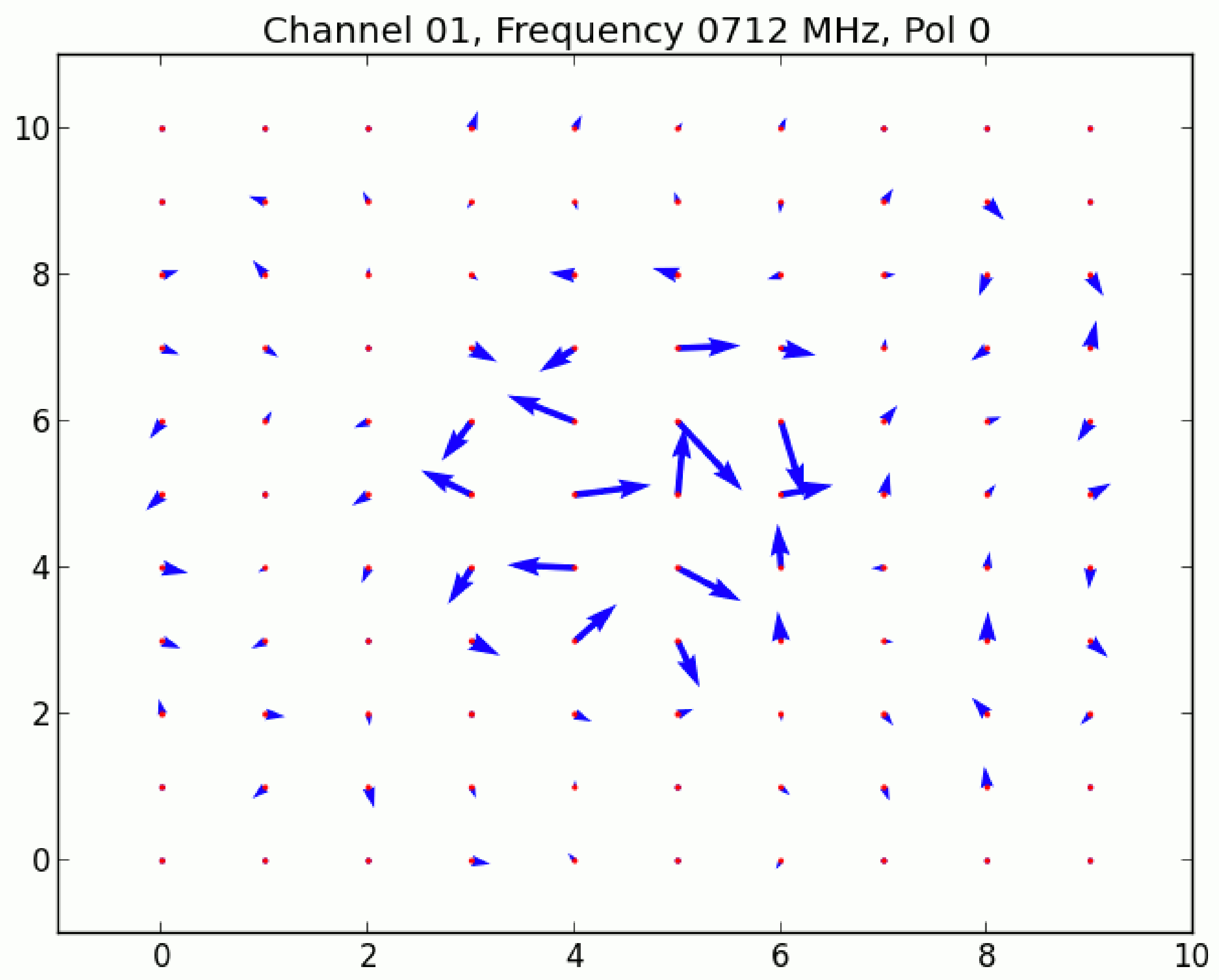
Single-Dish Beamforming on the Sun



$\widehat{\mathbf{R}}_n$ $\widehat{\mathbf{R}}_{s+n}$ $\widehat{\mathbf{R}}_{s+n} - \widehat{\mathbf{R}}_n$

