Phased Array Feeds

A new technology for multi-beam radio astronomy

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Outline

- Review of radio astronomy concepts.
  - Single antenna response to a distant point source (diffraction limit).
  - Dish antenna feeds, illumination and primary beam shape.
  - Imaging the primary beam with interferometry.

- Short history of phased arrays in radio astronomy.
- The use of phased arrays as dish antenna feeds.

- The mechanics of forming electronic beams.
  - How beam-forming works (from several perspectives).
  - Optimising beams for science.

Single antennas - the diffraction limit

- 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 at optical wavelengths, but in radio astronomy it is typically what defines the "primary beam" of a telescope.
- The "Airy disk" commonly associated with diffraction due to a circular aperture is also the sensitivity pattern (beam) of a uniformly illuminated parabolic reflector (John's talk).
- 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.

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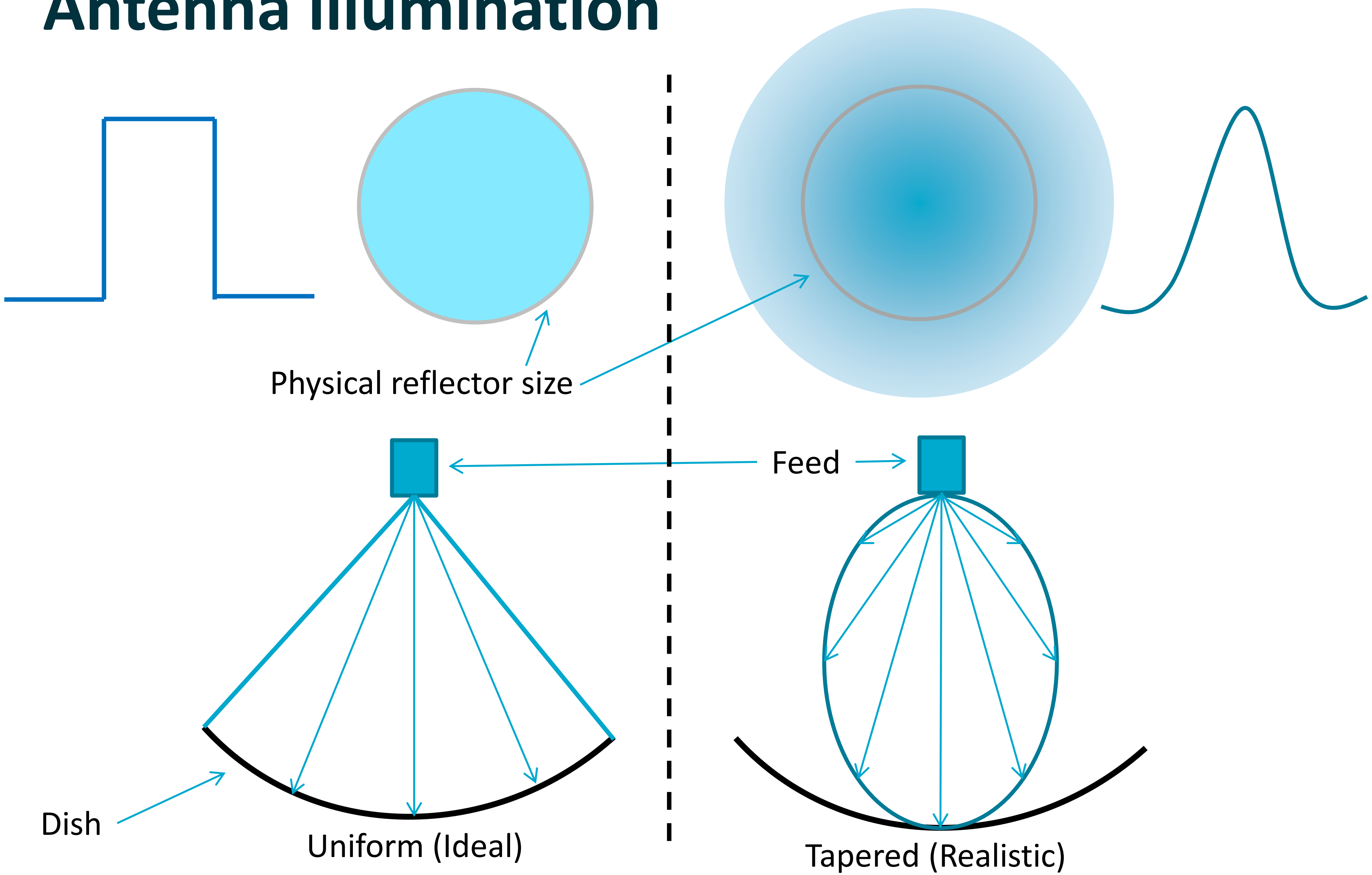
Traditional radio telescope design

- 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 (Christoph's talk).
  - 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 rapid cut-off, which is unphysical.
  - Tapered illumination must balance efficiency with spill-over and side-lobes.

Antenna illumination



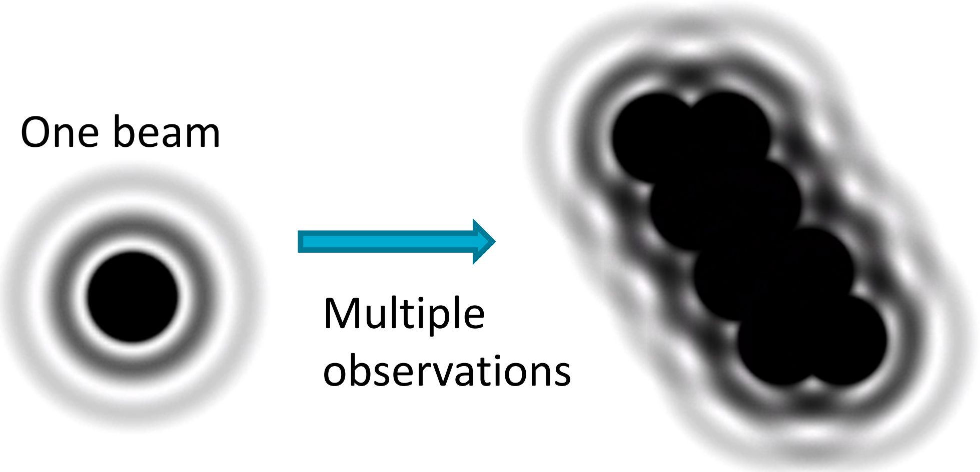
Gaussian primary beam approximation

- We often approximate the illumination pattern as a 2D Gaussian.
  - Neglecting blockage, reflections from support struts, etc.
- The point source response (beam) of a radio telescope is the 2D Fourier transform of its illumination pattern.
- The FT of a Gaussian is another Gaussian, so tapered illumination 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. Keep this in mind as a starting point!

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

Imaging with a single antenna

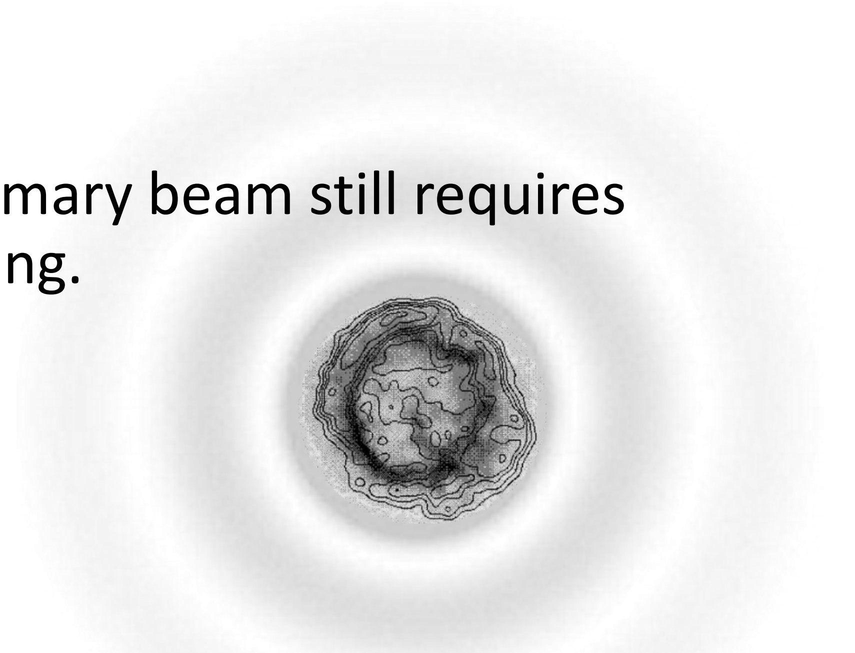
- A single dish has one pixel. It can only record the total power captured within its primary beam.
  - To make an image, the single beam must be pointed in different directions and the measurements plotted on a sky map.
- If the primary beam shape is known, it is possible to mosaic over a given field with near-uniform sensitivity (Josh's talk).
  - With a single dish, overall resolution is set by the diffraction limit.



Imaging with an interferometer

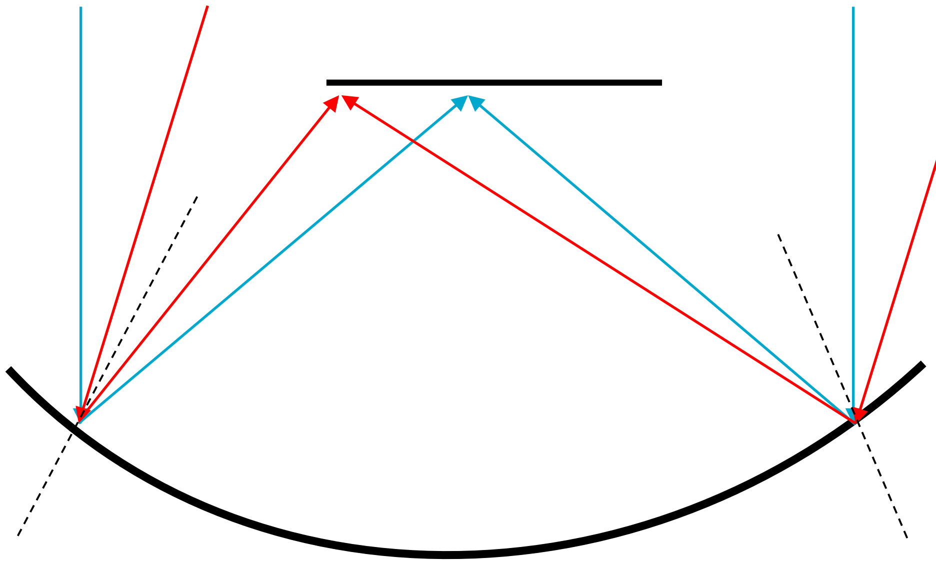
- Correlating the signals from several single-dish antennas allows you to make an image within the primary beam.
  - Resolution now limited by the longest distance between any two antennas and the field of view is limited by the primary beam size.
- Array antennas are usually smaller than single dish antennas, making the primary beam larger.
  - This provides a greater field of view.
- Imaging of areas larger than the primary beam still requires multiple observations and mosaicking.

- How can we improve on this?



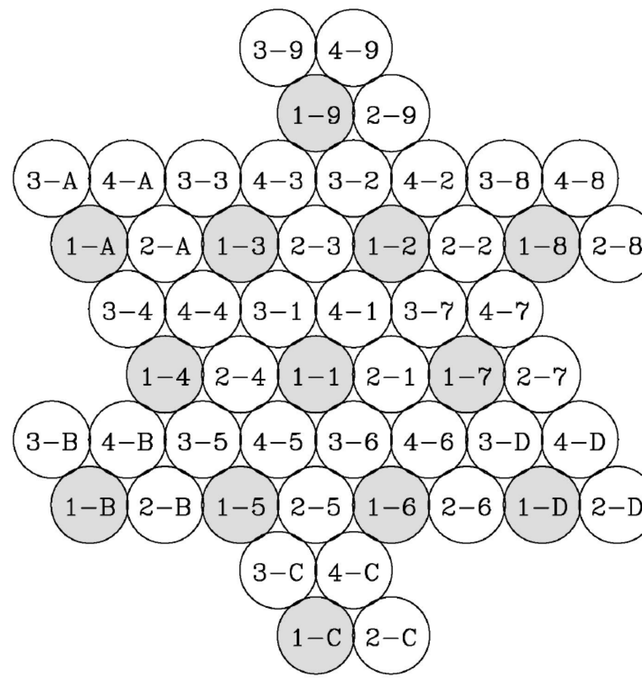
Room for improvement – off-axis beams

- Like an optical telescope, a parabolic radio dish will focus off-axis rays to an off-axis point in the focal plane.
  - Recall John's talk – off-axis plane waves don't add in phase at the focus, but you can find a focal plane location that compensates for the path differences.
  - Off-axis sources suffer from coma distortion with a parabolic reflector, but this is small within a reasonable area around the centre.



Multi-beam feeds

- 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 (several previous talks).



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 like beams on different antennas.
  - Can mosaic these simultaneous beams using standard techniques, or perhaps jointly de-convolve all the visibilities with future software.

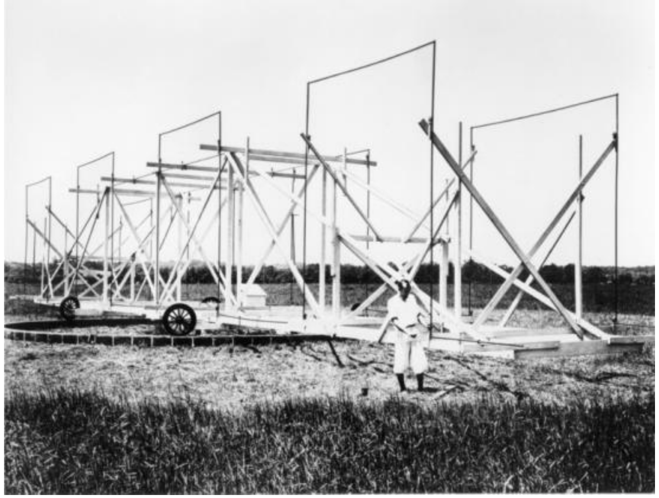
- Building multi-beam feeds for small antennas requires new receiver technology.
  - Multi-horn systems are cumbersome and expensive, hard to mass produce.

- 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 dipole 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.

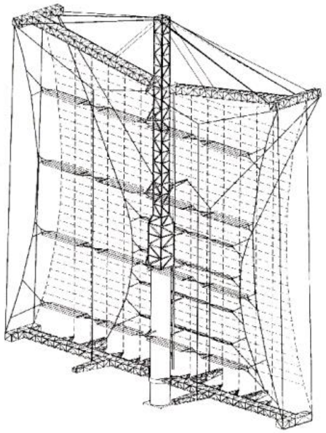
Jansky's antenna, Bell Labs, 1932. Operating at 20.5 MHz

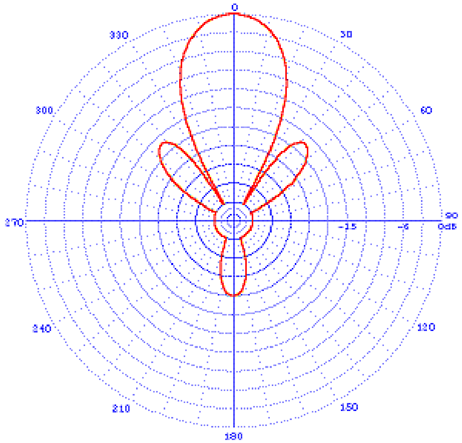


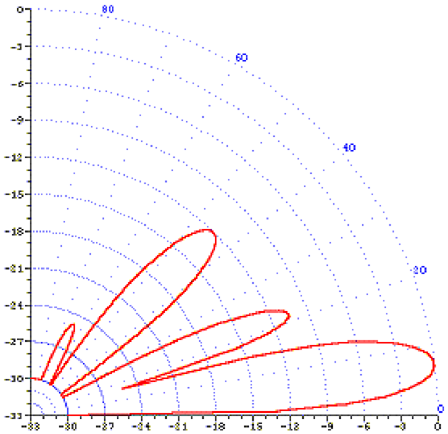
Phased arrays in communications

- 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 delays / phases) rather than moving the structure itself.