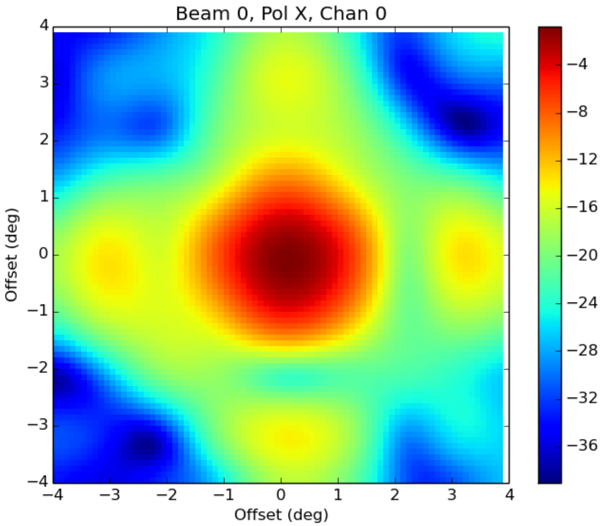
- Steering vector is the dominant Eigenvector of the difference.
- The Sun dominates the noise in the above example. This gives the weights high significance. Weaker sources have proven less effective.
- To make offset beams, point the antenna off boresight when measuring the steering vector.

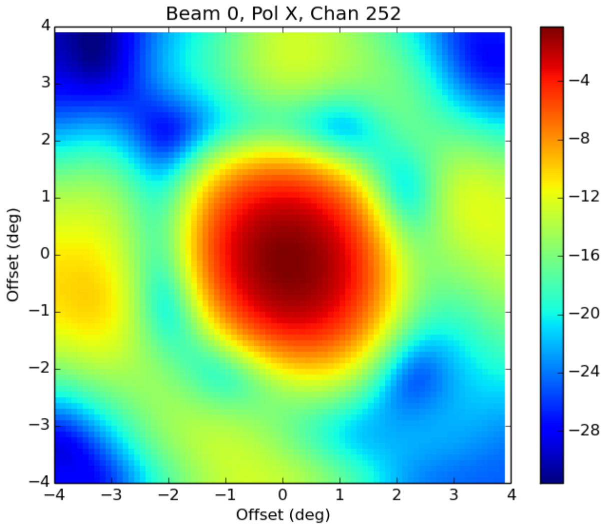
Example of ASKAP Beam Weights



Maximum Sensitivity Beam Shape

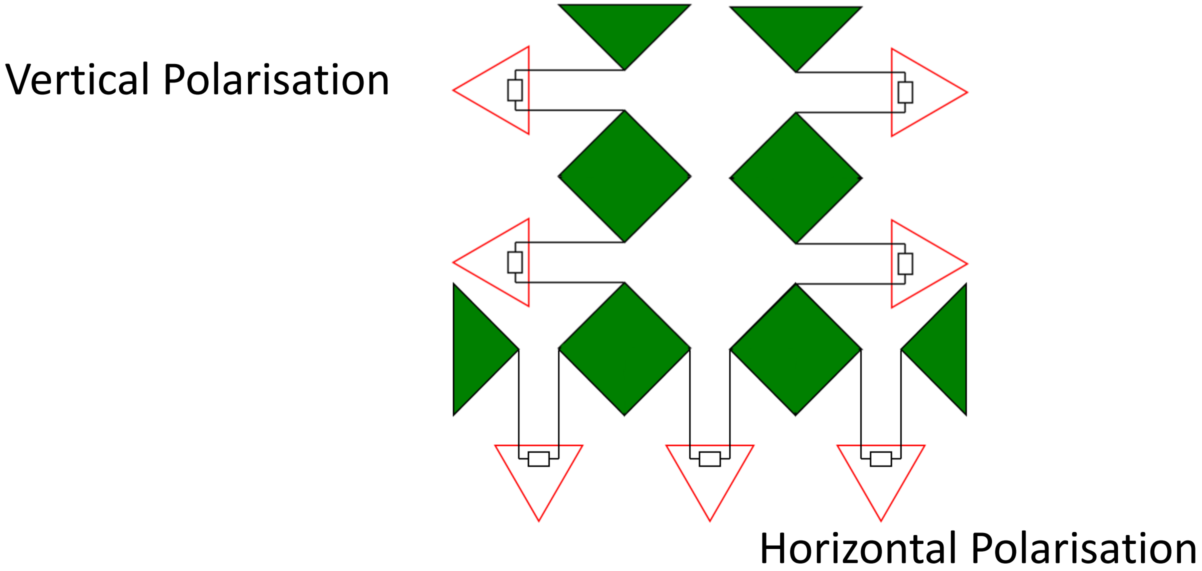
- Maximum sensitivity beamforming does not constrain the shape of the beam, its symmetry, side-lobe levels, etc.
  - Good for detecting point sources, but may not be optimal for high dynamic range imaging.
- In fact, beam pattern measurements show higher side-lobes than horn feeds using tapered illumination (and main lobe squashing).