Understanding phased arrays

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

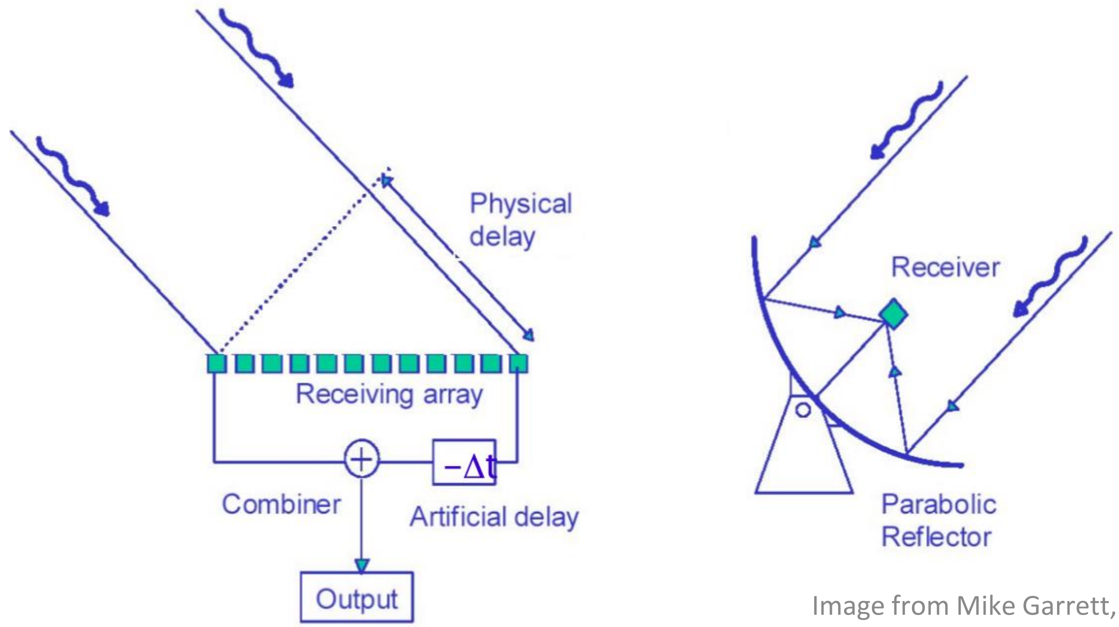
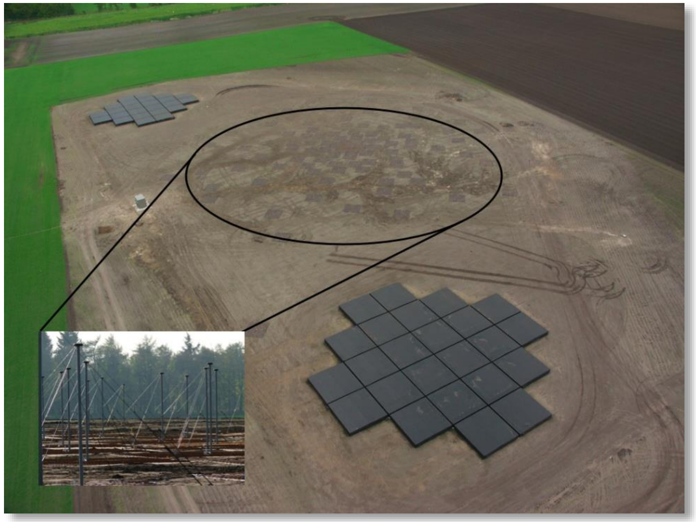
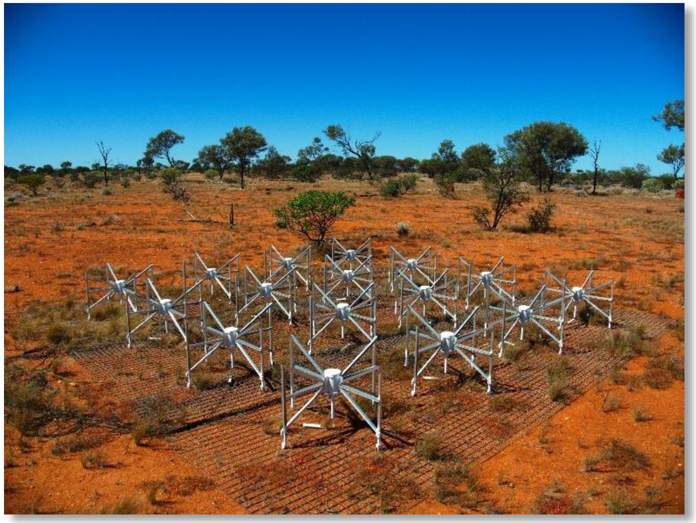


Image from Mike Garrett, Antikeythra to the SKA, 2012

Aperture arrays in radio astronomy

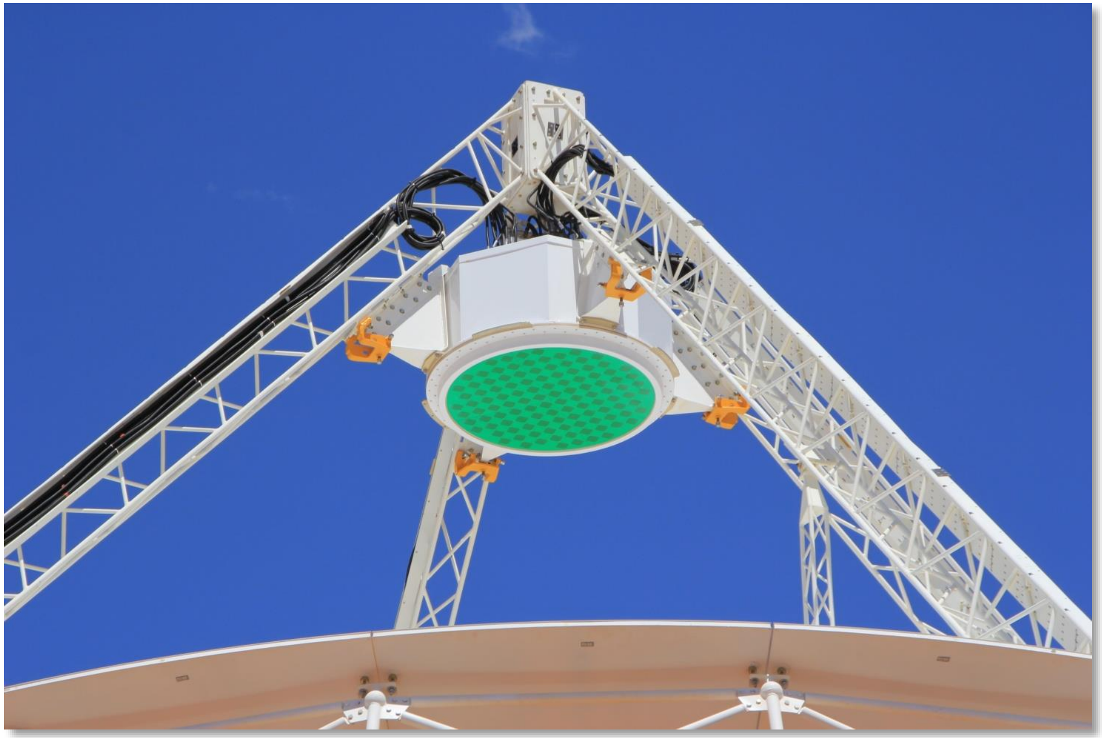
- In modern jargon, a phased array that receives radiation directly from the sky is known as an aperture array (because the elements themselves form the aperture of the telescope).
- LOFAR in the Netherlands and the MWA in Western Australia are both aperture array telescopes.
  - Aperture arrays will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

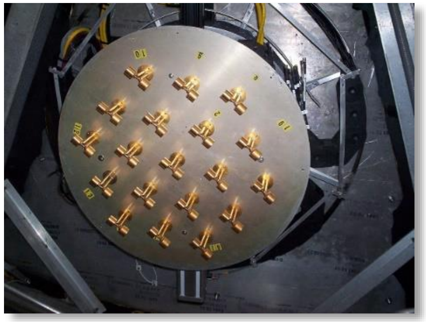


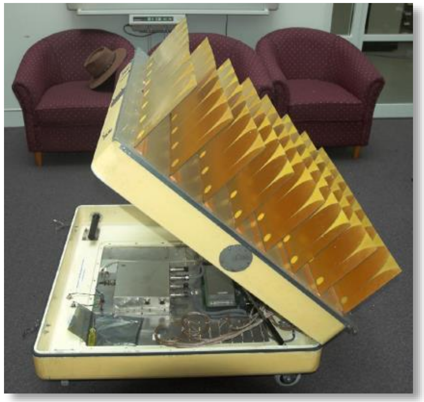


Phased array feeds in radio astronomy

- Dense arrays can 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.

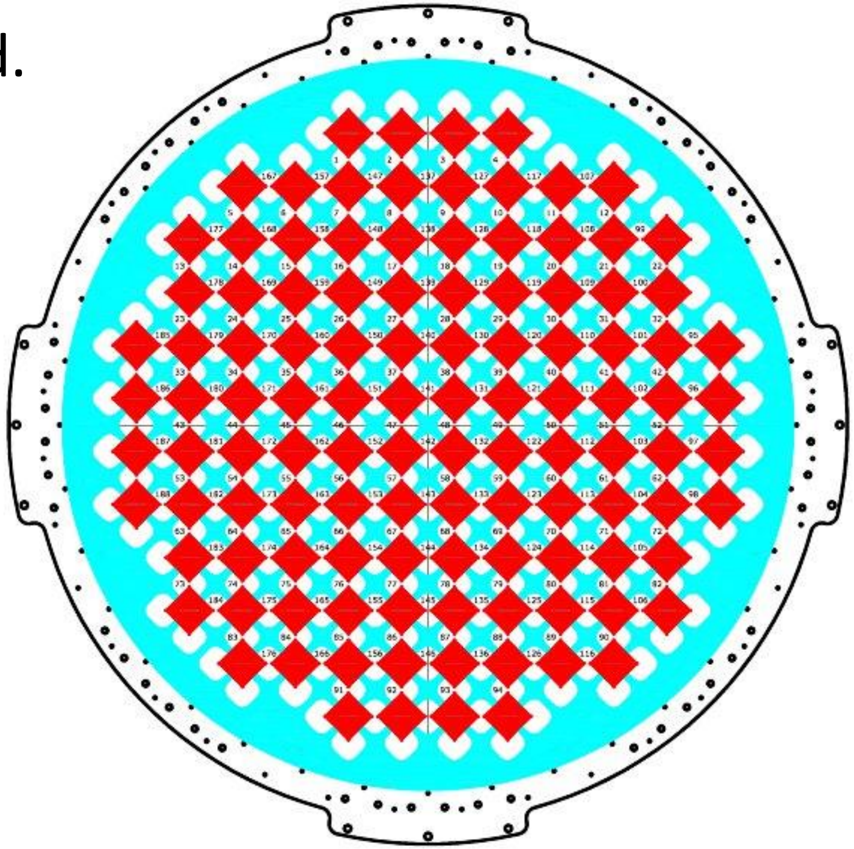




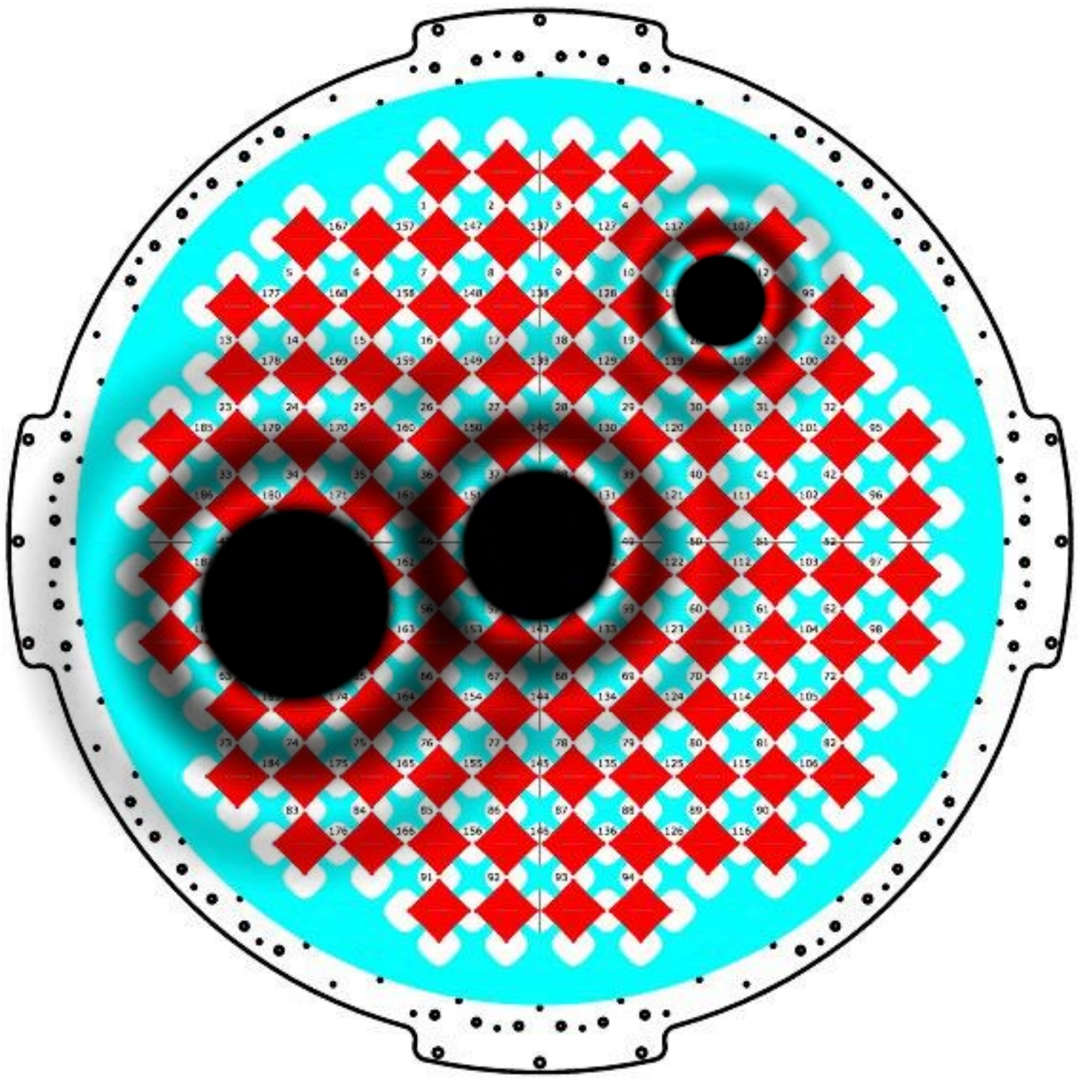


ASKAP’s chequerboard PAF

- 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 1.8 GHz.
- 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 by analog methods – delays between elements introduced by lengths of transmission line.
  - This tends to be simple and cost effective, but restrictive.
  - 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 intensive.
  - ASKAP uses this approach.

- Either way, we must include a beam-former in the signal path, adding complexity to the telescope systems.