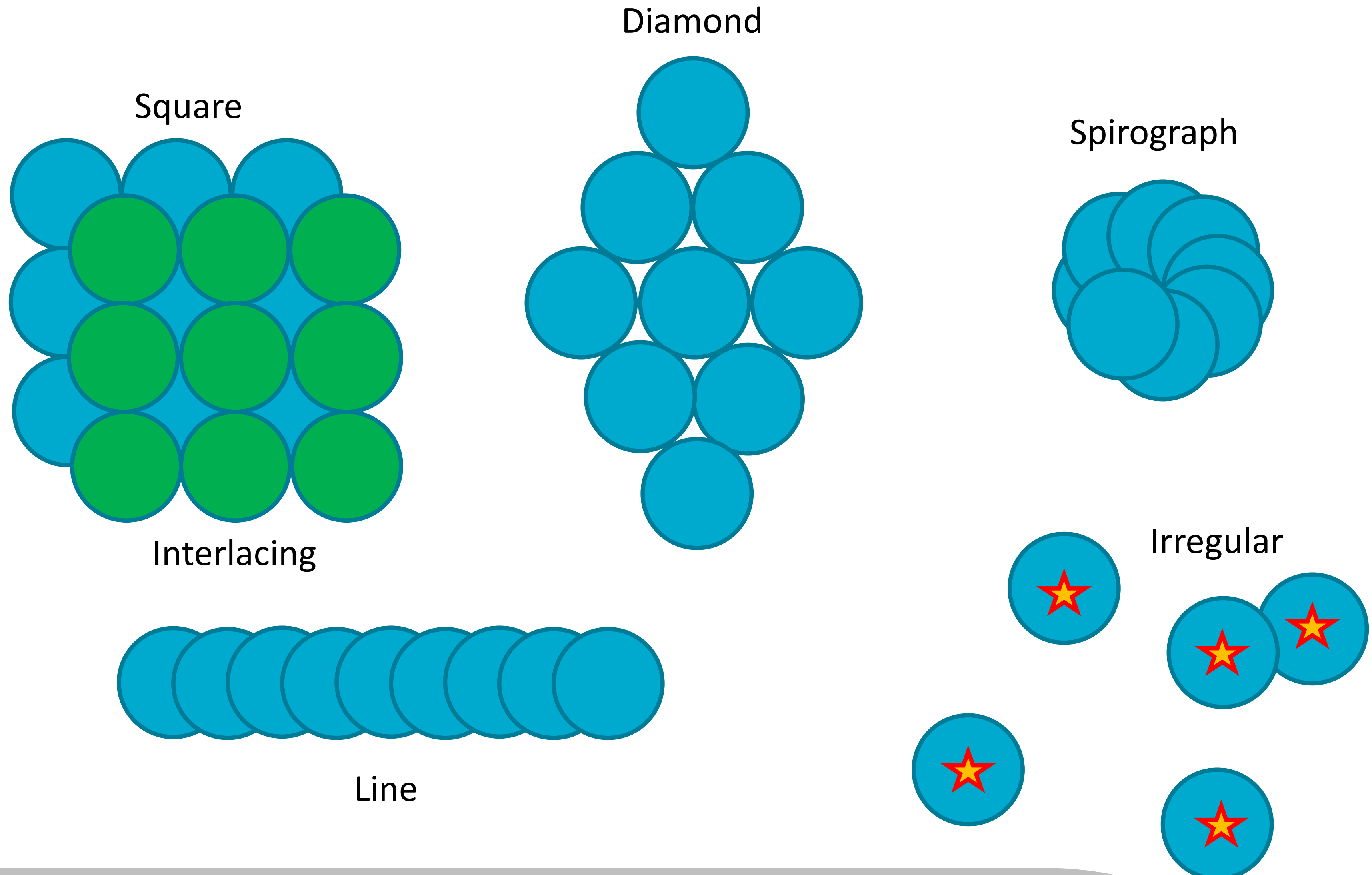


PAF Polarisation

- 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 cross-polarisations.
  - At the moment, we restrict the beam to contain like-polarised elements only.



Beam Footprints



Conclusions

- As we have seen this week, interferometry makes use of limited spatial frequency information to reconstruct an image.
- This process involves many assumptions:
  - The system and the sky are unchanging over the observation time.
  - The primary beam and the synthesised beam shapes are known.

- PAFs grant some degree of control over these parameters.
  - Adaptive beamforming vs fixed physical feeds and structures.
  - We are still learning how to take advantage of this power!

- More complex schemes may be possible in future:
  - Learn how to optimise beams for specific science goals.
  - Null out the signal from satellites as they move across the sky.

Thank you

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