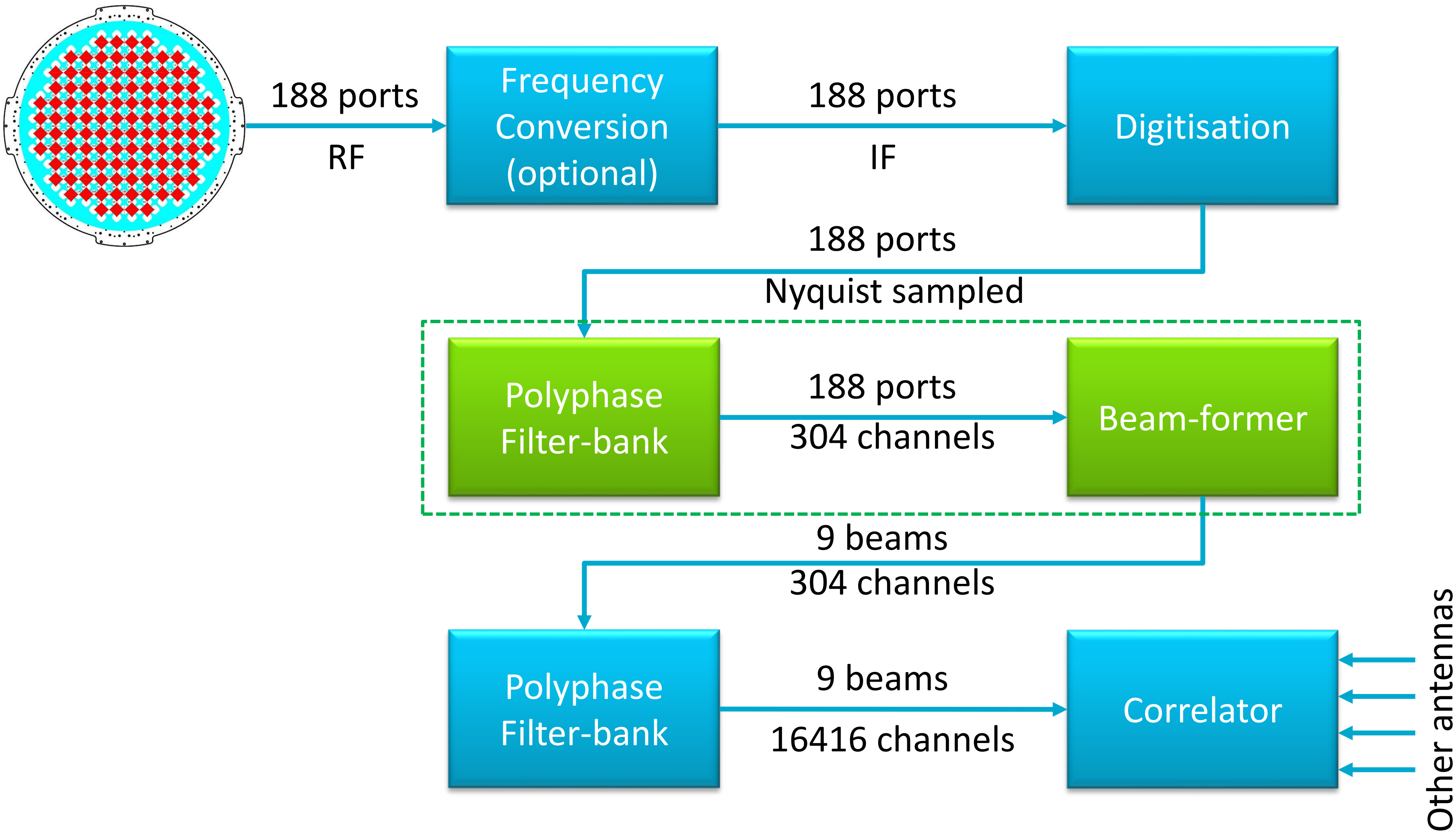
Beam-formers and bandwidth

- 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.

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

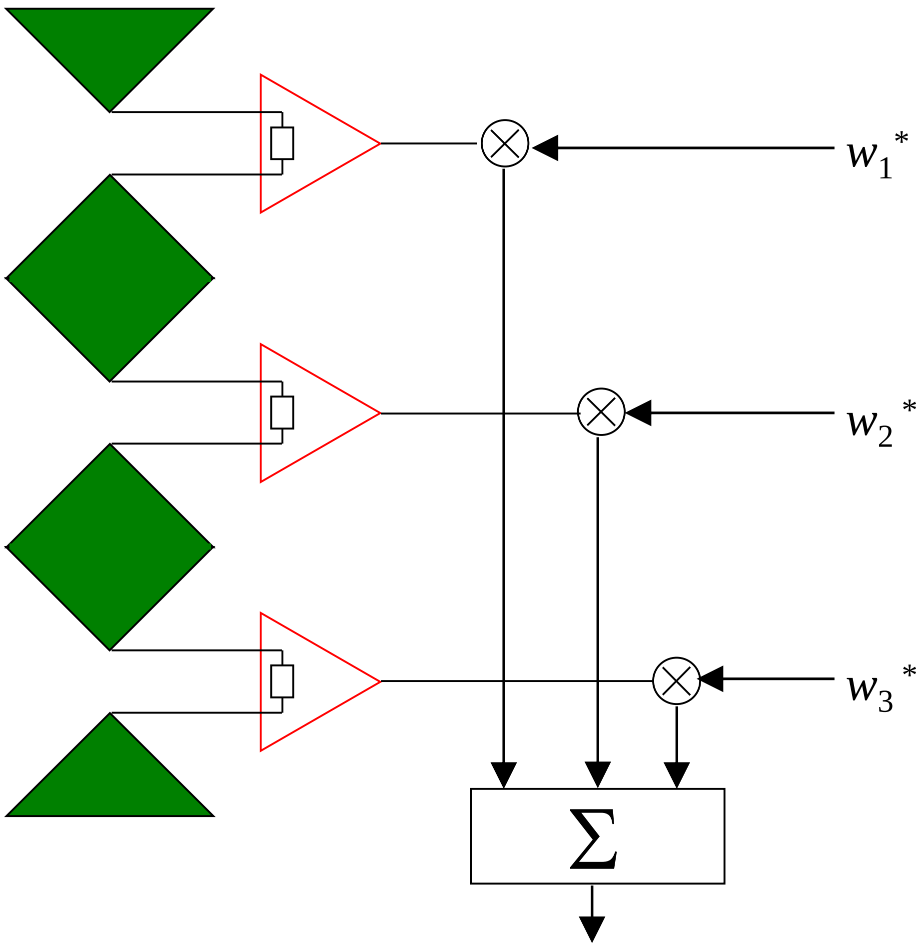
- For ASKAP, we independently form beams on 1 MHz channels.

Signal path including beam-former



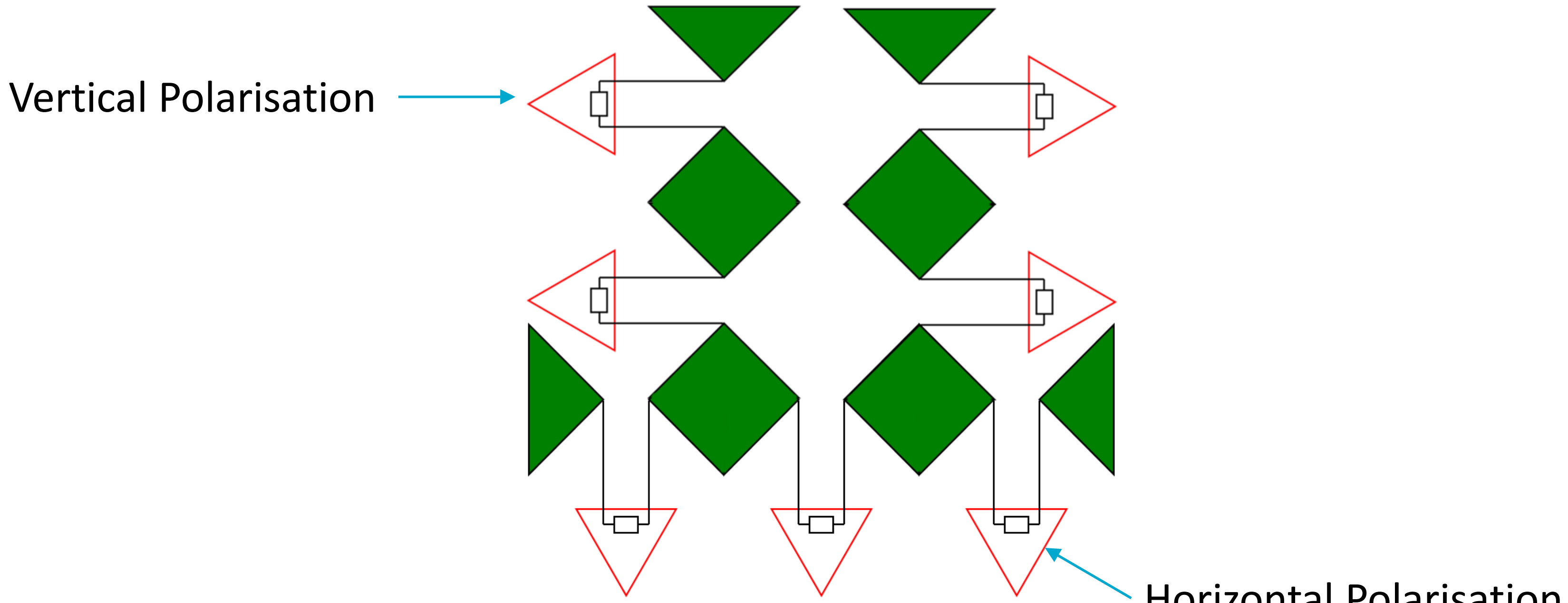
Forming beams – numerical perspective

- 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.



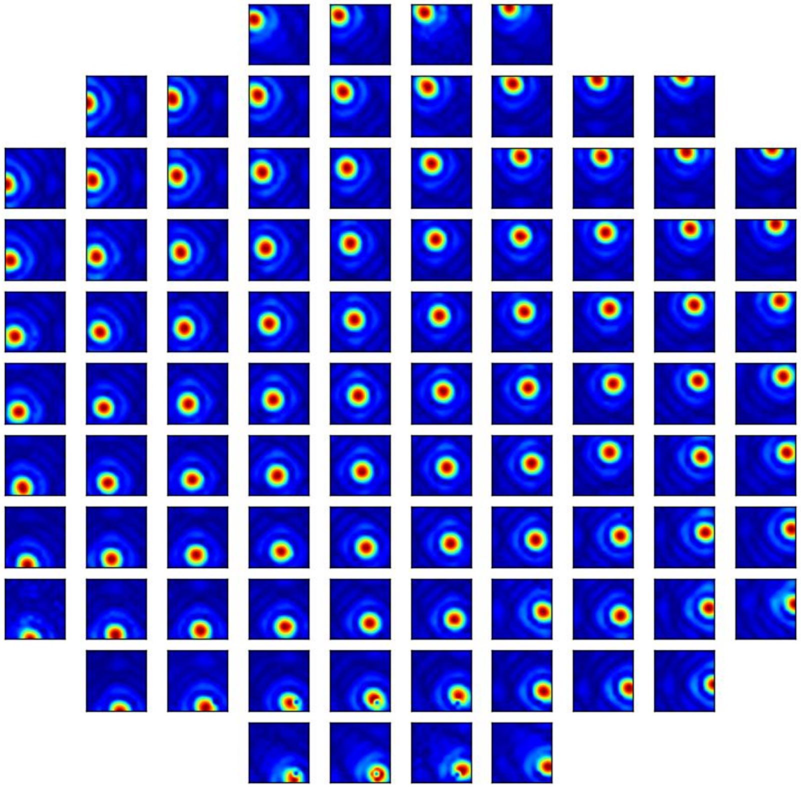
Polarisation of PAF elements

- 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 cross-polarisations.



Forming beams – visual 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 signals from these elements.
- Any formed beam is a linear combination of single port beams.
- If we can state our desired beam's properties, we can obtain weights by fitting for the closest match over all possible combinations of single elements.



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, weights are not known at the time of manufacturing.
- Much of what defines a beam is the geometric path length between individual elements.
- However, each amplifier has its own complex gain. 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 sky 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 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:

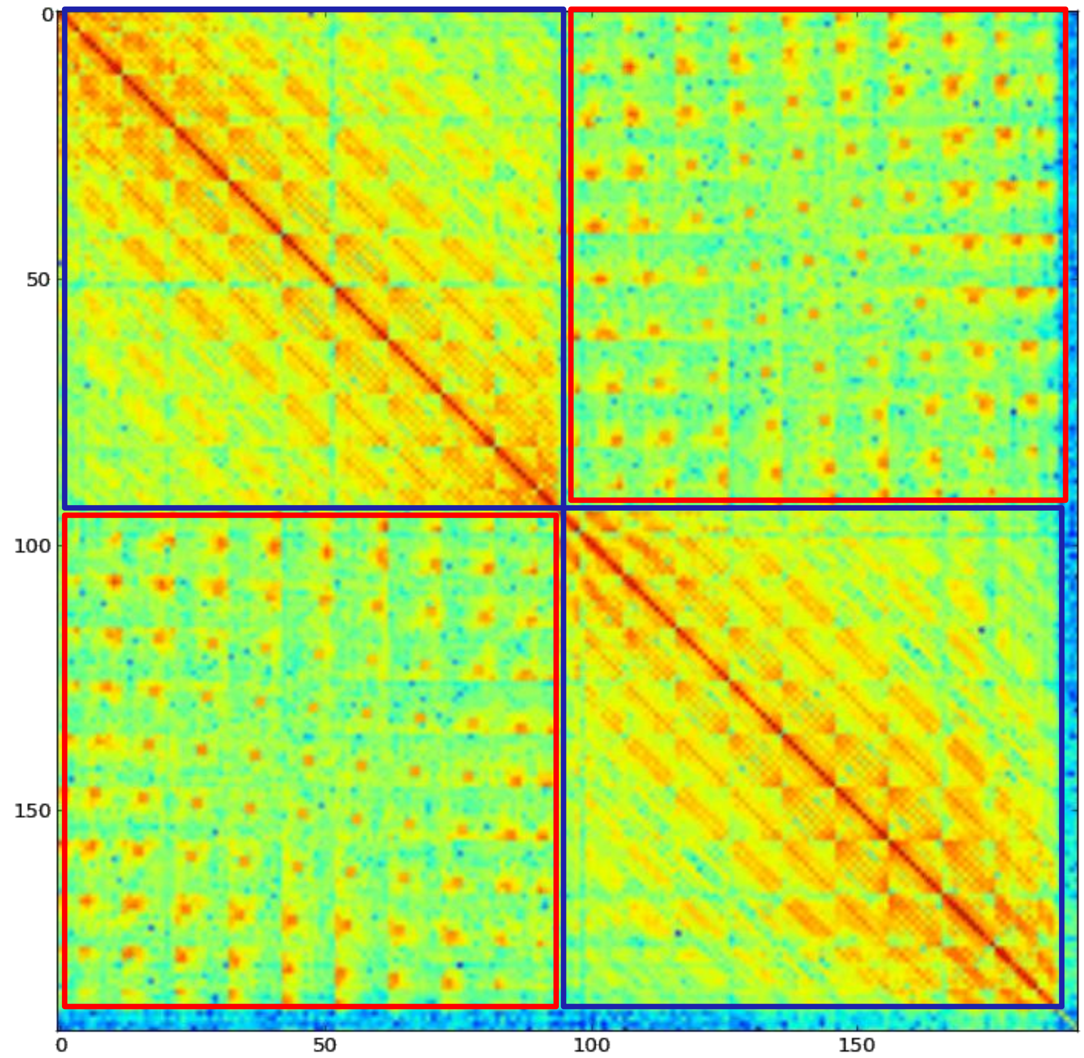
$$\mathbf{w}_k = \widehat{\mathbf{R}}_n^{-1} \hat{\mathbf{v}}_k$$

Noise covariance matrix

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

PAF element correlations – the ACM

- The beam-former must also compute the Array Covariance Matrix.
  - This is expensive, so only done for a subset of time samples.
- Local thermal emission and sky signals correlate in neighbouring ports.
- ACM structure is mostly due to polarisation and chequerboard geometry.



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Beam *k* output at time *i*

Weight vector for beam *k*

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

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*)

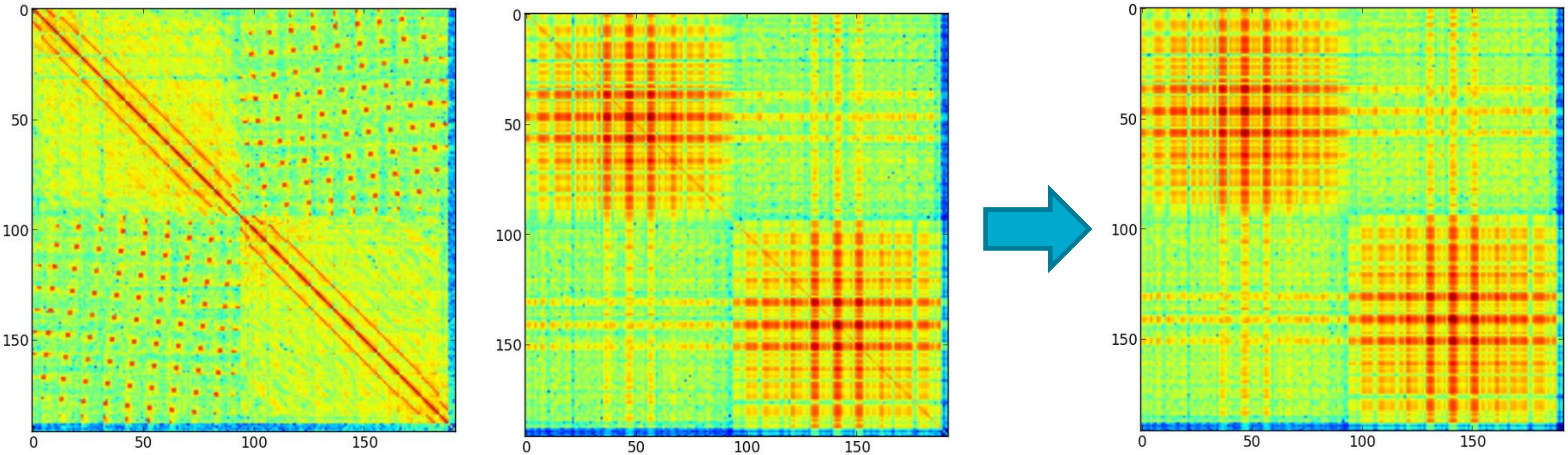
Obtaining a steering vector

- Can be done using single-dish ACM observations.
  - Recording ACMs while observing a strong source yields: $\widehat{\mathbf{R}}_{s+n}$ (Signal, Noise)
  - 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, but this is time consuming.

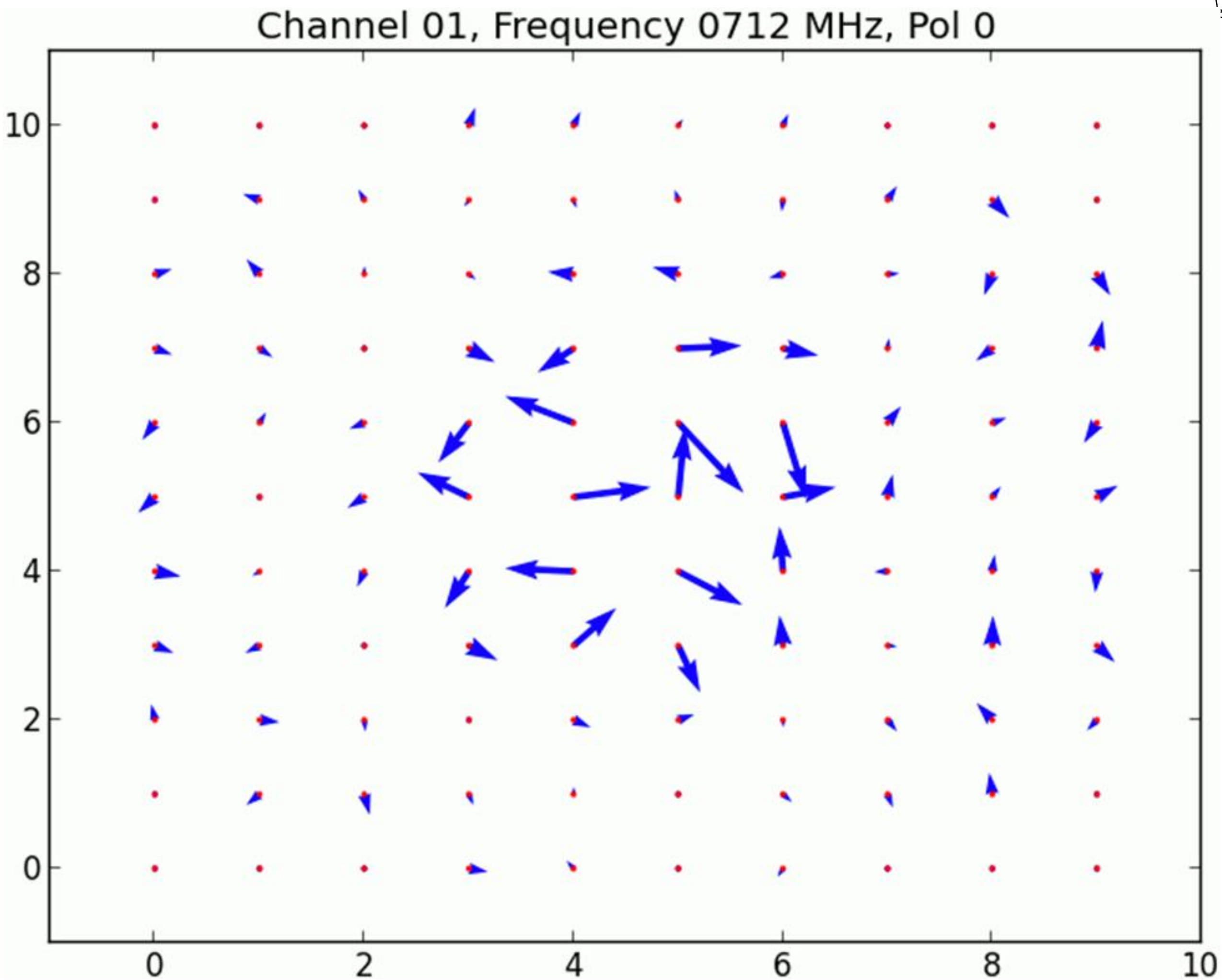
Beamforming on the Sun

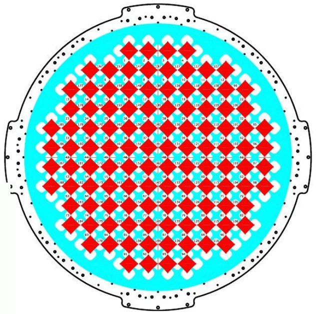


$\widehat{\mathbf{R}}_n$ $\widehat{\mathbf{R}}_{s+n}$ $\widehat{\mathbf{R}}_{s+n} - \widehat{\mathbf{R}}_n$

- 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 have proven 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

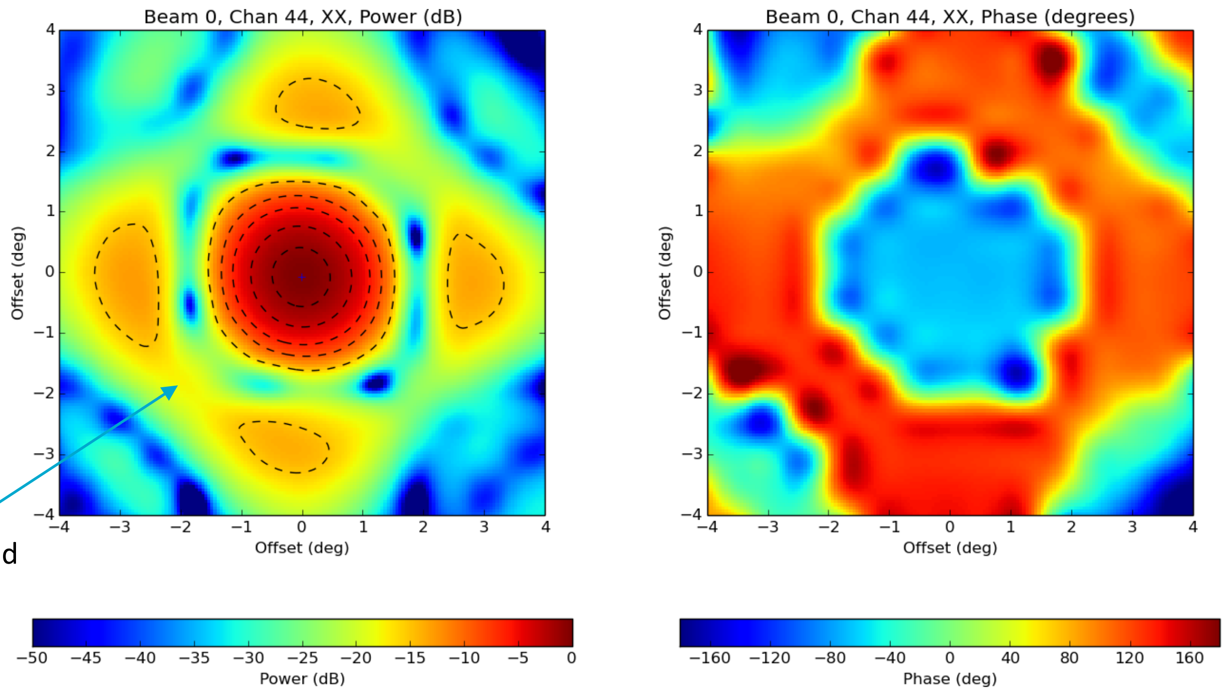




Shape of maximum sensitivity beams

- Maximum sensitivity beam-forming does not constrain the shape of the beam, its symmetry, side-lobe levels, etc.
  - Good for detecting point sources, but may not be optimal for mosaicking.
  - Holography measurements can be used to study the beam shape.

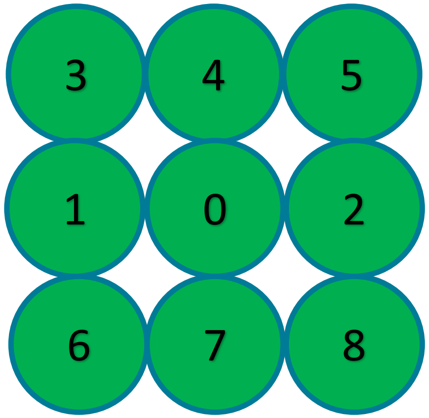
Amplitude

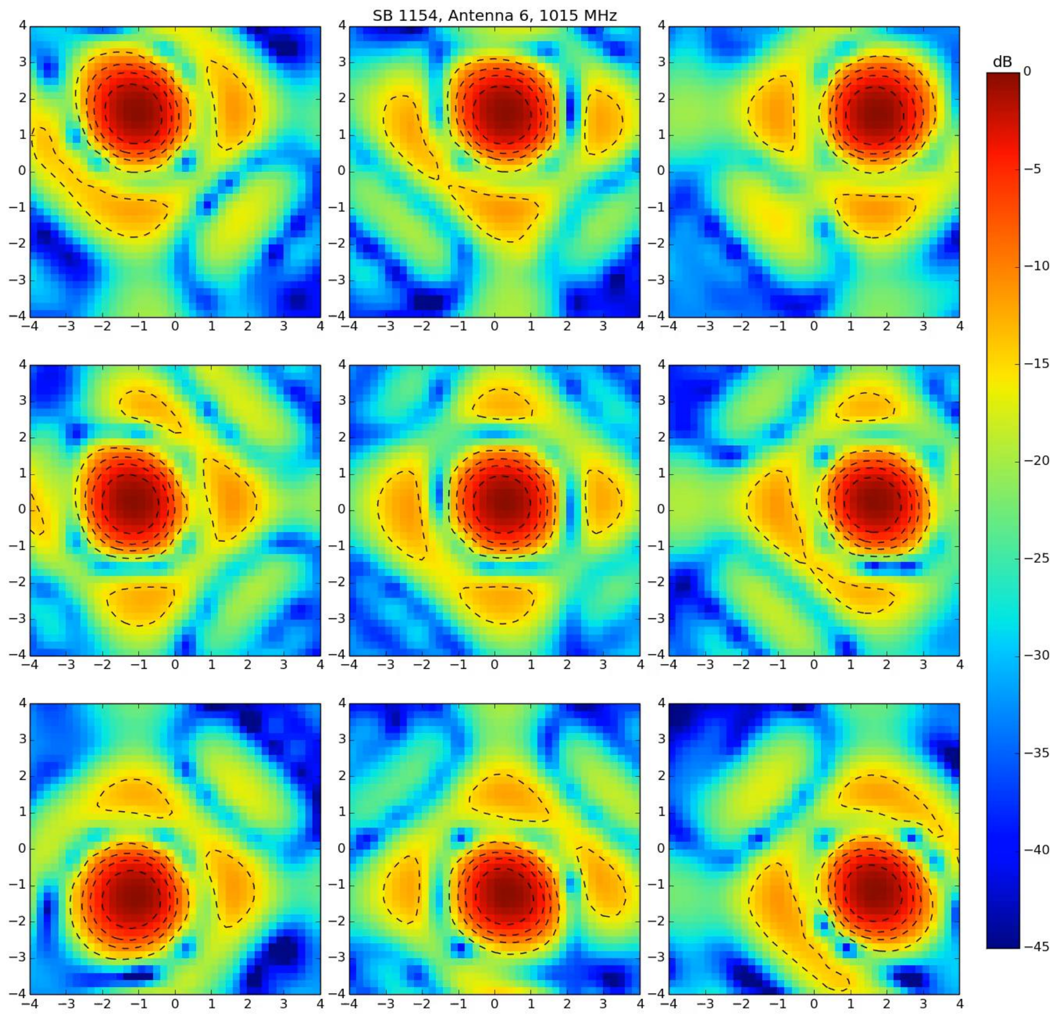


Phase

Asymmetry due to feed support structure

Offset maximum sensitivity beam shapes





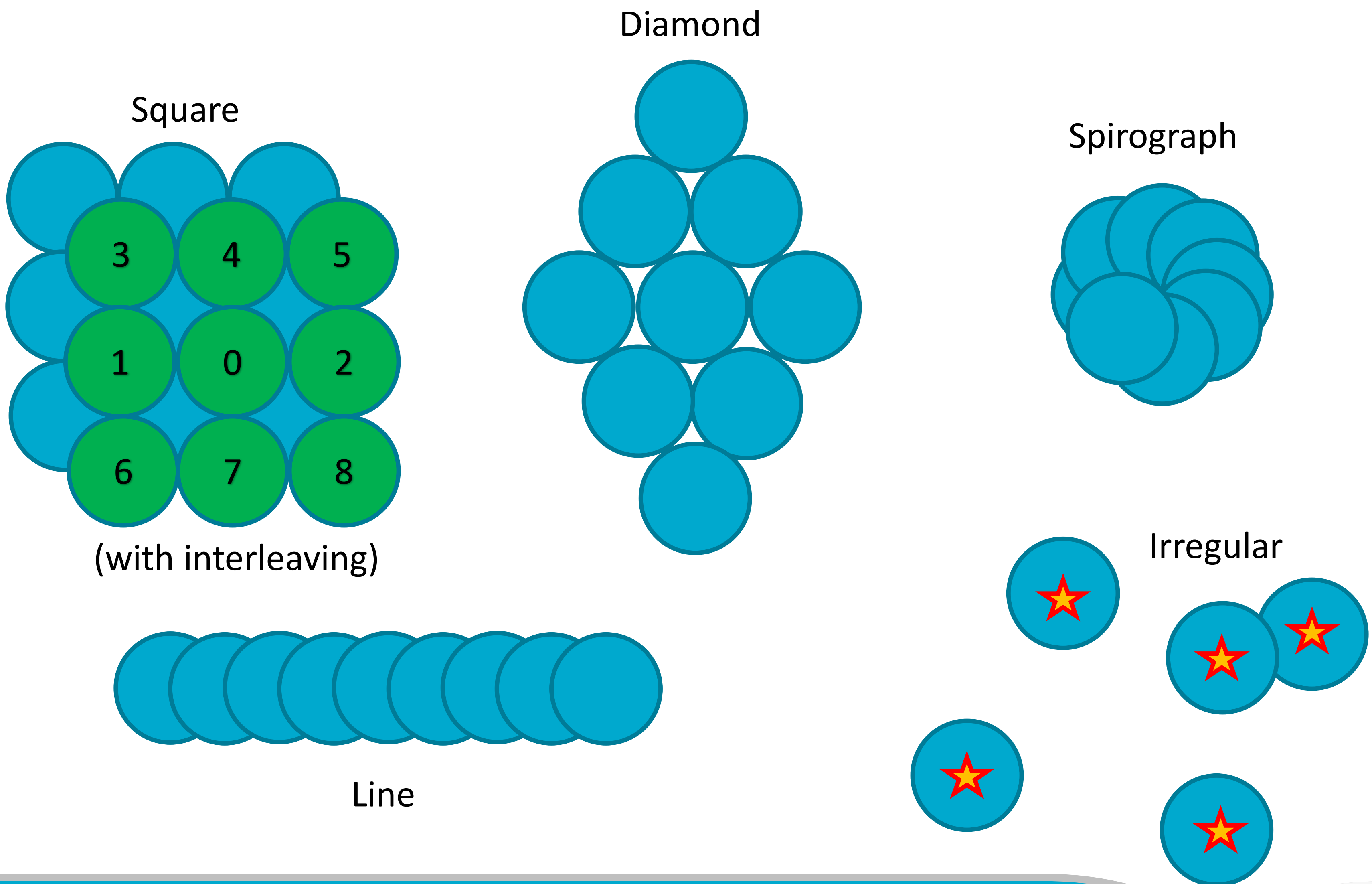
Tracking sources with offset beams

- 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.

Other beam-forming methods

- Maximum sensitivity beam-forming uses the minimum number of observational constraints.
  - An observation of a noise field and a single compact source per beam.
- Additional constraints can be used to optimise beams for parameters other than pure sensitivity.
  - Place the reference source on several points around the desired half-power contour to optimise for 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 through direct fitting.
  - This knowledge can come from electro-magnetic models, holography or both.

Example beam footprints



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 of 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.

- 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.
    - Limited by signal processing power and algorithm development.

Conclusions

- 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 over calibration intervals.
  - The primary beam and the synthesised beam shapes are known.

- PAFs increase the field of view of a radio telescope and grant some degree of control over our beams.
  - Adaptive beam-forming 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 science goals – particularly polarimetry.
  - Null out the signal from RFI sources as they move across the sky.

Thank you

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